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(12) **United States Patent**
Beeson et al.

(10) **Patent No.:** **US 8,481,977 B2**
(45) **Date of Patent:** **Jul. 9, 2013**

(54) **LED LIGHT SOURCE WITH THERMALLY CONDUCTIVE LUMINESCENT MATRIX**

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(73) Assignee: **Goldeneye, Inc.**, San Diego, CA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 249 days.

(21) Appl. No.: **12/807,770**

(22) Filed: **Sep. 13, 2010**

(65) **Prior Publication Data**

US 2012/0086028 A1 Apr. 12, 2012

Related U.S. Application Data

(63) Continuation-in-part of application No. 11/975,406, filed on Oct. 19, 2007, now Pat. No. 7,795,600, which is a continuation-in-part of application No. 11/389,311, filed on Mar. 24, 2006, now Pat. No. 7,285,791.

(51) **Int. Cl.**
G01N 21/64 (2006.01)
H01L 31/12 (2006.01)

(52) **U.S. Cl.**
USPC **250/486.1; 257/79; 313/498**

(58) **Field of Classification Search**
USPC 250/483.1, 484.2, 484.4, 486.1, 487.1;
257/79, 99; 313/483, 498
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

6,565,770	B1	5/2003	Mayer et al.
6,630,691	B1	10/2003	Mueller-Mach et al.
6,667,574	B2	12/2003	Aoki et al.
6,696,703	B2	2/2004	Mueller-Mach et al.
7,361,938	B2*	4/2008	Mueller et al. 257/94
2005/0006659	A1	1/2005	Ng et al.
2005/0269582	A1	12/2005	Mueller et al.

* cited by examiner

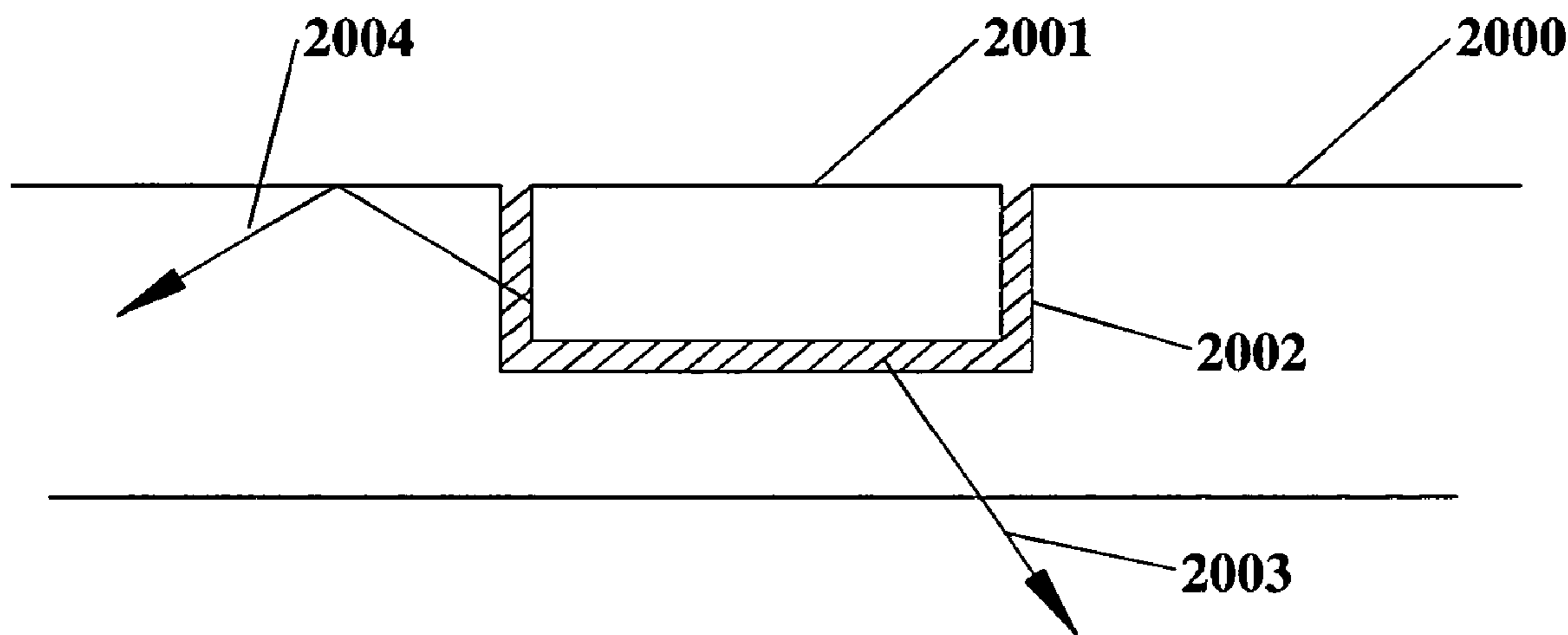
Primary Examiner — Mark R Gaworecki

(74) *Attorney, Agent, or Firm* — William Propp, Esq.

(57) **ABSTRACT**

A wavelength conversion chip is formed by depositing a wavelength conversion material on a substrate to form a layer, removing the resulting wavelength conversion layer from the substrate and then segmenting the wavelength conversion layer into a plurality of wavelength conversion chips. The wavelength conversion material can be annealed by thermal annealing or radiation annealing to increase the wavelength conversion efficiency of the chips or to sinter the wavelength conversion material to form a ceramic material. Optical coatings, vias, light extraction elements, electrical connections or electrical bond pads can be fabricated on the wavelength conversion chips.

20 Claims, 30 Drawing Sheets



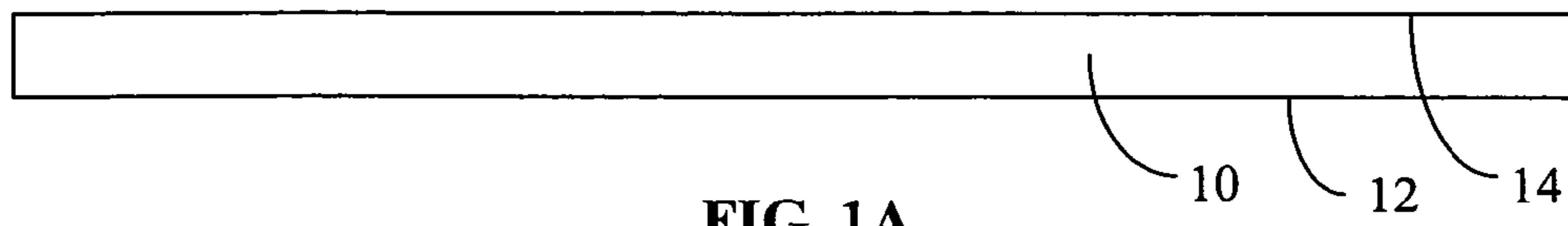


FIG. 1A

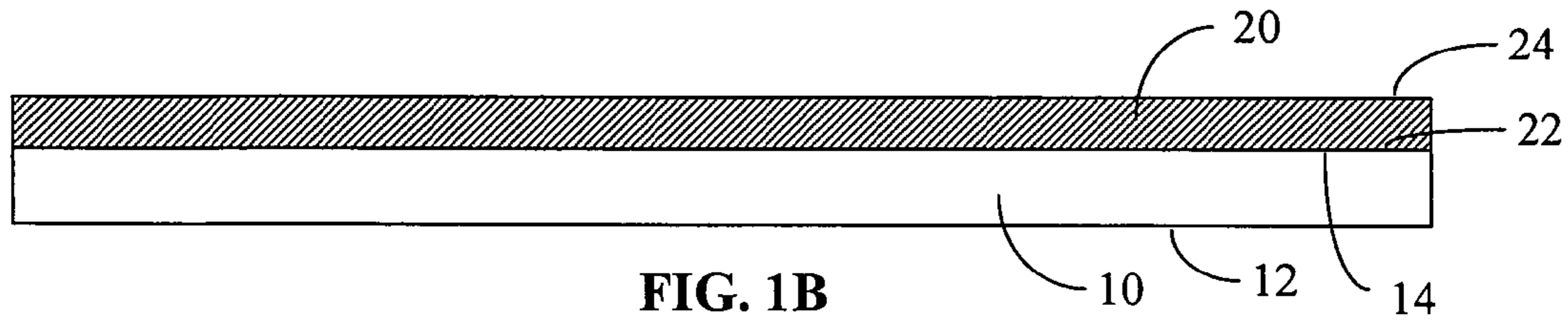


FIG. 1B

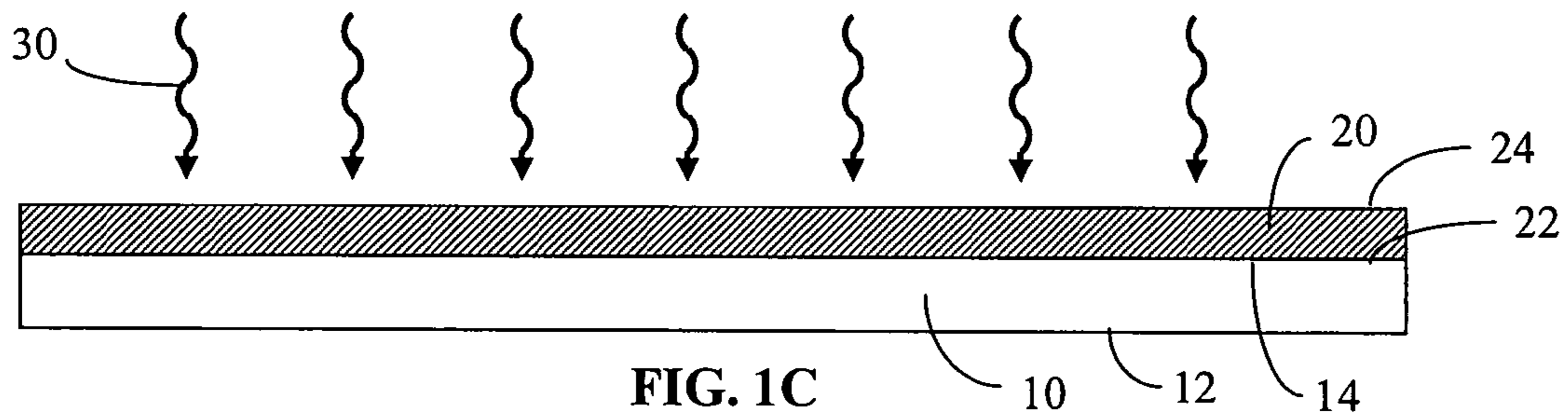


FIG. 1C

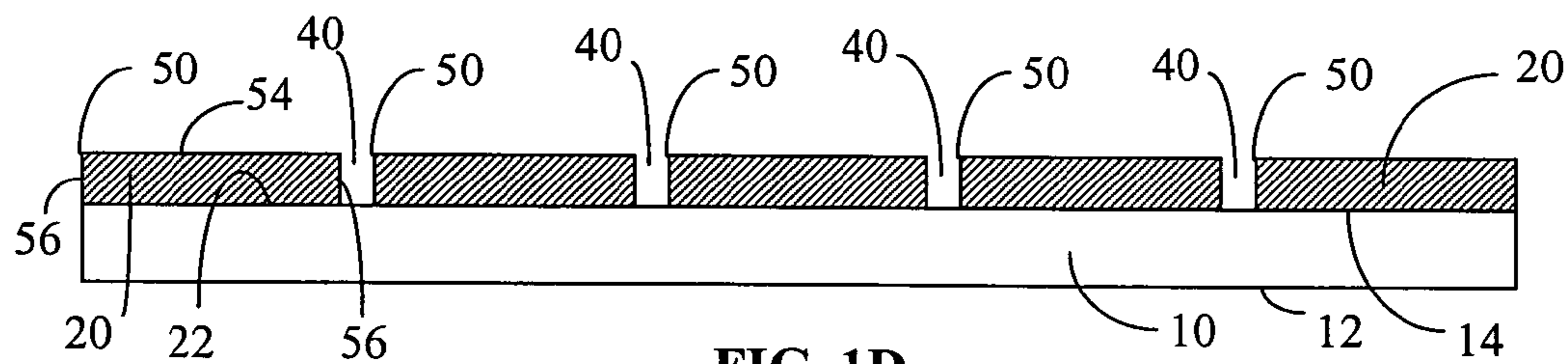


FIG. 1D

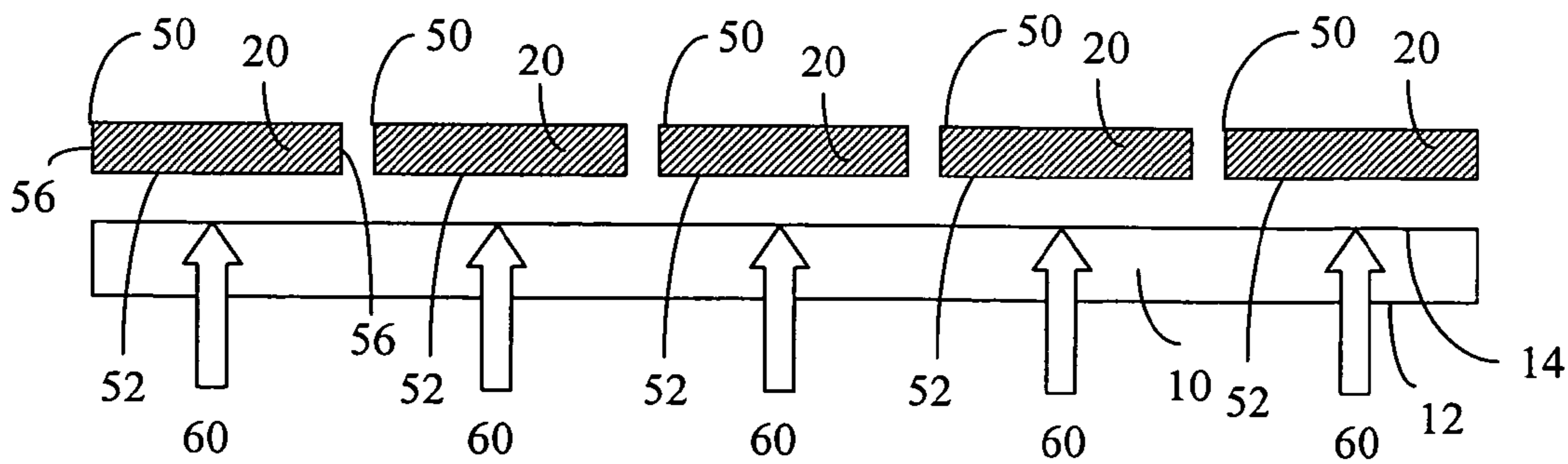


FIG. 1E

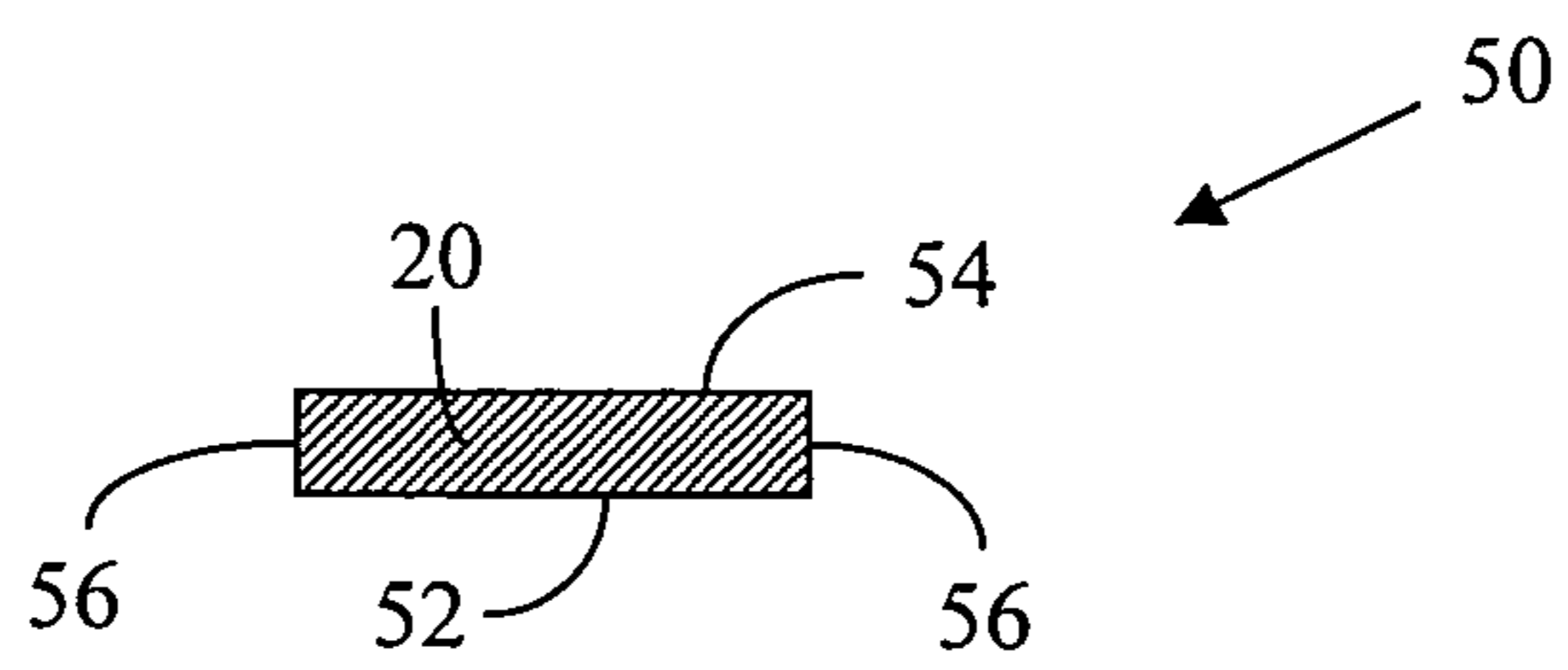


FIG. 1F

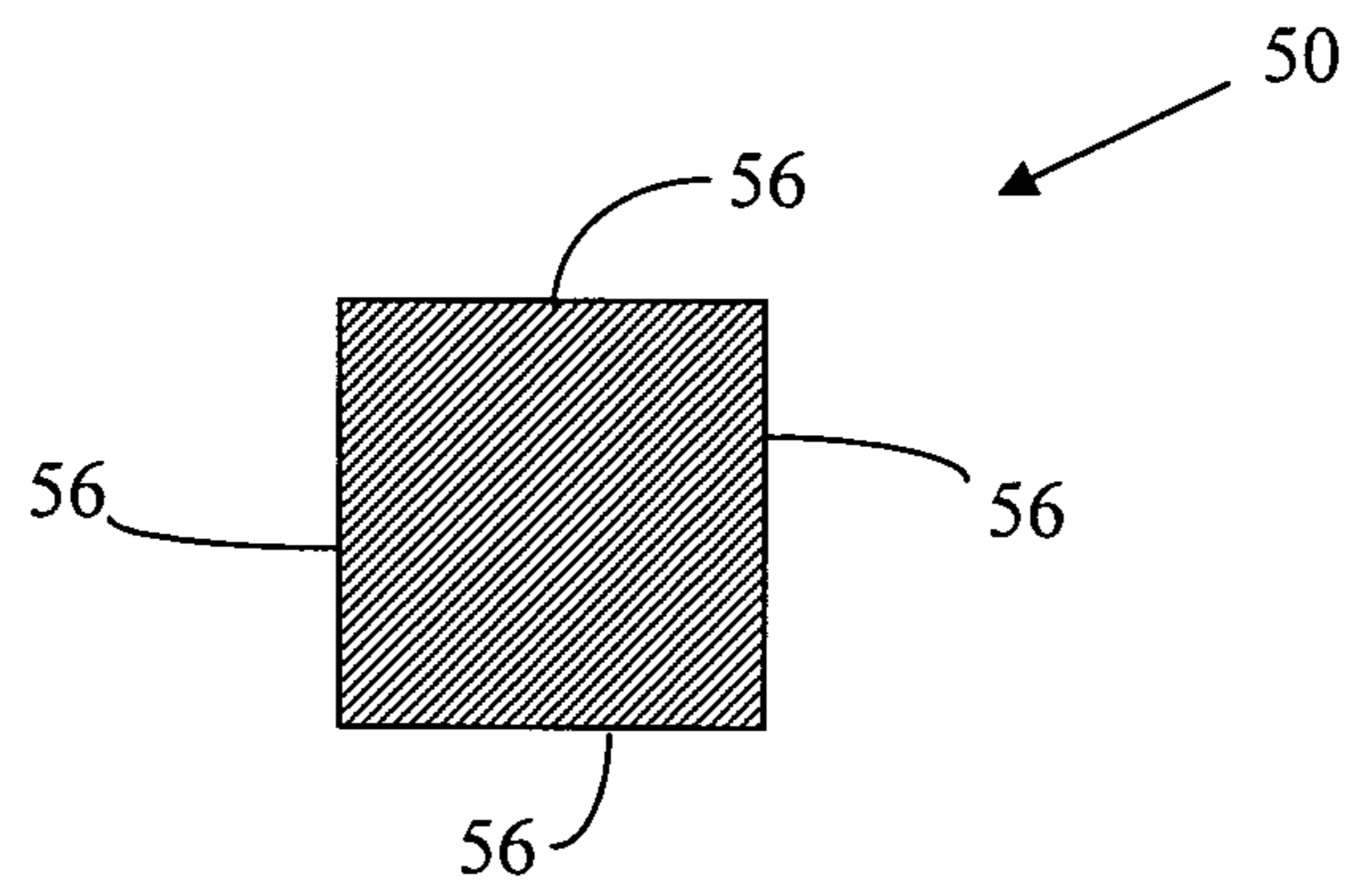


FIG. 1G

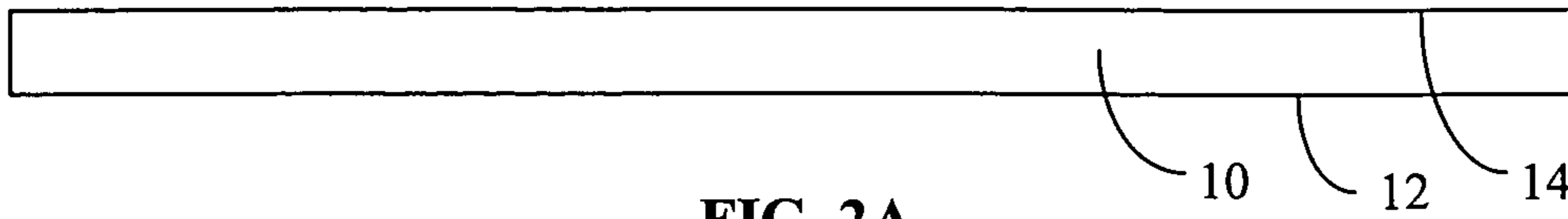


FIG. 2A

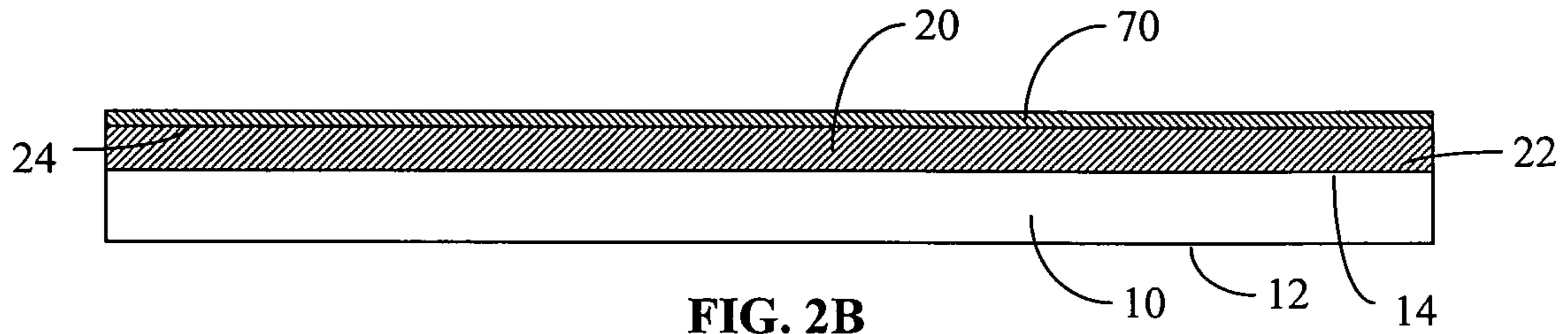


FIG. 2B

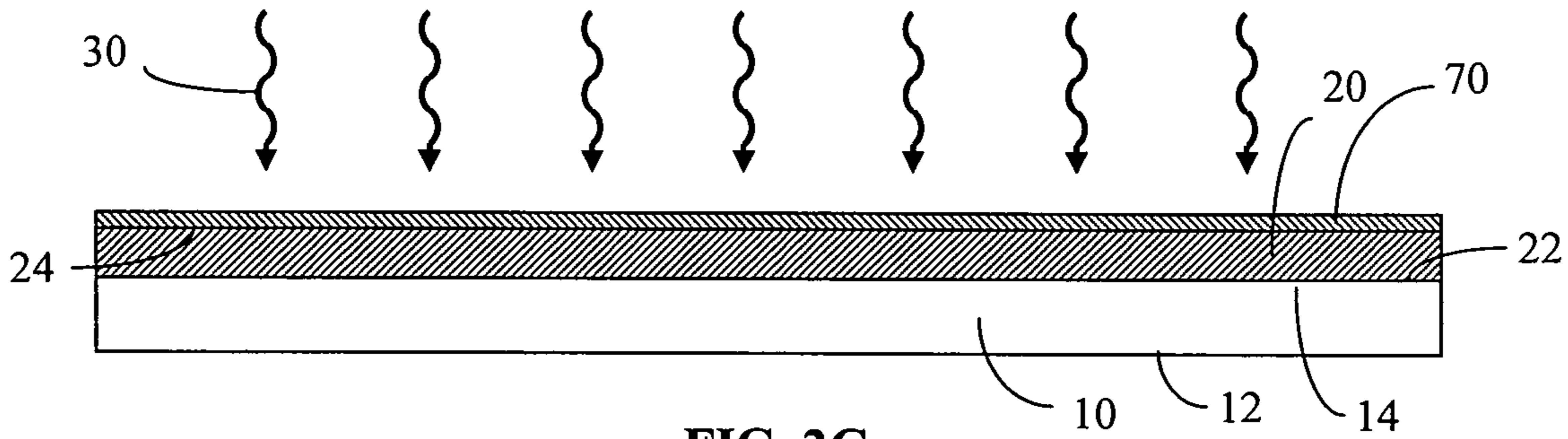


FIG. 2C

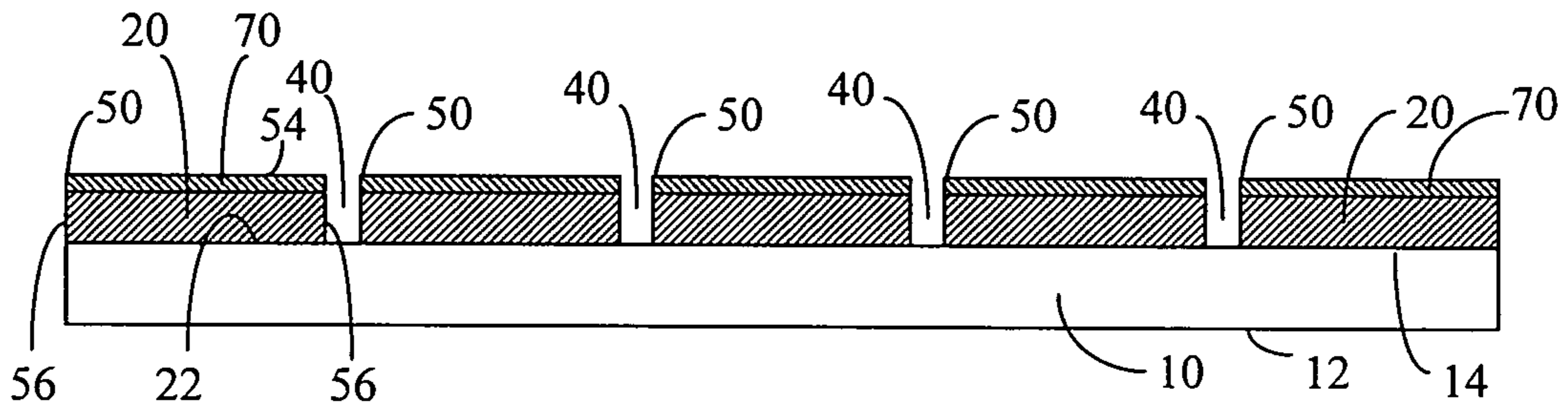


FIG. 2D

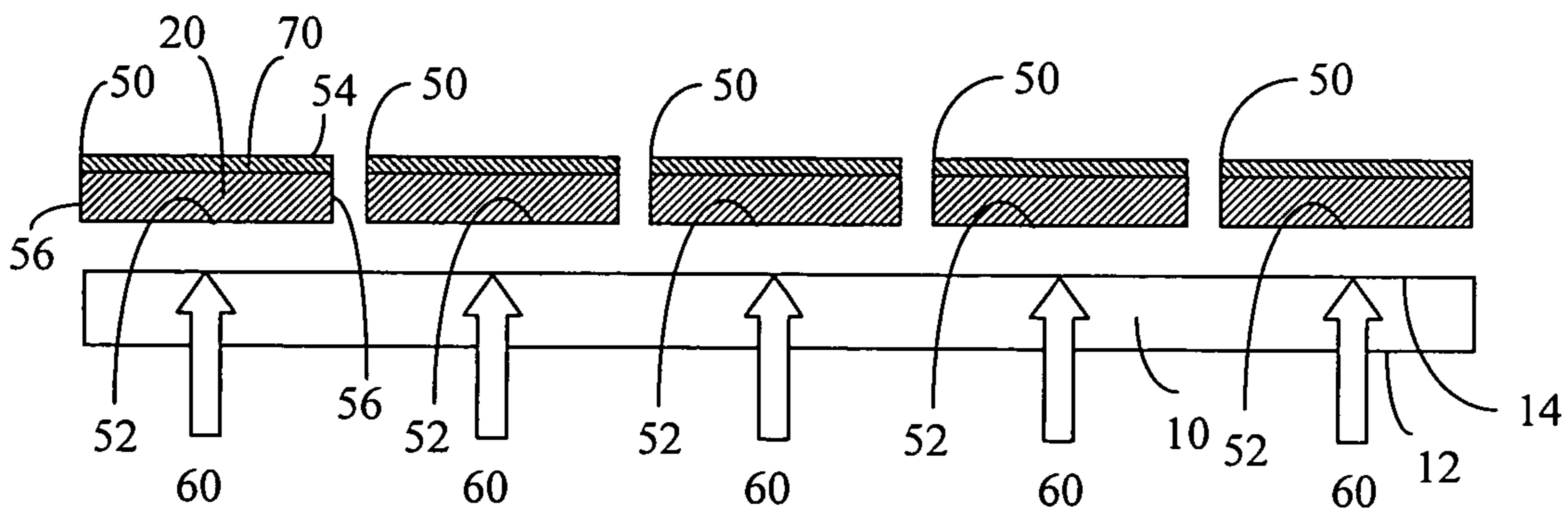


FIG. 2E

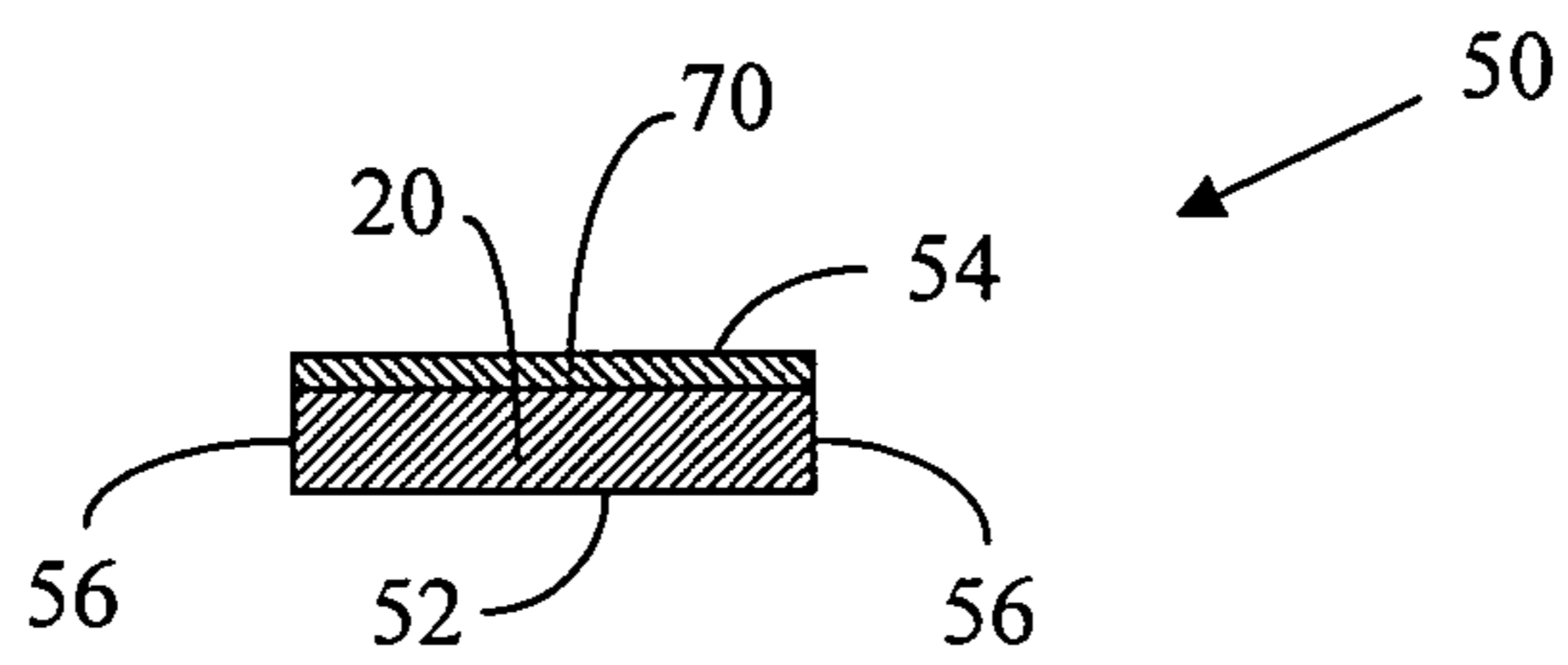


FIG. 2F

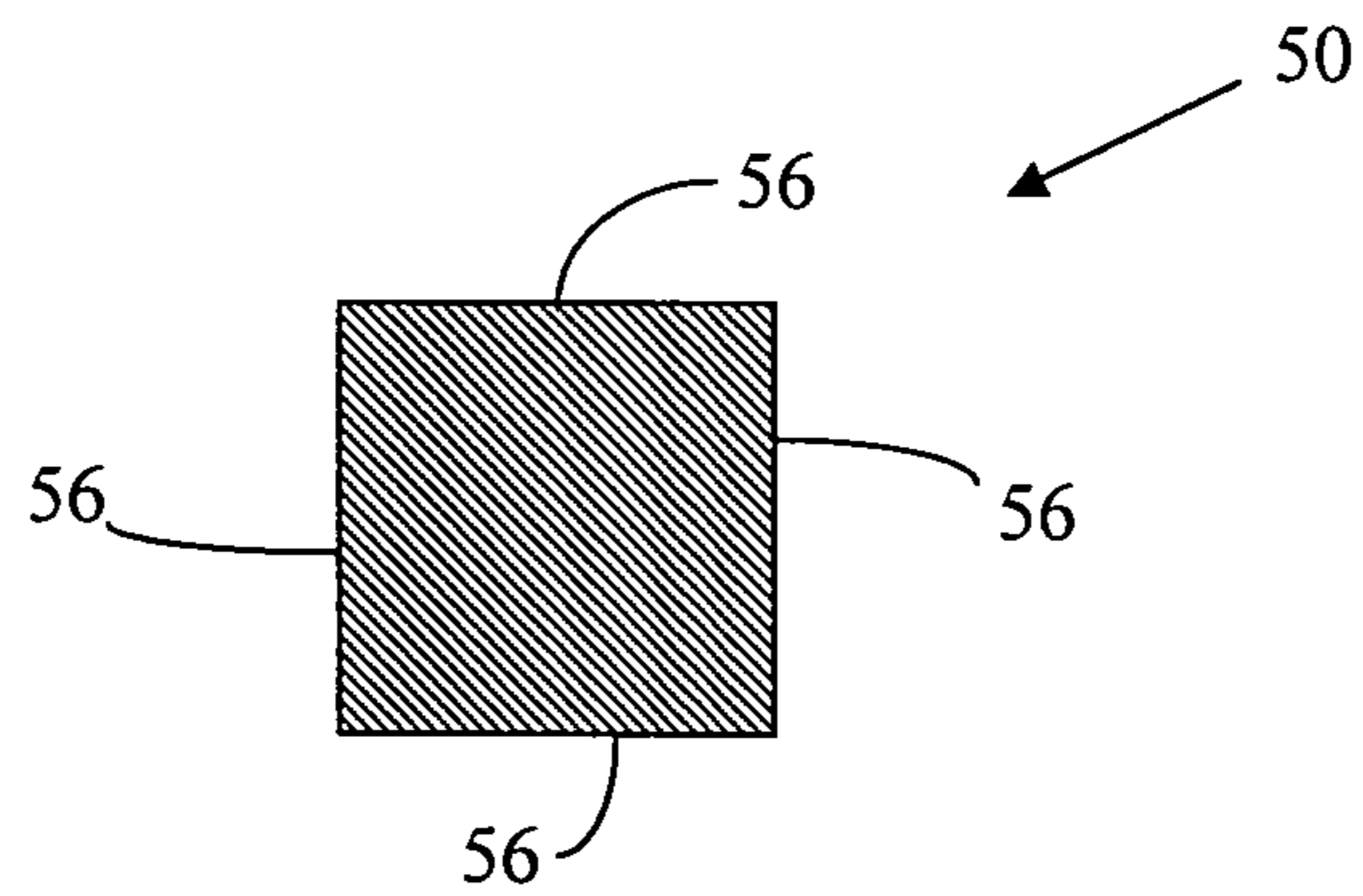
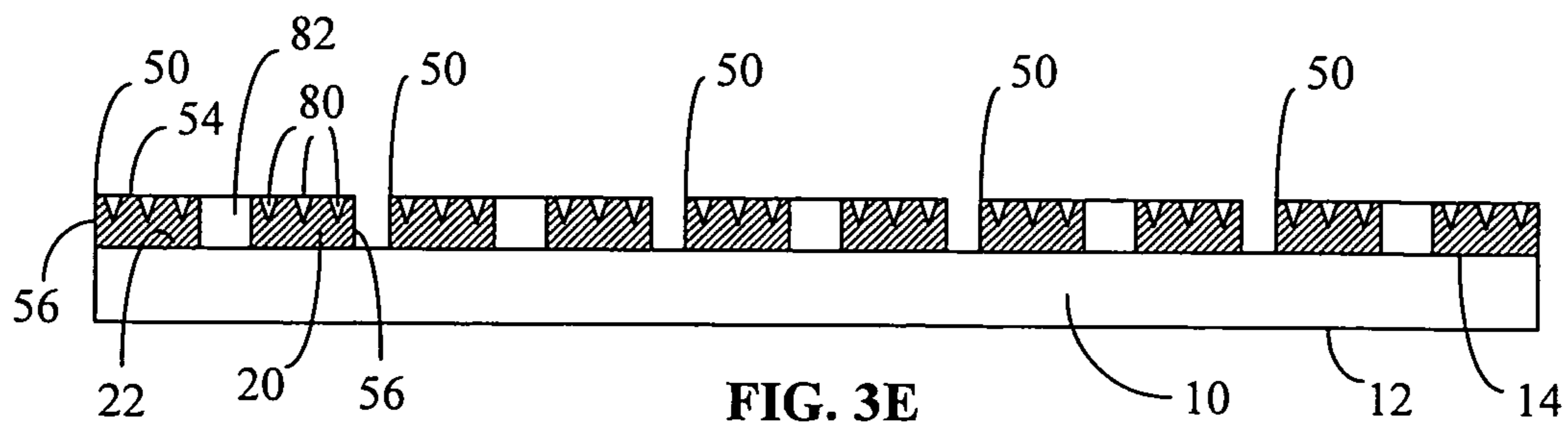
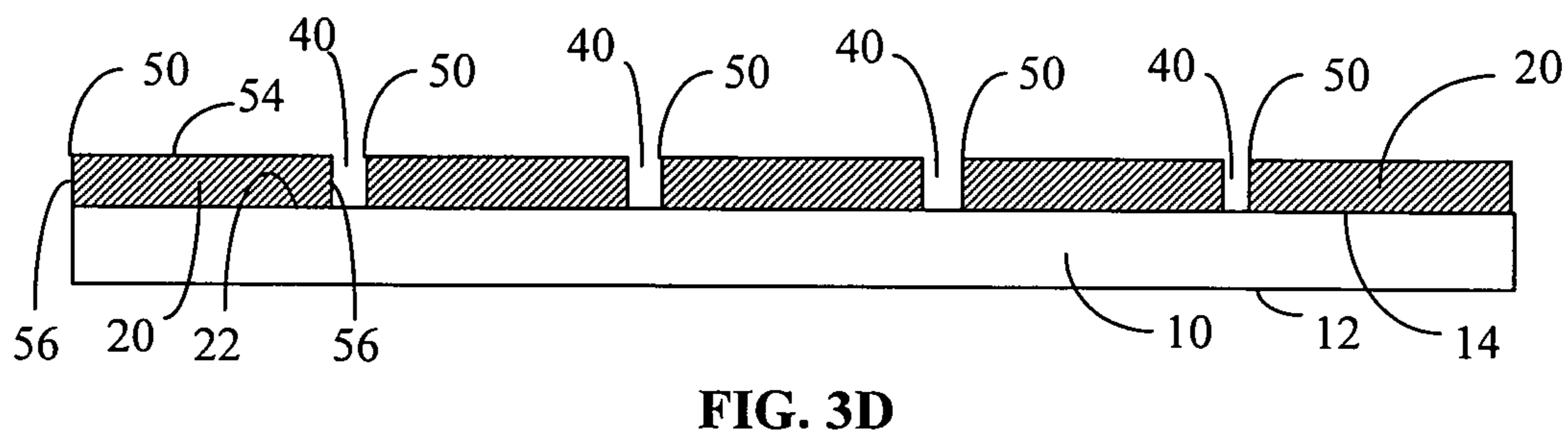
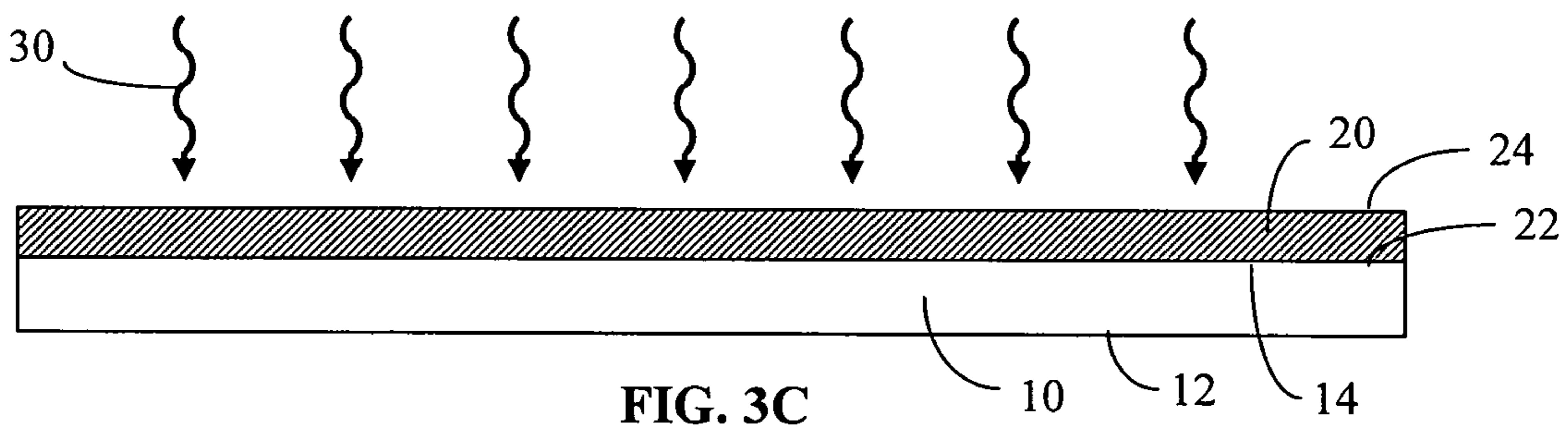
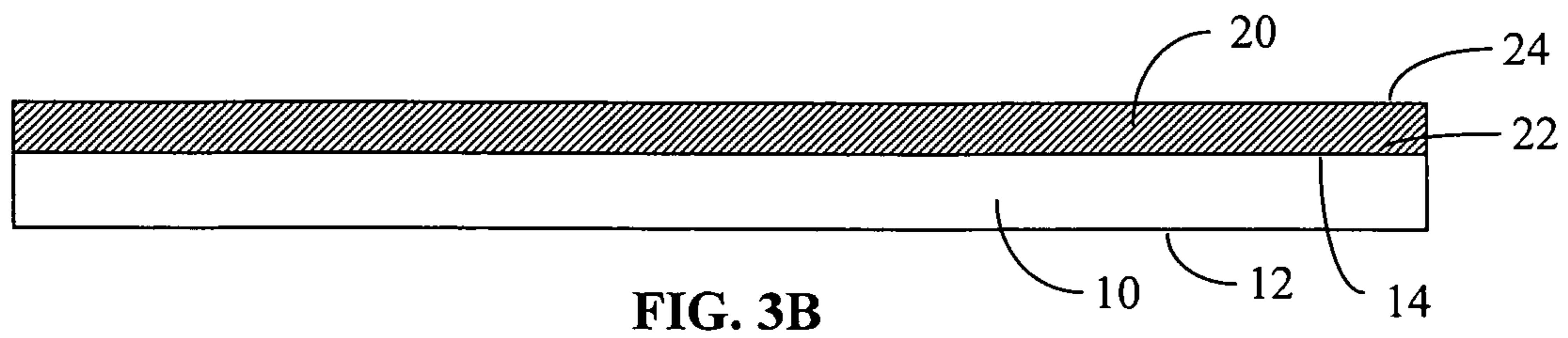
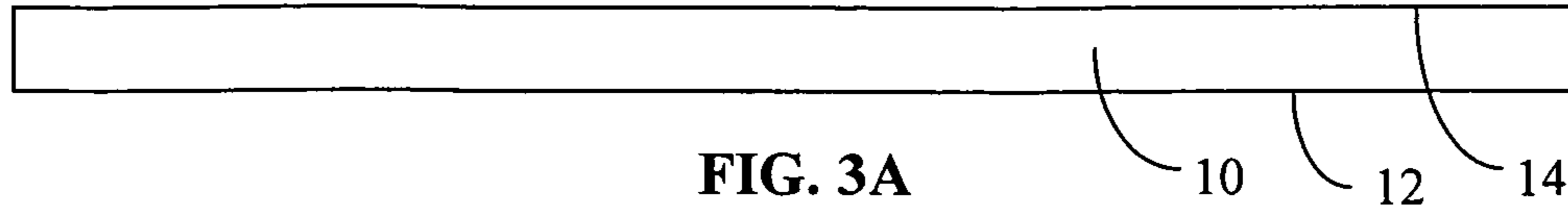


