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(72) Inventeurs/Inventors:
FAN, QI HUA, US;
SCHUELKE, THOMAS, US;
HAUBOLD, LARS, US;
PETZOLD, MICHAEL, US

(73) Propriétaires/Owners:
BOARD OF TRUSTEES OF MICHIGAN STATE UNIVERSITY, US;
FRAUNHOFER USA, US

(74) Agent: FASKEN MARTINEAU DUMOULIN LLP

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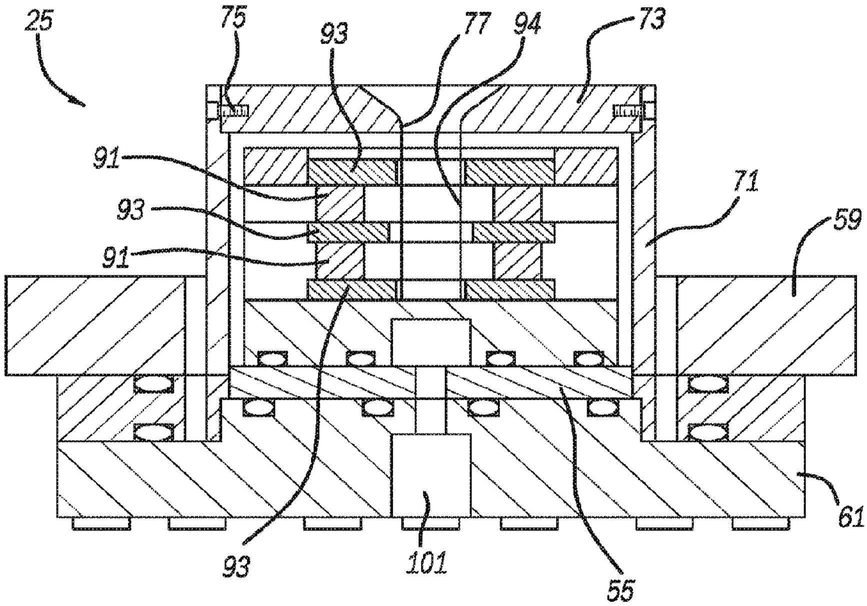

(57) Abrégé/Abstract:
A single beam plasma or ion source apparatus (21, 221, 321, 421, 521) is provided. Another aspect employs an ion source (25) including multiple magnets (91) and magnetic shunts (93) arranged in a generally E cross-sectional shape. A further aspect of an ion source includes magnets and/or magnetic shunts which create a magnetic flux (115) with a central dip (117) or outward undulation located in an open space within a plasma source. In another aspect, an ion source includes a removeable cap (73, 573) attached to an anode body (97) which surrounds the magnets. Yet a further aspect provides a single beam plasma source (221, 521) which generates ions simultaneously with target sputtering and at the same internal pressure.

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(71) Applicants: **BOARD OF TRUSTEES OF MICHIGAN STATE UNIVERSITY** [US/US]; 450 Administration Building, East Lansing, Michigan 48824-1046 (US). **FRAUNHOFER USA** [US/US]; 1449 Engineering Research Ct, East Lansing, Michigan 48824 (US).

(72) Inventors: **FAN, Qi Hua**; 2697 Elderberry Dr, Okemos, Michigan 48864 (US). **SCHUELKE, Thomas**; 11200 Darwood Rd, Pinckney, Michigan 48169 (US). **HAUBOLD, Lars**; 1974 Rutgers Circle, East Lansing, Michigan 48823 (US). **PETZOLD, Michael**; 5366 Timberwood Point Drive, Flint, Michigan 48532 (US).

(74) Agent: **FALCOFF, Monte L.**; HARNESS, DICKEY & PIERCE, P.L.C., P.O. Box 828, Bloomfield Hills, Michigan 48303 (US).

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(54) Title: SINGLE BEAM PLASMA SOURCE

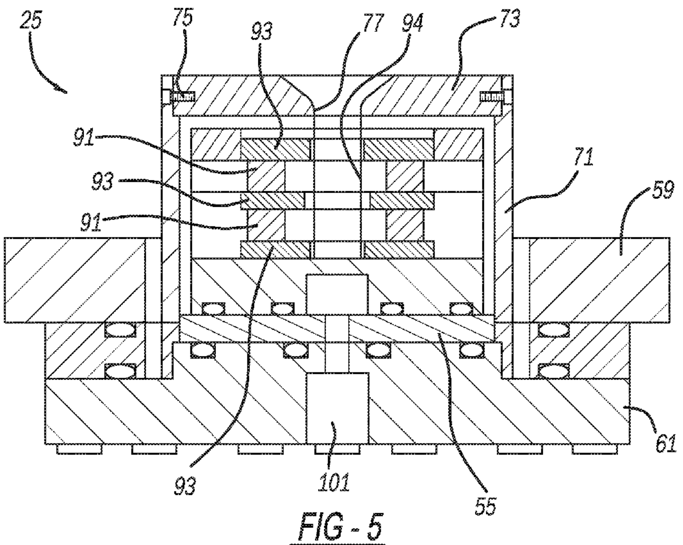

FIG - 5

(57) Abstract: A single beam plasma or ion source apparatus (21, 221, 321, 421, 521) is provided. Another aspect employs an ion source (25) including multiple magnets (91) and magnetic shunts (93) arranged in a generally E cross-sectional shape. A further aspect of an ion source includes magnets and/or magnetic shunts which create a magnetic flux (115) with a central dip (117) or outward undulation located in an open space within a plasma source. In another aspect, an ion source includes a removeable cap (73, 573) attached to an anode body (97) which surrounds the magnets. Yet a further aspect provides a single beam plasma source (221, 521) which generates ions simultaneously with target sputtering and at the same internal pressure.

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SINGLE BEAM PLASMA SOURCE

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. Provisional Application No. 62/687,357, filed June 20, 2018.

GOVERNMENT RIGHTS

[0002] This invention was made with government support under 1700785, 1700787 and 1724941 awarded by the National Science Foundation. The government has certain rights in the invention.

BACKGROUND AND SUMMARY

[0003] The present application generally pertains to an ion source and more particularly to a single beam plasma or ion source apparatus.

[0004] Thin film processing is widely used for manufacturing semiconductor devices, displays, solar panels, tribological coatings, sensors and micro-electro-mechanical systems. Conventional physical and chemical vapor depositions generally result in loosely packed atoms 1 on a workpiece 2 due to their limited kinetic energies, as is shown in Figure 1. The micro-porous structures lead to unstable material properties and device performance. Nevertheless, ion sources have become the essential tools for manufacturing high-quality thin films and devices.

[0005] One conventional ion source is of a racetrack design illustrated in Figures 2 and 3. This device consists of a racetrack- or ring-shaped anode 3, a pair of center and outer magnetic poles, and magnets 4. The anode is connected to the positive terminal of a DC power supply. The magnetic poles are connected to a ground potential and act as cathodes 5. Electrons attracted toward the anode experience a Lorenz force that drives the electrons in $E \times B$ direction (where E is an electrical field vector and B is a magnetic induction field vector). Hence, the electrons drift along the racetrack in an electron trajectory 6 instead of directly reaching the anode. The confined electrons ionize the process gases and create ions 7, which are subsequently extracted out of the plasma region.

[0006] There are two critical requirements for the racetrack ion sources to operate properly: 1) the electrons must drift in a closed loop (a racetrack or a circular ring) to ensure they are confined; and 2) the gap between the anode and cathode must

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be small (a few millimeters) to create a strong electrical field to extract the ions. Hence, a racetrack linear source actually produces two beams in the straight section and a circular source generates a ring-shaped beam. Therefore, the emitted ions have a wide distribution of emission angles; research has shown that the associated ion incident angle has a notable effect on the morphology of the treated surfaces. Furthermore, the racetrack ion sources require a voltage greater than 250 V to sustain the plasma discharges. This is determined by the electromagnetic fields inbetween the anode and cathode. Therefore, the ion energies could be so high that they can damage the deposited films and undesirably roughen the film surfaces.

[0007] The narrow emission slit in the traditional racetrack ion sources results in frequent maintenance due to undesired material deposition and contamination of the anode and cathode adjacent the exit slit. Furthermore, it is troublesome to realign the cathode after cleaning to maintain a uniform emission slit since the traditional racetrack construction mounts the magnetic steel cathode directly onto the magnets. Exemplary racetrack configurations are disclosed in U.S. Patent Publication No. 2016/0027608 entitled “Closed Drift Magnetic Field Ion Source Apparatus Containing Self-Cleaning Anode and a Process for Substrate Modification Therewith” which published to Madocks on January 28, 2016, and U.S. Patent Publication No. 2017/0029936 entitled “High Power Pulse Ionized Physical Vapor Deposition” which published to Chistyakov on February 2, 2017.

[0008] Another traditional ion source is disclosed in U.S. Patent No. 4,481,062 entitled “Electron Bombardment Ion Sources” which issued to Kaufman et al. on November 6, 1984. This approach commonly works at low pressure (for example, 10^{-4} Torr) which is incompatible with a typical sputtering pressure of at least 10^{-3} Torr. Furthermore, the Kaufman ion source undesirably uses a filament to thermionically emit electrons which makes it unsuitable for use with reactive gases. Moreover, the design typically employs metal grids across an outlet, thereby disadvantageously being prone to contamination, and requiring frequent downtime and maintenance.

[0009] In accordance with the present invention, a single beam plasma or ion source apparatus is provided. A further aspect of an ion source includes magnets and/or magnetic shunts which create a magnetic flux with a central dip or outward undulation located in an open space where a plasma is created. Another aspect employs an ion source including multiple magnets and at least three magnetic shunts arranged in a generally E cross-sectional shape. In another aspect, an ion source includes a removable non-magnetic cathode, cap or cover attached to an anode body which surrounds the magnets such that the cap can be easily removed without interaction with or direct attachment to the magnetic field for easy cleaning. Yet a further aspect provides a single beam plasma source which generates ions simultaneously with other deposition sources (such as sputtering magnetrons and plasma enhanced chemical vapor deposition equipment) at the same process pressure. Another aspect uses a single beam ion source for direct thin film deposition by either pointing the ion beam to and sputtering a target, or introducing a precursor gas that is subsequently dissociated by the ion source plasma. An additional aspect introduces a radio frequency electromagnetic field between the ion source and a specimen to enhance the beam plasma. Moreover, an ion source is centrally located within a surrounding sputter target in a further aspect of the present apparatus.

[0010] The present plasma source apparatus is advantageous over traditional devices. For example, the present apparatus advantageously emits a single ion beam, the cross-sectional diameter or width of which can be modulated from about 3 mm to at least 30 mm, and it can be made to any length in a single beam linear configuration. Moreover, the beam of the present apparatus can be generated in a wide range of operating pressures (for example 1 mTorr to >500 mTorr) which is compatible with simultaneous sputtering. The present apparatus beneficially operates with many different gases including inert and reactive gases since it does not use a filament. Furthermore, the present ion source can operate over a wide range of discharge voltages from 30 to greater than 500 V that lead to tunable ion energies for optimal ion-surface interactions.

