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(54) MICROFABRICATED STRUCTURES AND PROCESSES FOR MANUFACTURING SAME

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(60) Provisional application No. 60/506,641, filed on Sep. 26, 2003. Provisional application No. 60/506,226, filed on Sep. 26, 2003. Provisional application No. 60/506,321, filed on Sep. 26, 2003. Provisional application No. 60/506,424, filed on Sep. 26, 2003. Provisional application No. 60/506,635, filed on Sep. 26, 2003.

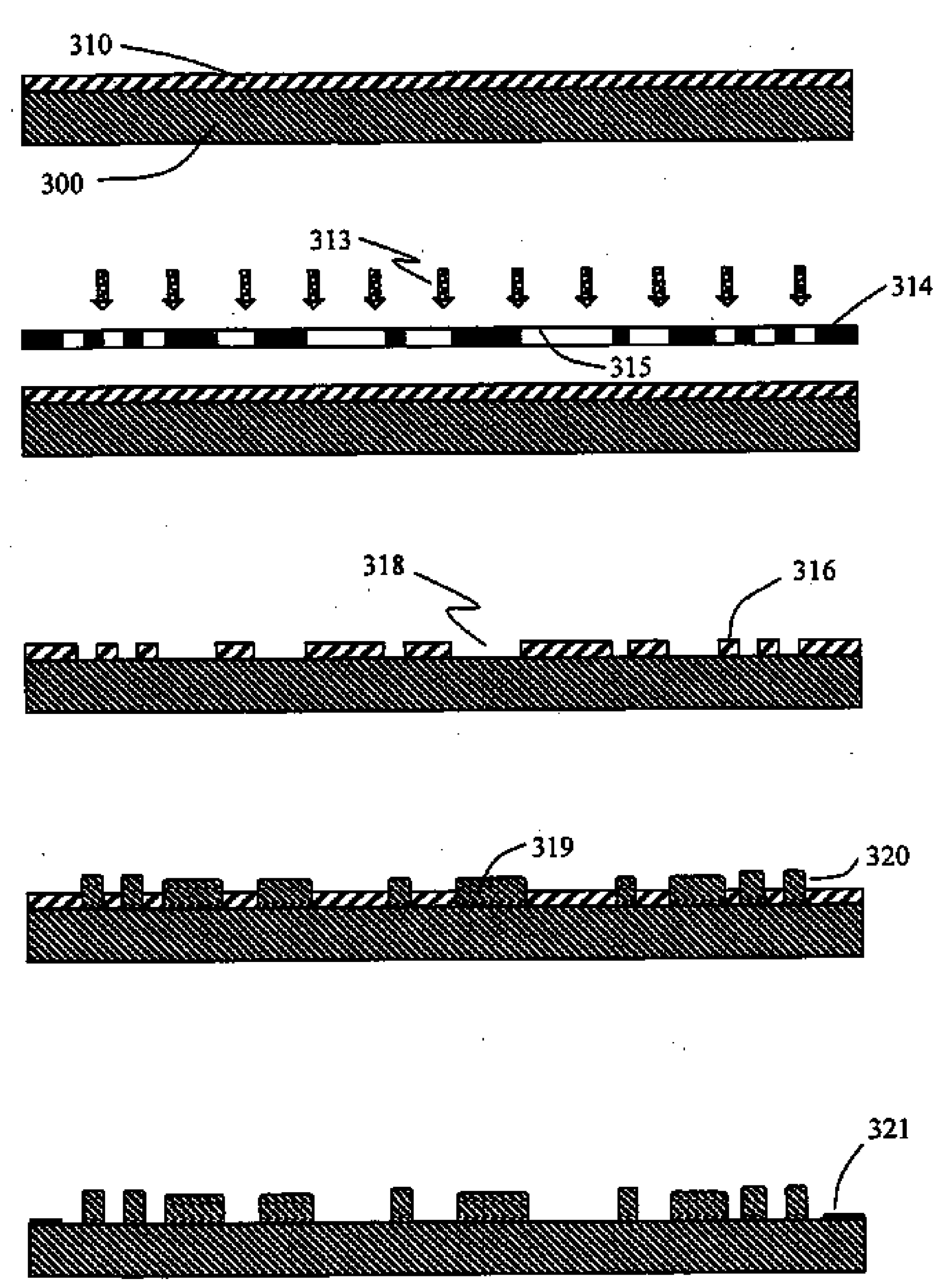
Publication Classification

(51) **Int. Cl.[7]** **C25D 1/10**

(52) **U.S. Cl.** **205/70**

(57) **ABSTRACT**

Various techniques for the fabrication of highly accurate master molds with precisely defined microstructures for use in plastic replication using injection molding, hot embossing, or casting techniques are disclosed herein. Three different fabrication processes used for master mold fabrication are disclosed wherein one of the processes is a combination of the other two processes. In an embodiment of the first process, a two-step electroplating approach is used wherein one of the metals forms the microstructures and the second metal is used as a sacrificial support layer. Following electroplating, the exact height of the microstructures is defined using a chemical mechanical polishing process. In an embodiment of the second process, a modified electroforming process is used for master mold fabrication. The specific modifications include the use of Nickel-Iron (80:20) as a structural component of the master mold, and the use of a higher saccharin concentration in the electroplating bath to reduce tensile stress during plating and electroforming on the top as well as sides of the dummy substrate to prevent peel off of the electroform. The electroforming process is also well suited towards the fabrication of microstructures with non-rectangular cross sectional profiles. Also disclosed is an embodiment of a simple fabrication process using direct deposition of a curable liquid molding material combined with the electroforming process. Finally, an embodiment of a third fabrication process combines the meritorious features of the first two approaches and is used to fabricate a master mold using a combination of the two-step electroplating plus chemical mechanical polishing approach and the electroforming approach to fabricate highly accurate master molds with precisely defined microstructures. The microstructures are an integral part of the master mold and hence the master mold is more robust and well suited for high volume production of plastic MEMS devices through replication techniques such as injection molding.