FIG. 2G



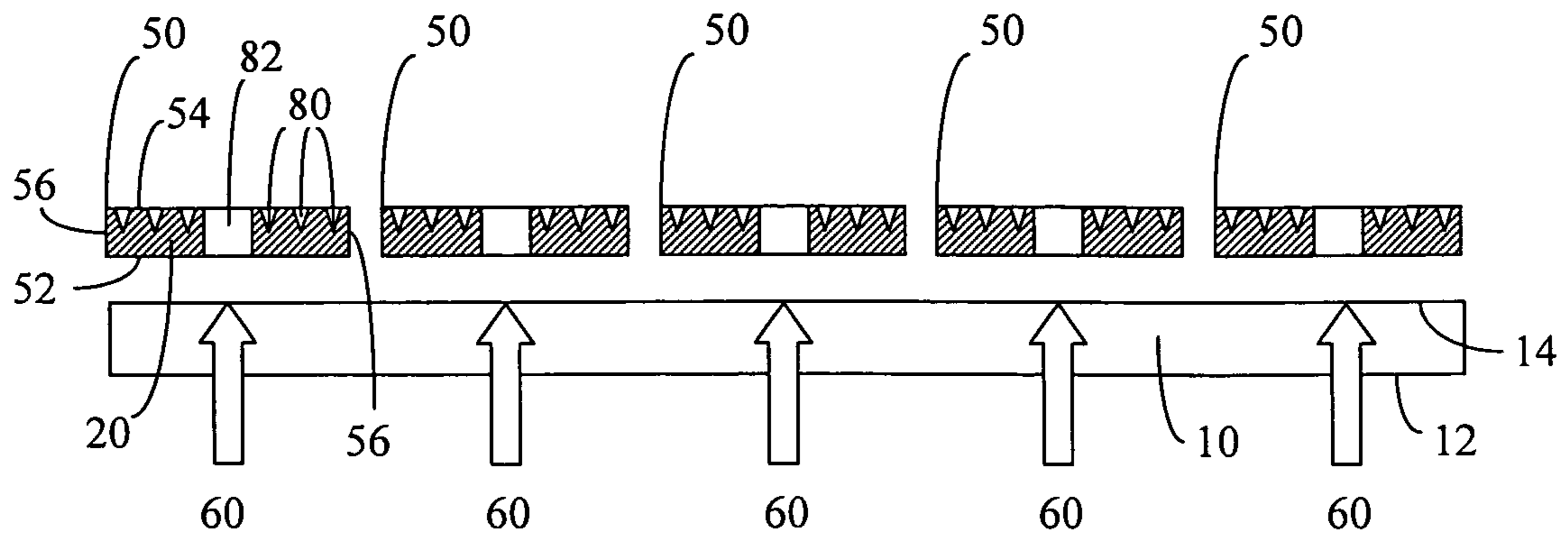


FIG. 3F

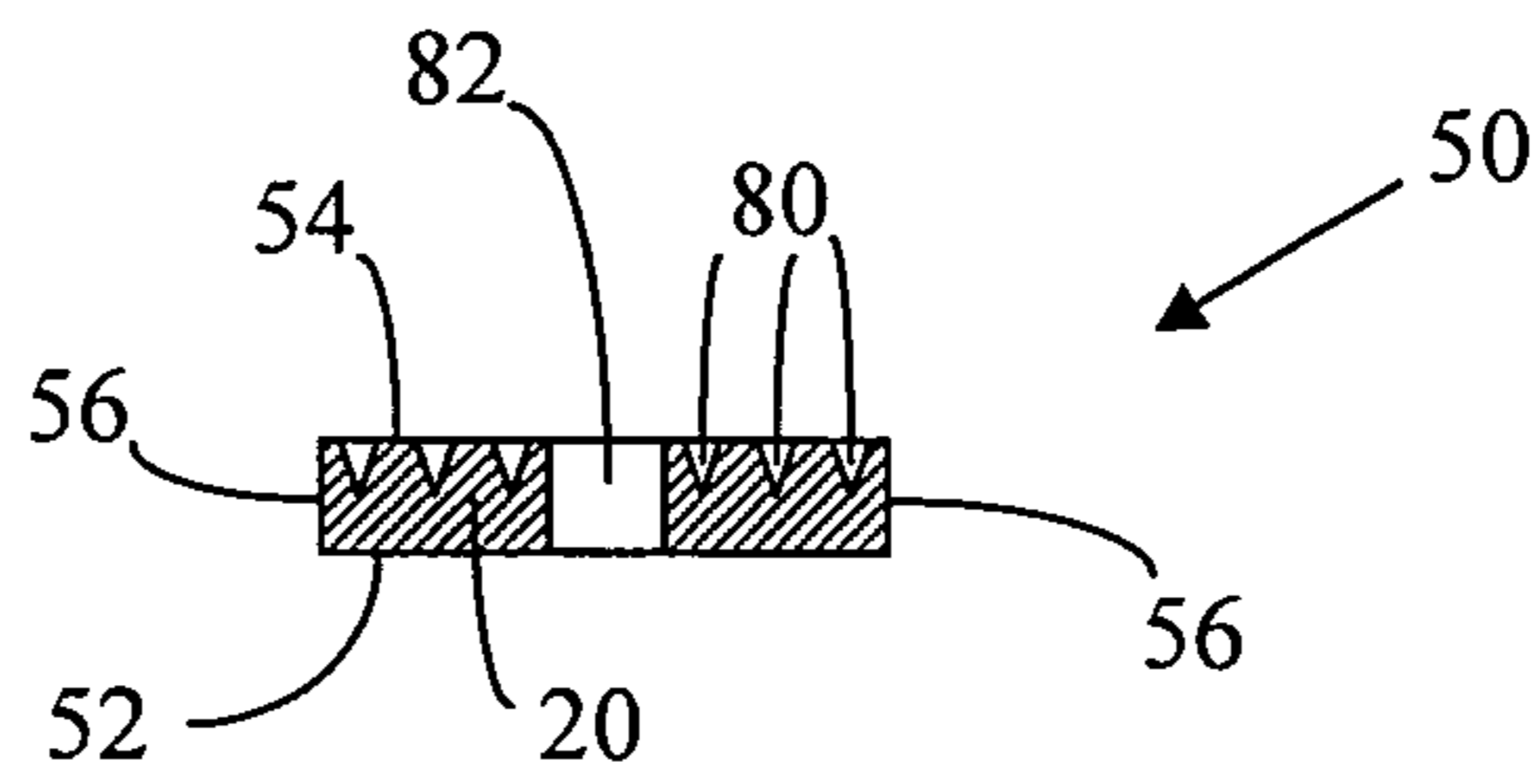


FIG. 3G

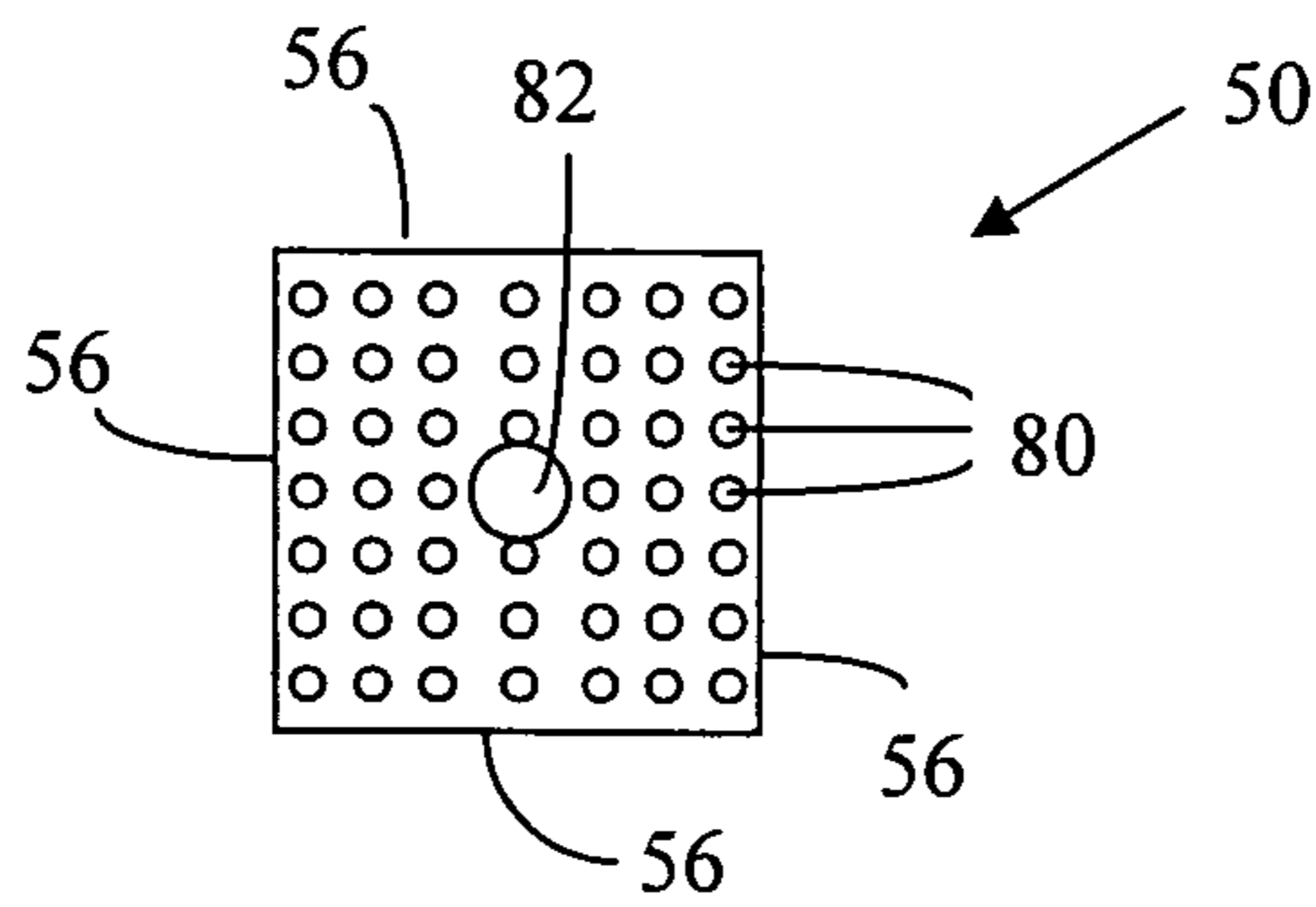


FIG. 3H

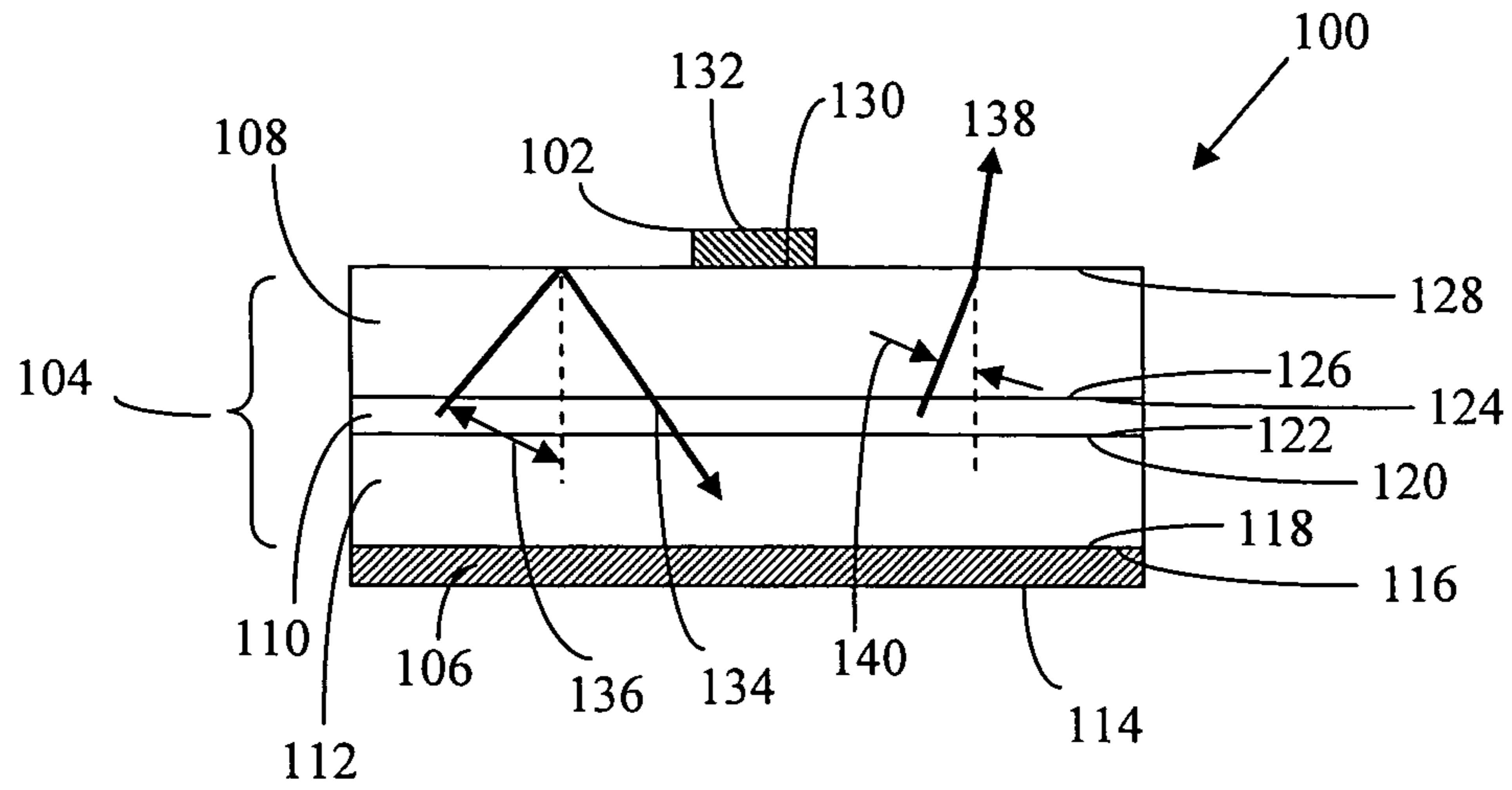


FIG. 4A

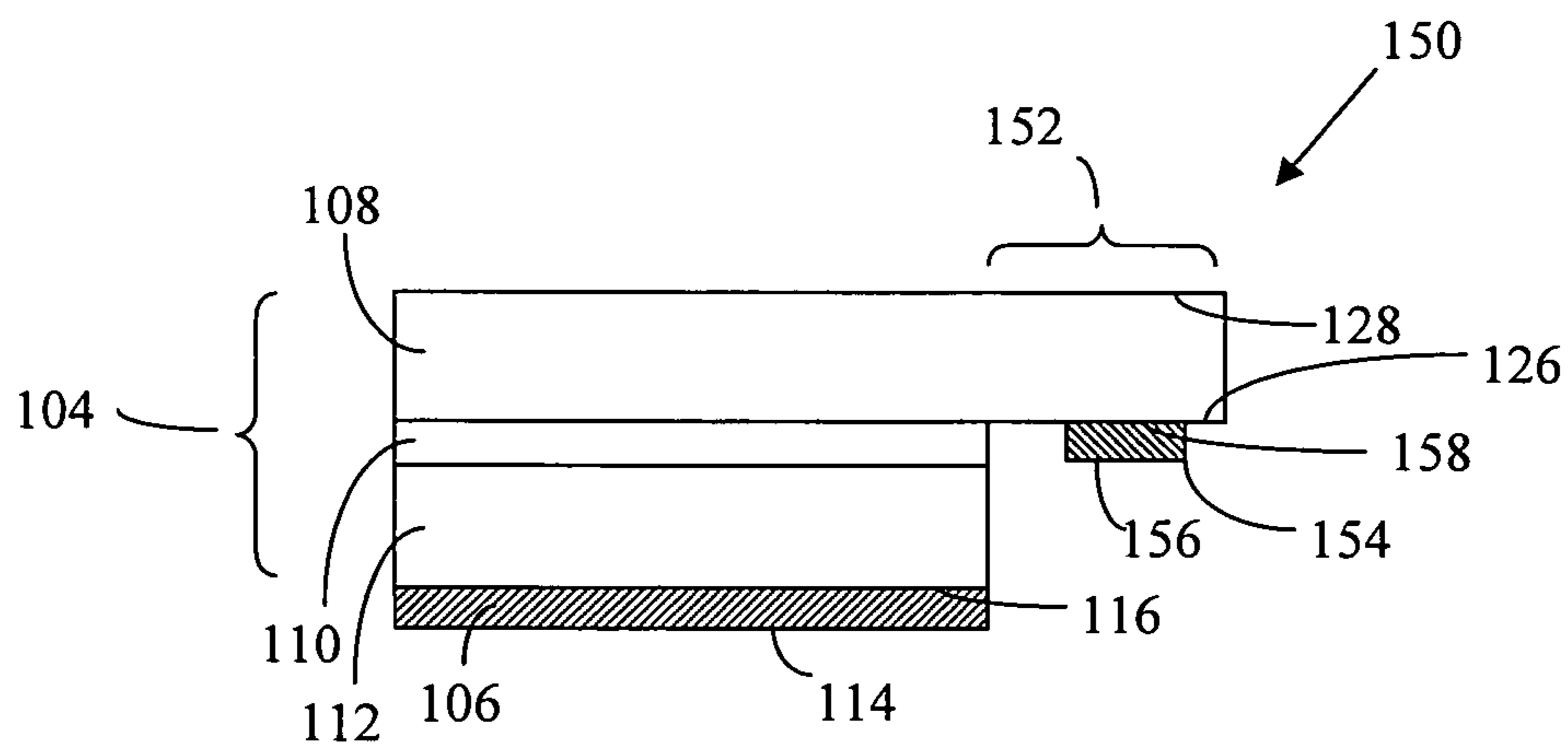


FIG. 4B

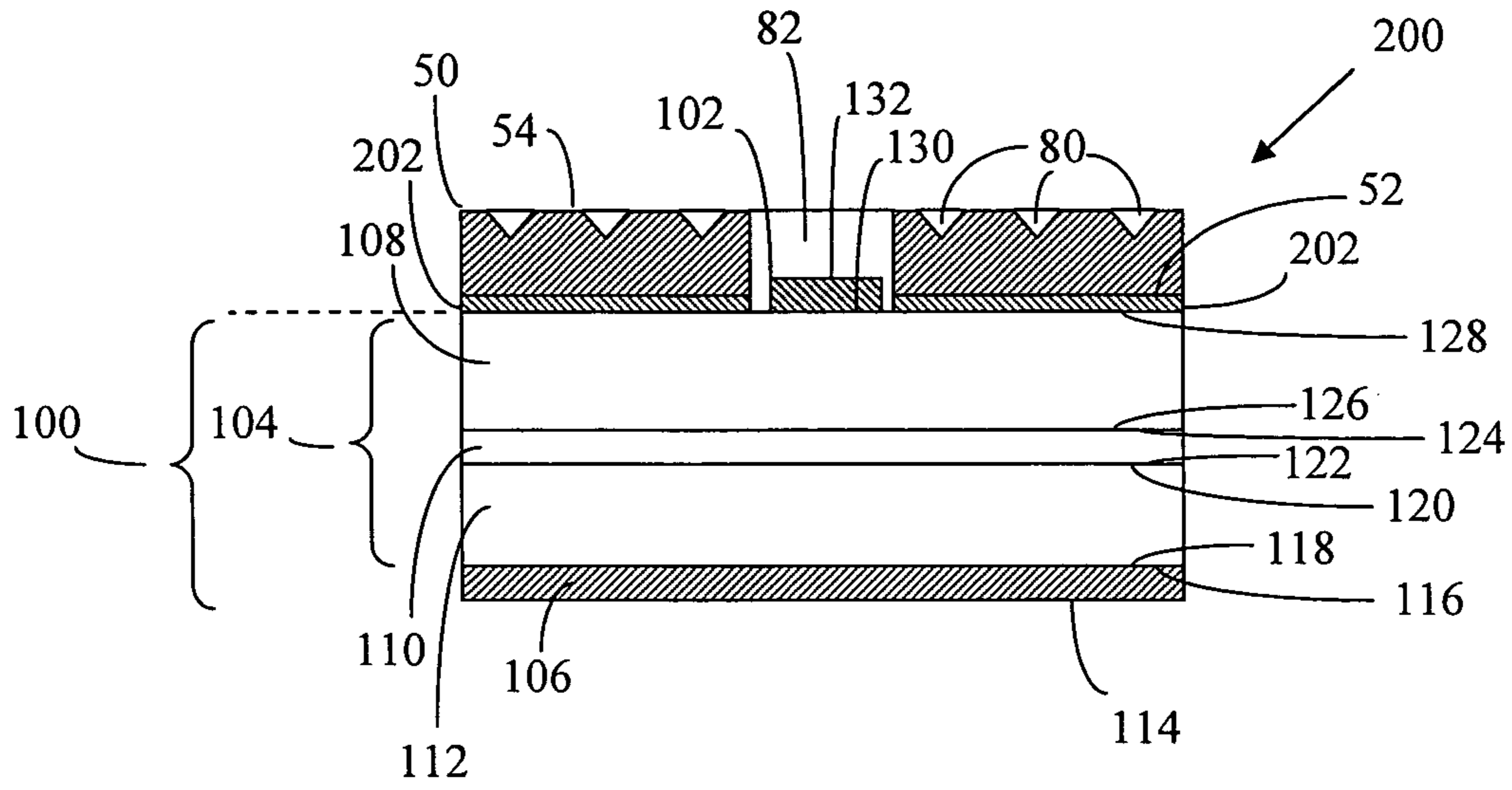


FIG. 5A

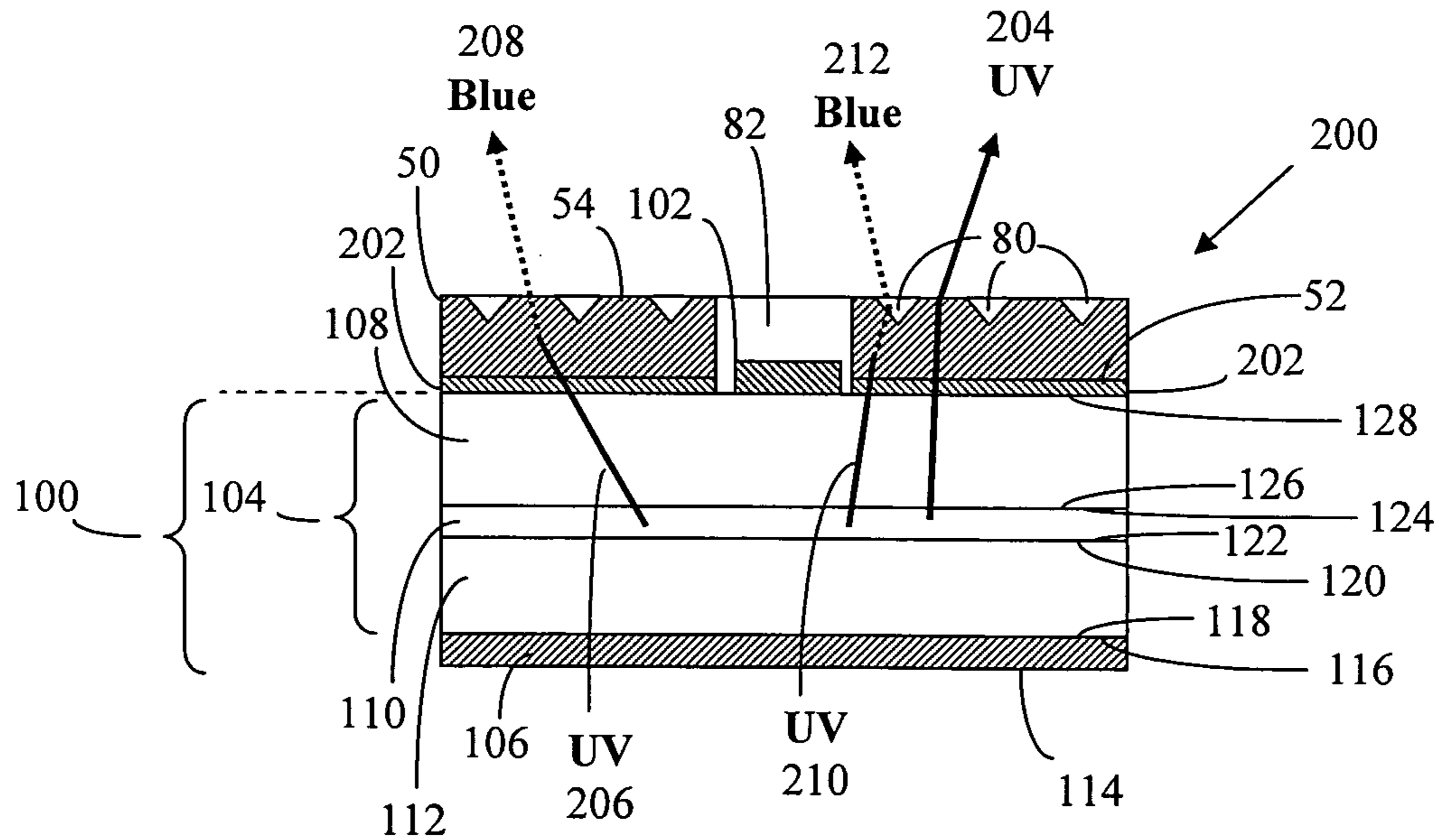


FIG. 5B

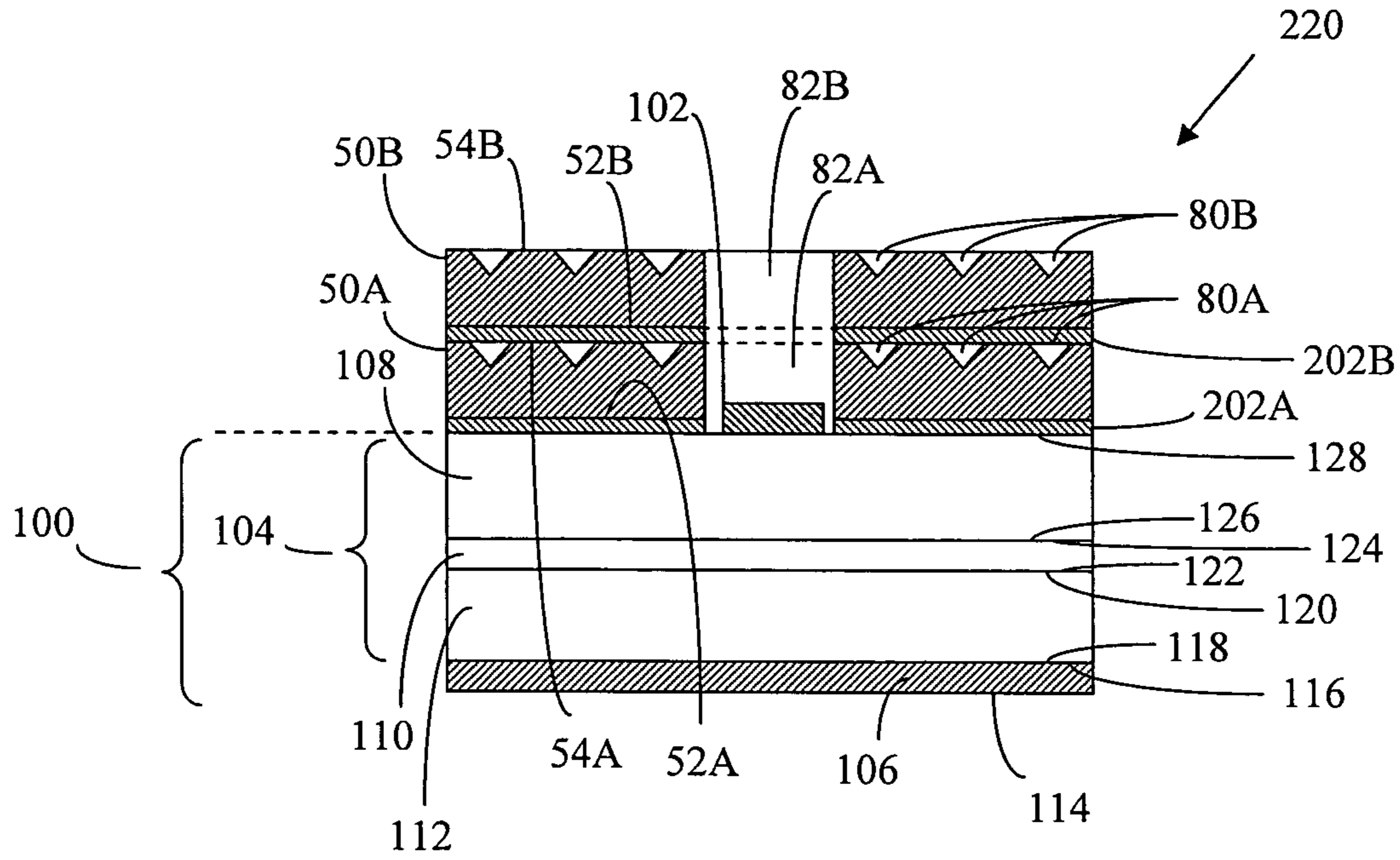


FIG. 6A

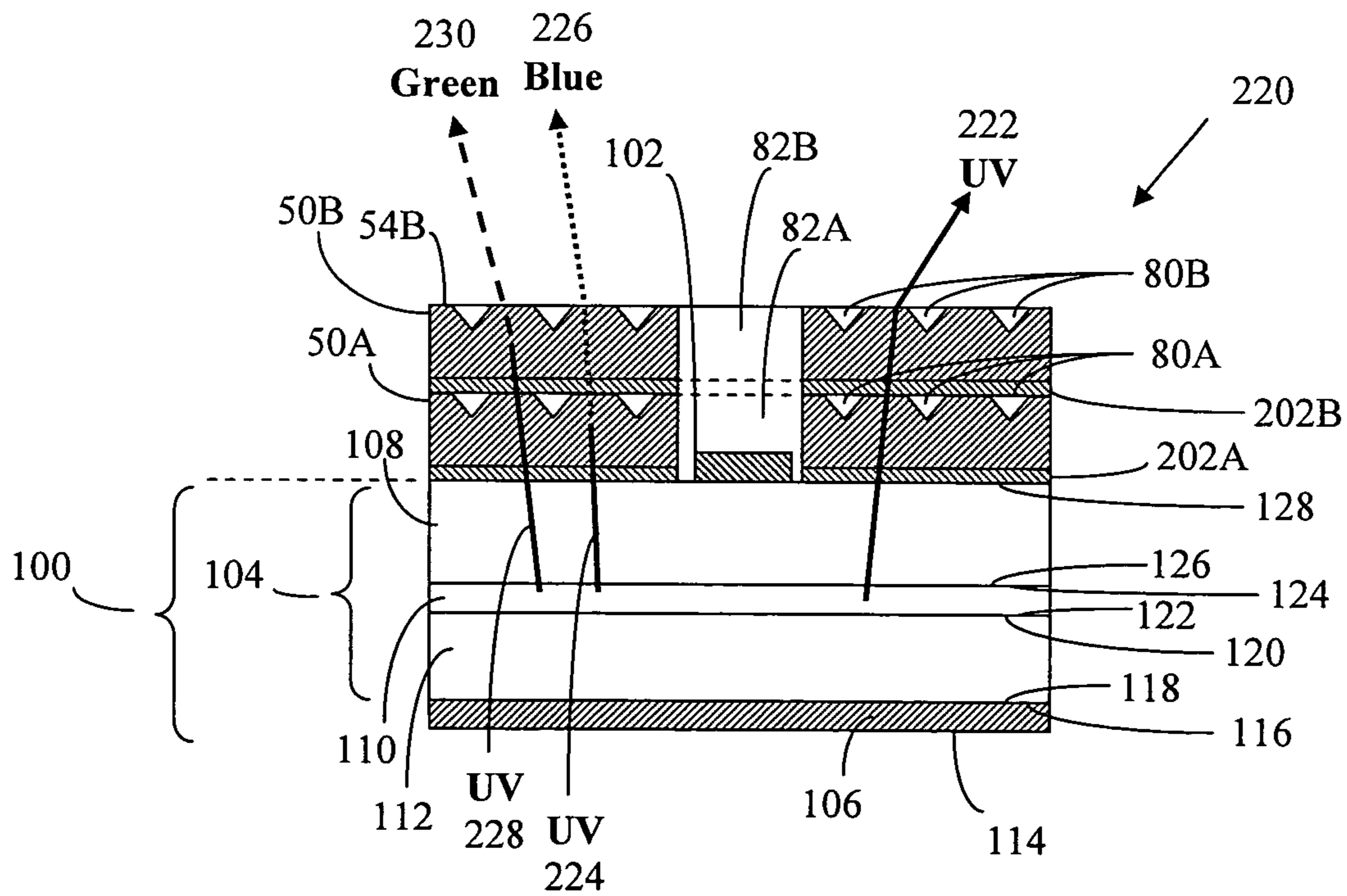


FIG. 6B

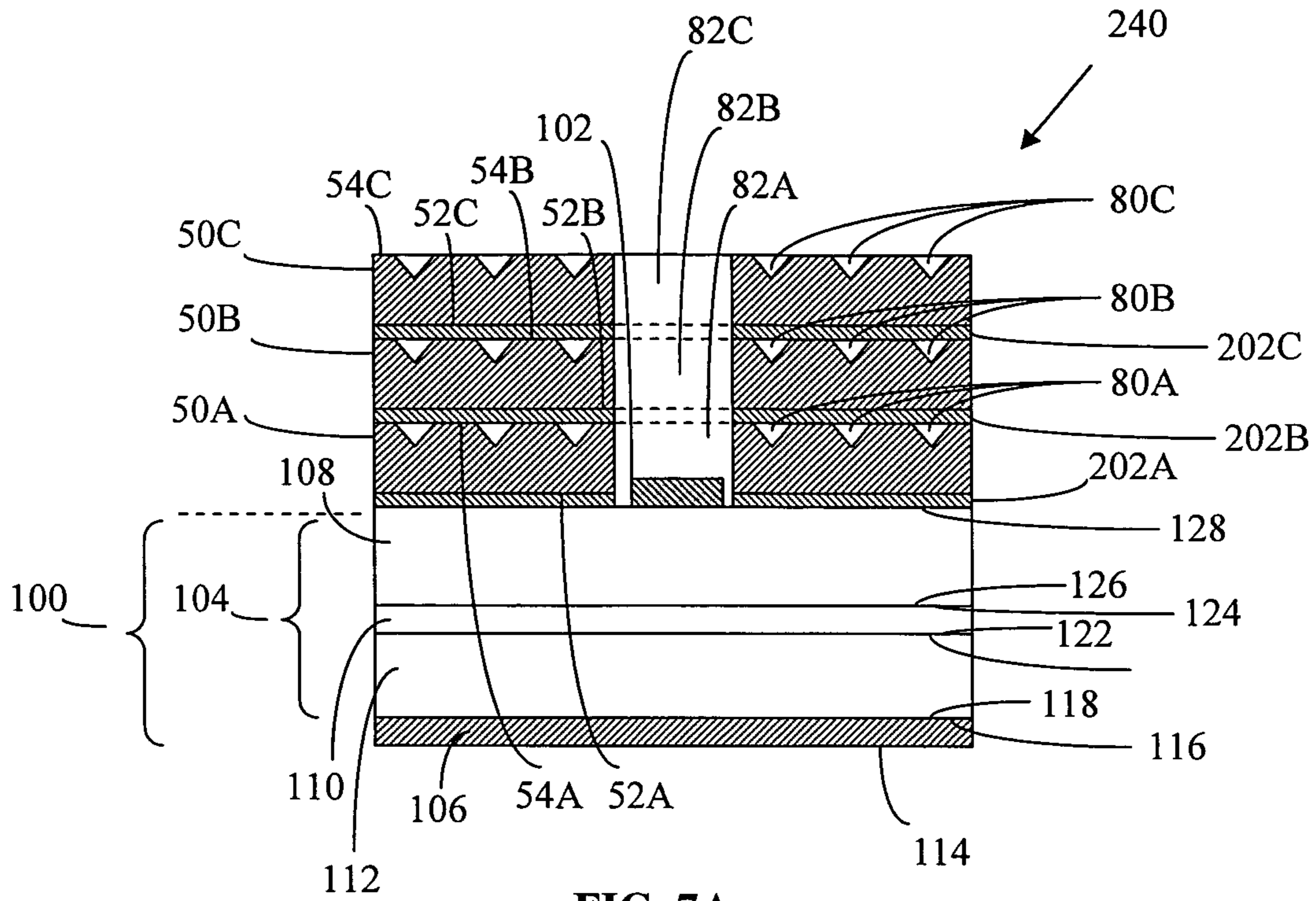


FIG. 7A

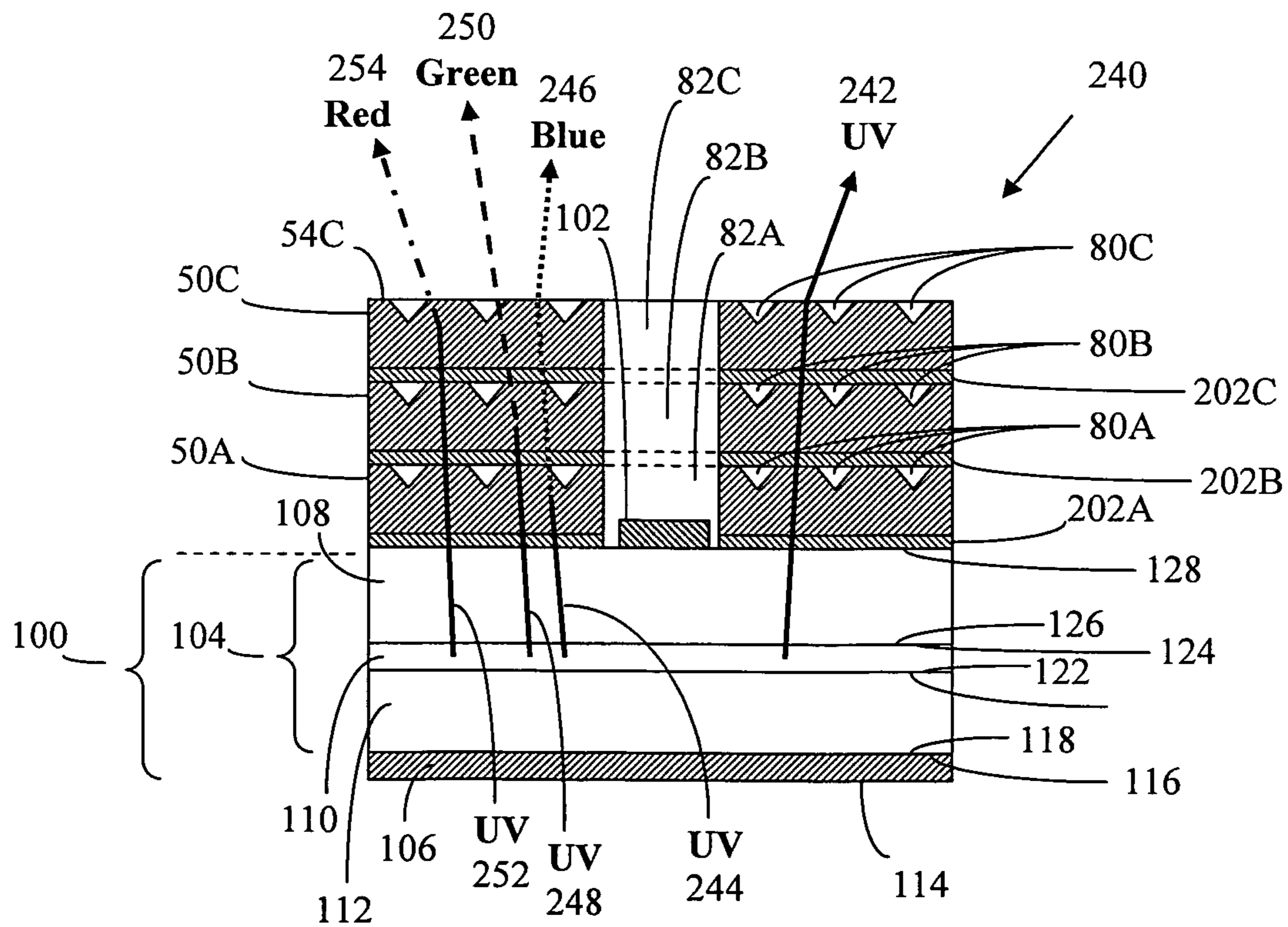


FIG. 7B

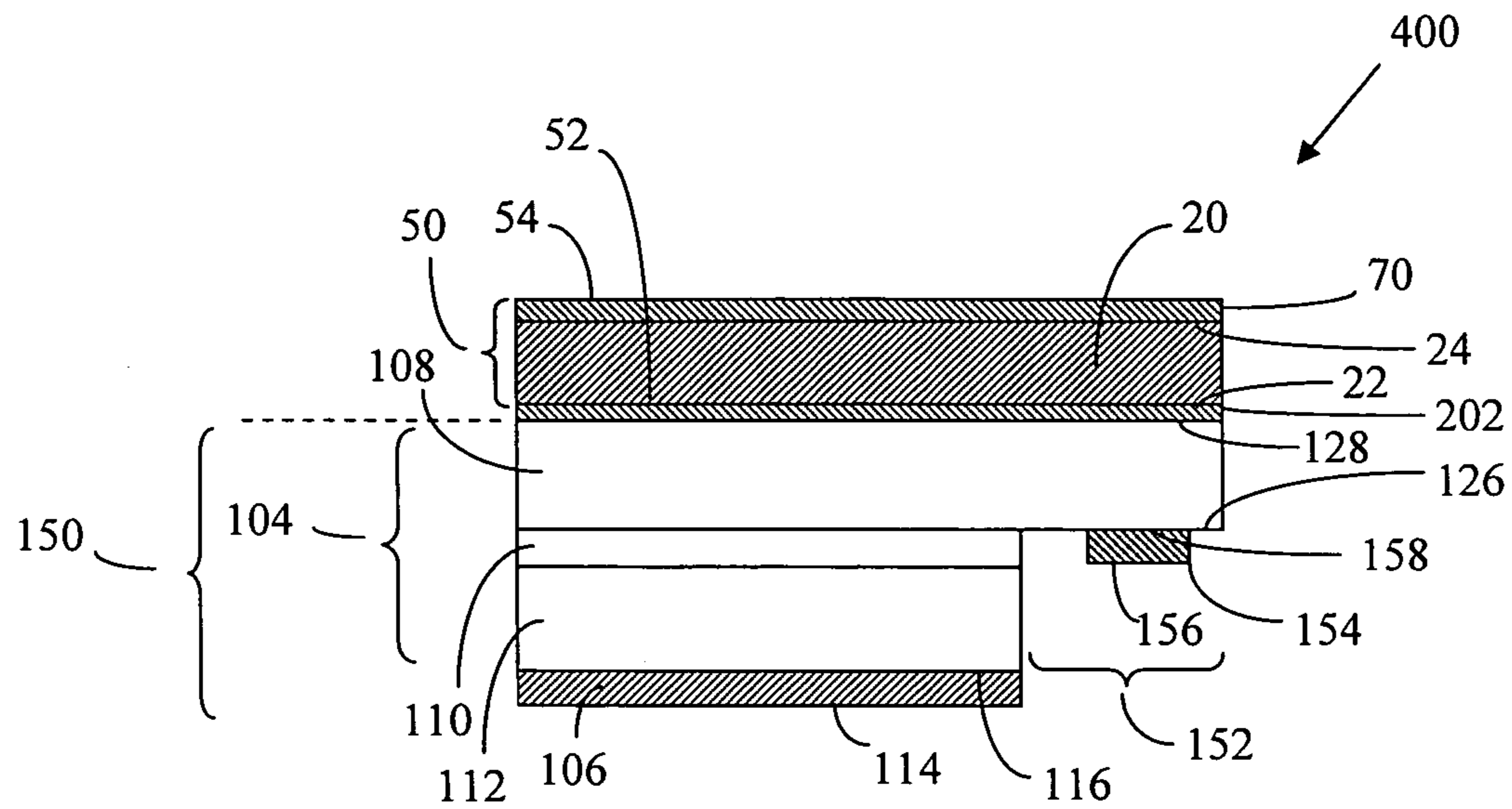


FIG. 9A

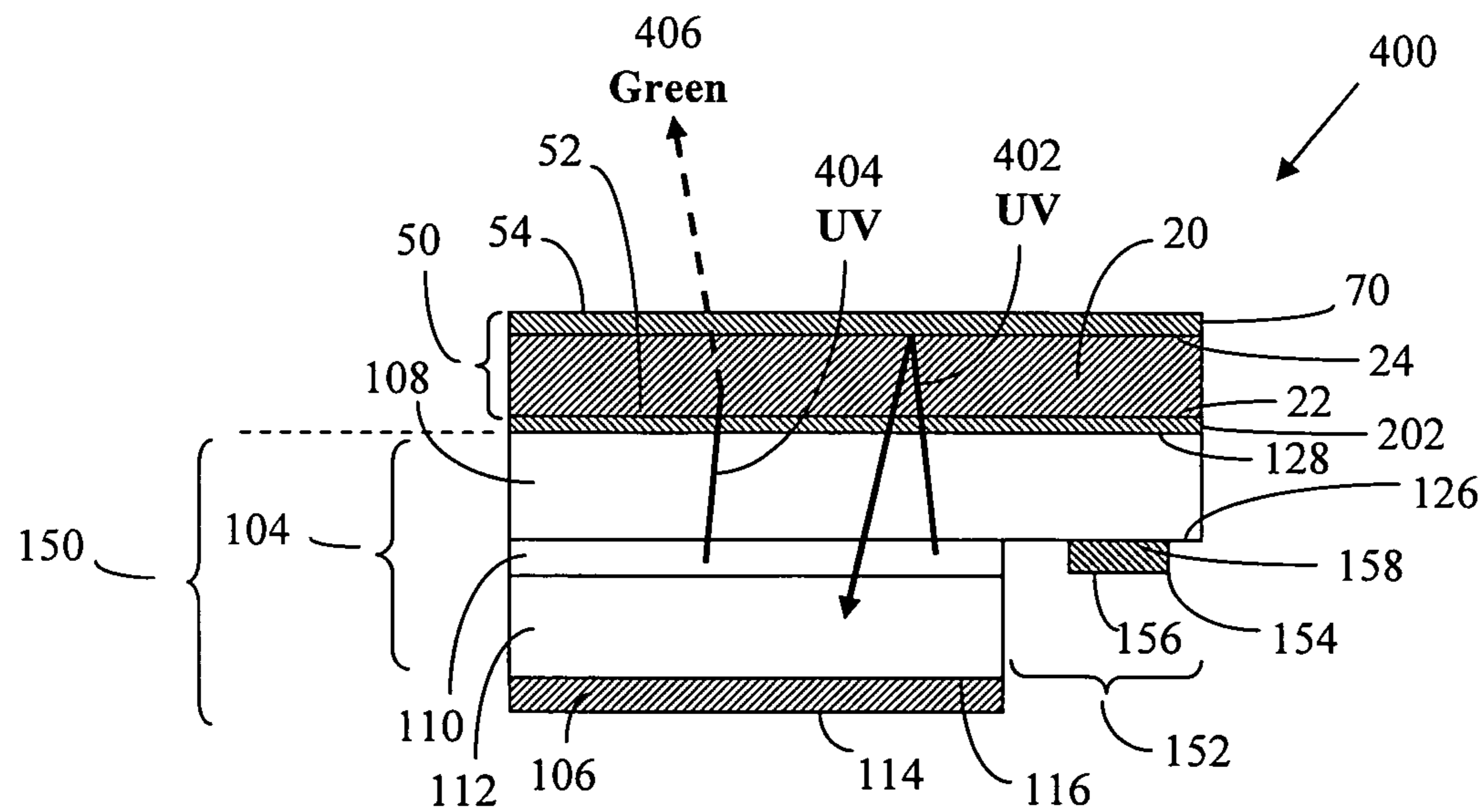