[0011] The present apparatus is also advantageous for long-term stable operation since: 1) the anode is unlikely to be contaminated because no direct coating flux can reach the active surfaces; 2) the cathode is not sensitive to the coatings because it can be set at a floating potential and gets automatically biased; and 3) the non-magnetic cap or cover can be easily disassembled and reassembled for maintenance, as compared to conventional devices. It is noteworthy that the present apparatus emits a stable ion beam without interference with other plasma sources that simultaneously operate. Another advantage is the single beam ion source leads to significant decrease in the discharge voltage of a sputtering source and subsequently improves a sputtered film quality. Additional features and benefits will become apparent from the following description and appended claims taken in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0012] Figure 1 is a diagrammatic cross-sectional view showing prior art coating atoms on a workpiece without the assistance of an ion source;

[0013] Figure 2 is a diagrammatic cross-sectional view showing a prior art ion source;

[0014] Figure 3 is a diagrammatic top view showing the prior art ion source of Figure 2;

[0015] Figure 4 is a perspective view showing the present ion source;

[0016] Figure 5 is a cross-sectional view, taken along line 5 – 5 of Figure 4, showing the present ion source, where the cathode is isolated from ground;

[0017] Figure 6 is a partially fragmented perspective view showing the present ion source;

[0018] Figure 7 is a cross-sectional view, like that of Figure 5, showing magnetic flux lines and ion emissions from the present ion source, where the cathode is connected to ground potential;

[0019] Figure 8 is a diagrammatic cross-sectional view showing an exemplary magnet assembly used in the present ion source;

[0020] Figure 9 is a diagrammatic view, taken in the direction of arrow 9 from Figure 8, showing the present ion source;

[0021] Figure 10 is a diagrammatic view showing the present plasma or ion source apparatus in simultaneous operation with a deposition source inside a vacuum chamber;

[0022] Figure 11 is a diagrammatic cross-sectional view showing an interaction of coating atoms on a workpiece using the present ion source;

[0023] Figure 12 is a perspective view showing an alternate embodiment of the present ion source;

[0024] Figure 13 is a perspective view showing the alternate embodiment ion source of Figure 12;

[0025] Figure 14 is a diagrammatic view showing an alternate embodiment of the present plasma or ion source apparatus that is used to treat a thin film deposited from a magnetron source;

[0026] Figure 15 is a graph of sheet resistance of indium-tin-oxide ("ITO") films produced by sputtering with the assistance of the present ion source at difference discharge voltages or ion energies;

[0027] Figures 16 and 17 are atomic force microscopy phase images of ITO films deposited by sputtering without and with the assistance of the present ion source, respectively;

[0028] Figure 18 is a diagrammatic view showing another alternate embodiment of the present plasma or ion source apparatus for direct deposition of thin films;

[0029] Figure 19 is a diagrammatic view showing another alternate view of the present plasma or ion source apparatus;

[0030] Figure 20 is a diagrammatic cross-sectional view showing another alternate embodiment of the present plasma or ion source apparatus; and

[0031] Figure 21 is an end elevational view, taken in the direction of arrow 21 from Figure 20, showing the Figure 20 alternate embodiment plasma or ion source apparatus.

DETAILED DESCRIPTION

[0032] A preferred embodiment of a single beam plasma or ion source apparatus 21 can be observed in Figures 4 – 7 and 10. Ion source apparatus 21 includes a vacuum chamber 23, an ion source 25, a deposition source 27, and a specimen or workpiece 29. Ion source 25 and deposition source 27 are mounted to vacuum chamber 23 through vacuum-sealed ports. The apparatus also includes a pumping port connected to a vacuum pump 31, an input gas port connected to a process gas source, pressure gauges and optional heaters. Various configurations of the vacuum chamber exist, depending upon the specific functions desired of the system.

[0033] Exemplary ion source 25 includes an anode 51 and a cathode 53. The anode is mounted upon an insulator 55. The cathode is mounted on a metallic closure plate 61, which in turn is mounted to flange 59 on vacuum chamber 23. In this case, cathode 53 is set at an electrical ground potential. Cathode 53 can be a single piece or two pieces that include an external structural body 71 and an end cap 73 removeably fastened thereto via screws 75. Cap 73 of cathode 53 inwardly overhangs anode 51 with a single through-opening 77 in a center thereof defining an ion emission outlet. In the presently illustrated embodiment, structural body 71 and cap 73 of cathode 53 have circular peripheries and opening 77 is circular. Furthermore, the presently illustrated cap 73 employs a frustoconically tapered surface 79 adjacent through-opening 77.

[0034] It is alternately envisioned that other arcuate shapes such as ovals or other single apertured, elongated hole shapes may be employed for these noted components. An alternate embodiment can be observed in Figures 12 and 13 where a tapered single through-opening 677 in a cap 673 of a cathode 653 is linearly elongated in a lateral direction generally perpendicular to an emission central plane or direction of ions 619. The internal anode components are also laterally elongated surrounding a plasma area below opening 677.

[0035] Returning to the exemplary embodiment illustrated in Figures 5 - 10, multiple permanent magnets 91, preferably two, and multiple magnetic shunts 93, preferably three, are enclosed in anode 51. An electrically conductive internal cover 94 defines an open plasma region or area 96 essentially aligned with opening 77. Magnets 91 and shunts 93 each have coaxially aligned, circular internal edges and circular external edges wherein they are each ring-shaped with a hollow center. Magnets 91 are sandwiched or stacked between the shunts 93 such that the magnets are spaced apart from each other by the middle shunt. The upper and lower magnets are placed in series, e.g. N-S/N-S or S-N/S-N. Moreover, the cross-section of each side of the magnet and shunt assembly has a generally E-shape with the elongated and internal edges of shunts 93 extending toward a centerline axis 95 of ion source 25. Magnets 91 and shunts 93 are internally secured within an anode body 97 which is coupled to an anode base 99 via screws or other threaded fasteners. An optional incoming gas or cooling fluid inlet 101 and associated passageways are disposed through anode base 99, insulator 55 and plate 61. It is noteworthy that all of anode 51, including magnets 91 and shunts 93, are spaced internally away from all of cathode 53 either by a gap or insulator.

[0036] In the Figure 5 configuration, the cathode is isolated from ground at an electrically floating or biased potential. In the Figure 7 version, however, the cathode is connected to ground potential through flange 59.

[0037] Figures 7 - 10 illustrate ion source apparatus 21 in operation. When energized, a precursor gas in an open plasma area 96 internal to anode 51 is converted into a plasma due to the energetic electrons 113 moving between the portions of the magnet and shunt assembly as acted upon by the associated electromagnetic fields. Magnetic flux lines 115 flow from one top shunt 93 to the bottom outer shunt 93 or vice versa. Furthermore, a dip 117 or outwardly depressed undulation of at least some of the magnet flux lines 115 are caused by the magnetic assembly. This dip 117 advantageously serves to delay and/or trap adjacent electrons 113 as they are otherwise flowing along magnetic flux lines 115 and reach the anode. This dip therefore advantageously increases ionization and promotes flux density of ions 119 emitted through outlet opening 77 of cathode cap 73 coaxially aligned with a longitudinal centerline axis 95. In certain configurations, the center shunt 93 is optional. Alternately, it is envisioned that multiple dips 117 may be provided between originating and terminating ends of the magnetic fields 115 within open plasma area 96.

[0038] The presently preferred construction of ion source 25 allows for adjustability of ion beam 119 from 3 mm to at least 30 mm in diameter or lateral width. This can be achieved through different sizing of outlet 77, magnets 91, and shunts 93. Furthermore, a single ion beam 119 is emitted from ion source 25 with the ions almost uniformly distributed around a center axis when viewed in cross-section, as contrasted to the traditional ring-like and hollow center ion beams generated from the racetrack ion sources. Moreover, while the presently preferred magnets 91 and shunts 93 are hollow annular rings coaxially aligned with centerline 95 in a circular single beam ion source, they may alternately consist of multiple solid rod or bar-like magnets that are arranged about centerline 119 in a circular or arcuate pattern, although some of the preferred advantages may not be realized. In a linear single beam ion source, the ends include half of the circular configuration described above and the straight section may consist of multiple solid rod or bar-like magnets. It is also alternately envisioned that more than two stacked magnets or electromagnets may be employed and if so, additional associated shunts may be provided so as to extend the generally E-cross-sectional configuration with more than three inwardly extending teeth or projecting edges.

[0039] In one embodiment shown in Figure 10, ion beam 119 is transmitted from ion source 25 to specimen 29, where target material 131 is subsequently deposited onto the surface of specimen 29 from source 27. In one structural configuration, specimen 29 is coupled to an electromagnetic actuator 135, such as an electrical motor or solenoid. A similar electromagnetic actuator 139 is coupled to source 27. These optional electromagnetic actuators 135 and 139 can impart rotational and/or linear movement to specimen 29 and source 27. The present ion source assisted deposition effectively overcomes the conventional loose atom packing problem and advantageously produces dense films with superior stability, smooth film surface, high electric conductivity, and strong coating adhesion, due to dense packing of atoms 120, as illustrated in Figure 11.

[0040] Figure 14 illustrates an alternate embodiment of the present single beam plasma or ion source apparatus 221. In the present exemplary configuration, ion source

25 including its anode 51 and cathode 73, are essentially the same as in the prior embodiments of Figures 5 - 7. However, a sputtering source 201 is employed to operate simultaneously with the ion source 25. Sputtering source 201 is a magnetron sputter gun or other type of sputtering device, which generally includes a target 227 and an assembly of magnets and shunts that create a proper magnetic field in front of the target surface. In this embodiment, the single ion beam 219, is directly emitted toward specimen or workpiece 229 while target material 231 is simultaneously sputtered from target 227 and deposited on specimen 229 to form coating 233. This ion treatment occurs simultaneously with the sputtering deposition at the same vacuum chamber pressure.

[0041] In a production setting, the apparatus components can be set vertical or horizontal. Furthermore, the specimen can be rigid or flexible. It is also noteworthy that a conveyor or roller system may be employed with any of the embodiments disclosed in the present application.

[0042] Ion beam 219 interacts with deposited thin film 233, which is expected to directly improve characteristics of the film such as density, electric conductivity and barrier properties. This ion beam assisted thin-film growth is ideally suited for achieving super-smooth thin films and also to fabricate polycrystalline thin films at low temperatures such as room temperature.

[0043] The present ion source apparatus advantageously allows a wide range of operating pressures, such as those from 1 mTorr to 500 mTorr, which allow the ion creation and emission to be entirely compatible with sputtering. Furthermore, the present ion source apparatus advantageously allows ion creation and emission independent of the operating gas since no filament is used; thus, argon, oxygen and other inert and reactive gases may be used. The present ion source also works in a voltage control mode or a current control mode, and the discharge voltages can be as low as 30 volts. Moreover, the narrow focused ion beam advantageously provides a stable discharge without arcing.

[0044] In one example, the process gases consist of argon mixed with 0.6% oxygen and the pressure is maintained at 3.3 mTorr. The power applied to sputtering magnetron 201 is fixed at 30 Watts. Without ion source 25 power on, a five-minute sputtering creates an ITO coating 133 of approximately 36 nm thickness, i.e. 7.2 nm per minute. On the other hand, the same magnetron is powered at 30 W and the ion source is turned on with a voltage of approximately 96 V. A five-minute deposition produces an ITO film of 52 nm thickness, i.e. 10.0 nm per minute. Hence, the ion source leads to approximately 39% increase in the deposition rates. Based on the deposition rates and the same deposition parameters, ITO films of about 100 nm thickness were deposited on glass substrates at room temperature with and without the ion source powered on. The sheet resistance of the ITO films decreased to 1/5 as shown in Figure 15.