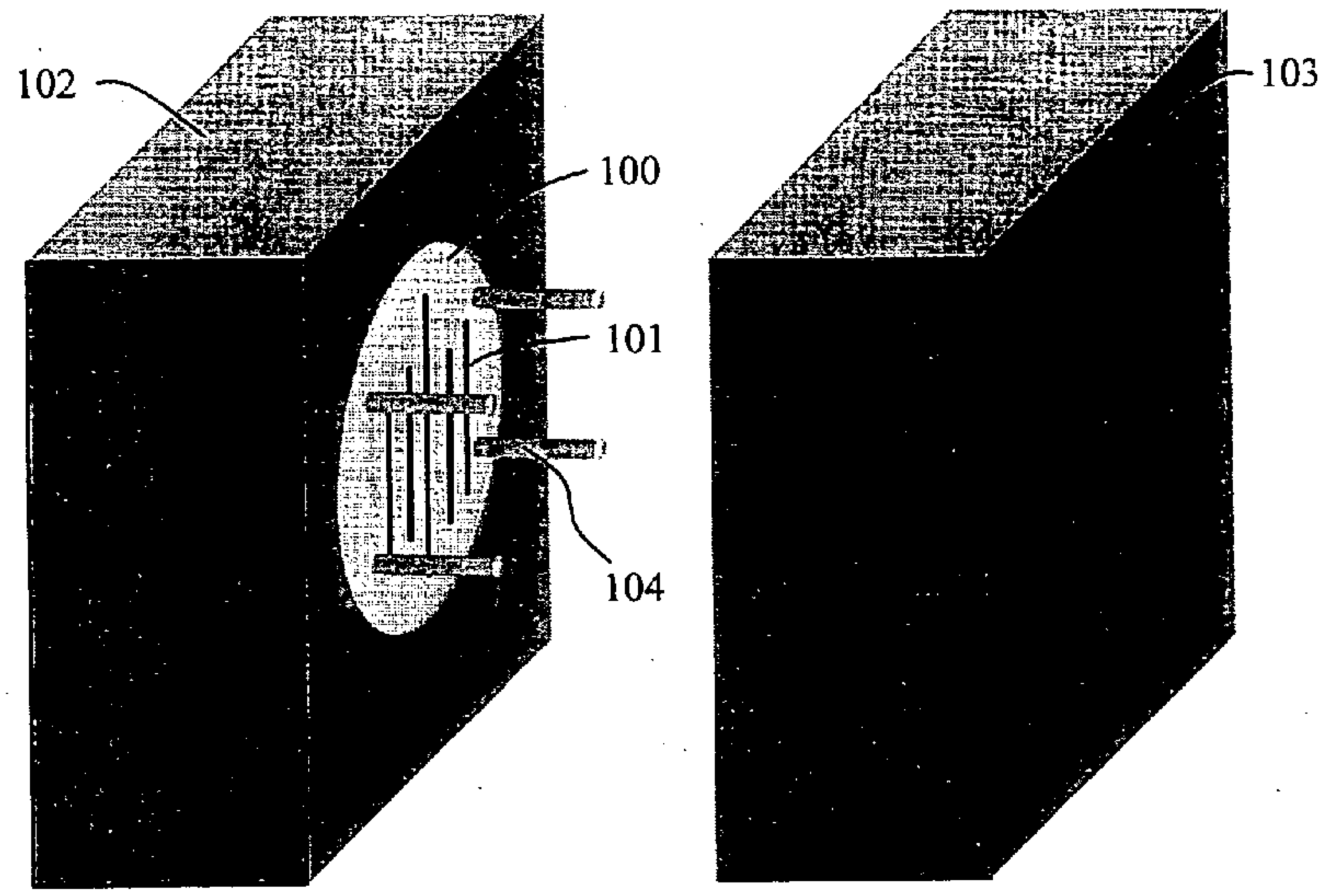


FIG. 1a

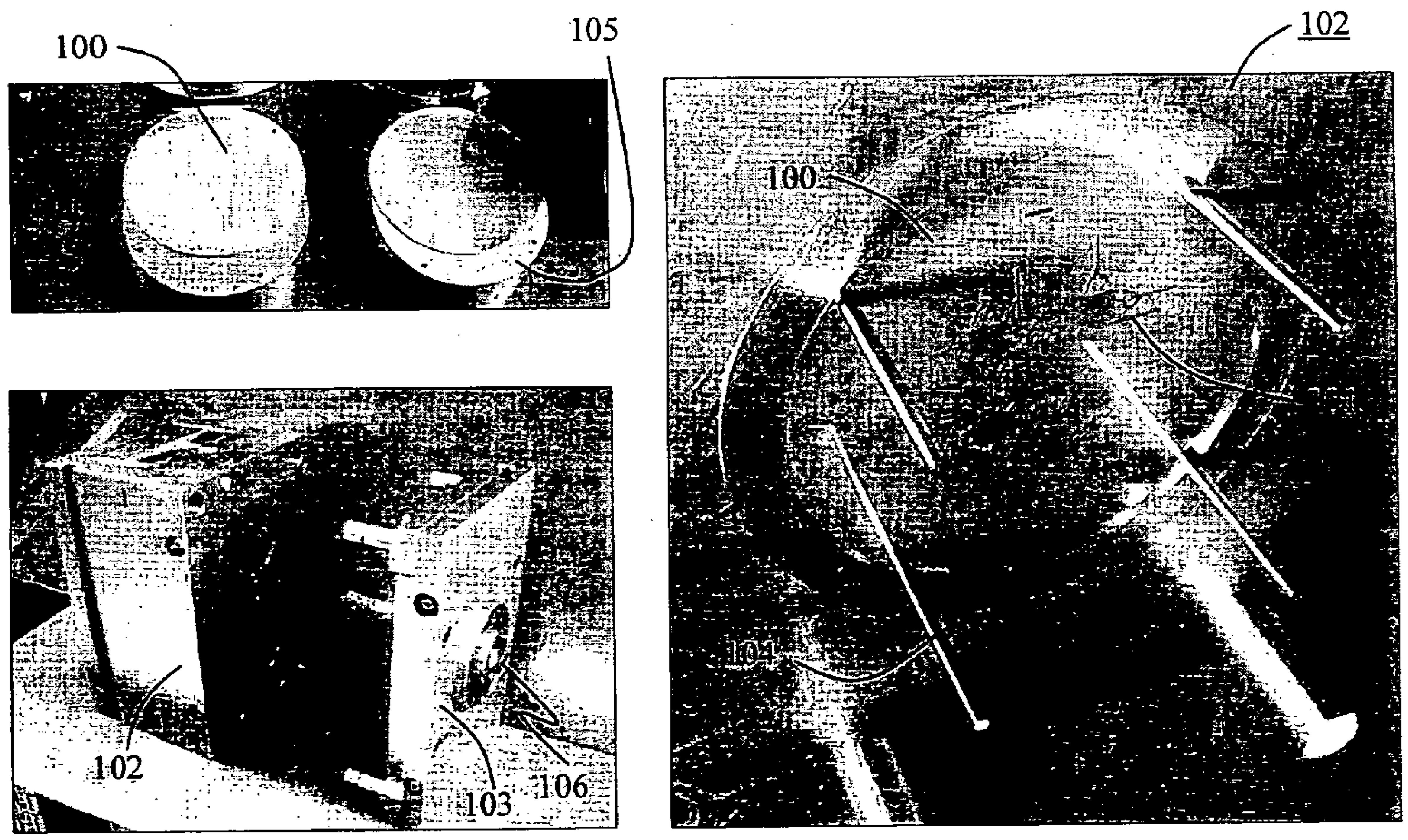


FIG. 1b

FIG. 2a

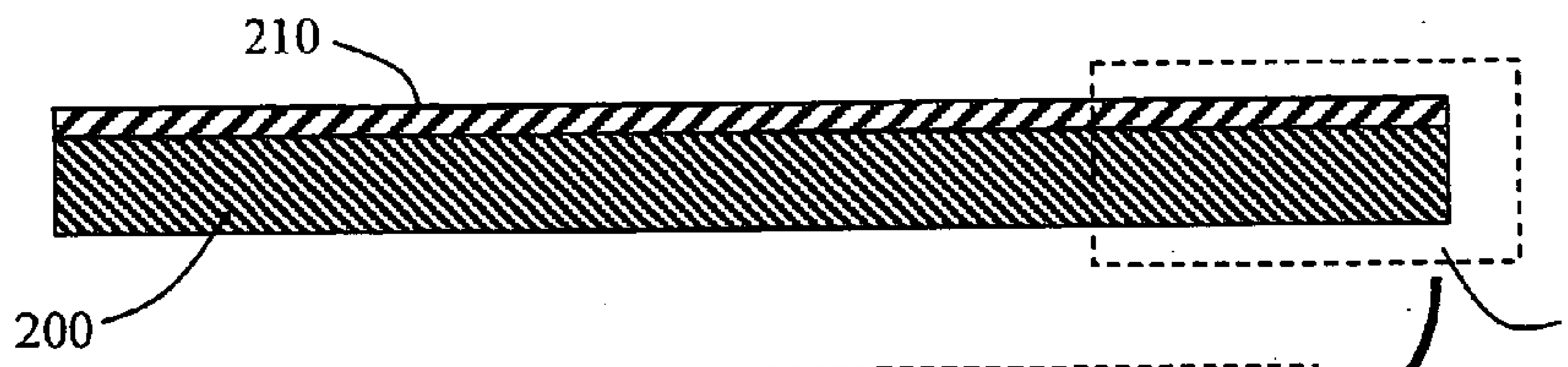


FIG. 2b

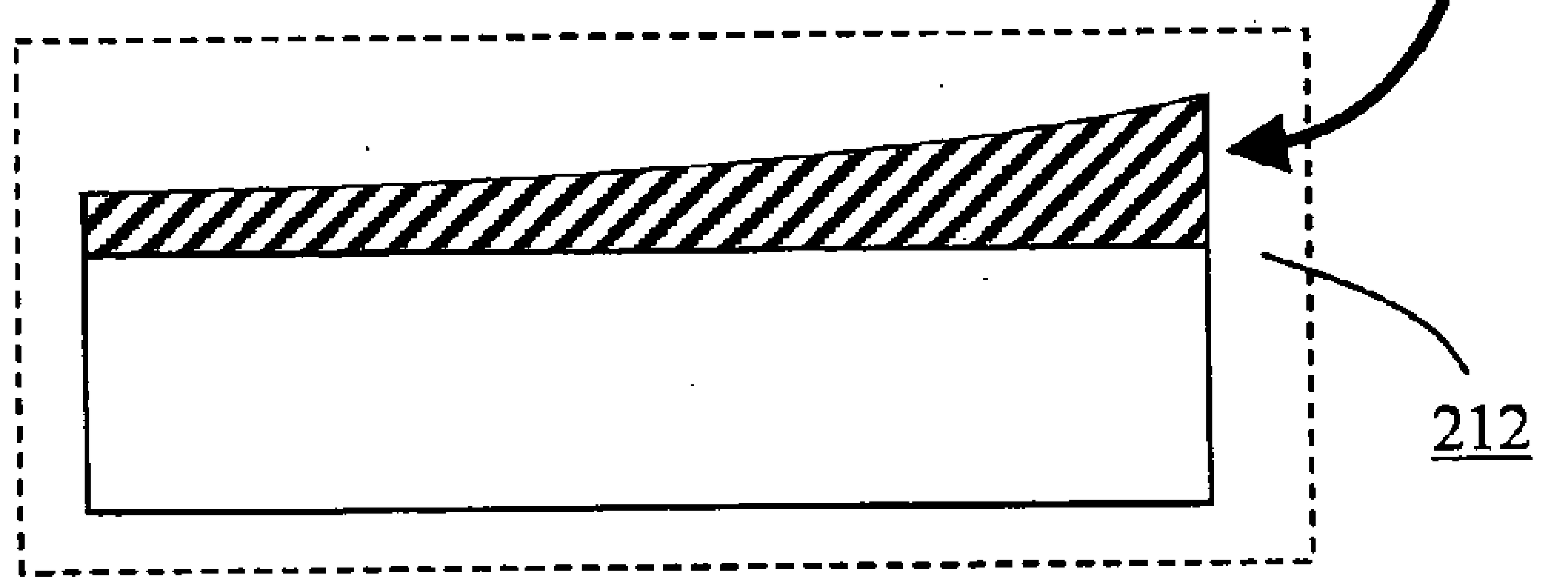


FIG. 2c

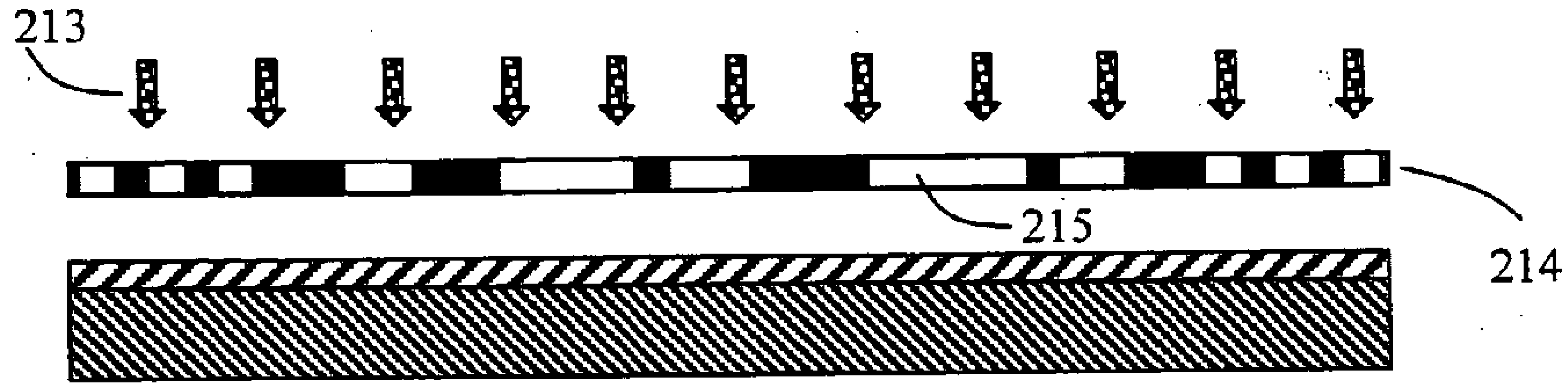


FIG. 2d

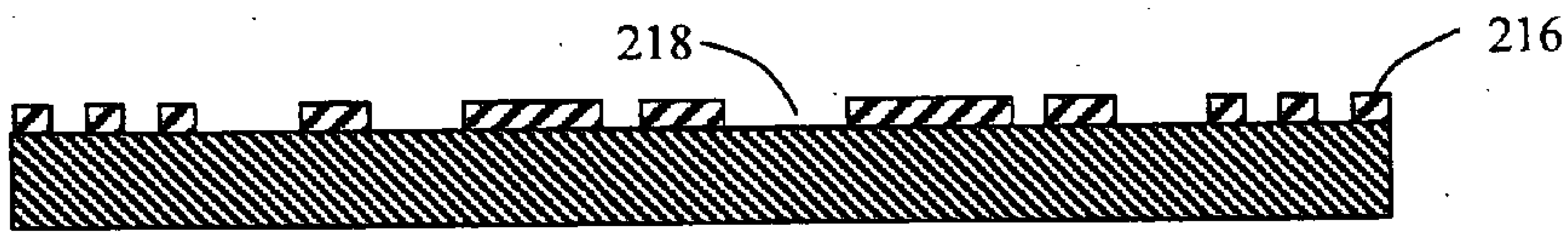


FIG. 2e

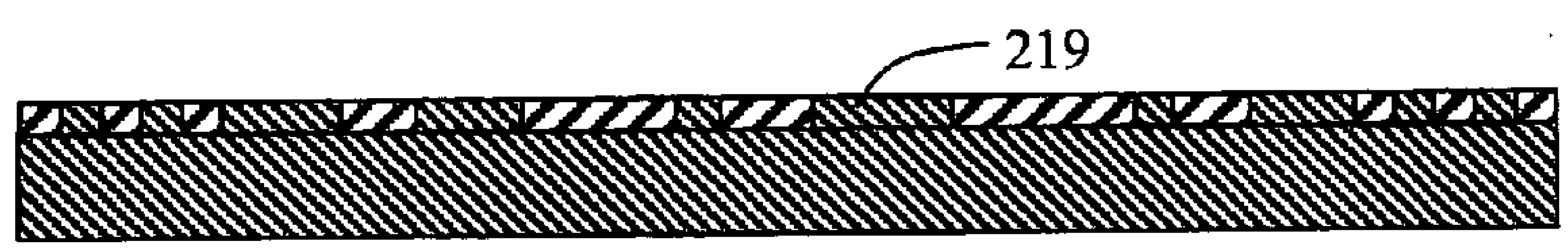


FIG. 2f

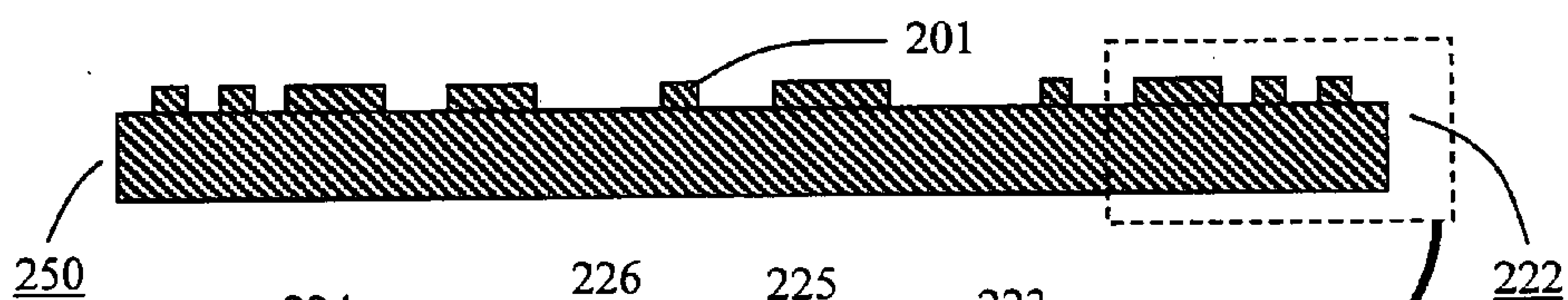


FIG. 2g

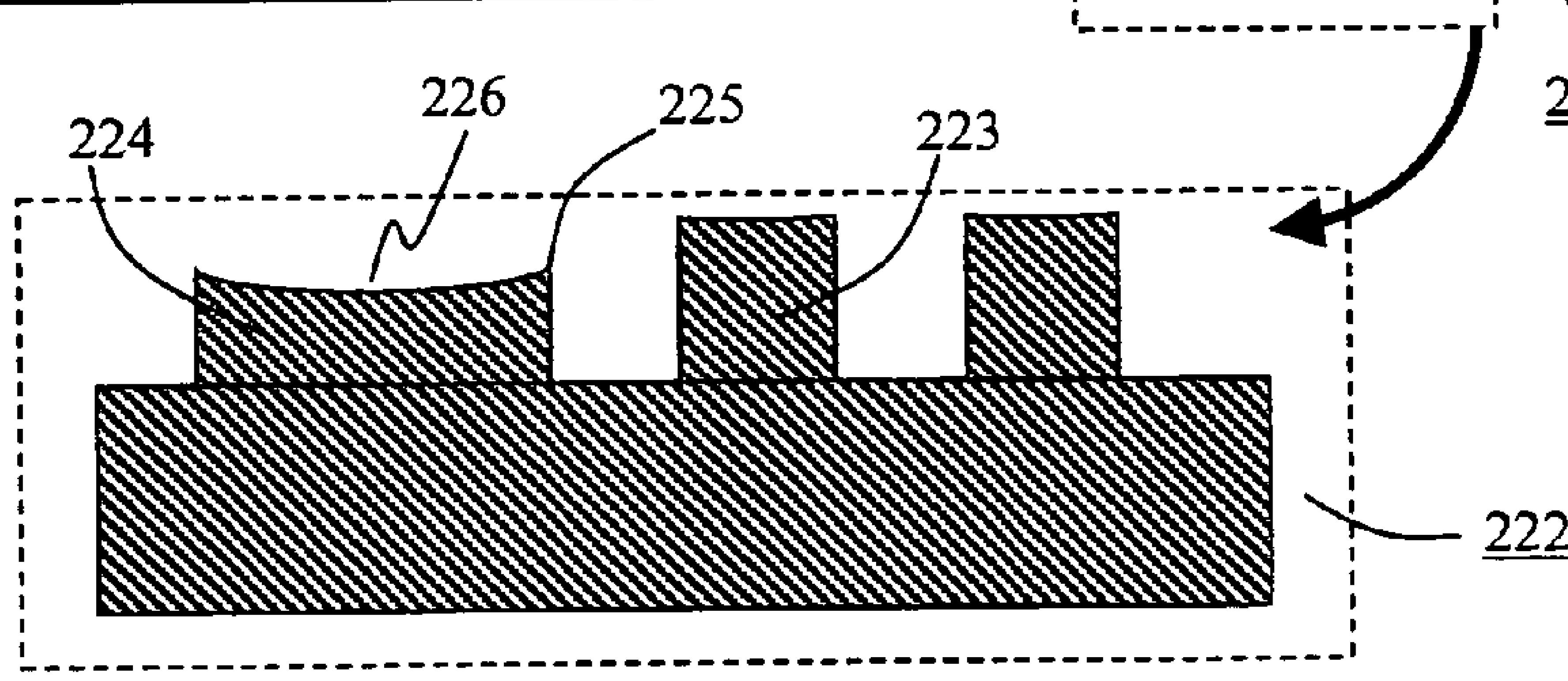


FIG. 3a

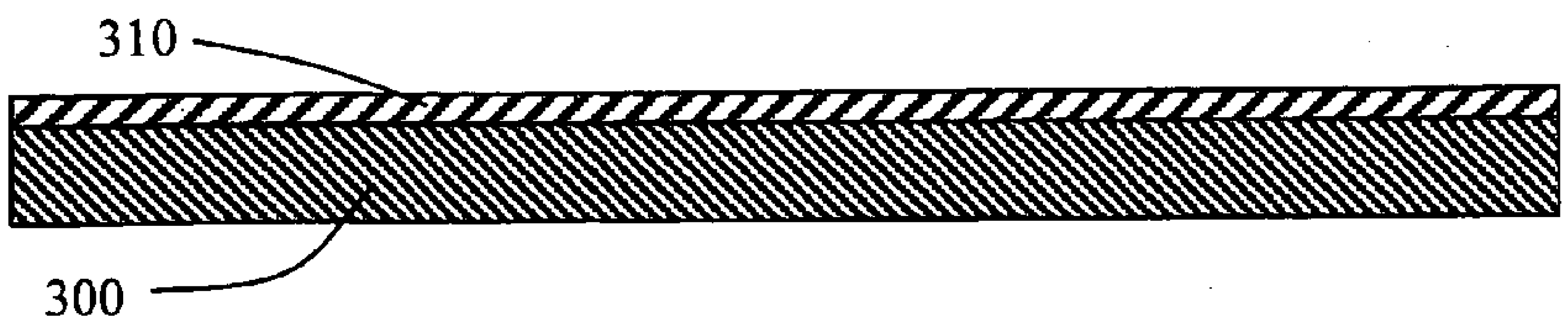


FIG. 3b

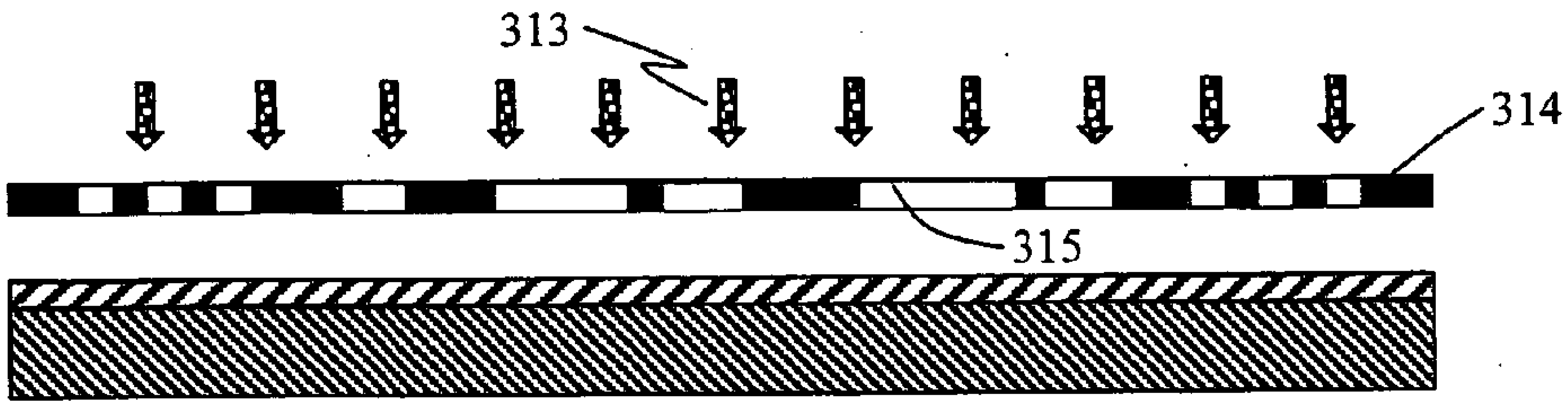


FIG. 3c

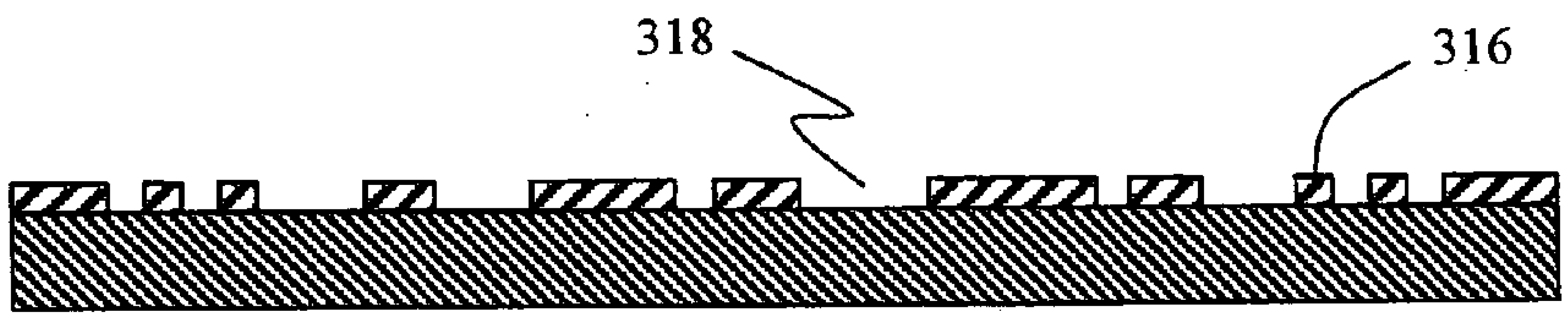


FIG. 3d

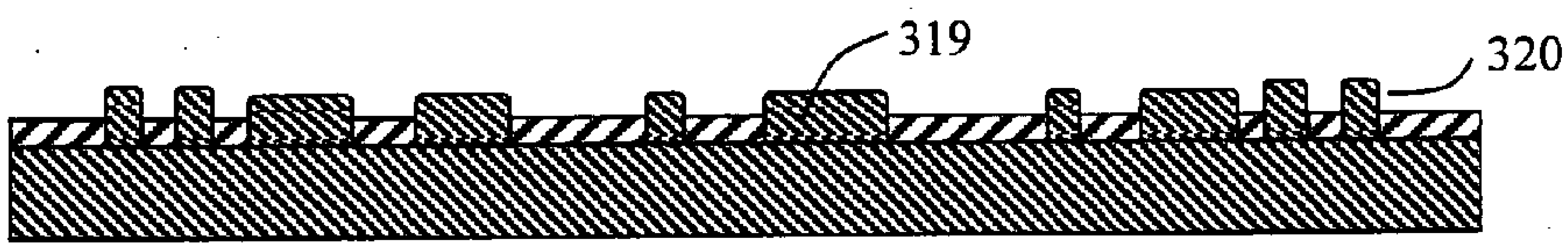


FIG. 3e

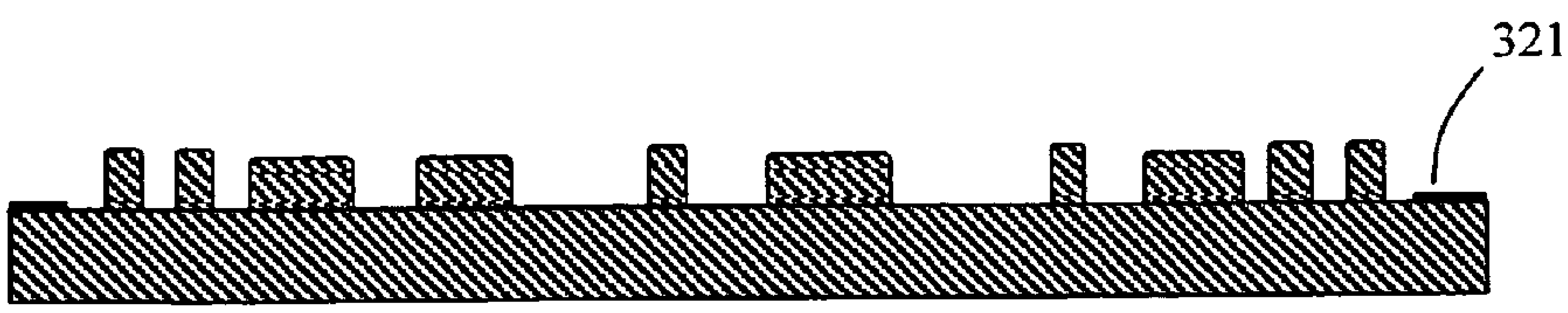


FIG. 3f

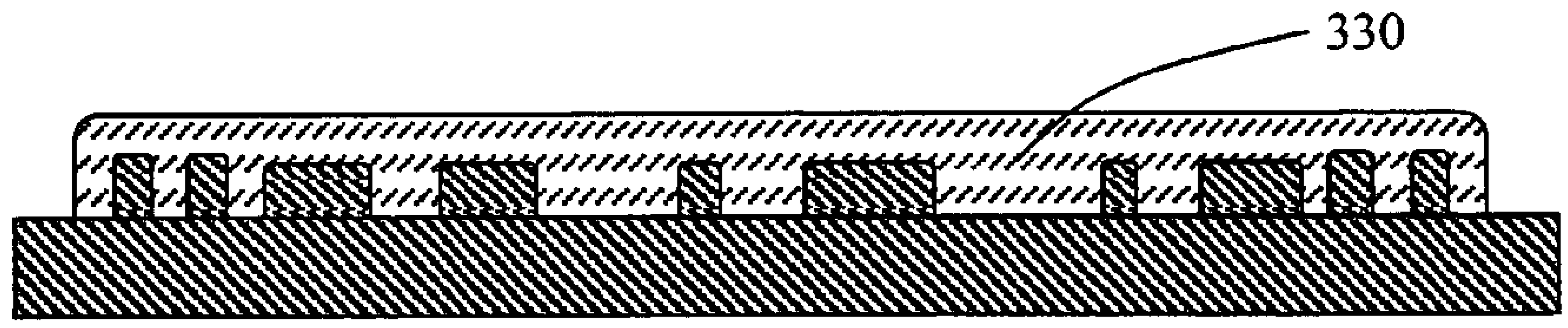


FIG. 3g

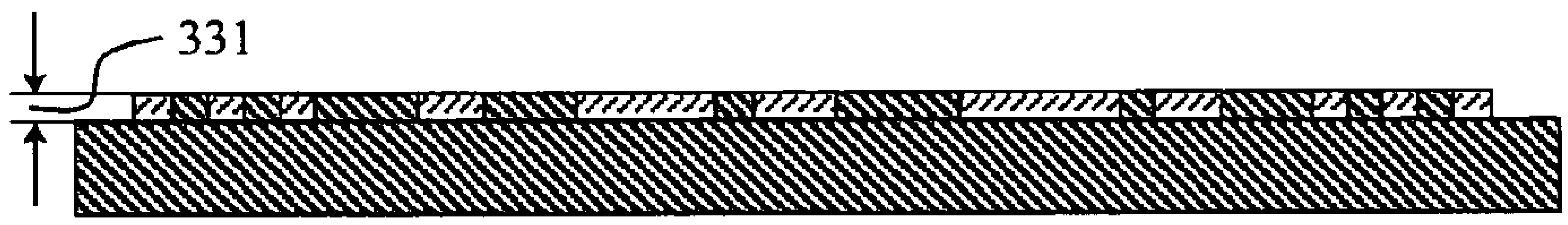


FIG. 3h

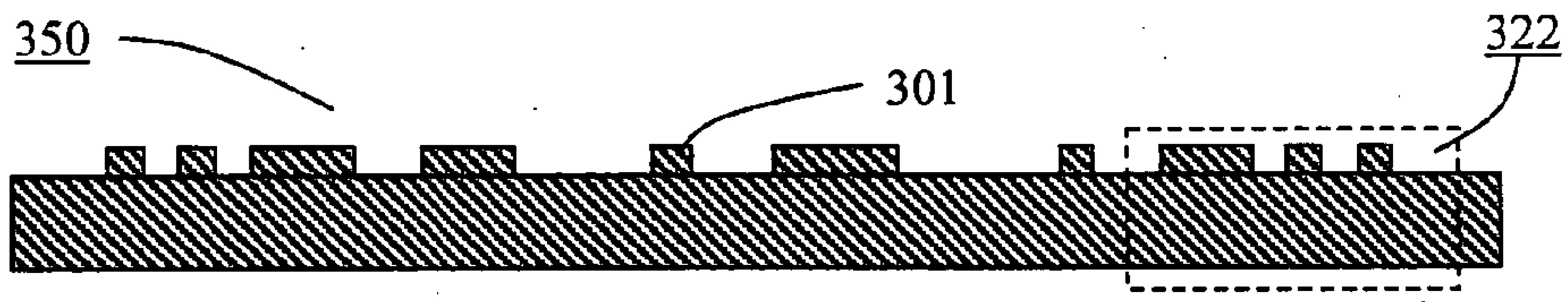


FIG. 3i

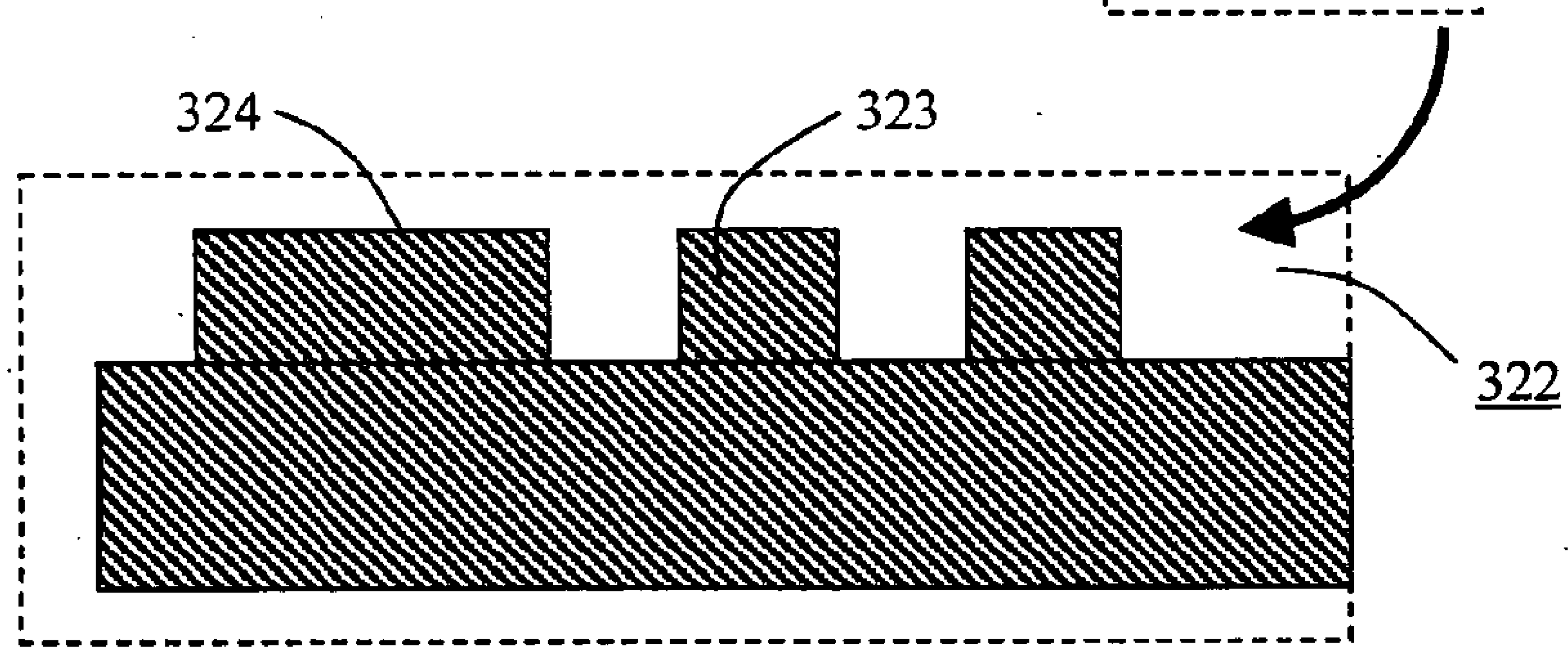


FIG. 3j

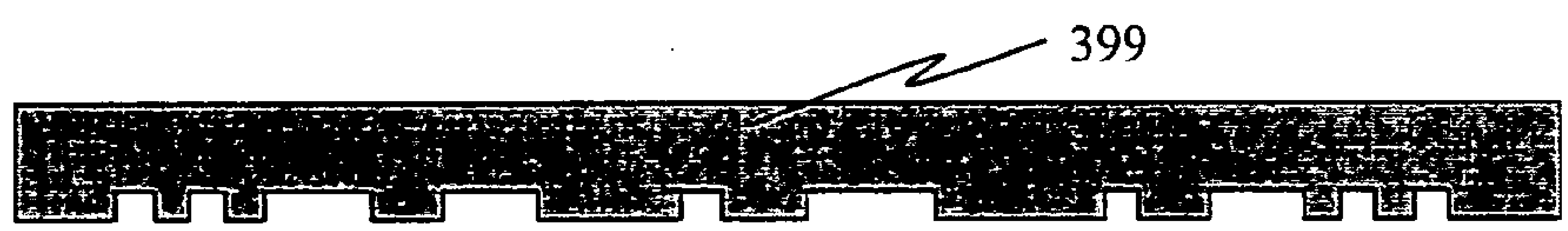


FIG. 4a

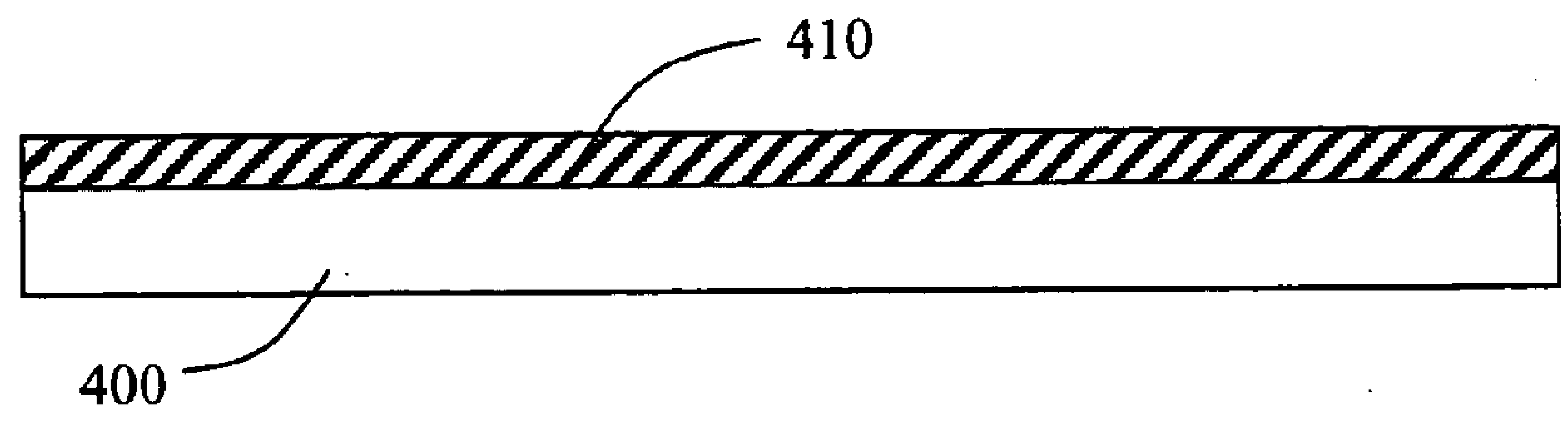


FIG. 4b

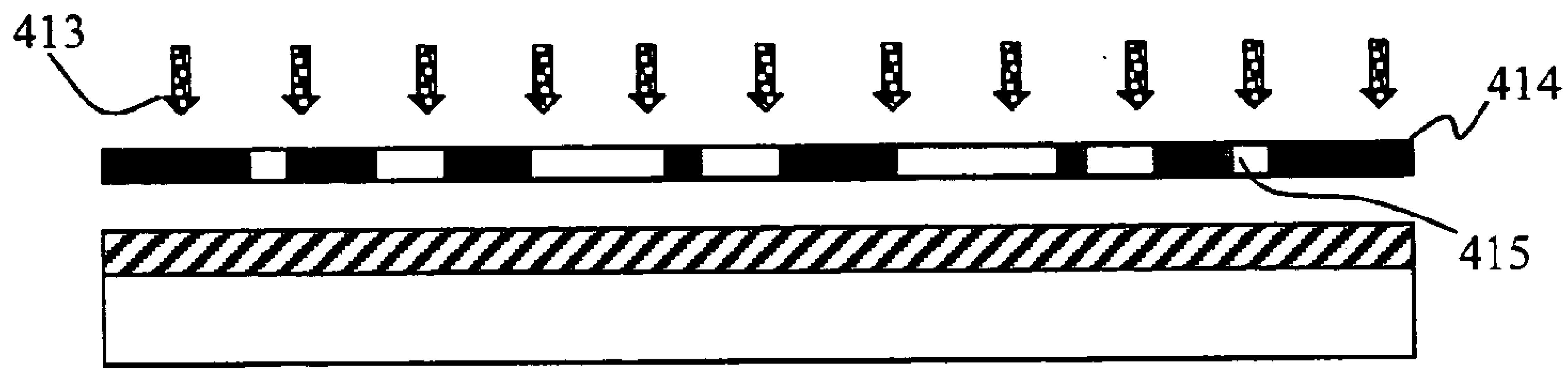


