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# (54) METHOD FOR MANUFACTURING SPUTTER-COATED SUBSTRATES, MAGNETRON SOURCE AND SPUTTERING CHAMBER WITH SUCH SOURCE

VERFAHREN ZUR HERSTELLUNG VON SPUTTERBESCHICHTETEN SUBSTRATEN, MAGNETRONQUELLE UND SPUTTERKAMMER MIT EINER SOLCHEN QUELLE

PROCEDE DE FABRICATION DE SUBSTRATS A REVETEMENT PRODUIT PAR PULVERISATION CATHODIQUE, SOURCE MAGNETRON ET CHAMBRE DE PULVERISATION CATHODIQUE POURVUE D'UNE TELLE SOURCE

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## Description

**[0001]** The present invention relates to plasma treating substrate surfaces, thereby especially to sputter-coating such surfaces and even more specifically to directional sputtering realized as long-throw sputtering and/or ionized physical vapor deposition (IPVD). It possibly may also be applied for etching.

**[0002]** So-called collimated sputtering and long-throw sputtering have been used for coating moderate aspect ratio holes. Ionized Physical Vapor Deposition, IPVD, has been used more recently to deposit films in holes. In the IPVD method a flux of ionized metal atoms is used. Such flux of positively charged metal ions is accelerated in the gap between the plasma and the substrate, e.g. a silicon wafer which has a negative bias with respect to the plasma. As the electric field is perpendicular to the substrate as to a silicon wafer surface, this results in a superior bottom coverage of high aspect ratio holes. There are various ways how to achieve high ionization fraction of metal for IPVD. One way is known from the US 6 352 629. Before discussing this prior art and proceeding to the present invention some definitions shall be established:

### 1. Magnetron magnetic field pattern

**[0003]** As exemplified in Fig. 1 a magnetron magnetic field pattern as established along a target surface 3 of a target 1 comprises, seen towards the target surface 3, a pattern of magnetic field $F_M$ which forms a closed loop. In a cross-sectional view onto the target the magnetron magnetic field pattern $F_M$ is tunnel-shaped with magnetic field arcing from an outer area $A_o$ of one magnetic polarity to an adjacent inner area $A_i$ with the other magnetic polarity. The magnetic flux out of the outer area $A_o$ which forms a substantially closed loop is substantially equal to the magnetic flux at the second, inner area $A_i$ except the signum.

**[0004]** Thereby, we define the outer area $A_o$ as confined by a closed loop locus line L' which is defined by the projection (dashed lines) of the locus L along the magnetic field pattern $F_M$ along which the component of magnetic field perpendicular to the target surface 3 is zero.

**[0005]** Further, whenever the present invention is applied with etching the target surface 3 is of a non-sputtered material. For the preferred application of the present invention, i.e. for sputter-coating the target surface 3, the target surface is of a material to be sputtered and is therefore a sputtering surface.

### 2. Magnetron magnetic field with unbalanced component pattern

**[0006]** The magnetron magnetic field pattern becomes unbalanced if, departing from the balanced configuration as of (1), the magnetic flux along one of the inner $A_i$ and of the outer - $A_o$ - areas is increased relative to such flux at the other area. In fig. 1 there is schematically shown the generation of the magnetron magnetic field pattern $F_M$ and, additionally, of an unbalanced field pattern $F_U$. Along the target 1 and adjacent the target surface opposite to the target surface 3 there is provided a magnet arrangement with an inner magnet subarrangement 5 and a second outer magnet subarrangement 7. The surface of first subarrangement 5 facing the target 1 is of one magnet polarity, S, whereas the surface of the outer subarrangement 7 facing target 1 has the second magnet polarity, N. Between the two magnet subarrangements there is formed the magnetron field pattern $F_M$, whereby the magnetic flux at the surfaces of the two magnet subarrangements 7 and 5 is substantially equal.

**[0007]** Whereas in fig. 1 the field pattern $F_M$ is generated by means of magnet subarrangements 5 and 7, which respectively have magnetic dipoles oriented perpendicularly to the target surface 3, this field pattern $F_M$ may also be generated by respective magnet arrangements with magnetic dipoles substantially parallel to the target surface 3, one pole providing for the magnetic flux at the inner area $A_i$, the other magnetic pole for the magnetic flux at the outer area $A_o$.

**[0008]** The magnetron field pattern becomes unbalanced if according to fig. 1 the magnetic flux at one of the respective surfaces with the subarrangements 5 and 7, according to fig. 1 at the outer area $A_o$, is significantly increased. There occurs, compared with the magnetron field pattern $F_M$, a considerable amount of magnetic flux $F_U$ with long range. In fig. 1 as an example there is shown a centered circular arrangement of the two subarrangements 5 and 7 with respect to a loop central axis $A_L$.

**[0009]** The unbalanced field pattern $F_U$ is evenly distributed along the outer magnet subarrangement 7.

**[0010]** Such known unbalanced field pattern $F_U$ is thus the result of increasing the magnetic flux e.g. at the outer area $A_o$ with a homogeneous increase of magnetic flux density along a loop of that area $A_O$. In view of the present invention we call such unbalanced field pattern $F_U$ as of fig. 1 a symmetrically unbalanced field pattern.

**[0011]** Turning to the US 6 352 629 it may be seen that there is provided a magnet arrangement which generates a symmetrically unbalanced field pattern as was explained with the help of fig. 1, which is moved around an axis offset from the loop central axis $A_L$ of the symmetrically unbalanced circular magnetron. There is provided a DC coil which is wrapped around the space between the target and the substrate being sputter-coated so as to generate an axial magnetic field guiding metal ions towards the substrate. The target area which is covered by the symmetrically unbalanced magnetron field pattern is considerably smaller than the overall sputtering surface. As a symmetrically unbalanced magnetron as shown in fig. 1 generates an extremely focused plasma on the loop central axis, the ion density at the substrate is strongly inhomogeneous.

**[0012]** US 6 491 801 a describes an asymmetrically unbalanced magnetron including a nested magnetron part having an outer magnetic pole of a first magnetic polarity surrounding an inner magnetic pole of an opposed second polarity and an auxiliary magnet increasing the asymmetrical unbalance and adjusting the uniformity of sputtering.

**[0013]** It is an object of the present invention to provide a method for manufacturing substrates with a vacuum plasma treated surface with an improved averaged homogeneity of plasma density distribution over the substrate surface and accordingly to propose a respective magnetron source and treatment chamber. Applied for IPVD, the present invention, due to the addressed homogeneity of plasma exposure along the substrate surface, leads to an improved homogeneity of averaged metal ion exposure of the substrate surface.

**[0014]** The addressed object is reached by the method of manufacturing substrates with a vacuum plasma treated surface as defined in claim 1. In particular, said method comprises the steps of

- providing a target with a target surface;
- providing at least one substrate, i.e. one single substrate or more than one substrate, distant from and opposite the target surface.

**[0015]** Along the target surface there is generated a magnetic field pattern of a magnetron field - as of $F_M$ of fig. 1 - forming a closed loop considered in direction towards the sputtering surface and, considered parallel to the sputtering surface, tunnel-like arcing from an outer area - $A_O$ - of first magnetic pole to an inner area - $A_i$ - of second magnetic pole, whereby the inner area - $A_i$ - is confined with respect to the outer area - $A_o$ - by a closed locus - L' - of zero component of magnetic field perpendicular to the target surface of the magnetron field pattern - $F_M$.

