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(54) **LASER MICROMACHINING AND METHODS AND SYSTEMS OF SAME**

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(76) Inventors: **Mark C. Huth**, Corvallis, OR (US);
Jeffrey R. Pollard, Corvallis, OR (US);
Graeme Scott, Maynooth (IE)

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Correspondence Address:

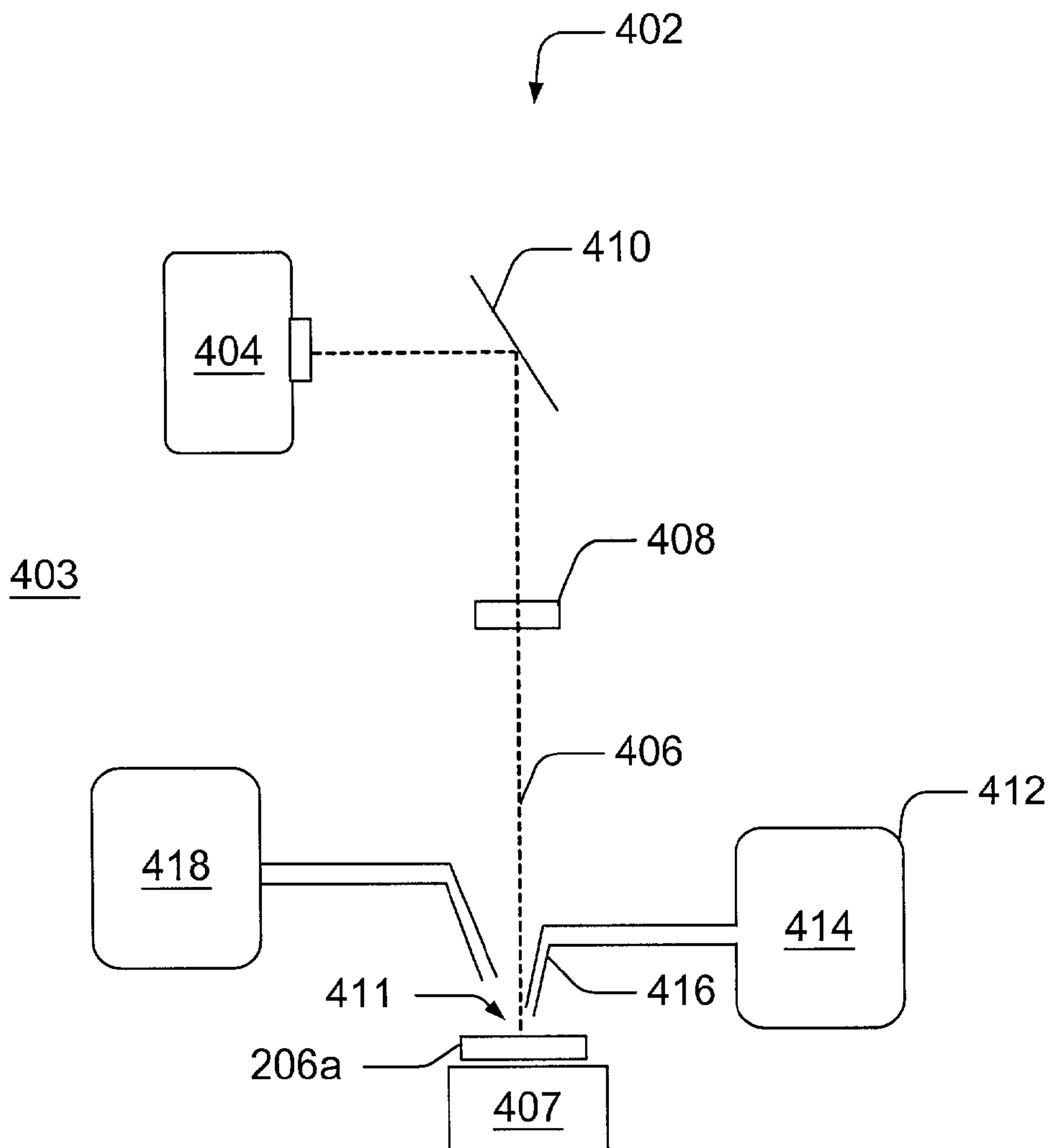
HEWLETT-PACKARD COMPANY
Intellectual Property Administration
P.O. Box 272400
Fort Collins, CO 90527-2400 (US)

(57) **ABSTRACT**

The described embodiments relate to methods and systems for laser micromachining a substrate. One exemplary embodiment positions a substrate in an open air environment. The substrate has a thickness defined by opposing first and second surfaces. The substrate can be cut by directing a laser beam at the first surface of the substrate and introducing an assist gas proximate to a region of the substrate contacted by the laser beam.

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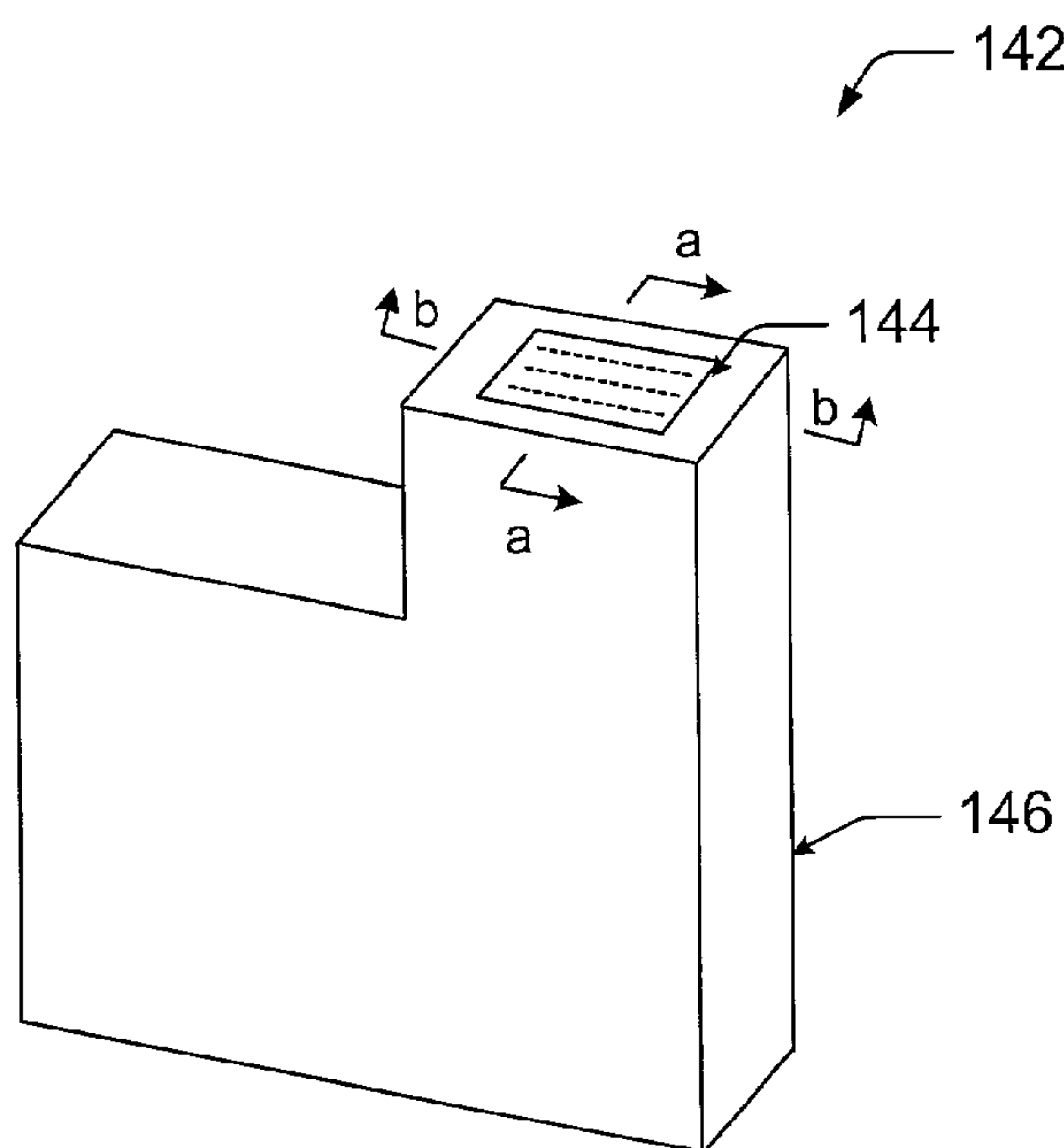


