



(51) International Patent Classification:

H05K 3/00 (2006.01) B23K 26/06 (2006.01)

H05K 3/40 (2006.01) B23K 26/073 (2006.01)

(21) International Application Number:

PCT/US2021/037375

(22) International Filing Date:

15 June 2021 (15.06.2021)

(25) Filing Language:

English

(26) Publication Language:

English

(30) Priority Data:

16/928,252 14 July 2020 (14.07.2020) US

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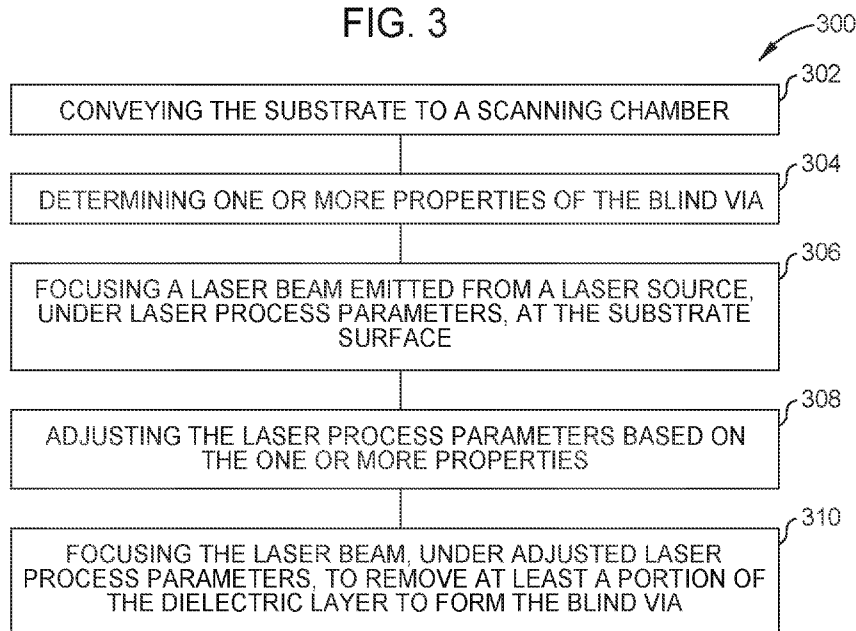
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(81) Designated States (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, IT, JO, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO,

(54) Title: METHOD AND APPARATUS FOR LASER DRILLING BLIND VIAS

FIG. 3



(57) Abstract: In an embodiment is provided a method of forming a blind via in a substrate comprising a mask layer, a conductive layer, and a dielectric layer that includes conveying the substrate to a scanning chamber; determining one or more properties of the blind via, the one or more properties comprising a top diameter, a bottom diameter, a volume, or a taper angle of about 80° or more; focusing a laser beam at the substrate to remove at least a portion of the mask layer; adjusting the laser process parameters based on the one or more properties; and focusing the laser beam, under the adjusted laser process parameters, to remove at least a portion of the dielectric layer within the volume to form the blind via. In some embodiments, the mask layer can be pre-etched. In another embodiment is provided an apparatus for forming a blind via in a substrate.

NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW,
SA, SC, SD, SE, SG, SK, SL, ST, SV, SY, TH, TJ, TM, TN,
TR, TT, TZ, UA, UG, US, UZ, VC, VN, WS, ZA, ZM, ZW.

- (84) Designated States** (*unless otherwise indicated, for every kind of regional protection available*): ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:

— *with international search report (Art. 21(3))*

METHOD AND APPARATUS FOR LASER DRILLING BLIND VIAS

BACKGROUND

Field

[0001] Embodiments of the present disclosure generally relate to methods and apparatus for drilling blind vias.

Description of the Related Art

[0002] With increasing demand for miniaturized electronic devices and components, the demand for faster processing capabilities with greater circuit densities imposes demands on the materials, structures, and processes used in the fabrication of integrated circuit chips and printed circuit boards. Incorporating blind vias enable more connections and greater circuit density. Laser drilling is an established method for forming blind vias.

[0003] Alongside the trend toward smaller vias, e.g., diameters from 5 μm to 10 μm , for higher interconnect density, certain blind via quality parameters remain. These include via top diameter and roundness, via bottom diameter and roundness, via taper angle (80° or more), and via pad cleanliness. However, conventional laser-drilling technologies cannot form quality blind vias having such small diameters for high-volume manufacturing.

[0004] Conventional approaches for laser drilling blind vias use nanosecond-pulsed 355 nm ultraviolet (UV) lasers or pulsed CO₂ lasers to directly drill blind vias in panels. However, both these approaches require complex beam shaping optics to convert the Gaussian laser beam profile emitted by the laser sources into a top-hat shaped beam profile. Further, top-hat shaped laser beam profiles generally have a very short depth-of-field within which the laser beam profile remains equal in intensity. Moreover such top-hat beam profiles are not capable of drilling diameters less than 40 μm , particularly 5 μm to 10 μm , in a consistent and cost-effective manner.

Moreover, conventional laser drilling methods cannot enable blind vias having a taper angle of 80° or more.

[0005] There is a need for new and improved methods and apparatus for drilling high-quality, small-diameter blind vias in high volumes.

SUMMARY

[0006] Embodiments of the present disclosure generally relate to methods and apparatus for drilling blind vias. In an embodiment is provided a method of forming a blind via in a substrate that includes conveying the substrate to a scanning chamber, the substrate comprising a conductive layer, a dielectric layer disposed on at least a portion of the conductive layer, and a mask layer disposed on at least a portion of the dielectric layer, the mask layer providing a substrate surface. The method further includes determining one or more properties of the blind via, the one or more properties comprising: a top diameter of the blind via and a bottom diameter of the blind via, the blind via having a height from the top diameter to bottom diameter, the top diameter being greater than the bottom diameter; a volume of the blind via, the volume corresponding to the top diameter, the bottom diameter, and the height; or a taper angle of about 80 degrees or more. The method further includes focusing a laser beam emitted from a laser source, under laser process parameters, at the substrate surface to remove at least a portion of the mask layer; adjusting the laser process parameters based on the one or more properties; and focusing the laser beam, under the adjusted laser process parameters, to remove at least a portion of the dielectric layer within the volume to form the blind via.

[0007] In another embodiment is provided a method of forming a blind via in a substrate that includes conveying the substrate to a scanning chamber, the substrate comprising a conductive layer of about 2 μm or more in height, a dielectric layer disposed on at least a portion of the conductive layer, and a pre-etched mask layer disposed on at least a portion of the dielectric layer, the pre-etched mask layer having blind via openings to expose at least a portion of the dielectric layer and the dielectric layer providing a substrate

surface. The method further includes determining one or more properties of the blind via, the one or more properties comprising: a top diameter of the blind via and a bottom diameter of the blind via, the blind via having a height from the top diameter to bottom diameter, the top diameter being greater than the bottom diameter, and the top diameter corresponding to the blind via openings; a volume of the blind via, the volume corresponding to the top diameter, the bottom diameter, and the height; or a taper angle of 80 degrees or more. The method further includes focusing a laser beam emitted from a laser source, under laser process parameters, at the substrate surface to remove a first portion of the dielectric layer within the volume without causing more than half-of-the thickness of mask layer damage to the pre-etched mask layer; adjusting laser process parameters based on the one or more properties; and focusing the laser beam, under the adjusted laser process parameters, to remove a second portion of the dielectric layer within the volume to form the blind via.

[0008] In another embodiment is provided an apparatus for forming a blind via in a substrate that includes an optical device comprising a galvanometer scanner having a plurality of reflecting facets and an axis of rotation; and a beam expander and collimator. The apparatus further comprises a femtosecond laser beam source configured to direct electromagnetic radiation to the beam expander; a transport assembly configured to position the substrate to receive the electromagnetic radiation reflected from at least one of the reflecting facets of the galvanometer scanner; a height sensor configured to detect a height of one or more layers of the substrate; and a controller configured to: receive signals from the height sensor; and control the femtosecond beam laser source and the transport assembly based on signals received from the height sensor.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] So that the manner in which the above recited features of the present disclosure can be understood in detail, a more particular description of the disclosure, briefly summarized above, may be had by reference to

embodiments, some of which are illustrated in the appended drawings. It is to be noted, however, that the appended drawings illustrate only exemplary embodiments and are therefore not to be considered limiting of its scope, and may admit to other equally effective embodiments.

[0010] FIG. 1A is an example substrate according to at least one embodiment of the present disclosure.

[0011] FIG. 1B is an example substrate according to at least one embodiment of the present disclosure.

[0012] FIG. 1C is an example substrate with a blank mask layer according to at least one embodiment of the present disclosure.

[0013] FIG. 1D illustrates an example substrate with a pre-etched mask layer according to at least one embodiment of the present disclosure.

[0014] FIG. 2A is an example substrate after forming a blind via according to at least one embodiment of the present disclosure.

[0015] FIG. 2B is an example substrate after forming a blind via in a substrate having a blank mask layer according to at least one embodiment of the present disclosure.

[0016] FIG. 2C is an example substrate after forming a blind via in a substrate having a pre-etched mask layer according to at least one embodiment of the present disclosure.

[0017] FIG. 3 is an example method of forming a blind via in a substrate according to at least one embodiment of the present disclosure.

[0018] FIG. 4 is an example method of forming a blind via in a substrate according to at least one embodiment of the present disclosure.

[0019] FIG. 5 is a schematic plan view of an example substrate having a plurality of blind vias formed by apparatus and methods disclosed herein according to at least one embodiment of the present disclosure.

[0020] FIG. 6A is a schematic side view of an example laser drilling system according to at least one embodiment of the present disclosure.

[0021] FIG. 6B is an enlarged side view of the example optical device of FIG. 6A according to at least one embodiment of the present disclosure.

[0022] FIG. 7 is an isometric view of an example laser drilling tool having the example laser drilling system of FIG. 6A disposed therein according to at least one embodiment of the present disclosure.

[0023] FIG. 8 is a side view of an example embodiment of the optical alignment device of FIG. 7 according to at least one embodiment of the present disclosure.

[0024] FIG. 9 is an isometric view of the example optical alignment device of FIG. 8 according to at least one embodiment of the present disclosure.

[0025] To facilitate understanding, identical reference numerals have been used, where possible, to designate identical elements that are common to the Figures. It is contemplated that elements and features of one embodiment may be beneficially incorporated in other embodiments without further recitation.

DETAILED DESCRIPTION

[0026] Embodiments of the present disclosure generally relate to methods and apparatus for drilling blind vias. The inventors have discovered a method and apparatus to laser drill blind vias in a panel that includes a conductive layer and an insulating layer. Unlike conventional laser drilling methods and apparatus, the method and apparatus described herein can enable formation of blind vias having taper angles greater than about 80°, and can enable formation of blind vias having diameters of less than about 40 μm , such as about 5 μm to about 10 μm . The methods and apparatus herein enable formation of quality blind vias for high-volume manufacturing.

[0027] Alongside the trend toward smaller diameter blind vias, e.g., diameters from 5 μm to 10 μm , for higher interconnect density, certain blind via quality parameters remain. These include via top diameter and roundness, via bottom diameter and roundness, via taper angle (80° or more), and via pad cleanliness. However, conventional laser-drilling technologies cannot form quality blind vias having such small diameters for high volume manufacturing.

[0028] Conventional approaches for laser drilling blind vias use nanosecond-pulsed 355 nm ultraviolet (UV) lasers or pulsed CO₂ lasers to directly drill blind vias in panels. These approaches have certain limitations. First, the Gaussian laser beam profile emitted by the laser sources requires complex beam-shaping optics to convert the beam into a top-hat shaped beam profile. Second, the beam-shaping optics employed result in about 40% optical energy loss. Third, the intensity profile of the top-hat shaped beam has a very short depth-of-field (DOF) within which the laser beam profile remains equal in intensity. Here, the intensity profile of the output top-hat beam deforms/degrades quickly from the image plane along the beam propagation axis because of its non-uniform phase distribution, which limits its application in imaging with large DOF. A smaller diameter top-hat image beam has a shorter DOF, and as the DOF becomes shorter than the variation range of panel thickness/chuck flatness, it is difficult to ensure that the top-hat beam always intersects the panel surface on each via drilling location, so the via quality is inconsistent, particularly for high-volume manufacturing. This inability to achieve consistent via quality at higher throughput is not cost-effective. Another conventional method employs a deep ultraviolet (DUV) light excimer laser with a wavelength of 193 to 308 nm. A mask projection converts the laser beam to a top-hat shaped beam profile. This method also has certain limitations. First, the equipment, e.g., laser and optics, and maintenance thereon can be expensive. Second, the intensity profile of the top-hat shaped beam has a very short DOF, thereby limiting its application. Third, the mask is consumable. The methods and apparatus described herein

can eliminate (or at least mitigate) the aforementioned deficiencies of conventional approaches to laser drill blind vias.