**[0016]** The magnet field pattern further comprises an unbalanced long-range field pattern which is asymmetrical and is generated by increasing magnetic flux along the outer area relative to magnetic flux along the inner area, whereby the long range field reaches the substrate surface with a component of magnetic field parallel to the substrate surface of at least 0.1 Gauss. In the magnetic field pattern there is generated a plasma discharge and the substrate surface is plasma treated, whereby the asymmetrically unbalanced field pattern is swept along the substrate surface.

**[0017]** Thus, not a symmetrically unbalanced magnetron, but an asymmetrically unbalanced magnetron is exploited.

## 3. Asymmetrically unbalanced magnetron field pattern

**[0018]** So as to fully understand the present invention as is going to be described with preferred embodiments the principal of an asymmetrically unbalanced magnetron as inventively exploited by the present invention shall be exemplified with the help of fig. 2.

**[0019]** According to fig. 2 there is generated in analogy to the embodiment of fig. 1 the magnetron magnetic field pattern $F_M$. As further shown in fig. 2 the magnetic flux along the surface of the second, outer magnet subarrangement $7_a$ is increased. If this was done homogeneously distributed along the outer magnet subarrangement 7 this would lead to a symmetrically unbalanced field pattern component $F_U$ according to fig. 1 and as introduced in fig. 2 in dashed lines.

**[0020]** Nevertheless, and according to the present invention as shown in fig. 2 the inventively exploited asymmetrically unbalanced field pattern $F_{AU}$ is most generically realized by disturbing the symmetrically unbalanced field pattern $F_U$ so that the respective field pattern is distorted in a direction parallel to the target surface 3 (see fig. 1). This is performed by inhomogeneously increasing the magnetic flux density along the outer area $A_o$. As exemplified in fig. 2 such inhomogeneous increasing of magnetic flux density in an azimuthal direction along the outer area $A_o$ is realized in one preferred embodiment in that there is locally applied a further magnetic field along a loop in the outer area as by providing along the outer area $A_o$ additionally to the first part 7a of magnet subarrangement 7 - which provides for symmetrically unbalanced pattern $F_U$ - a second magnet subarrangement part 7b, which is only provided along the predetermined area of outer area $A_o$ and thus locally applies the further magnetic field. Thereby this further field distorts the symmetrical unbalanced field pattern $F_U$ resulting in the asymmetrically unbalanced field pattern $F_{AU}$.

**[0021]** Turning back to preferred embodiments of the present invention, in a first preferred embodiment the target surface is a sputtering surface and plasma treating of the substrate surface is sputter-coating. Nevertheless, the method according to the present invention may also be applied for etching, e.g. for reactive plasma-enhanced etching of the surface of the substrate. In this case the target surface is selected of a material not being sputtered and the magnetron source with the inventively exploited asymmetrically unbalanced field pattern being swept along the surface of the substrate is merely provided for generating the respective plasma distribution. No material is freed from the target surface.

**[0022]** In a further preferred embodiment of the method according to the present invention the component of magnetic field parallel to the substrate surface is selected to be between 1 Gauss and 20 Gauss.

**[0023]** Further preferred, the tunnel-like magnetron field pattern - $F_M$ - covers more than 60 % of the target surface, thereby even more preferred, more than 85 % of the target surface. Thereby, especially with an eye on performing sputter coating of the substrate surface, it is advantageous to apply the addressed covering because it is primarily in the area covered by the magnetron field pattern - $F_M$ - in which, due to electron-trap effect, an increased plasma density is reached and material is sputtered off at high rate.

**[0024]** As was addressed above the asymmetrically unbalanced field pattern is realized by disturbing homogeneity of an increased magnetic flux density along the outer area - $A_o$ - by locally applying a further magnetic field along said outer area. Thereby, said further magnetic field is preferably generated by at least one permanent magnet and/or at least one electromagnet. Providing an electromagnet allows control of such further magnetic field so that also during processing the asymmetry of the unbalanced field pattern may controllably be varied.

**[0025]** In a further preferred embodiment not only the asymmetrically unbalanced field pattern is swept along the substrate surface, but the magnetron field pattern too. Due to the fact that the magnetron field pattern is also moved with respect to the substrate further increased treatment homogeneity is reached, especially with an eye on sputter coating.

**[0026]** In a further still preferred embodiment sweeping of the asymmetrically unbalanced magnetic field pattern along the substrate surface is performed by circularly moving the unbalanced magnetic field pattern around an axis which is perpendicular to the target surface.

**[0027]** With an eye on fig. 2 it may be seen that the asymmetrically unbalanced field pattern $F_{AU}$ is moved along a circular path around an axis $A_S$, whereby the location of such axis $A_S$ is selected remote from the area P of maximum flux of the asymmetrically unbalanced field pattern $F_{AU}$.

**[0028]** As further also shown in fig. 2 in a preferred embodiment sweeping is generated by moving the magnetron - $F_M$ - as well as the asymmetrically unbalanced field pattern $F_{AU}$ around an axis which is perpendicular to the target surface and which is offset from a geometrical center - $A_L$ - of the inner area $A_i$, so that by such moving both field patterns are swept with respect to the substrate surface.

**[0029]** In a further preferred mode the loop of magnetron field pattern is generated circularly around a loop central axis, as shown in fig. 2 around axis $A_L$.

**[0030]** In a further preferred embodiment of the method according to the present invention there is generated by the asymmetrically unbalanced field pattern - $F_{AU}$ - an area of maximum plasma density as shown at P of fig. 2 adjacent the periphery of the substrate surface and said maximum area is swept adjacent to and along this periphery.

**[0031]** In fig. 2 the substrate 6 is shown in dashed line representation. It is centered about axis $A_S$. The area P of maximum plasma density sweeps along the periphery of substrate 6 and adjacent to such periphery.

**[0032]** Further, in a preferred embodiment controlled adjusting of uniformity of ion current density at the substrate surface is performed by adjusting the further magnetic field which, as was explained, is provided for disturbing homogeneity of the unbalanced field pattern to make it asymmetrically unbalanced.

**[0033]** As was already addressed and with an eye on controllability of the asymmetrically unbalanced field pattern - $F_{AU}$ - providing an electromagnet for generating such further magnetic field is most advantageous. Thereby, in a further preferred embodiment there is provided at least one coil which generates a magnetic field which is substantially parallel to the target surface. With an eye on fig. 2 such magnetic field is schematically shown at $F_a$. Thereby, it may be seen that by varying such field $F_a$ generated by the said at least one coil the pattern of the asymmetrically unbalanced field $F_{AU}$ may be controllably adjusted. This leads to the further preferred mode that generating sweeping of the asymmetrically unbalanced pattern along the substrate surface comprises supplying the at least one coil with an alternating current which will generate an alternating field $F_a$, thereby sweeping the pattern $F_{AU}$ and thus the area P in an oscillating manner in the direction of $F_a$. If, in a further preferred embodiment, more than one of these coils are provided which generate respectively magnetic fields in different directions as e.g. and with an eye on fig. 2 additionally in direction of $F_b$, perpendicularly to the direction of $F_a$, and alternative currents are applied to the respective coils, the asymmetrically unbalanced field pattern $F_{AU}$ and thus area P will be swept in two dimensions along the surface of the substrate 6 and by appropriately selecting amplitudes, mutual phasing and/or frequencies of the alternating currents applied to the coil the sweeping pattern may be selected and controllably adjusted in the sense of realizing for sweeping of area P Lissajoux patterns along the substrate surface.