Fig. 1

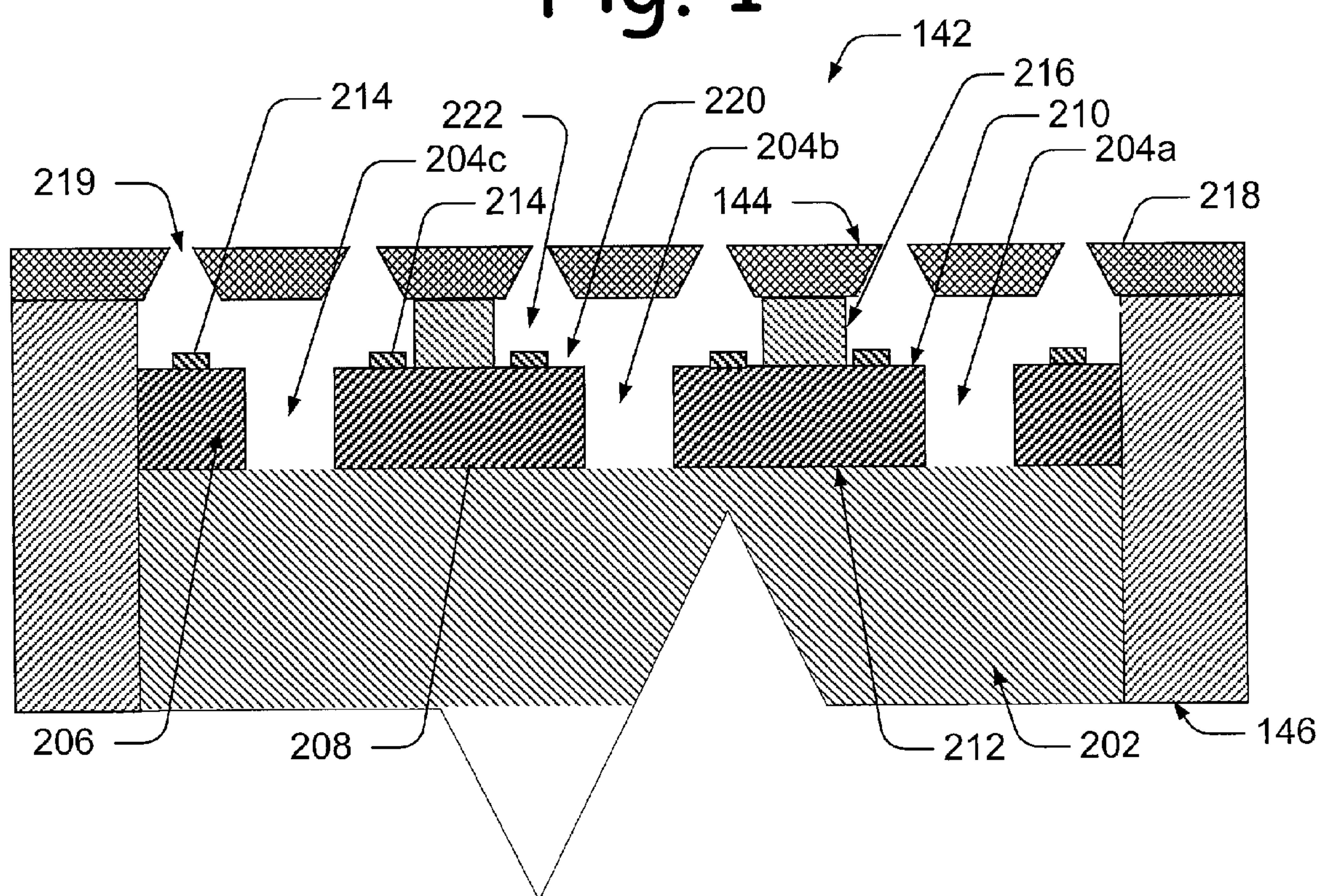


Fig. 2

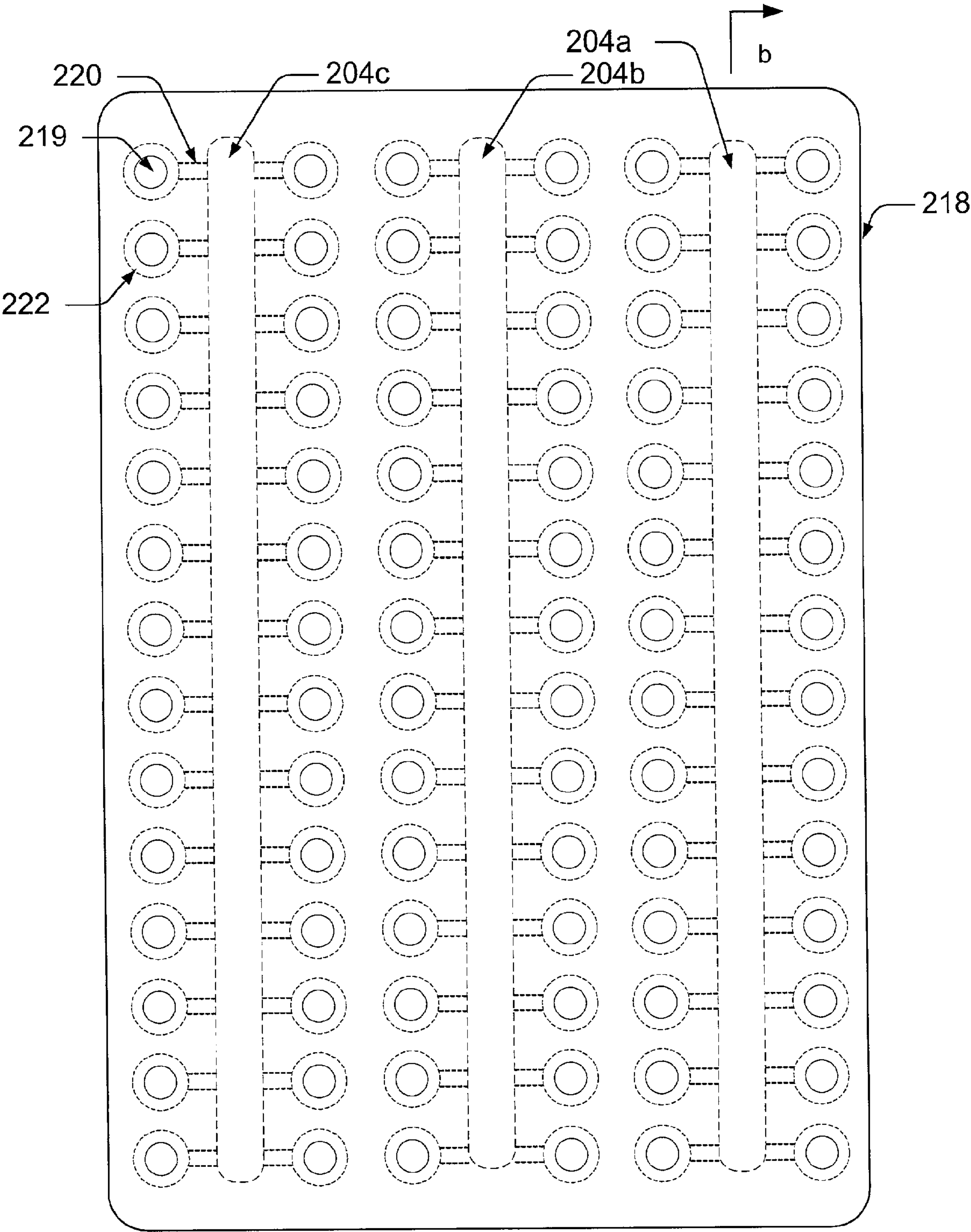


Fig. 3

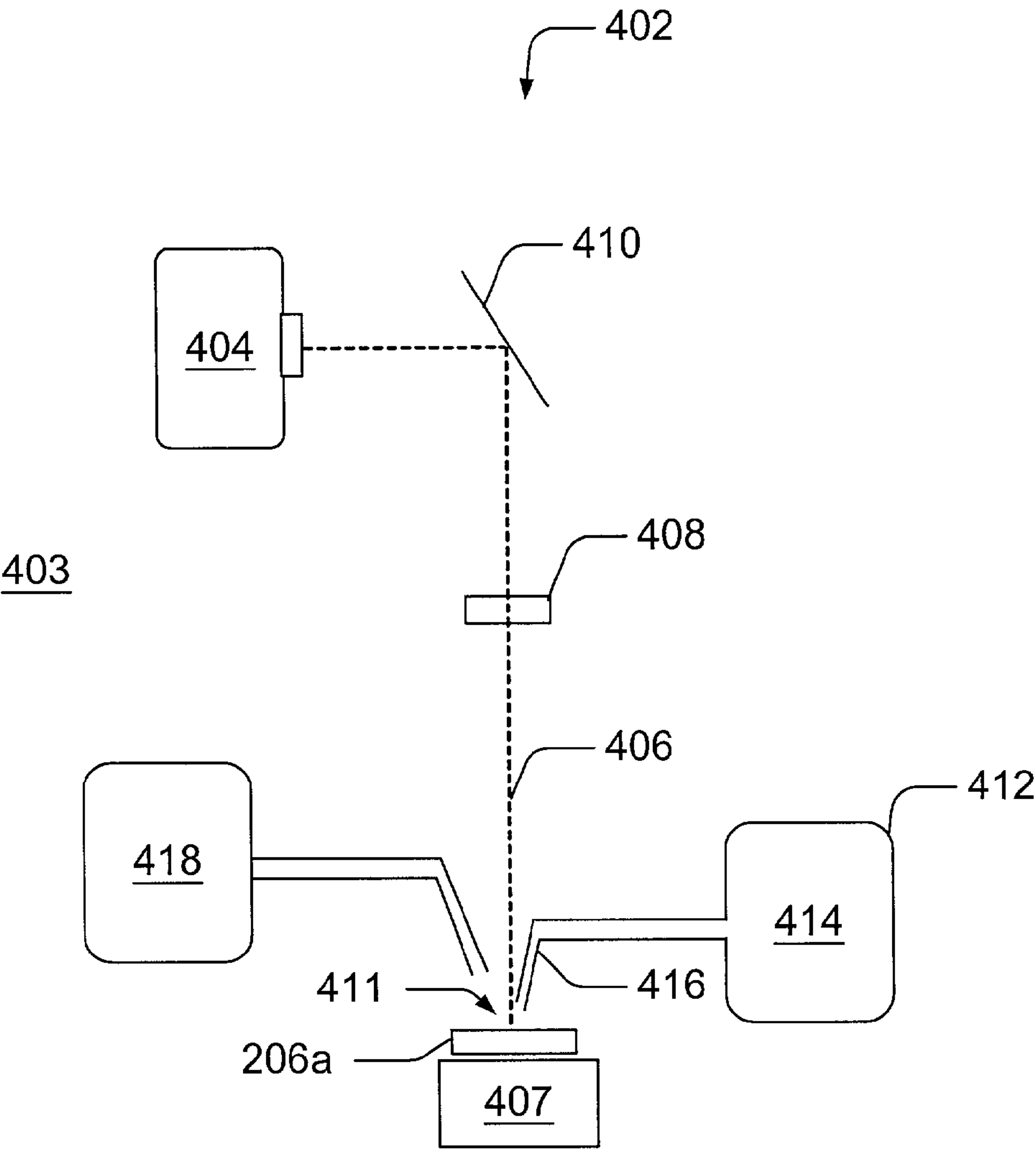


Fig. 4

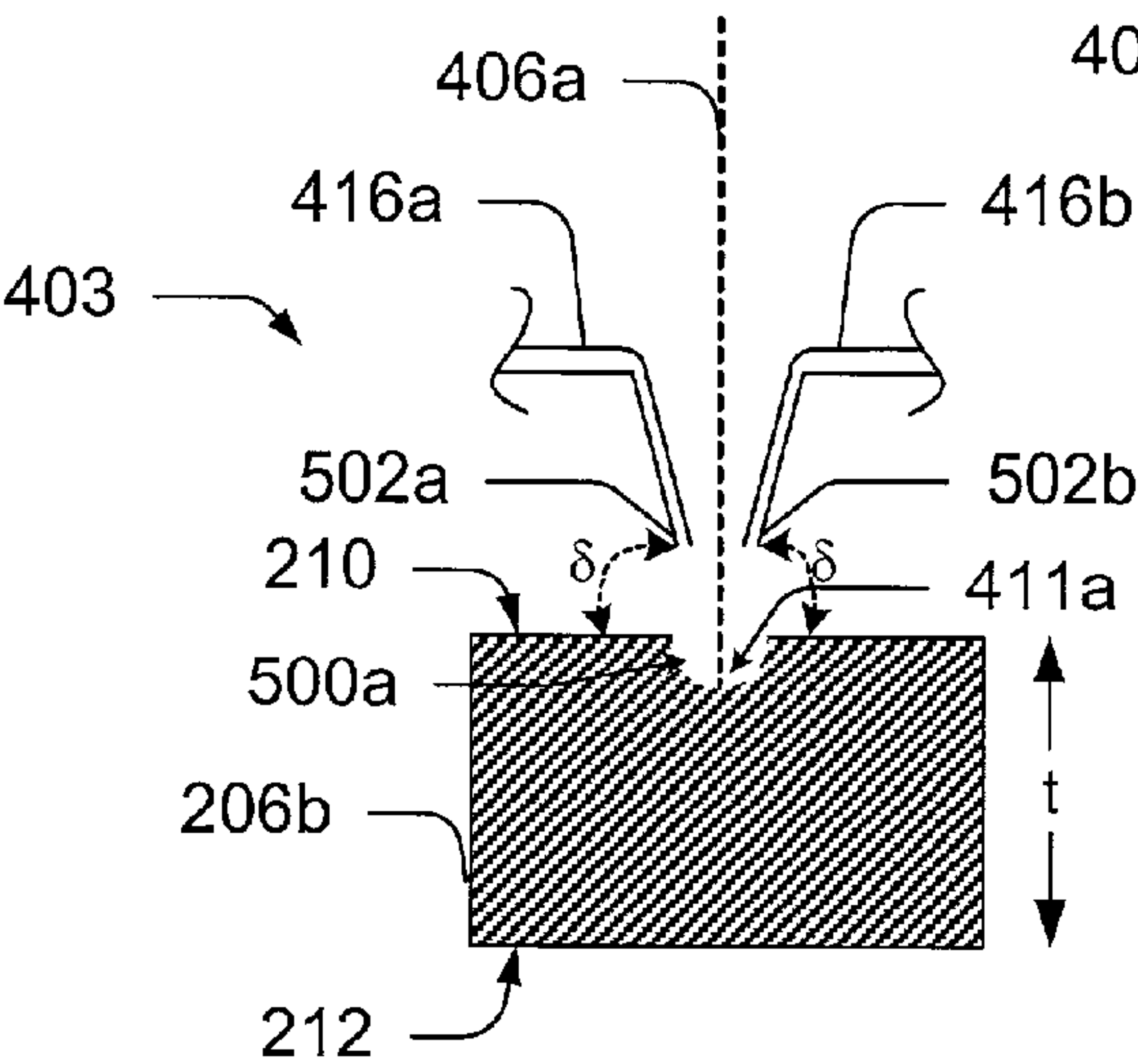


Fig. 5a

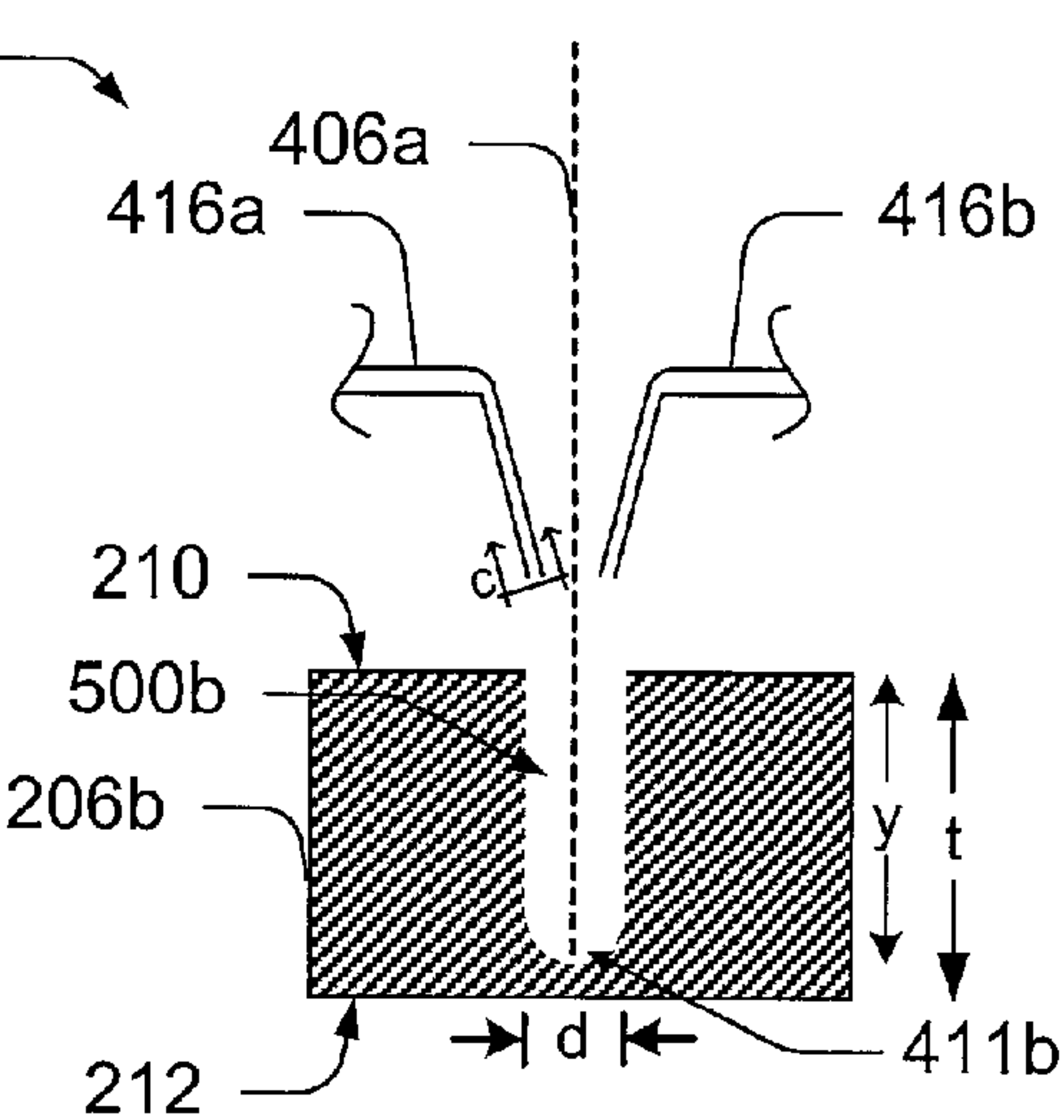


Fig. 5b

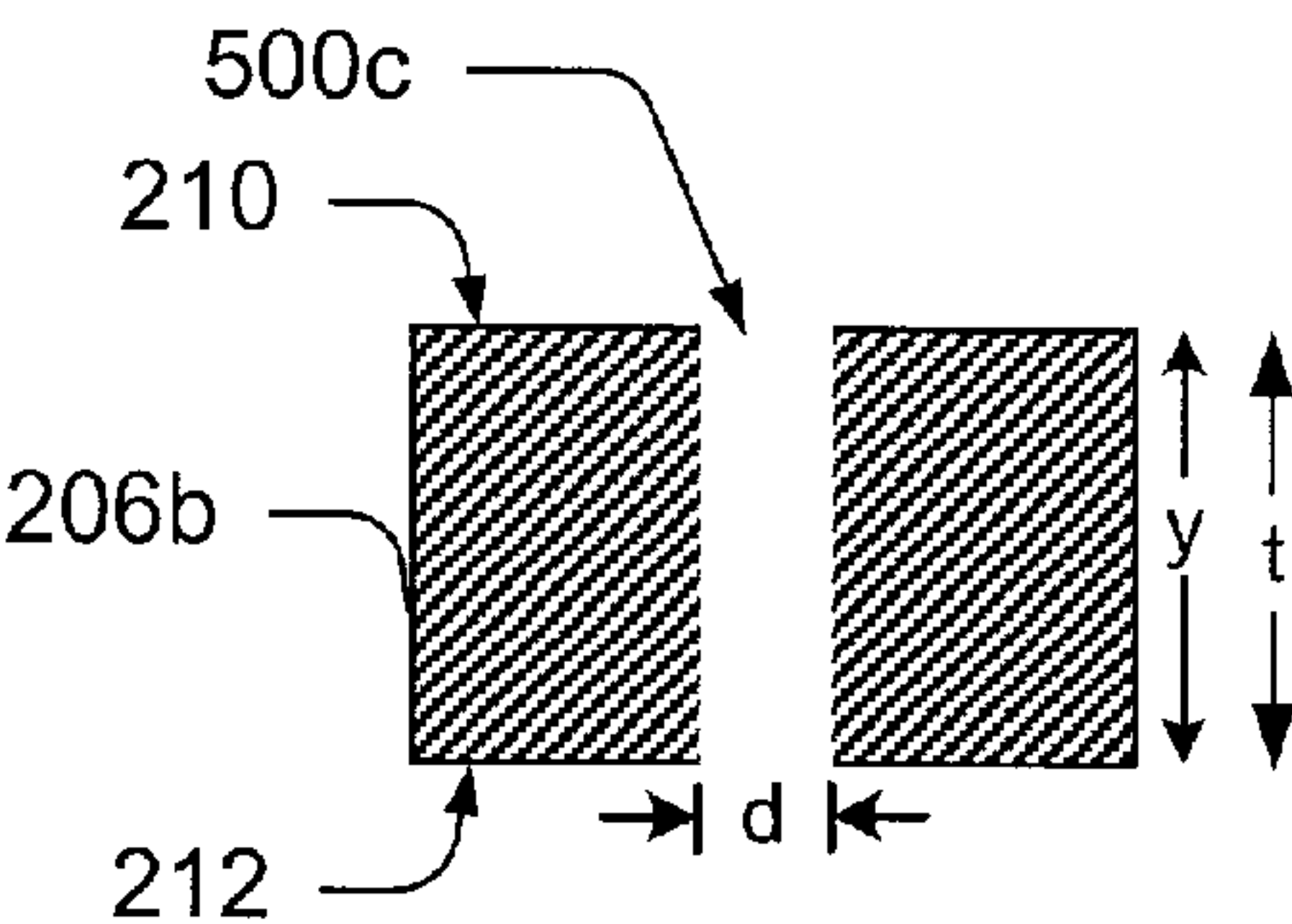


Fig. 5c

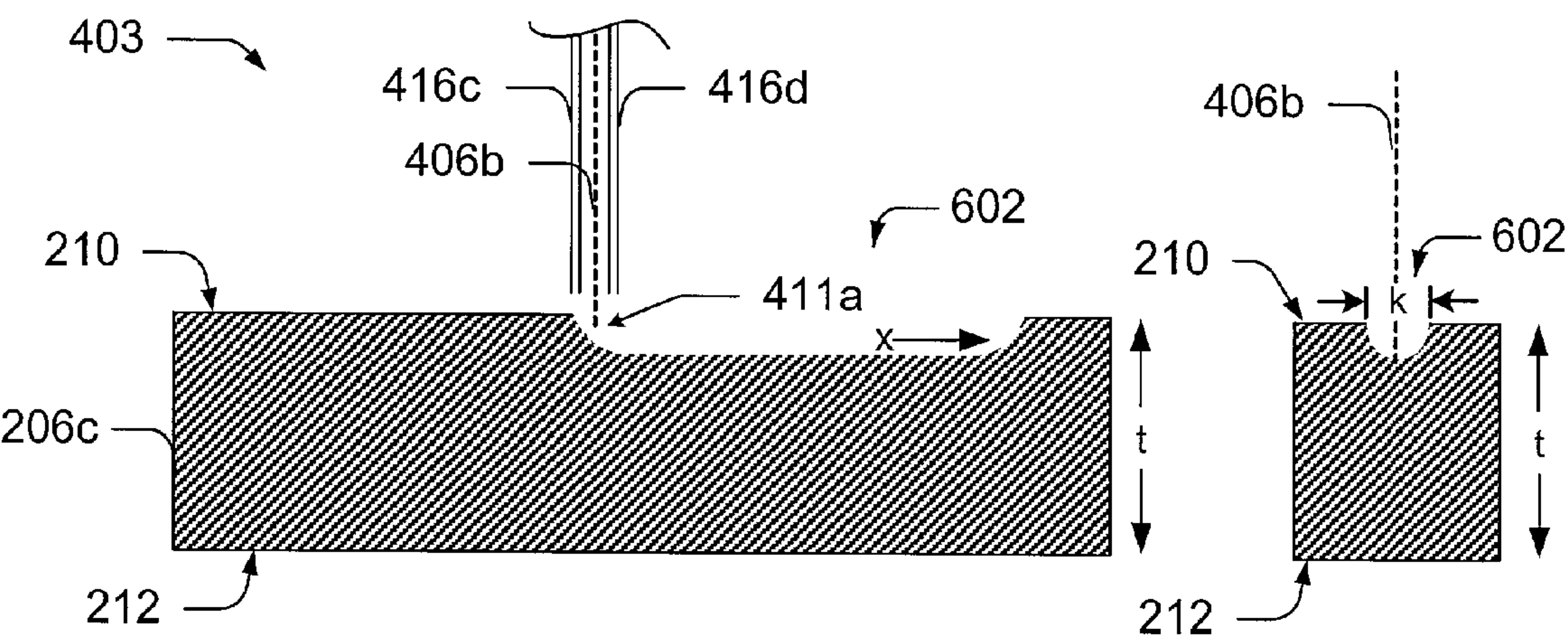


Fig. 6a

Fig. 6b

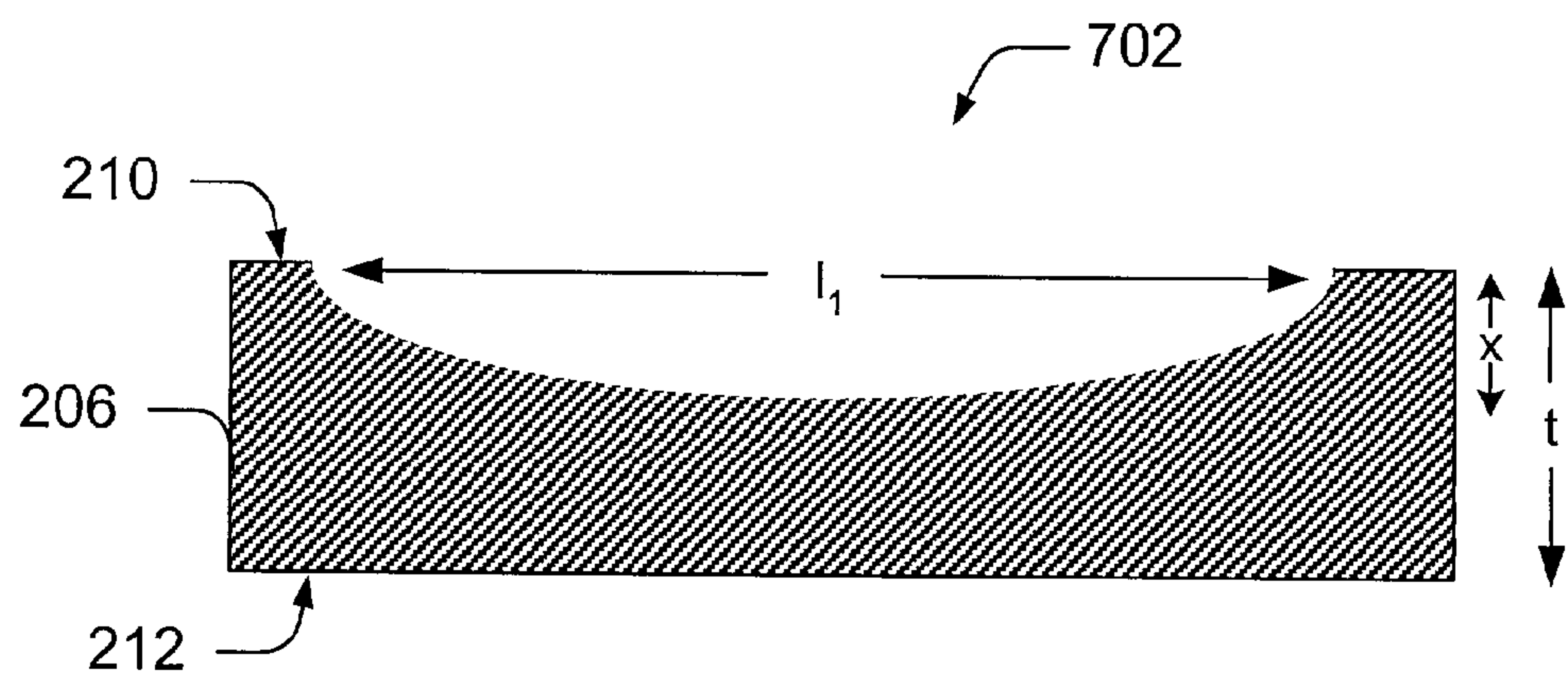


Fig. 7a

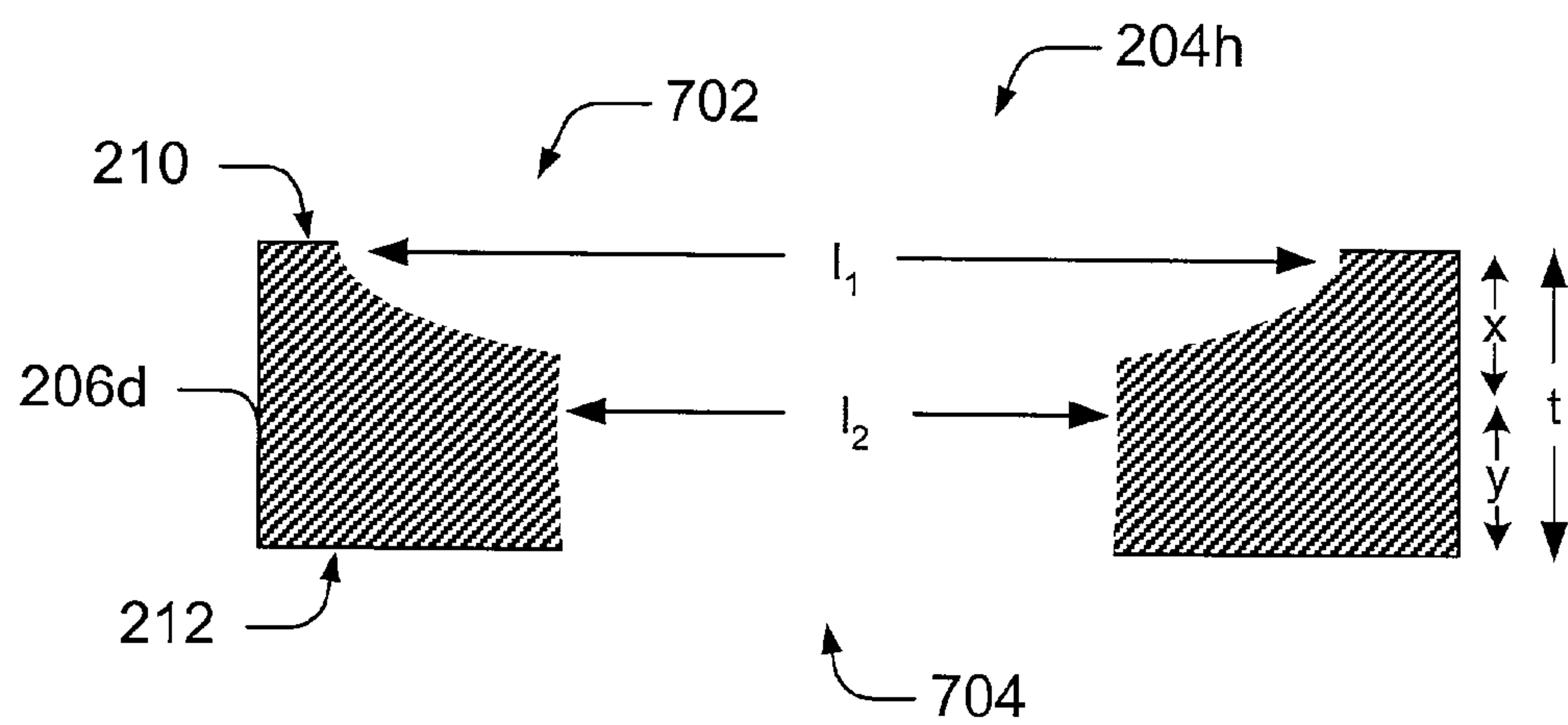


Fig. 7b

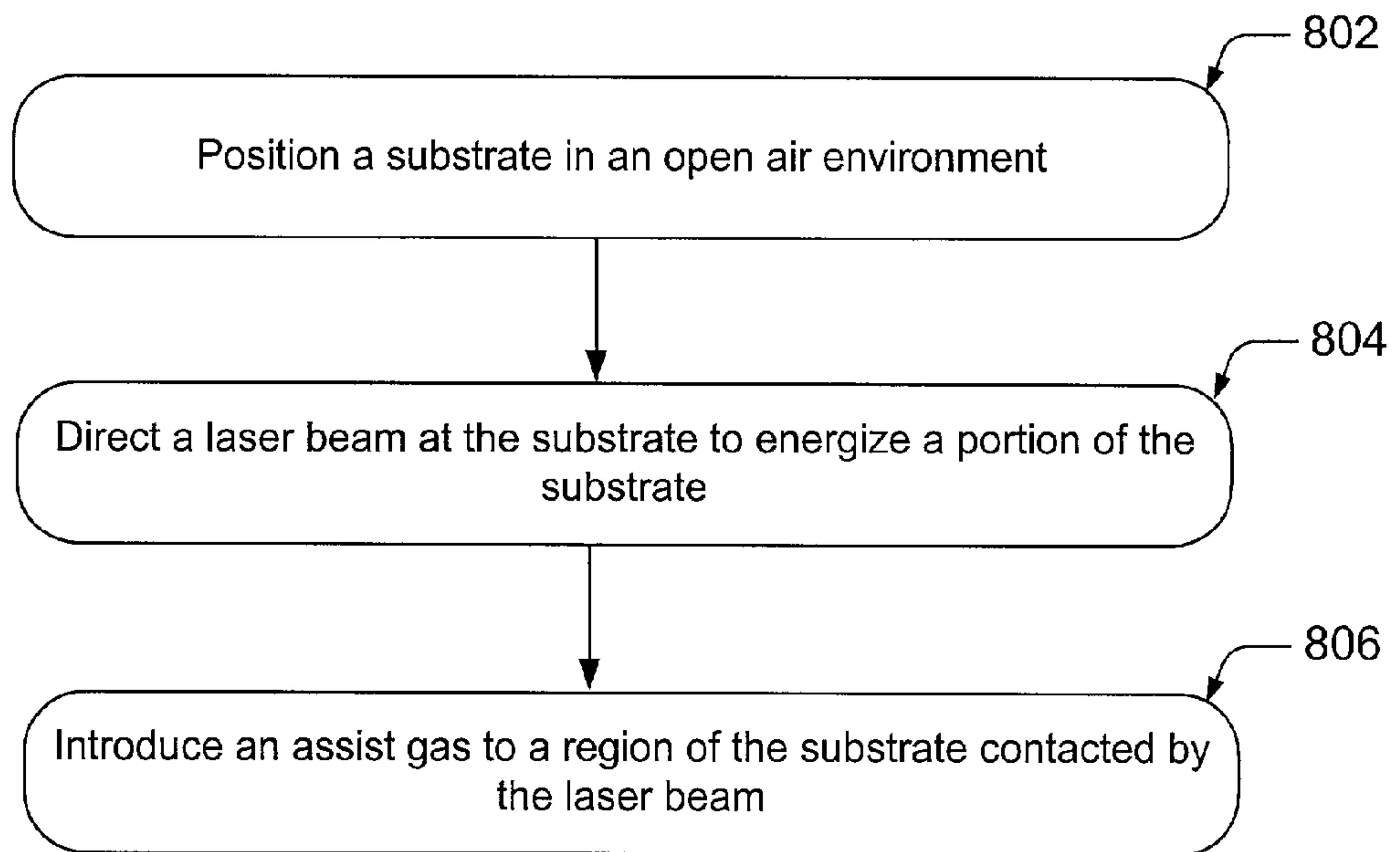


Fig. 8

LASER MICROMACHINING AND METHODS AND SYSTEMS OF SAME

BACKGROUND

[0001] The market for electronic devices continually demands increased performance at decreased costs. In order to meet these requirements, the components which comprise various electronic devices must be made ever more efficiently and to closer tolerances.

[0002] Laser micromachining is a common production method for controlled, selective removal of material. However, existing laser micromachining technologies are hindered by several deficiencies, such as a lack of uniformity in the cut they produce, as well as variations in removal speed as the laser cuts deeper into a substrate. Other laser micromachining technologies have attempted to address these problems, but are impractical for production techniques.

[0003] Accordingly, the present invention arose out of a desire to provide fast, economical methods of laser micromachining various substrates.

BRIEF DESCRIPTION OF THE DRAWINGS

[0004] The same components are used throughout the drawings to reference like features and components.

[0005] **FIG. 1** shows a perspective view of a print cartridge in accordance with one exemplary embodiment.

[0006] **FIG. 2** shows a cross-sectional view of a portion of a print cartridge in accordance with one exemplary embodiment.

[0007] **FIG. 3** shows a top view of a print head in accordance with one exemplary embodiment.

[0008] **FIG. 4** shows a front elevational view of a laser machining apparatus in accordance with one exemplary embodiment.

[0009] **FIGS. 5a-5c** show a cross-sectional view of a substrate in accordance with one exemplary embodiment.