Substrate

[0029] FIG. 1A is an example substrate 100 according to at least one embodiment. The example substrate 100 can be utilized for structural support and electrical interconnection of semiconductor packages. The example substrate 100 generally includes a core structure 102, a conductive layer 104, and an insulating layer 106.

[0030] In at least one embodiment, the core structure 102 includes a patterned (e.g., structured) substrate formed of any suitable substrate material. For example, the core structure 102 can include a substrate formed from a III-V compound semiconductor material, silicon, crystalline silicon (e.g., Si<100> or Si<111>), silicon oxide, silicon germanium, doped or undoped silicon, doped or undoped polysilicon, silicon nitride, quartz, glass (e.g., borosilicate glass), sapphire, alumina, and/or ceramic materials. In at least one embodiment, the core structure 102 includes a monocrystalline p-type or n-type silicon substrate. In some embodiments, the core structure 102 includes a polycrystalline p-type or n-type silicon substrate. In another embodiment, the core structure 102 includes a p-type or an n-type silicon solar substrate. The substrate utilized to form the core structure 102 can further have a polygonal or circular shape. For example, the core structure 102 can include a substantially square silicon substrate having lateral dimensions from about 120 to and about 180 mm, with or without chamfered edges. In another example, the core structure 102 includes a circular silicon-containing wafer having a diameter from about 20 mm to about 700 mm, such as from about 100 mm to about 50 mm, for example about 300 mm.

[0031] The conductive layer 104 is formed on one or more surfaces of the core structure 102. The conductive layer 104 can be formed of a metallic material, such as copper (Cu), tungsten (W), chromium (Cr), molybdenum (Mo), aluminum (Al), gold (Au), nickel (Ni), palladium (Pd), or the like, or a combination thereof. In at least one embodiment, the conductive layer

includes a layer of tungsten on copper. In at least one embodiment, the conductive layer 104 has a height H_0 that is about 100 μm or less, such as about 50 μm or less, such as 25 μm or less. For example, the conductive layer 104 can have a height H_0 from about 5 μm to about 20 μm , such as a height H_0 from about 7 μm to about 18 μm , such as from about 10 μm to about 15 μm . In at least one embodiment, the height H_0 ranges from H_{0a} to H_{0b} , where H_{0a} to H_{0b} can be, independently, e.g., about 1 μm , about 2 μm , about 3 μm , about 4 μm , about 5 μm , about 6 μm , about 7 μm , about 8 μm , about 9 μm , about 10 μm , about 11 μm , about 12 μm , about 13 μm , about 14 μm , about 15 μm , about 16 μm , about 17 μm , about 18 μm , about 19 μm , or about 20 μm , as long as $H_{0a} < H_{0b}$.

[0032] The insulating layer 106 is formed on one or more surfaces of the conductive layer 104. In at least one embodiment, the insulating layer 106 is formed of polymer-based dielectric materials. For example, the insulating layer 106 is formed from a flowable build-up material, typically in the form of a dry film. Accordingly, although hereinafter referred to as an “insulating layer,” the insulating layer 106 can also be described as a dielectric layer. In some embodiments, the insulating layer 106 is formed of an epoxy resin material having a ceramic filler, such as silica (SiO_2) particles. Other examples of ceramic fillers that can be utilized to form the insulating layer 106 include aluminum nitride (AlN), aluminum oxide (Al_2O_3), silicon carbide (SiC), silicon nitride (Si_3N_4 , $\text{Sr}_2\text{Ce}_2\text{Ti}_5\text{O}_{16}$, zirconium silicate (ZrSiO_4), wollastonite (CaSiO_3), beryllium oxide (BeO), cerium dioxide (CeO_2), boron nitride (BN), calcium copper titanium oxide ($\text{CaCu}_3\text{Ti}_4\text{O}_{12}$), magnesium oxide (MgO), titanium dioxide (TiO_2), zinc oxide (ZnO) and the like. In some examples, the ceramic fillers utilized to form the insulating layer 106 have particles ranging in size between about 40 nm and about 1.5 μm , such as between about 80 nm and about 1 μm . For example, the ceramic fillers have particles ranging in size between about 200 nm and about 800 nm, such as between about 300 nm and about 600 nm. In some embodiments, the insulating layer is a polymer with or without particle reinforcement. The insulating layer can be a dry dielectric film or a liquid dielectric film.

[0033] In at least one embodiment, the insulating layer 106 has a height H_1 that is about 100 μm or less, such as about 50 μm or less, such as 25 μm or less. For example, the insulating layer 106 can have a height H_0 from about 5 μm to about 20 μm , such as a height H_1 from about 7 μm to about 18 μm , such as from about 10 μm to about 15 μm . In at least one embodiment, the height H_1 ranges from H_{1a} to H_{1b} , where H_{1a} to H_{1b} can be, independently, e.g., about 1 μm , about 2 μm , about 3 μm , about 4 μm , about 5 μm , about 6 μm , about 7 μm , about 8 μm , about 9 μm , about 10 μm , about 11 μm , about 12 μm , about 13 μm , about 14 μm , about 15 μm , about 16 μm , about 17 μm , about 18 μm , about 19 μm , or about 20 μm , as long as $H_{1a} < H_{1b}$.

[0034] FIG. 1B is an example substrate 150 according to at least one embodiment. The example substrate 150 can be utilized for structural support and electrical interconnection of semiconductor packages. The example substrate 150 generally includes a core structure 152, conductive layers 154a, 154b formed on opposing surfaces of the core structure 152, an insulating layer 156a formed on a surface of the conductive layer 154a, and an insulating layer 156b formed on a surface of the conductive layer 154b. Example properties and characteristics of the core structure 152, conductive layers 154a, 154b, and insulating layers 156a, 156b are similar to those described above with respect to the core structure 102, conductive layer 104, and insulating layer 106, respectively.

[0035] FIG. 1C is an example substrate 170 with a blank mask layer (e.g., not pre-etched) according to at least one embodiment. The example substrate 170 can be utilized for structural support and electrical interconnection of semiconductor packages. The example substrate 170 generally includes a core structure 172, a conductive layer 174 formed on a surface of the core structure 172, an insulating layer 176 formed on a surface of the conductive layer 174, and a mask layer 178 formed on a surface of the insulating layer 176. Example properties and characteristics of the core structure 172, conductive layer 174, and insulating layer 176 are similar to those described above with respect to the core structure 102, conductive layer 104, and insulating layer 106, respectively.

[0036] In at least one embodiment, the mask layer 178 comprises Al, Cu, W, Mo, Cr, or a combination thereof. In some embodiments the mask layer (with or without openings) has a height H_2 of about 2 μm or less, such as from about 0.03 μm to about 2 μm or from about 0.05 μm to about 1 μm . In at least one embodiment, the height H_2 ranges from H_{2a} to H_{2b} , where H_{2a} to H_{2b} can be, independently, e.g., about 0.1 μm , about 0.2 μm , about 0.3 μm , about 0.4 μm , about 0.5 μm , about 0.6 μm , about 0.7 μm , about 0.8 μm , about 0.9 μm , about 1 μm , about 1.1 μm , about 1.2 μm , about 1.3 μm , about 1.4 μm , about 1.5 μm , about 1.6 μm , about 1.7 μm , about 1.8 μm , about 1.9 μm , or about 2 μm , as long as $H_{2a} < H_{2b}$.

[0037] The mask layer 178 can be formed by, e.g., deposition, sputter, or electrical plating. In at least one embodiment, the mask layer is laser ablated. In some embodiments, the mask layer 178 is removed by an etching operation after the blind via has been formed by processes described herein. In some embodiments, such as when the mask layer 178 is Mo and/or W, the mask is maintained after the blind via has been formed and is combined with a to-be-deposited conductive layer (e.g., Cu) to function as an interconnect layer.

[0038] In at least one embodiment, and referring again to FIG. 1B, the example substrate includes a mask on a surface of insulating layer 156a and/or a surface of insulating layer 156b. The mask layer can be blank or pre-etched to form via openings. Characteristics of each mask layer are similar to that described above in relation to mask layer 178.

[0039] FIG. 1D is an example substrate 180 with a pre-etched (or pre-opened) mask layer according to at least one embodiment. Here, the example substrate 180 is pre-etched to form via openings. The example substrate 180 can be utilized for structural support and electrical interconnection of semiconductor packages. The example substrate 180 generally includes a core structure 182, a conductive layer 184 formed on a surface of the core structure 182, an insulating layer 186 formed on a surface of the conductive layer 184, and a mask layer 188 formed on a surface of the

insulating layer 186. Example properties and characteristics of the core structure 182, conductive layer 184, and insulating layer 186 are similar to those described above with respect to the core structure 102, conductive layer 104, and insulating layer 106, respectively. Example properties and characteristics of the mask layer 188 are similar to those of mask layer 178 described above.

[0040] FIG. 2A is an example substrate 200 after forming a blind via in the example substrate 100 (shown in FIG. 1A) according to at least one embodiment. The example substrate 200 generally includes a core structure 202, a conductive layer 204, and an insulating layer 206. The blind via 208 extends from a surface of the insulating layer 206 to the conductive layer 204. The blind via 208 has a top diameter D_1 , a bottom diameter D_2 , a taper angle (A_1), and a volume V_1 . In some embodiments, the blind via 208 penetrates, or minimally penetrates, the conductive layer 204. In some embodiments, the blind via does not penetrate, or substantially does not penetrate, the conductive layer 204.

[0041] The diameters of the top diameter D_1 and the bottom diameter D_2 can be about 20 μm or less, such as about 15 μm or less, such as from about 5 μm to about 10 μm . In at least one embodiment, the top diameter D_1 ranges from D_{1a} to D_{1b} , where D_{1a} to D_{1b} can be, independently, e.g., about 1 μm , about 2 μm , about 3 μm , about 4 μm , about 5 μm , about 6 μm , about 7 μm , about 8 μm , about 9 μm , about 10 μm , about 11 μm , about 12 μm , about 13 μm , about 14 μm , about 15 μm , about 16 μm , about 17 μm , about 18 μm , about 19 μm , or about 20 μm , as long as $D_{1a} < D_{1b}$. In at least one embodiment, the bottom diameter D_2 ranges from D_{2a} to D_{2b} , where D_{2a} to D_{2b} can be, independently, e.g., about 1 μm , about 2 μm , about 3 μm , about 4 μm , about 5 μm , about 6 μm , about 7 μm , about 8 μm , about 9 μm , about 10 μm , about 11 μm , about 12 μm , about 13 μm , about 14 μm , about 15 μm , about 16 μm , about 17 μm , about 18 μm , about 19 μm , or about 20 μm , as long as $D_{2a} < D_{2b}$.

[0042] In some embodiments, the bottom diameter D_2 is less than the top diameter D_1 , such that the blind via has a taper. The taper corresponds to a ratio of the bottom diameter D_2 to top diameter D_1 . In at least one embodiment, the ratio of the bottom diameter D_2 to the top diameter D_1 is from about $0.353 \cdot H_{IL}$ (where H_{IL} is the height of the insulating layer, e.g., insulating layer 206) to about 1, such as from about $0.4 \cdot H_1$ to about 1, such as from about $0.5 \cdot H_1$ to about 1.

[0043] In at least one embodiment, the blind via 208 has a taper angle A_1 which corresponds to the angle between the interior wall of the blind via 208 and a surface of the conductive layer 204. In at least one embodiment, the taper angle A_1 is from about 75° to 90° , such as from about 80° to about 89° . In at least one embodiment, the taper angle A_1 ranges from A_{1a} to A_{1b} , where A_{1a} to A_{1b} can be, independently, e.g., about 71° , about 72° , about 73° , about 74° , about 75° , about 76° , about 77° , about 78° , about 79° , about 80° , about 81° , about 82° , about 83° , about 84° , about 85° , about 86° , about 87° , about 88° , about 89° , or about 90° , as long as $A_{1a} < A_{1b}$.

[0044] FIG. 2B is an example substrate 250 after forming a blind via in the example substrate 170 having a blank mask (shown in FIG. 1C) according to at least one embodiment. The example substrate 250 generally includes a core structure 252, a conductive layer 254, an insulating layer 256, and a mask layer 260. The blind via is shown by reference numeral 258. Characteristics of core structure 252, conductive layer 254, insulating layer 256, height H_0 , height H_1 , diameter D_1 , diameter D_2 , and taper angle A_1 are similar to those described above. Angle A_2 can correspond substantially to taper angle A_1 and/or can have similar characteristics of taper angle A_1 . In at least one embodiment, A_2 is equal to or smaller than A_1 . In at least one embodiment, the taper angle A_2 ranges from A_{2a} to A_{2b} , where A_{2a} to A_{2b} can be, independently, e.g., about 71° , about 72° , about 73° , about 74° , about 75° , about 76° , about 77° , about 78° , about 79° , about 80° , about 81° , about 82° , about 83° , about 84° , about 85° , about 86° , about 87° , about 88° , about 89° , or about 90° , as long as $A_{2a} < A_{2b}$.