[0045] The creation and emission of ion beam 119 from ion source 25 simultaneously with a sputtering of target material onto substrate 29 beneficially creates a smoother and denser external surface of coating 133 on substrate 29. This is achieved by ions 119 impacting against the target material atoms as the atoms are being deposited or attaching to the previously deposited target material, and thereby pushing the new atoms into voids in each prior layer in the coating growth and buildup (see Figure 11). This is ideally suited for depositing a coating 133 and improving the quality thereof including increased deposition rates and better crystallinity. These improvements based on the present apparatus obtain greater light transmittance through coating 133 when the coating is an ITO films, and/or the coating exhibits improved hardness. Figures 16 and 17 show the atomic force microscopy phase images of indium-tin-oxide ("ITO") films deposited using apparatus 221 without and with ion source 25 in simultaneous operation, respectively. The results indicate that the ion source assisted deposition leads to dense and smooth ITO films.

[0046] Reference should now be made to Figure 18. Another embodiment of a single beam plasma or ion source apparatus 321 includes ion source 25 with anode 51 and cathode 73 essentially like that of the prior embodiments. This apparatus emits a chemical precursor gas from inlet 101 or another remote entrance into ion source 25 such that the plasma generated therein by the electromagnetic fields creates desired chemical species that subsequently deposit as a coating 333 on a specimen or workpiece 329. One such gas precursor is CH_4. This chemical vapor deposition process deposits and grows carbon coatings. Alternately, a carbon-based sputter target can be employed as with any of the other embodiments disclosed herein to produce carbon atoms as the specimen coating.

[0047] In the present exemplary configuration, specimen 329 on a conveyor system moves across the ion source and gets coated. A roll-to-roll coating arrangement 301 can also coat a flexible PET film, flexible and thin stainless steel sheet, or the like. Such a film and roller configuration can be employed with any of the embodiments disclosed herein.

[0048] Figure 19 illustrates a different embodiment single beam plasma or ion source apparatus 421. Anode 51 and cathode 53 of ion source 25 are essentially the same as with the prior embodiments. Additionally, a radio frequency ("RF") induction coil 401 is mounted between, and spaced away from, ion source 25 and a specimen 429. Radio frequency induction coil 401 creates an electromagnetic field during the operation of ion source 25 such that a single source ion beam 419 passes from outlet hole 77 through a hollow center 403 of coil 401 and onto a coating 433 of substrate 429. The RF frequencies are preferably in the range of about 1 MHz to 60 MHz, and more preferably 13.56 MHz.

[0049] While radio frequency induction coil 401 is preferably located inside the vacuum chamber along with ion source 25 and specimen 429, they may alternately be configured such that radio frequency induction coil 401 can be on the opposite side of specimen 429 from ion source 25. Radio frequency induction coil 401 will advantageously generate additional ions and densify the ions within ion beam 419. It is also envisioned that the radio frequency induction coil shall assist in shaping ion beam 419 for better control and focusing when depositing coating or films 433 on specimen 429.

[0050] Turning now to Figures 20 and 21, another embodiment of a single beam or ion plasma source apparatus 521 includes an ion source 525 and a sputtering target 527. Ion source 525 is similar to that of the prior embodiments disclosed herein. Furthermore, ion source 525 preferably includes a cathode cap 573 with a single and central outlet hole 577 through which a single ion beam 519 is emitted to assist in creation of a coating 533 on a specimen or workpiece 529 within a vacuum chamber.

[0051] An annular pedestal 501 of conductive metallic material is mounted upon an insulator 555 and serves to mount an annular shaped sputter target 527 thereupon. Ion source 525 is concentrically and coaxially located within a hollow center of target 527 and pedestal 501. This provides an integrated and simultaneously acting sputtering and ion emission sources which advantageously operate at the same internal vacuum chamber pressure. It is beneficially envisioned that the present integrated and concentric sources can more quickly cover a larger specimen area in a shorter amount of time for both sputtered material deposition and ion emission interactions with the deposited atoms, than would otherwise be achieved with remotely offset ion and target sources. It is further envisioned that the present integrated and concentric sources may provide more complete ion-activated sputtering and in a more uniform manner than with conventional devices. More specifically, the present integrated and coaxial sources are expected to more advantageously be aligned with the specimen thereby achieving a more uniform coating versus offset angled sputtering target locations. A similar principle can be extended to a linearly elongated shape single beam ion source integrated with a sputtering magnetron or other deposition sources.

[0052] While various embodiments have been disclosed, it should be appreciated that other variations may be employed. For example, specific magnet and shunt quantities and shapes may be varied although some of the desired benefits may not be realized. Additionally, external body, insulator and base shapes and sizes may be varied, although certain advantages may not be achieved. Furthermore, exemplary target and specimen materials have been identified but other materials may be employed. Moreover, each of the features may be interchanged and intermixed between any and all of the disclosed embodiments, and any of the claims may be multiply dependent on any of the others. While various applications of the single beam plasma or ion sources have been disclosed, using the sources for other applications, such as direct sputtering or etching a target surface, is not to be regarded as a departure from the spirit or the scope of the present invention. Additional changes and modification are not to be regarded as a departure from the spirit or the scope of the present invention.

THE EMBODIMENTS FOR WHICH AN EXCLUSIVE PRIVILEGE AND PROPERTY IS CLAIMED ARE AS FOLLOWS:

1. An ion source apparatus comprising:

(a) an anode comprising magnetic shunts inwardly extending toward an ion emission axis, an open plasma area being located within a hollow central area of the anode;

(b) a cathode comprising a cap having a single outlet opening therethrough, the outlet opening being aligned with the axis;

(c) magnetic flux lines extending between uppermost and lowermost of the magnetic shunts, the magnetic flux lines including a central outward dip adjacent a middle of the magnetic shunts, the dip of the magnetic flux lines being in the open plasma area, and the dip changing movement of electrons adjacent the dip to increase ionization within a plasma inside the anode;

(d) permanent magnets located between the magnetic shunts in a stacked arrangement;

(e) the permanent magnets and the magnetic shunts each being of a closed loop shape; and

(f) the magnetic shunts inwardly projecting toward the axis further than the permanent magnets.

2. The apparatus of Claim 1, wherein the cathode further comprises a body concentrically surrounding the magnets and the shunts, and the cap of the cathode being directly and removeably attached to the body which is laterally spaced away from the anode, and the cap inwardly overhanging the magnets and shunts.

3. The apparatus of Claim 1, further comprising a single ion beam, with ions being substantially uniformly distributed around the emission axis when viewed in cross-section, emitted through the outlet opening along the emission axis.

4. The apparatus of Claim 3, further comprising:

a vacuum chamber containing a precursor gas;

a sputter target located in the vacuum chamber receiving the single ion beam; and

the magnetic shunts include at least three spaced apart shunts.

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5. The apparatus of Claim 3, wherein the single outlet opening is linearly elongated in a direction substantially perpendicular to the emission axis.

6. The apparatus of Claim 3, wherein the single outlet opening is circular with a frustoconical tapered surface on the cap surrounding the opening.

7. The apparatus of Claim 1, further comprising a deposition source, a portion of the magnetic shunts being at least partially concentrically located within the deposition source.

8. The apparatus of Claim 1, further comprising a specimen, and the anode and cathode emitting a single ion beam with a substantially uniformly distributed ion cross-section around the emission axis, to assist in depositing a thin film of a deposition material on the specimen.

9. The apparatus of Claim 1, further comprising a specimen, and the anode and the cathode emitting a single ion beam with a substantially uniformly distributed ion cross-section around the emission axis, to assist in depositing a carbon-based coating on a specimen with the assistance of a carbon-based precursor gas.

10. The apparatus of Claim 1, further comprising a radio frequency coil surrounding an ion beam emitted from the anode and the cathode, the coil being longitudinally spaced away from the anode and the cathode.

11. The apparatus of Claim 1, further comprising a sputter target, and the anode and the cathode being adapted to cause simultaneously ion emission and sputtering at the same pressure.

12. An ion source apparatus comprising:

(a) an anode comprising multiple magnets and multiple conductive shunts, and the shunts being spaced away from each other;

(b) a cathode comprising an internally overhanging cap defining a single outlet therethrough coaxially aligned with the magnets and the shunts, the magnets and the outlet having a coaxial centerline;

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(c) the magnets and the shunts defining a substantially E-cross-sectional shape with distal ends of the shunts internally pointing toward the centerline; and

(d) magnetic flux lines extending between an uppermost and a lowermost of the multiple conductive shunts including a central outward dip which delays or traps electron movement to increase ionization emitted through the outlet.

13. The apparatus of Claim 12, further comprising a single ion beam, with substantially uniformly distributed ions around the centerline when viewed in cross-section, created in a plasma within the anode and longitudinally emitted through the outlet along the centerline.

14. The apparatus of Claim 13, further comprising:

a deposition target receiving the single ion beam;

a gas inlet positioned adjacent at least one ion source component of: an insulator or the anode; and

each of the magnets and the shunts having a closed loop shape.

15. The apparatus of Claim 12, wherein the dip of the magnetic flux lines is in a plasma area laterally surrounded by at least one of: the magnets and the shunts.

16. The apparatus of Claim 12, further comprising a reactive gas being converted into a plasma within an anode region, and the apparatus not using a filament.

17. The apparatus of Claim 12, wherein the cathode further comprises a structural body concentrically surrounding the magnets and the shunts, the overhanging cap of the cathode being directly and removeably attached to the structural body, and the cap and the structural body being spaced away from the anode.

18. The apparatus of Claim 12, wherein the magnets are permanent magnets separated by a middle one of the shunts, and the shunts are each laterally elongated more than the magnets.

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19. The apparatus of Claim 12, further comprising a sputter target, and the anode and cathode being adapted to simultaneously cause ion emission and sputtering at the same pressure.

20. The apparatus of Claim 12, further comprising a deposition source, at least one of the magnets being at least partially concentrically located within the deposition source.

21. The apparatus of Claim 12, further comprising a specimen, and the anode and cathode emitting a single ion beam with substantially uniformly distributed ions around the centerline when viewed in cross-section, to assist in depositing a thin film of a deposition material on the specimen.

22. The apparatus of Claim 12, further comprising a specimen, and the anode and the cathode emitting a single ion beam with substantially uniformly distributed ions around the centerline when viewed in cross-section, to assist in depositing a carbon-based coating on a specimen with the assistance of a carbon-based precursor gas.

23. The apparatus of Claim 12, further comprising a radio frequency coil surrounding an ion beam emitted from the anode and the cathode, the coil being longitudinally spaced away from the anode and the cathode.

24. An ion source apparatus comprising:

(a) an anode comprising multiple magnets and multiple conductive shunts;

(b) a cathode comprising an internally overhanging cap having an ion emission outlet therethrough;

(c) a structural body externally surrounding the magnets and the shunts, the structural body being spaced away from the anode;

(d) the cap being removeably attached directly to the structural body; and

(e) magnetic flux lines extending between an uppermost and a lowermost of the multiple conductive shunts including a central outward dip which delays or traps electron movement to increase ionization emitted through the ion emission outlet.

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25. The apparatus of Claim 24, wherein the magnets and the shunts include a substantially E-cross-sectionally shaped orientation.

26. The apparatus of Claim 24, wherein the magnets, shunts, cap and structural body all have substantially circular peripheries, and the outlet is a single circular opening which is configured to emit a single ion beam from a plasma inside the anode.

27. The apparatus of Claim 24, wherein the outlet is a single linearly elongated opening extending in a direction substantially perpendicular to an ion emission direction from the cap.

28. The apparatus of Claim 24, further comprising:

a vacuum chamber within which the anode and cathode are located;

a sputter target located within the vacuum chamber;

a deposition source located within the vacuum chamber; and

a single ion beam emitted from the outlet simultaneously with deposition of material from the deposition source onto a specimen and at the same vacuum chamber internal pressure.