FIG. 4c

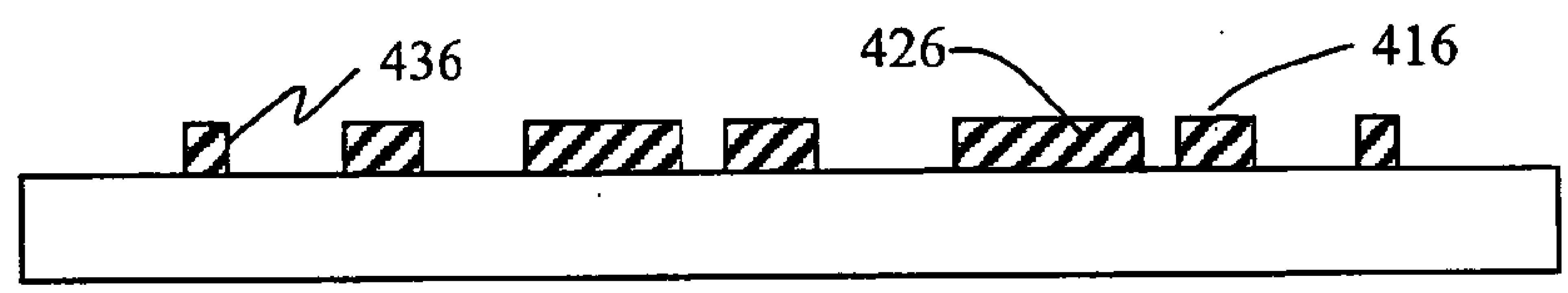


FIG. 4d

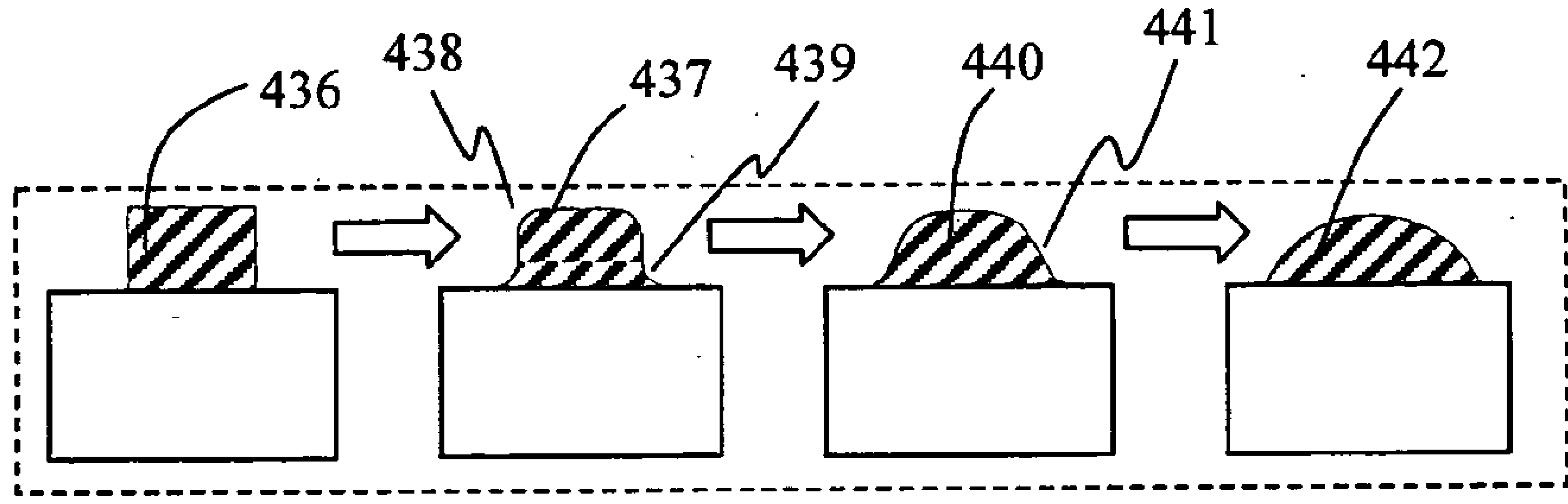


FIG. 4e

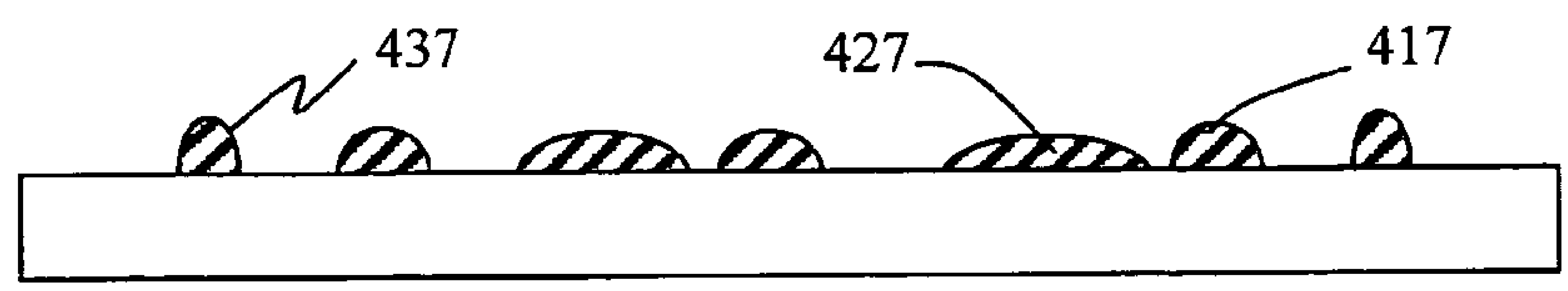


FIG. 4f

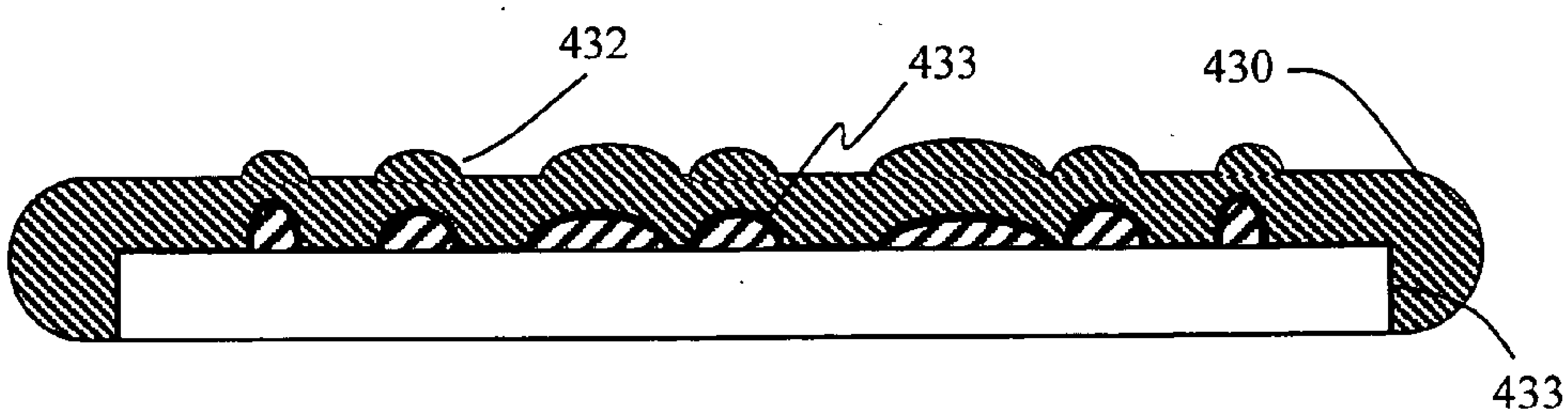


FIG. 4g

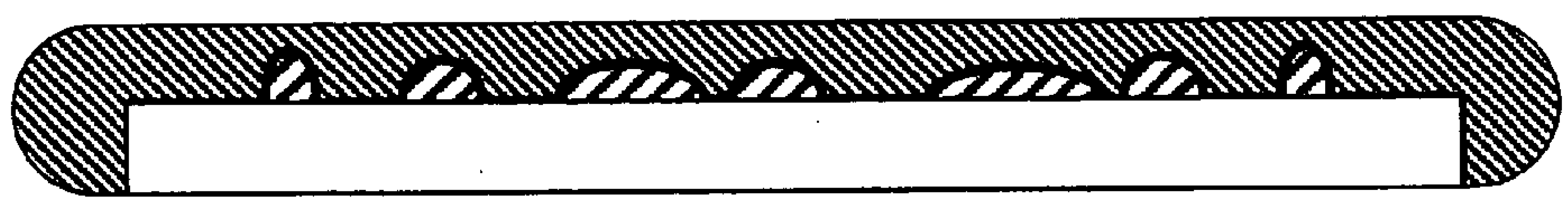


FIG. 4h

FIG. 4i

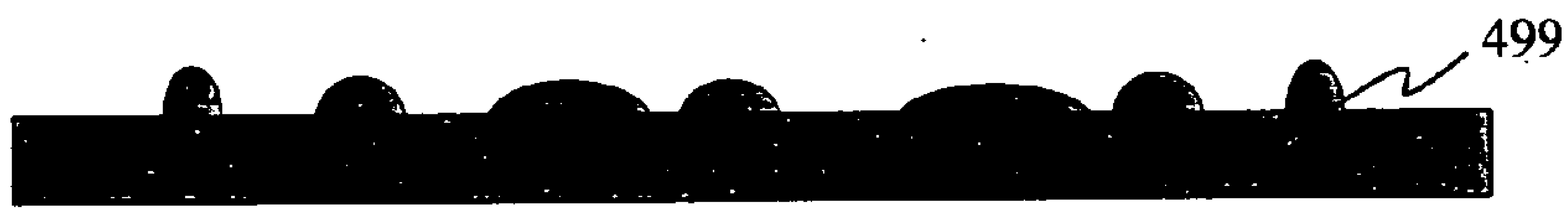


FIG. 5a

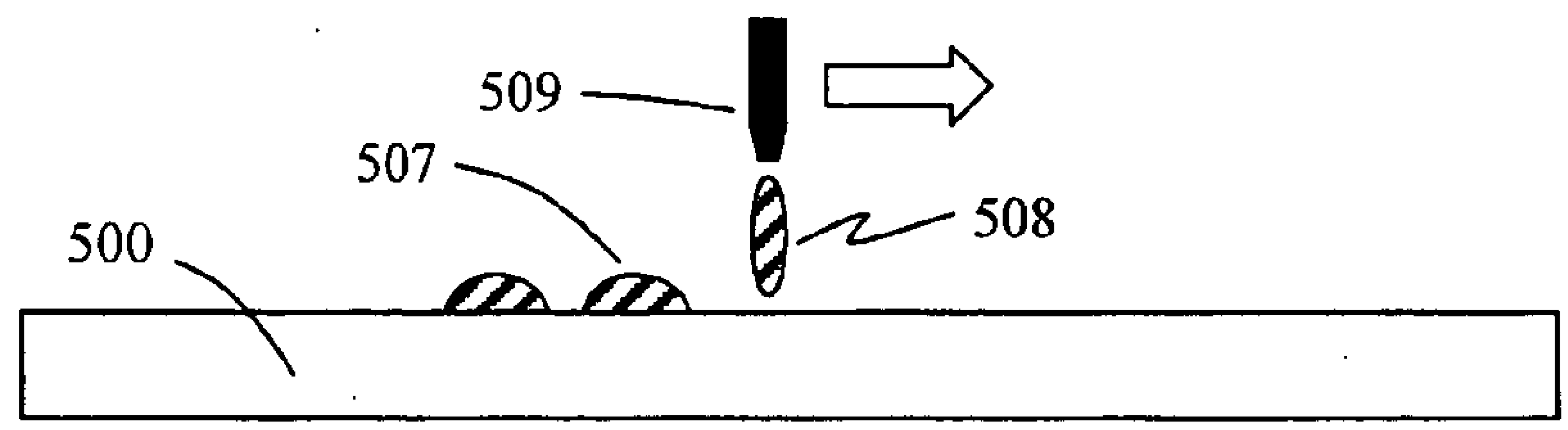


FIG. 5b

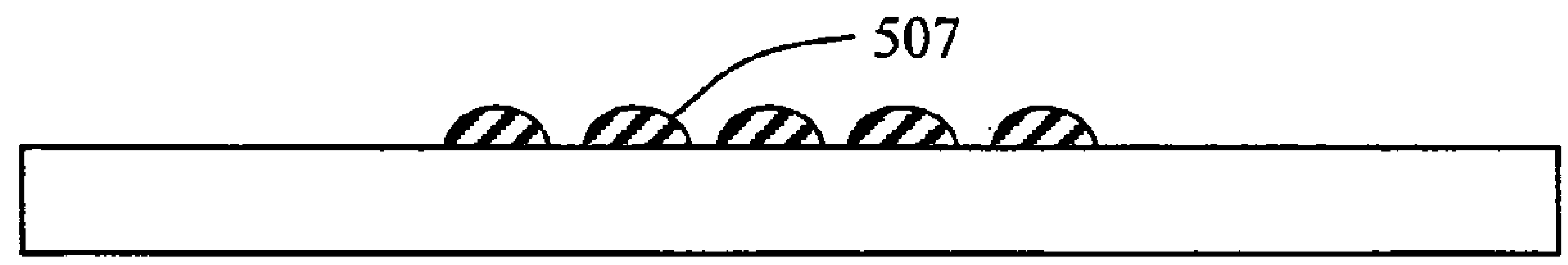


FIG. 5c

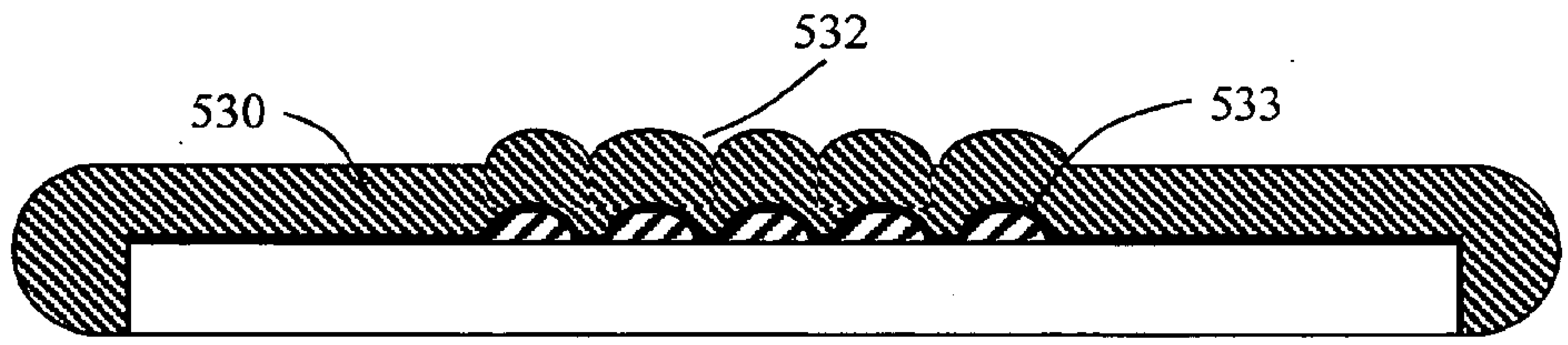


FIG. 5d

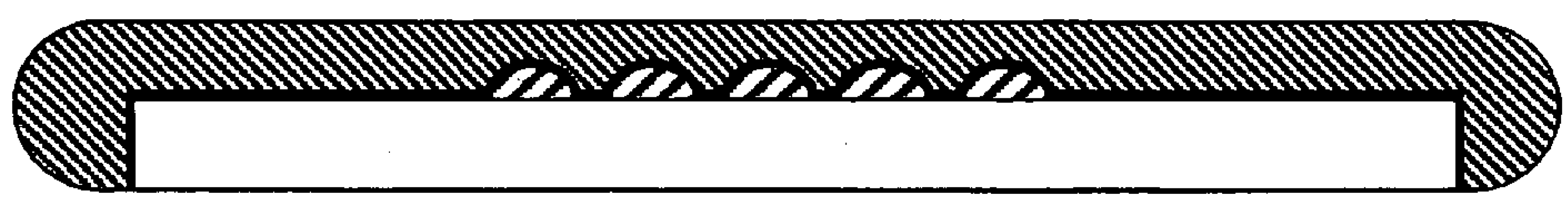


FIG. 5e

FIG. 5f

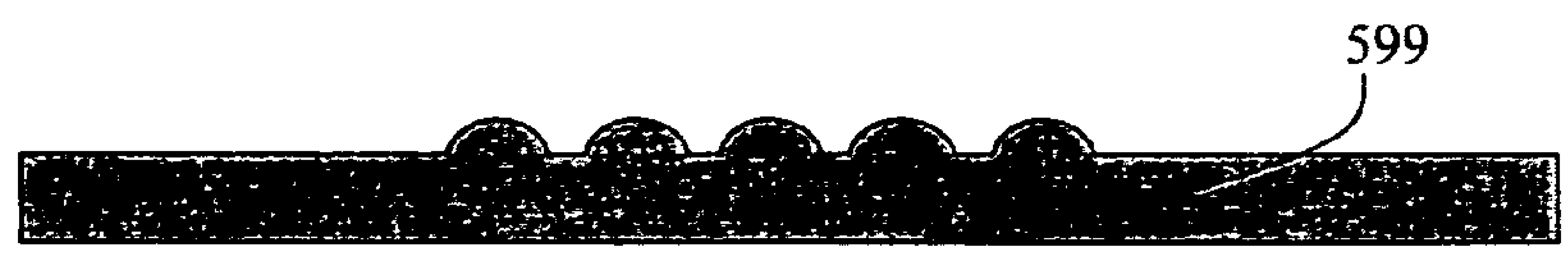


FIG. 6a

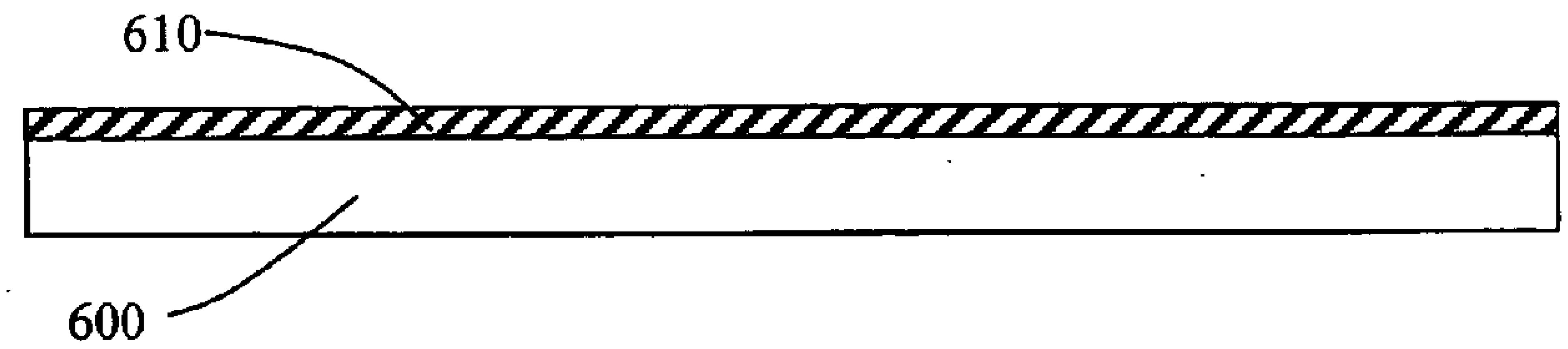


FIG. 6b

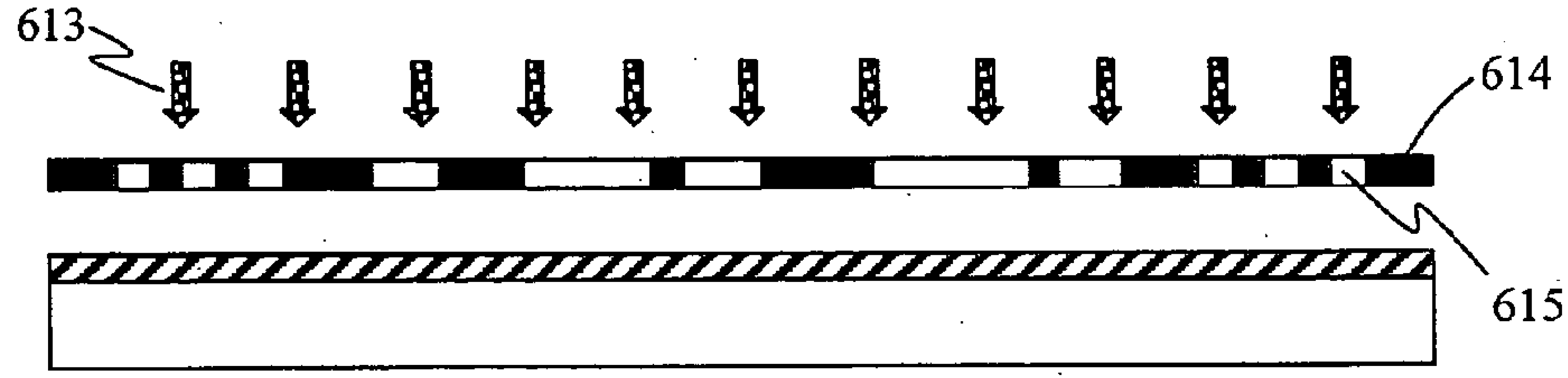


FIG. 6c

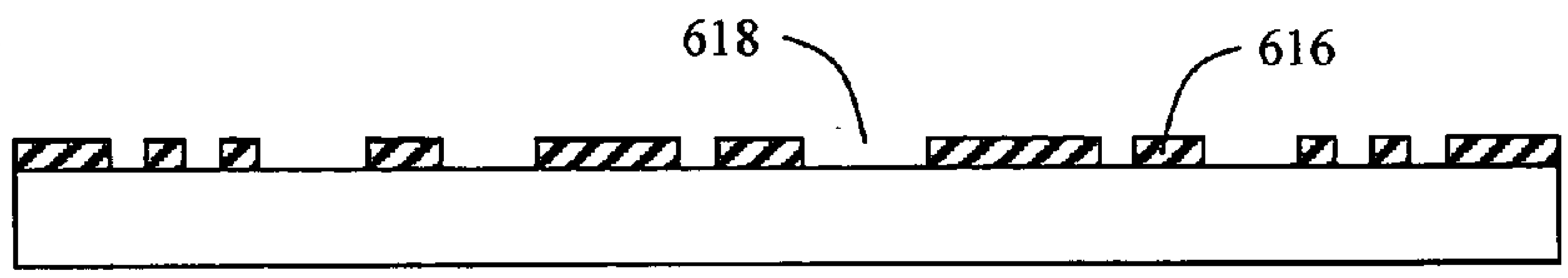


FIG. 6d

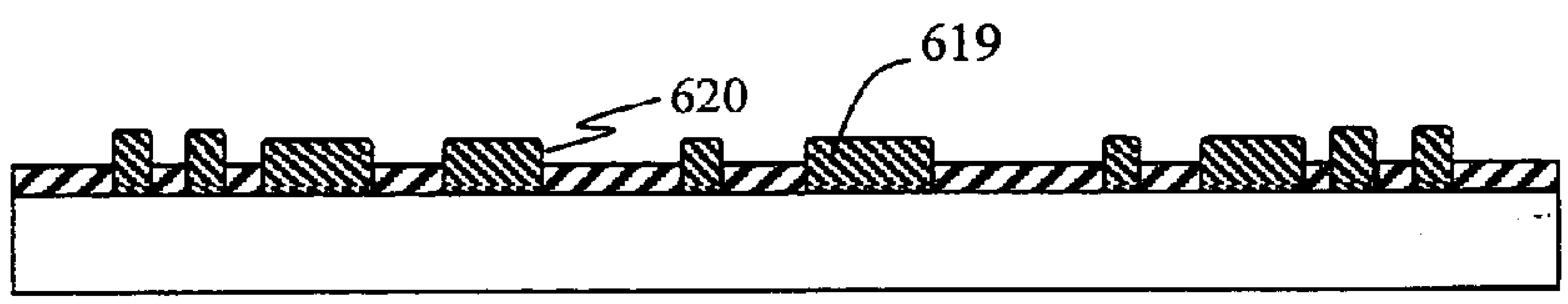


FIG. 6e

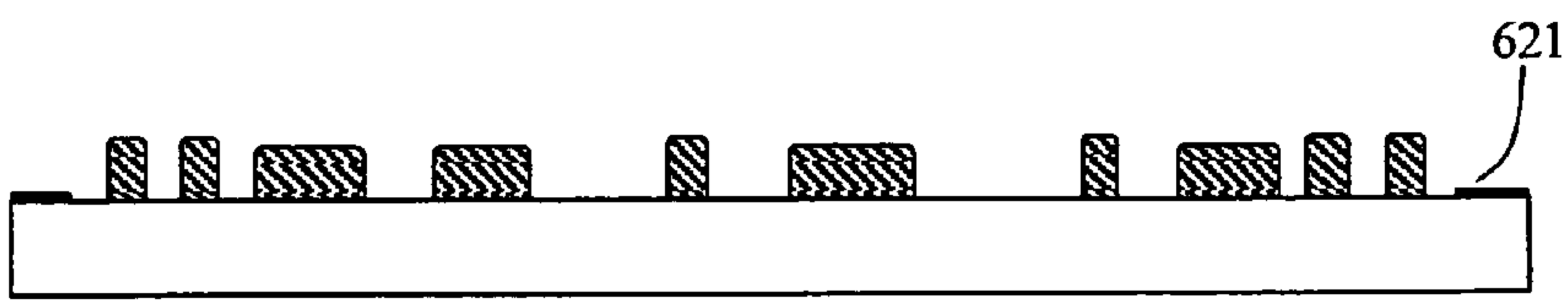


FIG. 6f

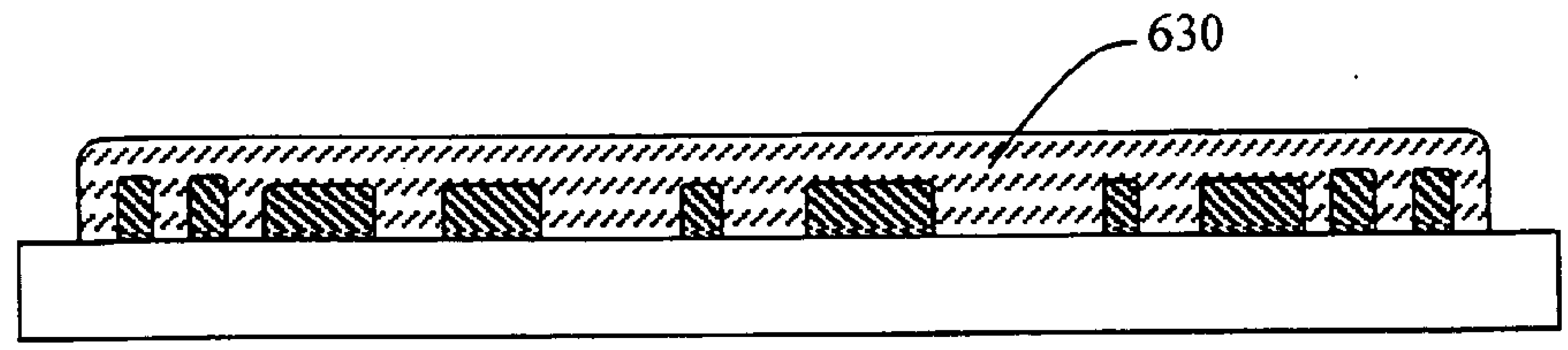


FIG. 6g

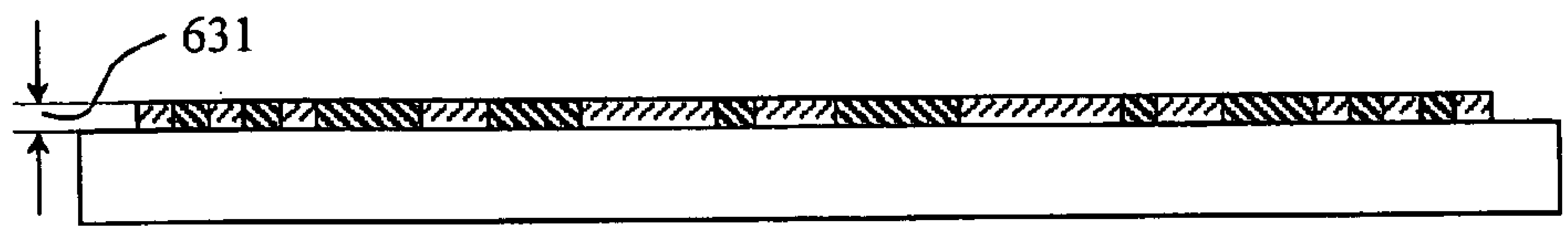
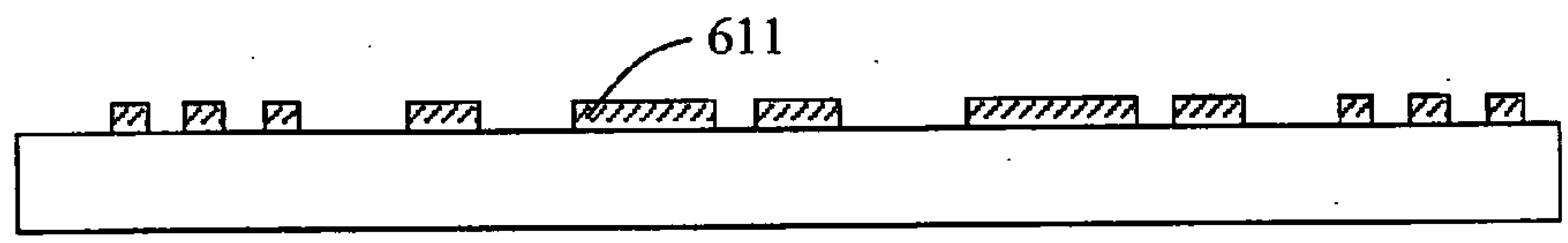


FIG. 6h



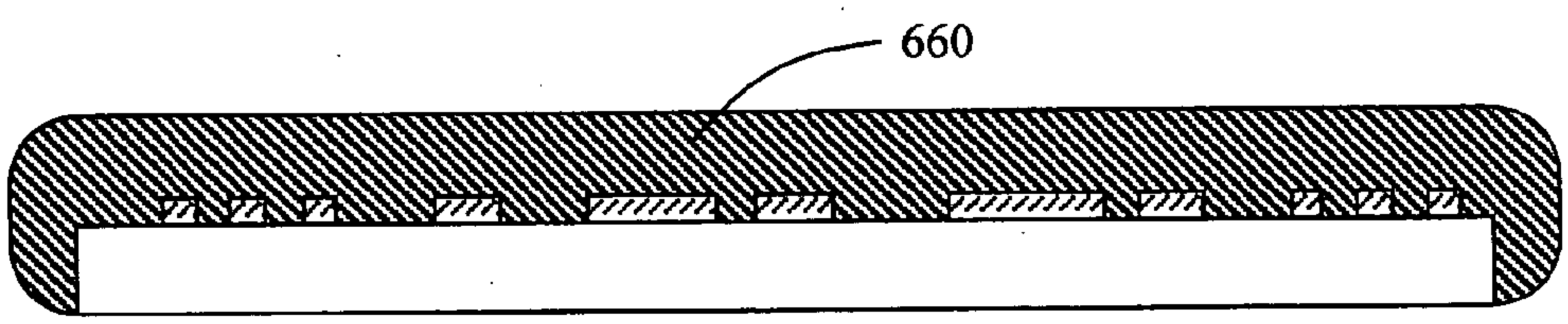


FIG. 6i

FIG. 6j