[0045] In some embodiments, diameter D_3 of mask layer 260 is about equal to diameter D_1 or larger, such as from about diameter D_1 to about diameter $D_1 + 5\mu\text{m}$, such as about diameter $D_1 + 4\mu\text{m}$, about diameter $D_1 + 3\mu\text{m}$, about diameter $D_1 + 2\mu\text{m}$, or about diameter $D_1 + 1\mu\text{m}$. In at least one embodiment, diameter $D_3 \geq$ diameter $D_1 \geq$ diameter D_2 . The blind via can correspond to reference numeral 258 when the mask layer is removed from the substrate after processing, or can correspond to numeral 262 when the mask layer is maintained on the substrate after processing.

[0046] FIG. 2C is an example substrate 270 after forming a blind via in the example substrate 180 having a pre-etched/pre-opened mask (shown in FIG. 1D) according to at least one embodiment. The example substrate 270 generally includes a core structure 272, a conductive layer 274, an insulating layer 276, and a mask layer 280. The blind via is shown by reference numeral 278. Characteristics of core structure 272, conductive layer 274, insulating layer 276, height H_0 , height H_1 , diameter D_1 , diameter D_2 , taper angle A_1 , and taper angle A_2 are similar to those described above. In at least one embodiment, taper angle A_2 is substantially 90° or corresponds substantially to taper angle A_1 . In at least one embodiment, taper angles A_1 and A_2 are, independently, e.g., about 71° , about 72° , about 73° , about 74° , about 75° , about 76° , about 77° , about 78° , about 79° , about 80° , about 81° , about 82° , about 83° , about 84° , about 85° , about 86° , about 87° , about 88° , about 89° , or about 90° . Taper angle A_1 can be equal to, less than, or greater than taper angle A_2 . Diameter D_3 (in units of μm) of mask layer 280 can be about $(D_1 + H_2)$ or less, such as from about D_1 to about $(D_1 + (1/4)H_2)$, such as from about D_1 to about $(D_1 + (1/3)H_2)$, such as from about D_1 to about $(D_1 + (1/2)H_2)$. In at least one embodiment, diameter $D_3 \geq$ diameter D_1 .

[0047] In some embodiments, the allowable variation range of taper angle A_2 is wider than that of taper angle A_1 , e.g., $70^\circ \leq A_2 \leq 90^\circ$, $75^\circ \leq A_1 \leq 90^\circ$. In some examples, $80^\circ \leq A_1$ for 5-10 μm diameter vias; for larger than 10 μm vias, $75^\circ \leq A_1$.

[0048] In at least one embodiment, the mask layer (with or without openings) has a height of about 2 μm or less, such as from about 0.03 μm to about 2 μm or from about 0.05 μm to about 1 μm .

[0049] The mask layers described herein can be opened by photolithography. In some embodiments, a photoresist layer is applied on top of the metal mask. The photoresist layer can be patterned by photolithography to define the sizes and locations of via openings on the metal mask layer. The opening on the metal mask layer can be formed by etching processes, such as a plasma etch and a wet chemical etch. Lithography-defined openings can allow for relaxed positional accuracies and can permit improved laser throughput.

Processes

[0050] Embodiments described herein also include processes for laser drilling blind vias. The laser source for laser drilling blind vias can be a femtosecond laser. Suitable femtosecond-based laser processes can be characterized by a high peak intensity (irradiance) that usually leads to nonlinear interactions in various materials.

[0051] FIG. 3 shows an example method 300 of forming a blind via in a substrate according to at least one embodiment. In at least one embodiment, example method 300 is used on a substrate having a mask layer with no openings (i.e., blank). The example method 300 includes conveying the substrate to a scanning chamber at operation 302. Here, the substrate can include a conductive layer (e.g., a copper layer), a dielectric layer disposed on at least a portion of the conductive layer, and a mask layer disposed on at least a portion of the dielectric layer, the mask layer providing a substrate surface. The example method 300 further includes determining one or more properties of the blind via at operation 304. The one or more properties can include a top diameter of the blind via, a bottom diameter of the blind via, a height of the blind via, a volume of the blind via, and a taper angle of the blind via. In at least one embodiment, the taper angle is greater than 75° or greater

than 80° as described above. In some embodiments, the top diameter is greater than the bottom diameter, and the top diameter corresponds to the blind via opening. The volume of the blind via corresponds to the top diameter, the bottom diameter, and the height. The example method 300 further includes focusing a laser beam emitted from a laser source, under laser process parameters, at the substrate surface at operation 306. This operation can result in removing a first portion of the dielectric layer within the volume, while only causing gentle melting and polishing on the surface of the conductive layer underneath the dielectric layer, with the ablation depth in the conductive layer no more than, e.g., about 2 μm . In some embodiments, operation 306 results in removing about half-of the thickness of the mask layer or less. Accordingly, and in some embodiments, the conductive layer has no substantial damage after operation 306.

[0052] The example method 300 further includes adjusting the laser process parameters based on the one or more properties at operation 308. In some embodiments, the laser process parameters include a laser power, a laser energy in a burst, a focal beam diameter, a focus height, a burst energy, a pulse energy, a number of pulses in a burst, a pulse frequency, a burst frequency, a beam spot size, an M^2 value, an offset of beam focusing from substrate surface (either above and/or below the substrate surface), or a combination thereof. M^2 is a unitless laser beam spatial characteristic. It measures the difference between an actual laser beam and a Gaussian beam. These and other laser process parameters are described below. The example method 300 further includes focusing the laser beam, under adjusted laser process parameters, to remove at least a portion of the dielectric layer within the volume to form the blind via at operation 310.

[0053] In some embodiments, further operations are performed such as removing the mask layer from the substrate. In at least one embodiment, and when the mask layer comprises Mo and/or W, a further operation includes depositing a layer of copper on the mask layer.

[0054] FIG. 4 shows an example method 400 of forming a blind via in a substrate according to at least one embodiment. In at least one embodiment, example method 400 is used to form a blind via on a substrate having a pre-etched mask layer. The example method 400 includes conveying the substrate to a scanning chamber at operation 402. Here, the substrate can include a conductive layer (e.g., a copper layer), a dielectric layer disposed on at least a portion of the conductive layer, and a pre-etched mask layer disposed on at least a portion of the dielectric layer, the pre-etched mask layer having blind via openings to expose at least a portion of the dielectric layer and the dielectric layer providing a substrate surface. The example method 400 further includes determining one or more properties of the blind via at operation 404. The one or more properties can include a top diameter of the blind via, a bottom diameter of the blind via, a height of the blind via, a volume of the blind via, and a taper angle of the blind via. In at least one embodiment, the taper angle is greater than 75° or greater than 80° as described above. In some embodiments, the top diameter is greater than the bottom diameter, and the top diameter corresponds to the blind via opening. The volume of the blind via corresponds to the top diameter, the bottom diameter, and the height. The example method 400 further includes focusing a laser beam emitted from a laser source, under laser process parameters, at the substrate surface at operation 406. This operation can result in removing a first portion of the dielectric layer within the volume, and can be performed without causing substantial damage to the pre-etched mask layer and/or without causing substantial damage to the conductive layer. “Without substantial damage to the pre-etched mask layer” refers to slightly melting the mask layer as to “shine/polish” mask surface but no visible ablation induced material removal from mask surface as to cause top via diameter change or induce oval shape of via. The mask is a sacrificial layer that can be removed. In at least one embodiment, the tolerable mask damage depends on the mask height. As a non-limiting example, if the mask height is about 0.3 μm , the damage/ablation depth into the mask should be less than about 0.3 μm . As another non-limiting example, if the mask height is about 2 μm , the damage/ablation depth into the mask should be less than about 2 μm .

[0055] The example method 400 further includes adjusting the laser process parameters based on the one or more properties at operation 408. In some embodiments, the laser process parameters include a laser power, a laser energy in a burst, a focal beam diameter, a focus height, a burst energy, a pulse energy, a number of pulses in a burst, a pulse frequency, a burst frequency, a beam spot size, an M^2 value, an offset of beam focusing from substrate surface, or a combination thereof. These and other laser process parameters are described below. The example method 400 further includes focusing the laser beam, under adjusted laser process parameters, to remove at least a portion of the dielectric layer within the volume to form the blind via at operation 410.

[0056] In some embodiments, further operations are performed, such as removing the pre-etched mask layer from the substrate. In at least one embodiment, and when the pre-etched mask layer comprises Mo and/or W, a further operation includes depositing a layer of copper on the pre-etched mask layer.

[0057] The femtosecond laser source (such as an ultraviolet laser) used in at least some embodiments herein has a number of adjustable characteristics (laser process parameters) as described below. In at least one embodiment, the laser process parameters include one or more of the following characteristics:

[0058] (1) The femtosecond laser source has a pulse width or pulse width range from about 1 femtosecond (fs) to about 1000 fs, such as from about 100 fs to about 750 fs, such as from about 200 fs to about 500 fs.

[0059] (2) The femtosecond laser source has a wavelength or wavelength range from about 250 nanometers (nm) to about 2000 nm, such as from about 266 nm to about 1500 nm, such as from about 350 nm to about 540 nm. In at least one embodiment, the femtosecond laser source has a wavelength of about 400 nm or lower.

[0060] (3) The femtosecond laser source and corresponding optical system provide a focal spot or focal spot range at the work surface in the range from about 1.5 microns (μm) to about 12 μm , such as from about 3 μm to about 10 μm , such as from about 4 μm to about 8 μm . The spatial beam profile at the work surface can be a single mode (Gaussian) profile.

[0061] (4) The femtosecond laser source outputs bursts of pulses. Within each burst, the pulse frequency or range of pulse frequency is about 500 MHz or more, such as about 1 GHz or more, such as 2 GHz or more, such as from about 1 GHz to about 10 GHz, such as from about 2 GHz to about 9 GHz, such as from about 3 GHz to about 8 GHz, such as from about 4 GHz to about 7 GHz, such as from about 5 GHz to about 6 GHz. In at least one embodiment, the pulse frequency or range of pulse frequency within each burst is from about 2 GHz to about 5 GHz.

[0062] (5) The number of pulses in each burst outputted from the femtosecond laser source can be adjusted. The number of pulses in each burst can be about 2 or more, or about 3 or more, such as from about 5 to about 100, such as from about 10 to about 100, such as from about 20 to about 90, such as from about 40 to about 80, such as from about 50 to about 70, such as from about 55 to about 65. In at least one embodiment, the number of pulses in each burst is from about 20 to about 100.

[0063] (6) The burst frequency can be adjusted. The burst frequency of the femtosecond laser source can be about 100 kHz or more, such as about 500 kHz or more. In at least one embodiment, the burst frequency is from about 200 kHz to about 5 MHz or from about 500 KHz to about 5 MHz, such as from about 300 KHz to about 2 MHz, from about 1 MHz to about 2 MHz, or from about 500KHz to about 1 MHz.

[0064] (7) The femtosecond laser source delivers an amount of laser energy in a burst from about 1 μJ to about 100 μJ , such as from about 1 μJ to about 80 μJ , such as from about 3 μJ to about 50 μJ , such as from about 5 μJ to about 20 μJ . In at least one embodiment, the laser and the burst frequency are set to achieve an amount of laser energy in a burst that can be about 5 μJ

or more, such as from about 5 μJ to about 50 μJ , such as from about 10 μJ to about 30 μJ .

[0065] (8) The laser power of the femtosecond laser source is about 1 W or more, such as from about 1 W to about 100 W, such as from about 5 W to about 80 W, such as from about 10 W to about 50 W.

[0066] (9) The M^2 value that characterizes laser beam quality is about 1.5 or less (M^2 is always ≥ 1.0), such as from about 1 to about 1.3, such as from about 1.1 to about 1.2, or from about 1 to about 1.15, or from about 1 to about 1.1.

[0067] (10) The focal beam diameter can be from about 2 μm to about 10 μm , such as from about 3 μm to about 6 μm for drilling 5 μm diameter vias. The focal beam diameter can be from about 7 μm to about 12 μm , such as from about 8 to about 11 μm for drilling 10 μm diameter vias. The focal beam diameter is the laser beam spot diameter at the work surface, which is the result of the output laser beam going through a beam expander and then being focused by a focusing lens.

[0068] (11) The offset of beam focusing from a substrate, which is also called the focus height, is from about 0 μm to 100 μm , such as from about 0 μm to about 50 μm , such as from about 0 μm to about 30 μm . Focus height is an adjustable parameter. In some embodiments, for example, the focal spot is set right on the panel surface to cut through the mask and remove some of the insulating layer material, and then the focus height is adjusted so that the focal plane is above the panel surface—that is, to set the laser beam intersecting panel surface off-focus to get a lower fluence that can only remove the insulating layer material but not damage mask layer and conductive layer at the via bottom.

[0069] (12) The number of bursts are about 2 or more, such as from about 5 to about 20.

[0070] (13) The focused beam spot size is about 80% to about 120% of the targeted entry diameter of the hole at the dielectric surface (e.g., entry diameter D_1 of the hole to be drilled as defined in FIG. 2C or the diameter D_1 of the hole to be drilled as defined in FIG. 2B), such as from about 90% to about 110%, such as from about 95% to about 100%.