29. The apparatus of Claim 24, further comprising:

an anode body attached to and surrounding the magnets and the shunts;

the structural body surrounding the anode body with a gap therebetween;

threaded fasteners securing the cap to the structural body;

an anode base being mounted to an end of the anode body opposite the outlet; and

an insulator coupling the anode base to the structural body.

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30. The apparatus of Claim 24, wherein the cap and structural body each have a substantially circular periphery, and the cap has a taper adjacent the outlet which is also substantially circular.

31. An apparatus comprising:

(a) a vacuum chamber;

(b) an ion source comprising an anode including magnets, and a cathode having an ion emission-outlet therein, the ion source being located in the vacuum chamber, the anode comprising shunts, the magnets and the shunts including a substantially E-cross-sectionally shaped orientation with edges of the shunts laterally extending past the magnets toward a centerline of the anode;

(c) a sputter target located in the vacuum chamber;

(d) the ion source being capable of creating an ion beam and emitting a single ion beam simultaneously with sputtering material from the sputter target, both the ion emission and the sputtering being capable of depositing a sputtered coating at a vacuum chamber pressure at any of 1 mTorr to 500 mTorr; and

(e) magnetic flux lines extending between an uppermost and a lowermost of the shunts including a central outward dip which delays or traps electron movement at the dip to increase ionization emitted through the outlet.

32. The apparatus of Claim 31, wherein the dip of the magnetic flux lines is in an open plasma area laterally surrounded by at least one of the magnets and the shunts.

33. The apparatus of Claim 31, further comprising a single ion beam, with substantially uniformly distributed ions around an emission axis when viewed in cross-section, emitted through the outlet.

34. The apparatus of Claim 31, wherein the sputter target concentrically surrounds at least part of the anode.

35. The apparatus of Claim 31, further comprising a gas inlet located adjacent a base of the anode, the gas being a reactive gas, and the apparatus not using a filament.

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36. The apparatus of Claim 31, further comprising a workpiece, and the anode and cathode emitting a single ion beam with substantially uniformly distributed ions around an emission axis when viewed in cross-section, to assist in depositing a thin film of a sputter material on the workpiece.

37. The apparatus of Claim 31, further comprising a workpiece, and the anode and the cathode emitting a single ion beam with a substantially laterally uniform cross-sectional ion center to assist in depositing a carbon-based coating on the workpiece with the assistance of a carbon-based precursor gas.

38. The apparatus of Claim 31, further comprising a radio frequency coil surrounding an ion beam emitted from the anode and the cathode, and the coil being longitudinally spaced away from the ion source.

39. The apparatus of Claim 31, further comprising a flexible workpiece spanning between feed and take-up rollers, the single ion beam emitted from the ion source causing material to sputter from the sputter target and be deposited on the flexible workpiece.

40. The apparatus of Claim 31, further comprising a glass sheet workpiece moveable within the vacuum chamber, the single ion beam emitted from the ion source causing material to sputter from the sputter target and be deposited on the glass sheet workpiece.

41. An apparatus comprising:

(a) a vacuum chamber;

(b) an ion source comprising an anode, including magnets, and a cathode having an ion emission-outlet therein, the ion source being located in the vacuum chamber, the anode comprising shunts, the magnets and the shunts are oriented in a substantially E-cross-sectional shape with edges of the shunts extending past the magnets toward a centerline of the anode;

(c) a deposition source located in the vacuum chamber;

(d) the ion source being coaxial with the deposition source, and the deposition source surrounding at least a portion of the ion source; and

(e) magnetic flux lines extending between an uppermost and a lowermost of the shunts including a central outward dip which delays or traps electron movement at the dip to increase ionization emitted through the ion emission outlet.

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42. The apparatus of Claim 41, wherein the deposition source is annular with a hollow center surrounding the portion of the ion source adjacent the outlet.

43. The apparatus of Claim 42, further comprising a second cathode pedestal spaced apart from the cathode of the ion source and spaced apart from the anode, the deposition source includes a sputter target being mounted on a distal end of the second cathode pedestal.

44. The apparatus of Claim 43, further comprising an insulator located adjacent an end of the ion source opposite the outlet, the second cathode pedestal being annular and fluid-cooled, and the second cathode pedestal being coupled to the insulator outboard of the ion source.

45. The apparatus of Claim 41, wherein the ion source creates and emits ions at a specimen simultaneously with depositing sputtered material from the deposition source to the specimen at the same pressure in the vacuum chamber.

46. The apparatus of Claim 41, further comprising a single ion beam, with substantially uniformly distributed ions around an emission axis when viewed in cross-section, emitted through the outlet.

47. The apparatus of Claim 41, further comprising a gas inlet located adjacent a base of the anode, the gas being a reactive gas, and the apparatus not using a filament.

48. An apparatus comprising:

(a) a vacuum chamber;

(b) an ion source comprising an anode, including magnets, and a cathode having an outlet therein, the ion source being located in the vacuum chamber, and the ion source being adapted to create an ion beam in a plasma and emit the ion beam through the outlet, the anode comprising shunts, the magnets and the shunts including a substantially E-cross-sectionally shaped orientation with edges of the shunts extending past the magnets toward a centerline of the anode;

(c) a deposition source located in the vacuum chamber;

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(d) radio frequency induction coil with a hollow center coaxially aligned with a longitudinally elongated ion beam axis from the ion source, and the coil being longitudinally spaced away from the ion source; and

(e) magnetic flux lines extending between an uppermost and a lowermost of the shunts including a central outward dip which delays or traps electron movement at the dip to increase ionization emitted through the outlet.

49. The apparatus of Claim 48, wherein the cathode further comprises a structural body concentrically surrounding the magnets and the shunts, and an overhanging cap of the cathode being directly and removeably attached to the structural body.

50. The apparatus of Claim 48, further comprising a single ion beam, with substantially uniformly distributed ions around the axis when viewed in cross-section, emitted through the outlet along the axis.

51. The apparatus of Claim 50, wherein the deposition source is a sputter target receiving the single ion beam, further comprising a gas inlet emitting a precursor gas to the anode.

52. The apparatus of Claim 48, further comprising a gas inlet located adjacent a base of the anode, the gas being a reactive gas, and the apparatus not using a filament.

53. The apparatus of Claim 48, wherein the coil generates additional ions and shapes an ion beam passing therethrough from the ion source.

54. An apparatus comprising;

(a) a vacuum chamber;

(b) an anode comprising multiple magnets and multiple conductive shunts, each of the magnets and the shunts having a closed loop shape, and the shunts being spaced away from each other;

(c) a cathode comprising a cap defining an outlet therethrough;

(d) a gas inlet operably supplying a carbon-based precursor gas to the anode;

(e) a workpiece spaced away from the anode and cathode within the vacuum chamber;

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(f) the anode and cathode operably being configured to create a single ion beam that is operably emitted from the outlet to assist in depositing a carbon-base coating on the workpiece; and

(g) at least one magnetic flux line extending between an uppermost and a lowermost of the shunts including a central outward dip which delays or traps electron movement at the dip to increase ionization emitted through the outlet which is a single opening.

55. The apparatus of Claim 54, wherein the workpiece is an internal combustion engine component.

56. The apparatus of Claim 54, wherein the precursor gas includes CH_4.

57. The apparatus of Claim 54, wherein the magnets are permanent magnets separated by a middle one of the shunts, and the shunts each are laterally longer than the magnets.

58. The apparatus of Claim 54, wherein the magnets and the shunts are oriented in a substantially E-cross-sectional shape.

59. The apparatus of Claim 54, further comprising a deposition source located in the vacuum chamber, and the outlet is a single circular-shaped opening surrounded by a frustoconically tapered surface on the cap.

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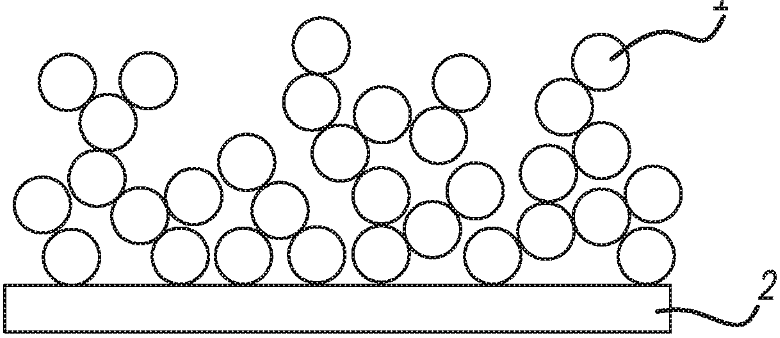
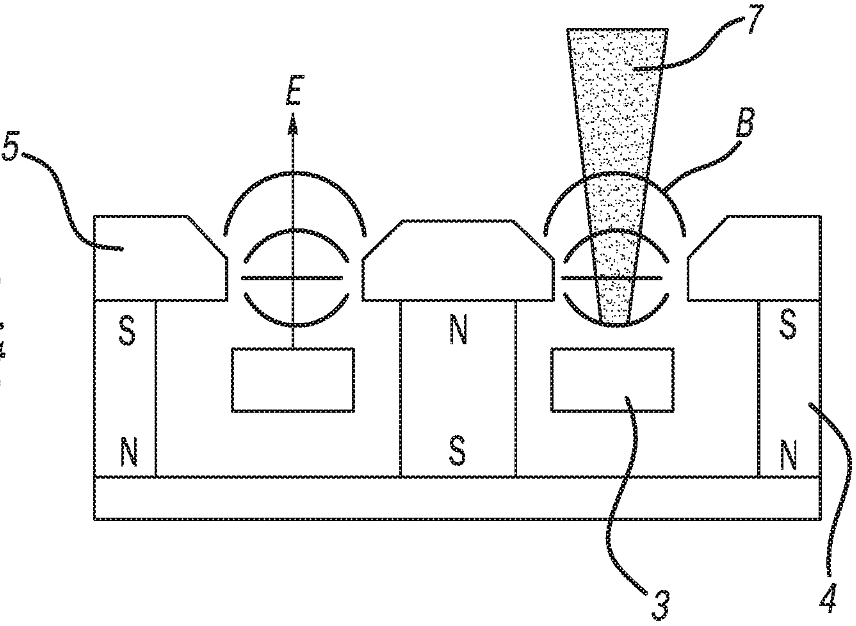