**[0034]** In a further preferred embodiment the substrate is selected to be circular and the asymmetrically unbalanced field pattern is swept around a center axis of the substrate, whereby if more than one substrate is provided the substrates are arranged within a circular area and the center axis is defined with respect to such circular area.

**[0035]** In a further preferred embodiment the current of ions at the substrate surface is adjusted by adjusting magnetic field components perpendicular to the substrate surface. Such component is on one hand adjustable by adjusting the asymmetrically unbalanced field pattern $F_{AU}$, but may additionally or alternatively be performed by applying, e.g. by means of a Helmholtz coil arrangement, a controllably variable additional magnetic field perpendicularly to the substrate surface, namely a magnetic field $F_c$ as shown in fig. 2. In a further preferred embodiment the electron current in the plasma is guided substantially perpendicular to the target surface towards the substrate surface which may be realized by applying a respective electrical potential difference between target surface and substrate surface and/or by providing appropriate shielding.

**[0036]** In a further preferred mode the plasma as generated is electrically fed by a pulsating supply voltage. Thereby, further preferred, the frequency f of pulsating is selected to be

$$5 \text{ kHz} \leq f \leq 500 \text{ kHz}$$

thereby to be preferably

$$100 \text{ kHz} \leq f \leq 200 \text{ kHz}.$$

**[0037]** In a further preferred embodiment the duty cycle of such pulsating is selected to have 1 % to 99 % off-times (both values included), thereby to have, even more preferred, off-times of between 35 % and 50 % (both limits included). Especially for long-throw and/or IPVD applications there is established a total pressure in the vacuum chamber to be at most $10^{-1}$ Pa, thereby preferably

$$10^{-2} \text{ Pa} \leq p \leq 5 \times 10^{-2} \text{ Pa}.$$

**[0038]** Further, in a preferred mode the substrate is biased with an Rf frequency power, whereby adjusting of the energy of ions bombarding the substrate surface comprises adjusting such Rf power. In a specially preferred embodiment for sputter-coating the substrate surface the target surface is provided with a sputtering surface of one of Ti, Ta, Cu. With an eye on figs. 1 and 2 it must be emphasized that the magnet arrangement which generates the magnetron field pattern $F_M$ is not necessarily selected circularly as shown in these figures, but such magnetron field pattern and respectively the magnet arrangements generating such pattern may be conceived to achieve a desired target erosion profile in sputter coating and a required thickness uniformity of coating on the substrate surface.

**[0039]** Appropriately tailoring the magnetron field pattern $F_M$ and especially its looping shape in a view towards the target surface is known in a huge variety to achieve the addressed desired results.

**[0040]** Following up the above mentioned object there is further proposed a magnetron source according to claim 29.

**[0041]** According to the present invention there is further proposed a magnetron treatment chamber which comprises a magnetron source according to the present invention and as was generically discussed above as well as a substrate carrier which is remote from and opposite to the target surface of the magnetron source.

**[0042]** Additionally to the figures addressed and the disclosure given above the present invention shall become even clearer to the skilled artisan by the further description of preferred embodiments by means of figures as well as by the appending claims. The further figures show:

| | |
|---|---|
| Fig. 3 | most schematically and simplified a magnetron treatment chamber according to the present invention incorporating a magnetron source according to the present invention and operated for manufacturing substrates according to the present invention; |
| Fig. 4 | in a representation in analogy to those of the figs. 1 and 2, the realization of a symmetrically unbalanced field pattern which is swept along a substrate surface by being moved around an axis perpendicular to the target surface; |
| Fig. 5 | over the radius of a circular substrate the ion current density as resulting from operating the chamber as of fig. 3 configured with the source as of fig. 4 and with varying coil current - J-parameter; |
| Fig. 6 | in a representation in analogy to that of fig. 5 the ion current density as results when the chamber as of fig. 3 is operated according to the present invention with an asymmetrically unbalanced field pattern as of fig. 2, again with different coil currents - J - as parameter; |
| Fig. 7 | in a most schematic representation a further embodiment for realizing an asymmetrically unbalanced magnetic field pattern swept along the substrate surface; |

| | |
|---|---|
| Fig. 8 | in a representation in analogy to that of fig. 7 still a further embodiment for realizing the asymmetrically unbalanced field pattern and sweeping with such field pattern along the surface of the substrate; |
| Fig. 9 | in a simplified and schematic representation in analogy to that of the Figs. 1, 2 and 4 a further embodiment of target and magnet arrangement to generate an asymmetrically unbalanced field pattern according to the present invention; |
| Fig. 10 | as a function of pulsating frequency the ratio of metal ions Ti+ to argon ions Ar+ resulting at the substrate surface when treated according to the present invention, thereby supplying the magnetron source with a pulsating voltage of the addressed frequency; |
| Fig. 11 | the ratio as of fig. 9 as a function of off-time % of said pulsating supply voltage with respect to pulse repetition period; |
| Fig. 12 | again the addressed ratio as a function of working gas pressure, namely argon pressure, and |
| Fig. 13 | again the addressed metal ions to working gas ions ratio as a function of electrical power supplied to the magnetron source. |

**[0043]** In fig. 3 there is schematically and simplified shown a treatment chamber according to the present invention, especially a sputter-coating chamber, incorporating a magnetron source according to the present invention and performing the method of manufacturing according to the present invention. The treatment chamber according to fig. 3 is the today's preferred embodiment which is trimmed for long-throw and/or IPVD sputter coating of substrates and combines preferred features, some of which may be deleted for specific applications.

**[0044]** The chamber comprises a circular target 10 and a magnet arrangement 12 driven around rotational axis $A_S$ by means of a motor drive as schematically shown at 14. Opposite the sputtering surface 13 of the target 10 and centered on axis As there is provided a substrate carrier 16 for centrally positioning a substrate arrangement 18 of one or more than one substrate to be sputter-coated. At least one coil 20 is mounted outside and along the walls 22 of the sputtering chamber with a coil axis coincident with axis As. Additionally or alternatively permanent magnets can be used to generate a magnetic field coaxially to axis $A_S$. An anode arrangement 24 is provided adjacent to the substrate carrier 16 and is substantially hidden from the processing space PR by means of a first shield 26 and a second shield 28 which shields substantially confine the processing space with respect to anode arrangement 24 and inner surface of chamber wall 22. The substrate carrier 16 is either operated electrically floating or on a DC bias potential or on an AC or AC plus DC potential, up to and preferably to frequencies in Rf range.

**[0045]** By means of the first and second shieldings 26 and 28 electrons within the plasma processing space PR are substantially hindered from flowing onto the chamber wall 22. The shields 26 and 28 may equally or differently be operated at electrically floating potential or on a DC potential, thereby preferably on an anodic electric potential. At least shield 28 is preferably electrically operated on an electric potential which is more negative than the electric potential applied to anode arrangement 24.