[0071] The focused beam diameter can be adjustable using a programmable beam expander to drill different diameter vias.

[0072] The femtosecond laser source can be an electromagnetic radiation source such as a diode-pumped solid state (DPSS) laser or other similar radiation emitting sources that can provide and emit a continuous or pulsed beam. According to the lasing medium (crystal) configuration, and in at least one embodiment, the DPSS lasers can be a rod crystal laser, a fiber laser, a disc laser, a rod-type photonic crystal fiber laser, an innoslab laser, or a hybrid of them. In some embodiments, the laser source includes multiple laser diodes, each of which produces uniform and spatially coherent light at the same wavelength.

Apparatus

[0073] Embodiments of the present disclosure also generally relate to apparatus for laser drilling blind vias. FIG. 6A is a schematic side view of an example laser drilling system 600 for carrying out certain aspects of the present disclosure according to some embodiments.

[0074] The laser drilling system 600 includes an enclosure 602 having a substrate positioning system 605 therein. The substrate positioning system 605 can be a conveyor for supporting and transporting substrates 510 through the laser drilling system 600. The laser drilling system 600 can be used to drill blind vias 501 (Figure 5) in one or more layers disposed on a substrate 510 in accordance with embodiments of the present disclosure. Each substrate 510 can be an example substrate illustrated in FIGS. 1 and 2. In at least one embodiment, the mask of the substrate 510 can face upward for processing in the laser drilling system 600.

[0075] In at least one embodiment, the substrate positioning system 605 is a linear conveyor system that includes a transport belt 615, which can be continuous, of a material configured to support and transport a line of the substrates 510 through the laser drilling system 600 in a flow path "A". The enclosure 602 is positioned between a loading station 617A for providing substrates 510 and an unloading station 617B for receiving processed substrates 510. The loading station 617A and the unloading station 617B can be coupled to the enclosure 602 and can include robotic equipment and/or transfer mechanisms that provide substrates 510 to the transport belt 615. The substrate positioning system 605 includes support rollers 620 that support and/or drive the transport belt 615. The support rollers 620 are driven by a mechanical drive 625, such as a motor/chain drive, and are configured to transport the transport belt 615 at a linear speed of from about 100 millimeters per second (mm/s) to about 2000 mm/s, such as from about 500 mm/s to about 2000 mm/s, or from about 500 mm/s to about 1500 mm/s during operation. The mechanical drive 625 can be an electric motor, such as an alternating current (AC) or direct current (DC) servo motor. The transport belt 615 can be made of, e.g., stainless steel, a polymeric material, and/or aluminum. In at least one embodiment, the transport belt 615 includes two parallel belts that can be spaced apart in the X-direction, wherein each of the two parallel belts have a width in the X-direction that is smaller than the X-direction dimension of the substrates 510. In this configuration, each substrate 510 in the laser drilling system 600 can be disposed on a portion of both parallel belts.

[0076] The substrate positioning system 605 can be a transfer device configured to sequentially transport a line of the substrates 510 (e.g., in the flow path "A") toward and through a laser scanning apparatus 630. The laser scanning apparatus 630 includes an optical device 635A coupled to a support member 640 that supports the optical device 635A above the transport belt 615 and substrates 510. The laser scanning apparatus 630 also includes a scanning chamber 635B that is fixed in position relative to the transport belt

615 adjacent the optical device 635A allowing the substrates 510 to pass therethrough on the transport belt 615.

[0077] FIG. 6B is a side view of the example optical device 635A of FIG. 6A, wherein the optical device 635A is rotated 90 degrees from its standard position shown in FIG. 6A for discussion purposes. FIG. 5 is a schematic plan view of an example substrate 510 having a plurality of blind vias 501 formed by the optical device 635A of FIGS. 6A and 6B. The optical device 635A includes a housing 641 that provides light or electromagnetic radiation that is directed toward the surface of the substrates 510 as the substrates 510 pass through the scanning chamber 635B on the transport belt 615. In at least one embodiment, the optical device 635A, in combination with the movement of the transport belt 615, is configured to form a pattern (P), as shown in FIG. 5, which can include a pattern of rows (R) and columns (C) of blind vias 501 formed in a substrate 510. In some embodiments, the optical device 635A forms the pattern (P) on the substrate 510 in a time period of about 0.5 milliseconds (ms) or less, such as from about 0.01 ms to about 0.1 ms or from about 0.001 ms to about 0.005 ms using an optics system that can provide a pulsed beam that traverses the substrate 510 at a high speed as the substrate 510 is moved on the transport belt 615. The optical device 635A also includes a laser source 642, such as a femtosecond laser source, that emits light or electromagnetic radiation through an optics system that provides, e.g., about 50000 blind vias in the substrate 510 having desired characteristics described herein, such as diameter and taper angle.

[0078] In laser machining processes, unlike typical plasma process in semiconductor processing, the plasma is more like a cloud or plume that can cover the whole wafer surface, a laser beam, particularly when being focused, is only a tiny spot, therefore, typically a relative movement between laser beam and sample (e.g., wafer) is needed to process a whole sample. The relative movement can be realized in different ways. In a first way, and in some embodiments, the laser beam is kept stationary and the substrate is moved by a linear stage with motion in X/Y/Z(height)/Theta angle (on X-Y plane to rotate sample)/A tilting angle (on X-Z and Y-Z plane to tilt sample)

directions. For micromachining, typically, X/Y/Z/theta movement can be enough. In a second way, and in some embodiments, the laser source and/or laser focusing head is mounted on a X/Y/Z/Theta stage.

[0079] In a third way and in some embodiments, the substrate is kept stationary on a chuck, and the laser beam is scanned across the substrate. Optical scanners are used to direct, position, and/or “scan” a laser beam over a desired area of a substrate. In this case, a light beam is refracted, diffracted, and/or reflected by optical scanners to realize its movement on a substrate surface. Generally, there are three types of optical scanners: acousto-optic scanners that deflect a beam using diffraction; electro-optic scanners that deflect a beam using refraction; and mechanical scanners (resonant, polygonal, and galvanometer scanning types) that deflect a beam using reflection.

[0080] A fourth way is hybrid movement of the laser beam and the sample. For example, the laser beam is scanned across a substrate while moving the substrate on the chuck/stage simultaneously or in sequence. Additionally, or alternatively, the scanner is mounted on a one-axis moving stage to move and scan beam.

[0081] In some embodiments, optical scanning technology such as mechanical scanners, such as polygon and/or galvos, are used to move the laser beam from one position to another position on the substrate surface in order to, e.g., drill via arrays at designated locations on the substrate. These mechanical scanners work by rotating a physical mirror that can be coated to reflect any wavelength or combination of wavelengths off the rotating mirror with very high reflectivity—and thus, high optical throughput. The achievable scan angle in optical degrees is double the actual motor rotation angle. Using that physical mirror, a polygonal scanner can be made to scan a beam over very wide angles, but having the limitation of scanning the same pattern over and over again. A polygon scanner performs one-axis scanning. To generate a 2-dimensional pattern, the other axis-movement can be provided by adding a linear stage or a galvo mirror.

[0082] Mechanical galvanometer-based scanners (or galvos), typically involve a physical mirror operated by a motor. Most often, the mirror is attached to the shaft of the motor, but in some designs the mirror and motor may be a single integral unit. Galvo motors can rotate over a range of angles (typically around $\pm 20^\circ$). Galvo motors can also incorporate a high-precision position detector that provides feedback to a separate controller, delivering pointing repeatability of 5 μ rad (5 mm at a distance of 1 km). Two galvanometer-scanners can be configured for two-axis scanning.

[0083] In at least one embodiment, the speed of the transport belt 215 is controlled at about 100 mm/s to about 5000 mm/s, such as about 250 mm/s to about 2000 mm/s, such as about 0.5 m/s to about 1 m/s, during operation, in order to form multiple blind vias 501 in a substantially linear row in the X-direction (FIG. 6A) on the substrates 510 as the substrates 510 pass below the optical device 635A on the transport belt 615 in the Y-direction.

[0084] In at least one embodiment, and as an alternative to (or in addition to transport belt 215), a galvoscaner is used to change drilling position from one via to the next.

[0085] Referring again to FIG. 6B, the laser source 642 can emit light or electromagnetic radiation 655 through a process of optical amplification based on stimulated emission of photons. In at least one embodiment, the laser beam emitted by the laser source 642 is a Gaussian beam. In some embodiments, the emitted electromagnetic radiation 655 has a high degree of spatial and/or temporal coherence. In at least one embodiment, the laser source 642 emits a continuous or pulsed wave of light or electromagnetic radiation 655 that is directed to the optics system, which includes a beam expander 644, a beam collimator 646, and a galvanometer scanner 650.

[0086] The galvanometer scanner 650 can include moveable mirrors to steer the laser beam, and the steering of the beam can be one-, two-, or three-dimensional. In order to position the laser beam in two dimensions, the galvanometer scanner 650 can rotate one mirror along two axes or can reflect the laser beam onto two closely spaced mirrors that are mounted on

orthogonal axes. To position the focus of the laser beam in three dimensions, a servo-controlled galvanometer scanner can be used. Characteristics of the laser source 642, such as a femtosecond laser source, are described above.

[0087] In some embodiments, the pulse width and frequency of the pulses of electromagnetic radiation 655 are controlled by providing the laser source 642 with an external trigger signal that is provided at a desired frequency from a controller 690.

[0088] The pulses of electromagnetic radiation 655 emitted from the laser source 642 are received at the beam expander 644 having a first diameter, such as from about 1 mm to about 6 mm, such as from about 2 mm to about 5 mm, such as from about 3 mm to about 4 mm. The beam expander 644 can increase the diameter of the electromagnetic radiation 655 to a second diameter by a preset magnification, such as about 2x magnification, such as about 5x magnification, such as about 8x magnification, or the beam expander 644 can have an adjustable range of magnification, such as from about 1x to about 8x. The pulses of electromagnetic radiation 655 are then delivered to the beam collimator 646 for narrowing the beam.

[0089] In at least one embodiment, the beam collimation function is integrated into the beam expander 644. That is, in such embodiments, the beam expander 644 is also itself a beam collimator. Here, the beam expander 644 has at least two functions—expanding to beam size by certain magnification AND collimating the beam. The beam expander can have a fixed magnification (e.g., 2x, then the output beam diameter is equal to 2x input beam diameter) or an adjustable range of magnification (e.g., 3x to 8x). For example, a 2 mm diameter laser beam can enter the input side of a 3x beam expander, then at the output (exit) side of beam expander is a 6 mm diameter beam as output. This 6 mm beam (as it propagates along the optical axis) can be a divergent beam, or a convergent beam, but typically not, a well collimated beam. A perfectly collimated beam neither diverges nor converges as it propagates along the optical axis. Through the operation of “beam collimating” the beam can be adjusted to have very minor divergence or

convergence so that over a few meters travel distance, the beam diameter may only change by about 1% to about 2%, or less.

[0090] From the beam collimator 646, the pulses of electromagnetic radiation 655 are delivered to the galvanometer scanner 650, which steers the pulses of electromagnetic radiation 655 through a focusing lens 652 and onto the substrate 510. The focusing lens 652 can be a telecentric focusing lens. The focusing lens 652 can have one or more lenses.

[0091] The galvanometer scanner 650 steers the pulses of electromagnetic radiation through the focusing lens 652, which is part of the optics system of the optical device 635A, and onto a surface of the substrate 510, which is continually moving in the Y-direction on the transport belt 615 in the scanning chamber 635B (FIG. 6A). Thus, the transport belt 615 does not need to stop/start during the blind via formation process on the substrate 510, which can increase throughput. However, in some embodiments, the surface of the substrate is periodically moving in the Y-direction on the transport belt 615 in the scanning chamber 635B (FIG. 6A). The galvanometer scanner 650 can include a mirror having multiple reflecting facets arranged such that each of the reflecting facets 653 can be generally angled relative to another one of the reflecting facets 653 in a direction relative to an axis of rotation 651 of the galvanometer scanner 650 (into the page in the X direction in FIG. 6B). The angle of each of the reflecting facets 653 of the galvanometer scanner 650 allows the electromagnetic radiation 655 to be scanned in one direction (X-direction in FIG. 6A) across the surface of the substrate 510 as the galvanometer scanner 650 is rotated about the axis of rotation 651 by an actuator 654. The actuator 654 can be used to control the speed of rotation of the galvanometer scanner 650 to a desired linear speed, such as a speed from about 0.5 m/sec to about 10 m/sec, such as from about 1 m/sec to about 6 m/sec, such as from about 2 m/sec to about 5 m/sec. The speed of scanning can be changed/fixed during the laser drilling process for creation of a pattern on the substrate 510. In at least one embodiment, the scanning speed is fixed such that all pulses are directed to one spot when drilling an

individual via. This is often called percussion drilling or punch. From via to via, the galvo mirror can scan to change the drilling location.