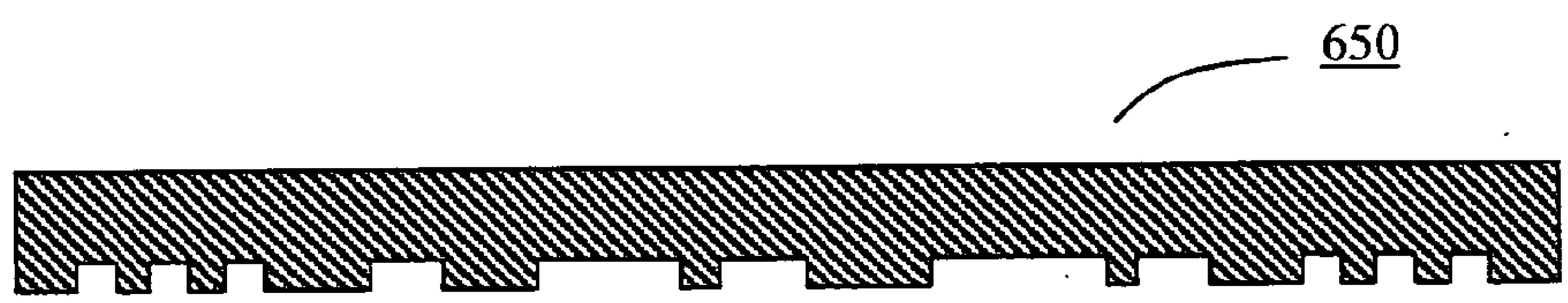
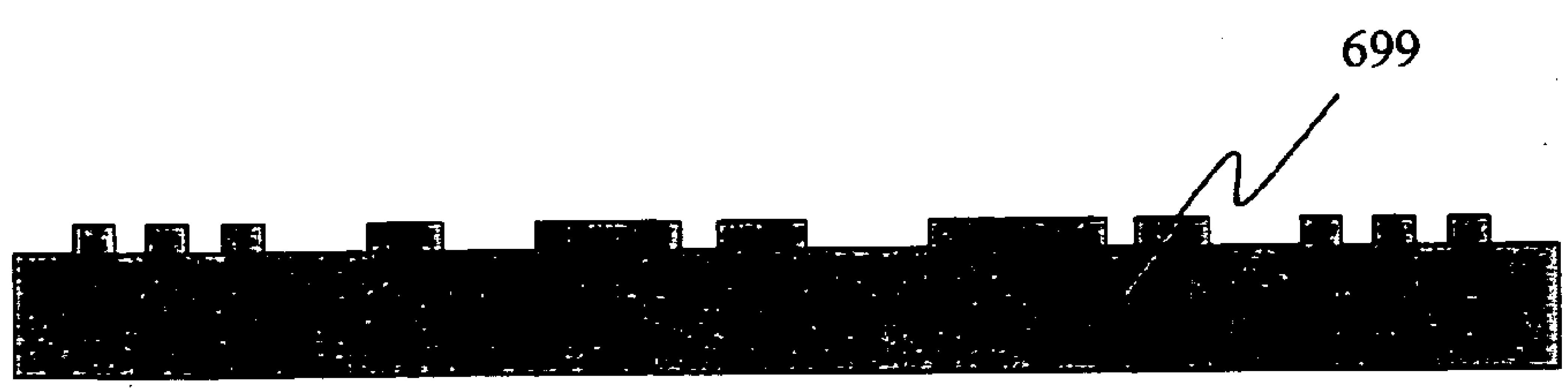


FIG. 6k



MICROFABRICATED STRUCTURES AND PROCESSES FOR MANUFACTURING SAME

CROSS-REFERENCE TO RELATED APPLICATIONS/INCORPORATION BY REFERENCE

[0001] This application claims priority to provisional U.S. Patent Applications Ser. Nos. 60/506,641; 60/506,226; 60/506,321; 60/506,424; and 60/506,635 all filed on Sep. 26, 2003, and all of which are incorporated herein by reference in their entirety.

GOVERNMENT SUPPORT

[0002] The U.S. Government has a paid-up license in this invention and the right in limited circumstances to require the patent owner to license others on reasonable terms as provided for by the terms of grant no. AF F30602-00-1-0569 awarded by the Defense Advanced Research Projects Agency (DARPA).

[0003] This patent application is being filed concurrently with U.S. Patent Applications having attorney docket numbers 200057.00008, 200057.00009, 200057.00010, and 200057.00011, which are incorporated herein by reference in their entirety.

TECHNICAL FIELD

[0004] Embodiments of the present invention generally relate to the fabrication of ultra-high precision master molds for high volume production of microfabricated structures through plastic replication processes like injection molding and hot embossing. Herein is described an approach for fabricating microstructures with extremely uniform features and high surface quality using a two-step electroplating process followed by a planarization approach where one of the metals is used as a sacrificial support structure. This technique is particularly well suited for fabricating rectangular cross-section microstructures as used in microfluidic devices. Nickel Iron (80:20) alloy is introduced as a low stress material for the fabrication of master molds using the process of electroforming. The electroforming process can be used for fabricating microstructures with rectangular cross-sections suited towards microfluidic applications, as well as other shapes more suited for optical applications. Also, a very simple technique for manufacturing a high density microlens array for optical applications is described herein.