**[0046]** Thereby, only one, two or more shields may be provided electrically driven differently or equally. By such shields electrons in the plasma and in the processing space PR are guided to flow substantially parallel to the axis As towards the substrate arrangement 18 on the substrate carrier 16. For certain applications it is also possible not to use any lateral shielding.

**[0047]** By means of the at least one coil 20 there is generated an additional magnetic field, $F_C$ in Fig. 2, in the processing space PR substantially parallel to the axis $A_S$. It is also possible not to make use of any such coil arrangement 20 or to provide more than one such coil arrangement. They are (not shown) operated with DC power. The orientation of the magnetic field generated by the coils 20 may be oriented in one and the same direction, or at least one coil can generate a magnetic field in opposite direction to produce mirror-like magnetic fields.

**[0048]** For experiments the chamber as schematically shown in fig. 3 was conceived as follows:

| | |
|---|---|
| Target material: | Ti |
| Target diameter: | 300 mm |
| Shape of processing chamber and shieldings: | cylindrical |
| Distance from substrate carrier to sputtering surface: | 330 mm/370 mm |
| Diameter of circular single substrate carrier: | 200 or 150 mm |
| Supply of plasma discharge: | DC or pulsed power |
| Single coil current: | 10 A |

(continued)

| | |
|---|---|
| Axial magnetic field by single coil: | 10 Gauss |
| Bias of the substrate carrier: | DC power |
| Target-to-substrate distance: | 37 cm |

**[0049]** As a first reference experiment the magnet system 12 was conceived according to fig. 1. Thus, there was applied an unbalanced magnetron with cylindrically symmetrical design. The long range of the symmetrically unbalanced magnet field pattern $F_U$ according to fig. 1 was varied by varying the DC current supply of the coil arrangement 20 according to fig. 3 with current polarity strengthening the unbalancing magnetic field pattern $F_U$ according to fig. 1. The large area symmetrical unbalanced magnetron arrangement was operated at a very low working gas pressure as of Ar, down to 0.025 Pa.

**[0050]** With an eye on fig. 1 it becomes clear that rotating this magnet arrangement around the loop central axis $A_L$, which is coincident with axis $A_S$ as of fig. 3, has no effect.

**[0051]** As a function of the coil current in coil arrangement 20 there is generated a sharply focused plasma beam concentrated in the centre of the substrate.

**[0052]** As a next reference experiment the magnet system 12 was changed from the system according to fig. 1 to the system according to fig. 4, still a prior art magnet system, e.g. according to the US 6 352 629. The magnet system as shown in fig. 4 is different with respect to that shown in fig. 1 by the fact that the loop central axis $A_L$ is offset from the rotating axis $A_S$. In the specific experiment considered the loop central axis $A_L$ was offset from the axis $A_S$ by a relatively small amount of 15 mm. This to keep the advantage of a large plasma confinement by the large symmetrically unbalanced magnetron covering nearly the full sputtering surface of the target (fig. 4). The ion density along the substrate surface to be sputter-coated was measured. The result is shown in fig. 5.

**[0053]** In spite of the fact that the symmetrically unbalancing field pattern $F_U$ is swept along the surface of the substrate arrangement with a maximum density area P according to fig. 4 offset from the rotational axis As, there resulted a centrally focused plasma distribution up to a sharply focused plasma beam in dependency of the coil current applied. The coil current by which the characteristics of fig. 5 are parameterized varies between 0 and 30 A. Further, there were applied five coil arrangements 20 as of fig. 3 operated at equal DC currents.

**[0054]** The substrate holder 16 of fig. 3 was operated at a bias of -80 V DC, an Ar flow was established of 15 sccm and a total pressure p of 0.14 Pa. The distance established between the sputtering surface and the substrate was 370 mm to experience long-throw effect.

**[0055]** As a third experiment now according to the present invention the magnet arrangement was changed to that as shown and as was described with the help of figure 2. The respective result is shown in fig. 6 in analogy to the results of fig. 5. It may clearly be seen that again dependent on the coil current the current density may be increased to values up to those experienced according to figure 5, but with a significantly improved uniformity of plasma density distribution and thus ion density distribution along the substrate arrangement surface, up to a radius of 100 mm. This is especially true for a medium-range coil current of 4 to 10 A.

**[0056]** With an eye back on the magnet arrangement of fig. 2 and as was already addressed in the introductory part, fig. 7 shows in a representation in analogy to that of fig. 2 an alternative technique of sweeping the maximum plasma density area P along the surface of the substrate arrangement. Thereby, the first and second magnet subarrangements 5 and 7 are kept stationary, looping around the loop centre axis $A_L$ which is coincident with the rotational axis $A_S$ which is further the central axis of the substrate arrangement. Thereby there is first generated a symmetrical unbalanced magnetron field according to fig. 1. The part $7_b$ of the second magnet arrangement 7, which is responsible for achieving asymmetrical unbalancing as was explained with the help of fig. 2, is drivingly rotated around the central axis $A_L = A_S$, thereby sweeping cyclically the maximum plasma density area P as of fig. 2 along and adjacent (not shown) the substrate surface.

**[0057]** Fig. 8 shows in a representation in analogy to that of fig. 7 a further preferred embodiment for generating the asymmetrically unbalanced magnetic field pattern $F_{AU}$ as of fig. 2 and sweeping this pattern along the substrate surface. Again the magnetron field pattern $F_M$ is generated between part 7a of magnet subarrangement 7 along the outer area $A_o$ and the magnet subarrangement 5 at the inner area $A_i$. The part 7a of the outer magnet subarrangement 7 provides for the symmetrically unbalanced field pattern $F_u$ according to fig. 2. Asymmetry is realized by providing a first coil arrangement $80_a$ adjacent and below the target surface at the magnet subarrangement 7 which coil arrangement $80_a$ generates a magnetic field $F_a$, as shown also in Fig. 2, parallel to and in radial direction along the target surface. As now evident to the skilled artisan by applying this magnetic field $F_a$ the formerly symmetrically unbalanced magnetic field pattern $F_U$ becomes an asymmetrically unbalanced field pattern $F_{AU}$. By applying to the coil arrangement $80_a$, which is in fact an electromagnet arrangement, an alternating current $I_a$ the area P of maximum field flux as of Fig. 2 is swept along the substrate surface forth and back as a function of amplitude of the applied current, shape of the current course over time, and frequency.

**[0058]** Whenever, in a further preferred embodiment, there is applied at least one second coil arrangement $80_b$ the same prevails as was explained with respect to the effect of coil arrangement $80_a$, but because the second coil arrangement $80_b$ generates a magnetic field $F_b$ as also shown in Fig. 2 e.g. perpendicularly to the direction of field $F_a$, the area P of maximum flux is moved along the substrate surface as a result of the superposition of the two magnetic field components $F_a$ and $F_b$. As known by the skilled artisan the trajectory path of area P along the substrate surface may controllably be adjusted by selecting mutual phasing of the two currents $I_a$, $I_b$ feeding the two coil arrangements, their amplitudes, their frequencies as well as the shape of their time courses. Controlling the trajectory path of area P is thus realized following principally the well-known rules of Lissajoux.