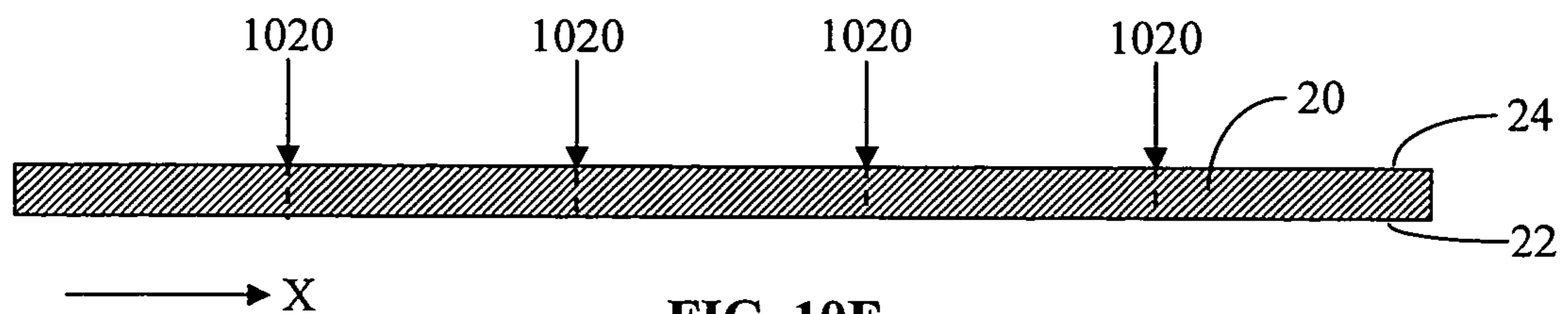
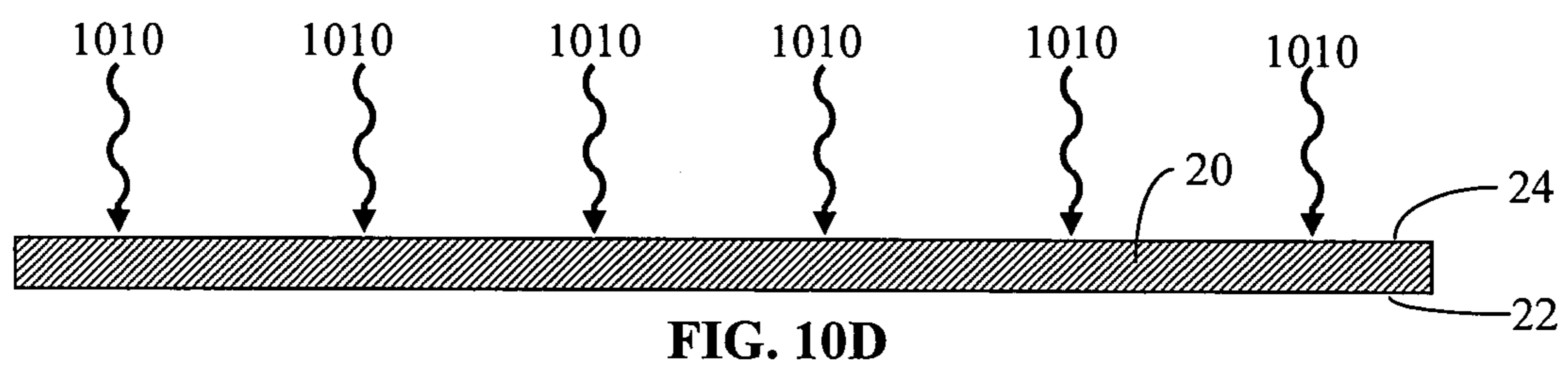
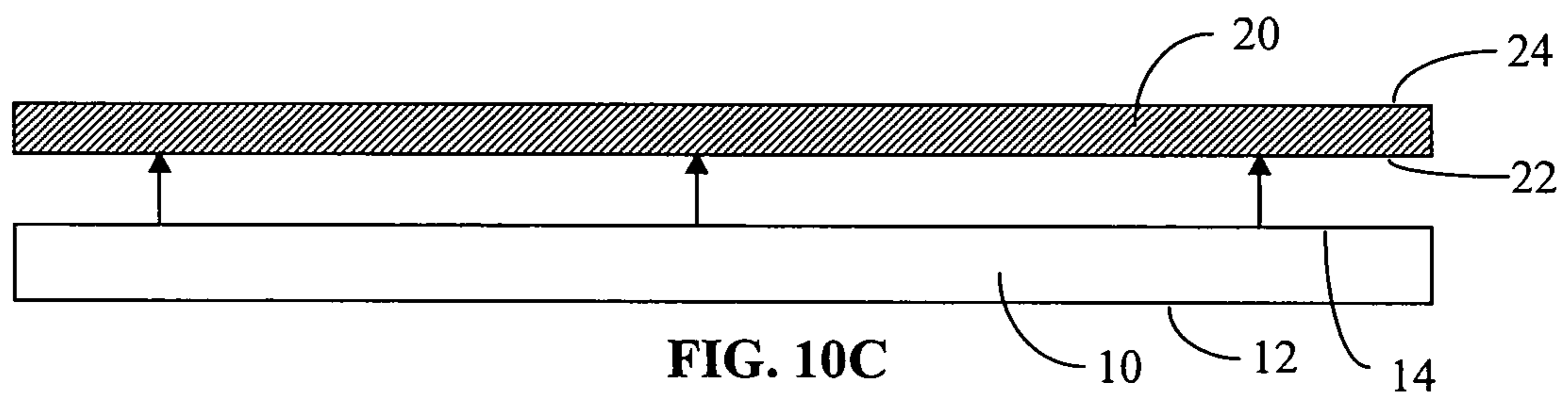
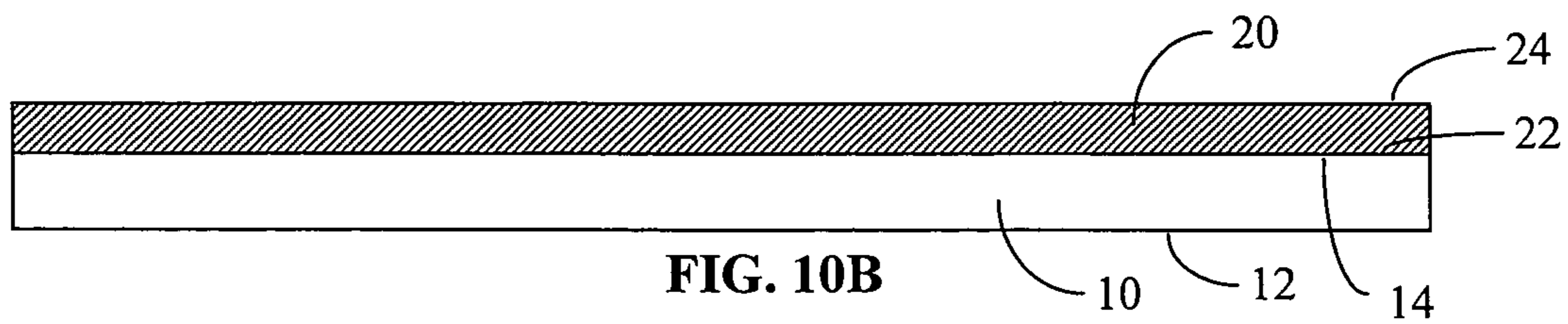
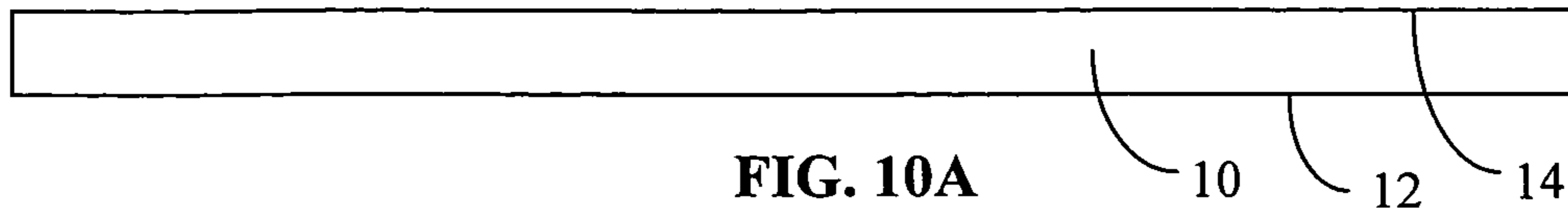


FIG. 9B



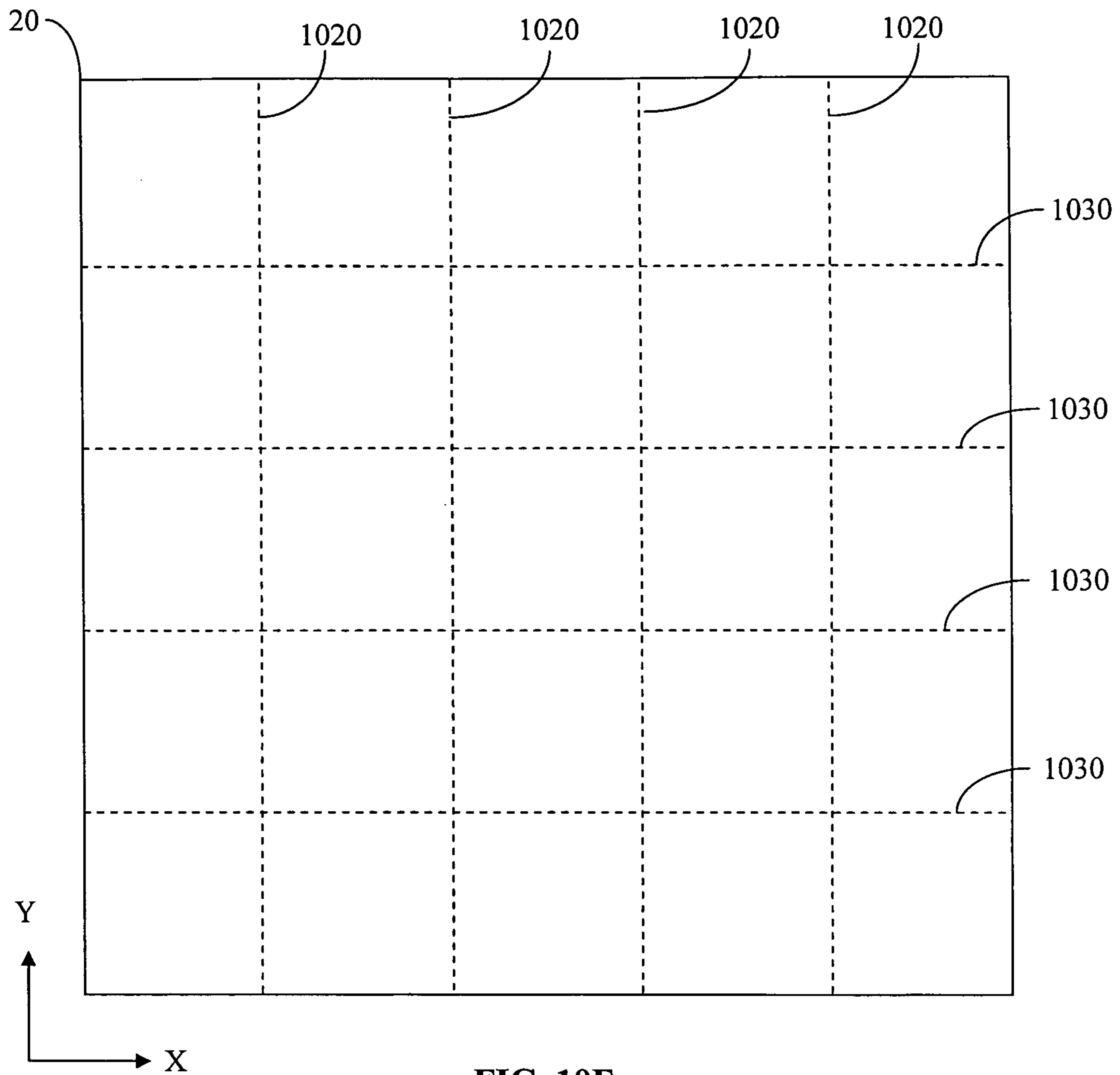


FIG. 10F

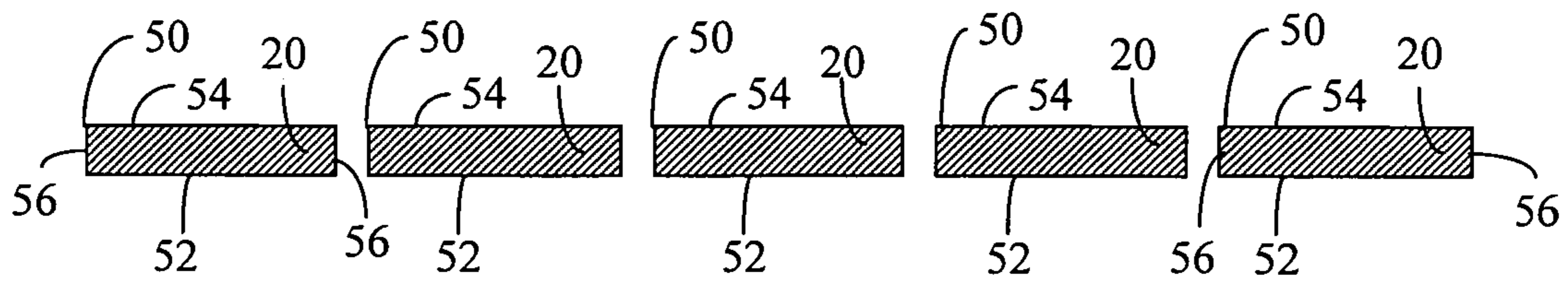


FIG. 10G

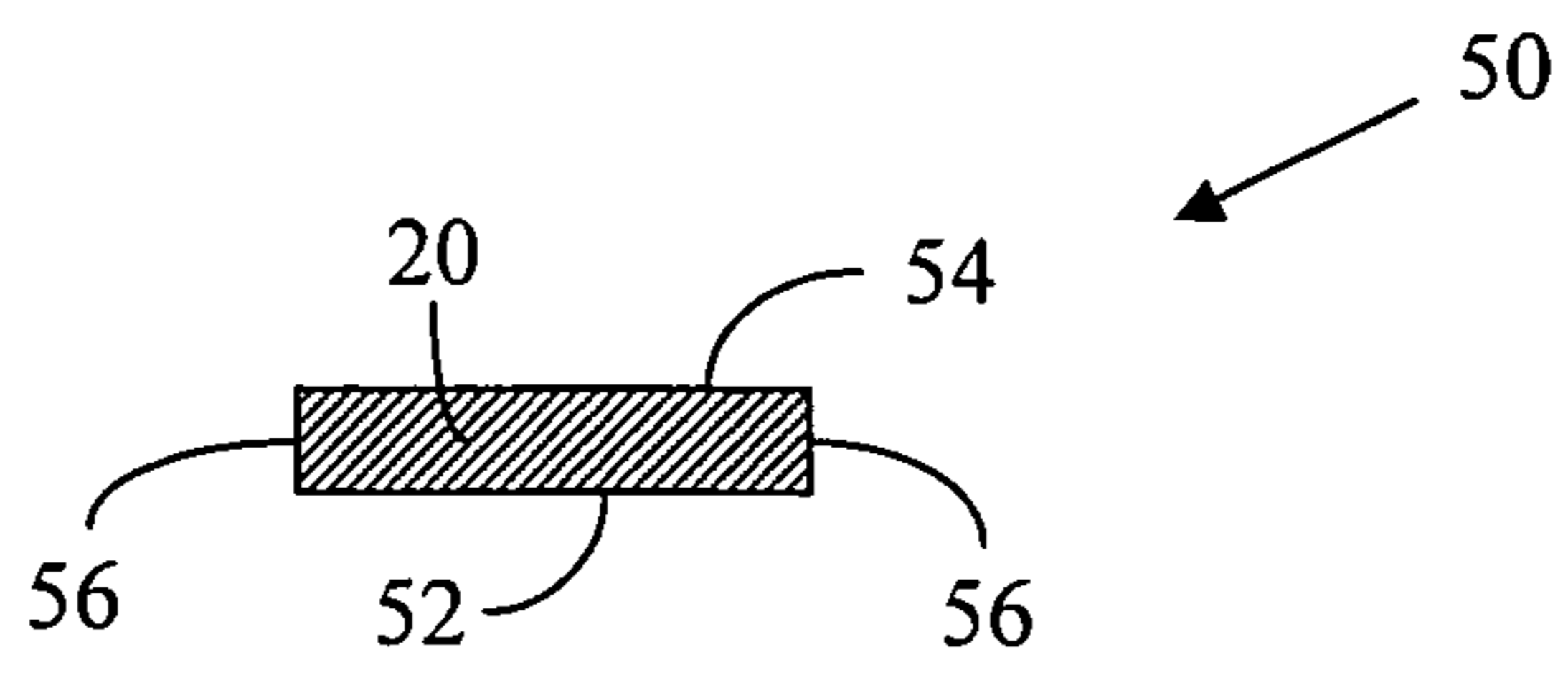


FIG. 10H

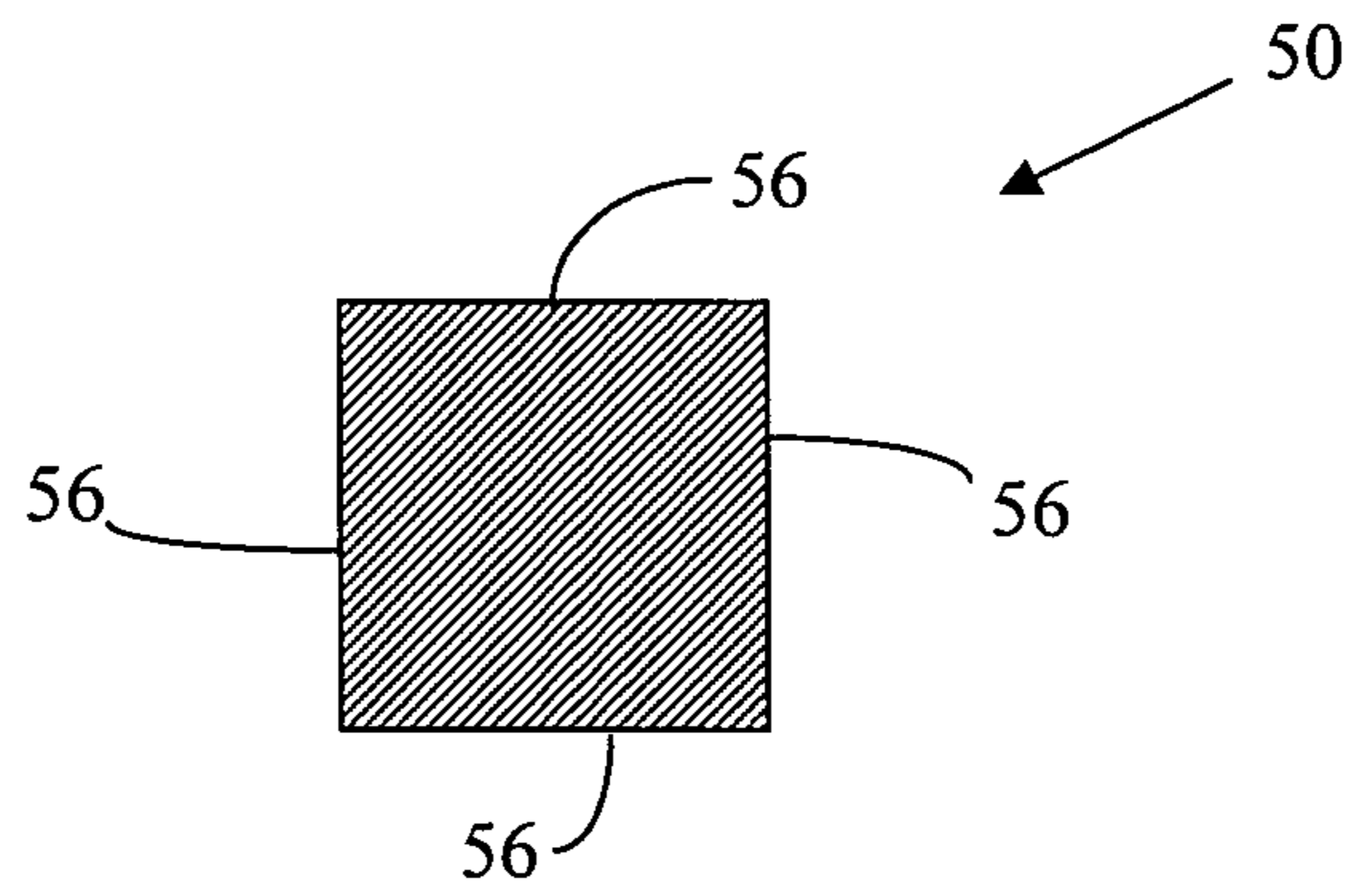
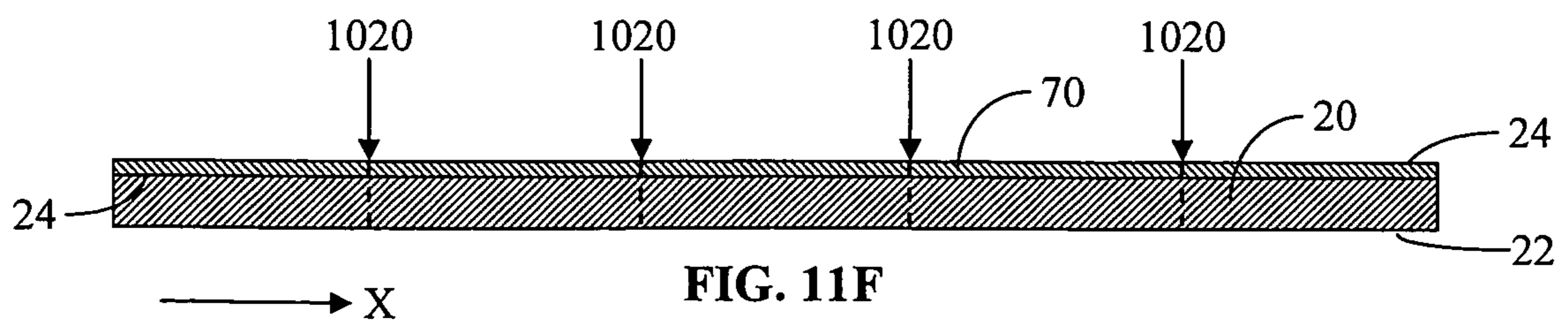
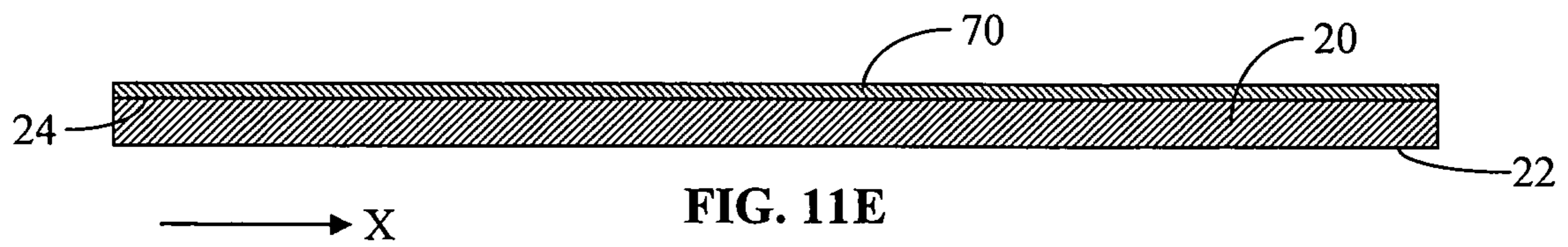
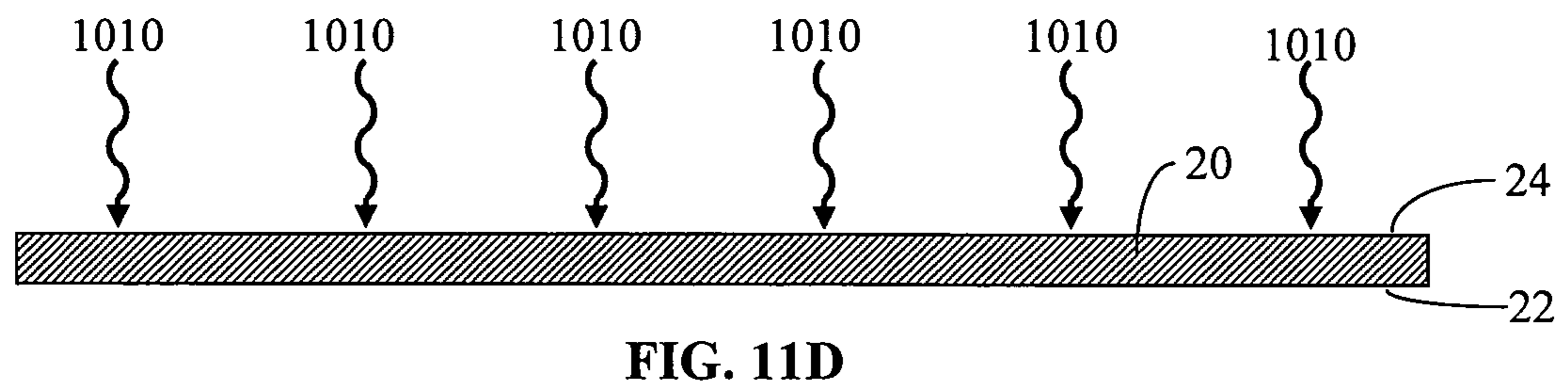
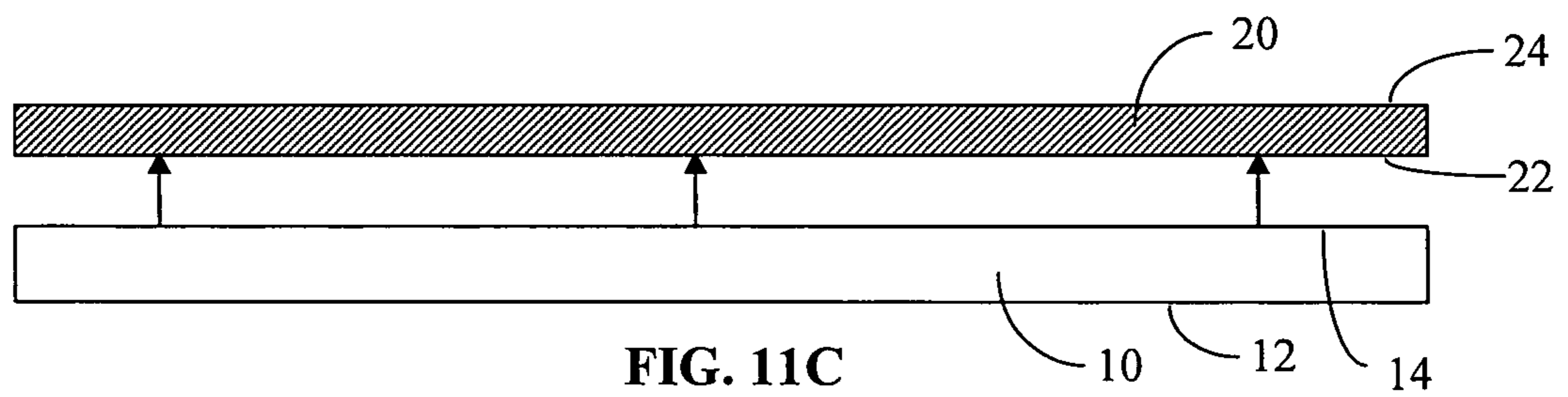
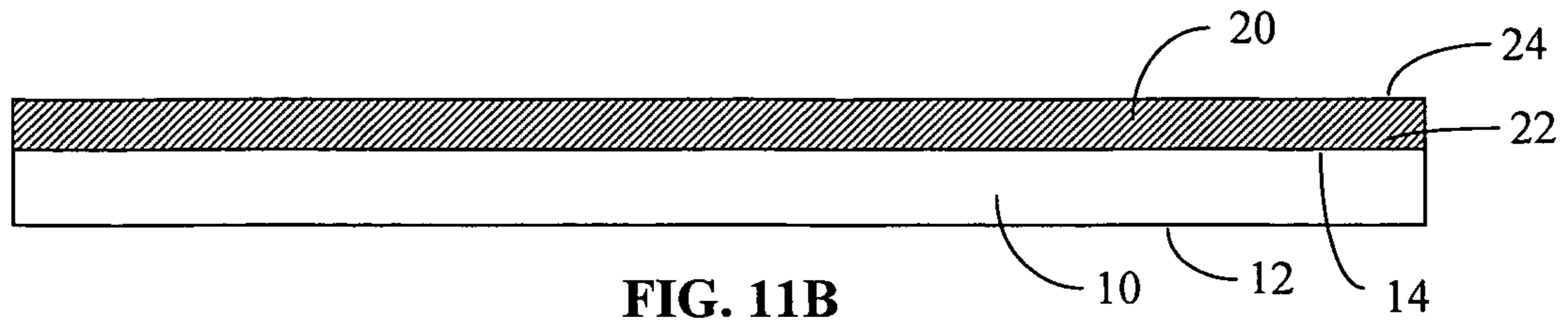
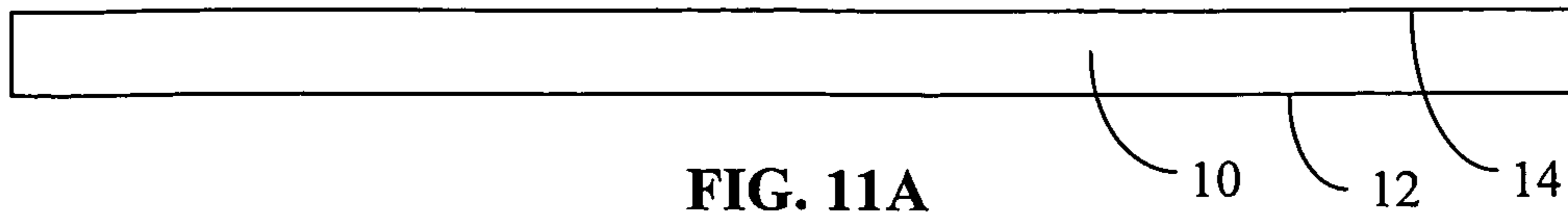