FIG - 1
Prior Art

FIG - 2
Prior Art



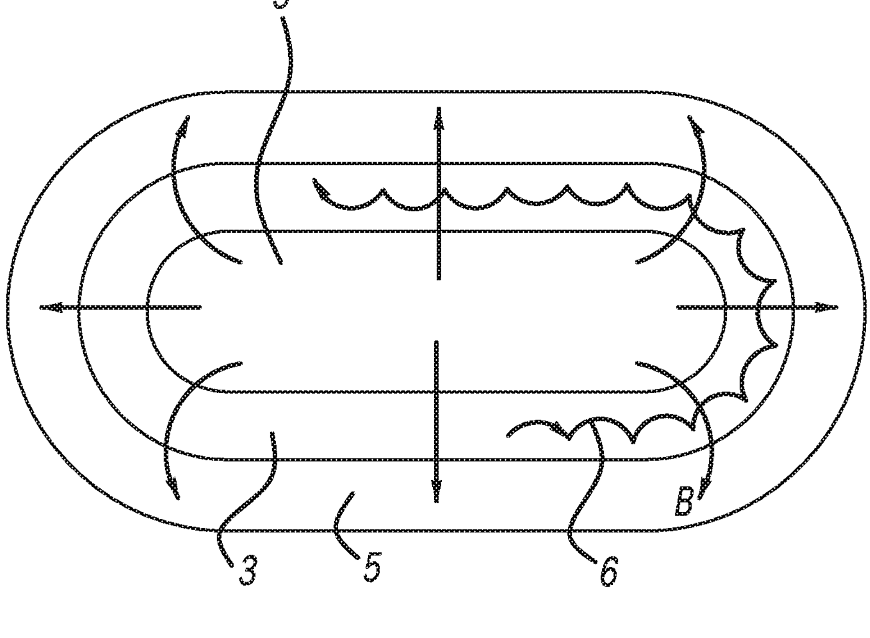


FIG - 3
Prior Art

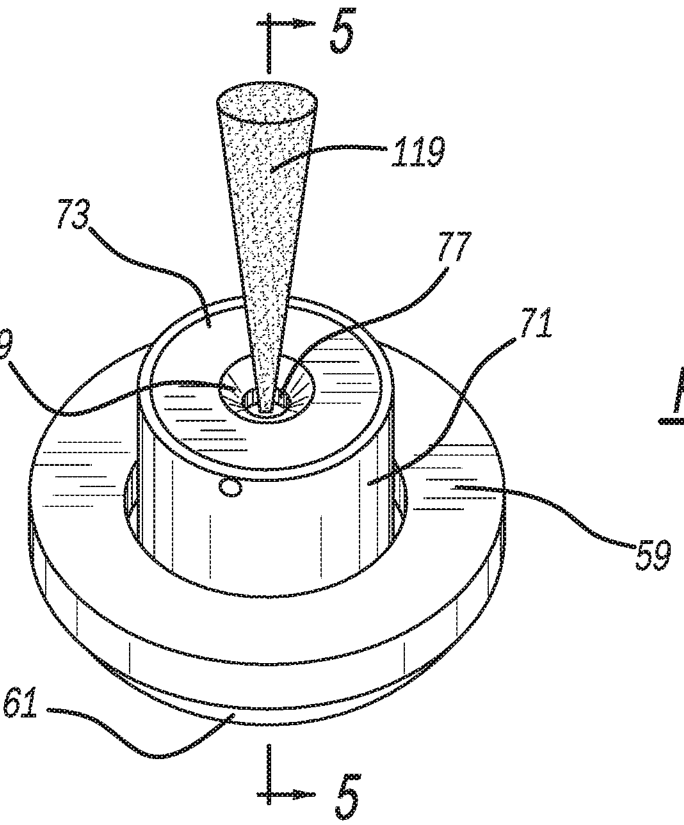


FIG - 4

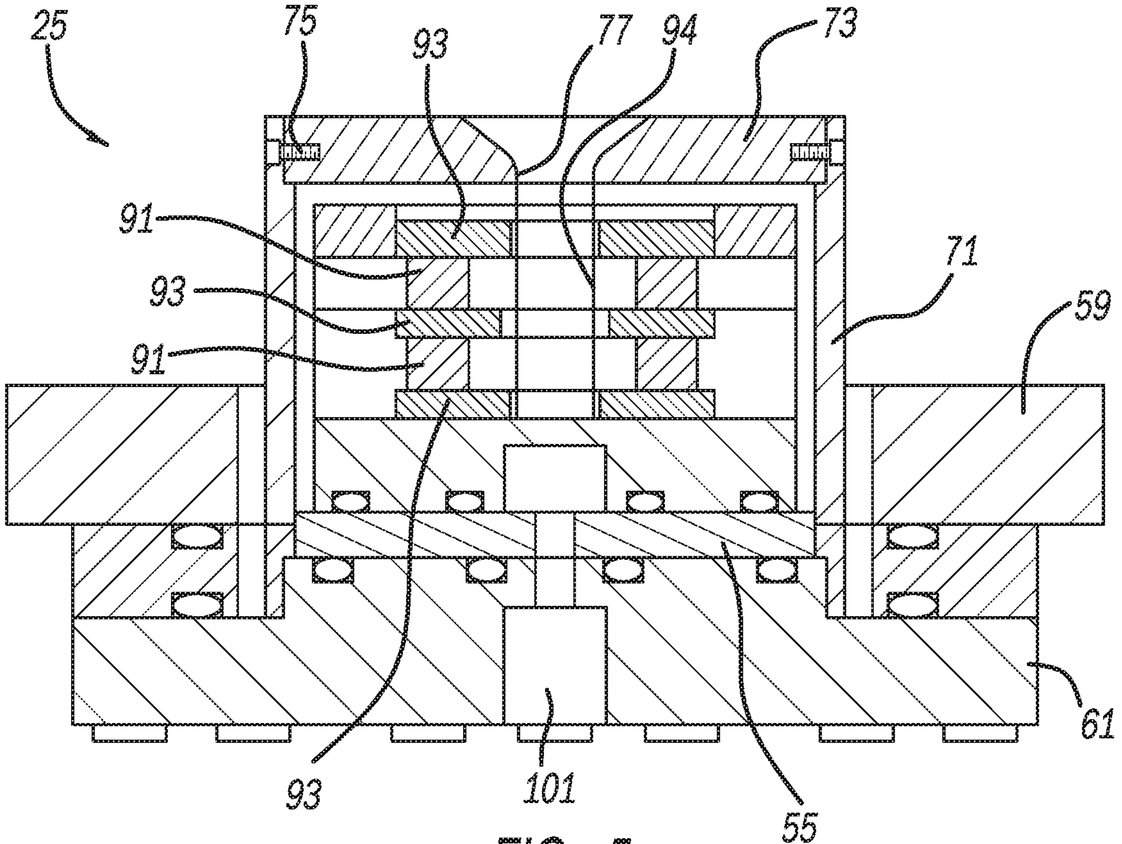


FIG - 5

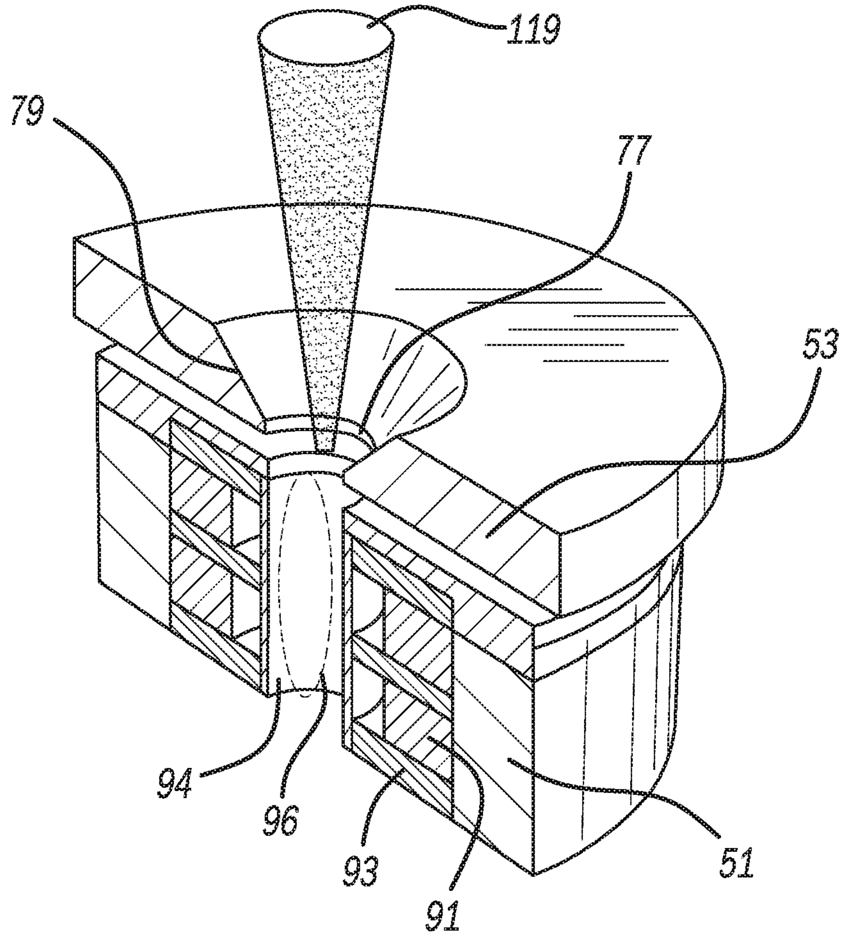


FIG - 6

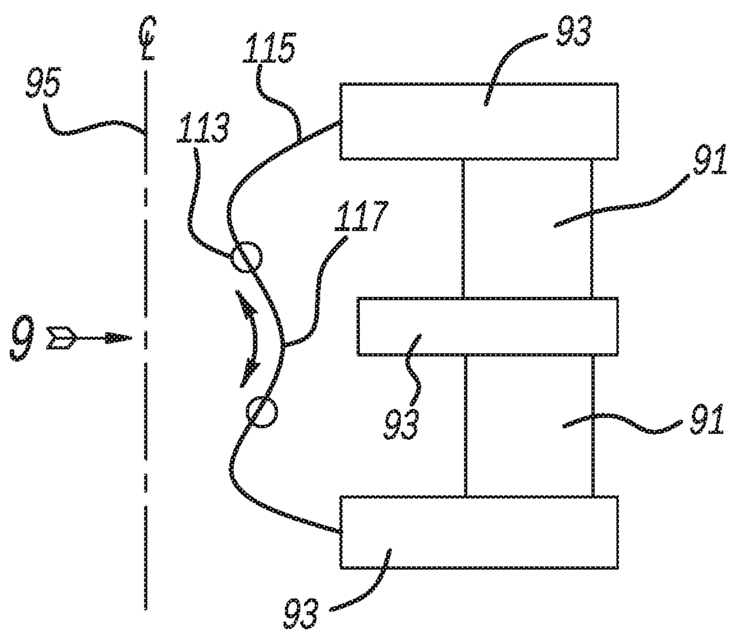
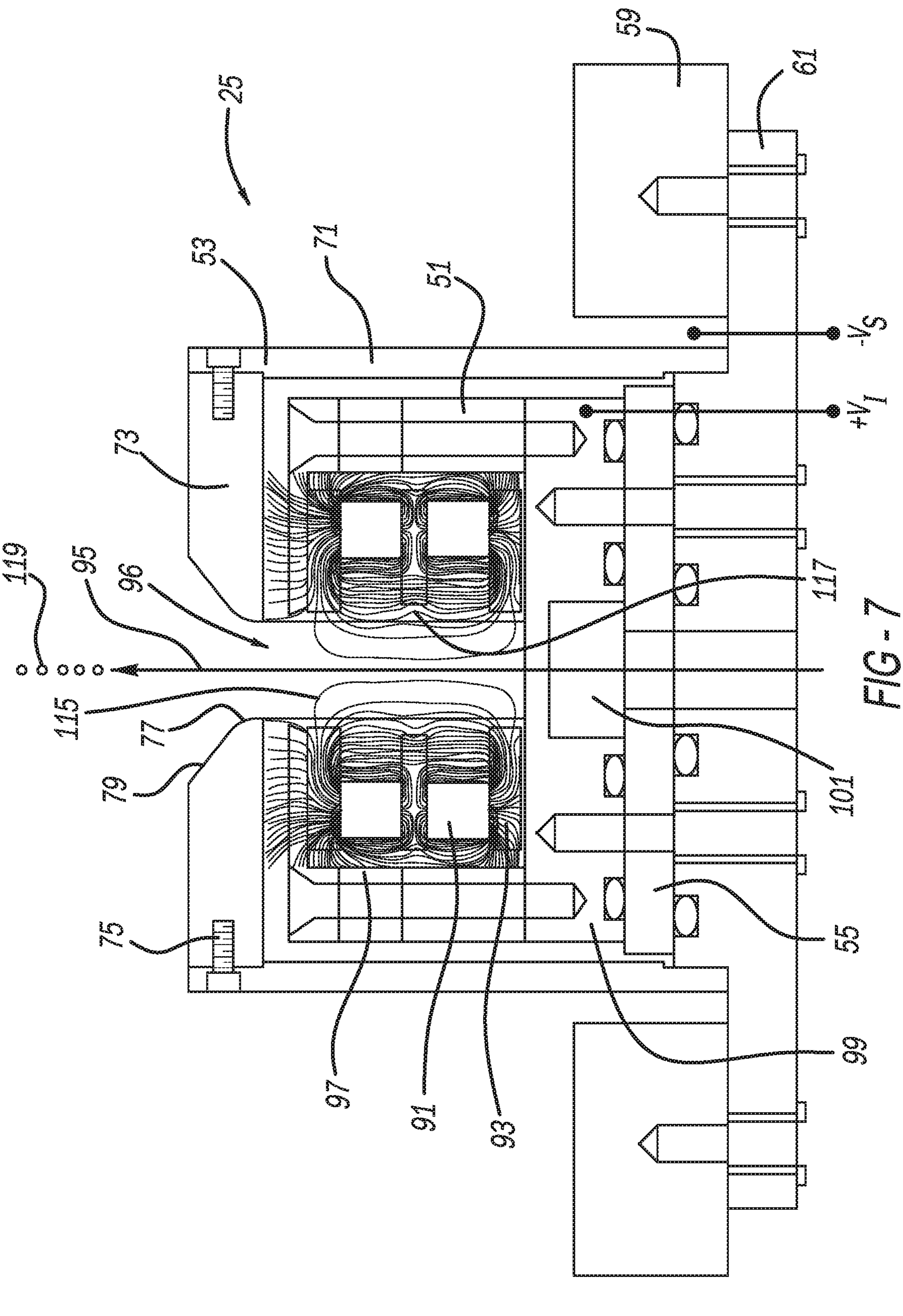