[0092] For example, the rotational speed of the galvanometer scanner 650 can be set at a first speed for creation of a first pattern on one or more first substrates, and the first speed can be maintained during the ablation of each of the one or more first substrates. If a different pattern is desired on one or more second substrates, the rotational speed of the galvanometer scanner 650 can be set at a second speed that is different than the first speed, and the second speed can be maintained during the ablation of each of the one or more second substrates.

[0093] In some embodiments, the rotation of a single facet of the galvanometer scanner 650, as it is reflecting the delivered pulses of electromagnetic radiation 655 from the laser source 642, creates a full row (R) of blind vias 501 (e.g., a row in the X-direction) in one or more layers formed on the substrate 510. The electromagnetic radiation 655 is scanned across the surface of the substrate 510 by use of the galvanometer scanner 650, while the substrate 510 is transferred in an orthogonally-oriented Y-direction resulting in rows (R) of blind vias 501 (e.g., in the X-direction) spanning the length of the substrate 510 (e.g., in the Y-direction). In another example, the Y-direction is positioned at an angle to the X-direction. In yet another example, the Y-direction is positioned at an angle of about 90 degrees plus or minus a few degrees relative to the X-direction.

[0094] In at least one embodiment, the optics system of the optical device 635A are configured to deliver a focused beam diameter from about 1.5 μm to about 7 μm , such as from about 2 μm to about 6 μm , such as from about 3 μm to about 5 μm , for formation of the blind vias 501 with an entry diameter D_1 equal to about 5 μm ; and to deliver a focused beam diameter from about 5 μm to about 14 μm , such as from about 7 μm to about 12 μm , such as from about 8 μm to about 10 μm , for formation of the blind vias 501 with an entry diameter D_1 equal to about 10 μm (e.g., D_1 as defined in FIG. 2B or FIG. 2C). In some embodiments, the number of pulse bursts to drill a hole can be from

about 1 burst per via to about 40 bursts per via, such as from about 3 bursts per via to about 30 bursts per via, such as from about 5 bursts per via to about 20 bursts per via.

[0095] Referring again to FIG. 6A, the laser drilling system 600 also includes a substrate sensing system 660 including one or more substrate position sensors. The substrate sensing system 660 uses an optical sensor 662 to detect a leading edge 665 of the substrate 510 and sends corresponding signals to a controller 690. The controller 690, in turn, sends signals to the optical device 635A to time the operation of the laser source 642 and the rotation of the galvanometer scanner 650 to begin the laser scanning operation as the leading edge 665 of the substrate 510 is beneath the focusing lens 652. The controller 690 further controls the rotational speed of the galvanometer scanner 650 to scan a row (R) of blind vias 501 in one or more layers disposed on the substrate 210 as each facet of the galvanometer scanner 650 is rotated across the pulses of electromagnetic radiation 655. The controller 690 further controls the speed of the substrate positioning system 605 and the rotation of the galvanometer scanner 650, such that as a first row (R) of blind vias 501 (e.g., aligned in the X-direction) is finished, the next row (R) of blind vias 501 can begin at a desired spacing (e.g., in the direction A) from the first row due to the linear movement of the substrate 510 by the substrate positioning system 605. Accordingly, and in some embodiments, as the substrate 510 is moved beneath the optical device 635A, rows (R) of blind vias 501 can be formed in one or more layers of the substrate 510 across the entire width and length of the substrate 510. The controller 690 further controls the timing of the optical device 635A, such that as a trailing edge 670 of the substrate 510 passes beneath the focusing lens 652, the scanning operation ceases after a desired period of time has elapsed until the leading edge of the next substrate 510 is positioned beneath the focusing lens 652. The controller 690 can be any controller having a suitable processor, software and memory for operation of the laser drilling system 600. The substrate sensing system 660 also includes a substrate alignment device

680 configured to align the substrates 510 prior to entry into the scanning chamber 635B.

[0096] The controller 690 generally includes a central processing unit (CPU) (not shown), memory (not shown), and support circuits (not shown). The CPU can be one of any form of computer processor used in industrial settings for controlling system hardware and processes. The memory can be connected to the CPU and can be one or more of a readily available memory, such as random access memory (RAM), read only memory (ROM), floppy disk, hard disk, or any other form of digital storage, local or remote. Software instructions and data can be coded and stored within the memory for instruction the CPU. The support circuits can also be connected to the CPU for supporting the processor in a conventional manner. The support circuits can include cache, power supplies, clock circuits, input/output circuitry subsystems, and the like. A program (e.g., instructions) readable by the controller 690 can include code to perform tasks relating to monitoring, executing, and controlling the movement, support, and positioning of the substrates 510 along with various process recipe tasks to be performed in the laser drilling system 600. In at least one embodiment of the controller 690, the process of forming holes on a surface of a substrate includes at least one scan (to form a full row (R) of blind vias 501 (shown in FIG. 2C)) that can be interrupted at desirable times to further control formation of blind vias 501 in a desirable location on the surface of the substrate. This capability can enable brief and/or selective stopping/starting the train of pulses, and enable advanced patterning features.

[0097] The controller 690 further controls a height sensor 664. Although FIG. 6A shows the height sensor 664 as being part of the substrate sensing system 660, the height sensor 664 can be a separate unit. During use of the laser drilling system 600, the height sensor 664 adjusts the optical device 635A about the Z-direction before, during, or after ablation as described in FIG. 8 and FIG. 9. In at least one embodiment, the height sensor 664 precisely determines the surface of the mask disposed on the one or more layers of the substrate 510.

[0098] FIG. 7 is an isometric view of an example laser drilling tool 700 having the optical device 635A and the scanning chamber 635B disposed therein. The laser drilling tool 700 includes a main frame 701 having a first side 702A that can be coupled to a loading station 617A (shown in FIG. 6A) and a second side 702B that can be coupled to an unloading station 617B (shown in FIG. 6A). The main frame 701 can include panels 705 that can function as doors or removable sheets, and a portion of the panels 705 are not shown to illustrate components within the laser drilling tool 700. The panels 705 include a view window 710 to provide visual access to the interior of the laser drilling tool 700. The view window 710 can include laser safety glass and/or filters that enable viewing of the electromagnetic radiation during a laser drilling process within the laser drilling tool 700 without the need for safety glasses. Power sources and control equipment, such as a laser power supply 715 (shown in dashed lines) is housed within the main frame 701. Additionally, an optical alignment device 720 (FIGS. 7 and 8) is coupled to the main frame 701 within the laser drilling tool 700. The optical alignment device 720 can adjust the position of the optical device 635A relative to the motion direction of the substrates 510 on the substrate positioning system 605, thereby adjusting the beam path emitted relative to a substrate.

[0099] As discussed above, the optical device 635A can be adjusted about the Z-direction before, during, or after ablation using a height sensor 664 as described in FIG. 8 and FIG. 9.

[0100] FIG. 8 is a side view of an example embodiment of the optical alignment device 720. The optical alignment device can be coupled to a height sensor 664 (not shown). The optical alignment device 720 includes a base plate 800 that is coupled to one or more support members 805 of the main frame 701. The base plate 800 is movably coupled to a first support plate 810 having a second support plate 815 extending therefrom in a plane substantially orthogonal to the plane of the first support plate 810. The second support plate 815 generally supports the optical device 635A. The first support plate 810 is coupled to the base plate 800 by a plurality of adjustment devices 820, which can include fasteners, linear guides, or a combination thereof. The

adjustment devices 820 can enable at least height adjustment (in the Z-direction) of the optical device 635A and can enable a theta adjustment in the X-Z plane and/or the Y-Z plane. The height adjustment can be used to adjust the focal length of the focusing lens 652 (FIGS. 6A and 6B) of the optical device 635A. The adjustment devices 820 can also be used to level the second support plate 815 relative to a plane of the transport belt 615. An adjustable aperture device 840 is provided between the second support plate 815 and the scanning chamber 635B. The adjustable aperture device 840 can be, e.g., a telescoping housing having an aperture formed therein that is sized to receive a beam path provided by the optical device 635A. The telescoping housing can be adjusted upward or downward based on a height adjustment of the optical alignment device 720.

[0101] In some embodiments, the optical alignment device 720 also includes an adjustable mount plate 825 disposed between the second support plate 815 and a lower surface of the optical device 635A. The adjustable mount plate 825 is secured to the lower surface of the optical device 635A and is fastened to the second support plate 815 by fasteners 830. The adjustable mount plate 825 can be adjusted for different angular orientations as well as leveling the optical device 635A to tune a scan plane 835 of a beam path emitted by the optical device 635A during processing. As described in more detail in FIG. 9, the adjustable mount plate 825 can be rotated about the scan-plane axis 635, e.g., the Z-direction, to adjust the orientation of the scan plane (e.g., plane aligned to the row (R) direction on the substrate in FIG. 5) of the output of the optical device 635A. Adjustment of the adjustable mount plate 825 can be performed to alter the beam path(s) within the scan plane of the optical device 635A to align a row (R) of blind vias 501 on a substrate 510 (FIG. 5).

[0102] FIG. 9 is an isometric view of the example optical alignment device 720 of FIG. 8. Although the optical device 635A is not shown in this view, the scan plane 835 of the optical device 635A is shown. The adjustable mount plate 825 includes a plurality of slots 900 that receive the fasteners 830 shown in FIG. 8. Each of the slots 900 can permit the adjustable mount plate

825 to rotate relative to the Z axis in order to adjust the scan plane of the optical device 635A. For example, a first alignment position 905 of the adjustable mount plate 825 can include a direction wherein the scan plane is substantially parallel to the leading edge 665 of the substrate 510 (shown in FIG. 2A). In at least one embodiment, the adjustable mount plate 825 is adjusted to a second alignment position 910, which corresponds to an angle 915. The angle 915 can be adjusted based on, e.g., the speed of the substrate(s) 510 on the transport belt 615 and/or the scan speed of the electromagnetic radiation 655. The scan speed of the electromagnetic radiation 655 can be at least partially based on pulse width of the electromagnetic radiation 655 and/or movement of the galvanometer scanner 650 (shown in FIG. 6B).

[0103] In at least one embodiment, the angle 915 is from about -20° degrees to about $+20^{\circ}$ degrees from the normal axis of the mirror surface, when the speed of the transport belt 615 is about 140 mm/s to about 180 mm/s, with a pulse width of about 1 fs to about 1.5 ms, and the scan speed of the galvanometer scanner 650 is about 1,000 RPM, which results in rows (R) of blind vias 501 that are substantially linear and/or parallel with the leading edge 665 of the substrate 510.

[0104] Any of the operations described above can be included as instructions in a computer-readable medium for execution by a control unit (e.g., controller 690) or any other processing system. The computer-readable medium can comprise any suitable memory for storing instructions, such as read-only memory (ROM), random access memory (RAM), flash memory, an electrically erasable programmable ROM (EEPROM), a compact disc ROM (CD-ROM), a floppy disk, and the like.

[0105] For the sake of brevity, only certain ranges are explicitly disclosed herein. However, ranges from any lower limit may be combined with any upper limit to recite a range not explicitly recited, as well as, ranges from any lower limit may be combined with any other lower limit to recite a range not explicitly recited, in the same way, ranges from any upper limit may be

combined with any other upper limit to recite a range not explicitly recited. Additionally, within a range includes every point or individual value between its end points even though not explicitly recited. Thus, every point or individual value may serve as its own lower or upper limit combined with any other point or individual value or any other lower or upper limit, to recite a range not explicitly recited.

[0106] For the purposes of this present disclosure, and unless otherwise specified, all numerical values within the detailed description and the claims herein are modified by “about” or “approximately” the indicated value, and consider experimental error and variations that would be expected by a person having ordinary skill in the art.

[0107] All documents described herein are incorporated by reference herein, including any priority documents and/or testing procedures to the extent they are not inconsistent with this text. As is apparent from the foregoing general description and the specific embodiments, while forms of the present disclosure have been illustrated and described, various modifications can be made without departing from the spirit and scope of the present disclosure. Accordingly, it is not intended that the present disclosure be limited thereby. Likewise, the term “comprising” is considered synonymous with the term “including.” Likewise whenever a composition, an element or a group of elements is preceded with the transitional phrase “comprising,” it is understood that we also contemplate the same composition or group of elements with transitional phrases “consisting essentially of,” “consisting of,” “selected from the group of consisting of,” or “is” preceding the recitation of the composition, element, or elements and vice versa.