[0010] **FIGS. 6a-6b** show a cross-sectional view of a substrate in accordance with one exemplary embodiment.

[0011] **FIGS. 7a-7b** show a cross-sectional view of a substrate in accordance with one exemplary embodiment.

[0012] **FIG. 8** shows a flow chart showing steps in accordance with one exemplary embodiment.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS OVERVIEW

[0013] The embodiments described below pertain to methods and systems for laser micromachining a substrate. Laser micromachining is a common production method for controlled, selective removal of material. In embodiments of the present invention, laser micromachining includes processes such as cutting, slotting, dicing, singulating, via drilling and 3-dimensional machining in a variety of substrate materials. This can include the machining of features either partially or completely through the substrate's thickness.

[0014] In one exemplary embodiment, the laser micromachining process utilizes a laser machine that can generate a laser beam for energizing and otherwise removing substrate

material in an open, ambient environment. Energizing can comprise melting, vaporizing, exfoliating, phase explosion, and/or ablating among other processes. In some embodiments, the energizing can occur within an interface region surrounding the laser beam and the substrate material which the laser beam contacts. In further embodiments, the efficiency of the energizing process can be improved by supplying a halogen containing assist gas to the interface area. The assist gas can be provided by a gas supply nozzle that directs the assist gas to the interface area. In some embodiments, the assist gas can react with energized substrate material to form compounds that are more readily removed and/or dissipated than could otherwise be achieved. By supplying the assist gas to the interface region, the speed and efficiency of the laser machining process can be improved without the need to operate in controlled conditions. The exemplary laser machining apparatus works in an open air environment without the need for chambers or other containment vessels, and is therefore well suited for production techniques.