FIG - 8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115
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101
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97
91
93
99
-V_S
+V_I

FIG - 7

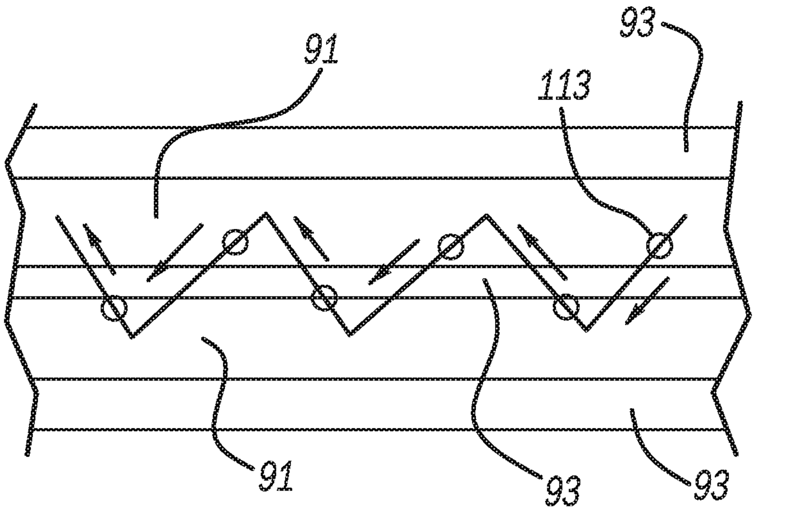


FIG - 9

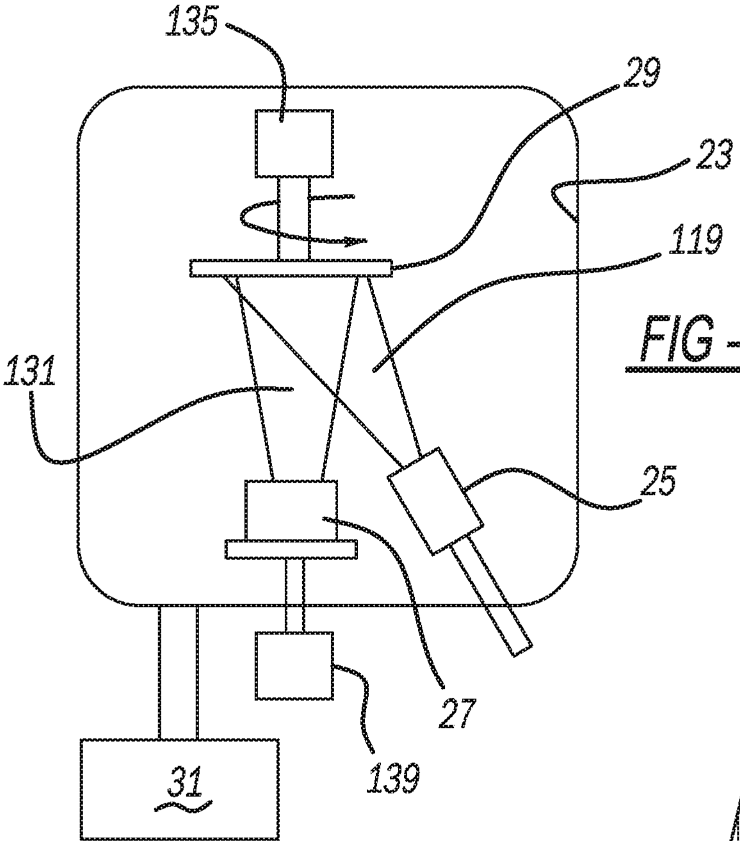


FIG - 10

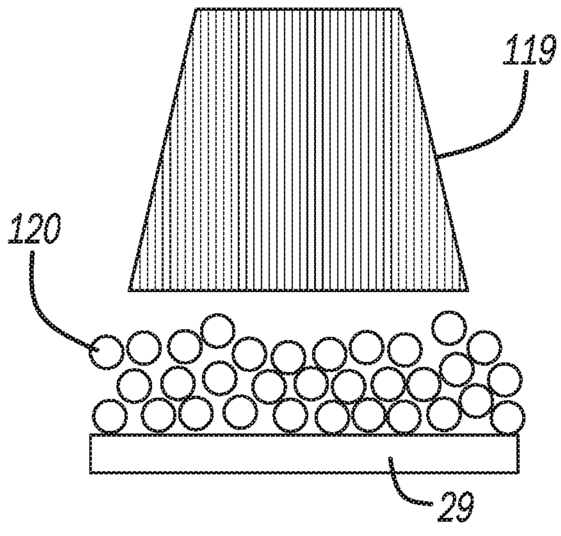


FIG - 11