FIG. 10I



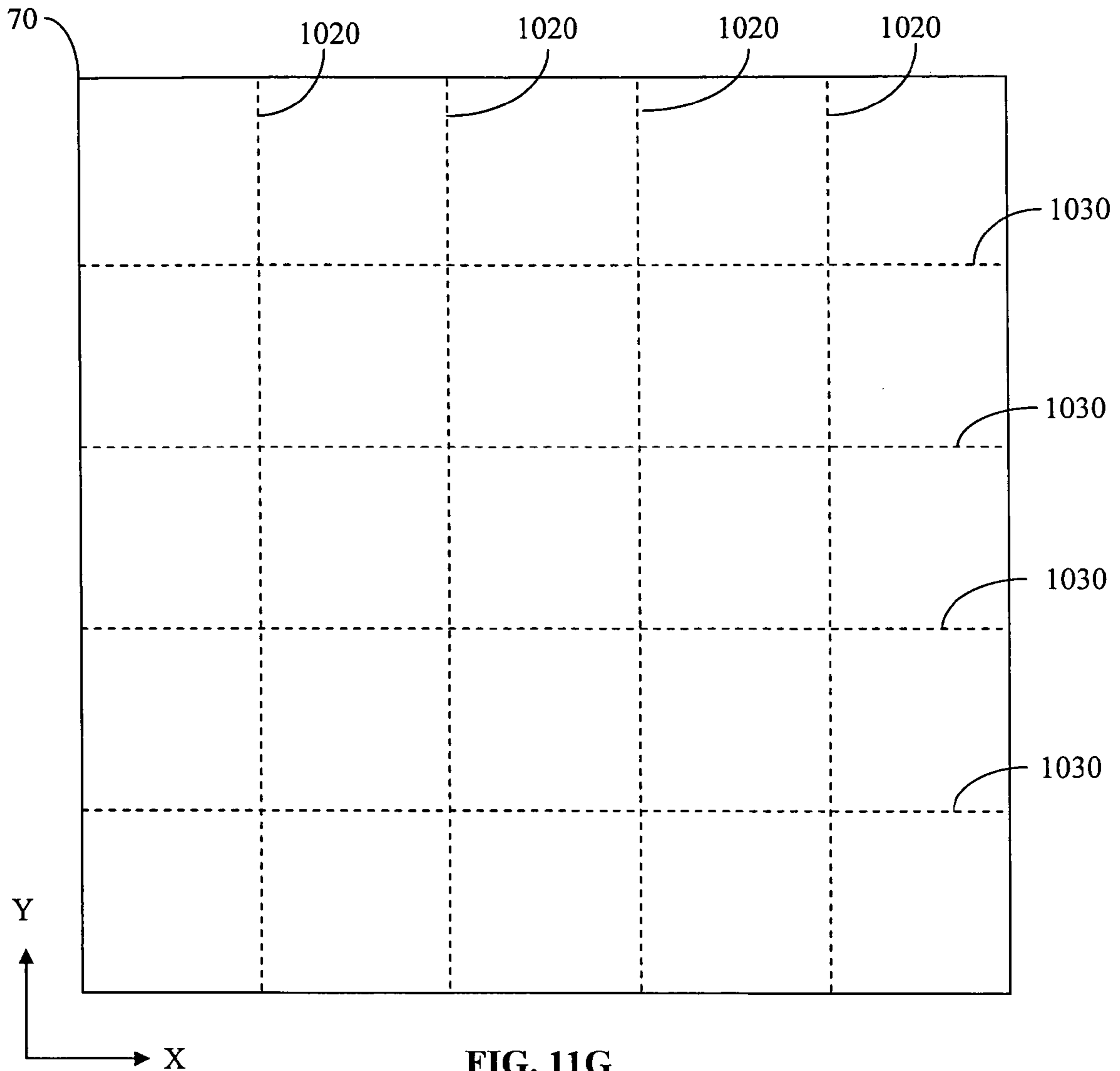


FIG. 11G

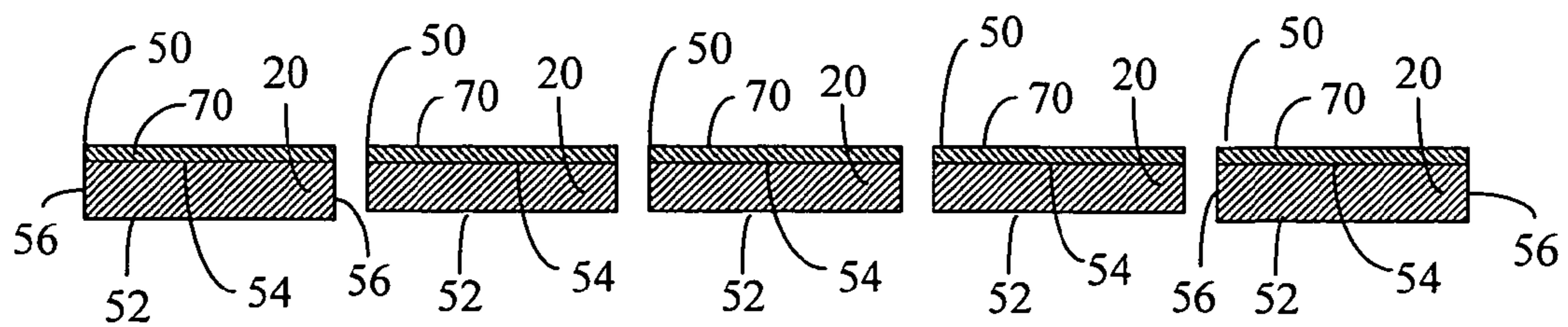


FIG. 11H

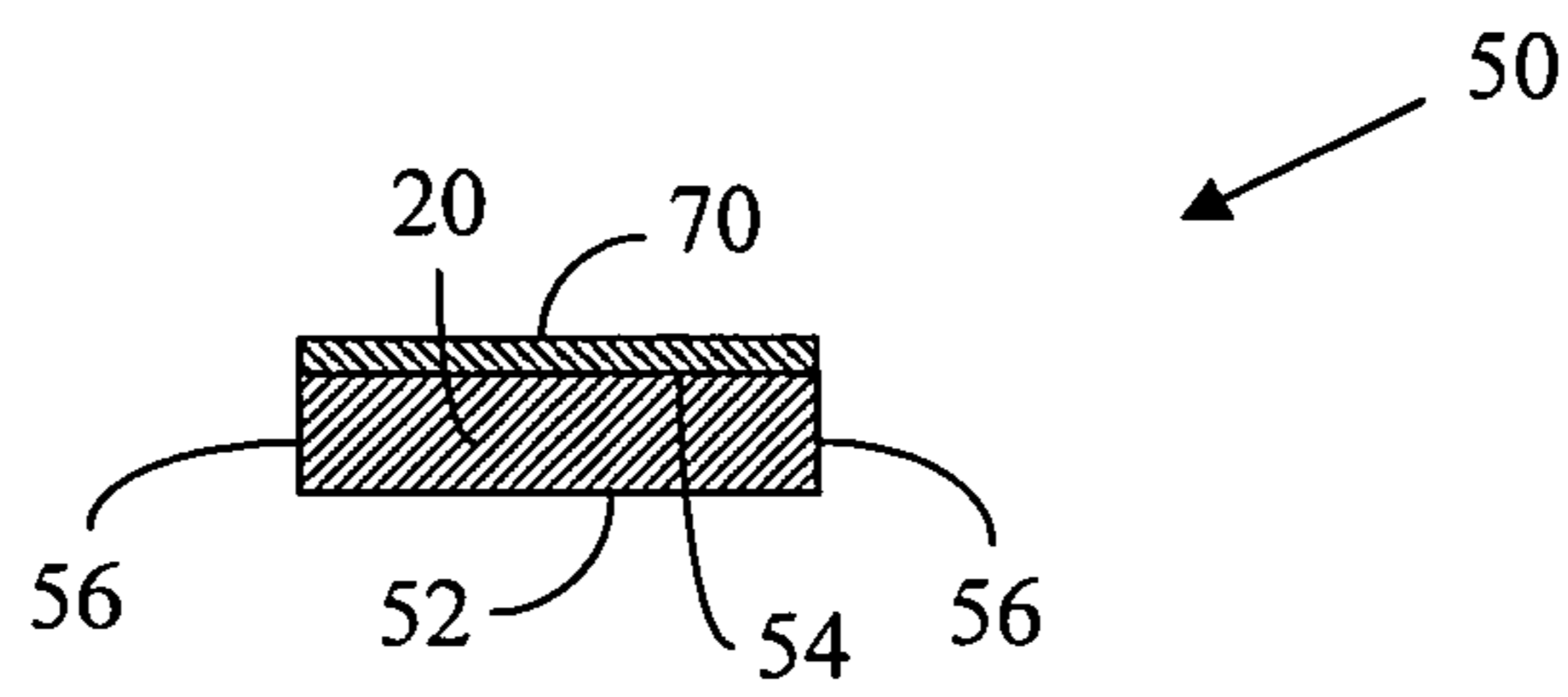


FIG. 11I

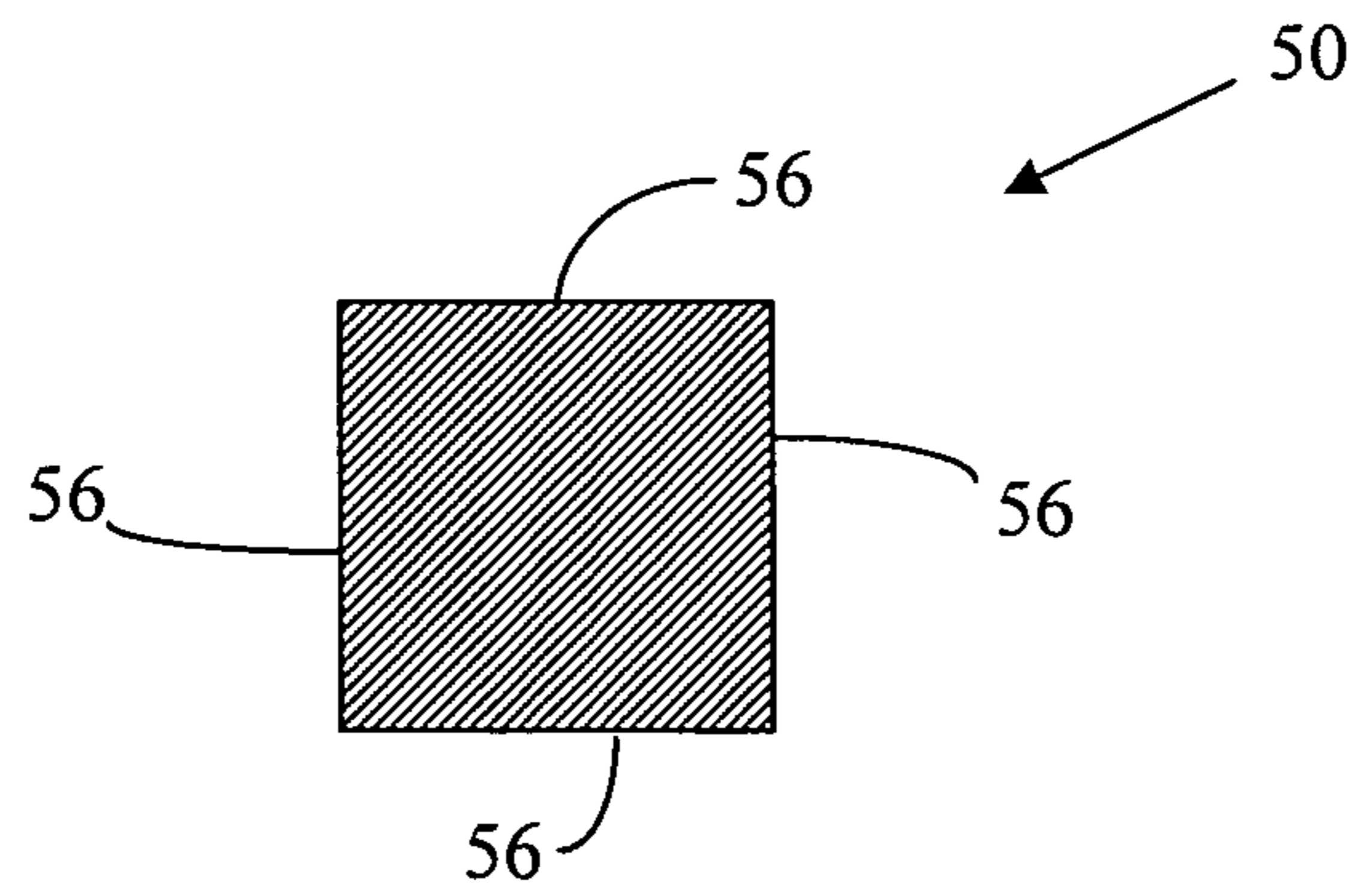
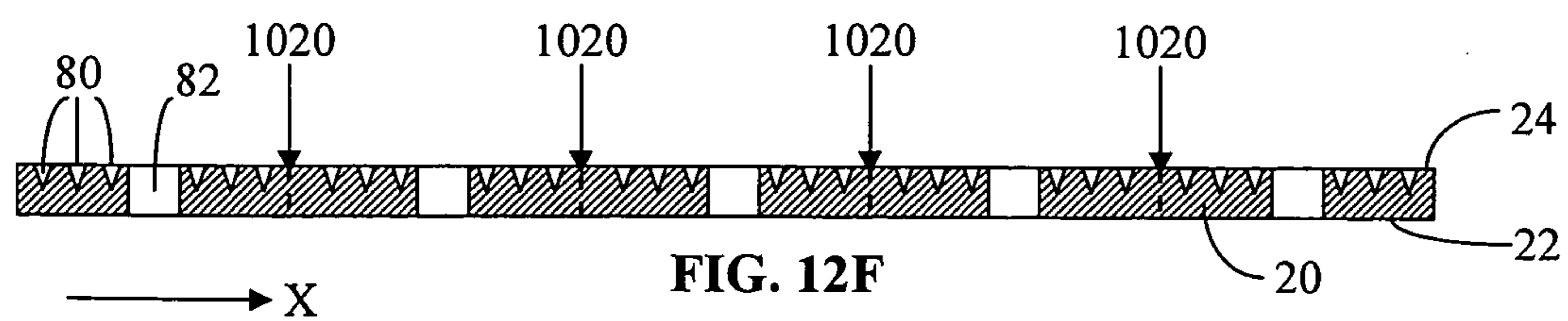
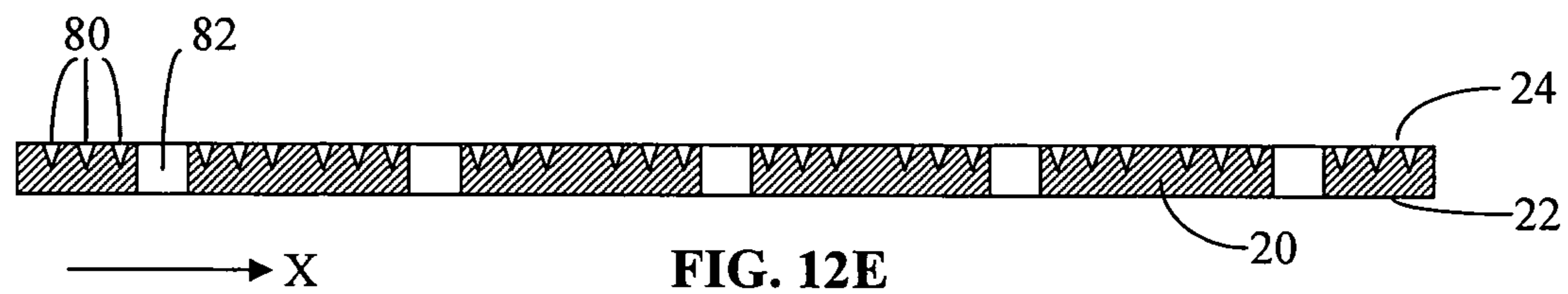
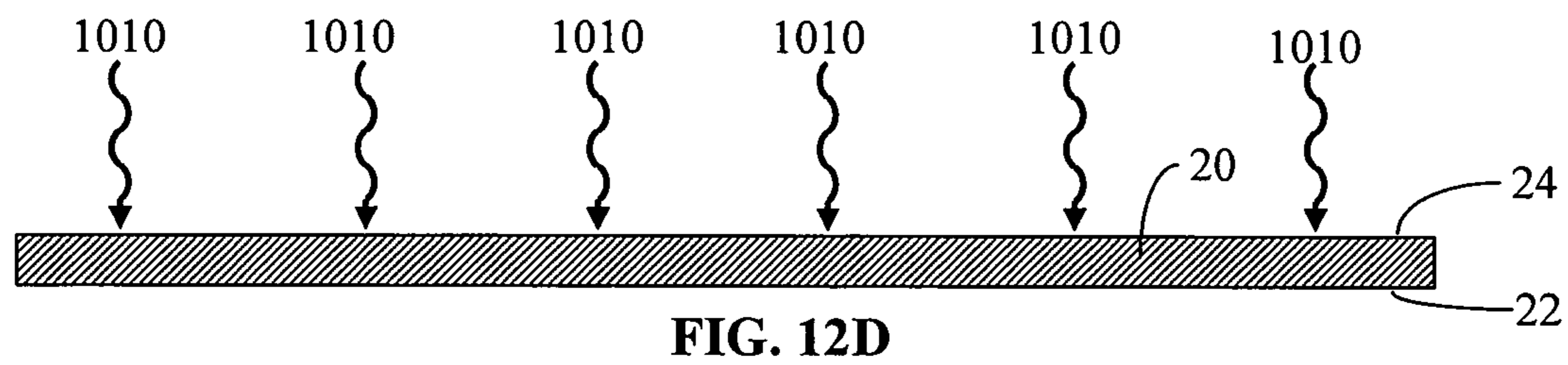
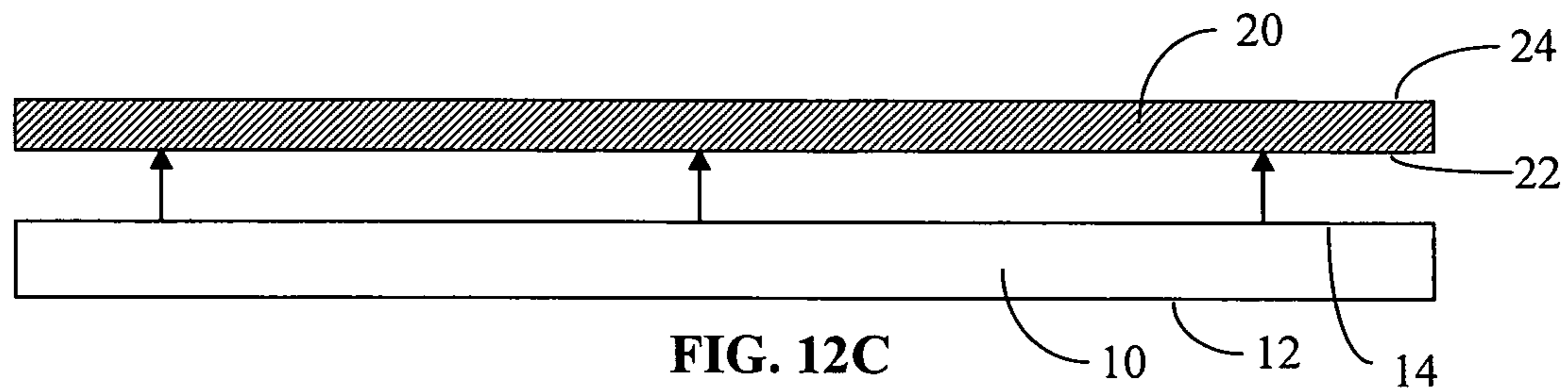
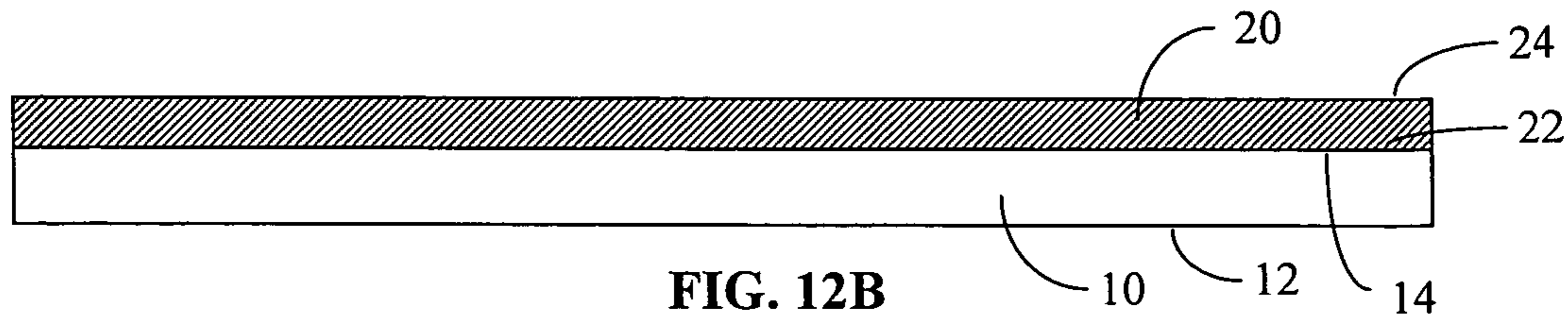
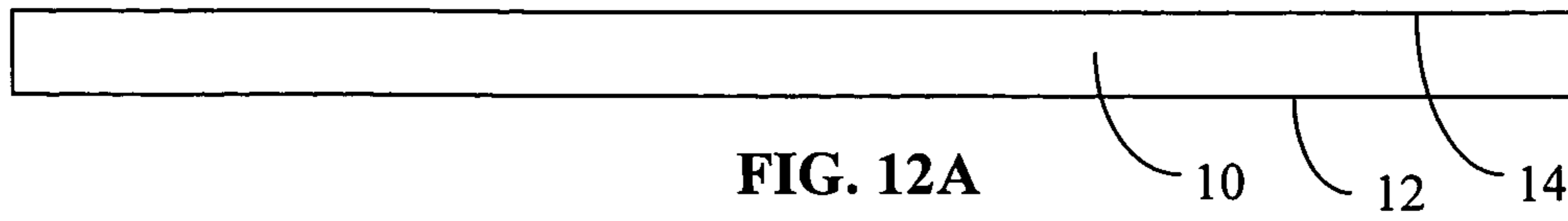
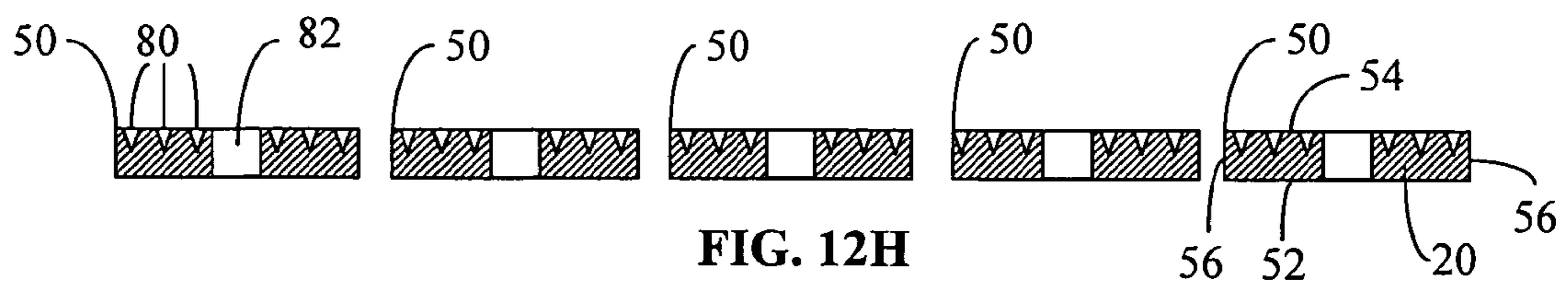
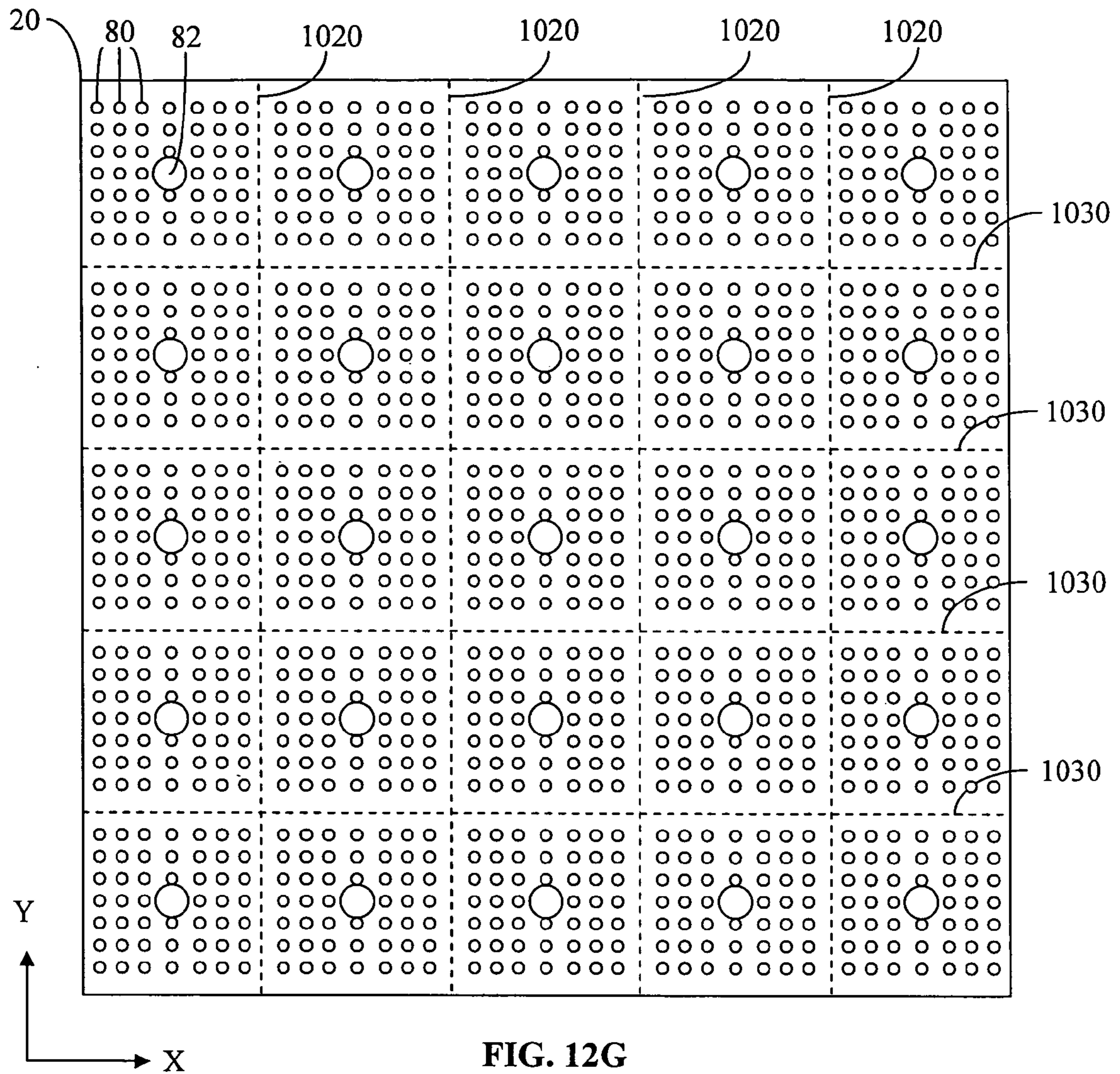


FIG. 11J





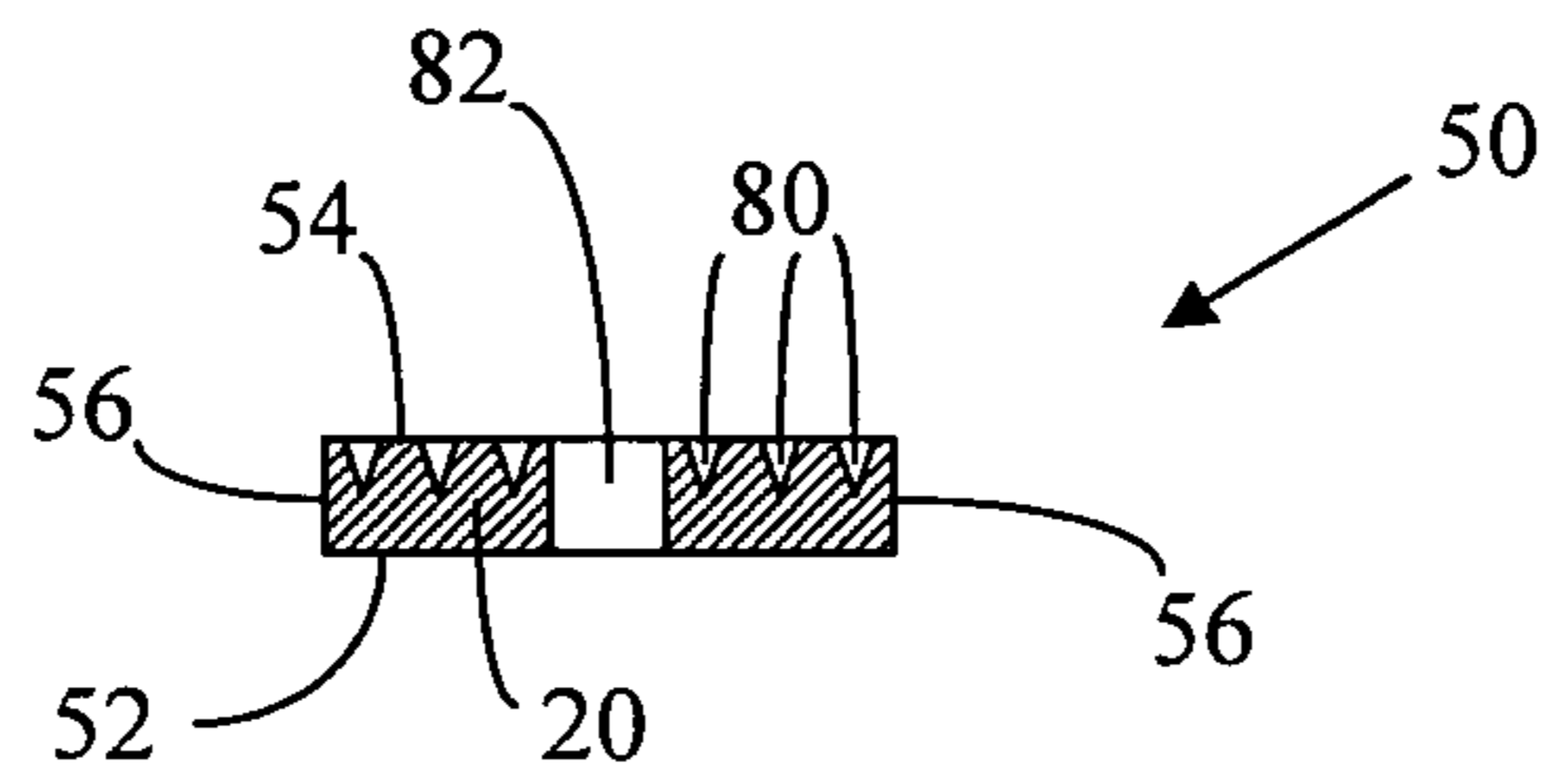


FIG. 12I

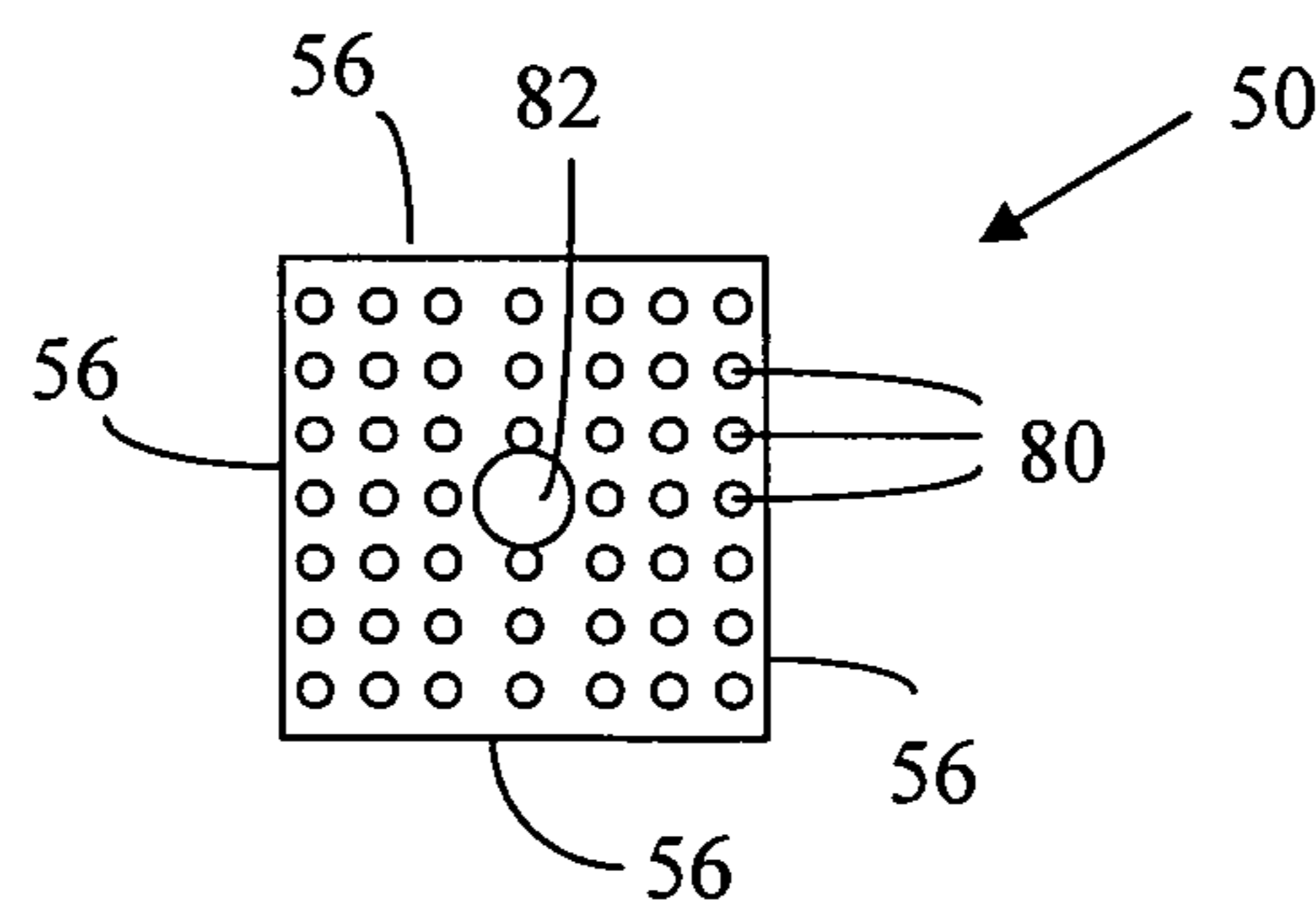
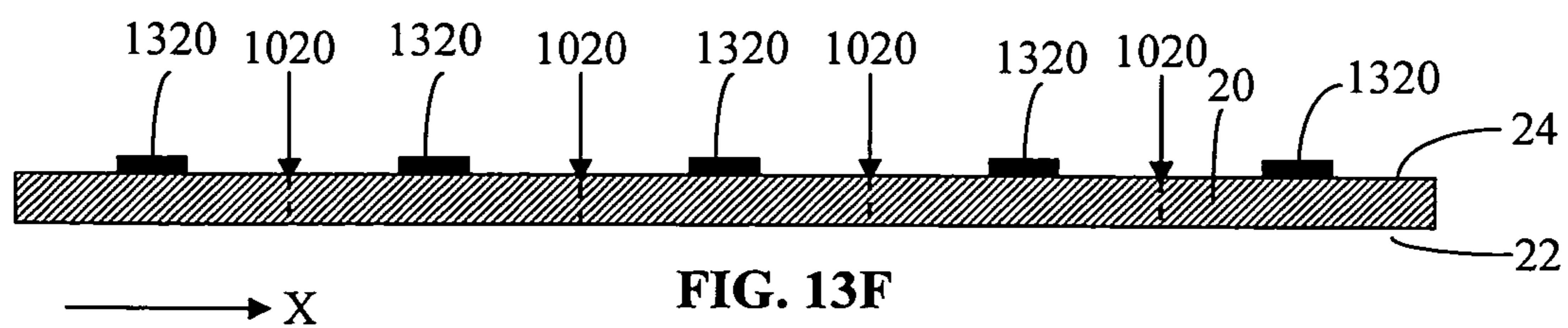
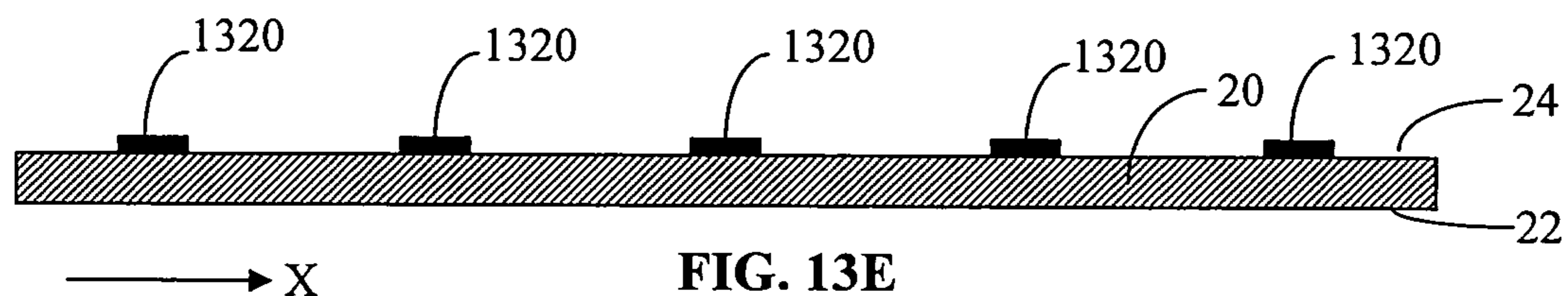
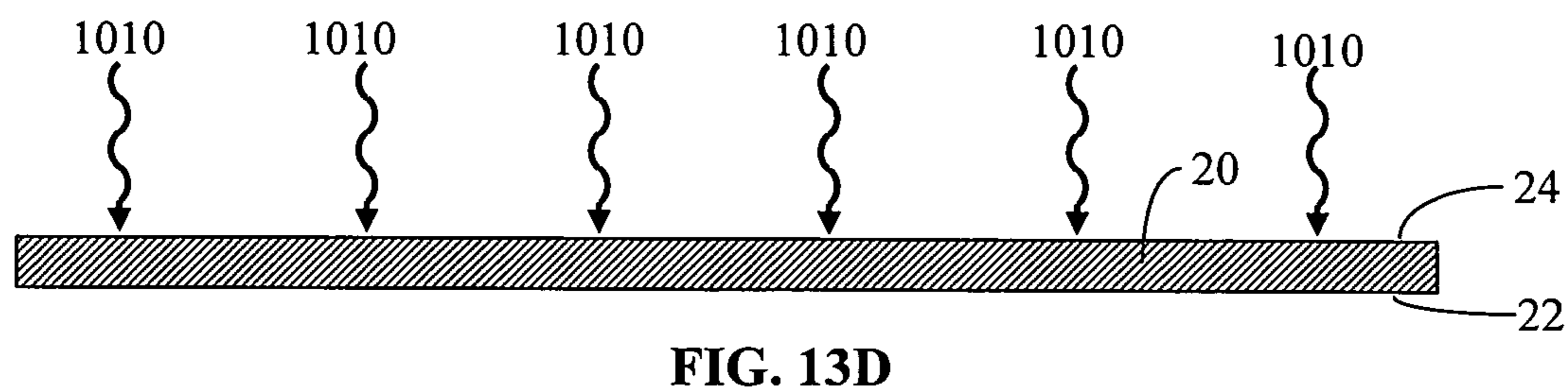
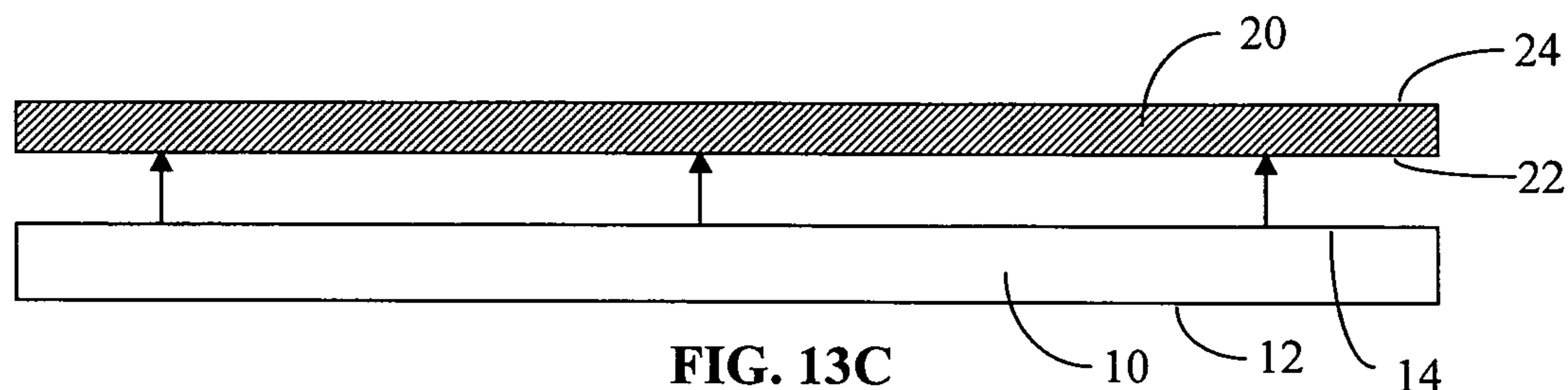
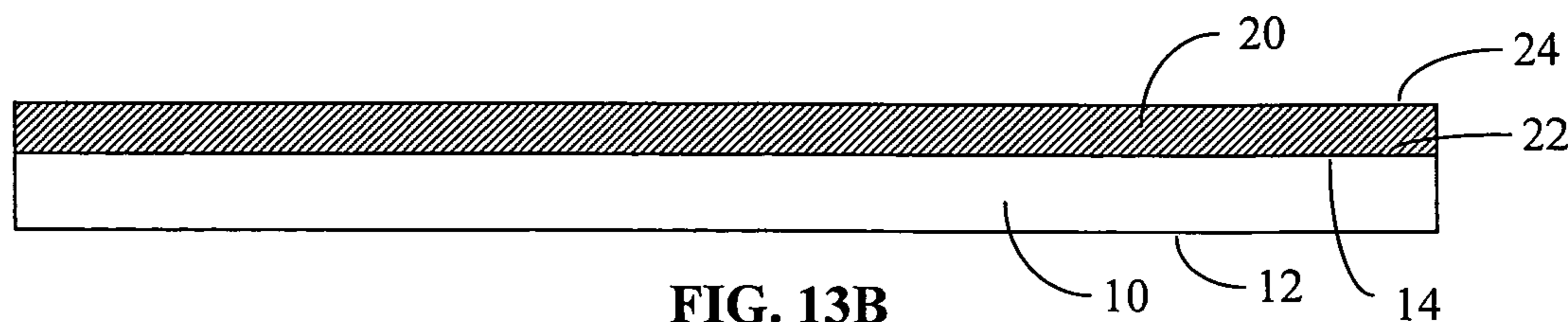
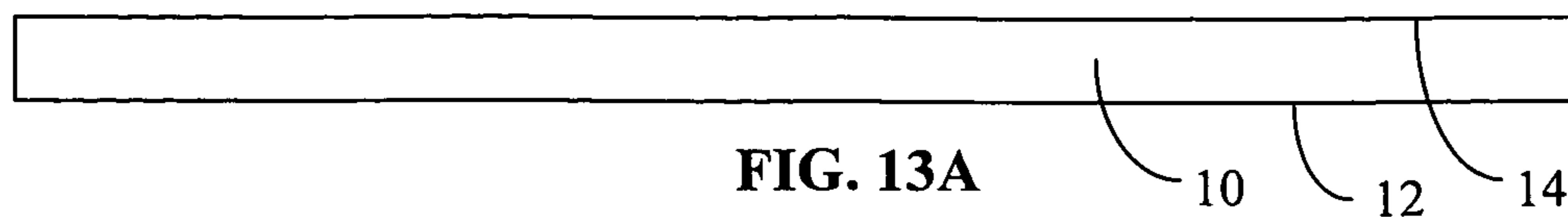