BACKGROUND OF THE INVENTION

[0005] MEMS (Micro Electro Mechanical Systems) technology has enabled fabrication of miniaturized devices with applications in a variety of fields like aerospace, medicine and telecommunications. Traditionally most MEMS based devices have been fabricated on Silicon or Glass substrate using the same technology as developed for the microelectronics industry. An example of this is disclosed by Chow et al in U.S. Pat. No. 6,167,910 (incorporated herein in its entirety by reference), wherein a three-dimensional microfluidic device is fabricated by stacking glass/Silicon substrates onto which microchannels for flow confinement have been defined. However, specifically for microfluidic and more specifically for BioMEMS related applications, Silicon and Glass were observed to have many limitations in terms of the surface exposed to the fluids and/or biological samples. One specific problem is non-specific adsorption of proteins commonly encountered in biological samples. Considerable care and conditioning are required to use Silicon or glass substrates in such applications. Furthermore, Silicon and Glass are processed using the so-called "serial process" wherein, for some of the processing steps, each substrate is processed individually (even if it forms part of a batch). With the high intrinsic cost of these substrates, the serial processing further adds to the cost of the device.

[0006] Hence, there has been considerable interest in using polymer or plastic substrates for MEMS and BioMEMS applications. The appropriate plastics offer numerous advantages such as low-cost, high durability, high strength, and excellent biocompatibility characteristics. Another area where plastic devices are obviously suited is Optical MEMS wherein optical transmission characteristics with respect to a range of wavelengths are critical. Polymer/Plastic substrates can be broadly divided into two categories: thermoplastic materials, which deform when heated, and thermoset materials, which solidify after heating. Amongst the two, thermoplastics have gained wider acceptance owing to the ability of using mass-manufacturing techniques such as injection molding and embossing. A notable exception to this is the use of Poly-dimethylsiloxane (PDMS), which is a thermoset material for rapid-prototyping of microfluidic devices as described in U.S. Pat. No. 6,686,184 and WO02100542A1, incorporated herein in their entirety by reference.

[0007] The most common approach to fabricate plastic microfluidic devices is to create a "master mold" and a suitable replication technique such as hot embossing or injection molding to transfer the pattern to a thermoplastic substrate. In earlier approaches, again Silicon was used as the material for the master mold and the desired features were formed by either wet-chemical etching or deep reactive ion etching (DRIE) as described in U.S. Pat. No. 6,136,243 and as discussed by G. Kovacs, Micromachined Transducers Sourcebook, WCB-McGraw Hill, New York, 1998. However, Silicon master-mold cannot be easily used with injection molding equipment due to processing complexities and the relatively fragile nature of the Silicon substrate. Silicon substrates are most commonly limited to replication with hot-embossing techniques as described in WO4022302A3 (incorporated herein in its entirety by reference). Hot embossing is an inherently slow-process and cannot match the short-cycle times of injection molding.

[0008] The most commonly accepted substrate material for injection molding is some form of a metallic substrate. Metallic substrates offer the desired strength and machining characteristics required for injection molding equipment. A common technique for creating master molds is the use of high-precision milling tools to define precise features onto a metal substrate. However, the milling process is limited in terms of achievable feature size and aspect ratio (the ratio of height to width for a microstructure). UV-LIGA is another one of the commonly used techniques to form micro fabricated master molds. It involves creating a mold from a photoresist, deposited onto a substrate, using photolithography followed by electroplating within the photoresist mold. After electroplating, the photoresist mold is dissolved using suitable solvents and the electroplated metal pattern (usually of the same material as the substrate) acts as a master mold for plastic replication.

[0009] One of the difficulties in this method is the fabrication of structures that do not have a rectangular cross-section. One example of such a structure being the hemi-spherical shape required to fabricated lenses or an array of microlenses for optical MEMS applications. A possible solution to this problem is offered by the use of the so-called "gray-scale" lithography techniques, wherein different sections of the photoresist are exposed to continuously varying UV energy thereby allowing for the formation of "sloped" or "rounded" features as described in U.S. Pat. No. 6,410,213 (incorporated herein in its entirety by reference).

[0010] Another major drawback in UV-LIGA based master mold fabrication is non-uniform electroplating thickness in photoresist mold patterns having different dimensions (specifically different widths). Due to the process described as "current-crowding", the plating rate is faster in channels with smaller widths than in channels with higher widths due to the concentrated current flux in narrow channels. This may give rise to problems where the microstructure needs to be very accurately defined e.g. in microfluidic applications. Furthermore, another problem of the current-crowding effect is the non-uniform cross-sectional profile achieved after electroplating, wherein typically (along the cross-section) the center of the microstructure is plated to a lower height as compared to the edges of the microstructure. This problem is discussed clearly in JP1165794A2 (incorporated herein in its entirety by reference), wherein a sharpened anode was used to plate within a narrow feature, and pulled out at approximately the same rate as the plating occurred. Though, this approach allows for uniform plating, it is fairly complex to set it up and may not be suitable for plating large areas.

[0011] Another method for creating master molds is by using the techniques of electroforming. In this approach, a photoresist mold is created on a dummy substrate. Alternately, the mold pattern can also be directly etched into the dummy substrate using wet chemical etching, electro-discharge machining (EDM) or conventional micro-milling. Following this, a metal seed layer is deposited on the photoresist (or substrate) mold and an appropriate metal is electroplated beyond the thickness of the mold. In most cases (for microfabricated master molds), the electroformed metal is plated to a thickness of <1 mm and then peeled off the dummy substrate. The concept of electroforming is certainly not new as illustrated by applications (JP54067561A2) dating back to 1979. The process of electroforming is well known to those skilled in the art and extensively described in WO03041934A1 and JP62111755A2, incorporated herein in their entirety by reference, amongst others.

[0012] One of the primary issues in electroforming is stress control. When a metal is electroplated to large thicknesses, the tensile and compressive stresses dominate the final electroform shape. If the stress is not controlled properly, the electroformed master mold is severely distorted making it useless for plastic replication. This issue has limited the use of electroforming techniques for injection molding applications.

[0013] On the other hand, electroforming techniques offer the advantage of non-rectangular cross-sections that are suitable for plastic replication techniques. Specifically, if a master mold feature is wider at the top than the bottom, it is not possible to injection mold (or emboss) a copy of it since the mold pattern will be "stuck" into the plastic substrate. However, when the master mold pattern is narrower at the top, it is easier to separate the master mold and the replicated plastic part. Such profiles are very difficult to create (except by using complex gray-scale lithography techniques as explained earlier) using UV-LIGA techniques. An innovative approach is described in JP2297409A2 (incorporated herein in its entirety by reference), wherein the photoresist mold is heated beyond the heat resistance temperature of the photoresist thereby causing reflow of the photoresist, leading to tapered structures, which are narrower at the top. Electroforming is done over the reflowed photoresist mold to create a master mold especially designed for easy separation of the master mold from replicated plastic.

[0014] For Optical MEMS applications, an array of recessed semi-spherical cavities within the master mold can be used to replicate Piano-Convex microlens arrays onto the replicated plastic. Several innovative approaches have been used to create this pattern in a master mold designed for electroforming. For example, in WO03041934A1 and JP1212789A2 (incorporated herein in their entirety by reference), the dummy substrate is directly machined to form suitable shapes and then the master mold is electroformed over it. U.S. Pat. No. 5,705,256 (incorporated herein in its entirety by reference), discloses a technique wherein, the recessed cavities are defined by isotropic, wet chemical etching- and subsequently used for electroforming of the master mold and yet another approach is described in U.S. Pat. No. 6,436,265 (incorporated herein in its entirety by reference). JP2001290006A2 (incorporated herein in its entirety by reference), discloses a method wherein the microlenses are formed directly onto a flat plastic substrate by depositing a controlled amount of another plastic material and heating the deposited plastic to its reflow temperature thereby forming the microlens array.

[0015] Finally, an issue of concern in master molds created using either UV-LIGA or electroforming techniques, is the surface roughness of the microstructures. For most BioMEMS applications, increased surface roughness leads to poor performance; specifically in the case of Capillary Electrophoresis (CE) chips, wherein poor surface quality can render the chip unusable for separation applications. Obviously, for Optical MEMS applications, even slight surface imperfections can lead to deviation in the optical path characteristic ergo, poor device performance.

[0016] For injection molding, the typical setup includes an arrangement to inject molten plastic material into a mold block. The mold block contains the features to be replicated. In most cases, the master mold is fabricated either as an integral part of the mold block or as a component, which can be assembled into the mold block. Obviously, when microfabrication techniques, such as UV-LIGA, are used the master mold is always an independent piece that is assembled into the mold block as explained in R. Trichur et al. in the Proceedings of the 6th International Conference on Micro Total Analysis Systems (micro-TAS 2002), Nara, Japan, Nov. 3-7, 2002, pp. 560-562, and A. Puntambekar et al. in Proceedings of the 6th International Conference on Micro Total Analysis Systems (micro-TAS 2002), Nara, Japan, Nov. 3-7, 2002, pp. 422-424 and J.-W. Choi et al. in

Proceedings of the 5th International Conference on Micro Total Analysis Systems (micro-TAS 2001), Monterey, Calif., Oct. 21-25, 2001, pp. 411-412.

SUMMARY OF THE INVENTION

[0017] Certain embodiments of the present invention seek to address the shortcoming listed above to develop a master mold for plastic replication with precisely defined microstructures and ultra-low surface roughness. Also, modifications to the electroforming process are disclosed to make it more amenable towards fabrication of master molds for injection molding. Finally, a simple yet elegant approach is presented to fabricate a master mold for microlens arrays on plastic substrates.

[0018] Disclosed herein is an embodiment of a two-step electroplating technique, wherein the height of the microstructures on the master mold is controlled precisely using a polishing step after electroplating of the microstructures. The structural integrity of the microstructures is preserved by the use of a second sacrificial support metal which is also electroplated, following the first electroplating step. The second sacrificial metal is selectively etched out after the polishing step. The polishing step ensures that all the microstructures are of uniform height (across the entire substrate) and furthermore each microstructure is exhibits uniform height along its cross-sectional profile. The polishing step also ensures that the surface roughness of the microstructures is minimized to yield high-quality replicated features.

[0019] Also disclosed herein are embodiments for making modifications to the electroforming technique to make it suitable for master mold fabrication for injection molding applications. More particularly, certain embodiments of the present invention use Nickel-Iron (80:20) alloy as a low stress material extremely suitable for electroforming where the stress can be controlled easily just by adjusting the current density, temperature, pH, and composition of the electroplating bath to obtain electroforms that are suited as master molds for plastic replication. Previously, Nickel-Iron (80:20) electroplating has been used to develop soft magnetic material due to this material's excellent magnetic properties. This is the first application where the alloy is used as a structural component of the master mold. Other modifications to the electroforming process will be apparent in the section entitled "Detailed Description of the Invention".

[0020] Certain embodiments of the present invention provide an elegant solution to creating a negative image of an array of Piano-Convex microlenses on a master mold and subsequently replicating the Plano-Convex lens array structure on the plastic substrate.

[0021] Embodiments of the present invention overcome the deficiencies and inadequacies in the prior art as described in the previous section and as generally known in the industry.

[0022] Certain embodiments of the present invention are concerned with developing a master mold for plastic replication, wherein the master mold is a discrete component, which can be easily assembled into the injection mold block for plastic replication.

[0023] Certain embodiments of the present invention are concerned with developing a master mold using a modified UV-LIGA fabrication process, specifically the two-step electroplating process with one of the electroplating used for sacrificial metal deposition, to create master molds with microstructures of uniform height across the entire master mold.

[0024] Other embodiments of the present invention are concerned with developing a master mold using a modified UV-LIGA fabrication process, specifically the two-step electroplating process with one of the electroplating used for sacrificial metal deposition, to create master molds wherein, the microstructures have uniform height across their cross-section.

[0025] Certain embodiments of the present invention are concerned with developing a master mold using a modified UV-LIGA fabrication process, specifically the two-step electroplating process with one of the electroplating used for sacrificial metal deposition, to create master molds with surface roughness less than 50 nanometers (nm).

[0026] Certain embodiments of the present invention are concerned with developing a master mold suitable for replication of microfluidic structures onto a plastic substrate.

[0027] Alternate materials have been investigated for the electroforming process thereby allowing for fabrication of very thick (more than 0.5 mm) electroforms.

[0028] Certain embodiments of the present invention are concerned with developing a fabrication process, using the alternate materials, for fabricating planar electroforms with minimal bending and/or curvature along the diameter of the master mold.

[0029] Certain embodiments of the present invention are concerned with developing a master mold suitable for replication of a microlens array onto a plastic substrate.

[0030] Certain embodiments of the present invention are concerned with developing a simplified process for the fabrication of the microlens array on a plastic substrate by replication techniques.

[0031] Other embodiments, features and advantages of the present invention will become apparent from the detailed description of the invention when considered in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0032] FIGS. 1*a*-1*b* are schematic sketches illustrating the replaceable mold disk technology and also shows actual photographs of the mold block and master mold with microfabricated features, in accordance with various embodiments of the present invention.

[0033] FIGS. 2*a*-2*g* are schematic sketches explaining the UV-LIGA process normally used for master mold fabrication.

[0034] FIGS. 3*a*-3*j* are schematic sketches explaining the sequence of steps used for fabricating the master mold using the two-step electroplating technique, in accordance with an embodiment of the present invention.

[0035] FIGS. 4*a*-4*i* are schematic sketches explaining the sequence of steps used for fabricating the master mold using the electroforming approach, in accordance with an embodiment of the present invention.

[0036] **FIGS. 5***a*-**5***f* are schematic sketches explaining the fabrication process for the manufacture of the master mold and subsequently the plastic replica with an array of microlenses, in accordance with an embodiment of the present invention.

[0037] **FIGS. 6***a*-**6***k* are schematic sketches showing the sequence of steps in the modified electroforming process for the manufacture of a highly accurate and precise master mold, in accordance with an embodiment of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

[0038] Broadly stated, certain embodiments of the present invention provide two technologies intended for developing master molds for plastic replication using injection molding techniques. The first part herein discloses an embodiment of a two-step electroplating/polishing approach wherein, one of the electroplated metals is used as a sacrificial support layer during polishing. The second part herein describes embodiments that provide modifications to the electroforming process, specifically: (a) the use of Nickel-Iron (80:20) as a structural component; (b) modifications to the electroplating bath for generating low-stress electroforms; and (c) modifications to the sequence of steps followed during electroforming for fabricating a uniform electroform. Also disclosed in the second part herein is the use of thermal treatment to the photoresist mold to generate an array of microlens pattern on the master mold. The second part herein also discloses a simplified fabrication process for manufacturing an array of microlenses on the master mold using electroforming techniques. Finally, a combined fabrication process that uses the electroforming approach after the two-step electroplating and planarization (or polishing) technique is disclosed for the fabrication of robust master molds suitable for high volume productions.

[0039] Definitions

[0040] The process of "Microfabrication" as described herein relates to the process used for manufacture of micrometer sized features on a variety of substrates using standard microfabrication techniques as understood widely by those skilled in this art. The process of microfabrication typically involves a combination of processes such as photolithography, wet etching, dry etching, electroplating, laser ablation, chemical deposition, plasma deposition, surface modification, injection molding, hot embossing, thermoplastic fusion bonding, low temperature bonding using adhesives and other processes commonly used for manufacture of MEMS (microelectromechanical systems) or semiconductor devices. "Microfabricated" or "microfabricated devices" as referred to herein refers to the patterns or devices manufactured using the microfabrication technology.

[0041] The term "BioMEMS" as used herein describes devices fabricated using MEMS techniques specifically applied towards biochemical applications. Such applications may include detection, sample preparation, purification, isolation etc. and are generally well know to those skilled in the art. One such technique that is commonly used in BioMEMS applications is that of "Capillary Electrophoresis" (CE). CE refers to the process wherein an electrical field is applied across a liquid column leading to the separation of its constituents based on their mass/charge ratio. The term "CE Chips" refers to microfluidic BioMEMS devices specifically used for CE applications.

[0042] The term "Optical MEMS" as used herein describes devices fabricated using MEMS techniques specifically applied towards optical applications. The term "MOEMS", which is an abbreviation for "Micro-Opto-Electro-Mechanical-Systems", is also used interchangeably with "Optical MEMS" herein.

[0043] The term "chip", "microchip", or "microfluidic chip" as used herein means a microfluidic device generally containing a multitude of microchannels and chambers that may or may not be interconnected with each another. Typically, such biochips include a multitude of active or passive components such as microchannels, microvalves, micropumps, biosensors, ports, flow conduits, filters, fluidic interconnections, electrical interconnects, microelectrodes, and related control systems. More specifically the term "biochip" is used to define a chip that is used for detection of biochemically relevant parameters from a liquid or gaseous sample. The microfluidic system of the biochip regulates the motion of the liquids or gases on the biochip and generally provides flow control with the aim of interaction with the analytical components, such as biosensors, for analysis of the required parameter.