[0015] One exemplary embodiment of the laser machining process will be described in the context of forming slots in a substrate. Such slots can be used for, among other things, fluid feed slots. In one exemplary embodiment, a substrate containing fluid feed slots can be incorporated into a print head or other fluid ejecting device. As commonly used in print head dice, the substrate can comprise a semiconductor substrate that has microelectronics incorporated within and supported by the substrate. In one exemplary embodiment, the fluid feed slot(s) allow a fluid such as ink to be supplied to fluid ejecting elements contained in ejection chambers within the print head. The fluid ejection elements commonly comprise firing resistors that heat ink causing increased pressure in the ejection chamber. A portion of that ink can be ejected through a firing nozzle with the ink being replaced by ink from the ink feed slot.

[0016] Although exemplary embodiments included herein are described in the context of providing dice for use in ink jet printers, it is recognized and understood that the techniques described herein can be applicable to other applications where micromachining a substrate is desired. For example, the described embodiments can be used for quickly and efficiently dicing or singulating semiconductor wafers.

[0017] The various components described below may not be illustrated accurately as far as their size is concerned. Rather, the included figures are intended as diagrammatic representations to illustrate to the reader various inventive principles that are described herein.

[0018] Exemplary Products

[0019] **FIG. 1** shows an exemplary print cartridge **142**. The print cartridge is comprised of the print head **144** and the cartridge body **146**. Other exemplary configurations will be recognized by those of skill in the art.

[0020] **FIG. 2** shows a cross-sectional representation of a portion of the exemplary print cartridge **142** taken along line a-a in **FIG. 1**. It shows the cartridge body **146** containing ink **202** for supply to the print head **144**. In this embodiment, the print cartridge is configured to supply one color of ink to the print head, though other exemplary configuration can supply multiple colors and/or black ink. A number of different ink