FIG. 12J



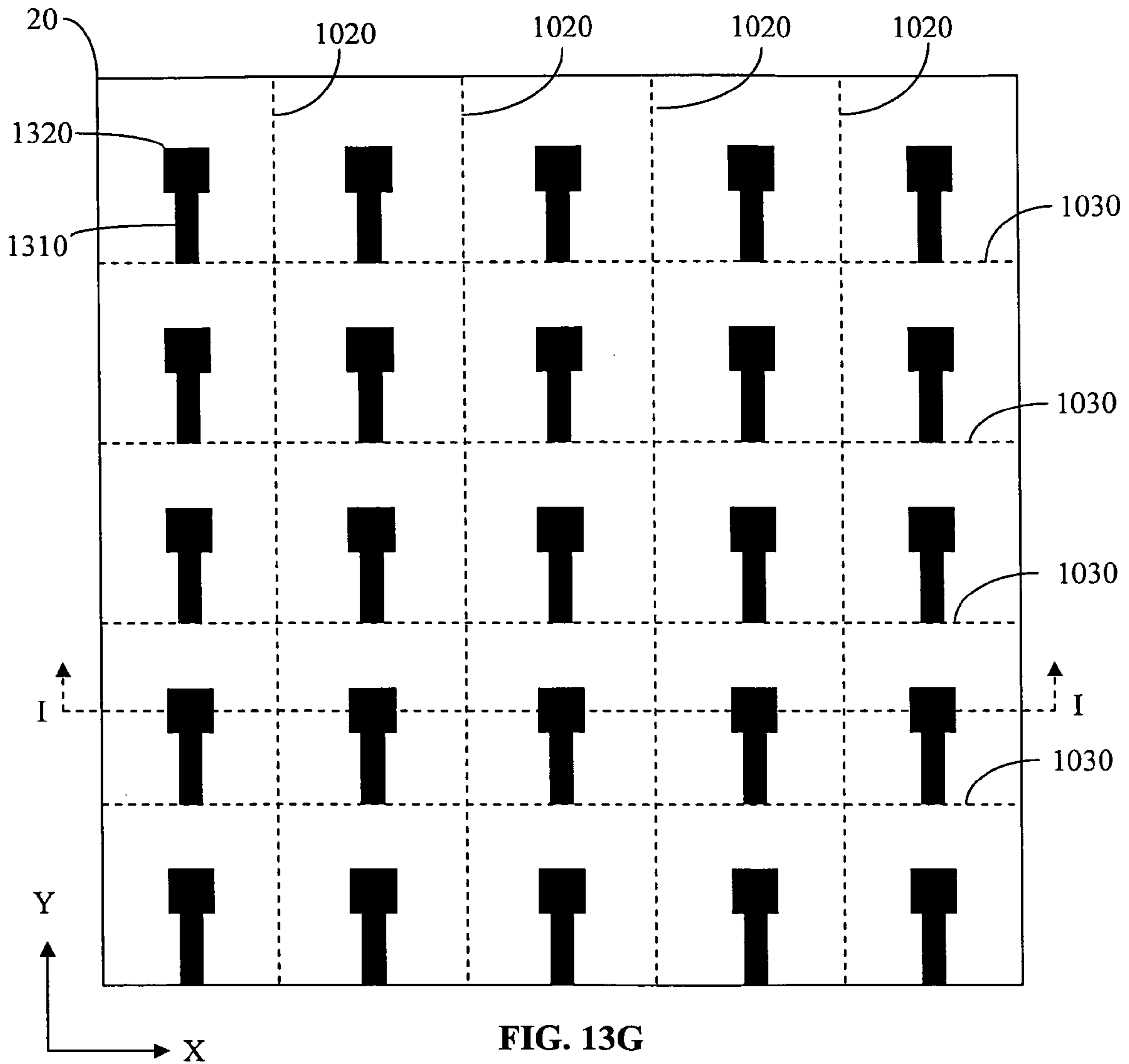


FIG. 13G

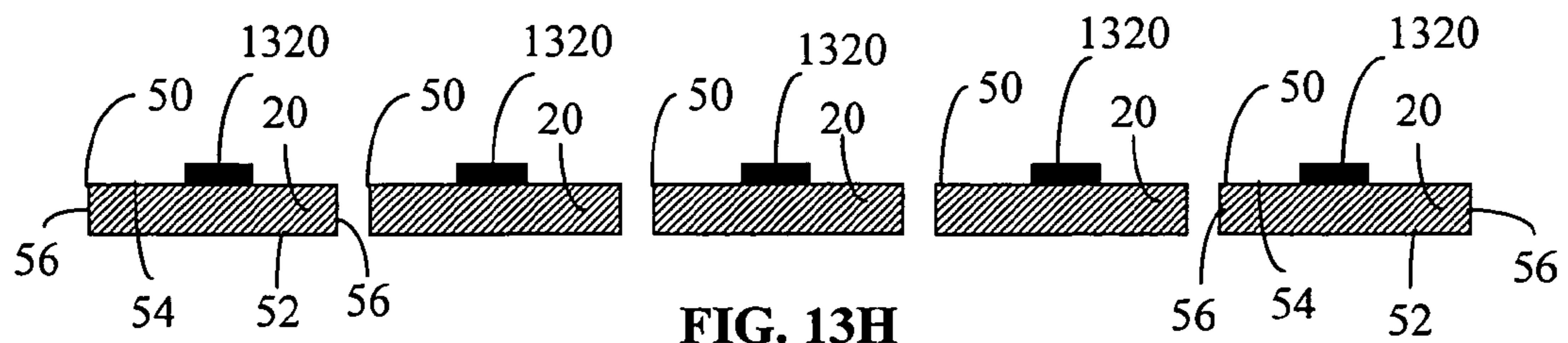


FIG. 13H

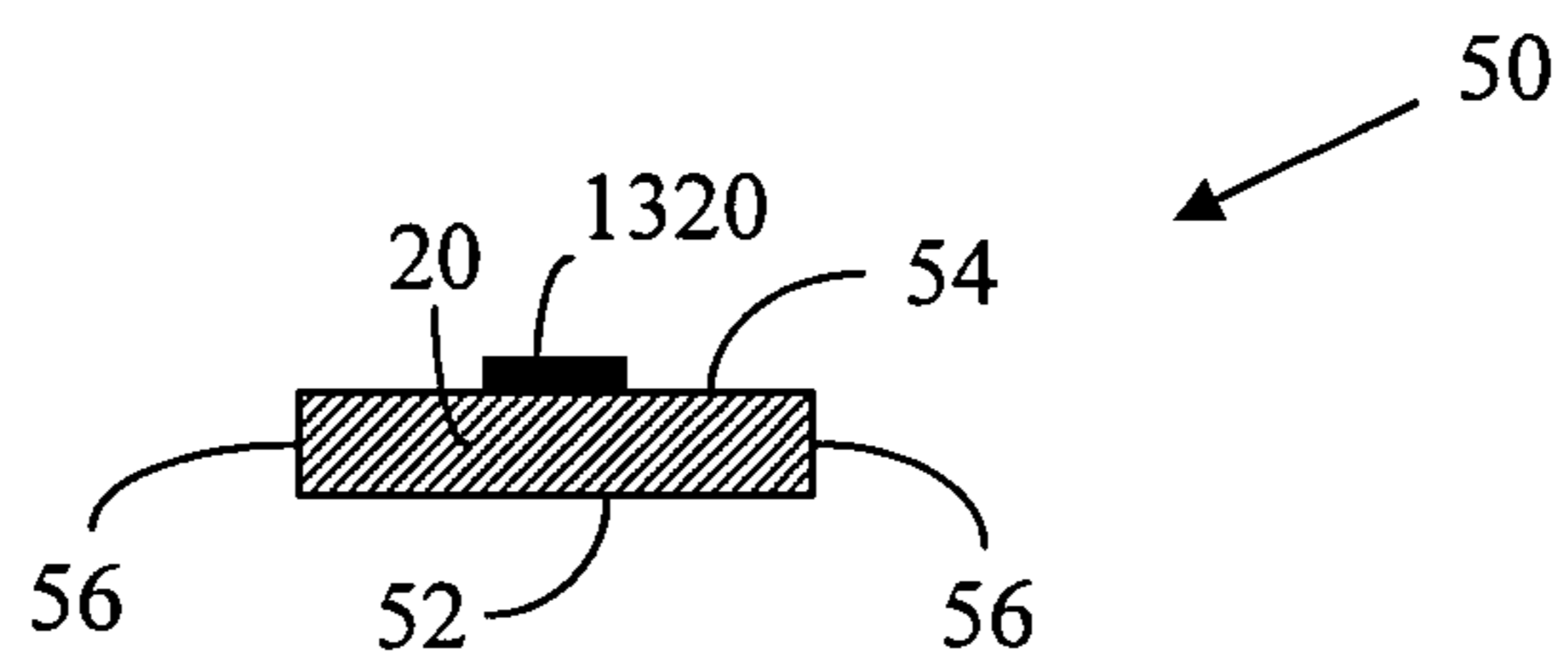


FIG. 13I

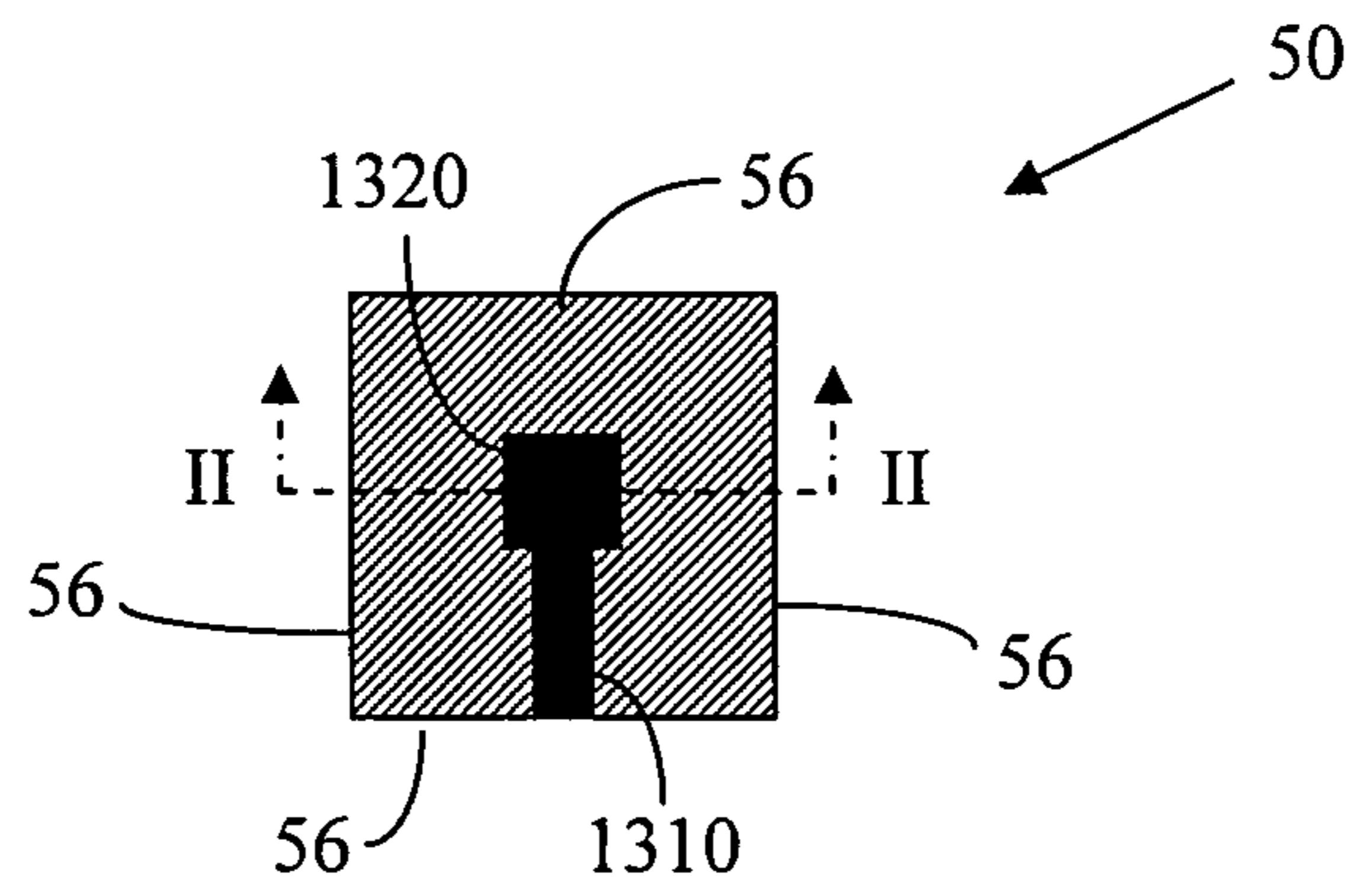


FIG. 13J

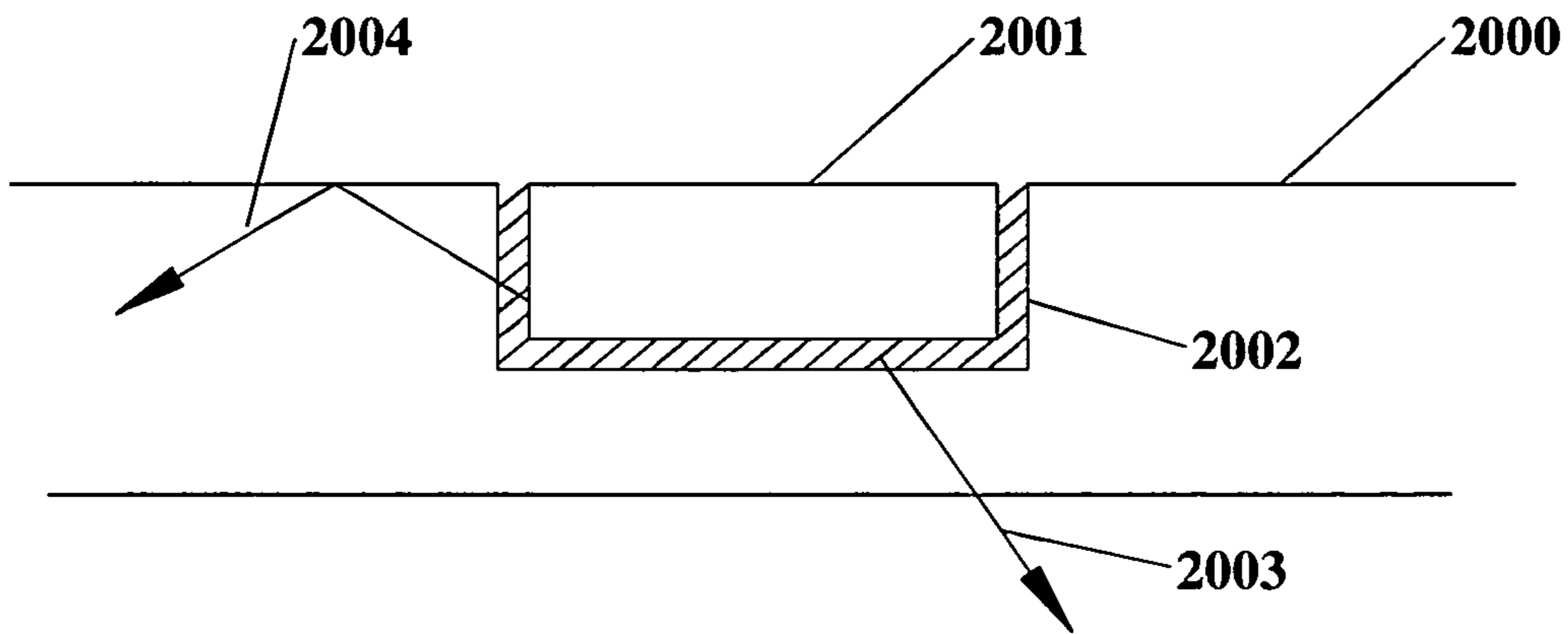


FIG. 14A

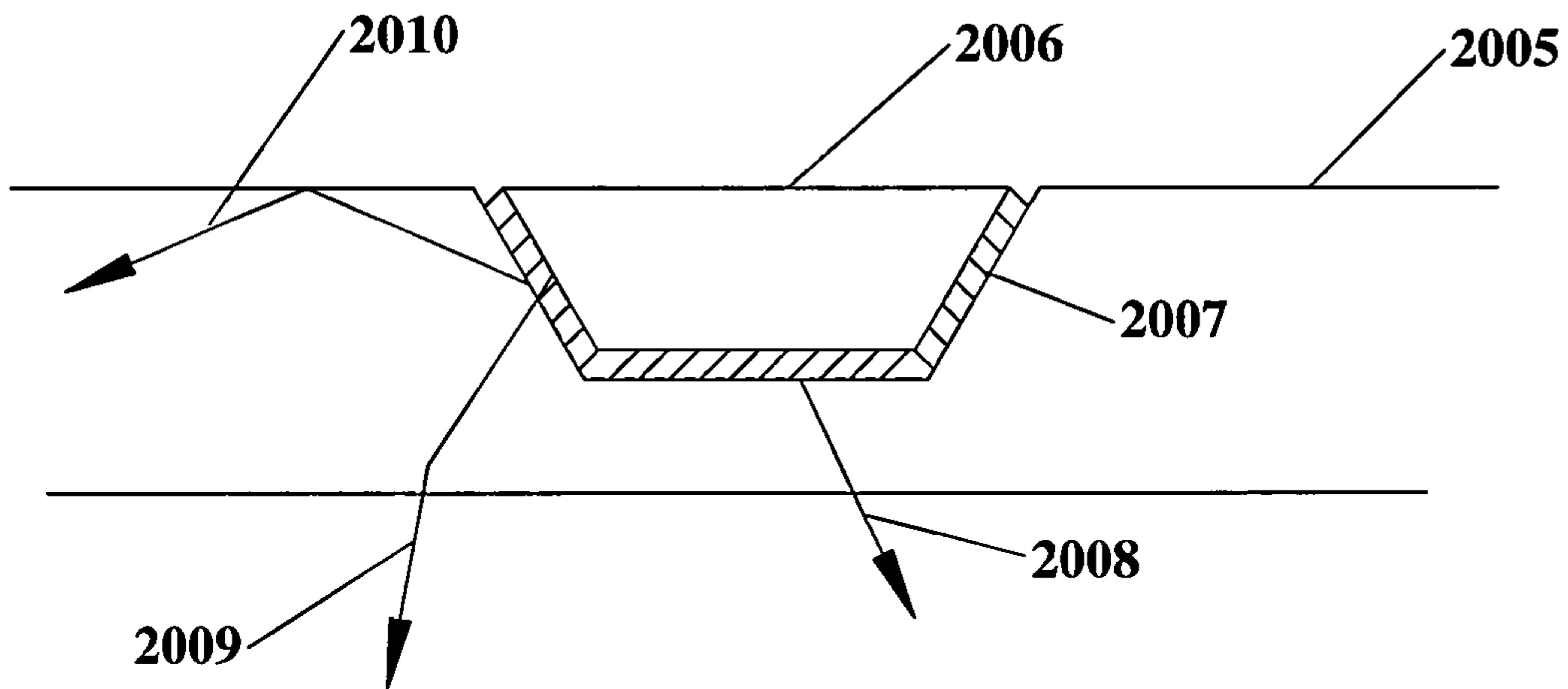


FIG. 14B

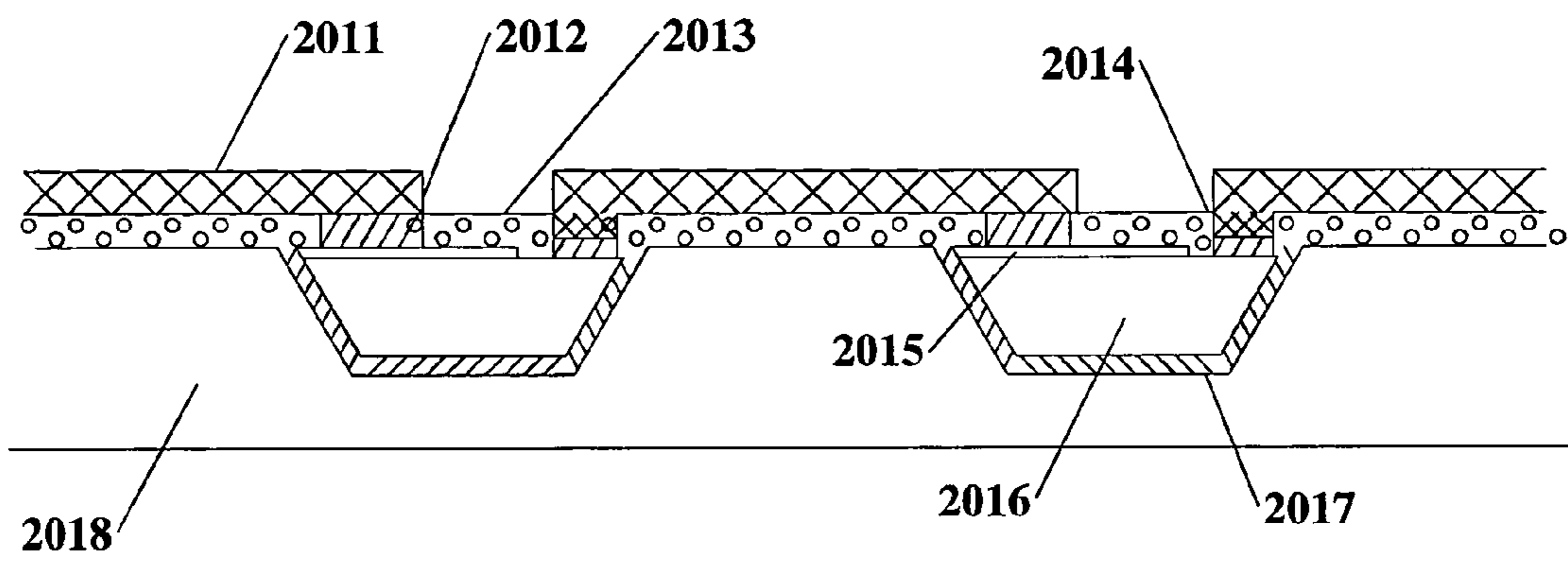


FIG. 15

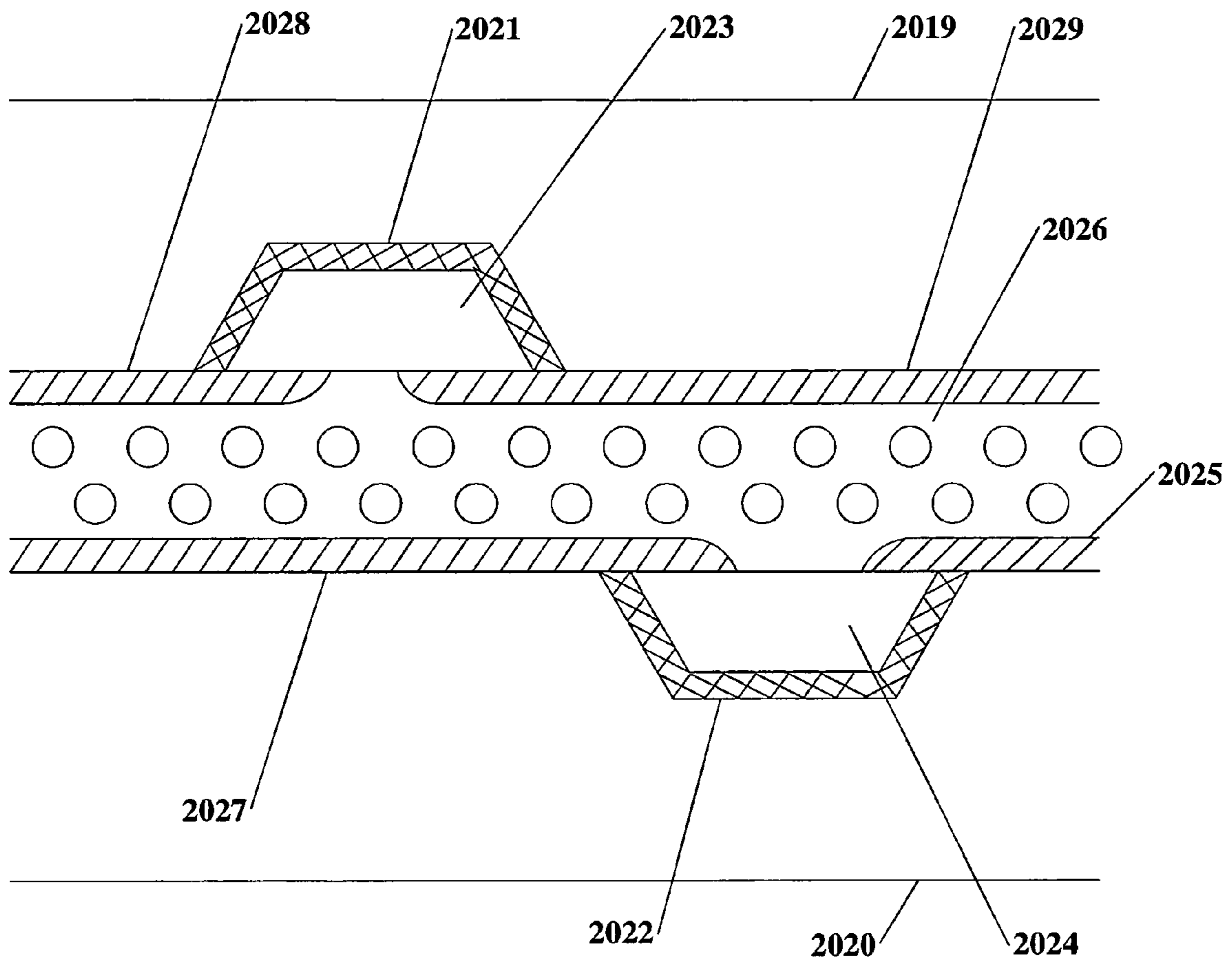


FIG. 16

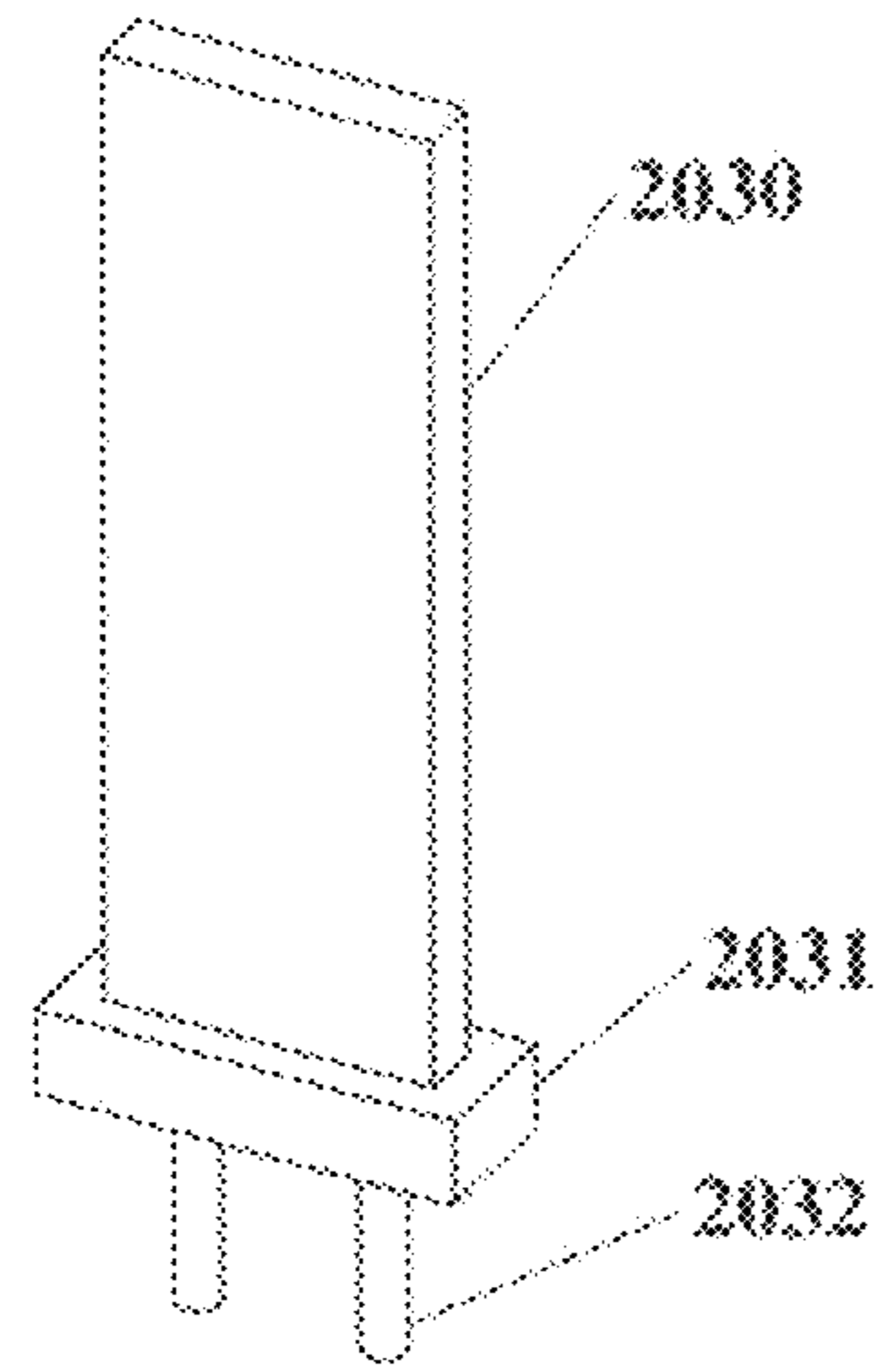


FIG. 17A

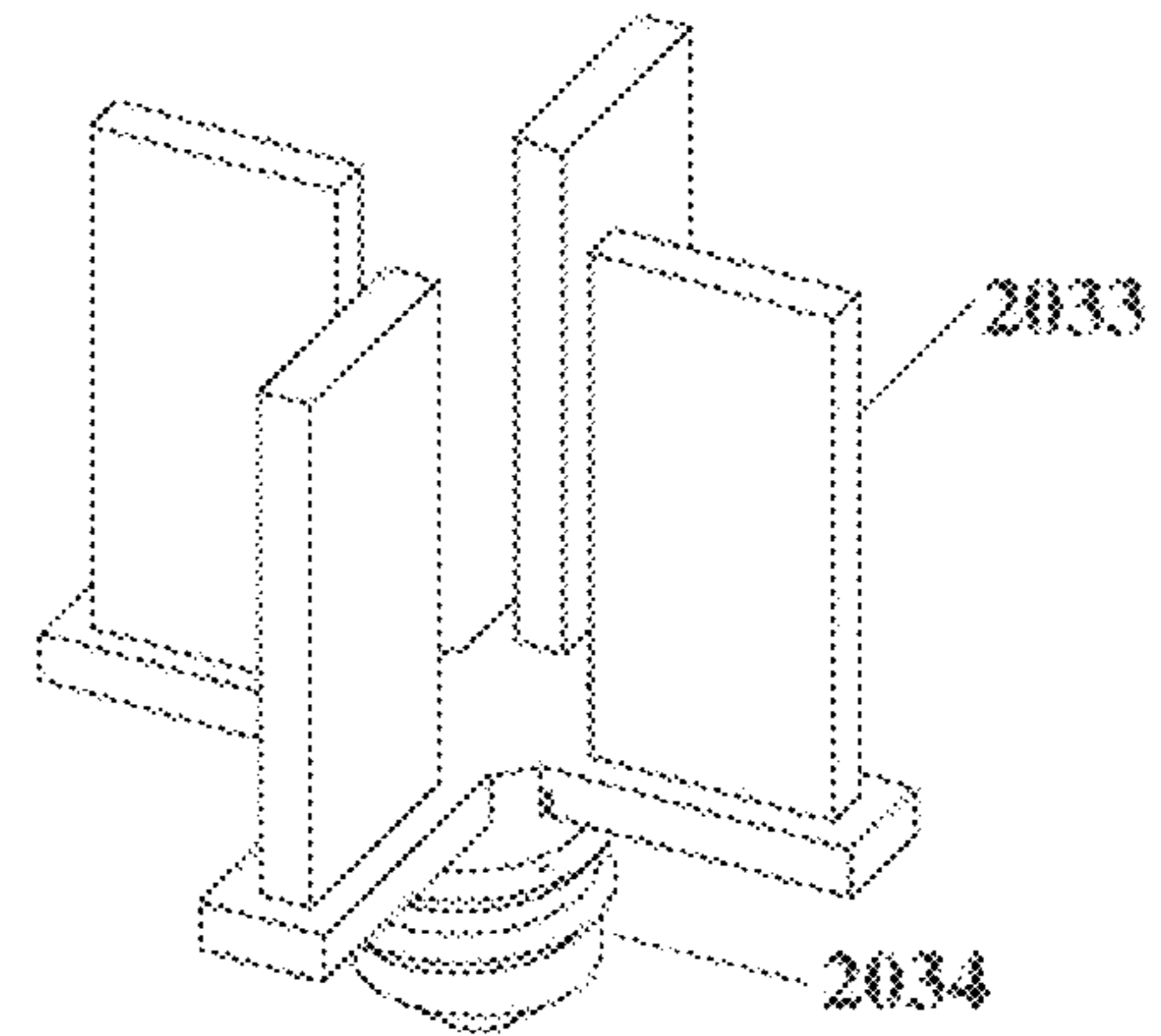


FIG. 17B

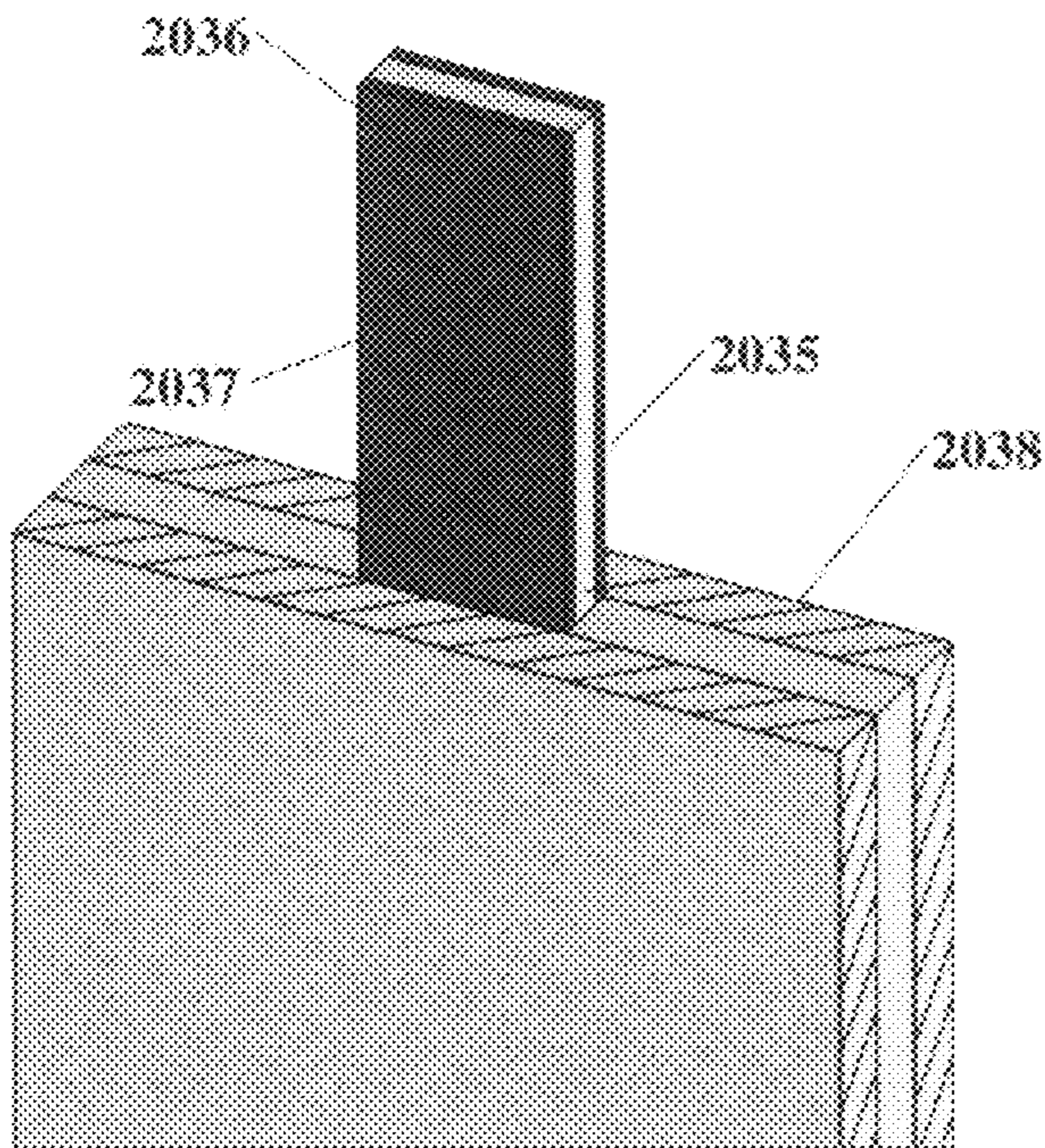


FIG. 17C

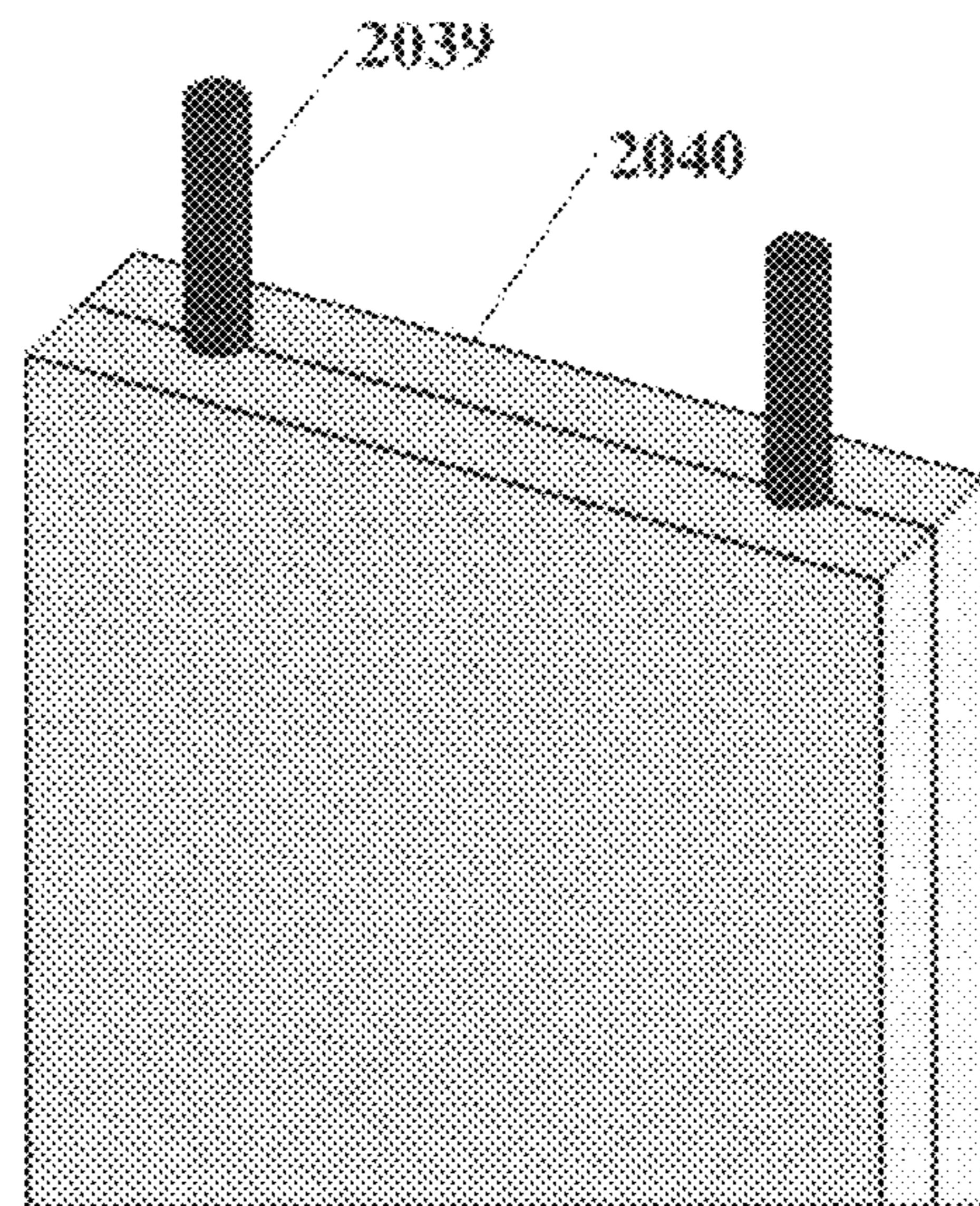


FIG. 17D

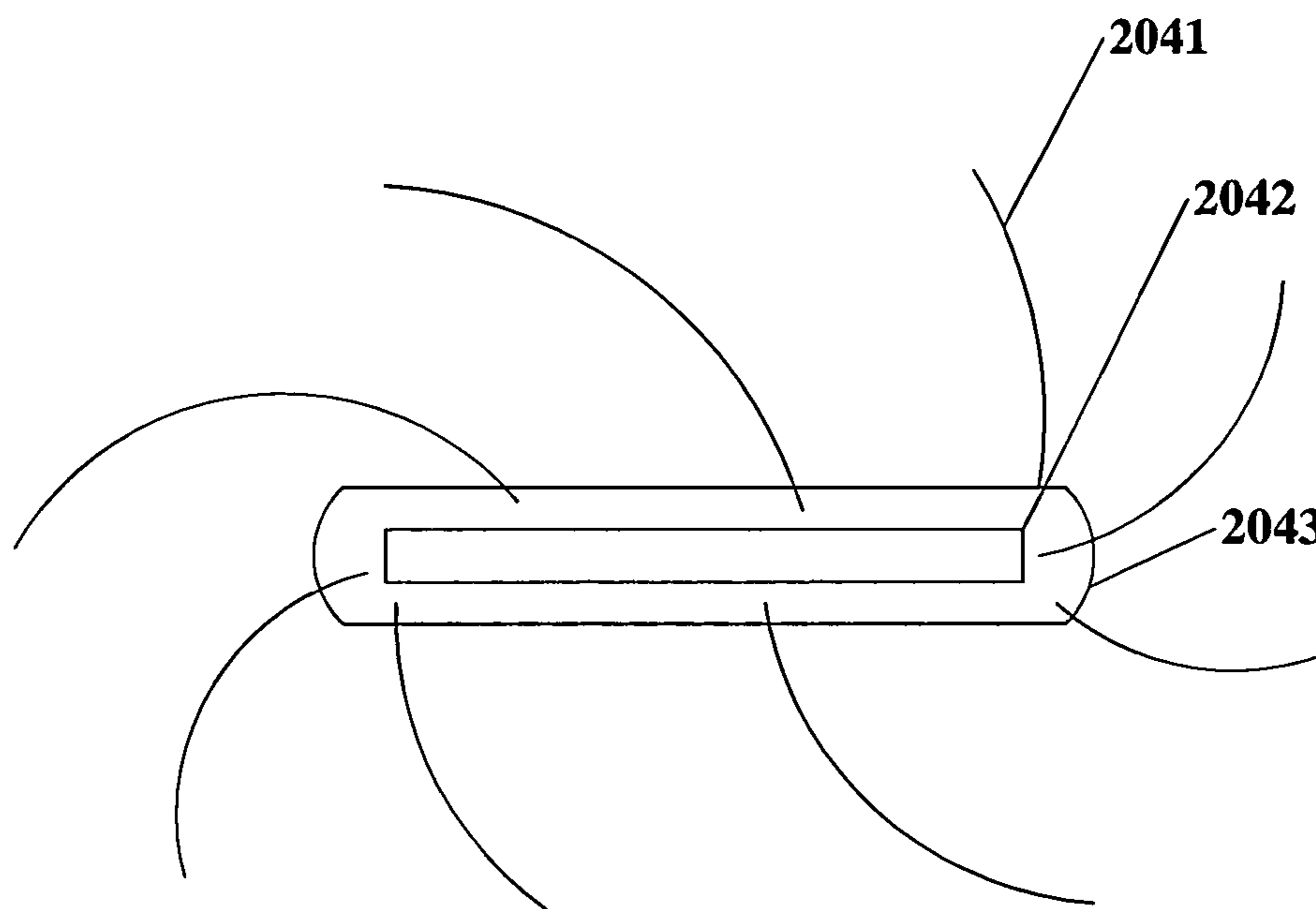


FIG. 18

LED LIGHT SOURCE WITH THERMALLY CONDUCTIVE LUMINESCENT MATRIX

CROSS REFERENCE TO RELATED APPLICATIONS

This application is a continuation-in-part of U.S. patent application Ser. No. 11/975,406 entitled "WAVELENGTH CONVERSION CHIP IN SOLID-STATE LIGHTING AND METHOD FOR MAKING SAME," filed Oct. 19, 2007 now U.S. Pat. No. 7,795,600, which was a continuation-in-part of U.S. patent application Ser. No. 11/389,311 entitled "WAVELENGTH CONVERSION CHIP IN SOLID-STATE LIGHTING AND METHOD FOR MAKING SAME," filed Mar. 24, 2006 now U.S. Pat. No. 7,285,7911, and claims benefits therefrom.

TECHNICAL FIELD

A chip containing a wavelength conversion material and a method for making the chip. The chip can be used in conjunction with a light emitting diode (LED) to convert light emitted by the LED into another wavelength.

BACKGROUND

The recent proliferation of solid-state lighting has created a need for high performance wavelength conversion materials. The standard approach is to form wavelength conversion materials (e.g. phosphors) using solid state processing as known in the art. These phosphors are then ground down to powders in the micron size range and deposited on a surface using a variety of deposition techniques such as settling, encapsulation, and spray coating. Large extended area devices such as cathode ray tubes (CRTs), fluorescent lighting, and plasma displays require a large amount of standard high volume phosphors. These phosphors can be acquired for less than \$100/Kg for the large extended area devices. Though relatively inexpensive, the phosphors generated using this method suffer from high levels of dislocations and lattice defects. In addition, the compositional purity is also difficult to maintain. In the majority of cases, this does not represent a major problem because of the reduced excitation levels. It has been shown, however, in accelerated aging studies that very high excitation levels can degrade the output luminescence of powdered phosphors severely and impact overall life performance. These levels of high excitation exist within solid-state lighting applications. This is mainly due to the small size and concentrated flux density of the LED die itself. It is also true that in the case of individual or arrays of LEDs, phosphor usage is measured in milligrams rather than grams. It is apparent that higher performance wavelength conversion materials are needed and can be afforded for applications like solid-state lighting. The expense of higher performance materials can be absorbed and even offset if the problems associated with the degradation and reduced conversion efficiency of phosphors used in solid-state lighting can be overcome.

Several material characteristics contribute to this degradation and/or loss in efficiency problem such as lattice defects, out-gassing, and compositional purity. It has been shown that polycrystalline and mono-crystalline phosphor films either grown on a substrate or as single crystal boules tend to exhibit much better luminosity and life characteristics than powders. In addition, every phosphor has a thermal quenching level that can degrade the output at the temperatures created by elevated excitation levels. In the case of powdered phosphors,

this can be a major issue because the phosphor particles are usually isolated from any reasonable thermal conduction path. At very high excitation levels the energy associated with less than unity quantum efficiency and Stokes shift losses can induce a significant localized thermal rise within the phosphor particles. The need exists for creation of an improved thermal conduction path for the luminescent material. Also, because the particles are roughly spherical the packing density can be significantly degraded. This affects the tradeoff between maximum absorption/conversion of the excitation energy and reabsorption of the emitted light. The scattering created by the use of a powder can reduce the overall light output due to the backscattering and subsequent absorption of the generated light.