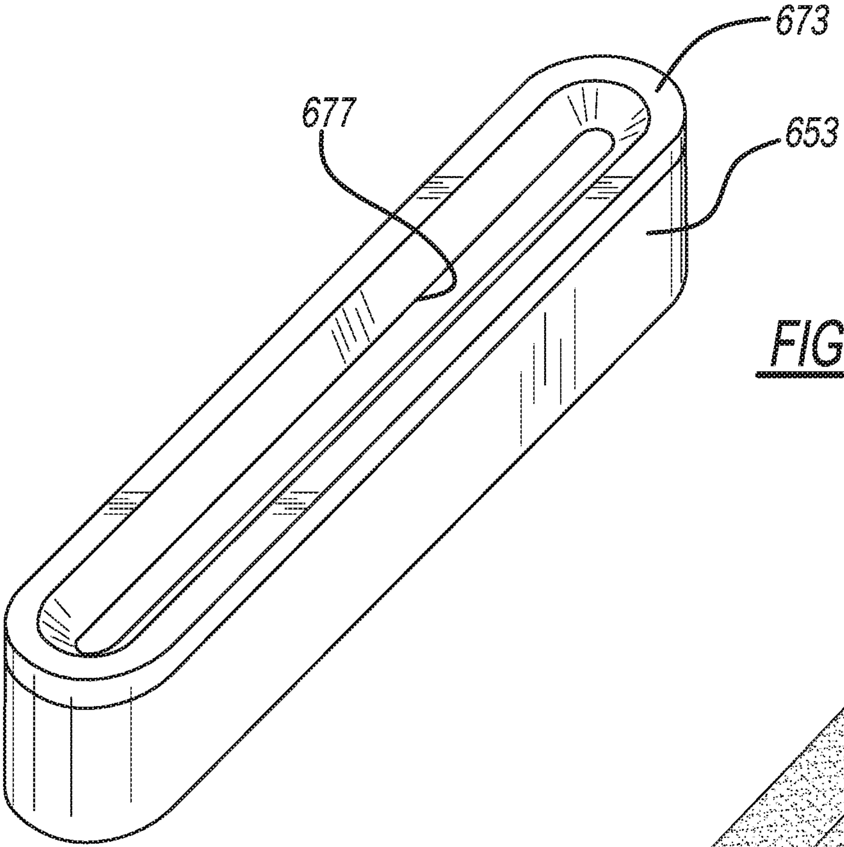


FIG - 12

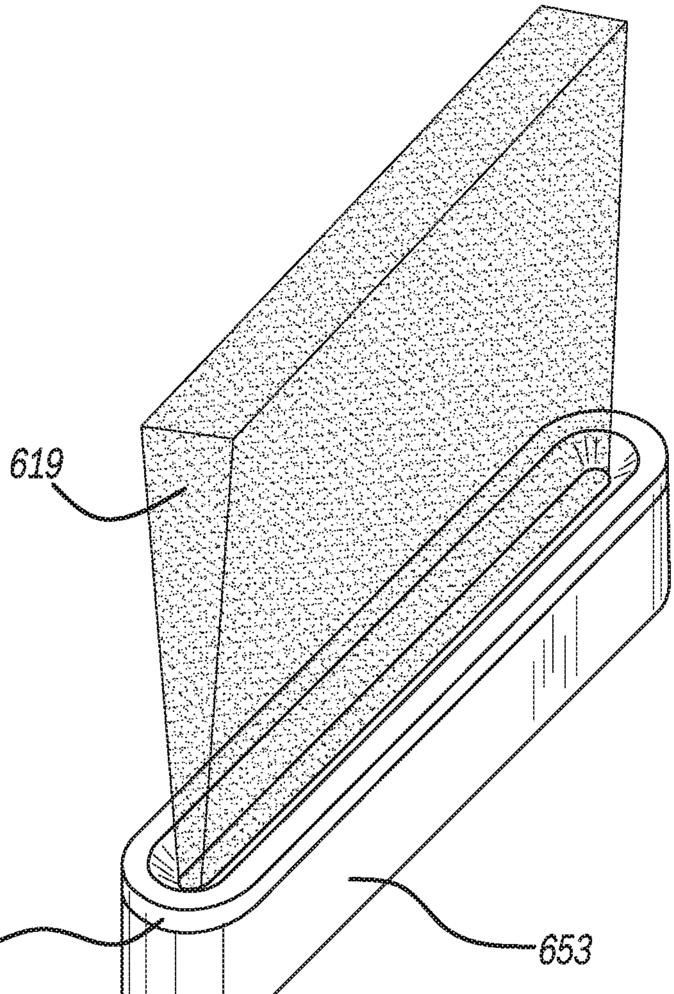


FIG - 13

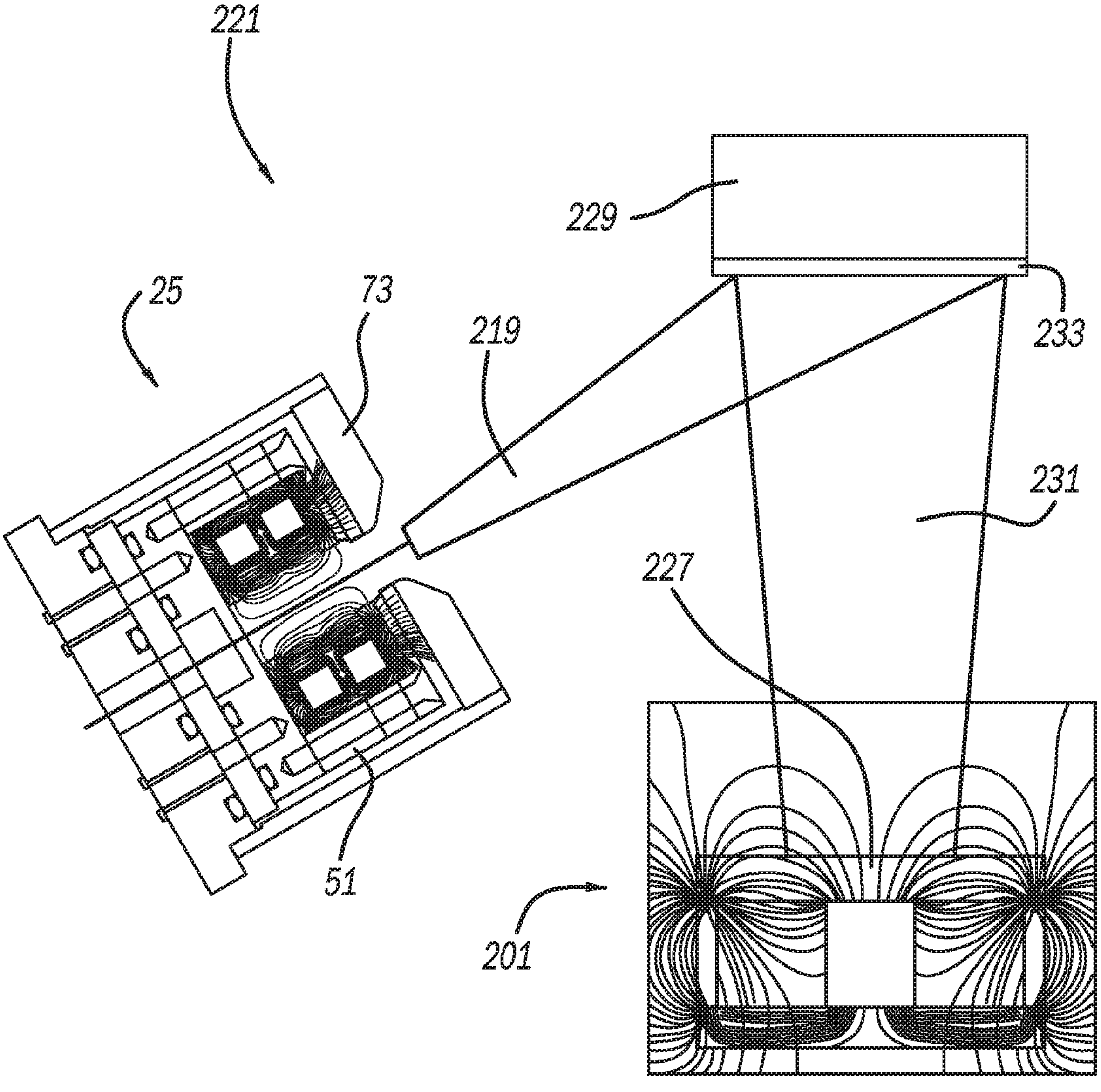


FIG - 14

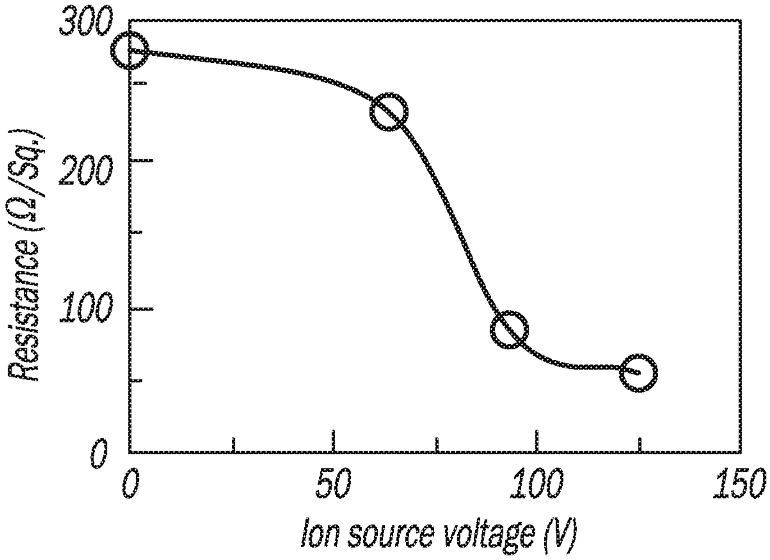

300
200
100
0
Resistance (Ω/Sq.)
0
50
100
150
Ion source voltage (V)

FIG - 15

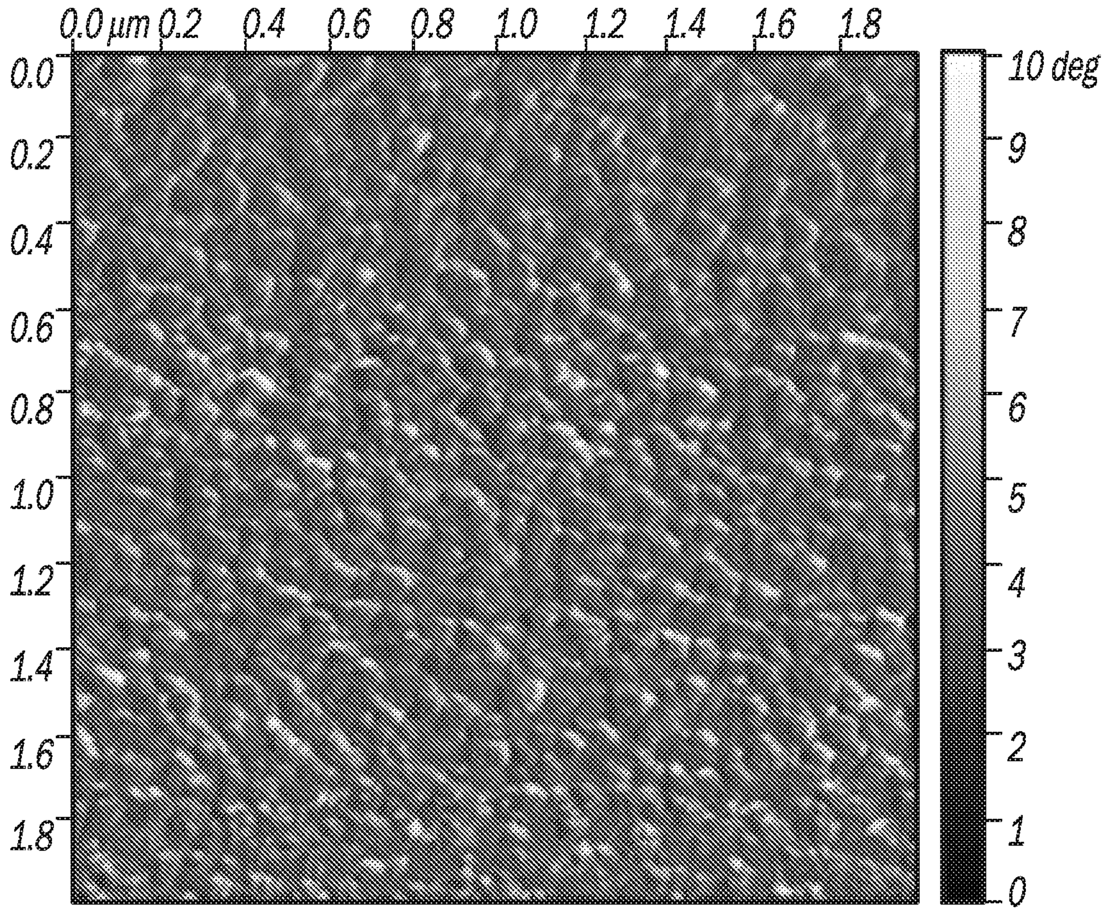
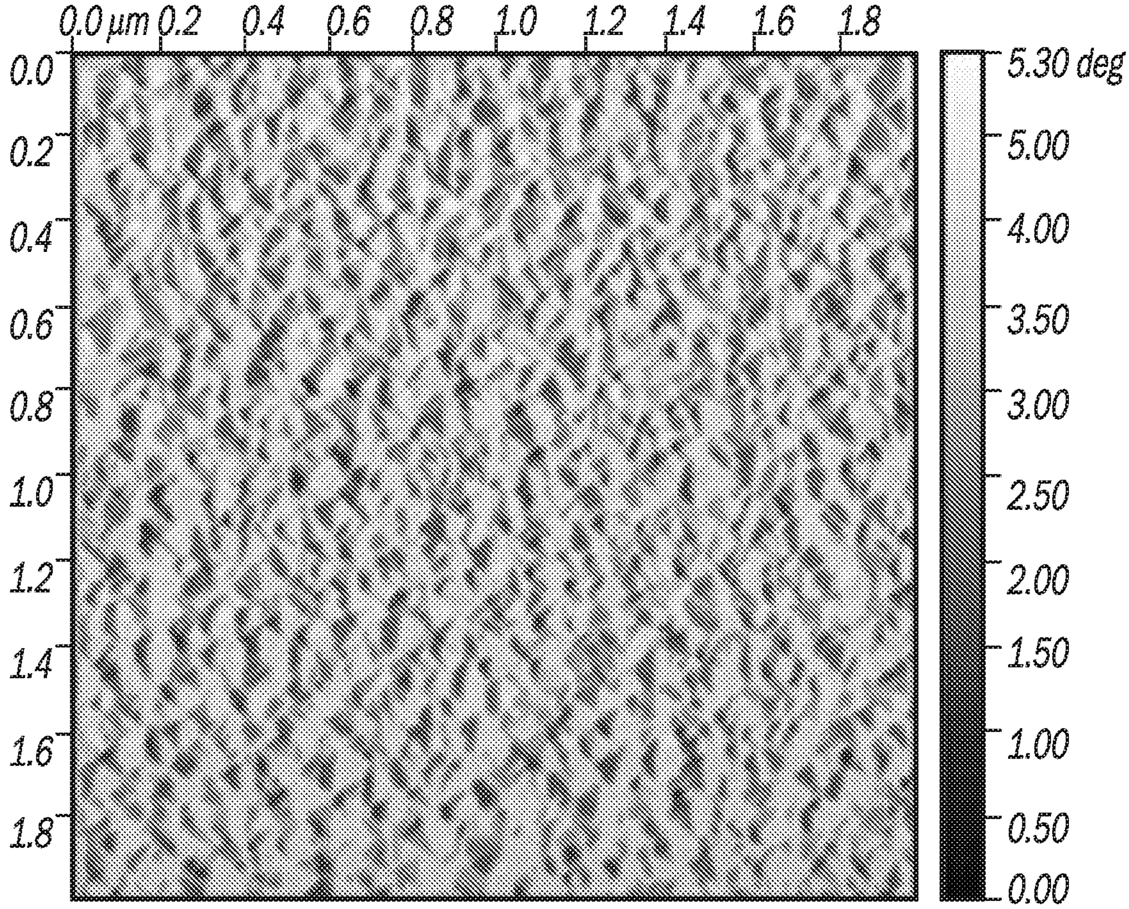