Claims

What is claimed is:

1. A method of forming a blind via in a substrate, comprising:
 - conveying the substrate to a scanning chamber, the substrate comprising a conductive layer, a dielectric layer disposed on at least a portion of the conductive layer, and a mask layer disposed on at least a portion of the dielectric layer, the mask layer providing a substrate surface;
 - determining one or more properties of the blind via, the one or more properties comprising:
 - a top diameter of the blind via and a bottom diameter of the blind via, the blind via having a height from the top diameter to bottom diameter, the top diameter being greater than the bottom diameter;
 - a volume of the blind via, the volume corresponding to the top diameter, the bottom diameter, and the height; or
 - a taper angle of about 80 degrees or more;
 - focusing a laser beam emitted from a laser source, under laser process parameters, at the substrate surface to remove at least a portion of the mask layer;
 - adjusting the laser process parameters based on the one or more properties;
 - and
 - focusing the laser beam, under the adjusted laser process parameters, to remove at least a portion of the dielectric layer within the volume to form the blind via.
2. The method of claim 1, wherein the laser process parameters include a laser power, a laser energy in a burst, a focal beam diameter, a focus height, a burst energy, a pulse energy, a number of pulses in a burst, a pulse frequency, a burst frequency, a beam spot size, an M2 value, an offset of beam focusing from substrate surface, or a combination thereof.
3. The method of claim 1, wherein the laser process parameters comprise:
 - an amount of laser energy in a burst of about 5 μ J or more;

a focal beam diameter that is from about 2 μm to about 10 μm for drilling 5 μm diameter vias;

a focal beam diameter that is from about 7 μm to about 12 μm for drilling 10 μm diameter vias;

a focus height that is from about 0 μm to about 50 μm ;

a pulse frequency that is about 500 MHz or more;

a number of pulses in a burst that is about 2 or more;

a number of bursts of about 2 or more;

a burst frequency of about 100 kHz or more; or

a combination thereof.

4. The method of claim 1, wherein the top diameter is about 10 μm or less.

5. The method of claim 1 further comprising removing the mask layer from the substrate.

6. The method of claim 1, wherein:
the mask layer comprises Al, Cu, W, Mo, Cr, or a combination thereof;
the mask layer has a height of about 2 μm or less; or
a combination thereof.

7. The method of claim 6, wherein when the mask layer comprises Mo or W, the method further comprises depositing a layer of copper on the mask layer.

8. The method of claim 1, wherein the laser source is a femtosecond ultraviolet laser with a wavelength of about 400 nm or shorter.

9. A method of forming a blind via in a substrate, comprising:
conveying the substrate to a scanning chamber, the substrate comprising a conductive layer of about 2 μm or more in height, a dielectric layer disposed on at least a portion of the conductive layer, and a pre-etched mask layer disposed on at least a portion of the dielectric layer, the pre-etched mask layer having blind via

openings to expose at least a portion of the dielectric layer and the dielectric layer providing a substrate surface;

determining one or more properties of the blind via, the one or more properties comprising:

a top diameter of the blind via and a bottom diameter of the blind via, the blind via having a height from the top diameter to bottom diameter, the top diameter being greater than the bottom diameter, and the top diameter corresponding to the blind via openings;

a volume of the blind via, the volume corresponding to the top diameter, the bottom diameter, and the height; or

a taper angle of 80 degrees or more;

focusing a laser beam emitted from a laser source, under laser process parameters, at the substrate surface to remove a first portion of the dielectric layer within the volume without causing more than half-of-the thickness of mask layer damage to the pre-etched mask layer;

adjusting laser process parameters based on the one or more properties; and

focusing the laser beam, under the adjusted laser process parameters, to remove a second portion of the dielectric layer within the volume to form the blind via.

10. The method of claim 9, wherein the laser process parameters include a laser power, a laser energy in a burst, a focal beam diameter, a focus height, a burst energy, a pulse energy, a number of pulses in a burst, a pulse frequency, a burst frequency, a beam spot size, an M2 value, an offset of beam focusing plane from substrate surface, or a combination thereof.

11. The method of claim 9, wherein the laser process parameters comprise:

an amount of laser energy in a burst of about 5 μ J or more;

a focal beam diameter that is from about 2 μ m to about 10 μ m for drilling 5 μ m diameter vias;

a focal beam diameter that is from about 7 μ m to about 12 μ m for drilling 10 μ m diameter vias;

a focus height that is from about 0 μ m to about 50 μ m;

- a pulse frequency that is about 500 MHz or more;
 - a number of pulses in a burst that is about 2 or more;
 - a number of bursts of about 2 or more;
 - a burst frequency of about 100 kHz or more; or
 - a combination thereof.
12. The method of claim 9, wherein the top diameter is about 10 μm or less.
13. The method of claim 9 further comprising removing the pre-etched mask layer from the substrate.
14. The method of claim 9, wherein:
- the pre-etched mask layer comprises Al, Cu, W, Mo, Cr, or a combination thereof;
 - the pre-etched mask layer has a height of 3 μm or less; or
 - a combination thereof.
15. The method of claim 14, wherein when the pre-etched mask layer comprises Mo or W, the method further comprises depositing a layer of copper on the pre-etched mask layer.
16. The method of claim 9, wherein the laser source is a femtosecond ultraviolet laser.
17. An apparatus for forming a blind via in a substrate, comprising:
- an optical device comprising:
 - a galvanometer scanner having a plurality of reflecting facets and an axis of rotation; and
 - a beam expander and collimator;
 - a femtosecond laser beam source configured to direct electromagnetic radiation to the beam expander;

a transport assembly configured to position the substrate to receive the electromagnetic radiation reflected from at least one of the reflecting facets of the galvanometer scanner;

a height sensor configured to detect a height of one or more layers of the substrate; and

a controller configured to:

receive signals from the height sensor; and

control the femtosecond beam laser source and the transport assembly based on signals received from the height sensor.

18. The apparatus of claim 17, wherein the femtosecond laser is configured to emit a Gaussian laser beam profile.

19. The apparatus of claim 17, further comprising a positioning sensor configured to detect a leading edge of the substrate.

20. The apparatus of claim 19, wherein the controller is further configured to:
receive signals from the positioning sensor; and
control the control the femtosecond beam laser source and the transport assembly based on signals received from the positioning sensor.

21. The method of claim 1, wherein the mask layer comprises Cr.

22. The method of claim 9, wherein the mask layer comprises Cr.

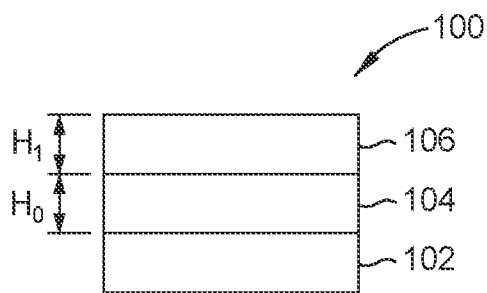


FIG. 1A

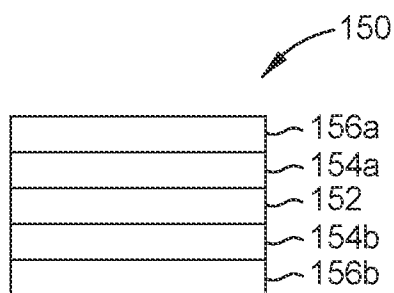


FIG. 1B

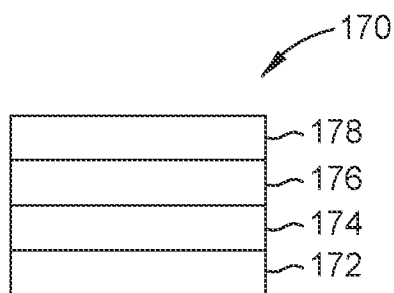


FIG. 1C

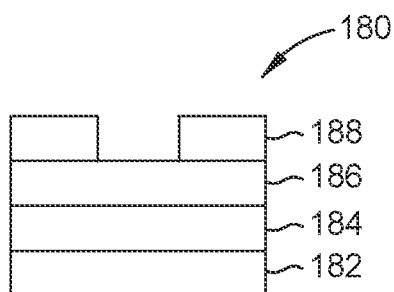


FIG. 1D

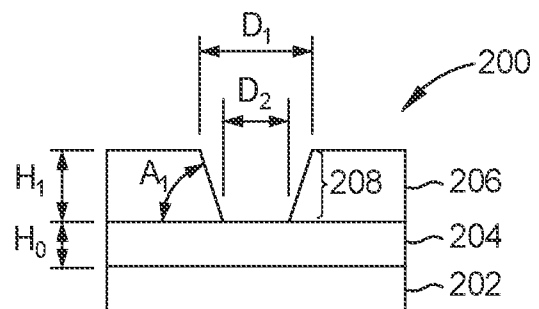


FIG. 2A

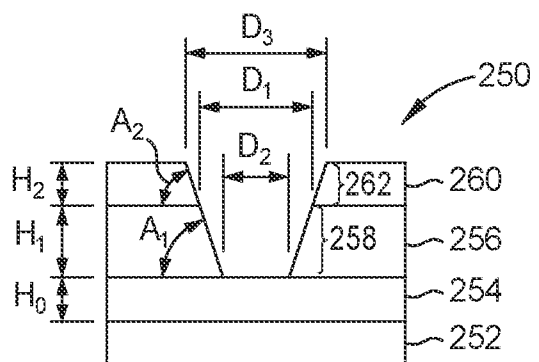


FIG. 2B

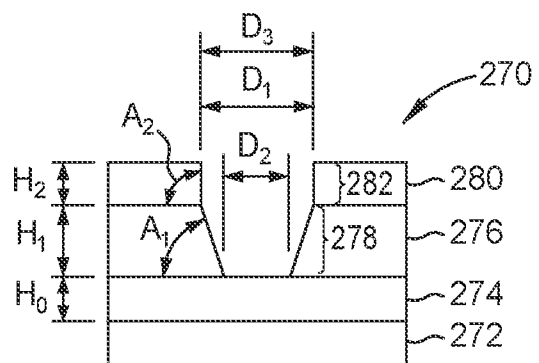


FIG. 2C

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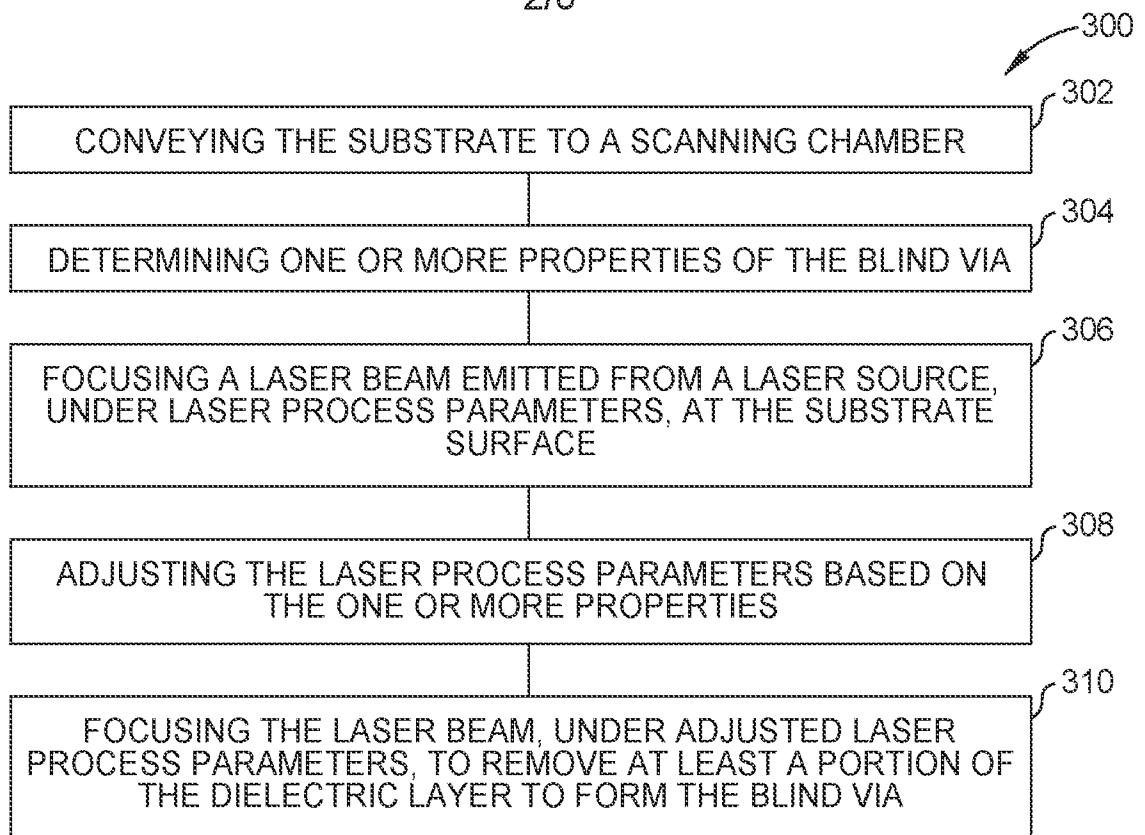