Mueller-Mach et al. in U.S. Pat. No. 6,696,703 disclose the deposition of a thin film phosphor directly on the LED die. However, as-deposited thin film phosphors have relatively poor wavelength conversion efficiency. A high-temperature annealing step is required in order to properly activate the phosphor. This annealing step can damage the semiconductor layers of the LED. In addition, the absorption cross-sections of most thin film phosphors are low, especially for blue and near ultraviolet (UV) excitations typically used within solid-state lighting. It is neither economical nor practical in most cases to create a sufficiently thick layer of luminescent material directly on the LED. Another drawback to depositing a phosphor directly on the LED die is that a large portion of the light generated within a deposited phosphor layer can be trapped due to total internal reflectance. The need therefore exists for a method to utilize high performance phosphors within an LED package such that the best phosphor can be used efficiently (e.g. with sufficient quantity, minimal backscatter, and maximum light extraction). The need also exists for a method to fabricate high efficiency phosphors without damaging the LED semiconductor layers.

Another important aspect of phosphors relates to characterization and overall device efficiency. Phosphors are typically characterized in terms of quantum efficiency and Stokes shift losses. As an example, a powder phosphor layer is deposited on a glass surface and excited. The luminescence is measured as a function of excitation energy and the result is usually compared to a standard phosphor of known quantum efficiency. The losses associated with Stokes shift can be subtracted and the result would be the intrinsic quantum efficiency. Several problems exist with this method of characterization such as backscattered light, coating thickness variability and light trapping. In the case of phosphor powders, the majority of the generated light can escape from the phosphor particles due to their substantially spherical nature and to scattering centers located on or in the material itself. The main problem measuring the efficiency of phosphor powders is backscattering of the light from thick samples. For deposited phosphor films or grown phosphor boules, however, the problem of measuring the phosphor efficiency is affected by light extraction. The majority of the light generated in the phosphor can be trapped within the material itself due to total internal reflection. Several approaches have been used to solve the total internal reflection problem including various roughening techniques and shaping approaches. In these cases, the overall efficiency becomes as much a function of the extraction means as the conversion efficiency. Deposited phosphor films have the added complication of a secondary substrate material with its associated indices and losses.

Mayer et al. in U.S. Pat. No. 6,565,770 describe thin interference pigment flakes that can be made on a flexible substrate and then mechanically removed by flexing the substrate. The dichroic reflectors discussed are used in security

enhancement on money and other decorative optical effects. The use of luminescent materials is discussed but is related to the formation of a particular optical effect such as UV illumination for security markings. No explanation for improving the output efficiency of LEDs or other light emitting devices is discussed and no device based on integrating the phosphor layer with the excitation source to form an efficient solid-state lighting element is disclosed.

The use of flake-like phosphors is also discussed by Aoki et al. in U.S. Pat. No. 6,667,574 for use in plasma displays, but the patent again lacks any reference to solid-state lighting applications or methods to enhance their output. In addition, the above two applications are very much cost driven because of the large areas typically required in making a plasma display or the marking of money or decorative items. In order to maximize the performance of these wavelength-converting materials high temperature processing is preferred.

Mueller-Mach et al. in U.S. Pat. No. 6,630,691 disclose a thin single-crystal phosphor substrate onto which an LED structure is fabricated by epitaxial growth techniques. However, single-crystal phosphor substrates are expensive and finding a single crystal phosphor substrate that has the proper lattice match to allow the growth of the LED structure can be difficult.

Ng et al. in US Patent Application No. 20050006659 disclose a planar sheet of a single-crystal phosphor that is placed over the output surface of an LED as a portion of a preformed transparent cap. However, single-crystal phosphor sheets must be grown by epitaxial processes or sliced from bulk single crystals of phosphor material. Single crystal phosphor sheets are therefore too expensive for most practical applications. Planar sheets of polycrystalline phosphors are not disclosed in US Patent Application No. 20050006659. Bonding the planar sheet of a single-crystal phosphor directly to the surface of the LED to improve heat dissipation in the phosphor sheet is also not disclosed.

A need exists to maximize the efficiency of wavelength conversion materials within a solid-state lighting application and to improve the thermal conductivity properties of the materials. In addition, a need exists for low-cost phosphors that have light extraction enhancements and the ability to control the level and type of scatter within the phosphor in order to enhance the overall conversion efficiency.

A need exists for distributed self-cooling light sources which do not require large heavy heatsinks. In recent life cost studies the heatsinks themselves represent a major portion of the life cost. The LED manufacturers have focused on getting more lumens/mm² to reduce die cost but this increases dramatically the cooling requirements of the heatsink. The authors of this invention have demonstrated LEDs embedded within As such the concept of lumens/gram is disclosed and articles and methods for forming light sources which exhibit high lumens/gram outputs are disclosed.

Present phosphors used in LED applications rely on high dopant concentrations powders within typically an organic matrix to minimize scattering losses. The thermal conductivity is mainly defined by the matrix rather than the phosphor itself with typical thermal conductivity significantly below 1 W/m/K. The industry has also focused on generating more watts/mm² from the LEDs themselves to decrease cost. There has also been a trend towards larger die size to decrease packaging costs. Unfortunately, this greatly increases the thermal load on the phosphor system. In many cases the phosphor must be remotely mounted such that the watts/mm² incident on the phosphor and more importantly the matrix is reduced. Inherently the C—H bonds found in virtually all organic systems are susceptible to UV/blue wavelength used

to excite the phosphors. In addition, many phosphors act also as photocatalysis further degrading the matrix at the interface between the phosphor powders and organic material. While glass based matrices have been disclosed the efficiency, thermal conductivity, or stability of these systems are lower than polycrystalline, ceramic, or single crystal chips previously disclosed by the authors. In general, powder phosphors within any matrix material does not perform as well as polycrystalline, ceramic, or single crystal luminescent elements.

High dopant concentrations inherently suffer from concentration quenching and as such are inherently less efficient than lower dopant concentrations. In addition, the need exists for methods to distribute the light generated over an area. This is from both an aesthetic standpoint and a safety standpoint. The formation of distributed light sources allows for lower surface brightness and more uniform lighting at a distance. From a safety standpoint, localized point sources represent a greater risk due to the eye's tendency to image these sources on the retina. The need therefore exists for distributed light sources where the surface brightness does not exceed safe and tolerable levels. The authors will disclose how low dopant concentration luminescent elements can be used as lossy waveguides to excitation light such that more uniform distributed light sources are formed.

Based on the above discussion a distributed self-cooling light source is needed. This invention discloses the use of thermal conductivity luminescent elements, articles and methods which meet this need by combining thermal cooling and optical distribution means substantially within the luminescent element itself.

SUMMARY OF THE INVENTION

The objective of this invention is to produce high performance wavelength conversion chips for solid-state lighting applications. One embodiment of this invention relates to a method for forming a high performance wavelength conversion layer on a substrate, then removing the wavelength conversion layer from the substrate in a manner that creates thin wavelength conversion chips of luminescent material that can then be attached intimately to LEDs.

Another embodiment of this invention is a method for forming a wavelength conversion chip that optionally includes an optical coating on at least one surface the chip. Example optical coatings include reflective coating layers that are wavelength dependent or polarization dependent and photonic bandgap coatings. Also included in this invention is the incorporation of single or multilayered antireflection coatings on the surface of the wavelength conversion chips in order to reduce Fresnel effects on one or more surfaces.

A method for forming a wavelength conversion chip that optionally includes one or more vias that are fabricated through the wavelength conversion chip is another embodiment of this invention. The vias allow for the attachment of electrical connections to the upper surface of the LED.

Another embodiment of this invention is a method for fabricating a wavelength conversion chip that includes optional light extraction elements that allow light to easily exit from the chip, leading to improved efficiency. The use of structures within or on the wavelength conversion chip as well as a variety of sub-wavelength optical elements within or on the chip can be used to induce controlled scatter or directional scatter.

Another embodiment of this invention is a method for fabricating a wavelength conversion chip that includes an electrical connection and/or an electrical bond pad.

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A further embodiment of this invention is a wavelength conversion chip formed by one of the above processes.

Bonding the wavelength conversion chip to the emitting surface of an LED to form a solid-state light source is another embodiment of this invention. Because the wavelength conversion chip is attached directly to the LED, the ability to conductively cool the wavelength conversion chip is vastly improved over a powder phosphor.

Another embodiment of this invention is a solid-state light source that includes a stack of wavelength conversion chips bonded to an LED. The stack of wavelength conversion chips can each be fabricated from the same wavelength conversion material or the chips can be fabricated from different wavelength conversion materials. The stack allows for an improved thermal conduction path from each wavelength conversion chip to the LED. The LED itself has a heat sink to maintain the LED die at a low temperature during operation.

The wavelength conversion chip can be attached to an LED by a transparent and thermally conducting bonding layer. Multiple wavelength conversion chips can be attached in a stack using multiple transparent bonding layers. Since the wavelength conversion material is no longer a light scattering powder, a further advantage of this approach is the reduction of backscatter of excitation light due to the reduction in scattering centers. It is also possible to form a much more effective refractive index match to the LED die itself. Total internal reflection within the LED die can be frustrated and the extraction of photons normally trapped within the LED die can be improved. Bonding materials can include transparent conducting oxides, inorganic glasses and polymer materials such as epoxies, acrylates, halogenated polymers, sol-gels, silicones, and xerogels.

The fact that the wavelength conversion chips are formed independent of the LED die allows for a wide range of phosphor processing methods. Conventional processes such as sol-gel, molecular beam epitaxy (MBE), chemical vapor deposition (CVD), metal-organic chemical vapor deposition (MOCVD), sputtering, electron beam evaporation, laser deposition, liquid phase epitaxy (LPE), spin coating, doctor blading and tape casting can be used to process phosphors. Preferred techniques include doctor blading, tape casting, CVD, MOCVD and sputtering. Also the formation of quantum dot and various other quantum conversion materials by spin coating, doctor blading, tape casting, self assembly, lithography, and nanoimprinting can be realized to process phosphors. These wavelength conversion layers can be grown on amorphous, poly-crystalline, and single-crystal substrates. The wavelength conversion layers are usually polycrystalline, although single-crystal layers can also be fabricated. The process for forming the luminescent material can be a batch or a continuous process. Advances in low temperature processing even allow deposition on flexible organic substrates with post processing possible after removal of the wavelength conversion layer from the low temperature substrate. Separation from the substrate can be accomplished in a variety of manners including optical, chemical and mechanical means. More preferred would be the use of laser degradation of the interface between the substrate and wavelength conversion layer in a manner similar to the release GaN multi-quantum-well (MQW) LEDs from sapphire single crystal wafers. A more preferable method would be the fabrication of a wavelength conversion layer on a flexible polymeric or metallic continuous web substrate followed by bending the substrate to mechanically release the phosphor layer. The layer can be released as a single layer and then diced into chips or the layer may be patterned directly while on the substrate using a

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variety of dicing techniques including but not limited to laser scribing, mechanical dicing, and lithography and then released as individual chips.

Another embodiment of this invention is the formation of a release layer between the substrate and the deposited wavelength conversion layer. This release layer can be removed to separate the wavelength conversion layer from the substrate and the release layer.

Because the fabrication of the wavelength conversion chip is independent of the LED fabrication, processes such as annealing, thermal and electron beam aging, recrystallization, and other processes known in the art can enhance the conversion efficiency of the wavelength conversion material or, in the case of phosphor powders, sinter the phosphor powders into ceramic elements either while the material is on the growth substrate or before application of the wavelength conversion chip to the LED. The resulting wavelength conversion chip can be homogeneous, graded, or porous in nature. Process selection would in part be based on a cost/performance tradeoff. Typical high performance phosphors can cost over \$1000/Kg. The cost of the fabrication process is, however, only a couple of milligrams per die, which allows the use of even more expensive approaches without significantly impacting part cost. Since wavelength conversion efficiency can be a major loss factor in many applications, extra pennies spent on improved wavelength conversion materials can translate into reduced device count within a given application.

A further embodiment of this invention is the use of multiple compositionally distinct luminescent materials that can be combined either within each wavelength conversion chip during wavelength conversion layer deposition or as a stack of chips during application. The combination of quantum converting structures and more conventional luminescent material is also included in this invention.

A preferred embodiment of the invention is a light source in which at least one luminescent element with a thermal conductivity greater than 1 W/m/K and a dopant concentration less than 2% is used to thermally cool and optically distributed light generated from LEDs in which those LEDs are embedded in, interconnected through, and substantially cooled by the luminescent element itself. Using this approach very high lumens/gram light sources can be generated which simplify mounting, decrease shipping costs, eliminate overhead safety issues, and dramatically reduce life costs of solid-state lighting systems.

An even more preferred embodiment of this invention is the formation of pockets within the luminescent element such that LEDs may be mounted within the luminescent material itself. Based on this mounting configuration the amount of waveguided versus transmitted excitation light can be controlled. By matching the dopant concentration, type and amount of extraction (including but not limited to surface structure, internal scatter, and combinations of both), geometry of the mounting and spacing of excitation LEDs the uniformity of the light source can be adjusted. Unlike conventional phosphor coated LEDs low dopant levels are preferred due to high efficiency and light spreading. In addition, low dopant concentration luminescent elements distribute the heat load associated with wavelength conversion over a larger volume than high dopant concentration luminescent elements. As such both optical and thermal distribution benefits from lower dopant concentration levels. Present blue LEDs are approaching 60% efficiency which is roughly equivalent to the wavelength conversion efficiency. As such the thermal load associated with wavelength conversion is as important as the thermal load from the LEDs themselves.

Another preferred embodiment is the use of shaped LEDs embedded within luminescent elements. In particular, forming a pocket for the LED in the luminescent element via laser ablation, ultrasonic drilling, photochemical etching, and reactive ion etching are embodiments of this invention. The geometry of these pockets, index of refractions of (luminescent element, bonding adhesive, and LEDs) and the shaped LEDs can be used to control the percentage of the excitation light which is waveguided versus transmitted. As well known in the art, high index materials such as wavelength conversion materials can be used as waveguides subject to the geometry and refractive indices of the materials used. In typical LEDs the majority of the wavelength converted light is generated as the excitation light transmits through the phosphor powder. In the case of low dopant concentration luminescent elements the excitation light can be waveguided a significant distance through the luminescent element before wavelength conversion actually occurs. This may be used to distribute emitted light but also distribute the thermal load associated with wavelength conversion. As such a preferred embodiment of this invention is the use of luminescent elements which are also substantially transparent or translucent in nature. Single crystal grown via pulling methods, floating zone, edge defined, or other crystal growth methods known in the art are embodiments of this invention. Transparent or translucent ceramics, polycrystalline and amorphous luminescent elements are also embodiments. Composites containing transparent or translucent waveguiding elements within a luminescent matrix are also disclosed. In particular, the use of glass or other transparent inorganic layers in which luminescent layers are bonded is also disclosed. Most preferred are the use of thermally conductivity (thermal conductivity greater than 1 W/m/K) transparent or translucent luminescent elements. The use of trimming via laser or etching techniques to further modify the optical uniformity and additive techniques are also disclosed.

BRIEF DESCRIPTION OF THE DRAWINGS

A more detailed understanding of the present invention, as well as other objects and advantages thereof not enumerated herein, will become apparent upon consideration of the following detailed description and accompanying drawings, wherein:

FIGS. 1A-1E are side cross-sectional views illustrating process steps needed to fabricate a wavelength conversion chip.

FIG. 1F is a side cross-sectional view and FIG. 1G is a top plan view of a wavelength conversion chip made by the process illustrated in FIGS. 1A-1E.

FIGS. 2A-2E are side cross-sectional views illustrating process steps needed to fabricate a wavelength conversion chip that includes an optical coating on one surface.

FIG. 2F is a side cross-sectional view and FIG. 2G is a top plan view of a wavelength conversion chip that includes an optical coating and that is made by the process illustrated in FIGS. 2A-2E.

FIGS. 3A-3F are side cross-sectional views illustrating process steps needed to fabricate a wavelength conversion chip that includes light extracting elements and a through via.

FIG. 3G is a side cross-sectional view and FIG. 3H is a top plan view of a wavelength conversion chip that includes light extracting elements and a through via and that is made by the process illustrated in FIGS. 3A-3F.

FIGS. 4A and 4B illustrate side cross-sectional views of example light emitting diodes that can be used with this invention.

FIG. 5A is a side cross-sectional view of a solid-state light source that includes one wavelength conversion chip.

FIG. 5B is a side cross-sectional view showing example light rays emitted by the solid-state light source illustrated in FIG. 5A.

FIG. 6A is a side cross-sectional view of a solid-state light source that includes two wavelength conversion chips.

FIG. 6B is a side cross-sectional view showing example light rays emitted by the solid-state light source illustrated in FIG. 6A.

FIG. 7A is a side cross-sectional view of a solid-state light source that includes three wavelength conversion chips.

FIG. 7B is a side cross-sectional view showing example light rays emitted by the solid-state light source illustrated in FIG. 7A.

FIG. 8A is a side cross-sectional view of a solid-state light source that includes one wavelength conversion chip.

FIG. 8B is a side cross-sectional view of a solid-state light source that includes two wavelength conversion chips.

FIG. 8C is a side cross-sectional view of a solid-state light source that includes three wavelength conversion chips.

FIG. 9A is a side cross-sectional view of a solid-state light source that includes one wavelength conversion chip that has an optical coating.

FIG. 9B is a side cross-sectional view showing example light rays emitted by the solid-state light source illustrated in FIG. 9A.

FIGS. 10A-10E are side cross-sectional views illustrating process steps needed to fabricate a wavelength conversion layer.

FIG. 10F is a top plan view of a wavelength conversion layer before it is segmented into wavelength conversion chips.

FIG. 10G is a side cross-sectional view of an array of wavelength conversion chips after segmentation.

FIG. 10H is a side cross-sectional view and FIG. 10I is a top plan view of a wavelength conversion chip made by the process illustrated in FIGS. 10A-10G.

FIGS. 11A-11F are side cross-sectional views illustrating process steps needed to fabricate a wavelength conversion layer that includes an optical coating on one surface.

FIG. 11G is a top plan view of a wavelength conversion layer before it is segmented into wavelength conversion chips. The wavelength conversion layer has an optical coating on one surface.

FIG. 11H is a side cross-sectional view of an array of wavelength conversion chips after segmentation. The wavelength conversion chips each have an optical coating on one side.

FIG. 11I is a side cross-sectional view and FIG. 11J is a top plan view of a wavelength conversion chip made by the process illustrated in FIGS. 11A-11H. The wavelength conversion chip has an optical coating on one side.

FIGS. 12A-12F are side cross-sectional views illustrating process steps needed to fabricate a wavelength conversion layer that includes vias and light extraction elements.

FIG. 12G is a top plan view of a wavelength conversion layer before it is segmented into wavelength conversion chips. The wavelength conversion layer includes vias and light extraction elements.

FIG. 12H is a side cross-sectional view of an array of wavelength conversion chips after segmentation. The wavelength conversion chips each have a via and light extraction elements.

FIG. 12I is a side cross-sectional view and FIG. 12J is a top plan view of a wavelength conversion chip made by the pro-

cess illustrated in FIGS. 12A-12H. The wavelength conversion chip has a via and light extraction elements.

FIGS. 13A-13F are side cross-sectional views illustrating process steps needed to fabricate a wavelength conversion layer that includes electrical connections (not shown) and electrical bond pads.

FIG. 13G is a top plan view of a wavelength conversion layer before it is segmented into wavelength conversion chips. The wavelength conversion layer includes electrical connections and electrical bond pads.

FIG. 13H is a side cross-sectional view of an array of wavelength conversion chips after segmentation. The wavelength conversion chips each have an electrical bond pad and an electrical connection (not shown).

FIG. 13I is a side cross-sectional view and FIG. 13J is a top plan view of a wavelength conversion chip made by the process illustrated in FIGS. 13A-13H. The wavelength conversion chip has an electrical connection and an electrical bond pad.

FIGS. 14A and 14B are side cross-sectional views illustrating at least one shaped LED in a pocket in a thermally conductive luminescent element.

FIG. 15 is a side cross-sectional view illustrating at least two shaped LEDs in pockets within a thermally conductive luminescent element with a dielectric overcoat and printed interconnect.

FIG. 16 is a side cross-sectional view illustrating two luminescent elements containing embedded shaped LEDs and interconnect means bonded together

FIG. 17 is a side cross-sectional view illustrating a light source containing at least one self-cooling distributed light source emitting greater than 30 lumen per square inch

FIG. 18 is a cross-sectional side view illustrating a light source with containing at least one self-cooling distributed light source and at least one diffuser and optionally at least one reflector.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

The preferred embodiments of the present invention will be better understood by those skilled in the art by reference to the above listed figures. The preferred embodiments of this invention illustrated in the figures are not intended to be exhaustive or to limit the invention to the precise form disclosed. The figures are chosen to describe or to best explain the principles of the invention and its applicable and practical use to thereby enable others skilled in the art to best utilize the invention. The above listed figures are not drawn to scale. In particular, the thickness dimensions of the LEDs and wavelength conversion chips are expanded to better illustrate the various internal layers of the devices.

An important solid-state light source is a blue or ultraviolet emitting LED used in conjunction with one or more wavelength conversion materials such as phosphors or quantum dots that convert at least some of the blue or ultraviolet light to other wavelengths. For example, combining a yellow phosphor with a blue emitting LED can result in a white light source. The yellow phosphor converts a portion of the blue light into yellow light. Another portion of the blue light bypasses the yellow phosphor. The combination of blue and yellow light appears white to the human eye. Alternatively, combining a green phosphor and a red phosphor with a blue LED can also form a white light source. The green phosphor converts a first portion of the blue light into green light. The red phosphor converts a second portion of the blue light into red light. A third portion of the blue light bypasses the green

and red phosphors. The combination of blue, green and red light appears white to the human eye. A third way to produce a white light source is to combine blue, green and red phosphors with an ultraviolet LED. The blue, green and red phosphors convert portions of the ultraviolet light into, respectively, blue, green and red light. The combination of the blue, green and red light appears white to the human eye.

In a typical solid-state light source of the prior art, powdered phosphor materials are mixed into a polymer host material and applied to the LED as a thin coating or as a lens-shaped element. This results in wavelength conversion elements that can degrade under intense illumination and that have poor thermal conductivity to the LED.

Solid-state light sources that are fabricated by depositing a thin layer of a phosphor directly on the surface of the LED also have significant deficiencies. It is important to separate the processes for making the wavelength conversion layers from the processes for fabricating the LED. Some steps required for optimizing the wavelength conversion layers, such as thermal annealing, may be incompatible with maintaining the output performance of the LED. Forming and optimizing the wavelength conversion layers separately from the LED fabrication overcomes such incompatibilities.

One embodiment of this invention is a process for forming high performance wavelength conversion chips that are fabricated separately from the LED sources and that can be subsequently bonded onto the light output surfaces of LEDs. The process can be a batch process or a continuous web process. The resulting wavelength conversion chips are substantially planar in order to facilitate bonding to the LEDs. The length and width dimensions of the wavelength conversion chips can be greater than, equal to or smaller than the length and width dimensions of the LEDs onto which the chips will be attached.

The first step in the process for forming wavelength conversion chips is to select a substrate **10**, which is shown in a side cross-sectional view in FIG. 1A. The substrate provides a physical support for the subsequent deposition of the wavelength conversion layer. Substrate **10** has a bottom surface **12** and a top surface **14** opposite bottom surface **12**. Substrate **10** can be a polymeric material or an inorganic material. The material of substrate **10** can be amorphous, polycrystalline or a single-crystal and can be a heterogeneous material or a homogeneous material. If substrate **10** is a polymeric material or a thin flexible metal layer, substrate **10** can be a web that allows for a continuous web process. Depending on the later process steps, the substrate **10** may need to be transparent to light so that a laser liftoff process can be used to remove any deposited wavelength conversion layer. If a mechanical or chemical process is used in later steps to remove any deposited wavelength conversion layer from substrate **10**, then substrate **10** does not need to be transparent. Example transparent polymeric materials include, but are not limited to, polyethylene and polyethylene terephthalate (PET). Example flexible metals include stainless steel, molybdenum and graphite. Example transparent inorganic materials include, but are not limited to, sapphire, silica and silicate glasses. Optionally, the top surface **14** of substrate **10** may include a release layer (not shown) to facilitate the removal of any subsequently deposited materials. The release layer is removed by thermal, radiation or mechanical means to separate the wavelength conversion layer from the substrate and the release layer. Example materials for the release layer include, but are not limited to, polymer layers, thin metal layer or inorganic materials that preferentially absorb light.

The next process step is to deposit a wavelength conversion layer **20** on the top surface **14** of substrate **10** as illustrated in

a side cross-sectional view in FIG. 1B. The wavelength conversion layer **20** has a bottom surface **22** in contact with the top surface **14** of substrate **10** and a top surface **24**.

The wavelength conversion layer **20** is formed from wavelength conversion materials. The wavelength conversion materials absorb light in a first wavelength range and emit light in a second wavelength range, where the light of a second wavelength range has longer wavelengths than the light of a first wavelength range. The wavelength conversion materials may be, for example, phosphor materials or quantum dot materials. The phosphor materials may be in the form of powders, ceramics, thin film solids or bulk solids. Preferred forms are ceramics and thin solid films. The wavelength conversion layer may be formed from two or more different wavelength conversion materials. The wavelength conversion layer **20** may also include optically inert host materials for the wavelength conversion materials of phosphors or quantum dots.

Phosphor materials are typically optical inorganic materials doped with ions of lanthanide (rare earth) elements or, alternatively, ions such as chromium, titanium, vanadium, cobalt, manganese or magnesium. The lanthanide elements are lanthanum, cerium, praseodymium, neodymium, promethium, samarium, europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium and lutetium. Optical inorganic materials include, but are not limited to, sapphire (Al_2O_3), gallium arsenide (GaAs), beryllium aluminum oxide (BeAl_2O_4), magnesium fluoride (MgF_2), indium phosphide (InP), gallium phosphide (GaP), yttrium aluminum garnet (YAG or $\text{Y}_3\text{Al}_5\text{O}_{12}$), terbium-containing garnet, yttrium-aluminum-lanthanide oxide compounds, yttrium-aluminum-lanthanide-gallium oxide compounds, yttrium oxide (Y_2O_3), calcium or strontium or barium halophosphates ($(\text{Ca},\text{Sr},\text{Ba})_5(\text{PO}_4)_3(\text{Cl},\text{F})$), the compound $\text{CeMgAl}_{11}\text{O}_{19}$, lanthanum phosphate (LaPO_4), lanthanide pentaborate materials ((lanthanide)(Mg,Zn) B_5O_{10}), the compound $\text{BaMgAl}_{10}\text{O}_{17}$, the compound SrGa_2S_4 , the compounds $(\text{Sr},\text{Mg},\text{Ca},\text{Ba})(\text{Ga},\text{Al},\text{In})_2\text{S}_4$, the compound SrS, the compound ZnS and nitridosilicate. There are several exemplary phosphors that can be excited at 250 nm or thereabouts. An exemplary red emitting phosphor is $\text{Y}_2\text{O}_3:\text{Eu}^{3+}$. An exemplary yellow emitting phosphor is $\text{YAG}:\text{Ce}^{3+}$. Exemplary green emitting phosphors include $\text{CeMgAl}_{11}\text{O}_{19}:\text{Tb}^{3+}$, ((lanthanide) $\text{PO}_4:\text{Ce}^{3+},\text{Tb}^{3+}$) and $\text{GdMgB}_5\text{O}_{10}:\text{Ce}^{3+},\text{Tb}^{3+}$. Exemplary blue emitting phosphors are $\text{BaMgAl}_{10}\text{O}_{17}:\text{Eu}^{2+}$ and $(\text{Sr},\text{Ba},\text{Ca})_5(\text{PO}_4)_3\text{Cl}:\text{Eu}^{2+}$. For longer wavelength LED excitation in the 400-450 nm wavelength region or thereabouts, exemplary optical inorganic materials include yttrium aluminum garnet (YAG or $\text{Y}_3\text{Al}_5\text{O}_{12}$), terbium-containing garnet, yttrium oxide (Y_2O_3), YVO_4 , SrGa_2S_4 , $(\text{Sr},\text{Mg},\text{Ca},\text{Ba})(\text{Ga},\text{Al},\text{In})_2\text{S}_4$, SrS, and nitridosilicate. Exemplary phosphors for LED excitation in the 400-450 nm wavelength region include $\text{YAG}:\text{Ce}^{3+}$, $\text{YAG}:\text{Ho}^{3+}$, $\text{YAG}:\text{Pr}^{3+}$, $\text{YAG}:\text{Tb}^{3+}$, $\text{YAG}:\text{Cr}^{3+}$, $\text{YAG}:\text{Cr}^{4+}$, $\text{SrGa}_2\text{S}_4:\text{Eu}^{2+}$, $\text{SrGa}_2\text{S}_4:\text{Ce}^{3+}$, $\text{SrS}:\text{Eu}^{2+}$ and nitridosilicates doped with Eu^{2+} . Other phosphor materials not listed here are also within the scope of this invention.

Quantum dot materials are small particles of inorganic semiconductors having particle sizes less than about 30 nanometers. Exemplary quantum dot materials include, but are not limited to, small particles of CdS, CdSe, ZnSe, InAs, GaAs and GaN. Quantum dot materials can absorb light at first wavelength and then emit light at a second wavelength, where the second wavelength is longer than the first wavelength. The wavelength of the emitted light depends on the particle size, the particle surface properties, and the inorganic semiconductor material.

The transparent and optically inert host materials are especially useful to process phosphor powders or to spatially separate quantum dots. Host materials include polymer materials and inorganic materials. The polymer materials include, but are not limited to, acrylates, polystyrene, polycarbonate, fluoroacrylates, chlorofluoroacrylates, perfluoroacrylates, fluorophosphinate polymers, fluorinated polyimides, polytetrafluoroethylene, fluorosilicones, sol-gels, epoxies, thermoplastics, thermosetting plastics and silicones. Fluorinated polymers are especially useful at ultraviolet wavelengths less than 400 nanometers and infrared wavelengths greater than 700 nanometers owing to their low light absorption in those wavelength ranges. Exemplary inorganic materials include, but are not limited to, silicon dioxide, optical glasses and chalcogenide glasses.

When the wavelength conversion layer **20** is formed from phosphor materials, the phosphors can be deposited by a variety of techniques. The techniques include, but are not limited to, chemical vapor deposition (CVD), metal-organic chemical vapor deposition (MOCVD), sputtering, electron beam evaporation, laser deposition, sol-gel deposition, molecular beam epitaxy (MBE), liquid phase epitaxy (LPE), spin coating, doctor blading and tape casting. Preferred techniques include doctor blading, tape casting, CVD, MOCVD and sputtering. When the wavelength conversion layer is formed from quantum dot materials and inert host materials, deposition techniques include spin coating, doctor blading or tape casting, self assembly, lithography, and nanoimprinting.

The thickness of the wavelength conversion layer **20** can range from about 0.1 micron to about 2000 microns or more. Preferred thicknesses range from about 0.1 micron to about 500 microns.

The next process step is an optional annealing step to thermally anneal or radiation anneal the wavelength conversion layer **20** in order to increase the wavelength conversion efficiency of the layer or, in the case of a phosphor powder, to sinter the powder to form a ceramic layer. This step is especially important for thin film phosphors, since as-deposited thin film phosphors may have low wavelength conversion efficiency if the deposited layer is not properly annealed. The annealing step can be any heat treatment or any radiation treatment of the wavelength conversion material in the wavelength conversion layer **20** that anneals the phosphor. Heating the wavelength conversion material in the wavelength conversion layer to, for example, 600 degrees Celsius for one hour can result in thermal annealing of the wavelength conversion material. Appropriate annealing temperatures and times may vary for different wavelength conversion materials. Example radiation annealing treatments include subjecting the wavelength conversion material in the wavelength conversion layer **20** to infrared, visible or ultraviolet light **30** as shown in FIG. 1C or subjecting the wavelength conversion material in the wavelength conversion layer to electron beam, atomic beam or ion beam bombardment. The radiation sources may be pulsed or continuous. The light sources may be incoherent or coherent (e.g. laser) sources.

If the wavelength conversion material is a phosphor powder mixed with an organic binder, the annealing step may be done in two or more steps. For example, a low temperature (less than 300 degrees Celsius) anneal can be done to remove the organic binder material. Following the removal of the organic material, a high temperature (greater than 500 degrees Celsius) anneal can then be done to sinter the phosphor powder into a ceramic solid.

The annealing step is illustrated in FIG. 1C to occur after the deposition of the wavelength conversion layer and before segmentation of the layer. However, the annealing step may

also be done later in the process sequence, including after the wavelength conversion layer is removed from the substrate. Doing the annealing step after the wavelength conversion layer is removed from the substrate is necessary if the substrate **10** cannot withstand high temperature or high radiation processing. The annealing step may be done in air, in an inert atmosphere such as nitrogen or argon or in a partial vacuum.

The next process step is to segment the wavelength conversion layer **20** into a plurality of wavelength conversion chips **50**. Grooves or streets **40** are formed through the wavelength conversion layer **20** as shown in a side cross-sectional view in FIG. 1D. The streets **40** are fabricated in two directions (only one direction is shown) to form a plurality of wavelength conversion chips **50** that can be square, rectangular or any other planar geometric shape. The plurality of wavelength conversion chips **50** is, at this stage, still attached to the substrate **10**. The wavelength conversion chips have a top surface **54** and side surfaces **56**. The bottom surface **22** of the wavelength conversion layer **20** is still attached to the top surface **14** of substrate **10**. The streets **40** can be formed by techniques that include, but are not limited to, laser scribing, mechanical scribing or optical lithography accompanied by wet chemical etching, sputter etching or ion beam etching.

The final step is to remove the plurality of wavelength conversion chips **50** from substrate **10**. For example, the plurality of wavelength conversion chips **50** can be removed by directing a pulsed laser beam **60** through substrate **10** to destroy the adhesion of the bottom surface **22** of the wavelength conversion layer **20** to the top surface **14** of the substrate **10** as shown in a side cross-sectional view in FIG. 1E. Other methods of removing the plurality of wavelength conversion chips include thermal, radiation, chemical or mechanical means. If the chips are fabricated on a continuous web, mechanically flexing the web will release the chips. The removal can be facilitated if the top surface **14** of substrate **10** includes a release layer (not shown) that can be degraded by thermal, radiation or chemical means. The detached wavelength conversion chips each have an exposed bottom surface **52**.

A side cross-sectional view of wavelength conversion chip **50** is illustrated in FIG. 1F. A top plan view of wavelength conversion chip **50** is shown in FIG. 1G. The wavelength conversion chip **50** has a bottom surface **52**, a top surface **54** and side surfaces **56**.

Another embodiment of this invention is a process shown in FIGS. 2A-2G for forming wavelength conversion chips that optionally include an optical coating on the top surface of the chips. Examples of optical coatings include a dichroic mirror coating that transmits light of a first wavelength range and reflects light of a second wavelength range, an antireflection coating, a reflecting polarizer coating or a photonic bandgap coating. The elements with the same numerical reference in FIG. 2 as in FIG. 1 are the same elements as in FIG. 1 and have the same properties as the elements in FIG. 1. Some of the steps of the process shown in FIGS. 2A-2G are identical to the process steps outlined above in FIGS. 1A-1G. The process can be either a batch process or a continuous web process. The resulting wavelength conversion chips are substantially planar in order to facilitate bonding to the LEDs. The length and width dimensions of the wavelength conversion chips can be greater than, equal to or smaller than the length and width dimensions of the LEDs onto which the chips will be attached.

The first step in the process for forming wavelength conversion chips that include an optical coating is to select a substrate **10**, which is shown in a side cross-sectional view in FIG. 2A. Substrate **10** has a bottom surface **12** and a top

surface **14** opposite bottom surface **12**. Substrate **10** can be a polymeric material, a metal layer or an inorganic material. Example substrate materials are described above for FIG. 1. Optionally, the top surface **14** of substrate **10** may include a release layer (not shown) to facilitate the removal of any subsequently deposited materials. The release layer may be activated by thermal, radiation or mechanical means. Example release layer materials are described above for FIG. 1.

The next process step is to deposit a wavelength conversion layer **20** on the top surface **14** of substrate **10** as illustrated in a side cross-sectional view in FIG. 2B. The wavelength conversion layer **20** has a bottom surface **22** in contact with the top surface **14** of substrate **10** and a top surface **24**.

The wavelength conversion layer **20** is formed from one or more wavelength conversion materials. The wavelength conversion materials may be, for example, phosphor materials or quantum dot materials or a plurality of such materials. The wavelength conversion layer **20** may also include optically inert host materials in addition to the phosphors or quantum dots. Examples of phosphor materials, quantum dot materials and inert host materials are described above for FIGS. 1A-1G. Deposition methods are also described above for FIG. 1.

An optical coating **70** is deposited on the top surface **24** of the wavelength conversion layer **20**. The optical coating can be deposited immediately following the deposition of the wavelength conversion layer **20** as shown in the side cross-sectional view in FIG. 2B. However, it is within the scope of this invention that the optical coating may be deposited later in the overall process. For example, the optical coating may be deposited after the wavelength conversion layer is segmented into wavelength conversion chips. Example optical coatings include reflective coating layers that are wavelength dependent or polarization dependent, photonic bandgap coatings and single or multilayered antireflection coatings on the surface of the wavelength conversion chips that reduce Fresnel reflection effects on one or more surfaces.

An example wavelength dependent reflective optical coating **70** is a dichroic coating that transmits light having a first range of wavelengths and reflects light having a second range of wavelengths. As a first example, a dichroic coating, **70** can be deposited on the surface of a green-emitting wavelength conversion layer **20**. The coating **70** can transmit green light and reflect blue or ultraviolet light. This type of coating is useful if the wavelength conversion chip **50** is attached to a blue or ultraviolet LED and the optical coating **70** is on the surface of the chip opposite the LED. In this example, blue or ultraviolet light emitted by the LED that is not absorbed during the first pass through the wavelength conversion layer **20** is reflected back through the wavelength conversion chip to interact with the wavelength conversion layer **20** a second time. This increases the probability that the blue or ultraviolet light will be absorbed by the wavelength conversion layer and re-emitted as green light, resulting in a higher output of green light.

As a second example, a dichroic coating **70** can be deposited on the surface of a green-emitting wavelength conversion layer **20**. The coating **70** can reflect green light and transmit blue or ultraviolet light. This type of coating is useful if the wavelength conversion chip **50** is attached to a blue or ultraviolet LED and the optical coating **70** is on the surface of the chip adjacent to the LED. In this example, green light emitted by the wavelength conversion layer toward the LED is reflected by the coating and directed through the output surface of the wavelength conversion chip opposite the LED. This reflection and direction prevents the green light from

entering the LED and being partially absorbed by the LED. The result is higher output of green light from the output surface.

As a third example of dichroic coatings, a wavelength conversion chip **50** may have two dichroic coatings deposited on opposite surfaces of the chip. Two dichroic coatings are useful if the wavelength conversion chip **50** is attached to a blue or ultraviolet LED and the first dichroic coating on the surface of the chip adjacent to the LED transmits blue or ultraviolet light and reflects green light and the second dichroic coating on the surface of the chip opposite the LED transmits green light and reflects blue or ultraviolet light. Both coating enhance the amount of green light emitted by the wavelength conversion chip.

Another example of a wavelength dependent reflective optical coating **70** is a reflecting polarizer composed of linear subwavelength optical elements. The optical coating **70** can transmit light that is polarized parallel to the linear subwavelength optical elements and can reflect light that is polarized perpendicular to the linear subwavelength optical elements.

An example of a photonic bandgap optical coating **70** is a photonic bandgap structure that provides directionality to light exiting the wavelength conversion chip. For example, the photonic bandgap optical coating can be a two-dimensional array of closely spaced vertical pillars on the surface of the wavelength conversion chip. The array of pillars can inhibit the transmission of light within the plane of the coating and direct the emitted light preferentially in a direction perpendicular to the plane of the coating.

An example of an antireflection optical coating **70** is a one-quarter wavelength thick layer of a low refractive index material such as magnesium fluoride or silicon dioxide. When the optical coating **70** has a lower refractive index than the wavelength conversion layer **20** and is one-quarter of an optical wavelength thick, the coating can reduce Fresnel reflections from the surface of the wavelength conversion chip.

The next process step is an optional annealing step to thermally anneal or radiation anneal the wavelength conversion layer **20** in order to increase the wavelength conversion efficiency of the layer or, in the case of a phosphor powder, to sinter the powder to form a ceramic layer. This step is important for thin film phosphors, since as-deposited thin film phosphors may have low wavelength conversion efficiency if the deposited layers are not properly annealed. The annealing step can be any heat treatment or any radiation treatment of the wavelength conversion material in the wavelength conversion layer **20** that anneals the phosphor. Heating the wavelength conversion material in the wavelength conversion layer to, for example, 600 degrees Celsius for one hour can result in thermal annealing of the wavelength conversion material. Appropriate annealing temperatures and times may vary for different wavelength conversion materials. Example radiation treatments include subjecting the wavelength conversion material in the wavelength conversion layer **20** and the optical coating **70** to infrared, visible or ultraviolet light **30** as shown in FIG. 2C or subjecting the wavelength conversion material in the wavelength conversion layer **20** and the optical coating **70** to electron beam, atomic beam or ion beam bombardment. The radiation sources may be pulsed or continuous. The light sources may be incoherent or coherent (e.g. laser) sources.

As described above for FIG. 1, the annealing step can be done later in the process sequence. For example, the annealing step can be done after the wavelength conversion chips are removed from the substrate **10**. In addition, if the wavelength conversion material is a phosphor powder mixed with an organic binder, the annealing step may be done in two or more

parts to first remove the organic binder and second to sinter the phosphor powder into a ceramic solid

The next process step is to segment the wavelength conversion layer **20** and the optical coating **70** into a plurality of wavelength conversion chips **50**. Grooves or streets **40** are formed through the optical coating **70** and the wavelength conversion layer **20** as shown in a side cross-sectional view in FIG. 2D. The streets **40** are fabricated in two directions (only one direction is shown) to form a plurality of wavelength conversion chips **50** that can be square, rectangular or any other planar geometric shape. The wavelength conversion chips are, at this stage, still attached to the substrate **10**. The wavelength conversion chips have a top surface **54** and side surfaces **56**. The bottom surface **22** of the wavelength conversion layer **20** is still attached to the top surface **14** of substrate **10**. The streets **40** can be formed by techniques that include, but are not limited to, laser scribing, mechanical scribing or optical lithography accompanied by wet chemical etching, sputter etching or ion beam etching.

The final step is to remove the plurality of wavelength conversion chips **50** from substrate **10**. For example, the wavelength conversion chips **50** can be removed by directing a pulsed laser beam **60** through substrate **10** to destroy the adhesion of the chips to the substrate as shown in a side cross-sectional view in FIG. 2E. Other methods of removing the wavelength conversion chips include thermal, radiation, chemical or mechanical means. The removal can be facilitated if the top surface **14** of substrate **10** includes a release layer (not shown) that can be degraded by thermal, radiation or chemical means.

A side cross-sectional view of wavelength conversion chip **50** is illustrated in FIG. 2F. A top plan view of wavelength conversion chip **50** is shown in FIG. 2G. The wavelength conversion chip **50** has a bottom surface **52**, a top surface **54** and side surfaces **56**.

Another embodiment of this invention is a process shown in FIGS. 3A-3H for forming wavelength conversion chips that optionally include vias that extend through the wavelength conversion chip or that optionally include arrays of light extracting elements. The elements with the same numerical reference in FIG. 3 as in FIG. 1 are the same elements as in FIG. 1 and have the same properties as the elements in FIG. 1. Some of the steps of the process shown in FIGS. 3A-3H are identical to the process steps outlined in FIGS. 1A-1G. As in the previously disclosed processes, the process that optionally includes vias or light extracting elements can be either a batch process or a continuous web process.