0.0 μm
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
10 deg
9
8
7
6
5
4
3
2
1
0

FIG - 16


0.0 µm
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0.00

FIG - 17

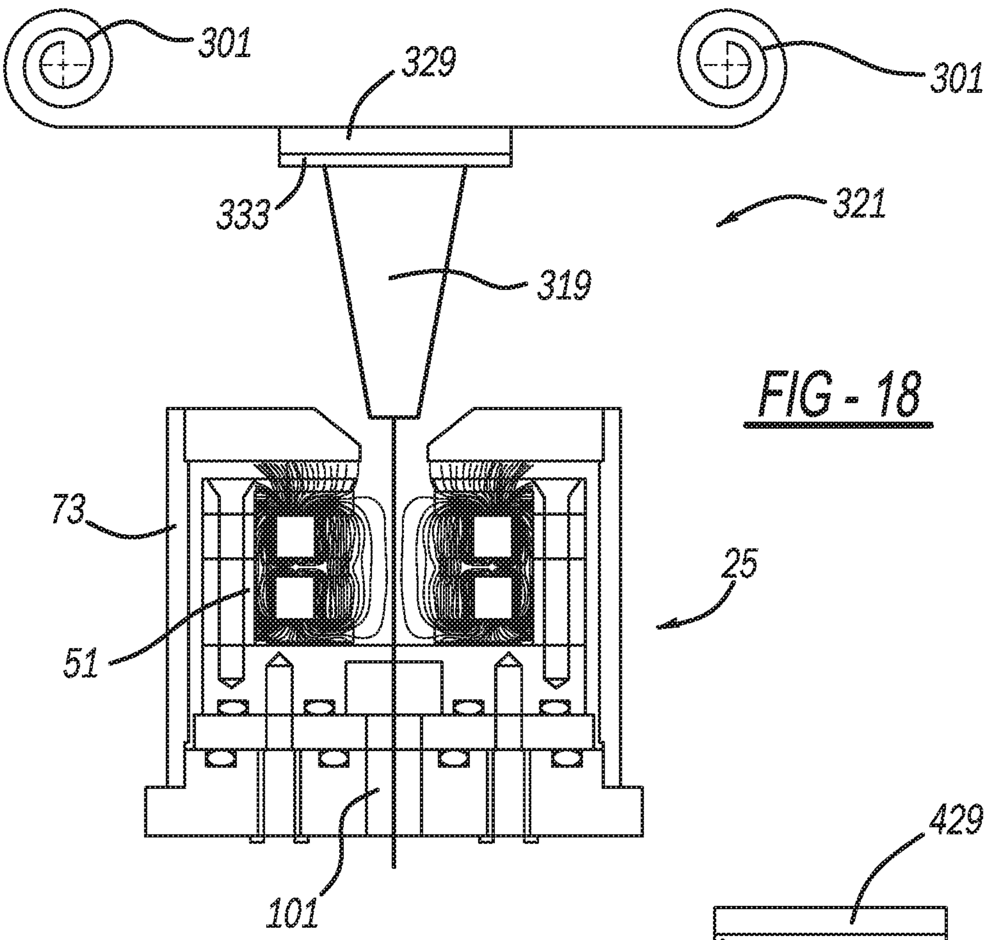
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FIG - 18

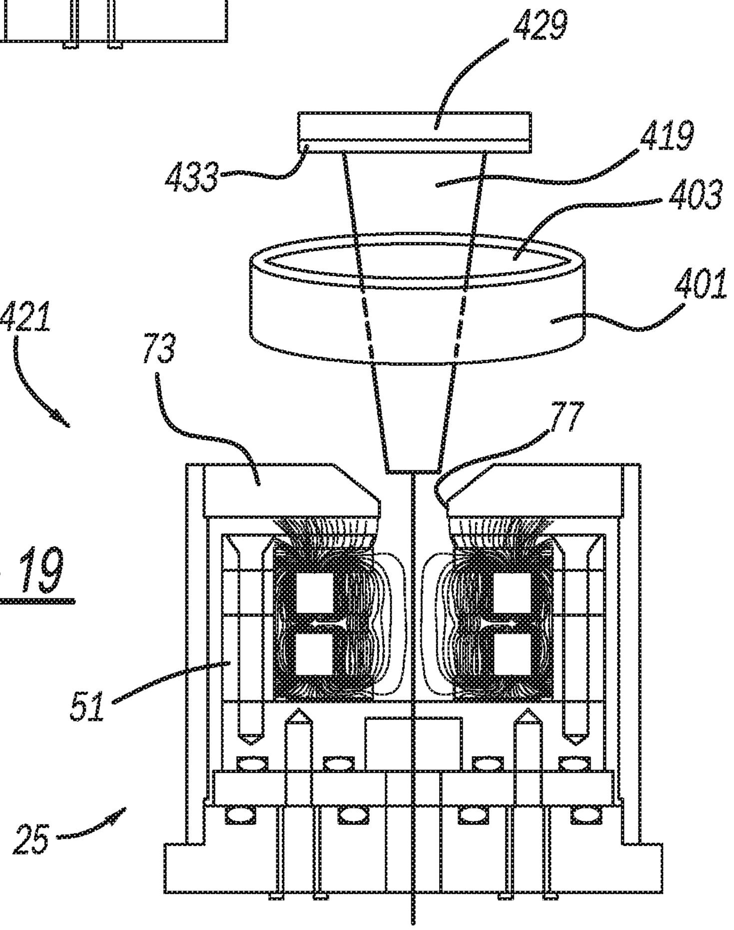
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FIG - 19

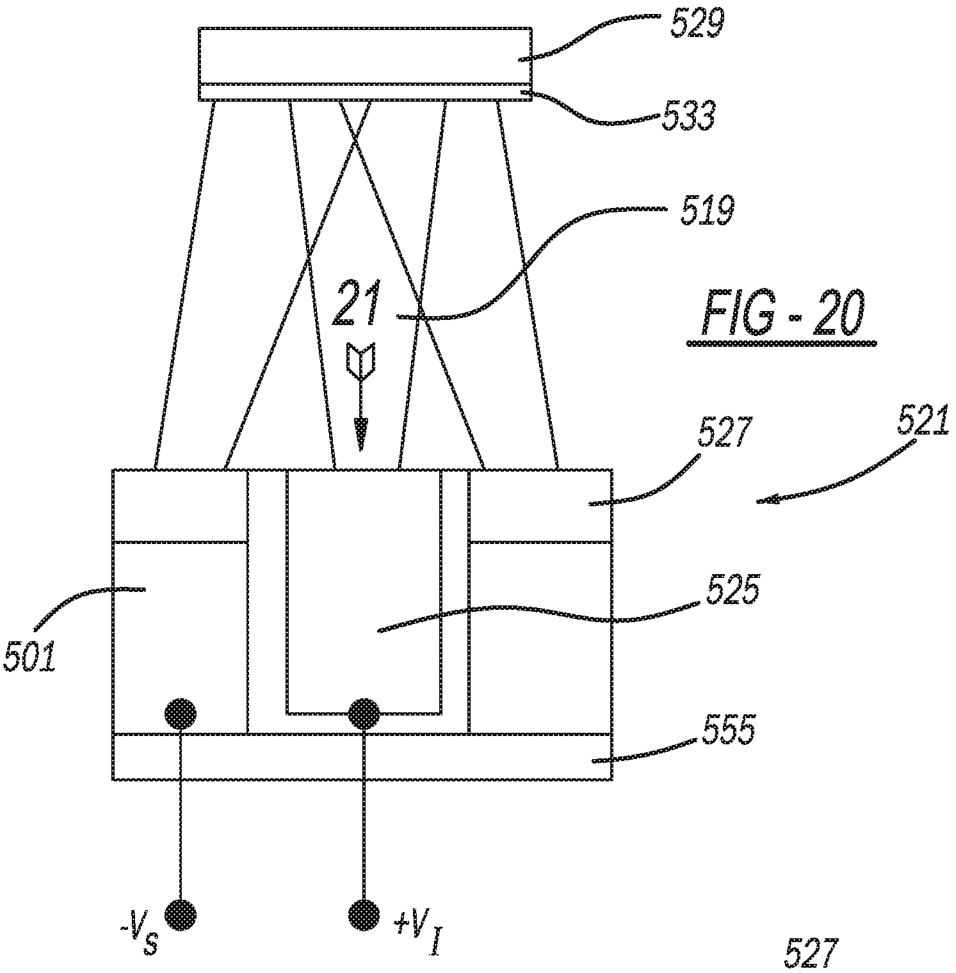


FIG - 20

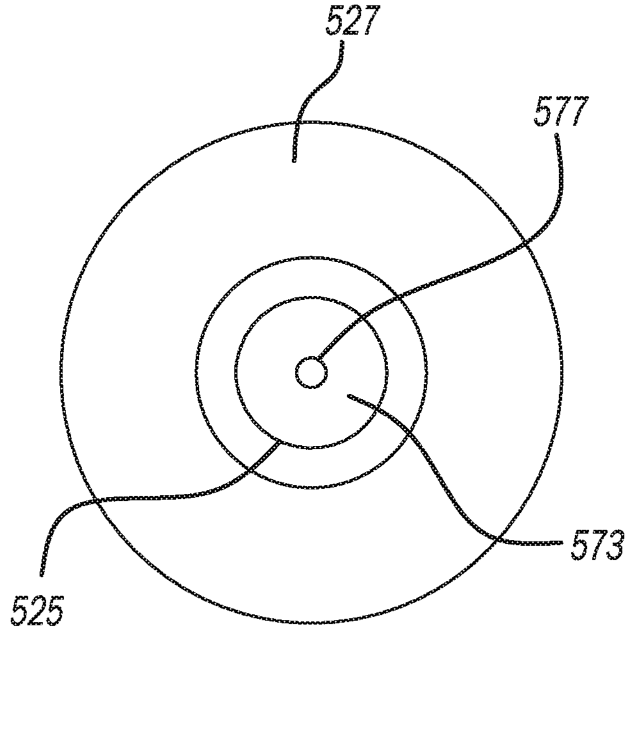
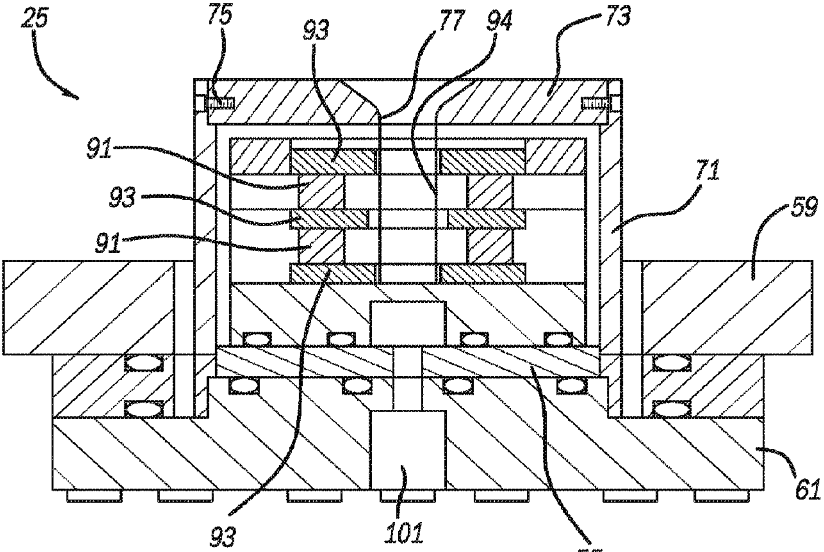


FIG - 21



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