FIG. 3

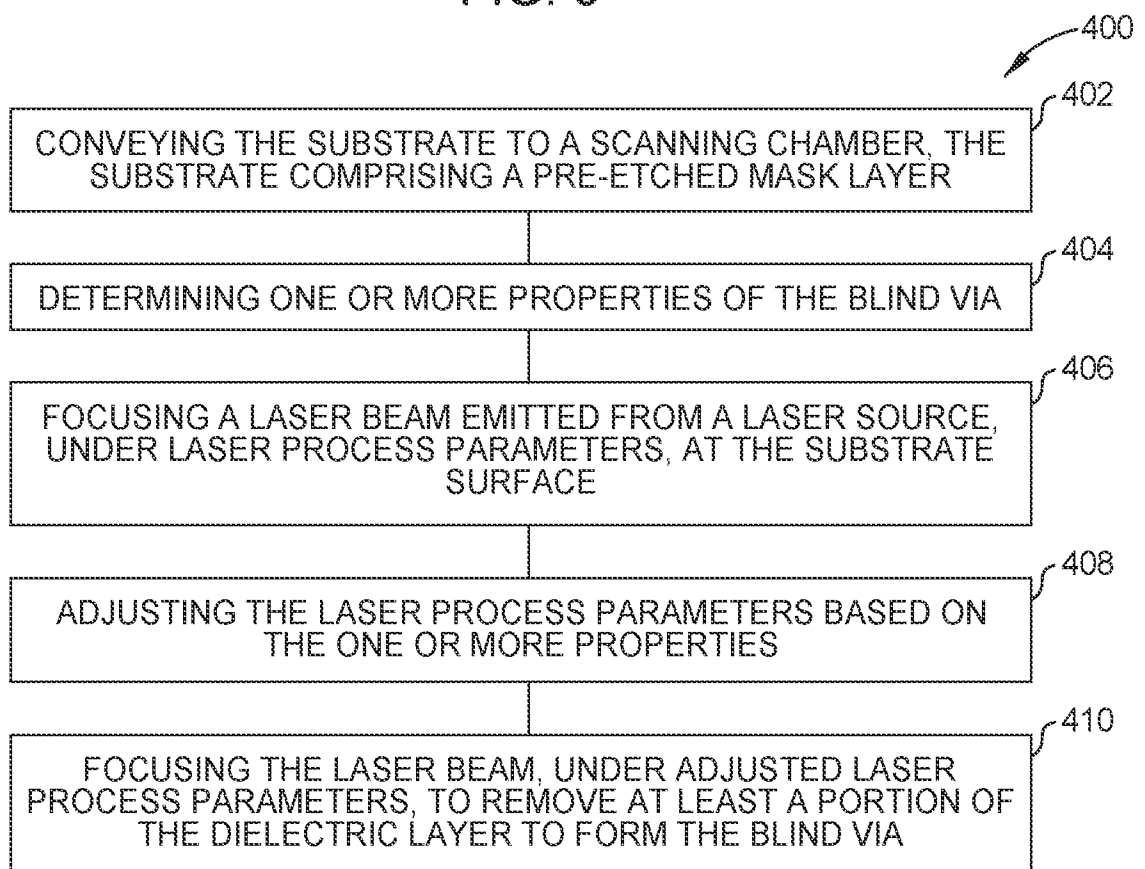
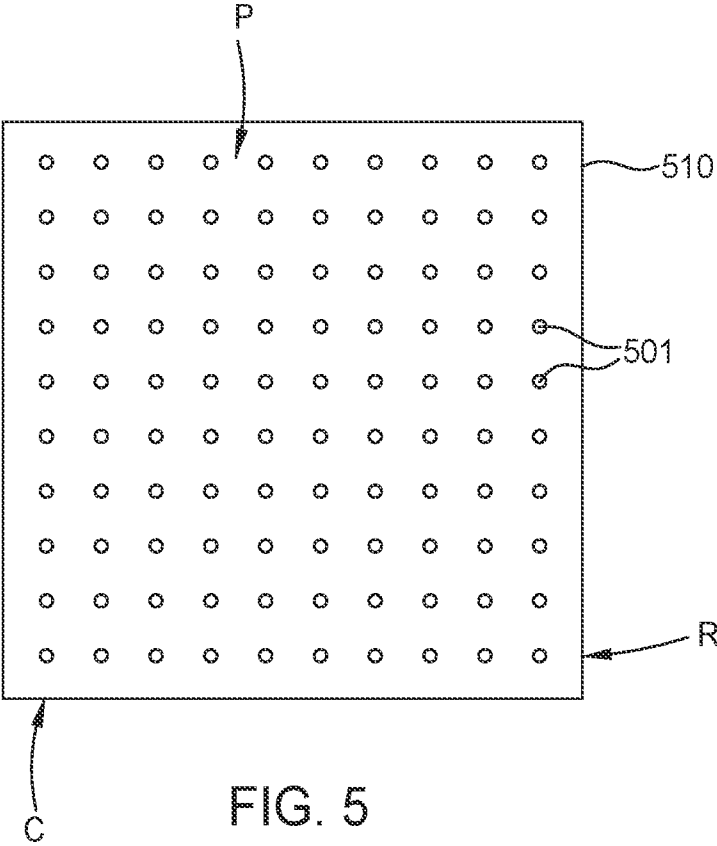
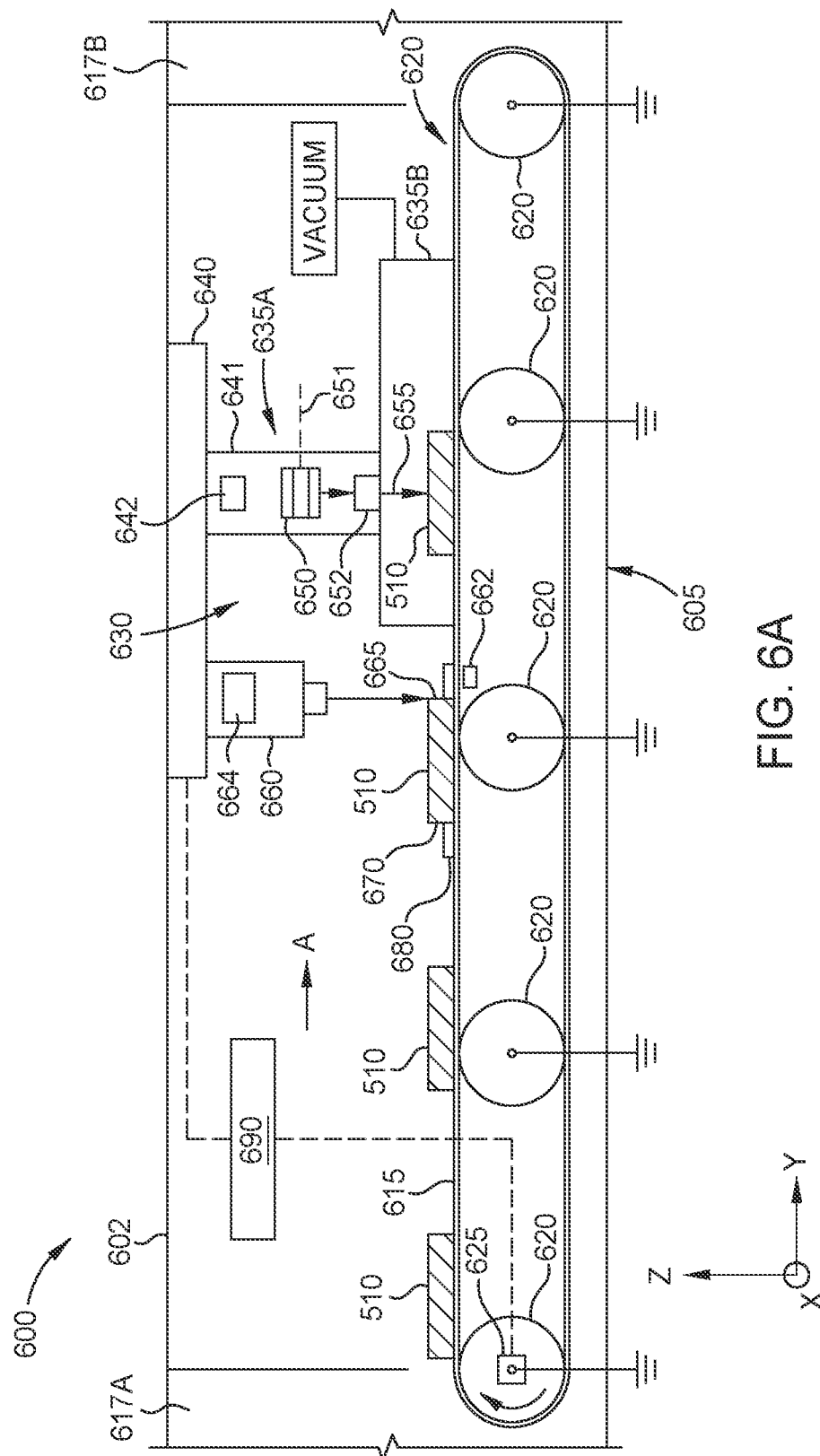
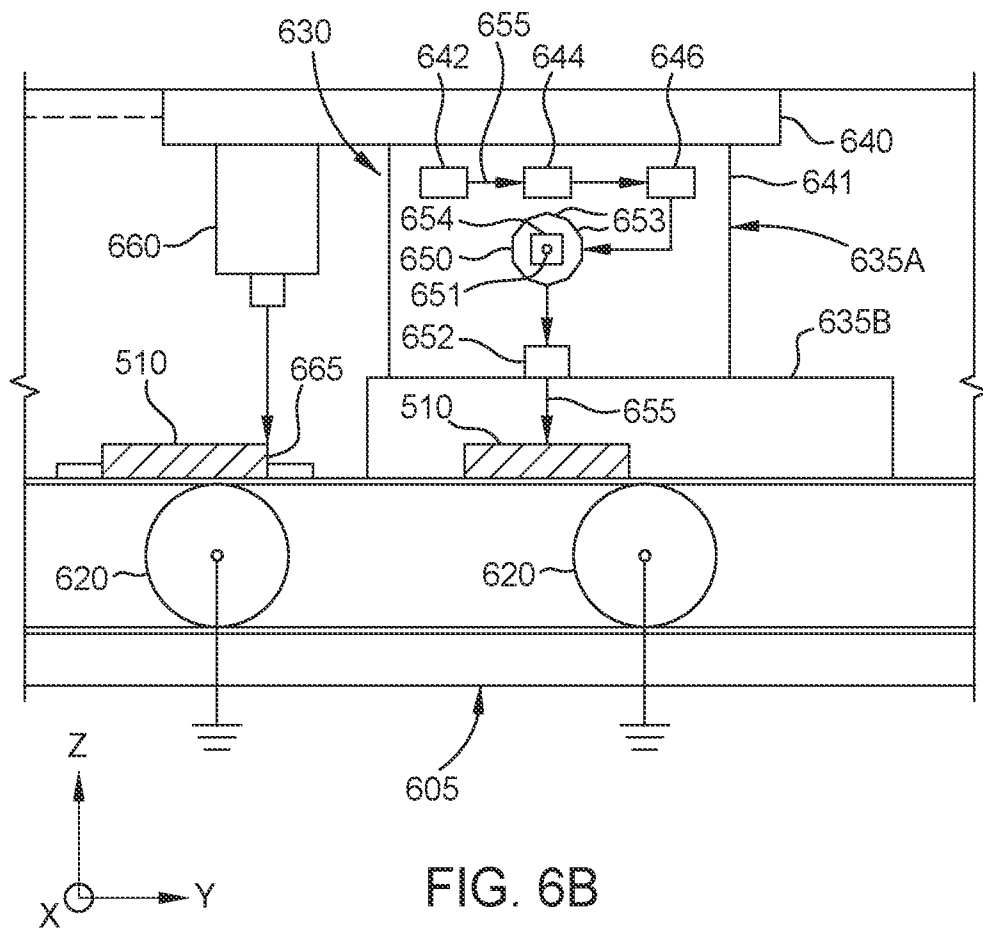