feed slots are provided, with three exemplary slots being shown at **204a**, **204b**, and **204c**. Other exemplary embodiments can utilize more or less ink feed slots. Some exemplary embodiments can divide the ink supply so that each of the three ink feed slots **204a-204c** receives a separate ink supply.

[0021] The various ink feed slots pass through portions of a substrate **206**. In some embodiments, silicon can be a suitable substrate. In some of these embodiments, the substrate **206** comprises a crystalline substrate such as single crystalline silicon or polycrystalline silicon. Examples of other suitable substrates include, among others, gallium arsenide, glass, silica, ceramics or a semi conducting material. The substrate can comprise various configurations as will be recognized by one of skill in the art. In this exemplary embodiment, the substrate comprises a base layer, shown here as silicon substrate **208**.

[0022] The silicon substrate has a first surface **210** and a second surface **212**. Positioned above the silicon substrate are the independently controllable ink energizing elements or firing elements that, in this embodiment, comprise firing resistors **214**. In this exemplary embodiment, the resistors are part of a stack of thin film layers on top of the silicon substrate **208**. The thin film layers can further comprise a barrier layer **216**. In some embodiments, the barrier layer can comprise, among other things, a photo-resist polymer substrate. Above the barrier layer can be an orifice plate **218** that can comprise, but is not limited to a nickel substrate. In an additional embodiment, the barrier layer **216** and the orifice plate **218** are integral, formed of the same material.

[0023] In some embodiments, the orifice plate has a plurality of nozzles **219** through which ink heated by the various resistors can be ejected for printing on a print media (not shown). The various layers can be formed or deposited upon the preceding layers. The configuration given here is but one possible configuration.