**[0059]** Fig. 9 shows a further embodiment of a magnet assembly at the target resulting in an asymmetrically unbalanced magnet field pattern. This assembly has a first looping magnet subarrangement $87_o$ of one polarity and having a radius-like extension $87_{o1}$. The second magnet subarrangement $87_i$ is provided distant from and along the outer magnet subarrangement $87_o$. These two magnet subarrangements do generate on one hand the magnetron field pattern $F_M$ and the asymmetrically unbalanced field pattern with an area P of maximum flux as shown in fig. 9. The locus of zero field component of the magnetron field pattern $F_M$ defines for the locus L' as was already shown in Figs. 1 and 2, thereby confining the outer area $A_o$ with respect to the inner area $A_i$. Thereby, at the right-hand side of the arrangement of Fig. 9 the outer magnet subarrangement $87_o$ projects from the respective edge of the target arrangement shown at 88.

**[0060]** The projecting area $A_\Delta$ of magnet subarrangement $87_o$ causes the asymmetry of the unbalanced magnetic field. Only at that area $A_\Delta$ the magnetron field pattern $F_M$ does not emanate from the target surface which is limited at line 88. This area $A_\Delta$ is not more than 12 % of the target surface area.

**[0061]** When performing the method according to the present invention, i.e. operating the magnetron source and magnetron chamber, especially for sputter-coating the following further settings are preferred:

**[0062]** The plasma is preferably fed with a power in the range of 0.1 to 60 kW, thereby even more preferred within a range of 1 to 40 kW.

**[0063]** The target surface is preferably exposed to a plasma density of 0.1 to 900 W/cm$^2$, thereby even more preferred to a plasma density of between 10 and 50 W/cm$^2$.

**[0064]** As was already addressed and in spite of the fact that the substrate may also be biased with DC, such biasing is preferably realized with Rf power. Such biasing Rf power has preferably a power density of 0.01 to 10 W/cm$^2$, even more preferred of 0.2 to 2 W/cm$^2$ per cm$^2$ of substrate surface.

**[0065]** Ion bombarding of the substrate is preferably adjusted to energy values of between 0.1 eV and 300 eV, which preferably comprises appropriately adjusting the Rf power which biases the substrate.

**[0066]** Further, especially when performing long-throw sputter-coating, the energy of ions bombarding the substrate surface is adjusted to values between 0.01 eV and 50 eV and the ion density of these ions is adjusted to less than 0.2 mA/cm$^2$ preferably by adjusting the gas pressure within the range of $10^{-2}$ Pa $\leq p \leq 5 \times 10^{-2}$ Pa and the magnetic flux perpendicular to the substrate surface to a value which is less than 0.5 Gauss.

**[0067]** For IPVD application the energy of ions bombarding the substrate is adjusted preferably to values between 20 eV and 300 eV and the ion density of these ions is selected in the range of 0.2 to 10 mA/cm$^2$ by setting working gas pressure in the vacuum chamber between $3 \times 10^{-2}$ Pa and $5 \times 10^{-1}$ Pa, selecting the magnetic field perpendicularly to the substrate surface to be between 0.5 Gauss and 50 Gauss.

**[0068]** The radial uniformity of ion current density at the substrate surface is further preferably adjusted by adjusting the magnetic flux of the magnetic field component perpendicularly to the substrate surface. Especially when long-throw sputtering one of the metals Ti, Ta or Cu the metal ionization degree adjacent the substrate surface is adjusted preferably to a level of less than 10 % which is done by adjusting at least one of pressure, electric power to the magnetron source, pulsing characteristic of the electrical magnetron supply and magnetic flux of field components perpendicular to the substrate surface.

**[0069]** On the other hand e.g. when sputtering Ti, Ta or Cu the metal ionization may be selected at a level which is more than 20 %, even more than 50 %, by adjusting at least one of pressure in the magnetron chamber, electric power applied to the magnetron source, pulsating characteristic of supply power to the magnetron source and magnetic flux of magnetic field perpendicularly to the substrate surface.

**[0070]** Further, whenever holes in a substrate have to be coated by the method according to the present invention this is preferably performed in at least two subsequent steps. The first step consists of a long-throw sputtering step with metal ionization degree especially of one of the metals Ti, Ta, Cu of more than 20 %, preferably even of more than 50 %, which is adjusted as was just outlined above. In a second subsequent step, which is an IPVD step, the metal ionization degree of the addressed metal is adjusted by the parameters as outlined above to a level which is less than 10 %.

**[0071]** In a further preferred embodiment of the present invention the plasma is generated only for ignition with the help of a working gas as e.g. argon and then only metal atoms are present in the reaction volume of the chamber.

**[0072]** Further, and with an eye on the magnetron chamber as shown in Fig. 3 the asymmetrically unbalanced magnetic field pattern which is swept along the substrate surface may be passed during predetermined amounts of time or during predetermined extents of sweeping trajectory path, beneath a magnetic shield provided between the magnetron source and substrate surface so as to shield at least a part of the asymmetrically unbalanced magnetic field pattern from reaching and affecting treatment at the substrate surface.

**[0073]** Experiments have been performed to determine the metal ionization ratio and its dependencies at the substrate surface which led to the above preferred embodiments. An energy-resolved mass spectrometer was used to measure the ratio between the intensity of Ti ions $^{48}Ti^+$ and argon ions $^{36}Ar^+$. The ratio of their intensities reflects the metal ionization probability. The results are shown in the figures 10 to 13. One can see that the rate of metal ionization can vary in a very broad range. Higher working gas pressure as well as higher sputtering power according to the results of figs. 12 and 13 lead to an increase of Ti ionization relative to Ar ionization, even when DC sputtering.

**[0074]** Moreover with predetermined fix electrical supply power to the magnetron source and predetermined fix pressure in the magnetron chamber pulsating of the magnetron supply and thus of the magnetron discharge helps to ionize the metal with increased degree. From Fig. 11 where the metal ionization ratio is shown in dependency of the percentage amount of off-time at the pulsating electric magnetron source supply it becomes evident that with increasing off-time percentage the metal ionization increases. At a duty cycle with 50 % off-times of the pulsating electrical magnetron source supply Fig. 10 reveals a preferred optimum frequency range between 100 and 200 kHz for optimum metal ionization.

**[0075]** Especially in long-throw sputtering mode the coating of the bottom and sidewalls of high-aspect ratio holes in the substrate surface can be realized with neutral metal atoms sputtered at very low working gas flows and thus low pressures between $5 \times 10^{-3}$ Pa and $5 \times 10^{-2}$ Pa to avoid collision between metal atoms and gas atoms. The described large coverage of the whole target surface with plasma also during ON-time spans of the pulsating supply of the magnetron source allows working at extremely low-pressure neutral metal atoms eliminating damage of the holes in the substrate surface by excessive ion bombardment.

**[0076]** The arrangement also allows an IPVD step using higher pressures for higher bottom and sidewall coverage exploiting all the effects of high ionization including the resputtering by argon and metal ions.

**[0077]** Especially for IPVD applications, where the bottom of holes with high aspect ratio is coated by metal ions and resputtering from the bottom layer coats the sidewalls, a high flow and thus high pressure between $5 \times 10^{-2}$ Pa and 2 Pa is used to create predominantly metal ion deposition. Measurements have shown that the processing according to the present invention is able to produce more than 50 % ionization in the case of Ti sputtering when all the plasma confinement and ionization facilities are used: The asymmetrically unbalanced field pattern, the confining field of the coils 20 as of Fig. 3, floating shielding 28 and 26 of Fig. 3, an anode 24 close to the substrate, selecting proper pressure range and pulsating the electrical magnetron source supply as described above. It should be stressed that the same configuration allows a uniform ion current density over the substrate in the range below 5 % resulting in very uniform conditions for step coverage at the substrate.