FIG. 4







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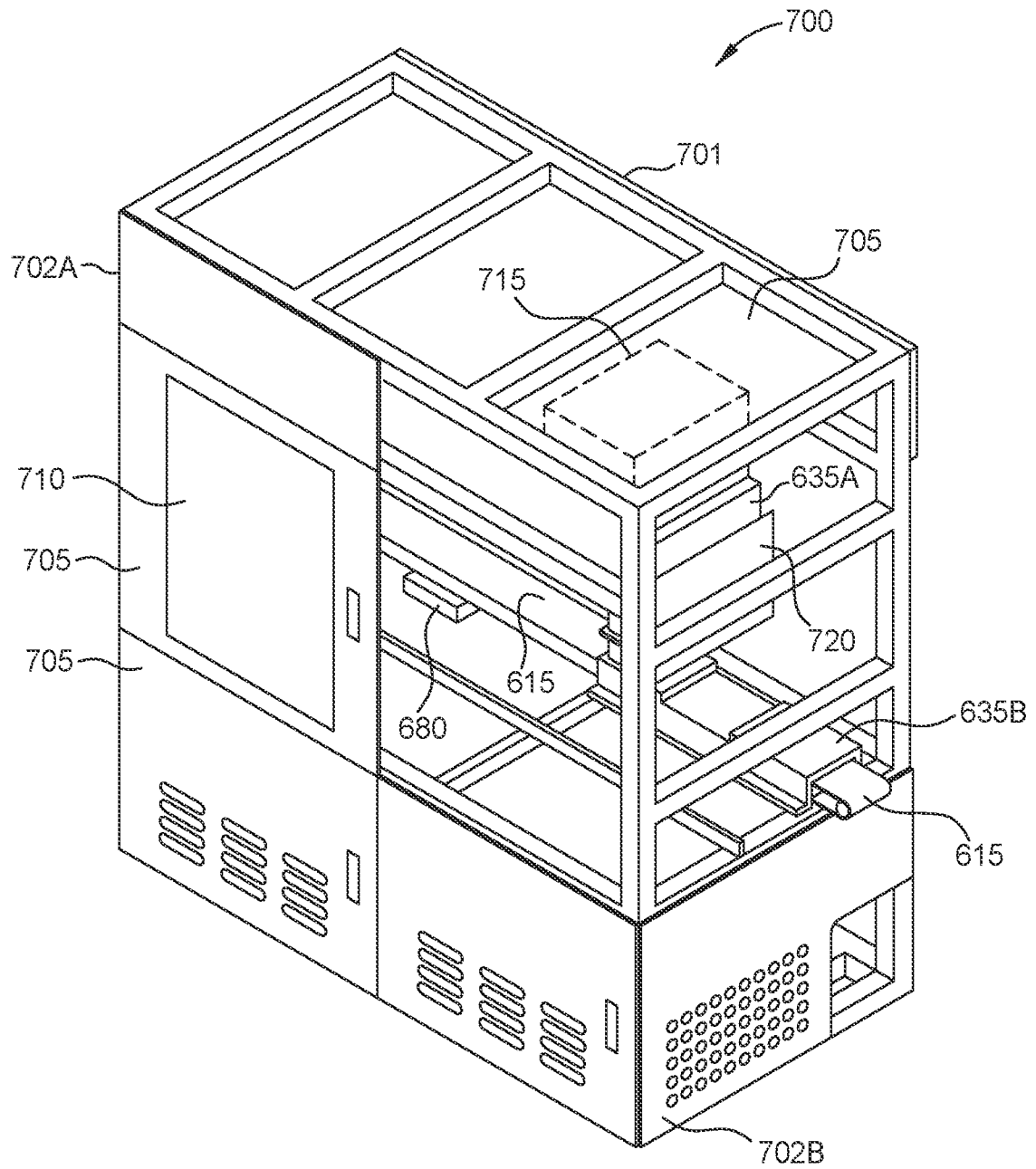


FIG. 7

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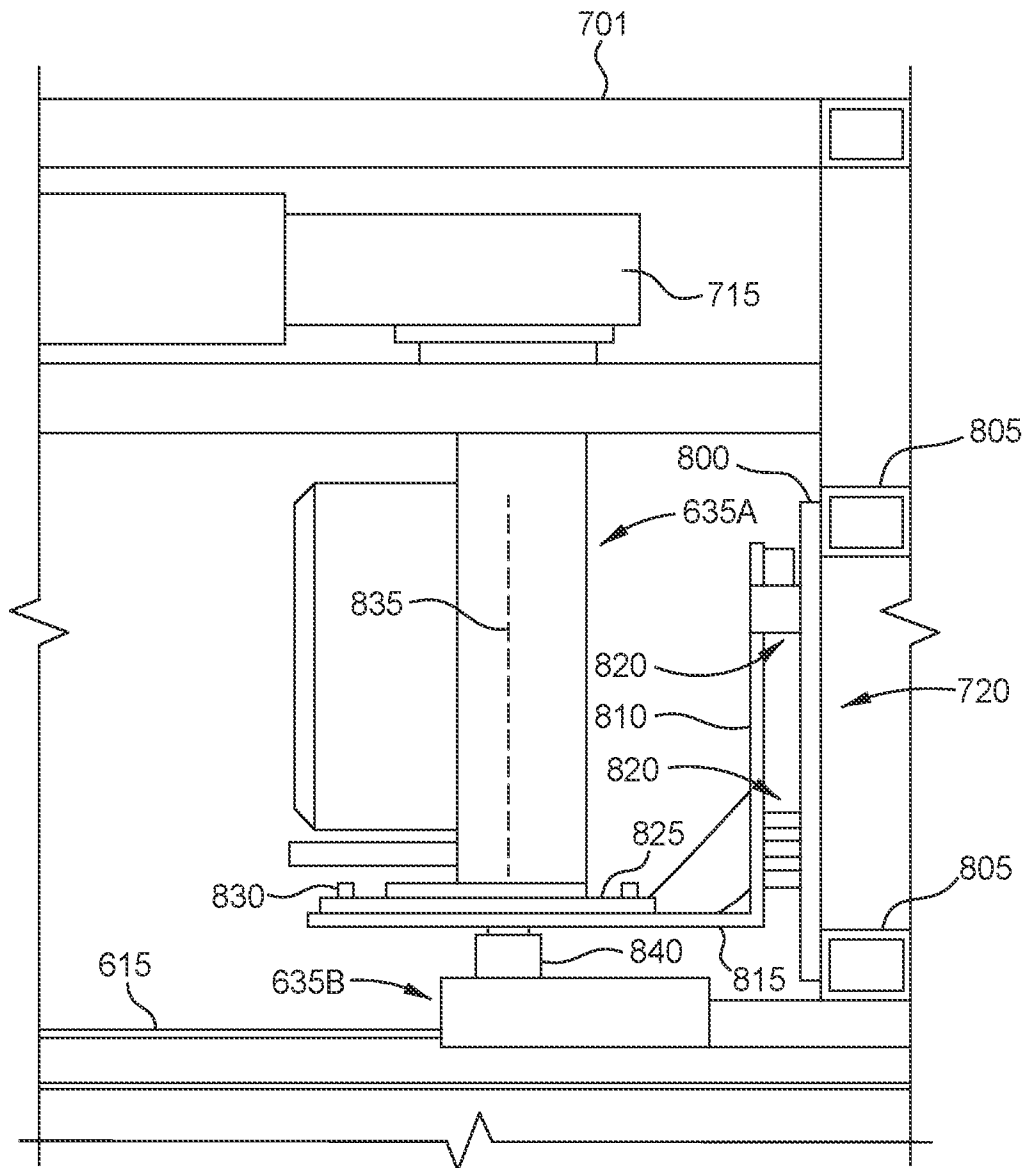
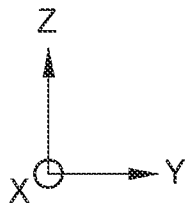


FIG. 8



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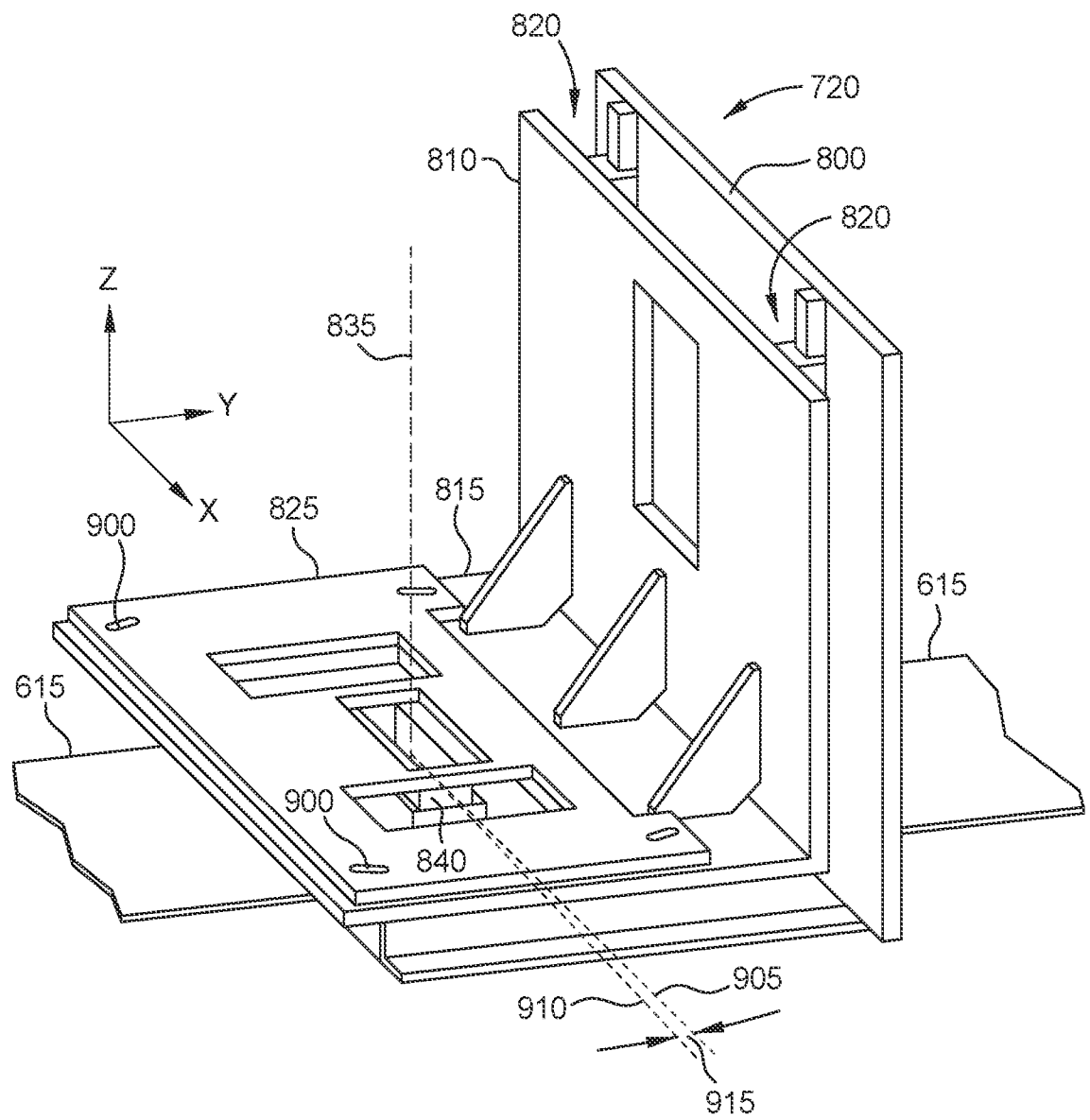


FIG. 9

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US2021/037375

A. CLASSIFICATION OF SUBJECT MATTER H05K 3/00(2006.01)i; H05K 3/40(2006.01)i; B23K 26/06(2006.01)i; B23K 26/073(2006.01)i According to International Patent Classification (IPC) or to both national classification and IPC		
B. FIELDS SEARCHED Minimum documentation searched (classification system followed by classification symbols) H05K 3/00(2006.01); B23K 26/38(2006.01); B23K 26/384(2014.01); B23K 26/386(2014.01); H01L 31/18(2006.01); H01S 3/10(2006.01) Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched Korean utility models and applications for utility models Japanese utility models and applications for utility models Electronic data base consulted during the international search (name of data base and, where practicable, search terms used) eKOMPASS(KIPO internal) & Keywords: blind via, substrate, laser, drilling, taper		
C. DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y A	US 2008-0296273 A1 (WEISHENG LEI et al.) 04 December 2008 (2008-12-04) paragraphs [10]-[21] and claims 1-5	1-16,21-22 17-20
X Y	WO 2015-126438 A1 (APPLIED MATERIALS, INC.) 27 August 2015 (2015-08-27) paragraphs [28]-[36], claims 1-4 and figures 2A-2B	17-20 1-16,21-22
A	CN 105436718 A (AKM ELECTRONIC TECHNOLOGY (SUZHOU) CO., LTD.) 30 March 2016 (2016-03-30) claims 1-6	1-22
A	US 2002-0170891 A1 (ADRIAN BOYLE et al.) 21 November 2002 (2002-11-21) claims 1-32	1-22
☒ Further documents are listed in the continuation of Box C. ☒ See patent family annex.		
* Special categories of cited documents: "A" document defining the general state of the art which is not considered to be of particular relevance "D" document cited by the applicant in the international application "E" earlier application or patent but published on or after the international filing date "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified) "O" document referring to an oral disclosure, use, exhibition or other means "P" document published prior to the international filing date but later than the priority date claimed "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone "Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art "&" document member of the same patent family		
Date of the actual completion of the international search 07 October 2021		Date of mailing of the international search report 07 October 2021
Name and mailing address of the ISA/KR Korean Intellectual Property Office 189 Cheongsa-ro, Seo-gu, Daejeon 35208, Republic of Korea Facsimile No. +82-42-481-8578		Authorized officer PARK, Hye Lyun Telephone No. +82-42-481-3463

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US2021/037375

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Information on patent family members

International application No.

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