[0024] The exemplary print cartridge shown in **FIGS. 1 and 2** is upside down from the common orientation during usage. When positioned for use, ink can flow from the cartridge body **146** into one or more of the slots **204a-204c**. From the slots, the ink can travel through an ink feed passageway **220** that leads to a firing chamber **222**. In some embodiments, the firing chamber can be comprised of a firing resistor, a nozzle, and a given volume of space adjacent thereto. Other configurations are also possible. When an electrical current is passed through the resistor in a given firing chamber, the ink is heated and expands to eject a portion of the ink from the nozzle **219**. The ejected ink can then be replaced by additional ink from the ink feed passageway **220**.

[0025] **FIG. 3** shows an embodiment of a view from above the thin-film surface of a substrate incorporated into a print head. The substrate is covered by the orifice plate **218** with underlying structures of the print head indicated in dashed lines. The orifice plate is shown with numerous nozzles **219**. Below each nozzle lies a firing chamber **222** that is connected to an ink feed passageway **220** and then to slot **204a-c**. The slots are illustrated in this embodiment as an elliptical configuration when viewed from above the first surface of the substrate. Other exemplary geometries include rectangular among others.

[0026] Exemplary Systems

[0027] **FIG. 4** shows an exemplary apparatus or laser machine **402** capable of micromachining a substrate **206a** in accordance with one exemplary embodiment. The laser machine can be configured for use in an open air environment or region **403**. The laser machine can have a laser source **404** capable of emitting a laser beam **406**. The laser beam can contact, or otherwise be directed at, the substrate **206a**. In some exemplary embodiments, the substrate can be positioned on a fixture **407** in the open air environment.

[0028] Exemplary laser machines are commercially available. One such exemplary laser machine is the Xise 200 laser Machining Tool, manufactured by Xsil Ltd. of Dublin, Ireland.

[0029] Exemplary laser machines can utilize various laser sources. A laser source has a crystal or other structure that when energized can emit the laser beam. An exemplary laser source is the Coherent AVIA 355-4500 which contains Crystalline Nd:YVO₄ (also known as Vanadate). Other exemplary crystals include among others, Nd:YAG and Nd:YLF.

[0030] Each of these materials can produce a laser beam with a fundamental wavelength of about 1064 nanometers (nm) in one embodiment. Laser beams of various wavelengths can provide satisfactory embodiments. For example, some embodiments can have a wavelength in the range of less than about 550 nm.

[0031] In some exemplary embodiments, the wavelength of the laser beam can be modified within the laser source **404**. For example, one embodiment can utilize the AVIA **355**, where the frequency is tripled to yield a laser beam wavelength of 355 nm. Another exemplary embodiment can utilize a laser source with a wavelength of 532 nm. For example, the Lambda Physik PG532-15 can be utilized as a laser source that can provide a laser beam that has such a wavelength. Other exemplary embodiments can utilize laser beams having wavelengths ranging from less than 100 nm to more than 1500 nm. Other satisfactory embodiments can be achieved with laser beams having various properties as will be discussed in more detail below.

[0032] Various exemplary embodiments can utilize one or more lens(es) **408** to focus or expand the laser beam. In some of these exemplary embodiments, the laser beam can be focused in order to increase its energy density to more effectively machine the substrate. In these exemplary embodiments, the laser beam can be focused with one or more lenses **408** to achieve a desired diameter where the laser beam contacts the substrate **206a**. In some of these embodiments, this diameter can range from about 1 micron to more than 100 microns. In one embodiment, the diameter is about 20 microns. Also, the laser beam can be pointed directly from the laser source **404** to the substrate **206a**, or indirectly through the use of one or more mirror(s) **410**.

[0033] Exemplary laser beams can provide sufficient energy to energize substrate material that the laser beam is directed at. Energizing can comprise melting, vaporizing, exfoliating, phase explosion, and/or ablating among others processes. Some exemplary embodiments can energize substrate material equal to or above its material removal threshold. The material removal threshold is the energy density level necessary to remove substrate material by melting, vaporizing, exfoliating, and/or phase explosion. Energy den-

sity will be discussed in more detail below. The substrate that the laser beam is directed at and the surrounding region containing energized substrate material is referred to in this document as an interface region **411**.

[0034] In some exemplary embodiments, the laser machine **402** can also have a gas supply **412** for supplying an assist gas **414** to the interface region **411**. In some exemplary embodiments, the assist gas can be supplied via one or more gas supply nozzles **416**.

[0035] Some exemplary embodiments can also utilize a debris extraction system **418** that can remove vaporized substrate materials and/or molecules formed from substrate material and a component of the assist gas, as well as various other molecules. In some embodiments, the debris extraction system can comprise a vacuum system and filtration system positioned to evacuate material in proximity to the laser beam and substrate. Exemplary debris extraction systems will be discussed in more detail below.

[0036] In some embodiments, the assist gas can increase the speed and/or efficiency at which the laser beam cuts or removes substrate material. Various mechanisms can contribute to the increased removal rate. For example, in some embodiments, molecules of the assist gas can be ionized by the laser beam energy. At least some of the resultant ions can react with energized substrate material. Such reactions can form resultant compounds that can be volatile and relatively non-reactive. These properties can allow the resultant compounds to diffuse or otherwise dissipate from the interface region and thus can decrease the incidence of redeposition of substrate material.

[0037] This is an advantage over other embodiments of laser machining techniques where a significant amount of the substrate material removed by the laser redeposits back on the substrate. Redeposited material adjacent to the interface region can result in undesired debris or component damage. Redeposited material in the interface region hinders the laser/substrate interaction and reduces the material removal rate.

[0038] Further, some embodiments of laser machining processes also lead to the formation of particulate debris typically having dimensions or diameters of 1 micron or less. In these embodiments, this debris can be formed from molten material directly released from the substrate's surface as well as from condensation of the vaporized substrate material. This particulate material or debris can cause scattering and absorption of laser light towards the end of the laser pulse, especially in laser pulses with a duration of longer than 5-10 nanoseconds (nsec), decreasing the amount of useful laser light reaching the target material surface, in this embodiment. Such particulate material can subsequently deposit on the area within or adjacent to the interface region.

[0039] Accordingly, these techniques result in redeposition which, in turn, decreases the speed of cutting or machining, as well as the quality of the finished machined substrate. Conversely, some embodiments of the invention described herein can greatly reduce or eliminate redeposition and can produce much cleaner, more uniform, cuts or machining as a result. In some exemplary embodiments, less than about 1.0 percent of removed material is redeposited. In a particular embodiment, less than about 0.5 percent of the removed material is redeposited.

[0040] Various mechanisms can contribute to this increased performance, including but not limited to, the following mechanisms. In some embodiments, the assist gas and/or disassociated components of the assist gas can interact with particulate debris generated by the action of the laser beam. This interaction can reduce the dimensions of the debris and allow the debris to be more easily removed by the extraction system. Another of the various mechanisms can increase performance by reacting the assist gas or its components with condensing material in a vapor plume of substrate material in the interface region to reduce the dimensions of any condensed material allowing it to be more easily removed by an extraction system.

[0041] FIGS. 5a-5c show an exemplary embodiment of cross sections through a substrate **206b**. Here, a feature is being micromachined into the substrate. In this embodiment, the feature is a trench into the substrate that eventually is formed all the way through the substrate to form a via. Other exemplary features can also be formed as will be discussed below.

[0042] In the embodiments shown in FIGS. 5a-5c, the substrate can have a thickness t defined by a first surface **210** and an opposite second surface **212**. In further embodiments, the substrate's thickness can range from less than 100 microns to more than 2000 microns. In these exemplary embodiments, the thickness is about 675 microns.

[0043] Referring now to FIG. 5a, the laser beam **406a** is shown directed at the substrate **206b**. As shown here, the laser beam is orthogonal to the first surface **210** of the substrate, though other configurations can provide satisfactory embodiments. The laser beam has formed a shallow cut **500a** in the substrate through the first surface **210**. In this embodiment, two gas assist nozzles (**416a** and **416b**) are shown positioned on opposite sides of the laser beam to supply the assist gas (not shown) to the interface area **411a**. Though two gas assist nozzles are utilized here, other satisfactory embodiments can use more or less nozzles. The term 'nozzle' is used to describe the hardware that is used to deliver the assist gas to the interface region of the substrate. In various embodiments, this can include an exit aperture (**502a** and **502b**). In some embodiments the exit aperture can be generally circular in transverse cross-section to plane c as shown in FIG. 5b.

[0044] In other exemplary embodiments, the exit aperture can comprise other configurations. For example, the exit aperture can be in a manifold configuration, an air knife configuration, and a ring shaped annulus configuration, among others.

[0045] In one exemplary embodiment, the exit aperture (**502a** and **502b**) of the gas assist nozzles can be about 12 mm vertically above the first surface **210** and about 3.2 mm horizontally from the laser beam **406**, though other satisfactory embodiments position the nozzles at different combinations of distances and angles. The nozzles can be positioned to eject the assist gas from the exit aperture at an angle δ of about 45 to about 90 degrees relative to the first surface of the substrate. In the exemplary embodiment shown in FIGS. 5a-5b, the angle δ is about 70 degrees.

[0046] The assist gas can be supplied at various delivery pressures and velocities. For example, in one embodiment, the gas supply nozzle's exit aperture can be a relatively

small diameter to produce higher velocities for a given flow rate or the diameter can be relatively large to provide a lower velocity for a given flow rate. In one exemplary embodiment, the diameter is about 1.0 mm.

[0047] Exemplary embodiments can utilize various assist gases. In some embodiments, the assist gas can comprise a halide or a halogen containing gas. Exemplary assist gases can comprise, but are not limited to halocarbons and sulfur hexafluoride.

[0048] Many exemplary assist gases, including many of the halocarbon gases can have deleterious environmental consequences. Some exemplary embodiments can utilize a filtration system alone, or the filtration system can be used as a component of a debris extraction system 418 to remove or minimize any gases of environmental concern that could otherwise diffuse into the ambient environment from the interface area. This filtration system can include mechanisms for converting the assist gas and various by-product gases from the interface area into more inert compounds.

[0049] Other exemplary embodiments can utilize assist gases such as 1,1,1,2 tetrafluoroethane that can be effective assist gases and are understood to be relatively benign to the environment and thus can be advantageous. Other exemplary assist gases can also combine effectiveness in increasing laser machining performance and reduced environmental consequences. Although embodiments utilizing a single assist gas have been described in the exemplary embodiments, other embodiments can utilize multiple assist gases, the combination of which can provide beneficial characteristics.