## Claims

1. A method of manufacturing substrates with a vacuum plasma treated surface comprising the steps of

   - providing a target (1) with a target surface (3);
   - providing at least one substrate distant from and opposite said target surface having a substrate surface;
   - generating in the volume between said target surface and said substrate surface a magnetic field pattern of

     a) a magnetron field pattern ($F_M$) forming a closed loop considered in direction towards said sputtering surface and, considered parallel to said sputtering surface, tunnel-like arcing from an outer area ($A_o$) of first magnetic pole to an inner area ($A_i$) of second magnetic pole, whereby said inner area is confined with respect to said outer area by a closed locus (L') of zero component of magnetic field perpendicular to said target surface;

     b) an unbalanced long-range field pattern ($F_{AU}$) which is asymmetrically by generated by increasing magnetic flux along a distinct area of said outer area relative to magnetic flux along said inner area and relative to the remainder of said outer area and whereby said long-range field reaching the substrate surface has a component of the magnetic field parallel to said substrate surface of at least 0.1 Gauss;

   - generating a plasma discharge in said magnetic field pattern;
   - plasma treating said substrate surface, thereby
   - sweeping said asymmetrically unbalanced field pattern along said substrate surface,

   **characterized by** performing said sweeping by moving said distinct area along said outer area

**2.** The method of claim 1, said target surface being a sputtered surface, said plasma treating being sputter-coating.

**3.** The method of claim 1, wherein said component of magnetic field parallel to said substrate surface is selected to be between 1 and 20 Gauss.

**4.** The method of claim 1, further comprising covering with said tunnel-like magnetron field pattern more than 60 % of said target surface.

**5.** The method of claim 4, thereby covering with said tunnel-like magnetron field pattern more than 85 % of said target surface.

**6.** The method of claim 1, further comprising generating said asymmetrically unbalanced field pattern by inhomogeneously increasing magnetic flux density along said outer area relative to substantially homogeneous magnetic flux density along said inner area.

**7.** The method of claim 6, further comprising disturbing homogeneity of increased magnetic flux density by locally applying a further magnetic field along said outer area.

**8.** The method of claim 7, further comprising generating said further magnetic field by at least one permanent magnet and/or electro-magnet.

**9.** The method of one of claims 1 to 8, further comprising sweeping said magnetron field pattern and said unbalanced field pattern along said substrate.

**10.** The method of one of claims 1 to 9, further comprising the step of generating said sweeping by circularly moving said unbalanced magnetic field pattern around an axis perpendicular to said target surface.

**11.** The method of one of claims 1 to 10, further comprising the step of generating said sweeping by moving said magnetron and unbalanced field patterns around an axis perpendicularly to said target surface and offset from a geometrical center of said inner area.

**12.** The method of one of claims 1 to 11, further comprising the step of generating said loop of said magnetron field pattern circularly around a loop central axis.

**13.** The method of one of claims 1 to 12, further comprising the step of generating by said asymmetrically unbalanced field pattern an area of maximum plasma density adjacent the periphery of said substrate surface and sweeping said maximum adjacent to and along said periphery.

**14.** The method of claim 7, further comprising adjusting uniformity of ion current density at said substrate surface by adjusting said further magnetic field.

**15.** The method of claim 7, further comprising generating said further magnetic field by at least one coil generating a magnetic field substantially parallel to said target surface.

**16.** The method of claim 15, generating said sweeping comprising supplying said at least one coil with an alternating current.

**17.** The method of claim 15, further providing more than one of said coils generating respectively magnetic fields in different directions, generating said sweeping comprising applying alternative currents to said coils.

**18.** The method of one of claims 1 to 17, further comprising providing more than one substrate.

**19.** The method of claim 18, further comprising the step of selecting said substrate to be circular or said more than one substrate to be arranged within a circular area, sweeping said unbalanced field pattern around a center axis of said substrate or area.

**20.** The method of one of claims 1 to 19, further comprising adjusting the current of ions at said substrate surface by adjusting magnetic field component perpendicular to said substrate surface.

**21.** The method of one of claim 20, comprising the step of guiding electron current in said plasma substantially perpendicular to said target surface towards said substrate surface.

**22.** The method of one of claims 1 to 21, comprising the step of feeding said plasma by a pulsating supply voltage.

**23.** The method of claim 22, further comprising selecting frequency f of said pulsating to be

$$5\ \text{kHz} \leq f \leq 500\ \text{kHz},$$

preferably to be

$$100\ \text{kHz} \leq f \leq 200\ \text{kHz}.$$

**24.** The method of one of claims 22 or 23, further comprising selecting duty cycle of said pulsating to have 1 % to 99 % off-times (both values included), to have preferably 35 % to 50 % off-times (both limits included).

**25.** The method of one of claims 1 to 24, further comprising establishing in said vacuum chamber a total pressure p to be at most $10^{-1}$ Pa, preferably

$$10^{-2}\ \text{Pa} \leq p \leq 5 \times 10^{-2}\ \text{Pa}.$$

**26.** The method of one of claims 1 to 25, further comprising biasing said substrate with an Rf frequency power.

**27.** The method of claim 26, further comprising adjusting energy of ions bombarding said substrate surface by adjusting said Rf power.

**28.** The method of one of claims 1 to 27, further comprising the step of providing said target with a sputtering surface of one of Ti, Ta, Cu.

**29.** A magnetron source comprising

- a target (1) with a target surface (3) and an opposite surface;
- a magnet arrangement adjacent said opposite surface and having:
    - at least one first magnet subarrangement (5);
    - at least one second magnet subarrangement (7,7a);
    - said first magnet subarrangement having a first area pointing towards said opposite surface and of one magnetic polarity;
    - said second magnet subarrangement having a second area pointing towards said opposite surface and of the other magnetic polarity;
    - said second area forming a loop around and distant from said first area;
    - said first area generating a first magnetic flux ($F_M$) through said target surface;
    - said second area generating a second magnetic flux ($F_U$) through said target surface;
    - said second magnetic flux being larger than said first magnetic flux and further
    - comprising a third magnet sub-arrangement (7b) generating a third magnetic flux superimposed to said second magnetic flux through said sputtering surface, thereby resulting in a resultant magnetic flux ($F_{AU}$) along a distinct area of said second area which is larger than said second magnetic flux along the remainder of said second area, thereby generating an unbalanced, asymmetric, long-range magnetic field,

**characterized by** a sweeping arrangement adapted to move said third magnet sub-arrangement relative to and along said second area.

**30.** The source of claim 29, wherein said second area loops around a loop central axis, said sweeping arrangement comprising a drive moving said third magnet subarrangement around said loop central axis.

**31.** The source of one of claims 29 or 30, said second area looping around a central loop axis, said sweeping arrangement comprising a drive moving said second magnet subarrangement around a rotational axis offset from said loop central axis.

**32.** The source of claim 31, wherein said central loop axis, said rotational axis and said third magnet subarrangement are substantially aligned in radial direction from said rotational axis.

**33.** The source of one of claims 29 to 32, further comprising a magnetic shield movable with respect to said second magnetic flux to generate said second magnetic flux to be unevenly distributed along said second area.