The first step in the process for forming wavelength conversion chips is to select a substrate **10**, which is shown in a side cross-sectional view in FIG. 3A. Substrate **10** has a bottom surface **12** and a top surface **14** opposite bottom surface **12**. Substrate **10** can be a polymeric material, a metal layer or an inorganic material. Example substrate materials are described previously. Optionally, the top surface **14** of substrate **10** may include a release layer (not shown) to facilitate the removal of any subsequently deposited materials. The release layer may be activated by thermal, radiation or mechanical means. Example release layer materials are described previously.

The next process step is to deposit a wavelength conversion layer **20** on the top surface **14** of substrate **10** as illustrated in a side cross-sectional view in FIG. 2B. The wavelength conversion layer **20** has a bottom surface **22** in contact with the top surface **14** of substrate **10** and a top surface **24**.

The wavelength conversion layer **20** is formed from one or more wavelength conversion materials. The wavelength con-

version materials may be, for example, phosphor materials or quantum dot materials or a plurality of such materials. The wavelength conversion layer **20** may also include optically inert host materials in addition to the phosphors or quantum dots. Examples of phosphor materials, quantum dot materials and inert host materials are described above for FIGS. 1A-1G. Deposition methods are also listed previously.

The next process step is an optional annealing step illustrated in FIG. 3C to thermal anneal or radiation anneal the wavelength conversion material. Details of the annealing step are described above for FIGS. 1 and 2.

The next process step is to segment the wavelength conversion layer **20** into a plurality of wavelength conversion chips **50**. Grooves or streets **40** are formed through the wavelength conversion layer **20** as shown in a side cross-sectional view in FIG. 3D. The streets **40** are fabricated in two directions (only one direction is shown) to form a plurality of wavelength conversion chips **50** that can be square, rectangular or any other planar geometric shape. The wavelength conversion chips **50** are, at this stage, still attached to the substrate **10**. The wavelength conversion chips have a top surface **54** and side surfaces **56**. The bottom surface **22** of the wavelength conversion layer **20** is still attached to the top surface **14** of substrate **10**. The streets **40** can be formed by techniques that include, but are not limited to, laser scribing, mechanical scribing or optical lithography accompanied by wet chemical etching, sputter etching or ion beam etching.

The next step is to form one or more vias and/or one or more light extracting elements in the wavelength conversion chips **50**. Via **82** is illustrated in FIGS. 3E-3H. Via **82** is interior to the edges **56** of the wavelength conversion chip **50** and passes through the wavelength conversion chip **50** from side **52** to side **54** as shown in FIGS. 3F and 3G. Vias are required if one wishes to form electrical pathways through the chip. The vias may be air-filled vias or the vias may be filled with an electrically conducting material (not shown) such as a metal.

Light extracting elements **80** are elements that aid in the removal of light from the wavelength conversion chip **50**. In general, the refractive index of the wavelength conversion layer **20** is higher than the refractive index of air. A portion of the light that is emitted by the wavelength conversion material can be trapped inside the wavelength conversion chip **50** by total internal reflection. Light extracting elements **80** cause a larger portion of the emitted light to exit the chip. Examples of light extracting elements **80** include, but are not limited to, vertical holes, conical-shaped holes, holes with polygonal cross-sections, conical-shaped bumps, hemispherical-shaped bumps, bumps with polygonal cross-sections such as pyramids, grooves, ridges and subwavelength optical elements. Other examples of light extracting elements are arrays of subwavelength optical elements such as holes or grooves that are arranged to form photonic crystals. For illustrative purposes, the light extracting elements shown in FIGS. 3E-3H are conical-shaped holes.

The light extracting elements **80** may be formed on the top surface **54** of the wavelength conversion chip **50** and may extend either part way or all the way through the chip. If the light extracting elements are subwavelength optical elements, the light extracting elements may be positioned either on the top surface **54** of the chip or may be fabricated inside the chip.

Vias **82** and light extracting elements **80** may be formed by techniques that include, but are not limited to, laser ablation, mechanical etching or by optical lithography accompanied by wet chemical etching, sputter etching or ion beam etching.

Vias **82** and light extracting elements **80** are shown in FIG. 3E to be fabricated in a process step that occurs after the

segmentation of the wavelength conversion layer **20** into wavelength conversion chips. However, it is within the scope of this invention that the fabrication of vias and light extracting elements may occur before or at the same time as the segmentation of the wavelength conversion layer.

The final step is to remove the plurality of wavelength conversion chips **50** from substrate **10**. For example, the wavelength conversion chips **50** can be removed by directing a pulsed laser beam **60** through substrate **10** to destroy the adhesion of the chips to the substrate as shown in a side cross-sectional view in FIG. 3F. Other methods of removing the wavelength conversion chips include thermal, radiation, chemical or mechanical means. The removal can be facilitated if the top surface **14** of substrate **10** includes a release layer (not shown) that can be degraded by thermal, radiation or chemical means.

A side cross-sectional view of wavelength conversion chip **50** is illustrated in FIG. 3G. A top plan view of wavelength conversion chip **50** is shown in FIG. 3H. The wavelength conversion chip **50** has a bottom surface **52**, a top surface **54**, side surfaces **56**, light extraction elements **80** and via **82**.

As stated previously, wavelength conversion chips **50** can be used in conjunction with light emitting diodes to form solid-state light sources. Two examples of suitable light emitting diode structures are illustrated in FIGS. 4A and 4B. Other types of light emitting diode structures can also be used with this invention.

Light emitting diodes can be constructed from inorganic or organic materials. Inorganic light-emitting diodes can be fabricated from GaN-based semiconductor materials containing gallium nitride (GaN), aluminum gallium nitride (AlGaN), indium gallium nitride (InGaN) and aluminum indium gallium nitride (AlInGaN). Other appropriate LED materials include, for example, aluminum nitride (AlN), indium nitride (InN), aluminum gallium indium phosphide (AlGaInP), gallium arsenide (GaAs), indium gallium arsenide (InGaAs), indium gallium arsenide phosphide (InGaAsP), diamond or zinc oxide (ZnO), for example, but are not limited to such materials. Especially important LEDs for this invention are inorganic GaN-based LEDs or ZnO-based LEDs that emit light in the ultraviolet and blue regions of the optical spectrum.

FIG. 4A is a side cross sectional view of example LED **100**. LED **100** includes a first reflecting electrode **102**, a multi-layer semiconductor structure **104** and a second reflecting electrode **106**, which is on the opposite side of the multi-layer semiconductor structure **104** from the first reflecting electrode **102**. The multi-layer semiconductor structure **104** includes a first doped semiconductor layer **108**, an active region **110** and a second doped semiconductor layer **112**, which is on the opposite side of the active region **110** from the first doped semiconductor layer **108**.

The first reflecting electrode **102** and the second reflecting electrode **106** may be fabricated from reflecting metals. For example, the first reflecting electrode **102** and the second reflecting electrode **106** may be formed from one or more metals or metal alloys containing, but not limited to, silver, aluminum, nickel, titanium, chromium, platinum, palladium, rhodium, rhenium, ruthenium and tungsten. Preferred metals are aluminum and silver.

The first reflecting electrode **102** and the second reflecting electrode **106** may also optionally include a thin layer (not shown) of a transparent material in addition to the metal layer. The optional transparent layer is located between the metal layer and the multilayer semiconductor structure **104**. Having a two-layer reflecting electrode increases the reflectivity of the reflecting electrode compared to a single-layer reflecting

electrode. Increasing the reflectivity of the reflecting electrode increases the light extraction of LED 100 and the overall external quantum efficiency of LED 100. Preferably the refractive index of the optional transparent layer is less than the refractive index of the semiconductor materials. The preferred refractive index of the optional transparent layer is between 1.05 and 2.3. The thickness of the optional transparent layer can be one-quarter wave or thicker than one-quarter wave. A thickness of one wave is defined as the wavelength in air of the light emitted by the LED divided by the refractive index of the transparent layer. The preferred thickness of the transparent layer is one-quarter wave or three-quarter wave. The optional transparent layer can be fabricated, for example, from dielectric materials such as silicon dioxide (SiO₂), silicon nitride (Si₃N₄), magnesium fluoride (MgF₂) or from electrically conducting materials such as transparent conductive oxides. Transparent conductive oxides include, but are not limited to, indium tin oxide, ruthenium oxide, copper-doped indium oxide and aluminum-doped zinc oxide.

The multi-layer semiconductor structure 104 of the LED 100 is fabricated, for example, from nitride-based semiconductor materials containing gallium nitride (GaN), aluminum gallium nitride (AlGaN), indium gallium nitride (InGaN), aluminum indium gallium nitride (AlInGaN), aluminum nitride (AlN) or indium nitride (InN) or alternatively from ZnO-based semiconductor materials.

The active region 110 of the multi-layer semiconductor structure 104 is a p-n homojunction, a p-n heterojunction, a single quantum well or a multiple quantum well of the appropriate semiconductor material for the LED 100.

LED 100 is assumed for purposes of illustration to be a GaN-based LED. GaN-based LEDs can include the materials GaN, AlGaN, InGaN and AlInGaN. It should be noted, however, that LED 100 may be fabricated from any suitable light-emitting semiconductor material such as the materials listed. To briefly summarize the important fabrication steps for this GaN-based, illustrative example, first a multi-layer semiconductor structure 104 is fabricated on a growth substrate (not shown). A second reflecting electrode 106 is deposited onto the multi-layer semiconductor structure opposite the growth substrate, followed by the attachment of a sub-mount (not shown) to the second reflecting electrode. The structure is inverted (flipped) and a liftoff process removes the growth substrate, exposing the surface 128 of the multi-layer semiconductor structure that was originally attached to the growth substrate. Finally, a first reflecting electrode 102 is deposited and patterned on the exposed surface 128 of the multi-layer semiconductor structure 104 opposite the second reflecting electrode 106.

The details of the structure and fabrication of the illustrative example LED 100 will now be described.

The first doped semiconductor layer 108 is an n-doped GaN layer, which is epitaxially deposited or otherwise conventionally fabricated on a growth substrate (not shown). The n-doped GaN semiconductor layer has a first or upper surface 128 and a second or lower surface 126, opposite the first surface 128.

The active region 110 is a GaN-based p-n heterojunction, which is epitaxially deposited or otherwise conventionally fabricated on the first doped semiconductor layer 108. As an illustrative example, the GaN-based p-n heterojunction can be a GaN/AlGaN heterojunction. The GaN-based p-n heterojunction active region 110 has a first or upper surface 124, deposited or fabricated on the second surface 126 of the first doped semiconductor layer 108, and a second or lower surface 122, opposite the first surface 124.

The second doped semiconductor layer 112 is a p-doped GaN layer, which is epitaxially deposited or otherwise conventionally fabricated on the active region 110. The p-doped GaN semiconductor layer has a first or upper surface 120, epitaxially deposited or otherwise fabricated on the second surface 122 of the active region 110, and a second or lower surface 118, opposite the first surface 120.

The second reflecting electrode 106 of LED 100 is silver, which is deposited or otherwise conventionally fabricated on the lower surface 118 of the second doped semiconductor layer 112. The second reflecting electrode has a first, upper and inner surface 116 and a second, lower or outer surface 114, opposite the first surface 116.

The first reflecting electrode 102 is aluminum, which is deposited or otherwise conventionally fabricated on the first doped semiconductor layer 108. The first reflecting electrode 102 has a first, inner or lower surface 130, deposited or fabricated on the first surface 128 of the first doped semiconductor layer 108, and a second, outer or upper surface 132, opposite the first surface 130.

The inner surface 130 of the first reflecting electrode 102 is an inner reflecting surface for the multi-layer semiconductor structure 104 of the LED 100. The outer surface 132 of the first reflecting electrode 102 is an outer reflecting surface for externally incident light directed to LED 100.

The first reflecting electrode 102 only partially covers the surface 128 of the first doped semiconductor layer 108. Portions of the surface 128 of the first doped semiconductor layer 108, not covered by the first reflecting electrode 102, are exposed and those exposed portions of the surface 128 of the first doped semiconductor layer 108 are an output or exit surface for the light emitted by the LED 100. The portion of the surface 128 not covered by the first reflecting electrode 102 may be covered with light extracting elements (not shown) to improve light extraction from LED 100.

The light emitting diode 100 has a first reflecting electrode 102, a multi-layer semiconductor structure 104 having a first doped semiconductor layer 108, an active region 110 and a second doped semiconductor layer 112, and a second reflecting electrode 106.

The active region 110 emits internally generated light in a wavelength range when a voltage is applied across the first reflecting electrode 102 and the second reflecting electrode 106. The emitting wavelength range of the internally generated light can include any optical wavelength. For an LED having a p-n heterojunction active region 110, the emitting wavelength range typically has a full width of approximately 50 nm at the half-maximum points of the wavelength range. For wavelength conversion applications, preferably the emitting wavelength range is between about 250 nm and about 500 nm.

The total thickness of the multi-layer semiconductor structure 104 is usually on the order of a few microns. For example, the total thickness of the multi-layer semiconductor structure 104 can be two to five microns.

Example light rays 134 and 138 illustrate internally generated light that is emitted by the active region 110. Internally generated light ray 134 is emitted by active region 110 toward output surface 128 of LED 100. Internally generated light ray 134 is directed at an angle 136 that is greater than the critical angle for output surface 128. Internally generated light ray 134 is reflected by total internal reflection and is redirected toward internal reflective surface 116 of the second reflecting electrode 106.

Internally generated light ray 138 is emitted by active region 110 toward outer surface 128 of the first semiconductor layer 108 of LED 100. Internally generated light ray 138

is directed at an angle **140** that is less than the critical angle for outer surface **128**. Internally generated light ray **138** is transmitted through outer surface **128**.

In the illustrative example LED **100**, the first doped semiconductor layer **108** is a n-doped layer and the second doped semiconductor layer **112** is a p-doped layer. However, the two layers can be reversed. If the first doped semiconductor layer **108** is a p-doped layer, then the second doped semiconductor layer **112** is an n-doped layer. The two doped semiconductor layers **108** and **112** will have opposite n and p conductivity types.

It is well known by those skilled in the art that the multi-layer semiconductor structure **104** may include additional layers in order to adjust and improve the operation of the LED **100**. For example, a current spreading layer may be inserted between surface **130** of the first reflecting electrode **102** and surface **128** the first doped semiconductor layer **108**. Such a current spreading layer will have the same conductivity type as the first doped semiconductor layer and will improve the uniformity of current injection across the entire active region. In addition, a current spreading layer may be inserted between surface **118** of the second doped semiconductor layer and surface **116** of the second reflecting electrode **106**. The latter current spreading layer will have the same conductivity type as the second doped semiconductor layer. As another example, an electron blocking layer may be inserted either between surface **126** of the first doped semiconductor layer **108** and surface **124** of the active region **110** or between surface **122** of the active region **110** and surface **120** of the second doped semiconductor layer. The electron blocking layer reduces the escape of electrons from the active region.

FIG. **4B** is a cross sectional view of another example light emitting diode, LED **150**. LED **150** is similar to LED **100** except that LED **150** is constructed in a flip-chip configuration with both the first reflecting electrode **154** and the second reflecting electrode **106** located on the same side of the LED **150**. In this embodiment, the first doped semiconductor layer **108** has a larger surface area than the active region **110** and the second doped semiconductor layer **112**. A portion **152** of the first doped semiconductor layer **108** will extend away from the active region **110** and the second doped semiconductor layer **112** exposing a portion **152** of the second surface **126** of the first doped semiconductor layer **108**. The first reflecting electrode **154** is located on the exposed second or inner surface **126** of the first doped semiconductor layer **108** adjacent to the active region **110** instead of the first or outer surface **128** of the first doped semiconductor layer **108**. The first reflecting electrode **154** has a first or upper surface **158** and a second or lower surface **156**, opposite the first surface **158**. The first surface **158** of the first reflecting electrode **154** is deposited or fabricated on the exposed second surface **126** of the first doped semiconductor layer **108**.

The first reflecting electrode **154** is in electrical contact with the first doped semiconductor layer **108**. The first doped semiconductor layer **108** functions as a current spreading layer that directs electrical current from the first reflecting electrode **154** to the active region **110**.

The first surface **128** of the first doped semiconductor layer **108** has no reflecting electrode on its surface. Light emitted by the active region **110** can exit across the entire area of the first surface **128** of the first doped semiconductor layer **108**. The entire surface functions as an output surface. The surface **128** may also include optional light extracting elements (not shown) to improve light extraction from LED **150**. The first reflecting electrode **154**, now on the lower side of LED **150**, can reflect both internally generated light and externally incident light.

Solid-state light sources can be constructed by combining an LED with one or more wavelength conversion chips. Some illustrative examples are shown in FIGS. **5-9**. FIGS. **5-7** illustrate solid-state light sources that have one or more wavelength conversion chips that include one or more vias and one or more light extracting elements. The LEDs in FIGS. **5-7** each have a top first reflecting electrode. Vias through the wavelength conversion chips are required in order to make electrical contacts with the first reflecting electrodes. FIG. **8A-8C** illustrate solid-state light sources that have one or more wavelength conversion chips that include light extracting elements, but no vias. The LEDs in FIGS. **8A-8C** each have first reflecting electrodes on the second or bottom surface of the first semiconductor layer **108**. FIG. **9** illustrates a solid-state light source that has a wavelength conversion chip that includes an optical coating on the top surface of the chip. In the latter example, the wavelength conversion chip does not include a via or a light extracting element.

Another embodiment of this invention is solid-state light source **200** shown in a side cross-sectional view in FIG. **5A**. Solid-state light source **200** includes LED **100**, which has a top first reflecting electrode **102**, wavelength conversion chip **50** and a bonding layer **202**. The wavelength conversion chip **50** includes light extracting elements **80** and via **82** that extends through the chip.

The LED **100** of the solid-state light source **200** emits light in a first wavelength range. The wavelength conversion chip **50** converts light of a first wavelength range into light of a second wavelength range, different than the first wavelength range. The light of a second wavelength range has longer wavelengths than the light of a first wavelength range.

In FIG. **5A**, the wavelength conversion chip covers the entire surface **128** of LED **100** except for the area occupied by via **82**. It is also within the scope of this invention that the wavelength conversion chip **50** may have an area that is larger or smaller than the area of the top surface **128** of LED **100**.

The wavelength conversion chip is attached to LED **100** by a transparent and thermally conducting bonding layer **202**. Preferably the refractive index of bonding layer **202** is 1.30 or higher. The high refractive index of the bonding layer frustrates total internal reflection and improves the extraction of photons normally trapped within the LED die. The bonding layer also provides a thermal conduction path from the wavelength conversion chip **50** to LED **100**. Heat generated inside the wavelength conversion chip **50** can pass through the bonding layer **202** and through LED **100** to a heat sink (not shown) attached to the bottom surface **114** of the LED.

Example materials for bonding layer **202** include low melting point transparent conducting oxides (TCOs), low melting point inorganic glasses and polymers. Example transparent conducting oxides include tin oxide, indium oxide, gallium oxide, indium tin oxide, ruthenium oxide, copper-doped indium oxide and aluminum-doped zinc oxide. Low melting point inorganic glasses include alkali glasses. Polymer materials include epoxies, acrylates, sol-gels, silicones, chlorinated or fluorinated polymers and xerogels. An example fluorinated polymer is tetrafluoroethylene.

If bonding layer **202** is a TCO or inorganic glass, sputtering, electron beam evaporation, chemical vapor deposition or metal-organic chemical vapor deposition can be used to deposit the bonding layer. If bonding layer **202** is a polymer, spin coating or spray coating can be used to deposit the bonding layer.

Example light rays **204**, **206**, **208**, **210** and **212** in FIG. **5B** illustrate the operation of solid-state light source **200**. When an electrical current is applied through LED **100** via the first reflecting electrode **102** and the second reflecting electrode

106, the active region **110** emits internally generated light. The wavelength of the internally generated light can be any optical wavelength. Preferably the wavelength of the internally generated light is in the wavelength range from about 250 nm to about 500 nm. For wavelength conversion applications, usually the wavelength of the internally generated light is in the ultraviolet (UV) or blue regions of the optical spectrum. For illustrative purposes only, LED **100** is shown to emit UV light. For example, LED **100** can emit 360 nm UV light.

Internally generated UV light ray **204** is emitted by active region **110** of LED **100**. UV light ray **204** is transmitted through the first doped semiconductor layer **108**, through top surface **128** of LED **100**, through bonding layer **202** and through the wavelength conversion chip **50** without being converted. UV light ray **204** exits solid-state light source **200** through surface **54** of the wavelength conversion chip **50**.

Internally generated UV light ray **206** is emitted by active region **110** of LED **100**. UV light ray **206** is transmitted through the first doped semiconductor layer **108**, through top surface **128** of LED **100**, through bonding layer **202** and into the wavelength conversion chip **50**. Wavelength conversion chip **50** converts UV light ray **206** into blue light ray **208**. The conversion of UV light ray **206** to blue light is an illustrative example. Depending on the composition of the wavelength conversion layer, the UV light could be converted instead into, for example, cyan, green, yellow, red or infrared light. Blue light ray **208** passes through the remainder of the wavelength conversion chip **50** and exits solid-state light source **200** through surface **54** of the wavelength conversion chip.

Internally generated UV light ray **210** is emitted by active region **110** of LED **100**. UV light ray **210** is transmitted through the first doped semiconductor layer **108**, through top surface **128** of LED **100**, through bonding layer **202** and into the wavelength conversion chip **50**. Wavelength conversion chip **50** converts UV light ray **210** into blue light ray **212**. Blue light ray **212** passes through the remainder of the wavelength conversion chip **50**, is extracted from the wavelength conversion chip by light extracting element **80** and exits the solid-state light source **200**. Light extraction element **80** improves the light extraction efficiency of wavelength conversion chip **50** by reducing the probability of total internal reflection of light ray **212** at the top surface **54** of the wavelength conversion chip.

The wavelength conversion chip **50** converts UV light rays **206** and **210** into blue light. Light ray **204** passes through wavelength conversion chip **50** without conversion. Only a portion of the UV light emitted by the active region of the LED that passes through the wavelength conversion chip is converted into blue light.

Another embodiment of this invention is solid-state light source **220** shown in a side cross-sectional view in FIG. **6A**. Solid-state light source **220** includes LED **100**, which has a top first reflecting electrode **102**, two wavelength conversion chips **50A** and **50B** and two bonding layers **202A** and **202B**. The wavelength conversion chip **50A** includes light extracting elements **80A** and via **82A** that extends through the chip. The wavelength conversion chip **50B** includes light extracting elements **80B** and via **82B** that extends through the chip.

LED **100** of solid-state light source **220** emits light in a first wavelength range. Wavelength conversion chip **50A** converts light of a first wavelength range into light of a second wavelength range, different than the first wavelength range. The light of a second wavelength range has longer wavelengths than the light of a first wavelength range. Wavelength conversion chip **50B** converts light of a first wavelength range into light of a third wavelength range, different than the first

wavelength range and the second wavelength range. The light of a third wavelength range has a longer wavelength than the light of a first wavelength range.

In FIG. **6A**, the wavelength conversion chips **50A** and **50B** cover the entire surface **128** of LED **100** except for the area occupied by vias **82A** and **82B**. It is also within the scope of this invention that the wavelength conversion chips **50A** and **50B** may have an area that is larger or smaller than the area of the top surface **128** of LED **100**.

The wavelength conversion chips are attached to LED **100** by transparent and thermally conducting bonding layers **202A** and **202B**. Preferably the refractive index of bonding layers **202A** and **202B** is 1.30 or higher. The high refractive index of the bonding layers **202A** and **202B** frustrates total internal reflection and improves the extraction of photons normally trapped within the LED die. The bonding layers also provide a thermal conduction path from the wavelength conversion chips **50A** and **50B** to LED **100**. Heat generated inside wavelength conversion chip **50A** can pass through the bonding layer **202A** and through LED **100** to a heat sink (not shown) attached to the bottom surface **114** of the LED. Heat generated inside wavelength conversion chip **50B** can pass through the bonding layer **202B**, through wavelength conversion chip **50A**, through bonding layer **202A** and through LED **100** to a heat sink (not shown) attached to the bottom surface **114** of the LED. Example materials and deposition methods for bonding layers **202A** and **202B** have been listed previously.

Example light rays **222**, **224**, **226**, **228** and **230** in FIG. **6B** illustrate the operation of solid-state light source **220**. When an electrical current is applied through LED **100** via the first reflecting electrode **102** and the second reflecting electrode **106**, the active region **110** emits internally generated light. The wavelength of the internally generated light can be any optical wavelength. Preferably the wavelength of the internally generated light is in the wavelength range from about 250 nm to about 500 nm. For illustrative purposes only, LED **100** is shown to emit UV light. For example, LED **100** can emit 360 nm UV light.

Internally generated UV light ray **222** is emitted by active region **110** of LED **100**. UV light ray **222** is transmitted through the first doped semiconductor layer **108**, through top surface **128** of LED **100**, through bonding layer **202A**, through wavelength conversion chip **50A** without being converted, through bonding layer **202B** and through the wavelength conversion chip **50B** without being converted. UV light ray **222** exits solid-state light source **220** through surface **54B** of the wavelength conversion chip **50B**.

Internally generated UV light ray **224** is emitted by active region **110** of LED **100**. UV light ray **224** is transmitted through the first doped semiconductor layer **108**, through top surface **128** of LED **100**, through bonding layer **202A** and into the wavelength conversion chip **50A**. Wavelength conversion chip **50A** converts UV light ray **224** into blue light ray **226**. The conversion of UV light ray **224** to blue light is an illustrative example. Depending on the composition of the wavelength conversion layer, the UV light could be converted instead into, for example, cyan, green, yellow, red or infrared light. Blue light ray **226** passes through the remainder of the wavelength conversion chip **50A**, through bonding layer **202B**, through wavelength conversion chip **50B** without being converted and exits solid-state light source **220** through surface **54B** of the wavelength conversion chip **50B**.

Internally generated UV light ray **228** is emitted by active region **110** of LED **100**. UV light ray **228** is transmitted through the first doped semiconductor layer **108**, through top surface **128** of LED **100**, through bonding layer **202A**,

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through wavelength conversion chip **50A** without being converted, through bonding layer **202B** and into the wavelength conversion chip **50B**. Wavelength conversion chip **50B** converts UV light ray **228** into green light ray **230**. Green light ray **230** passes through the remainder of the wavelength conversion chip **50B** and exits the solid-state light source **220** through surface **54B** of the wavelength conversion chip **50B**.

The wavelength conversion chip **50A** converts UV light ray **224** into blue light. The wavelength conversion chip **50B** converts UV light ray **228** into green light. Light ray **222** passes through wavelength conversion chips **50A** and **50B** without conversion. Only a portion of the UV light passing through the wavelength conversion chips is converted into blue or green light. The wavelength conversion chip **50B** does not convert the already converted blue light ray **226** from the wavelength conversion chip **50A**. The blue light ray **226** is transmitted through the wavelength conversion chip **50B** without being converted.

Another embodiment of this invention is solid-state light source **240** shown in a side cross-sectional view in FIG. **7A**. Solid-state light source **240** includes LED **100**, which has a top first reflecting electrode **102**, three wavelength conversion chips **50A**, **50B** and **50C** and three bonding layers **202A**, **202B** and **202C**. The wavelength conversion chip **50A** includes light extracting elements **80A** and via **82A** that extends through the chip. The wavelength conversion chip **50B** includes light extracting elements **80B** and via **82B** that extends through the chip. The wavelength conversion chip **50C** includes light extracting elements' **80C** and via **82C** that extends through the chip.

LED **100** of solid-state light source **240** emits light in a first wavelength range. Wavelength conversion chip **50A** converts light of a first wavelength range into light of a second wavelength range, different than the first wavelength range. The light of a second wavelength range has longer wavelengths than the light of a first wavelength range. Wavelength conversion chip **50B** converts light of a first wavelength range into light of a third wavelength range, different than the first wavelength range and the second wavelength range. The light of a third wavelength range has longer wavelengths than the light of a first wavelength range. Wavelength conversion chip **50C** converts light of a first wavelength range into light of a fourth wavelength range, different than the first wavelength range and the second wavelength range and the third wavelength range. The light of a fourth wavelength range has longer wavelengths than the light of a first wavelength range.

In FIG. **7A**, the wavelength conversion chips **50A**, **50B** and **50C** cover the entire surface **128** of LED **100** except for the area occupied by vias **82A**, **82B** and **82C**. It is also within the scope of this invention that the wavelength conversion chips **50A**, **50B** and **50C** may have an area that is larger or smaller than the area of the top surface **128** of LED **100**.

The wavelength conversion chips are attached to LED **100** by transparent and thermally conducting bonding layers **202A**, **202B** and **202C**. Preferably the refractive index of bonding layers **202A**, **202B** and **202C** is 1.30 or higher. The high refractive index of the bonding layers **202A**, **202B** and **202C** frustrates total internal reflection and improves the extraction of photons normally trapped within the LED die. The bonding layers also provide a thermal conduction path from the wavelength conversion chips **50A**, **50B** and **50C** to LED **100**. Heat generated inside wavelength conversion chip **50A** can pass through the bonding layer **202A** and through LED **100** to a heat sink (not shown) attached to the bottom surface **114** of the LED. Heat generated inside wavelength conversion chip **50B** can pass through the bonding layer **202B**, through wavelength conversion chip **50A**, through

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bonding layer **202A** and through LED **100** to a heat sink (not shown) attached to the bottom surface **114** of the LED. Heat generated inside wavelength conversion chip **50C** can pass through the bonding layer **202C**, through the wavelength conversion chip **50B**, through the bonding layer **202B**, through wavelength conversion chip **50A**, through bonding layer **202A** and through LED **100** to a heat sink (not shown) attached to the bottom surface **114** of the LED. Example materials and deposition methods for bonding layers **202A**, **202B** and **202C** have been listed previously.

Example light rays **242**, **244**, **246**, **248**, **250**, **252** and **254** illustrate the operation of solid-state light source **240**. When an electrical current is applied through LED **100** via the first reflecting electrode **102** and the second reflecting electrode **106**, the active region **110** emits internally generated light. The wavelength of the internally generated light can be any optical wavelength. Preferably the wavelength of the internally generated light is in the wavelength range from about 250 nm to about 500 nm. For illustrative purposes only, LED **100** is shown to emit UV light. For example, LED **100** can emit 360 nm UV light.

Internally generated UV light ray **242** is emitted by active region **110** of LED **100**. UV light ray **242** is transmitted through the first doped semiconductor layer **108**, through top surface **128** of LED **100**, through bonding layer **202A**, through wavelength conversion chip **50A** without being converted, through bonding layer **202B**, through the wavelength conversion chip **50B** without being converted, through bonding layer **202C** and through wavelength conversion chip **50C** without being converted. UV light ray **242** exits solid-state light source **240** through surface **54C** of the wavelength conversion chip **50C**.

Internally generated UV light ray **244** is emitted by active region **110** of LED **100**. UV light ray **244** is transmitted through the first doped semiconductor layer **108**, through top surface **128** of LED **100**, through bonding layer **202A** and into the wavelength conversion chip **50A**. Wavelength conversion chip **50A** converts UV light ray **244** into blue light ray **246**. The conversion of UV light ray **244** to blue light is an illustrative example. Depending on the composition of the wavelength conversion layer, the UV light could be converted instead into, for example, cyan, green, yellow, red or infrared light. Blue light ray **246** passes through the remainder of the wavelength conversion chip **50A**, through bonding layer **202B**, through wavelength conversion chip **50B** without being converted, through bonding layer **202C**, through wavelength conversion chip **50C** without being converted and exits solid-state light source **240** through surface **54C** of the wavelength conversion chip **50C**.

Internally generated UV light ray **248** is emitted by active region **110** of LED **100**. UV light ray **248** is transmitted through the first doped semiconductor layer **108**, through top surface **128** of LED **100**, through bonding layer **202A**, through wavelength conversion chip **50A** without being converted, through bonding layer **202B** and into the wavelength conversion chip **50B**. Wavelength conversion chip **50B** converts UV light ray **248** into green light ray **250**. Green light ray **250** passes through the remainder of the wavelength conversion chip **50B**, through bonding layer **202C**, through wavelength conversion chip **50C** without being converted and exits the solid-state light source **240** through surface **54C** of the wavelength conversion chip **50C**.

Internally generated UV light ray **252** is emitted by active region **110** of LED **100**. UV light ray **252** is transmitted through the first doped semiconductor layer **108**, through top surface **128** of LED **100**, through bonding layer **202A**, through wavelength conversion chip **50A** without being con-

verted, through bonding layer 202B, through wavelength conversion chip 50B without being converted, through bonding layer 202C and into the wavelength conversion chip 50C. Wavelength conversion chip 50C converts UV light ray 252 into red light ray 254. Red light ray 254 passes through the remainder of the wavelength conversion chip 50C and exits the solid-state light source 240 through surface 54C of the wavelength conversion chip 50C.

The wavelength conversion chip 50A converts UV light ray 244 into blue light. The wavelength conversion chip 50B converts UV light ray 248 into green light. The wavelength conversion chip 50C converts UV light ray 252 into red light. Light ray 242 passes through wavelength conversion chips 50A, 50B and 50C without conversion. Only a portion of the UV light passing through the wavelength conversion chips is converted into blue, green or red light. The wavelength conversion chips 50B and 50C do not convert the already converted blue light ray 246 from the wavelength conversion chip 50A. The blue light ray 246 is transmitted through the wavelength conversion chips 50B and 50C without being converted. The wavelength conversion chip 50C does not convert the already converted green light ray 250 from the wavelength conversion chip 50B. The green light ray 250 is transmitted through the wavelength conversion chip 50C without being converted.

FIGS. 8A-8C illustrate embodiments of this invention that utilize LED 150. LED 150 has the first reflecting electrode 154 positioned on the bottom surface 126 of the first doped semiconductor 108. Since there is no top electrode on LED 150, the wavelength conversion chips do not require via holes in order to make electrical contact to the first reflecting electrode.

Example light rays will not be illustrated in FIGS. 8A-8C since the conversion of UV light, for example, into blue, green or red light occurs in the same manner as previously illustrated light rays in FIGS. 5, 6 and 7.

Another embodiment of this invention is solid-state light source 300 shown in a side cross-sectional view in FIG. 8A. Solid-state light source 300 includes LED 150, which has a first reflecting electrode 154 positioned on the bottom surface 126 of the first doped semiconductor layer 108, wavelength conversion chip 50 and a bonding layer 202. The wavelength conversion chip 50 includes light extracting elements 80 and does not include a via.

In FIG. 8A, the wavelength conversion chip covers the entire surface 128 of LED 150. It is also within the scope of this invention that the wavelength conversion chip 50 may have an area that is larger or smaller than the area of the top surface 128 of LED 150.

The wavelength conversion chip is attached to LED 150 by a transparent and thermally conducting bonding layer 202. Preferably the refractive index of bonding layer 202 is 1.30 or higher. The high refractive index of the bonding layer 202 frustrates total internal reflection and improves the extraction of photons normally trapped within the LED die. The bonding layer also provides a thermal conduction path from the wavelength conversion chip 50 to LED 150. Heat generated inside the wavelength conversion chip 50 can pass through the bonding layer 202 and through LED 150 to a heat sink (not shown) attached to the bottom surface 114 of the LED. Example bonding layer materials have been listed previously.

The wavelength conversion chip 50 converts light of a first wavelength range emitted by LED 150 into light of a second wavelength range. For example, wavelength conversion chip can convert UV light into blue light.

Another embodiment of this invention is solid-state light source 320 shown in a side cross-sectional view in FIG. 8B.

Solid-state light source 320 includes LED 150, which has a first reflecting electrode 154 positioned on the bottom surface 126 of the first doped semiconductor layer 108, two wavelength conversion chips 50A and 50B and two bonding layers 202A and 202B. The wavelength conversion chip 50A includes light extracting elements 80A and the wavelength conversion chip 50B includes light extracting elements 80B.

In FIG. 8B, the wavelength conversion chips 50A and 50B cover the entire surface 128 of LED 150. It is also within the scope of this invention that the wavelength conversion chips 50A and 50B may have an area that is larger or smaller than the area of the top surface 128 of LED 150.

The wavelength conversion chips are attached to LED 150 by transparent and thermally conducting bonding layers 202A and 202B. Preferably the refractive index of bonding layers 202A and 202B is 1.30 or higher. The bonding layers also provide a thermal conduction path from the wavelength conversion chips 50A and 50B to LED 150. Heat generated inside wavelength conversion chip 50A can pass through the bonding layer 202A and through LED 150 to a heat sink (not shown) attached to the bottom surface 114 of the LED. Heat generated inside wavelength conversion chip 50B can pass through the bonding layer 202B, through wavelength conversion chip 50A, through bonding layer 202A and through LED 150 to a heat sink (not shown) attached to the bottom surface 114 of the LED. Example materials and deposition methods for bonding layers 202A and 202B have been listed previously.

As an illustrative example, the wavelength conversion chip 50A converts UV light into blue light. The wavelength conversion chip 50B converts UV light into green light.

Another embodiment of this invention is solid-state light source 340 shown in a side cross-sectional view in FIG. 8C. Solid-state light source 340 includes LED 150, which has a first reflecting electrode 154 positioned on the bottom surface 126 of the first doped semiconductor layer 108, three wavelength conversion chips 50A, 50B and 50C and three bonding layers 202A, 202B and 202C. The wavelength conversion chip 50A includes light extracting elements 80A. The wavelength conversion chip 50B includes light extracting elements 80B. The wavelength conversion chip 50C includes light extracting elements 80C.

In FIG. 8C, the wavelength conversion chips 50A, 50B and 50C cover the entire surface 128 of LED 150. It is also within the scope of this invention that the wavelength conversion chips 50A, 50B and 50C may have an area that is larger or smaller than the area of the top surface 128 of LED 150.

The wavelength conversion chips are attached to LED 150 by transparent and thermally conducting bonding layers 202A, 202B and 202C. Preferably the refractive index of bonding layers 202A, 202B and 202C is 1.30 or higher. The bonding layers also provide a thermal conduction path from the wavelength conversion chips 50A, 50B and 50C to LED 150. Heat generated inside wavelength conversion chip 50A can pass through the bonding layer 202A and through LED 150 to a heat sink (not shown) attached to the bottom surface 114 of the LED. Heat generated inside wavelength conversion chip 50B can pass through the bonding layer 202B, through wavelength conversion chip 50A, through bonding layer 202A and through LED 150 to a heat sink attached to the bottom surface 114 of the LED. Heat generated inside wavelength conversion chip 50C can pass through the bonding layer 202C, through the wavelength conversion chip 50B, through the bonding layer 202B, through wavelength conversion chip 50A, through bonding layer 202A and through LED 150 to a heat sink attached to the bottom surface 114 of the

LED. Example materials and deposition methods for bonding layers **202A**, **202B** and **202C** have been listed previously.

As an illustrative example, the wavelength conversion chip **50A** converts UV light into blue light. The wavelength conversion chip **50B** converts UV light into green light. The wavelength conversion chip **50C** converts UV light into red light.

FIGS. **9A** and **9B** illustrate side cross-sectional views of another embodiment of this invention, solid-state light source **400**. Solid-state light source **400** has a wavelength conversion chip that includes an optical coating. The optical coating in this example is a dichroic mirror.

Solid-state light source **400** includes LED **150**, which has a first reflecting electrode **154** positioned on the bottom surface **126** of the first doped semiconductor layer **108**, a wavelength conversion chip **50** and a bonding layer **202**. The wavelength conversion chip **50** includes an optical coating **70**, but in this example the wavelength conversion chip does not include light extracting elements or a via. However, it is within the scope of this invention that the wavelength conversion chip can optionally include light extracting elements and vias in addition to the optical coating **70**. It is also within the scope of this invention that a wavelength conversion chip that has an optical coating may also be used with other types of LEDs such as LED **100**.

In FIG. **9A**, the wavelength conversion chip covers the entire surface **128** of LED **150**. It is also within the scope of this invention that the wavelength conversion chip **50** may have an area that is larger or smaller than the area of the top surface **128** of LED **150**.

The wavelength conversion chip is attached to LED **150** by a transparent and thermally conducting bonding layer **202**. Preferably the refractive index of bonding layer **202** is 1.30 or higher. The bonding layer also provides a thermal conduction path from the wavelength conversion chip **50** to LED **150**. Heat generated inside the wavelength conversion chip **50** can pass through the bonding layer **202** and through LED **150** to a heat sink (not shown) attached to the bottom surface **114** of the LED. Example bonding layer materials have been listed previously.

The wavelength conversion layer **20** of the wavelength conversion chip **50** converts light of a first wavelength range emitted by LED **150** into light of a second wavelength range. For example, the wavelength conversion layer can convert UV light into green light.

The optical coating **70** is on the top surface **24** of the wavelength conversion layer **20** and is also on the top surface **54** of the wavelength conversion chip **50**. The optical coating **70** is a dichroic mirror in this example. The dichroic mirror transmits light in a first wavelength range and reflects light in a second wavelength range. For example, if the LED **150** emits UV light and the wavelength conversion chip converts UV light into green light, then the dichroic mirror is preferably designed to transmit green light and to reflect UV light. The dichroic mirror prevents UV light from exiting the solid-state light source **400** and causes the UV light to be recycled back through the wavelength conversion layer a second time in order to increase the amount of green light produced by the solid-state light source.

Another example (not shown) of an optical coating is a reflecting polarizer. A reflecting polarizer reflects light of a first polarization state and transmits light of a second polarization state. The reflected light of a first polarization state is recycled back to LED **150** as externally incident light.

In cases where a portion of the internally generated light emitted by LED **150** is reflecting by an optical coating and recycled back to LED **150** as externally incident light, pref-

erably LED **150** is designed to reflect a significant fraction of the externally incident light. The overall reflectivity of LED **150** to externally incident light depends on several factors including the absorption coefficient of the multi-layer semiconductor structure **104**, the reflectivity of the first reflecting electrode **154** and the reflectivity of the second reflecting electrode **106**. By lowering the absorption coefficient of the multi-layer semiconductor structure, the reflectivity of LED **150** to externally incident light will increase. Furthermore, increasing the reflectivity of the first reflecting electrode and/or the second reflecting electrode will increase the reflectivity of LED **150** to externally incident light.

In order to maximize the reflectivity of LED **150** to externally incident light, preferably the absorption coefficient (i.e. the thickness-weighted average absorption coefficient of the multiple layers) of the multi-layer semiconductor structure **104** in the emitting wavelength range of the internally generated light is less than 50 cm^{-1} . More preferably, the absorption coefficient of the multi-layer semiconductor structure in the emitting wavelength range is less than 25 cm^{-1} . Most preferably, the absorption coefficient of the multi-layer semiconductor structure in the emitting wavelength range is less than 10 cm^{-1} .

Furthermore, in order to improve the reflectivity of LED **150** to externally incident light, preferably the surface **158** of the first reflecting electrode **154** has a reflectivity greater than 60 percent in the emitting wavelength range. More preferably, the surface **158** of the first reflecting electrode **154** has a reflectivity greater than 80 percent in the emitting wavelength range. Suitable materials for the first reflecting electrode that have a reflectivity greater than 80 percent include aluminum and silver.

The second reflecting electrode **106** covers a larger surface area than the first reflecting electrode **154**. Consequently, the reflectivity of the second reflecting electrode is more critical than the reflectivity of the first metal electrode. In order to improve the reflectivity of LED **150** to externally incident light, preferably the reflectivity of surface **116** of the second reflecting electrode **106** is greater than 85 percent in the emitting wavelength range. More preferably the reflectivity of the surface **116** of the second reflecting electrode is greater than 90 percent in the emitting wavelength range. Most preferably, the reflectivity of the surface **116** of the second reflecting electrode is greater than 95 percent in the emitting wavelength range. A suitable material for the second reflecting electrode that has a reflectivity greater than 95 percent is silver. In the illustrative example for LED **150**, the second reflecting electrode is fabricated from silver.

The overall reflectivity of LED **150** to externally incident light is preferably greater than 50 percent. More preferably, the overall reflectivity of LED **150** to externally incident light is greater than 60 percent.