[0050] In one exemplary embodiment the assist gas can comprise a halogen precursor, at least some of the molecules of which can be ionized or disassociated by laser energy in the interface area. In a further exemplary embodiment, the assist gas can dissociate or ionize in an extremely hot environment around the laser energized region and can react with energized substrate material to form, at least in part, one or more volatile compounds. This process can decrease the incidence of redeposition and/or are more easily removed by an extraction system.

[0051] In some embodiments, the assist gas can be supplied at a flow rate sufficient to be an excess reagent in the interface region. In one exemplary embodiment, where the assist gas comprises 1,1,1,2 tetrafluoroethane, the gas assist nozzles deliver the assist gas at a flow rate in a range of about 0.08 grams/second (gm/sec) to about 0.5 gm/sec. A further embodiment supplies about 0.33 gm/sec of 1,1,1,2 tetrafluoroethane. Other exemplary flow rates for various exemplary assist gases will be recognized by one of skill in the art.

[0052] FIG. 5b is an exemplary embodiment showing another cross section of the substrate where the laser has cut a trench 500b most of the way through the thickness of the substrate 206b. The depth of the trench is indicated as y and can be compared to the substrate's thickness t. In this exemplary embodiment, the assist gas can still be supplied to the interface region 411b to maintain efficient cutting despite the interface region being at least in part, at the bottom of the trench 500b. This can allow the laser to cut at generally the rate and efficiency as it did when the trench was shallower, for example as shown in FIG. 5a. This

embodiment can also allow the laser to cut a trench of generally uniform diameter d for the entire depth of the trench.

[0053] FIG. 5c shows the trench 500c having been completed through the entire thickness t of the substrate. Thus, the depth y of the trench 500c equals the thickness t of the substrate 206b. Such a through hole, also known as a via, can be useful for many aspects of incorporating microelectronics onto a substrate among others. As shown here, the via has a generally consistent diameter d throughout. In these embodiments, the diameter can be less than about 60 microns, though larger diameters can be achieved.

[0054] Some embodiments can produce trenches and/or vias that have diameters less than or equal to about 30 microns. The efficiencies of these embodiments can allow these trenches or vias to have an aspect ratio (feature depth divided by the feature width) of at least about 10 with further embodiments having aspect ratios greater than 20. Thus, in the trench shown in FIG. 5b, the feature depth equals y and the feature width equals the diameter d. Referring again to FIG. 5c the depth of the via y equals the substrate's thickness t. So in this embodiment, the aspect ratio equals the substrate's thickness t divided by the diameter d. Although a via is shown here, these embodiments can also form other features, such as trenches, slots and/or cuts, as will be discussed in more detail in relation to FIGS. 6a-6b and 7a-7b.

[0055] The laser machining apparatus in some embodiments can cut into a specific point on the substrate and can form a trench of less than or about 30 microns through the same substrate without moving the laser or substrate. This not only allows smaller trenches to be made in the substrate, but the trench forming process can be made correspondingly faster and of better quality, while affecting less of the surrounding substrate material than can be achieved with other typical technologies.

[0056] Some embodiments of the present invention allow for the formation of trenches and vias having small diameters that are generally consistent for their entire depth. This is achieved, by among other things, maintaining the rate and efficiency of the removal process by reducing redeposition and particle build-up.

[0057] In other embodiments, where technologies attempt to use various gases to promote laser function, however, these systems typically require a controlled environment usually achieved through the use of a chamber into which the substrate is placed. In this embodiment, the conditions and constituent gases of the chamber are then altered before commencing laser machining. The constraints imposed by having to open and close and reseal the chamber and then reestablish the controlled environment whenever components are added or removed has prevented such processes from becoming commercially practicable. In contrast, some embodiments described herein, by virtue of the fact that they are configured for use in open air environments, are inherently well adapted to mass production applications such as assembly lines.

[0058] FIGS. 6a-6b show a laser beam cutting or removing substrate material to form a trench 602. FIG. 6a is a view taken in cross section along the long axis of the trench, while FIG. 6b is a cross section taken transverse the long axis.

[0059] FIG. 6a shows a cross section along the length of a trench 602 formed from the laser beam contacting the substrate while the substrate was moved in the x direction relative to the laser beam. In another exemplary embodiment, the laser beam can be moved relative to the substrate in several ways. For example, the laser beam can be moved, in either or both the x and y directions, while the substrate remains stationary. The gas assist nozzles can be moved in conjunction with the laser beam or left stationary. Alternatively, the substrate can be moved and the laser beam kept stationary. For example, in one embodiment, the substrate 206c can be placed on a fixture 407 that in some embodiments has the capability to move the substrate relative to the laser beam. Other exemplary embodiments can utilize a combination of these techniques, among others, to move the substrate and the laser beam relative to one another.

[0060] FIG. 6a further shows two gas assist nozzles 416c and 416d adjacent and parallel to the laser beam 406b so that each of them is orthogonal to the substrate's first surface 210. This is one exemplary configuration that can supply assist gas to the interface area.

[0061] FIG. 6b shows an embodiment where the laser beam forms a kerf k in the substrate. The kerf is the width of the cut formed by the laser beam as it is moved relative to the substrate. The kerf width can be affected by several factors including the amount of redeposition of substrate material as well as the laser's parameters and speed at which the laser beam is moved in relation to the substrate.

[0062] In some exemplary embodiments, the laser parameters can establish a laser beam with a peak power density of greater than 1 GW/cm², with one exemplary embodiment having a peak power density of about 4.78 GW/cm². The laser machine, in various embodiments, can generate the laser in pulses in any suitable range of values. In some embodiments, pulse values range from about 1 kilohertz (kHz) to about 200 kHz. In one embodiment the pulse rate is about 20 kHz. Other satisfactory embodiments can use rates below and above the range given here. The laser beam pulse width can be about 1 to 100 nanoseconds, with one exemplary embodiment using about 15 nanoseconds.

[0063] The movement of the laser beam relative to the substrate per unit of time is referred to in this document as the laser scan rate. Exemplary embodiments can utilize a laser scan rate of about 1 to about 1000 millimeters/second (mm/sec). Some exemplary embodiments can utilize a laser scan rate of about 10 to about 300 mm/sec with other exemplary embodiments utilizing about 100 mm/sec. In one embodiment, these parameters can allow a laser to quickly make a cut having a consistent kerf width so that the resultant trench has a surface roughness less than existing technologies.

[0064] Maintaining a uniform kerf can result in a better quality trench, slot or other feature that is more uniform along its length and depth and closer to the desired dimensions. The described embodiments improve kerf uniformity, as well as allow for increased cutting speed.

[0065] The described embodiments can efficiently form high aspect ratio features while maintaining high cutting efficiency. In one embodiment, aspect ratios in the range of about 4.5 to about 11.25 can be achieved with the laser removing at least about 9,800,000 cubic microns of substrate

material per joule of laser energy. In some embodiments, the features can be made with even higher aspect ratios with very little reduction in efficiency. This is in contrast to other embodiments of laser machining technology where efficiency decreases dramatically with increasing feature aspect ratio.

[0066] FIGS. 7a-7b show an embodiment where the laser has been used in combination with another removal technique to form a slot in the substrate. The slot can comprise a fluid feed slot, and in some embodiments can comprise a fluid feed slot in a substrate that can be incorporated into a fluid ejecting device.

[0067] Referring now to FIG. 7a, a laser cut has formed a trench 702 in the substrate 206d. In this embodiment, the trench has a depth x and a length 1₁. In this example, the trench depth passes through less than the entire thickness t of the substrate. Other examples can be shallower or deeper than shown, or can pass all the way through the thickness of the substrate for at least a portion of its length to form a slot through the substrate.

[0068] In this embodiment, the trench can be formed from one or more passes of the laser beam over the substrate. As can be seen from this view along the long axis of the trench, the trench has a contoured configuration. Other configurations can include tapered and stepped configurations, among others.

[0069] FIG. 7b shows an embodiment of a cross section taken along the long axis of the substrate and showing a second trench 704 having a length 1₂ where 1₂ is less than 1₁, formed through the second surface 212 to intercept at least portions of the first trench to form a through-slot 204h. The second trench can be formed utilizing various substrate removal techniques, including but not limited to: sand drilling, dry etching, wet etching, laser micromachining, and mechanical machining. If laser machining is used as the second removal technique, the laser beam can have the same properties as the laser beam used to make the first trench or feature, or the second laser beam can have different properties. For example, in one embodiment a first laser beam having a wavelength of about 1100 nm can be used to cut a first trench followed by a second laser beam having a wavelength of about 355 nm to remove additional material. Such an exemplary embodiment can take advantage of the various cutting properties of different wavelength lasers.

[0070] In the example given in FIGS. 7a and 7b, the first trench or feature is formed first using the laser machining process followed by a subsequent removal process forming the second trench. Such need not be the case, for example in some embodiments, substrate material can be removed from a first side using sand drilling, among others. This process can then be followed by laser machining to remove additional substrate material. In these embodiments, the laser machining process can be conducted from the same side or surface as the sand drilling process or from an opposite second side.

[0071] Other exemplary embodiments can employ additional intermediary steps to achieve a desired feature. Some intermediary steps can apply or deposit material that is further configured by subsequent removal steps.

[0072] The various exemplary embodiments have so far been described in the context of cutting or forming trenches,

vias and slots in a substrate. However, the exemplary embodiments can also be used wherever controlled, selective, removal of material is desired. This can include other processes such as cutting, dicing, singulating, and 3 dimensional machining in a variety of substrate materials. This can further include the micromachining of features either partially or completely through the substrate's thickness.

[0073] For example, in the semiconductor industry in recent years there has been a drive toward smaller and smaller devices for both size constraints of the product and for cost considerations. The more devices per semiconductor substrate or wafer, the lower the device cost. It is common for a semiconductor substrate to contain a plurality of devices, which require dicing or singulation before being packaged for assembly into an electronic device, such as a fluid ejecting device, ink-jet print head or some other device.

[0074] Traditionally in the industry, mechanical dicing saws have been used to singulate or dice these components. The existing technologies are restricted to straight line cuts in the substrate material, whereas the described laser micromachining embodiments can form features or cuts having complex shapes, straight, curved, non-continuous cuts, or any combination thereof.

[0075] The described embodiments can also accomplish this with kerf widths of 10 to 15 microns and lower. Conversely, mechanical dicing saws produce minimum kerf widths of 50 to 100 microns, depending on the substrate material and thickness. Smaller kerfs can result in more devices per wafer and therefore can lower device cost.

[0076] Further, mechanical dicing is a wet process that typically uses a cooling fluid for the cutting process. The described embodiments eliminate exposing the devices to potential damage from the cooling fluid, and also are very efficient with little or no redeposition of removed debris material. These and other features allow the described embodiments to better perform many micromachining tasks than existing technologies.