**34.** The source of one of claims 29 to 33, wherein said loop is circular about a loop central axis.

**35.** A magnetron treatment chamber comprising a magnetron source as claimed in one of the claims 29 to 34 and a substrate carrier remote from and opposite to the target surface of said magnetron source.

**36.** The chamber of claim 35, further comprising an anode arrangement adjacent said substrate holder.

**37.** The chamber of claim 36, further comprising a shield confining a process area between said source and said substrate carrier and being electrically floating or on an anodic potential, preferably on a more negative potential than said anode.

**38.** The chamber of claim 36, wherein said anode is hidden behind a shield arrangement and with respect to processing volume.

**39.** The chamber of one of claims 36 to 38, further comprising at least one coil with a coil axis perpendicular to the sputtering surface of said source.

**40.** The chamber of one of claims 35 to 39, wherein said substrate carrier is electrically floating or connectable to a predetermined biasing potential.

## Patentansprüche

**1.** Verfahren zur Herstellung von Substraten mit einer vakuumplasmabehandelten Oberfläche, umfassend die Schritte:

- Bereitstellen eines Targets (1) mit einer Targetoberfläche (3);
- Bereitstellen mindestens eines Substrates, das beabstandet von und gegenüber der Targetoberfläche liegt und eine Substratoberfläche aufweist;
- Erzeugen eines Magnetfeldmusters im Volumen zwischen der Targetoberfläche und der Substratoberfläche aus

  a) einem Magnetronfeldmuster ($F_M$), das in Richtung auf die Sputteroberfläche zu eine geschlossene Schleife bildet und parallel zu der Sputteroberfläche tunnelartig von einem äußeren Bereich ($A_O$) von erstem magnetischen Pol zu einem inneren Bereich ($A_i$) von zweitem magnetischen Pol gebogen ist, wobei der innere Bereich bezüglich des äußeren Bereichs durch eine geschlossene Ortskurve (L') mit Null betragender Magnetfeldkomponente senkrecht zur Targetoberfläche begrenzt ist;
  b) einem unbalancierten langreichweitigen Feldmuster ($F_{AU}$), das durch die Erhöhung des Magnetflusses entlang eines bestimmten Bereichs des äußeren Bereichs relativ zu dem Magnetfluss entlang des inneren Bereichs und relativ zu dem übrigen Teil des äußeren Bereiches asymmetrisch erzeugt wird, und wobei das langreichtweitige Feld, das die Substratoberfläche erreicht, eine zu der Substratoberfläche parallele Komponente des Magnetfeldes von zumindest 0,1 Gauss aufweist;

- Erzeugen einer Plasmaentladung in dem Magnetfeldmuster;
- Plasmabehandeln der Substratoberfläche, und dabei
- Bewegen des asymmetrisch unbalancierten Feldmusters entlang der Substratoberfläche,

**dadurch gekennzeichnet, dass** das genannte Bewegen durch Bewegung des genannten bestimmten Bereiches entlang des äußeren Bereiches erfolgt.

**2.** Verfahren gemäß Anspruch 1, wobei die die Targetoberfläche eine gesputterte Oberfläche ist und die Plasmabehandlung Sputterbeschichtungen ist.

**3.** Verfahren gemäß Anspruch 1, wobei die zu der Substratoberfläche parallele Magnetfeldkomponente zwischen 1 und 20 Gauss gewählt ist.

**4.** Verfahren gemäß Anspruch 1, weiter umfassend, dass mehr als 60 % der Targetoberfläche durch das tunnelförmige Magnetronfeldmuster abgedeckt ist.

**5.** Verfahren gemäß Anspruch 4, wobei mehr als 85 % der Targetoberfläche durch das tunnelförmige Magnetronfeldmuster abgedeckt ist.

**6.** Verfahren gemäß Anspruch 1, weiter umfassend, dass das asymmetrisch unbalancierte Feldmuster durch inhomogenes Erhöhen der Magnetflussdichte entlang des äußeren Bereiches relativ zu im Wesentlichen homogener Magnetflussdichte entlang des inneren Bereiches erzeugt wird.

**7.** Verfahren gemäß Anspruch 6, weiter umfassend ein Stören der Homogenität erhöhter Magnetflussdichte durch die lokale Anwendung eines weiteren Magnetfeldes entlang des äußeren Bereiches.

**8.** Verfahren gemäß Anspruch 7, weiter umfassend das Erzeugen des weiteren Magnetfeldes durch zumindest einen Permanentmagneten und/oder einen Elektromagneten umfasst.

**9.** Verfahren gemäß einem der Ansprüche 1 bis 8, **dadurch gekennzeichnet, dass** das Verfahren ferner das Bewegen des Magnetronfeldmusters und des unbalancierten Feldmusters entlang des Substrates umfasst.

**10.** Verfahren gemäß einem der Ansprüche 1 bis 9, **dadurch gekennzeichnet, dass** das Verfahren ferner den Schritt der Erzeugung des Bewegens durch ein kreisförmiges Bewegen des unbalancierten Magnetfeldmusters um eine zu der Targetoberfläche senkrechte Achse umfasst.

**11.** Verfahren gemäß einem der Ansprüche 1 bis 10, **dadurch gekennzeichnet, dass** das Verfahren ferner den Schritt der Erzeugung des Bewegens durch eine Bewegung des Magnetron- und des unbalancierten Feldmusters um eine zu der Targetoberfläche senkrechte und gegenüber einer geometrischen Mitte des inneren Bereiches versetzte Achse umfasst.

**12.** Verfahren gemäß einem der Ansprüche 1 bis 11, **dadurch gekennzeichnet, dass** das Verfahren ferner den Schritt der Erzeugung der Schleife des Magnetronfeldmusters zirkular um eine zentrale Achse der Schleife umfasst.

**13.** Verfahren gemäß einem der Ansprüche 1 bis 12, **dadurch gekennzeichnet, dass** das Verfahren ferner den Schritt der Erzeugung eines Bereiches maximaler Plasmadichte neben dem Rand der Substratoberfläche mittels des asymmetrisch unbalancierten Feldmusters umfasst und den Schritt des Bewegens dieses Maximums neben den Umfang und entlang des Umfangs.

**14.** Verfahren gemäß Anspruch 7, **dadurch gekennzeichnet, dass** das Verfahren ferner die Anpassung der Gleichmäßigkeit der Ionenstromdichte an der Substratoberfläche durch die Anpassung des weiteren Magnetfeldes umfasst.

**15.** Verfahren gemäß Anspruch 7, **dadurch gekennzeichnet, dass** das Verfahren ferner die Erzeugung des weiteren Magnetfeldes durch mindestens eine Spule, die ein Magnetfeld im Wesentlichen parallel zu der Targetoberfläche erzeugt, umfasst.

**16.** Verfahren gemäß Anspruch 15, **dadurch gekennzeichnet, dass** das Erzeugen des Bewegens die Versorgung der mindestens einen Spule mit einem Wechselstrom umfasst.

**17.** Verfahren gemäß Anspruch 15, **dadurch gekennzeichnet, dass** das Verfahren ferner das Bereitstellen mehr als eine der genannten Spulen umfasst, wobei die Spulen Magnetfelder in jeweils unterschiedlichen Richtungen erzeugen und wobei das Erzeugen des Bewegens das Beaufschlagen der Spulen mit Wechselstrom umfasst.