When an electrical current is applied through LED **150** via the first reflecting electrode **154** and the second reflecting electrode **106**, the active region **110** emits internally generated light. The wavelength of the internally generated light can be any optical wavelength. Preferably the wavelength of the internally generated light is in the wavelength range from about 250 nm to about 500 nm. For wavelength conversion applications, usually the wavelength of the internally generated light is in the ultraviolet (UV) or blue regions of the optical spectrum. For illustrative purposes only, LED **150** is shown to emit UV light. For example, LED **150** can emit 360 nm UV light.

Example light rays **402**, **404** and **406** illustrate the operation of solid-state light source **400**.

Internally generated UV light ray **402** is emitted by active region **110** of LED **150**. UV light ray **402** is transmitted through the first doped semiconductor layer **108**, through top surface **128** of LED **150**, through bonding layer **202** and through the wavelength conversion layer **20** a first time without being converted. UV light ray **402** is reflected and recycled back toward LED **150** by optical coating **70**, which is designed to reflect UV light. UV light ray **402** is transmitted through the wavelength conversion layer **20** a second time without being converted, through bonding layer **202** a second time and reenters LED **150** directed toward second reflecting electrode **106**. Although in this example, UV light ray **402** was not converted during either the first or second passage through the wavelength conversion layer, it was possible for UV light ray **402** to be converted during either transit. The probability of conversion of the UV light ray **402** to, for example, green light depends on the absorption coefficient of the wavelength conversion layer to UV light. Increasing the number of transits by UV light through the wavelength conversion layer increases the probability of conversion. If UV light ray **402** is subsequently reflected (not shown) by the second reflecting electrode **106**, UV light ray **402** may pass through the wavelength conversion layer a third time or more than three times.

Internally generated UV light ray **404** is emitted by active region **110** of LED **150**. UV light ray **404** is transmitted through the first doped semiconductor layer **108**, through top surface **128** of LED **100**, through bonding layer **202** and into the wavelength conversion layer **20** of the wavelength conversion chip **50**. Wavelength conversion layer **20** converts UV light ray **404** into green light ray **406**. The conversion of UV light ray **404** to green light is an illustrative example. Depending on the composition of the wavelength conversion layer, the UV light could instead be converted into, for example, blue, cyan, yellow, red or infrared light. Green light ray **406** is transmitted through the remainder of the wavelength conversion layer **20**, through optical coating **70**, which is a dichroic mirror designed to transmit green light, and exits the wavelength conversion chip **50** and the solid-state light source **400** through surface **54**.

FIGS. **1-3** illustrate examples of the fabrication of wavelength conversion chips where the wavelength conversion material is deposited on a substrate as a layer and the layer is then segmented into chips while the chips are still attached to the substrate. In other embodiments of this invention, the wavelength conversion layer is first removed from the substrate prior to segmentation into chips. Examples of such embodiments are described below.

Another embodiment of this invention is a process shown in FIGS. **10A-10I** for forming wavelength conversion chips. The first step in the process for forming wavelength conversion chips is to select a substrate **10**, which is shown in a side cross-sectional view in FIG. **10A**. The substrate provides a physical support for the subsequent deposition of the wavelength conversion layer. Substrate **10** has a bottom surface **12** and a top surface **14** opposite bottom surface **12**. Substrate **10** can be a polymeric material or an inorganic material. The material of substrate **10** can be amorphous, polycrystalline or a single-crystal and can be a heterogeneous material or a homogeneous material. If substrate **10** is a polymeric material or a thin flexible metal layer, substrate **10** can be a web that allows for a continuous web process. Depending on the later process steps, the substrate **10** may need to be transparent to light so that a laser liftoff process can be used to remove any deposited wavelength conversion layer. If a mechanical or chemical process is used in later steps to remove any deposited wavelength conversion layer from substrate **10**, then

substrate **10** does not need to be transparent. Example transparent polymeric materials include, but are not limited to, polyethylene and polyethylene terephthalate (PET). Example flexible metals include stainless steel, molybdenum and graphite. Example transparent inorganic materials include, but are not limited to, sapphire, silica and silicate glasses. Optionally, the top surface **14** of substrate **10** may include a release layer (not shown) to facilitate the removal of any subsequently deposited materials. The release layer is removed by thermal, radiation or mechanical means to separate the wavelength conversion layer from the substrate and the release layer. Example materials for the release layer include, but are not limited to, polymer layers, thin metal layer or inorganic materials that preferentially absorb light.

The next process step is to deposit a wavelength conversion layer **20** on the top surface **14** of substrate **10** as illustrated in a side cross-sectional view in FIG. **10B**. The wavelength conversion layer **20** has a bottom surface **22** in contact with the top surface **14** of substrate **10** and a top surface **24**.

The wavelength conversion layer **20** is formed from one or more wavelength conversion materials. The wavelength conversion materials may be, for example, phosphor materials or quantum dot materials or a plurality of such materials. The wavelength conversion layer **20** may also include optically inert host materials in addition to the phosphors or quantum dots. Examples of phosphor materials, quantum dot materials and inert host materials are described above for FIG. **1**. When the wavelength conversion layer **20** is formed from phosphor materials, the phosphors can be deposited by a variety of techniques. The techniques include, but are not limited to, chemical vapor deposition (CVD), metal-organic chemical vapor deposition (MOCVD), sputtering, electron beam evaporation, laser deposition, sol-gel deposition, molecular beam epitaxy (MBE), liquid phase epitaxy (LPE), spin coating, doctor blading and tape casting. Preferred techniques include doctor blading, tape casting, CVD, MOCVD and sputtering. When the wavelength conversion layer is formed from quantum dot materials and inert host materials, deposition techniques include spin coating, doctor blading or tape casting, self assembly, lithography, and nanoimprinting.

The thickness of the wavelength conversion layer **20** can range from about 0.1 micron to about 5000 microns or more. Preferred thicknesses range from about 0.1 micron to about 500 microns.

The next process step shown in FIG. **10C** is removing the wavelength conversion layer **20** from substrate **10** by separating the bottom surface **22** of the wavelength conversion layer from the top surface **14** of the substrate. Methods of removing the wavelength conversion layer include using thermal heating to fracture the interface between the layer and the substrate, directing ion beam radiation through the wavelength conversion layer or the substrate to sever the interface, directing optical radiation such as pulsed laser radiation through the wavelength conversion layer or the substrate to sever the interface between the layer and the substrate, or using chemical or mechanical means to sever the interface. If the wavelength conversion layer is fabricated on a flexible substrate, mechanically flexing of the wavelength conversion layer or the flexible substrate will release the layer. The removal can be facilitated if the top surface **14** of substrate **10** includes a release layer (not shown) that can be degraded by thermal, radiation, chemical or mechanical means. The detached wavelength conversion layer has an exposed bottom surface **22**.

The next process step is an optional annealing step illustrated in FIG. **10D** to thermally anneal or radiation anneal the wavelength conversion layer **20** in order to increase the wave-

length conversion efficiency of the layer or, if the layer includes a phosphor powder, to sinter the powder to form a ceramic layer.

The annealing step is important for thin film phosphors, since as-deposited thin film phosphors may have low wavelength conversion efficiency if the deposited layer is not properly annealed. The annealing step can be any heat treatment or any radiation treatment of the wavelength conversion material in the wavelength conversion layer **20** that anneals the phosphor. Heating the wavelength conversion material in the wavelength conversion layer to, for example, 600 degrees Celsius for one hour can result in thermal annealing of the wavelength conversion material. Appropriate annealing temperatures and times may vary for different wavelength conversion materials. Example radiation annealing treatments include subjecting the wavelength conversion material in the wavelength conversion layer **20** to infrared, visible or ultraviolet light **1010** as shown in FIG. **10D** or subjecting the wavelength conversion material in the wavelength conversion layer to electron beam, atomic beam or ion beam bombardment. The radiation sources may be pulsed or continuous. The light sources may be incoherent or coherent (e.g. laser) sources.

If the wavelength conversion material is a phosphor powder mixed with an organic binder, the annealing step may be done in two or more parts. For example, a low temperature (less than 300 degrees Celsius) anneal can be done to remove the organic binder material. Following the removal of the organic material, a high temperature (greater than 500 degrees Celsius) anneal can then be done to sinter the phosphor powder into a ceramic solid. The high temperature annealing step can be done between two graphite or metal plates to prevent the wavelength conversion layer from curling. Other methods, such as annealing a stack of two or more wavelength conversion layers at the same time, may also be utilized to prevent curling of the layers.

The annealing step is illustrated in FIG. **10D** to occur after the removal of the wavelength conversion layer from the substrate. However, the annealing step may also be done earlier or later in the process sequence, including before the wavelength conversion layer is removed from the substrate or after the wavelength conversion layer is segmented into chips. Doing the annealing step after the wavelength conversion layer is removed from the substrate is necessary if the substrate **10** cannot withstand high temperature or high radiation processing. The annealing step may be done in air, in an inert atmosphere such as nitrogen or argon or in a partial vacuum as appropriate.

The next process step is to segment the wavelength conversion layer **20** into a plurality of wavelength conversion chips **50**. Segmentation can be done in both the X and Y directions indicated in FIG. **10F**. For example, the segmentation can occur through the wavelength conversion layer at the dashed lines **1020** illustrated in the side cross-sectional view in FIG. **10E** and in the top plan view in FIG. **10F**. The segmentation can also occur along the dashed lines **1030** shown in FIG. **10F**. Techniques for doing the segmentation include, but are not limited to, laser scribing, mechanical scribing, optical lithography accompanied by wet chemical etching, sputter etching or ion beam etching. After segmenting the wavelength conversion layer, wavelength conversion chips **50** are formed. The wavelength conversion chips are illustrated in side cross-sectional views in FIGS. **10G** and **10H** and in a top plan view in FIG. **10I**. The wavelength conversion chips have a bottom surface **52**, a top surface **54** and side surfaces **56**.

FIG. **10I** illustrates a square shaped wavelength conversion chip. However, the wavelength conversion chips may have

any shape including, but not limited to, a square, a rectangle, a polygon, a circle, an oval. Preferably the bottom surface **52** and the top surface **54** of the wavelength conversion chips are substantially coplanar to allow easy attachment to LEDs.

Another embodiment of this invention is a process shown in FIGS. **11A-11J** for forming wavelength conversion chips that optionally include an optical coating **70** on at least one surface of the chips. Examples of optical coatings include a dichroic coating that transmits light of a first wavelength range and reflects light of a second wavelength range, an antireflection coating, a reflecting polarizer coating or a photonic bandgap coating. The coating examples are described in more detail in the descriptions of the coatings for FIG. **2**.

The elements with the same numerical reference in FIG. **11** as in FIGS. **1** and **10** are the same elements as in FIGS. **1** and **10** and have the same properties as the elements in FIGS. **1** and **10**. Some of the steps of the process shown in FIG. **11** are identical to the process steps outlined above in FIG. **10**. In particular, the step of selecting a substrate **10** in FIG. **11A** is identical to the step described for FIG. **10A**. The step of depositing a wavelength conversion layer **20** on the substrate in FIG. **11B** is identical to the step described for FIG. **10B**. The step of removing the wavelength conversion layer from the substrate in FIG. **11C** is identical to the step described for FIG. **10C**. The step of optionally annealing the wavelength conversion layer in FIG. **11D** is identical to the step described for FIG. **10D**.

The next step following the optional annealing step is to deposit an optical coating **70** to the top surface **24** of the wavelength conversion layer. The coating is shown in FIG. **11E** and can be deposited by a variety of techniques including, but not limited to, chemical vapor deposition (CVD), metal-organic chemical vapor deposition (MOCVD), sputtering, electron beam evaporation, laser deposition, sol-gel deposition, molecular beam epitaxy (MBE), liquid phase epitaxy (LPE) or spin coating. In FIG. **11E**, the optical coating is deposited on the wavelength conversion layer following the optional annealing step. However, the optical coating can be applied at an earlier step or at a later step in the overall process. For example the optical coating could be applied before the wavelength conversion layer is removed from the substrate or the optical coating could be applied after the wavelength conversion layer is segmented into chips.

The next process step is to segment the wavelength conversion layer **20** and the optical coating **70** into a plurality of wavelength conversion chips **50**. Segmentation can be done in both the X and Y directions indicated in FIG. **11G**. For example, the segmentation can occur through the optical coating and the wavelength conversion layer at the dashed lines **1020** illustrated in the side cross-sectional view in FIG. **11F** and in the top plan view in FIG. **11G**. The segmentation can also occur along the dashed lines **1030** shown in FIG. **11G**. Techniques for doing the segmentation include, but are not limited to, laser scribing, mechanical scribing, optical lithography accompanied by wet chemical etching, sputter etching or ion beam etching. After segmenting the wavelength conversion layer that includes an optical coating, wavelength conversion chips **50** are formed that have an optical coating on surface **24** of the wavelength conversion layer. The wavelength conversion chips are illustrated in side cross-sectional views in FIGS. **11H** and **11I** and in a top plan view in FIG. **11J**. The wavelength conversion chip includes a wavelength conversion layer that has a bottom surface **52**, side surfaces **56** and a top surface **54** that is covered by the optical coating **70**.

FIG. **11J** illustrates a square shaped wavelength conversion chip that includes an optical coating. However, the wave-

length conversion chips may have any shape including, but not limited to, a square, a rectangle, a polygon, a circle, an oval.

Another embodiment of this invention is a process shown in FIGS. 12A-12J for forming wavelength conversion chips that optionally include vias **82** that extend through the wavelength conversion chip or that optionally include arrays of light extracting elements **80**.

The elements with the same numerical reference in FIG. 12 as in FIGS. 1 and 10 are the same elements as in FIGS. 1 and 10 and have the same properties as the elements in FIGS. 1 and 10. Some of the steps of the process shown in FIG. 12 are identical to the process steps outlined above in FIG. 10. In particular, the step of selecting a substrate **10** in FIG. 12A is identical to the step described for FIG. 10A. The step of depositing a wavelength conversion layer **20** on the substrate in FIG. 12B is identical to the step described for FIG. 10B. The step of removing the wavelength conversion layer from the substrate in FIG. 12C is identical to the step described for FIG. 10C. The step of optionally annealing the wavelength conversion layer in FIG. 12D is identical to the step described for FIG. 10D.

The next step following the optional annealing step is to form one or more vias and/or one or more light extracting elements in the wavelength conversion layer **20**. Via **82** is illustrated in FIGS. 12E-12J. Via **82** passes through the wavelength conversion layer **20** from side **22** to side **24** as shown in FIGS. 12E and 12F. Vias are required to form electrical pathways through the wavelength conversion layer and the final wavelength conversion chips. The vias may be air-filled vias or the vias may be filled with an electrically conducting material (not shown) such as a metal.

Light extracting elements **80** are elements that aid in the removal of light from the light emitting layers such as wavelength conversion layer **20** or wavelength conversion chip **50**. In general, the refractive index of the wavelength conversion layer **20** or wavelength conversion chip **50** is higher than the refractive index of air. A portion of the light that is emitted by the wavelength conversion material can be trapped inside the wavelength conversion layer **20** or the wavelength conversion chip **50** by total internal reflection. Light extracting elements **80** cause a larger portion of the emitted light to exit the layer or chip. Examples of light extracting elements **80** include, but are not limited to, vertical holes, conical-shaped holes, holes with polygonal cross-sections, conical-shaped bumps, hemispherical-shaped bumps, bumps with polygonal cross-sections such as pyramids, grooves, ridges and subwavelength optical elements. Other examples of light extracting elements are arrays of subwavelength optical elements such as holes or grooves that are arranged to form photonic crystals. For illustrative purposes, the light extracting elements shown in FIGS. 12E-12J are conical-shaped holes.

The light extracting elements **80** may be formed on the top surface **24** of the wavelength conversion layer **20** and may extend either part way or all the way through the layer. If the light extracting elements are subwavelength optical elements, the light extracting elements may be positioned either on the top surface **24** of the chip or may be fabricated inside the chip.

Vias **82** and light extracting elements **80** may be formed by techniques that include, but are not limited to, laser ablation, mechanical etching, optical lithography accompanied by wet chemical etching, sputter etching or ion beam etching.

Vias **82** and light extracting elements **80** are shown in FIG. 12E to be fabricated in a process step that occurs after the optional annealing step for the wavelength conversion layer **20**. However, it is within the scope of this invention that the fabrication of vias and light extracting elements may occur at

other points in the overall process. For example, fabrication of vias and light extracting elements may be done before the annealing step or after the wavelength conversion layer is segmented into wavelength conversion chips.

The next process step is to segment the wavelength conversion layer **20** into a plurality of wavelength conversion chips **50**. Segmentation can be done in both the X and Y directions indicated in FIG. 12G. For example, the segmentation can occur through the wavelength conversion layer at the dashed lines **1020** illustrated in the side cross-sectional view in FIG. 12F and in the top plan view in FIG. 12G. The segmentation can also occur along the dashed lines **1030** shown in FIG. 12G. Techniques for doing the segmentation include, but are not limited to, laser scribing, mechanical scribing, optical lithography accompanied by wet chemical etching, sputter etching or ion beam etching. After segmenting the wavelength conversion layer, wavelength conversion chips **50** are formed that include optional vias and/or light extracting elements. The wavelength conversion chips are illustrated in side cross-sectional views in FIGS. 12H and 12I and in a top plan view in FIG. 12J. The wavelength conversion chip includes a wavelength conversion layer that has a bottom surface **52**, side surfaces **56**, top surface **54**, via **82** and light extracting elements **80**.

FIG. 12J illustrates a square shaped wavelength conversion chip. However, the wavelength conversion chips may have any shape including, but not limited to, a square, a rectangle, a polygon, a circle, an oval.

Another embodiment of this invention is a process shown in FIGS. 13A-13J for forming wavelength conversion chips that optionally include at least one electrical connection and/or electrical bond pad on the surface of the chip. The electrical connections may be designed for one or more LEDs per wavelength conversion chip. Electrical connections and/or electrical bond pads may allow for parallel, series, anti-parallel or combinations of the previous three types of interconnect. Electrical connections and/or electrical bond pads for additional devices including but not limited to photodiodes, surge protection devices, diodes, power supplies, audio devices, motion sensors, solar cells, batteries, and microphones are also disclosed. The formation of electronic connections and/or electrical pads for external connectors is also disclosed.

The elements with the same numerical reference in FIG. 13 as in FIGS. 1 and 10 are the same elements as in FIGS. 1 and 10 and have the same properties as the elements in FIGS. 1 and 10. Some of the steps of the process shown in FIG. 13 are identical to the process steps outlined above in FIG. 10. In particular, the step of selecting a substrate **10** in FIG. 13A is identical to the step described for FIG. 10A. The step of depositing a wavelength conversion layer **20** on the substrate in FIG. 13B is identical to the step described for FIG. 10B. The step of removing the wavelength conversion layer from the substrate in FIG. 13C is identical to the step described for FIG. 10C. The step of optionally annealing the wavelength conversion layer in FIG. 13D is identical to the step described for FIG. 10D.

The next step following the optional annealing step is to form one or more electrical connections and/or one or more electrical bond pads on the wavelength conversion layer **20**. Electrical bond pad **1320** is illustrated in FIGS. 13E-13J. Electrical connection **1310** is illustrated in FIGS. 13G and 13J. Electrical bond pad **1320** and electrical connection **1310** are positioned on surface **24** of the wavelength conversion layer **20**. Electrical bond pads and/or electrical connections may be required to bond a wavelength conversion chip to the surface of an LED such as LED **100** in FIG. 5A without using

vias. An electrical pathway can be formed along the surface of the wavelength conversion layer of the wavelength conversion chip to electrode **102** even if the chip covers the electrode.

Electrical bond pads and electrical connections can be fabricated from materials that have high electrical conductivity. Materials with high electrical conductivity include, but are not limited to, metals, graphite, graphene, carbon nanotubes and transparent conductive oxides (TCOs). The electrical bond pads and electrical connections can be fabricated by first depositing a highly conductive film by techniques such as electron beam evaporation, sputtering, chemical vapor deposition or spin coating. The conductive film can then be patterned by standard lithographic techniques including, but not limited to, optical lithography accompanied by wet chemical etching, sputter etching or ion beam etching and by pulsed laser etching.

Another way (not illustrated) to make an electrical connection on a wavelength conversion layer or chip is to etch a groove into surface **24** of the wavelength conversion layer or surface **54** of the wavelength conversion chip and press an electrical wire or other type of electrode into the resulting groove. The groove may be formed by techniques that include, but are not limited to, laser ablation, mechanical etching, optical lithography accompanied by wet chemical etching, sputter etching or ion beam etching. An adhesive may be required to hold the electrical wire or electrode in the groove.

Electrical bond pads are shown in FIG. **13E** to be fabricated in a process step that occurs after the optional annealing step for the wavelength conversion layer **20**. However, it is within the scope of this invention that the fabrication of electrical connections and/or electrical bond pads may occur at other points in the overall process. For example, fabrication of electrical connections and electrical bond pads may be done before the annealing step or after the wavelength conversion layer is segmented into wavelength conversion chips.

The next process step is to segment the wavelength conversion layer **20** into a plurality of wavelength conversion chips **50**. Segmentation can be done in both the X and Y directions indicated in FIG. **13G**. For example, the segmentation can occur through the wavelength conversion layer at the dashed lines **1020** illustrated in the side cross-sectional view in FIG. **13F** and in the top plan view in FIG. **13G**. The segmentation can also occur along the dashed lines **1030** shown in FIG. **13G**. Techniques for doing the segmentation include, but are not limited to, laser scribing, mechanical scribing, optical lithography accompanied by wet chemical etching, sputter etching or ion beam etching. After segmenting the wavelength conversion layer, wavelength conversion chips **50** are formed that include optional vias and/or light extracting elements. The wavelength conversion chips are illustrated in side cross-sectional views in FIGS. **13H** and **13I** and in a top plan view in FIG. **13J**. The cross-sectional view in FIG. **13I** is along the II-II plane shown in FIG. **13J**. The wavelength conversion chip includes a wavelength conversion layer that has a bottom surface **52**, side surfaces **56**, top surface **54**, electrical connection **1310** and electrical bond pad **1320**.

FIG. **13J** illustrates a square shaped wavelength conversion chip. However, the wavelength conversion chips may have any shape including, but not limited to, a square, a rectangle, a polygon, a circle, an oval.

FIG. **14A** depicts at least one LED **2001** embedded in a thermally conductive luminescent element **2000** as a light source. Preferably, thermally conductive luminescent element **2000** contains at least one transparent or translucent layer such that the ray **2004** emanating from LED **2001** can be

waveguided within thermally conductive luminescent element **2000**. The geometry and position of at least one LED **2001**, placement, pocket geometry within thermally conductive luminescent element **2000** and refractive indices of at least one LED **2001**, thermally conductive luminescent element **2000**, and bonding layer **2002** are chosen to optimize the light extraction and waveguiding through and out the thermally conductive luminescent element **2000**. The pocket is formed such that at 5 sides of the shaped LED are in contact with the thermally conductive luminescent element. Transmitted ray **2003** is also a function of the geometry of at least one LED **2001**, pocket geometry within thermally conductive luminescent element **2000**, and refractive indices of at least one LED **2001**, thermally conductive luminescent element **2000**, and bonding layer **2002**. More specifically, color temperature and efficiency can be adjusted by controlling the ratio of transmitted rays **2003** to waveguided ray **2004**. In addition increasing the amount of waveguided rays **2004** can be used to increase emission area significantly compared to the area of at least one LED **2001**. Low absorption and high thermal conductivity within at least one LED **2001** is also a critical embodiment of this invention. Preferred are LEDs with low average alpha such as undoped SiC, ZnO, and GaN. Preferred are LEDs grown on freestanding nitride foils. Most preferred are LEDs grown on freestanding nitride foils with an average alpha less than 1 cm⁻¹. Thermally conductive luminescent element **2000** is most preferably formed using crystal growth techniques including but not limited to Czochralski, laser heated pedestal, edge defined, floating zone, and other crystal growth methods known in the art. Alternatively, transparent or translucent ceramic methods to form thermally conductive luminescent element **2000** may also be used. Alternatively, layered composites may be used in which at least one layer within thermally conductive luminescent element **2000** is substantially transparent to the light emitted by at least one LED **2001**. This layer may include but not limited to glass, single crystal materials including but not limited to yag, sapphire, zno, mgo, spinel, alon, yttria, as well as other thermally conductive inorganic materials that are substantially transparent to visible light. Optionally nanocomposites may be used to impart translucency or transparency or (or a mix of both) to thermally conductive luminescent element **2000**. As a preferred example, ZnO nanoparticles doped (Bi preferred) or undoped combined with Ce:Yag powders and consolidated using one of the following methods; spark plasma sintering, HIP, vacuum sintering, laser sintering, plasma spraying, or other consolidation methods as known in the art. Most preferred is a thermally conductive luminescent element **2000** with a thermal conductivity greater than 1 W/m/K and which has sufficient transparency to the light emitted by at least one LED **2001**.

FIG. **14B** depicts at least one shaped LED **2006** embedded in a thermally conductive luminescent element **2005** bonded in with a bonding layer **2007** as a light source. Waveguided ray **2010**, escape ray **2009**, and transmitted ray **2008** are also depicted. At least one shaped LED **2006** allows for higher extraction efficiency from at least one shaped LED **2006**. By mounting the at least one shaped LED **2006** within a pocket within thermally conductive luminescent element **2005** optical and thermal extraction can be enhanced. The trough shaped pocket in the thermally conductive luminescent element in FIG. **14b** may be fabricated by simple molds after tape casting prior to sintering, or using a mold during sintering or alternatively (if after sintering or if using grown ingots) cut via laser ablation, ultrasonic drilling with reciprocal shaped drill head, ion milled, or reactively ion etched or using other drilling methods as known in the art.

FIG. 15 depicts shaped LEDs **2016** mounted using bonding layer **2017** in thermally conductive luminescent element **2018** as a light source. In this depiction top side contacts **2012** and **2014** are separated by active region **2015**. Optionally a dielectric layer **2013** may be used to isolate the surface of shaped LEDs **2016** from the electrically conductive interconnect **2011**. The interconnect **2011** can be used to electrically connect the multiple shaped LEDs **2016** together and to a power source. Serial, parallel, series/parallel, and anti-parallel interconnects are embodiments of this invention. Dielectric layer **2013** may also contain luminescent elements as does thermally conductive luminescent element **2018**. In general both these elements may be luminescent materials including but not limited to phosphor materials which are typically optical inorganic materials doped with ions of lanthanide (rare earth) elements or, alternatively, ions such as chromium, titanium, vanadium, cobalt, manganese or magnesium. The lanthanide elements are lanthanum, cerium, praseodymium, neodymium, promethium, samarium, europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium and lutetium. Optical inorganic materials include, but are not limited to, sapphire (Al.sub.2O.sub.3), gallium arsenide (GaAs), beryllium aluminum oxide (BeAl.sub.2O.sub.4), magnesium fluoride (MgF.sub.2), indium phosphide (InP), gallium phosphide (GaP), yttrium aluminum garnet (YAG or Y.sub.3Al.sub.5O.sub.12), terbium-containing garnet, yttrium-aluminum-lanthanide oxide compounds, yttrium-aluminum-lanthanide-gallium oxide compounds, yttrium oxide (Y.sub.2O.sub.3), calcium or strontium or barium halophosphates (Ca,Sr,Ba).sub.5(PO.sub.4).sub.3(Cl,F), the compound CeMgAl.sub.11O.sub.19, lanthanum phosphate (LaPO.sub.4), lanthanide pentaborate materials ((lanthanide) (Mg,Zn)B.sub.5O.sub.10), the compound BaMgAl.sub.10O.sub.17, the compound SrGa.sub.2S.sub.4, the compounds (Sr,Mg,Ca,Ba)(Ga,Al,In).sub.2S.sub.4, the compound SrS, the compound ZnS and nitridosilicate. There are several exemplary phosphors that can be excited at 250 nm or thereabouts. An exemplary red emitting phosphor is Y.sub.2O.sub.3:Eu.sup.3+. An exemplary yellow emitting phosphor is YAG:Ce.sup.3+. Exemplary green emitting phosphors include CeMgAl.sub.11O.sub.19:Tb.sup.3+, ((lanthanide)PO.sub.4:Ce.sup.3+,Tb.sup.3+) and GdMgB.sub.5O.sub.10:Ce.sup.3+,Tb.sup.3+. Exemplary blue emitting phosphors BaMgAl.sub.10O.sub.17:Eu.sup.2+ and (Sr,Ba,Ca).sub.5(PO.sub.4).sub.3Cl:Eu.sup.2+. For longer wavelength LED excitation in the 400-450 nm wavelength region or thereabouts, exemplary optical inorganic materials include yttrium aluminum garnet (YAG or Y.sub.3Al.sub.5O.sub.12), terbium-containing garnet, yttrium oxide (Y.sub.2O.sub.3), YvO.sub.4, SrGa.sub.2S.sub.4, (Sr,Mg,Ca,Ba)(Ga,Al,In).sub.2S.sub.4, SrS, and nitridosilicate. Exemplary phosphors for LED excitation in the 400-450 nm wavelength region include YAG:Ce.sup.3+, YAG:Ho.sup.3+, YAG:Pr.sup.3+, YAG:Tb.sup.3+, YAG:Cr.sup.3+, YAG:Cr.sup.4+, SrGa.sub.2S.sub.4:Eu.sup.2+, SrGa.sub.2S.sub.4:Ce.sup.3+, SrS:Eu.sup.2+ and nitridosilicates doped with Eu.sup.2+. Other phosphor materials not listed here are also within the scope of this invention.

Quantum dot materials are small particles of inorganic semiconductors having particle sizes less than about 30 nanometers. Exemplary quantum dot materials include, but are not limited to, small particles of CdS, CdSe, ZnSe, InAs, GaAs and GaN. Quantum dot materials can absorb light at first wavelength and then emit light at a second wavelength, where the second wavelength is longer than the first wave-

length. The wavelength of the emitted light depends on the particle size, the particle surface properties, and the inorganic semiconductor material.

The transparent and optically inert host materials may also be used to create composites containing phosphor powders or to spatially separate quantum dots. Host materials include polymer materials and inorganic materials. The polymer materials include, but are not limited to, acrylates, polystyrene, polycarbonate, fluoroacrylates, chlorofluoroacrylates, perfluoroacrylates, fluorophosphinate polymers, fluorinated polyimides, polytetrafluoroethylene, fluorosilicones, sol-gels, epoxies, thermoplastics, thermosetting plastics and silicones. Fluorinated polymers are especially useful at ultraviolet wavelengths less than 400 nanometers and infrared wavelengths greater than 700 nanometers owing to their low light absorption in those wavelength ranges. Exemplary inorganic materials include, but are not limited to, silicon dioxide, optical glasses and chalcogenide glasses. As LED **2016** efficiency increases it is anticipated that lower thermal conductivity composites such as those listed above may be used including organic host materials. It should be noted however that some loss in long term stability may result due to the stability of C—H bonds discussed previously. However, just as metal filled polymer composites have been able to be used in some heatsinking applications this invention does recognize that at some efficiency point or power density level organic hosts may also be able to use the disclosed approach.

Most preferred is the use of transparent Ce:Yag boules formed via floating zone growth with less than 2% Ce dopant concentration. Alpha for blue light emitted from shaped LEDs **2016** is typically 6 cm⁻¹ allowing for a significant number of the waveguided rays to propagate farther than 5 mm from the shaped LEDs **2016** before being absorbed. The boules are sliced into 500 micron thick plates and laser ablated to form shaped pockets which match the shaped LEDs **2016**. The shaped LEDs **2016** are bonded into the pockets using an inorganic adhesive for bonding layer **2017**. A similar high temperature inorganic coating is used for dielectric **2013** and cured. After curing a silver or other metal based inorganic ink is screen printed or alternatively ink jet printed to form interconnects **2011** followed by a final cure. At this point the assembly can be tested.

Dielectric layer **2013** may be applied via printing, vapor phase deposition, plasma spraying, spin coating, and inkjet printing. Contacts **2012** and **2014** may be covered with a sacrificial coating using similar techniques as needed to prevent overcoating with dielectric layer **2013**. Interconnect **2011** may consist of thick film, vapor deposited, or inkjet printed conductive layers. Preferred is screen printed traces based on inorganic silver based inks. Even more preferred is an interconnect **2011** with a reflectivity greater than 60%. High reflectivity of the interconnect **2011** increases the efficiency of the overall structure. Most preferred is a high reflectivity/high thermal conductivity interconnect **2011** such as silver based thick film. In this manner the interconnect **2011** can be used to enhance the overall thermal conductivity of the structure.

FIG. 16 depicts thermal conductivity luminescent elements **2019** and **2020** in which shaped LEDs **2024** and **2023** with bonding layers **2021** and **2022** form an integrated luminescent sandwich which emits light from both top and bottom luminescent elements as a light source. Interconnects **2028**, **2029**, **2027**, and **2025** electrically connect shaped LEDs **2024** and **2023** together. The interconnects optionally connect multiple LEDs in series or parallel or combinations thereof. There is no limit to the number of LEDs that may be used in the sandwich. The number is determined by the desired amount

of light to be generated by the completed light source. The spacing of the LEDs is determined by the amount of area of the thermally conductive luminescent elements required to dissipate the heat from each LED. As a rough rule of thumb one square centimeter will dissipate approximately one tenth of a watt in natural convection with a temperature differential of 10° C. to 20° C. between ambient and the radiating element. Since the heat dissipating area is dependent on this temperature differential the area required is dependent on the maximum operating temperature of the LEDs. LEDs can safely operate with junction temperatures of <80° that generate over 5000 foot lamberts, preferably over 10000 foot lamberts, more preferably 20000 foot lamberts and most preferably over 40000 foot lamberts wherein the emitting area is the only predominate heat sink. The novelty of this LED light source is that the luminescent surface of the light source accounts for over 70% of the heat dissipated by the light source. Preferably the luminescent surface of the light source accounts for over 80% of the heat dissipated by the light source. And most preferably the luminescent surface of the light source accounts for over 90% of the heat dissipated by the light source. Joining layer **2026** may consist of fusible glasses, epoxies, or inorganic adhesives. Optionally the use of luminescent, reflective, scattering, fracture resistant fiber, thermally conductive, or thermally insulative fillers in joining layer **2026** may be used. The use of dual sided emitters for shaped LEDs **2024** and **2023** is a preferred embodiment of this invention. However the use of lambertian emitters for shaped LEDs **2024** and **2023** are also anticipated by this invention. In this case joining layer **2026** may or may not be an opaque material including but not limited to metals, AlN, Silicon, and metal composites. If opaque materials are used higher reflectivity materials such as silver and aluminum is a preferred embodiment to reduce optical losses. Surface reflectivity enhanced materials like coated aluminum or silver or other high reflectivity materials may be used which have optically transparent subwavelength thick coatings that enhance reflectivity over large angles.

FIG. **17** depicts self-cooling distributed light sources with a variety of connector bases and mounting configurations. FIG. **17A** depicts a single self-cooling distributed light source **2030** with a support mount **2031** and a dual pin base **2032**. This configuration is similar to G type halogen lamps. While the shape of single self-cooling distributed light source **2030** shown is a solid rectangular, a wide range of shapes are anticipated including but not limited to; ovals, triangles, shapes with holes for both improved air flow for cooling and aesthetics, and non-flat geometries (tubes, spirals, and spherical pieces). A preferred embodiment is circular self-cooling distributed light source **2030** with multiple holes. In this embodiment the self-cooling distributed light source **2030** maybe mounted as shown or all the way to horizontally mounted with the holes allowing for enhanced natural convection relative to a horizontally mounted self-cooling distributed light source **2030** without holes. FIG. **17B** depicts multiple self-cooling distributed light sources **2033** mounted on an Edison screw base **2034**. In this case Edison screw base **2034** may also include power conversion electronics for converting AC to DC. FIG. **17C** depicts a flex tab connector consisting of conductive layers **2035** and **2037** with a flexible dielectric **2036**. The flex tab connector is sandwiched between self cooling distributed light source **2038**. As an example, flexible dielectric may consist of 10 micron Kapton and conductive layers **2035** and **2037** may consist of 5 micron copper. The addition of electrical elements to the flex tab connector including but not limited to sensors, power converters, power conditioners, clamping diodes, microphones,

and cameras as known in the art is also disclosed. FIG. **17D** depicts self-cooling distributed light source **2040** with flexible wire leads **2039**. In this embodiment multiple sources can be strung together to create a wide range of aesthetic and functional effects.

FIG. **18** depicts a single self-cooling distributed light source **2042** similar to FIG. **17A** to which is added diffusive/reflective elements **2041** which mount either directly to self-cooling distributed light source **2042** and/or base **2043**. In this embodiment additional diffusion and/or directivity can be imparted to the source while maintain airflow to the majority of the surface of self-cooling distributed light source **2042**. As an example, a self-cooling distributed light source **2042** consisting of two—1 inch×½ inch Ce doped Yag (14 W/m/K) plates 350 microns thick can dissipate approximately 3 watts of heat while maintaining a junction temperature less than 100 C. on forty 300 micron×300 micron LEDs embedded between the Yag plates. This configuration is capable of generating over a 100 lumens with a color temperature under 6000K with no additional heatsinking and weight of approximately 1 gram. This source therefore can deliver an optical density of 100 lumens/gram. As a comparison commercially available PAR 30 LED lamps typically output 600 lumens and weight 300 grams due mainly to the heatsinks required. As stated earlier, low optical density leads to safety, increased life costs and reliability issues. A preferred embodiment of this invention is a self cooling distributed light source with an optical density greater than 30 lumens/gram. Alternately, the light source area is approximately 0.5 square inches indicating a lumens per square inch of over 200. Another preferred embodiment is a self-cooling distributed light source with that emits greater than 30 lumen per square inch.

While the invention has been described with the inclusion of specific embodiments and examples, it is evident to those skilled in the art that many alternatives, modifications and variations will be evident in light of the foregoing descriptions. Accordingly, the invention is intended to embrace all such alternatives, modifications and variations that fall within the spirit and scope of the appended claims.

What is claimed is:

1. A light source comprising at least one LED, and a thermally conductive luminescent matrix, said at least one LED being embedded within said thermally conductive luminescent matrix, wherein said thermally conductive luminescent matrix acts as a waveguide for a desired proportion of the light emitted by said at least one LED, and wherein said thermally conductive luminescent matrix is larger than the minimum required for wavelength conversion and provides a light emitting and heat emitting surface larger than that of the at least one LED.
2. The light source of claim 1 wherein said thermally conductive luminescent matrix has a dopant concentration less than 2% and thermal conductivity greater than 1 W/m/K.
3. The light source of claim 1 further comprising at least one pocket in said thermally conductive luminescent matrix, wherein said at least one LED is optically bonded into said at least one pocket in such a way that only one face of the at least one LED is not optically bonded to the luminescent matrix material.
4. The light source of claim 1 wherein said light source is a self-cooling distributed light source.
5. The light source of claim 4 wherein the optical output of said distributed self-cooling distributed light source is greater than 30 lumens per square inch.
6. The light source of claim 4 wherein more than 50% of the heat generated within said self-cooling distributed light

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source is dissipated by the emitting surfaces of said self-cooling distributed light source.

7. A light source comprising
at least one LED,
a thermally conductive luminescent matrix, said at least
one LED being embedded within said thermally conduc- 5
tive luminescent matrix, wherein said thermally conduc-
tive luminescent element acts as a waveguide for a
desired proportion of the light emitted by said at least
one LED, and 10
at least one pocket in said thermally conductive lumines-
cent matrix, wherein said at least one LED is optically
bonded into said at least one pocket;
wherein said at least one LED is a shaped LED such that 5
sides of said shaped LED are in contact with said ther- 15
mally conductive luminescent matrix.

8. A light source comprising
at least one LED,
a thermally conductive luminescent matrix, said at least
one LED being embedded within said thermally conduc- 20
tive luminescent matrix, wherein said thermally conduc-
tive luminescent matrix acts as a waveguide for a desired
proportion of the light emitted by said at least one LED,
and
at least one pocket in said thermally conductive lumines- 25
cent matrix, wherein said at least one LED is optically
bonded into said at least one pocket;
wherein said pocket is formed via at least one of the fol-
lowing methods; laser ablation, photochemical etching,
ultrasonic drilling, or reactive ion etching. 30

9. A light source comprising
at least one LED,
a thermally conductive luminescent matrix, said at least
one LED being embedded within said thermally conduc- 35
tive luminescent matrix, wherein said thermally conduc-
tive luminescent matrix acts as a waveguide for a desired
proportion of the light emitted by said at least one LED,
and
at least one pocket in said thermally conductive lumines- 40
cent matrix, wherein said at least one LED is optically
bonded into said at least one pocket;
wherein at least one shaped LEDs is bonded into pockets
within at least one thermally conductive luminescent
matrix forming a generally flat surface, a dielectric coat- 45
ing is used to electrically isolate all but the contacts of at
least one shaped LEDs on said generally flat surface and
an electrically conductive interconnect is formed to
interconnect said at least one shaped LEDs on said gener-
ally flat surface.

10. A generally isotropic distributed self-cooling light 50
source comprising
at least one LED,
a waveguiding and thermally conductive luminescent ele-
ment, and
an interconnect means between said at least one LED and 55
said waveguiding and thermally conductive luminescent
element.

11. A generally lambertian distributed self-cooling light
source comprising
at least one LED, 60
a waveguiding and thermally conductive luminescent ele-
ment,
an interconnect means between said at least one LED and
said waveguiding and thermally conductive luminescent
element, and 65
a reflecting element.

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12. A light source comprising:
at least one light emitting diode (LED); and
at least one thermally conductive luminescent matrix posi-
tioned in thermal contact and optically coupled with the
at least one LED, to perform its principal function of
wavelength conversion of light emitted from the at least
one LED;

wherein the at least one thermally conductive luminescent
matrix has a light emitting surface;
and wherein more than half of the heat generated within the
light source is dissipated by the light emitting surface of
the at least one luminescent matrix.

13. The light source of claim 12, and further comprising:
at least one pocket in the at least one luminescent matrix, in
which the at least one LED is embedded to enhance
coupling of light and heat to the at least one luminescent
matrix.

14. The light source of claim 13, wherein the at least one
luminescent matrix acts as a waveguide to spread light emit-
ted by the at least one LED over a wider cross section of the
luminescent matrix.

15. The light source of claim 13, wherein:
the at least one thermally conductive luminescent matrix
includes a first such matrix and a second such matrix
arranged in a stack and having their light emitting sur-
faces facing outward in opposite directions and having
opposite surfaces facing inward, and
the at least one LED includes at least first and second LEDs
embedded in the opposite surfaces of the first and second
luminescent matrices, respectively, whereby light and
heat from the first and second LEDs are emitted from the
light source outwardly in opposed directions.

16. The light source of claim 12, wherein the at least one
luminescent matrix acts as a waveguide to spread light emit-
ted by the at least one LED over a wider cross section of the
luminescent matrix.

17. A light source comprising:
at least one light emitting diode (LED);
at least one thermally conductive luminescent matrix posi-
tioned in thermal contact and optically coupled with the
at least one LED, to perform its principal function of
wavelength conversion of light emitted from the at least
one LED; and

electrical interconnect means positioned between the at
least one LED and the at least one luminescent matrix, to
provide electrical connection to the at least one LED.

18. The light source of claim 17, wherein the at least one
luminescent matrix acts as a waveguide to spread light emit-
ted by the at least one LED over a wider cross section of the
luminescent matrix.

19. The light source of claim 17, wherein:
the at least one thermally conductive luminescent matrix
has a light emitting surface; and
more than half of the heat generated within the light source
is dissipated by the light emitting surface of the at least
one luminescent matrix.

20. The light source of claim 17, wherein:
the electrical interconnect means includes a metal-based
layer screen-printed onto the at least one thermally con-
ductive luminescent matrix.