[0077] Exemplary Methods

[0078] FIG. 8 is a flow chart that helps to illustrate the various exemplary methods described herein.

[0079] Step 802 positions a substrate in an open air environment. Various examples of exemplary substrates have been described above. In this embodiment, the substrate can be positioned on a fixture 407 or other suitable structure. Step 804 directs or projects a laser beam at the substrate to energize a portion of the substrate material. Such energizing can cut or remove substrate material in some embodiments. Various exemplary laser machines and laser beams have been described above.

[0080] Step 806 introduces or directs an assist gas to a region of the substrate contacted by the laser beam. In some exemplary embodiments the assist gas can be directed to the interface region. Some exemplary embodiments supply the assist gas via one or more gas assist nozzles of various configurations, exemplary embodiments of which are described above. Various assist gases can be directed to the interface area and can increase the performance of the laser beam in cutting substrate material.

[0081] Conclusion

[0082] The described embodiments can utilize a laser beam to cut or micromachine substrates in an open air environment. In several embodiments, the laser beam cuts with greater efficiency and speed by supplying an assist gas to the interface area where the laser beam energizes substrate material. In particular, the laser beam, when supplied with assist gas, can form cuts with higher aspect ratios than existing technologies. Additionally, the cuts can be maintained closer to desired parameters and can have less variation in their dimensions, in some embodiments. Some of the described embodiments can form narrower cuts than present and past technology and the speed and efficiency of those cuts can be maintained through the depth of the cut, while forming a higher quality product than existing technologies. All of this can be achieved utilizing systems and methods that are conducive to production techniques.

[0083] Although the invention has been described in language specific to structural features and methodological steps, it is to be understood that the invention defined in the appended claims is not necessarily limited to the specific features or steps described. Rather, the specific features and steps are disclosed as preferred forms of implementing the claimed invention.

What is claimed is:

1. An apparatus for micromachining a substrate comprising:
 - an open air region within which substrates can be processed;
 - a laser source operably positioned relative to the open air region to generate a laser beam configured to energize substrate material of a substrate positioned within the open air region;
 - a gas supply that supplies a halogen containing assist gas into the open air region wherein at least some substrate material can be energized by the laser beam and wherein at least some of the energized substrate material can chemically react with the assist gas to form one or more compounds that can dissipate into the open air region.
2. The apparatus of claim 1, further comprising a fixture for positioning the substrate in the open air environment and upon which the substrate can be contacted by the laser beam and wherein the fixture can move the substrate in relation to the laser beam.
3. The apparatus of claim 1, further comprising a mechanism for moving the laser source relative to the substrate.
4. The apparatus of claim 1, further comprising a fixture that positions the substrate in the open air environment and upon which the substrate can be contacted by the laser beams and a mechanism that moves the laser source relative to the substrate, wherein the fixture and the mechanism can be used in combination to move the substrate in relation to the laser beam.
5. The apparatus of claim 1, wherein the laser beam is capable of energizing substrate material equal to or above a material removal threshold of the substrate.
6. The apparatus of claim 1, wherein the gas supply comprises at least one gas supply nozzle positioned to supply the assist gas in proximity to the substrate.
7. The apparatus of claim 6, wherein said at least one gas supply nozzle has a circular exit aperture.

8. The apparatus of claim 7, wherein said circular exit aperture has a diameter of about 1.0 mm.

9. The apparatus of claim 1, wherein the halogen containing assist gas comprises a halosulfide.

10. The apparatus of claim 1, wherein the halogen containing assist gas comprises a halocarbon.

11. The apparatus of claim 10, wherein the halocarbon comprises a fluorocarbon.

12. The apparatus of claim 11, wherein the fluorocarbon comprises 1,1,1,2 tetrafluoroethane.

13. The apparatus of claim 1, wherein the laser beam has a peak power density of at least about 1 GW/cm².

14. The apparatus of claim 1, wherein less than or equal to about 0.5 percent of the energized substrate material redeposits on the substrate.

15. The apparatus of claim 1, wherein the substrate comprises a semiconductor substrate for use in a fluid ejecting device.

16. The apparatus of claim 1, wherein the substrate comprises a wafer.

17. An apparatus for micromachining a substrate comprising:

a laser source operably positioned to generate a laser beam configured to make a cut by removing material from a substrate, wherein the laser beam is configurable to make a cut having an aspect ratio ranging from about 4.5 to about 11.25 and at said range of aspect ratios the laser beam removes greater than or equal to about 9,800,000 cubic microns of substrate material per joule of laser energy.

18. The apparatus of claim 17, wherein said substrate comprises crystalline silicon.

19. The apparatus of claim 17, wherein the laser beam has a wavelength between about 300 nm and about 1100 nm.

20. The apparatus of claim 17, wherein the laser beam has a wavelength of about 355 nm.

21. A method of processing a semiconductor substrate comprising:

positioning a substrate in an open air region;

energizing a portion of the substrate to promote removal of at least some substrate material; and,

introducing a halogen containing assist gas proximate to an energized portion of the substrate so that the assist gas chemically reacts with energized substrate material to form, at least in part, one or more volatile compounds.

22. The method of claim 21, wherein said act of energizing and said act of introducing form a slot in the substrate.

23. The method of claim 21, wherein said act of energizing and said act of introducing form a fluid feed slot in the substrate.

24. The method of claim 21, wherein said act of energizing and said act of introducing cuts the substrate into multiple pieces.

25. A method of laser micromachining a substrate comprising:

positioning a substrate in an open air environment, wherein the substrate has a thickness defined by opposing first and second surfaces; and,

cutting the substrate by directing a laser beam at the first surface of the substrate and introducing an assist gas proximate to a region of the substrate contacted by the laser beam.

26. The method of claim 25, wherein said introducing comprises introducing multiple assist gases.

27. The method of claim 25, wherein said cutting forms a slot generally free of redeposited substrate material.

28. The method of claim 25, wherein said cutting forms a slot generally free of redeposited substrate material during said act of cutting.

29. The method of claim 25, wherein said cutting forms a via having an aspect ratio of at least about 10.

30. The method of claim 25, wherein said cutting forms a via having an aspect ratio ranging from about 10 to about 20.

31. The method of claim 25, wherein said cutting forms a via having an aspect ratio of at least about 20.

32. The method of claim 25, wherein said cutting forms a slot at least a portion of which is contoured.

33. The method of claim 25 further comprising removing additional material from the substrate that, in combination with said cutting, forms a desired feature in the substrate.

34. The method of claim 33, wherein the removing is accomplished from the second surface of the substrate.

35. The method of claim 33, wherein the removing comprises one or more of:

sand drilling, dry etching, wet etching, and mechanical machining.

36. The method of claim 33, wherein the removing comprises laser machining.

37. The method of claim 36, wherein said laser machining comprises laser machining with a laser beam having a wavelength different from the wavelength of the laser beam utilized in said cutting.

38. A method of processing a substrate comprising:

positioning a substrate in an open air environment;

projecting a laser beam at the substrate; and,

directing a halogen containing assist gas toward an area of the substrate contacted by the laser through one or more gas supply nozzles oriented at an angle between about 45 and about 90 degrees relative to a first surface of the substrate.

39. The method of claim 38, wherein said directing supplies sufficient concentrations of the assist gas to maintain the assist gas as an excess reagent.

40. The method of claim 38, wherein said directing supplies the assist gas at a rate of between about 0.08 gm/sec to about 0.5 gm/sec where the assist gas is 1,1,1,2 tetrafluoroethane.

41. The method of claim 38, wherein said directing supplies the assist gas at a rate of about 0.33 gm/sec where the assist gas is 1,1,1,2 tetrafluoroethane.

42. A method of processing a semiconductor substrate comprising:

directing a laser beam at a print head substrate positioned in an open air environment;

introducing a halogen containing assist gas proximate a region of the substrate at which the laser is directed; and,

wherein the laser beam in the presence of the assist gas forms a cut in the substrate having an aspect ratio of at least about 10.

43. The method of claim 42, wherein said introducing allows the laser beam to maintain a kerf in the substrate of essentially uniform dimensions during the cut.

44. A method of processing a semiconductor substrate comprising:

positioning a substrate in an open air region for processing; and,

removing material from the substrate by directing a laser beam and a halogen containing assist gas at a portion of the substrate, wherein less than about 1.0 percent of removed substrate material redeposits on the substrate.

45. A method of laser micromachining a substrate comprising:

positioning a substrate to be contacted by a laser beam; and,

directing a laser beam at the substrate to form a cut having an aspect ratio in a range from about 4.5 to about 11.25, and wherein said directing removes at least about 9,800,000 cubic microns of substrate material per joule of laser energy for said range of aspect ratios.

46. The method of claim 45, wherein said directing comprises directing a laser beam having a wavelength between about 300 nm and about 1100 nm.

47. The method of claim 45, wherein said directing comprises directing a laser beam having a wavelength of about 355 nm.

48. The method of claim 45, wherein said directing removes substrate material at a generally constant removal rate through the depth of the cut.

49. A method of processing a substrate comprising:

positioning a substrate in an open air environment;

cutting substrate material by directing a laser beam at the substrate and providing an assist gas to an area of the substrate contacted by the laser beam; and,

wherein said cutting occurs in the open air environment, and wherein said cutting process maintains a generally constant cutting rate for the depth of the cut.

50. The method of claim 49, wherein said cutting dices the substrate into multiple pieces.

51. A method of cutting features on a semiconductor substrate comprising:

positioning a substrate in an open air environment;

supplying an assist gas to an area of the substrate to be cut; and,

cutting a feature into the substrate by directing a laser beam at the substrate in the presence of the assist gas to form a feature having an aspect ratio of greater than or equal to 10.

52. The method of claim 51, wherein said cutting a feature comprises making multiple laser beam passes over the substrate to achieve said feature.

53. One or more computer-readable media having computer readable instructions thereon which, when executed by a computer, cause the computer to:

cause a laser beam to be directed at a substrate positioned in an open air environment; and,

cause an assist gas to be introduced to a region where the laser beam contacts the substrate.

54. A method of processing a semiconductor substrate comprising:

means for positioning a substrate in an open air region;

means for energizing a portion of the substrate to promote removal of at least some substrate material; and,

means for introducing an assist gas proximate an energized portion of the substrate so that the assist gas chemically reacts with energized substrate material to form at least in part one or more volatile compounds.

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