[0044] The term "microstructure" as used herein, describes a structure created using well-known microfabrication processes wherein at least one of the dimensions of the microstructure ranges from 1 μm to 1000 μm. In the case of microfluidic devices, the microstructures may be referred to as "microchannels" or simply "channels" whereas for Optical MEMS devices, the microstructures may be referred to as "microlens" or "microlens array". It is to be understood that "microstructures" is a generic term whereas more specific terms are used in contexts where the microstructures are used for a specific application. Microstructures are generally characterized by their "aspect ratio", which used herein describes the ratio of the height to width of the microstructure. The term "surface roughness" refers to the root mean square (rms) value of surface irregularity for the surface of the microstructure which extends out of the plane of the substrate and is parallel to the plane of the substrate. The term "cross-section" as used herein follows the commonly accepted meaning, specifically the area created by a plane cutting through the microstructure.

[0045] The term "microchannel" as used herein refers to a groove or plurality of grooves created on a suitable substrate with at least one of the dimensions of the groove being in the micrometer range. Microchannels can have widths, lengths, and/or depths ranging from 1 μm to 1000 μm. It should be noted that the terms "channel" and "microchannel" are used interchangeably in this description. Microchannels can be used as stand-alone units or in conjunction with other microchannels to form a network of channels with a plurality of flow paths and intersections.

[0046] The term "microfluidic" generally refers to the use of microchannels for transport of liquids or gases. The microfluidic system consists of a multitude of microchannels forming a network and associated flow control components such as pumps, valves and filters. Microfluidic systems are ideally suited for controlling minute volumes of liquids or gases. Typically, microfluidic systems can be designed to handle fluid volumes ranging from picoliter to milliliter ranges.

[0047] The term "microlens" as used herein refers to a physical configuration on the substrate that can be used for focusing or diverging an incident beam of light, and where at least one dimension of the microlens ranges from 1 μm to 1000 μm. The term "microlens array" is used herein to describe a plurality of microlenses wherein at least 2 microlenses are fabricated in close proximity of each other. The microlens array may be symmetric (i.e. a 2×2 or a 4×4 etc. arrangement of microlenses) or asymmetric (i.e. a 2×1 or a 5×2 etc. arrangement of microlenses). The term "Plano-Convex" describes a lens structure wherein one side of the lens is flat and the other side has a convex structure.

[0048] The term "substrate" as used herein refers to the structural component used for fabrication of the micrometer sized features using microfabrication techniques. A wide variety of substrate materials are commonly used for microfabrication including, but not limited to; silicon, glass, polymers, plastics, ceramics to name a few. The substrate material may be transparent or opaque, dimensionally rigid, semi-rigid or flexible, as per the application they are used for. Generally, microfluidic devices consist of at least two substrate layers where one of the faces of one substrate layer contains the microchannels and one face of the second substrate is used to seal the microchannels. The terms "substrate" and "layer" are used interchangeably in this description. Also, the terms "plastics" and "polymers" are used interchangeably. It is to be understood that the terms "plastics" or "polymers" encompass thermoplastics (material which deform when pressurized at elevated temperatures), thermosets (materials which "set" or attain final shape at elevated temperatures) as well as two-part polymers (that are mixed for curing). The choice of the plastic substrate is dictated by the application area of the MEMS device (e.g. for BioMEMS application; biocompatibility is an important criteria; whereas optical transmission properties may be of greater importance for MOEMS applications) and not limited to a particular material or even a set of materials.

[0049] The term "dummy substrate" as used herein refers to a substrate that is used in the fabrication process and is selectively destroyed as a part of the fabrication process such that it does not constitute a part of the final product.

[0050] The term "UV-LIGA" describes a photolithography process modeled on the "LIGA" fabrication approach. LIGA refers to the microfabrication process for creating microstructures with high aspect ratio using synchrotron radiation and thick photoresists (ranging in film thickness from 1 μm to 5 mm). The LIGA process is used to form a template that can be used directly or further processed using techniques such as electroplating to create the microfluidic template. UV-LIGA uses modified photoresists that can be spin coated in thicknesses of 1 μm to 1 mm and are sensitive to UV radiation. UV radiation sources are commonly used in microfabrication facilities and hence UV-LIGA offers a lower cost alternative to LIGA for fabrication of high aspect ratio microstructures.

[0051] The term "current crowding" as used herein refers to the phenomenon wherein the current flux is concentrated in certain areas of the substrate during the electroplating process. Current crowding in turn results in non-uniform electroplating rates.

[0052] The term "reflow" as used herein, refers to the process where a thermoplastic material (such as photoresist) is heated beyond a critical temperature at which stage it starts changing to a liquid phase. Surface tension forces will then alter the shape of the molten thermoplastic material to minimize the free surface energy.

[0053] The term "sacrificial" as used herein refers to a component used during the fabrication process which is only present in intermediate steps of the fabrication process and is completely destroyed in the process such that it does not form a part of the fabricated device.

[0054] The term "chemical mechanical polishing (CMP)" as used herein describes a process wherein a reasonably flat substrate is polished on one or both sides to achieve parallelism between two opposite surfaces as well as desired surface uniformity on one or both surfaces. This process is also referred to as "planarization" and the two terms are used interchangeably in this description.

[0055] The term "electroforming" as used herein carries the same meaning as the conventionally accepted meaning to those skilled in this art. Specifically, it is "An electrochemical process of master mold fabrication using an electrolyte, an anode to supply the metal, and a control of the electrical current and of the deposition of metal onto a suitable mold, which is fabricated on a dummy substrate."

[0056] The term "master mold" as used herein refers to a replication template, typically manufactured on a metallic or Silicon substrate. Specifically herein, "master mold" refers to a metallic mold wherein the microstructures are either an integral part of the master mold or are deposited on one of the surfaces of the master mold. The features of the master mold are fabricated using the UV-LIGA and other microfabrication processes. The microstructures created on the master mold may be of the same material as the master mold substrate e.g. Nickel microstructures on a Nickel substrate or may be a dissimilar material e.g. photoresist on a Silicon surface. The master mold is typically used for creating patterns on a polymer substrate using techniques such as hot embossing, injection molding, and casting.

[0057] The term "bonding" as used herein refers to the process of joining at least two substrates, at least one of which has microfabricated structures, e.g. a microchannel, on its surface to form a robust bond between the two substrates such that any liquid introduced in the microchannel is confined within the channel structure. A variety of techniques can be used to bond the two substrate including thermoplastic fusion bonding, liquid adhesive assisted bonding, use of interfacial tape layers, etc. Specifically, in this description, the terms "bonding" and "thermoplastic fusion bonding" are used interchangeably. Thermoplastic fusion bonding involves heating the two substrates to be joined to their glass transition temperature and applying pressure on the two substrates to force them into intimate contact and cause bond formation. Another bonding process, namely the use of UV-adhesive assisted low temperature bonding, is also described herein and is specifically and completely referred to in all occurrences.

[0058] The intent of defining the terms stated above, is to clarify their use in this description and does not explicitly or implicitly limit the application of embodiments of the present invention by modifications or variations in perception of said definitions.

[0059] Two-step electroplating and planarization technique for master mold fabrication using UV-LIGA process:

[0060] **FIG. 1***a* shows the basic concept of a replaceable master mold disk within the mold block. As shown in **FIG. 1***a*, the injection mold block consists of two halves A **102** and B **103**. Mold Block A **102**, houses the master mold whereas Mold block B **103**, has two cavities opposite to the master molds and the depth of these cavities defines the thickness of the injection molded plastic part. The replaceable master mold **100** contains microfabricated features **101** and is mounted on the A block **102**. The replaceable mold disks are mounted on mounting cylinders **105** as shown in **FIG. 1***b* and the mounting cylinder plus mold disk assembly is positioned within the mold block half A **102** (note that the schematic sketch shows only one mold disk whereas the actual mold block can contain two master molds at the same time). After inserting the mounting cylinders and master mold, the two mold blocks are assembled together and mounted in an injection molding machine (not shown). The injection molding machine contains a hopper to store plastic pellets from which they are fed into an extrusion screw, which is maintained at an elevated temperature. The plastic pellets are melted in the screw and forced out as molten plastic through a nozzle which connects to the inlet in mold block B **103**. The molten plastic is then injected through an inlet **106** in the B block **103** shown in **FIG. 1***b*. The molten plastic fills up the cavity in mold block B **103**. One end of this cavity is exposed to the master mold and the molten plastic will replicate the shape of the master mold. Upon cooling, the plastic part will solidify and is subsequently ejected using ejector pins **104**. It is clear from this description that the microstructures in the plastic part will be a negative image of those on the mold master and using appropriate injection molding conditions very high fidelity reproductions can be achieved. Hence, it is critical that the master mold microstructures are very precisely and accurately defined.

[0061] **FIGS. 2***a*-**2***g* show the conventional UV-LIGA process that is commonly used to make the master mold. As shown in **FIG. 2***a*, initially photoresist **210** is spin-coated onto a (typically) metallic substrate **200**. Most commonly a Nickel substrate is used because of its excellent mechanical properties as well as the ease of subsequent electroplating of Nickel microstructures. The negative photoresist **210**, is exposed to a UV-radiation **213** through opening **215** in a photomask **214**. Next, the exposed photoresist is developed in a suitable developer to retain photoresist in the exposed areas **216**, and washed out to expose the underlying metal layer in the unexposed areas **218**, as shown in **FIG. 2***c* and **FIG. 2***d*. Note that the location of the resist areas and cavities can be reversed by using a positive photoresist, while using the same photomask. Following development, Nickel **219** (or the same metal as the underlying substrate) is electroplated within the cavities of the photoresist mold. After this step, the photoresist mold is dissolved using a suitable solvent to leave behind free standing microstructures **201** as shown in **FIG. 2***f*.

[0062] Although this process or minor variations thereof is very commonly used, it suffers from a couple of serious drawbacks. As shown in the magnified view **212** of **FIG. 2***b*, the spin-coated photoresist does not coat the entire substrate uniformly. Specifically, because of difference in centripetal force experienced during spin-coating and due to surface tension forces at the edge of the wafer, the photoresist tends to form a so-called "edge-bead" along the circumference of the substrate. This problem can be partly circumvented by using alternate coating techniques such as spray-coating or dip-coating but these techniques are not widely accepted in the art.

[0063] Another and more serious problem is due to the phenomenon of current crowding. In the electroplating setup, the anode is (typically) approximately equal in area and dimensions to the substrate (which acts as the cathode in the electrochemical reactions involved in electroplating). The anode and the substrate are maintained at a specific distance from each another and a constant (or pulsed) current is applied across this arrangement. Because of the difference in widths, the current flux tends to be more concentrated at the narrower features leading to a faster electroplating rate and higher microstructures **223** when compared to microstructures with larger widths **224**. Furthermore, even along the width of the microstructures, due to current flux concentration at the edges, the edges of the microstructures **225** tend to be taller than the middle sections **226**. These problems are well known in the art and are tolerated as there has been no solution proposed which can effectively address these problems. For example, if a pulsed current is used wherein an asymmetrical square wave current with longer duration in the positive cycle is used, it has been demonstrated that this problem is minimized yet it is not fully addressed and variations, though of a lesser magnitude, are still observed.

[0064] The non-uniform microstructure dimensions can be a significant problem in microfluidics applications. In this case, the microchannels need to be of precise dimensions to accurately govern the flow characteristics, and even small variations in the dimensions can lead to substantial changes in flow characteristics. For example, it has been observed in our experiments that a 20 μm wide channel is electroplated almost twice as fast as a 500 μm wide channel leading to significant variations in the volumes that can be accommodated in these channels. Furthermore, this discrepancy is not even predictable and can be severely affected by the overall layout, density and physical proximity of microchannels of different widths.

[0065] **FIGS. 3***a*-**3***j* show the sequence of events for the two-step electroplating and planarization method, in accordance with an embodiment of the present invention, which addresses most of the problems listed above. As is readily obvious, steps shown in **FIGS. 3***a*, **3***b* and **3***c* are similar to those described above. However, as shown in **FIG. 3***d*, the microstructures **319** are electroplated beyond the thickness of the photoresist so that each microstructure extends beyond **320** the photoresist mold. Following this step, the photoresist is dissolved in a suitable solvent as shown in **FIG. 3***e*. Also, some sections of the substrate are blocked using an electrical non-conductive layer **321** to prevent electroplating in these areas. Then a second sacrificial metal layer **330** is electroplated on the substrate such that this metal layer extends well beyond the thickness of the electroplated microstructures and effectively covers all the microstructures. In an embodiment of the present invention, the materials involved are a Nickel substrate, electroplated Nickel microstructures, and a sacrificial Copper layer. These are by no means a unique combination and indeed any combinations of metallic substrates and sacrificial layer may be used with equal success. The only criterion for choosing the metal pair is that the sacrificial metal layer can be etched without affecting the substrate and electroplated microstructures. Secondary factors such as cost prohibit the use of obviously precious metals such as Gold though technically that may also be used since it can be selectively etched against (in this case) the Nickel patterns.

[0066] Following electroplating of the sacrificial metal layer, the substrate wafer is flipped over and polished using CMP techniques. Initially the sacrificial metal layer is polished out using a coarse grit, until the first microstructures (which would be the narrowest and hence the tallest) start showing through. Following this the CMP is done using a fine grit to ensure slow removal and low surface roughness on the top surface of the microstructures. An intermediate step in the polishing process is when all the microstructures can be seen without any sacrificial metal on top. At this stage all the microstructures are of exactly the same height and furthermore, have uniform height across the width of the pattern. The height **331** of the polished microstructures and sacrificial metal layer is checked periodically as shown in **FIG. 3***g* and lapping is continued until the desired height is obtained. As is readily apparent from the drawing, the polishing step could also have been started after step **4** (**FIG. 3***d*) in the sequence. However, the relatively soft photoresist material cannot provide enough structural support to high aspect ratio microstructures during the polishing process. A very high shear force is exerted on the microstructures during polishing and if they are not properly supported in the sides, they can easily peel off the substrate. The sacrificial metal layer is used precisely for this reason to provide the strong support required.

[0067] Following the polishing step, the sacrificial metal layer is selectively etched using an etchant that does not affect the substrate or electroplated metal. At this stage the master mold **350**, contains microstructures **301** which are of extremely uniform height across the entire mold surface. Furthermore, as shown in the magnified view **322**, of **FIG. 3***i* the patterns are not only of exactly the same height but also are perfectly uniform across the entire width of the patterns. **FIG. 3***j* shows the replicated plastic part **399**, using the microfabricated master mold **350**.

[0068] The surface roughness on the top of the microstructures is directly governed by the grit size of the polishing compound use during the final steps of the polishing process. By choosing an appropriate grit size (which are available down to nm size), a very uniform surface with ultra-low rms roughness value can be achieved. In the preferred embodiment, the final grit size used for polishing is a 150 nm grit which yields rms surface roughness of <50 nm across all the microstructures. This can obviously be changed easily by using different grit sizes.

[0069] The two-step electroplating described above is well suited for certain MEMS applications such as microfluidics. Without intent of limiting the scope of embodiments of the present invention, it is anticipated that this technique could primarily benefit the development of high accuracy master molds for microfluidic plastic devices. However, this technique is not well suited to the fabrication of microstructures with non-rectangular cross sectional areas. The electroforming process described in the next two sub-sections is more appropriate for creating features with different cross-sectional profiles. Another issue that needs to be addressed is the longevity and durability of the master mold. Since, in the two-step electroplating process (or in the commonly accepted UV-LIGA process) the microstructures are deposited onto a substrate, there are inherent problems with the adhesion of the microstructures to the base substrate layer. In accordance with an embodiment of the present invention described above, Nickel microstructures are deposited onto a Nickel substrate, or more generically stating, the microstructures are commonly the same material as the substrate to ensure that there is good adhesion and matching of the compressive or tensile stress between the two. Nevertheless, the microstructures are still "foreign" to the substrate and after repeated injection molding cycles, the microstructures eventually start peeling off because of the high shear rate exerted on them during the injection molding process. In the electroforming process, the microstructures form an integral part of the substrate since the base substrate layer is "grown" on top of the microstructures hence, in this case adhesion failure is not an issue of concern. Hence, for applications where it is anticipated that a very large volume of plastic parts will be replicated (e.g. in high volume manufacturing scenarios) the electroforming process may be more suitable than the UV-LIGA or two-step electroplating process. The process for developing master molds with the same high accuracy is described later in this description.

[0070] Master Mold Fabrication Using a Modified Electroforming Process:

[0071] As explained previously, the electroforming process is particularly well suited for fabricating features with non-rectangular cross-sectional profiles. One such process is illustrated schematically in **FIGS. 4***a*-**4***i*. Again, as in previous cases, a layer of photoresist **410** is deposited onto a dummy substrate **400**. In accordance with an embodiment of the present invention, the dummy substrate is a 2 mm thick Silicon wafer. Of course, as is obvious to those skilled in the art, a number of different dummy substrate material may be used such as, but not limited to, Glass, Ceramics, rigid plastics, or even highly polished metallic substrates. After depositing the photoresist, it is exposed to UV-radiation **413** through openings **415** in a photomask **414** as shown in **FIG. 4***b*. Following this, the exposed photoresist is developed with a suitable developer solution and the unexposed regions (in the case of a negative resist) are washed away.

[0072] At this stage, a free standing photoresist pattern is formed on the dummy substrate as shown in **FIG. 4***c*. After this, the substrate plus photoresist patterns are heated to the so-called glass transition temperature of the photoresist. Most photoresist consist of a polymeric or epoxy backbone with light sensitive chemicals added thereafter. The photosensitive material confers the patterning ability. However, most of the polymeric or epoxy bases used for photoresist are thermoplastic in nature wherein application of heat (to cured or hardened photoresist) causes it to gradually transition from a solid to a gel to a liquid. Surface tension forces come into effect during the transition and modify the shape of the photoresist patterns. The surface tension forces always try to minimize the surface area in order to minimize the free surface energy. It is well known that a sphere has the lowest surface area for a given volume and the surface tension forces try to shape the molten resist into a spherical shape. However, surface tension forces are also active at the interface between the molten resist and the substrate material which prevent formation of the spherical shape. For any liquid-solid pair there exists a contact angle depending on the various surface tension forces. As shown in **FIG. 4***d*, upon heating, the rectangular cross-section is initially rounded at the edges then the vertical sidewalls become more sloped and eventually in the ideal case, the molten photoresist will achieve a shape resembling a section of a sphere. The final shape of the molten photoresist depends upon the temperature, the duration of exposure to the elevated temperature, the volume of the photoresist, the initial shape of the photoresist, the composition of the photoresist itself, the contact area per unit volume between the photoresist and the substrate and the contact angle between the molten resist and the substrate. Varying any one of these conditions can lead to a different shape. The concept of melting photoresist to achieve non rectangular cross-sectional areas has never been applied to generating a quasi semi-spherical shape before. In accordance with an embodiment of the present invention, the photoresist is heated to approximately 10° C. higher than the glass transition temperature and the temperature is maintained for an extended period of time (ranging from a few minutes to more than 2 hours) to allow the photoresist to reflow completely. Thus, in this case the primary governing factors determining the final shape are very stable and repeatable for a given photoresist/substrate combination. Of course, any of the intermediate shapes shown in **FIG. 4***d* can also be achieved.

[**0073**] As shown in **FIG. 4***e*, depending on the initial shape (narrow or wide) the photoresist will reflow to quasi semi-spherical shapes with different radii of curvature **417**, **427** and **437**. As is readily apparent, this is of great significance for MOEMS applications, wherein each different radius of curvature can generate a lens with a different focal point.

[**0074**] Following the photoresist reflow step, the dummy substrate is completely cooled down (to approximately room temperature or ~25° C.) and the top and sides are coated with a metallic seed layer **433**. One of the novel ideas exercised in this invention is that the SIDES as well as the "top" surface of the substrate is coated with the seed layer whereas the back side does not have a seed layer coating. The reasons for this will be apparent from further disclosures later in this section. The dummy substrate is then immersed in an electroplating bath for deposition of the actual substrate material. As explained previously, normally Nickel is used as a substrate material owing to its suitable mechanical properties. For this particular application, Nickel is not a suitable substrate material since electroplated Nickel films develop very high stress and are likely to peel off the dummy substrate.

[**0075**] In accordance with an embodiment of the present invention, we disclose the use of Nickel-Iron (80:20) as a substrate material. Formerly, Nickel-Iron (80:20) has been extensively used as a material with excellent magnetic properties. However, in accordance with an embodiment of the present invention, we have used Nickel-Iron (80:20) for the first time as a structural component of the master mold. Electroplated Nickel-Iron (80:20) has considerably lower stress than Nickel thereby allowing for much thicker electroplated films. Indeed the examples listed in the Background section herein all report electroformed film with thicknesses ranging from 200 μm to 500 μM. The only cases which report higher thicknesses use electroforming on large scale substrates and are not related to microfabrication processes. Furthermore, we have also modified the electroplating bath composition used for Nickel-Iron (80:20) electroplating. Normally, a Nickel-Iron (80:20) electroplating bath contains 3 gm/l of saccharin to reduce the tensile stress on the electroformed film. In accordance with an embodiment of the present invention, we have used 5 gm/l of saccharin which is an optimum concentration to minimize the tensile stress for creating thick electroforms. The composition of the Nickel-Iron (80:20) electroplating bath (total volume 8 liters) is shown in Table 1.

TABLE 1

Compound	concentration (g/l)
Nickel sulphate	200
Iron sulphate	8
Nickel chloride	5
Boric Acid	25
Saccharin	5

[**0076**] In order to further reduce the probability of the electroform peeling off the dummy substrate, electroplating is also done of the sides of the substrate as shown in **FIG. 4***f*. From our experiments we have concluded that without electroplating on the sides of the substrate it is almost impossible to create a electroform of substantial thickness since even with the reduced stress of Nickel-Iron (80:20) and the extra Saccharin, the electroform will still peel away if it is not clamped at the sides. The growth of the electroform on the sides of the dummy wafer anchors the electroform firmly to the dummy substrate and allows for higher thicknesses.

[**0077**] It is well known in the art that a number of parameters such as pH, temperature and current density affect the electroplated Nickel Iron alloy. Lower current densities lead to decreased current efficiency that leads to secondary cathode reactions like evolution of hydrogen that significantly increases stress, whereas higher current densities lead to very fast electroplating, which is usually under massive tensile stress. Our experiments have demonstrated that an optimum current density of 10 mA/cm^2 leads to increased current efficiency and low stress deposition. During electroplating the pH was maintained between 2.9-3.1. The pH increases with plating duration and is controlled via the addition of dilute sulfuric acid. The plating rate was ~9-10 micrometer/hour. The electroplating was carried out at room temperature to avoid thermally induced stress. The electroplating was carried out for a period of around 160 hours to obtain a plated thickness of ~1.6 mm. It is impossible to avoid the roughness **432** at the back end of the electroform **430**.

[**0078**] Following this step, the back of the electroform is polished to make it planar as shown in **FIG. 4***g*. By visual inspection, no curvature or bending due to stress was observed during actual fabrication processes. The thick silicon dummy substrate **400** is then removed from the electroplated Nickel Iron layer by chemical-mechanical polishing from the dummy substrate side (note that the dummy substrate can also be removed by using a selective etchant that does not affect the electroform). Then the seed layer is etched out using suitable selective metal etchants. Finally, the electroform is machined to trim the edges and create a finished circular substrate **450** with concave depression as shown in **FIG. 4***h*. **FIG. 4***i* shows the replicated plastic part clearly illustrating that each concave depression in the master-mold results in a Plano-Convex lens shape of the plastic substrate. Since this process is based on microlithography techniques it is possible to create and array of microlenses with equal ease.

[**0079**] If the intent of the fabrication process is specifically the development of microlens arrays, a highly simplified yet much more versatile approach can also be used as illustrated in **FIGS. 5***a*-**5***f*. In this case, the mold material **507**, which can be any polymer composition that is easily cured at room temperature, or at elevated temperatures or by exposure to (say) UV light etc., is directly deposited onto the dummy substrate in the form of droplets **508**. Conventional micro-dispensers **509** capable of accurate dispensing in the microliter-nanoliter range are well known in the art and are in fact commercially available. Furthermore, such dispensing systems also incorporate a high precision X-Y stage such that the liquid can be dispensed at precise locations on the substrate over the entire area of the substrate. In addition to simplicity, another significant advantage of this technique is the wide choice of materials that are available for this application. Since the mold material in this case does not have to be a photosensitive material such as photoresist, a huge variety of materials can be used for this application. The only constraints in the choice of the mold material are that (a) it should exhibit good adhesion to the dummy substrate and (b) it can selectively be etched against the electroform material. Furthermore, in order to control the spread of the dispensed liquid onto the substrate, the surface energy (and hence that contact angle) of the substrate can be modified by using a wide variety of techniques well known in the art.

[**0080**] Following deposition of the droplets onto the dummy substrate, the surface tension forces will govern the final shape of the droplet as explained previously. All the factors listed previously also apply here with the exception of the high temperature and the duration of exposure to elevated temperatures since these are not required in this case. The quasi semi-spherical droplets **507** will then be cured to a solid in their final positions as shown in **FIG. 5***b*. Since the lens array mold is created by direct deposition of the mold material, it is also conceivable that a variety of materials be used for creating lenses with slightly different shapes. For example, if a low viscosity and another high viscosity mold material are used on the same substrate, the low viscosity material would generate lens shapes with very long focal distance (due to larger radius of curvature) whereas, the high viscosity material would create lens shapes with shorter focal lengths (due to smaller radius of curvature). Using this approach, it is possible to create lenses with different focal lengths as part of the same array or such that each lens array has identical lenses but that each array varies from another one on the same substrate.

[**0081**] After this step, the dummy substrate and the mold pattern are electroplated to create the electroform **550** and, subsequently, the replicated plastic device **599** with the array of Plano-Convex lenses, as shown in **FIGS. 5***e*-**5***f*, in a process similar to the one explained previously.

[**0082**] In yet another embodiment, the two processes described above can be combined to fabricate a master mold with the high accuracy and precision of the two-step electroplating process as well as the robust characteristics of the electroforming process. This process is illustrated schematically in **FIGS. 6***a*-**6***k*.

[**0083**] The initial sequence of events is exactly the same as the two-step electroplating process wherein photoresist **610** is coated onto a dummy substrate **600**, then exposed to UV radiation **613** through and appropriate photomask **614** to create a photoresist mold pattern **616** and **618**. In accordance with an embodiment of the present invention, Nickel is then electroplated **619** beyond the thickness of the photoresist mold **620**. Then, the photoresist mold is removed and copper **630** is electroplated to cover the Nickel microstructures. Then the plated patterns are planarized and polished to the desired height **631**.

[**0084**] Following this step, the NICKEL is now selectively etched out (instead of etching out the copper as is done in the previous approach) to leave a free standing copper microstructure pattern **611** as shown in **FIG. 6***h*. Then a metal seed layer is deposited in the microstructures, the exposed areas on the top of the dummy substrates as well as the sides of the dummy substrate. Following this, the assembly is immersed in a Nickel-Iron (80:20) plating bath and an electroplating process similar to the one described in the electroforming approach is used to create a Nickel-Iron (80:20) electroform. Then, the dummy substrate is removed by CMP and the copper microstructures are selectively etched out. Then, the electroform is machined to the desired dimensions to achieve the final master mold **650** shown in **FIG. 6***j* and subsequently used for plastic replication to create patterns as shown in **FIG. 6***k*.

[**0085**] This approach combines the advantages of the two techniques disclosed previously. Since, the two-step electroplating process and planarization approach is used to define the copper patterns on the dummy substrate, all the microstructures are of uniform height, exhibit uniform height across their widths, and have very low surface roughness. Since the master mold is actually an electroform, the microstructures on the master mold are now an integral part of the mold and hence are not subject to peeling and consequently can be used for many more replication cycles.

[**0086**] It will be readily obvious to those skilled in the art that the choice of dummy substrate, electroplated microstructure material, sacrificial support layer material and electroforming material is not unique and can be easily extended to include other materials. Furthermore, the application areas listed for the above disclosures are by no means complete and the techniques disclosed in accordance with various embodiments of the present invention can be readily applied to a broader spectrum of applications where high accuracy and precision are important aspects for the master mold design. Such modifications do not depart from the essential novelty of the present invention and are hereby incorporated within the scope of the present invention.

[**0087**] The aforementioned fabrication processes offer numerous advantages as well as fabrication options for MEMS devices, a few of which are enumerated hereafter.

[**0088**] An advantage of certain embodiments of the present invention is the ability to fabricate extremely uniform microstructures (in terms of height) across the entire area of a large master mold.

[0089] Another advantage of certain embodiments of the present invention is the ability to fabricate a master mold containing microstructures with extremely uniform height across the entire width of the microstructure, irrespective of the width itself.

[0090] Yet another advantage of certain embodiments of the present invention is the ability to fabricate a master mold containing microstructures with ultra-low surface roughness on the top surface of the microstructures.

[0091] Yet another advantage of certain embodiments of the present invention is the ability to fabricate a master mold with high aspect ratio microstructures that incorporate the advantage listed above.

[0092] Yet another advantage of certain embodiments of the present invention is the ability to fabricate a thick (greater than 1 mm thickness) master mold using modifications to the electroforming techniques and specifically tailoring it towards MEMS based master mold development.

[0093] Yet another advantage of certain embodiments of the present invention is the ability to create electroforms with low tensile stress.

[0094] Yet another benefit of certain embodiments of the present invention is the ability to use existing electroplating setups and other standard microfabrication techniques without the need to develop specialized equipment.

[0095] Yet another advantage of certain embodiments of the present invention is the ability to create robust master molds wherein the microstructures are an integral part of the master mold thereby allowing use of the master mold for high volume production runs of plastic replication.

[0096] Yet another advantage of certain embodiments of the present invention is the ability to manufacture precise microlens arrays with a wide range of focal lengths using a highly simple fabrication process.

[0097] Yet another advantage of certain embodiments of the present invention is the quick turn-around time offered by the use of the replaceable mold disk technology with the high accuracy, robust master molds thereby avoiding the necessity of having to change the entire mold block for a new design,

[0098] Yet another advantage of certain embodiments of the present invention is the reduction in manufacturing costs achieved by eliminating the need to replace the entire mold block for each new design.

[0099] Yet another advantage of certain embodiments of the present invention is the ability to develop a wide variety of cross sectional profiles including square/rectangular, rounded trapezoidal, quasi-semi circular, and semi-circular.

[0100] Yet another advantage of certain embodiments of the present invention is the wide choice of material that can be employed for use as substrate, dummy substrate, sacrificial support layer and mold material.

[0101] While the invention has been described with reference to certain embodiments, it will be understood by those skilled in the art that various changes may be made and equivalents may be substituted without departing from the scope of the invention. In addition, many modifications may be made to adapt a particular situation or material to the teachings of the invention without departing from its scope. Therefore, it is intended that the invention not be limited to the particular embodiment disclosed, but that the invention will include all embodiments falling within the scope of the appended claims.

What is claimed is:

1. A method to generate a master mold used for micro-fabricating plastic substrates, said method comprising:

depositing a micro-structure pattern of photo-resist onto a substrate;

over-plating a first metal onto said pattern to generate a plurality of metal micro-structures;

removing said pattern of photo-resist from said substrate; and

over-plating a second metal onto said substrate and said plurality of metal micro-structures.

2. The method of claim 1 further comprising lapping said second metal and said plurality of metal micro-structures to create a planar surface.

3. The method of claim 2 further comprising removing said second metal from said substrate and said plurality of metal micro-structures, leaving said master mold comprising said substrate and said plurality of metal micro-structures.

4. The method of claim 1 wherein said substrate comprises nickel.

5. The method of claim 1 wherein said first metal comprises nickel.

6. The method of claim 1 wherein said first metal comprises an alloy of nickel and iron.

7. The method of claim 1 wherein said second metal comprises copper.

8. The method of claim 1 wherein said depositing said micro-structure pattern of said photo-resist comprises performing a photolithography process.

9. The method of claim 1 wherein said over-plating said first metal comprises performing an electroplating process such that said first metal is electroplated past a height of said photo-resist.

10. The method of claim 1 wherein said removing said pattern of said photo-resist comprises performing a stripping process using a remover solution.

11. The method of claim 1 wherein said over-plating said second metal comprises performing an electroplating process such that said second metal is electroplated past a height of said plurality of metal micro-structures.

12. The method of claim 2 wherein said lapping comprises performing a chemical-mechanical polishing process.

13. The method of claim 3 wherein said removing said second metal comprises performing an etching process.

14. A method to generate a master mold used for micro-fabricating plastic substrates, said method comprising:

generating a micro-structure pattern on a substrate;

heating said micro-structure pattern to form a pattern of at least one quasi-semi-spherical feature on said substrate;

coating said substrate and said pattern of at least one quasi-semi-spherical feature with a seed layer; and

depositing a metal layer onto said seed layer.

15. The method of claim 14 further comprising polishing a back of said metal layer to form a planar surface.

16. The method of claim 15 further comprising removing said substrate from said metal layer, said seed layer, and said at least one quasi-semi-spherical feature.

17. The method of claim 16 further comprising removing said seed layer to leave only said polished metal layer as said master mold.

18. The method of claim 14 wherein generating said micro-structure pattern is accomplished using a photo-resist and photolithography techniques.

19. The method of claim 14 wherein said micro-structure pattern comprises photoresist.

20. The method of claim 14 wherein said substrate comprises one of silicon, glass, ceramic, plastic, and metal.

21. The method of claim 14 wherein said metal layer comprises an alloy of Nickel and Iron.

22. The method of claim 14 wherein said step of depositing a metal layer comprises an electroplating step.

23. The method of claim 16 wherein said substrate is removed using a chemical-mechanical polishing technique.

24. The method of claim 17 wherein said seed layer is removed using an etching technique.

25. A method to generate a master mold used for microfabricating plastic substrates, said method comprising:

generating a micro-structure pattern of at least one quasi-semi-spherical feature on said substrate by dispensing droplets of a polymer material onto said substrate;

allowing said droplets of polymer material to cure;

coating said substrate and said pattern of at least one quasi-semi-spherical feature with a seed layer; and

depositing a metal layer onto said seed layer.

26. The method of claim 25 further comprising polishing a back of said metal layer to form a planar surface.

27. The method of claim 26 further comprising removing said substrate from said metal layer, said seed layer, and said at least one quasi-semi-spherical feature.

28. The method of claim 27 further comprising removing said seed layer to leave only said polished metal layer as said master mold.

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