**18.** Verfahren gemäß einem der Ansprüche 1 bis 17, **dadurch gekennzeichnet, dass** das Verfahren ferner die Bereitstellung von mehr als einem Substrat umfasst.

**19.** Verfahren gemäß Anspruch 18, **dadurch gekennzeichnet, dass** das Verfahren ferner den Schritt der Auswahl des Substrats umfasst, so dass dieses kreisförmig ist oder dass mehr als ein Substrat innerhalb einer Kreisfläche angeordnet ist, sowie den Schritt des Bewegens des unbalancierten Feldmusters um eine Mittelachse des Substrates oder des Bereiches umfasst.

**20.** Verfahren gemäß einem der Ansprüche 1 bis 19, **dadurch gekennzeichnet, dass** das Verfahren ferner die Anpassung des Ionenstroms an der Substratoberfläche durch die Anpassung der zur Substratoberfläche senkrechten Magnetfeldkomponente umfasst.

**21.** Verfahren gemäß Anspruch 20, **dadurch gekennzeichnet, dass** das Verfahren den Schritt der Elektronenstromführung im Plasma im Wesentlichen senkrecht zu der Targetoberfläche in Richtung der Substratoberfläche umfasst.

**22.** Verfahren gemäß einem der Ansprüche 1 bis 21, **dadurch gekennzeichnet, dass** das Verfahren den Schritt der Speisung des Plasmas durch eine pulsierende Versorgungsspannung umfasst.

**23.** Verfahren gemäß Anspruch 22, **dadurch gekennzeichnet, dass** das Verfahren ferner die Auswahl der Frequenz f des Pulsierens im Bereich von

$$5\ \text{kHz} \leq f \leq 500\ \text{kHz},$$

bevorzugt im Bereich von

$$100\ \text{kHz} \leq f \leq 200\ \text{kHz}$$

umfasst.

**24.** Verfahren gemäß einem der Ansprüche 22 oder 23, **dadurch gekennzeichnet, dass** das Verfahren ferner die Auswahl der Einschaltdauer des Impulses umfasst, so dass die Abschaltzeiten 1 % bis 99 % (beide Werte enthalten) betragen, und dass die Abschaltzeiten bevorzugt 35 % bis 50 % (beide Grenzwerte enthalten) betragen.

**25.** Verfahren gemäß einem der Ansprüche 1 bis 24, **dadurch gekennzeichnet, dass** das Verfahren ferner die Erstellung eines Gesamtdruckes p in der Vakuumkammer von höchstens $10^{-1}$ Pa, bevorzugt im Bereich

$$10^{-2}\ \text{Pa} \leq p \leq 5 \times 10^{-2}\ \text{Pa},$$

umfasst.

**26.** Verfahren gemäß einem der Ansprüche 1 bis 25, **dadurch gekennzeichnet, dass** das Verfahren ferner die Vorspannung des Substrates mit einer Radiofrequenzleistung umfasst.

**27.** Verfahren gemäß Anspruch 26, **dadurch gekennzeichnet, dass** das Verfahren ferner die Einstellung der Energie von Ionen, die die Substratoberfläche bombardieren, durch die Anpassung der Radiofrequenzleistung umfasst.

**28.** Verfahren gemäß einem der Ansprüche 1 bis 27, **dadurch gekennzeichnet, dass** das Verfahren ferner den Schritt der Bereitstellung des Targets mit einer Sputteroberfläche aus einem von Ti, Ta und Cu umfasst.

**29.** Magnetronquelle, umfassend

- ein Target (1) mit einer Targetoberfläche (3) und einer gegenüberliegenden Oberfläche;
- eine Magnetanordnung neben der gegenüberliegenden Oberfläche, aufweisend:

    - mindestens eine erste Magnetunteranordnung (5);
    - mindestens eine zweite Magnetunteranordnung (7, 7a);
    - die erste Magnetunteranordnung aufweisend einen ersten Bereich, der der gegenüberliegenden Oberfläche zugewandt ist und eine magnetische Polarität aufweist;
    - die zweite Magnetunteranordnung aufweisend einen zweiten Bereich, der der gegenüberliegenden Seite zugewandt ist und die andere magnetische Polarität aufweist;
    - der zweite Bereich bildet um den ersten Bereich eine Schleife, die von dem ersten Bereich beabstandet ist;
    - der erste Bereich erzeugt einen ersten Magnetfluss ($F_M$) durch die Targetoberfläche;
    - der zweite Bereich erzeugt einen zweiten Magnetfluss ($F_U$) durch die Targetoberfläche;
    - der zweite Magnetfluss ist größer als der erste Magnetfluss, und ferner
    - umfassend eine dritte Magnetunteranordnung (7b), die einen dritten Magnetfluss erzeugt, der den zweiten Magnetfluss durch die Sputteroberfläche überlagert, wodurch ein resultierender Magnetfluss ($F_{AU}$) entlang eines bestimmten Bereiches des zweiten Bereiches resultiert, der größer als der zweite Magnetfluss entlang des übrigen Teils des zweiten Bereiches ist, wodurch ein unbalanciertes, asymmetrisches, langreichweitiges Magnetfeld erzeugt wird,

    **gekennzeichnet durch** eine Anordnung zum Bewegen, die zum Bewegen der dritten Magnetunteranordnung relativ zu dem zweiten Bereich und entlang des zweiten Bereiches ausgelegt ist.

**30.** Quelle gemäß Anspruch 29, **dadurch gekennzeichnet, dass** der zweite Bereich um eine Schleifenmittelachse umkreist, wobei die Anordnung zum Bewegen einen Antrieb umfasst, der die dritte Magnetunteranordnung um die Schleifenmittelachse bewegt.

**31.** Quelle gemäß einem der Ansprüche 29 oder 30, **dadurch gekennzeichnet, dass** der zweite Bereich um eine Schleifenmittelachse umkreist, wobei die Anordnung zum Bewegen einen Antrieb umfasst, der die zweite Magnetunteranordnung um eine Drehachse bewegt, die gegenüber der Mittelachse der Schleife versetzt ist.

**32.** Quelle gemäß Anspruch 31, **dadurch gekennzeichnet, dass** die Mittelschleifachse, die Drehachse und die dritte Magnetunteranordnung im Wesentlichen in eine radiale Richtung von der Drehachse ausgerichtet sind.

**33.** Quelle gemäß einem der Ansprüche 29 bis 32, **dadurch gekennzeichnet, dass** die Quelle ferner eine Magnetabschirmung umfasst, die bezüglich des zweiten Magnetflusses bewegbar ist, um den zweiten Magnetfluss hervorzurufen, dass dieser entlang des zweiten Bereiches ungleich verteilt ist.

**34.** Quelle gemäß einem der Ansprüche 29 bis 33, **dadurch gekennzeichnet, dass** die Schleife um eine Schleifenmittelachse kreisförmig ist.

**35.** Magnetron-Behandlungskammer umfassend eine Magnetronquelle gemäß einem der Ansprüche 29 bis 34 und einen Substratträger, der von der Targetoberfläche der Magnetronquelle entfernt und ihr gegenüber liegt.

**36.** Kammer gemäß Anspruch 35, **dadurch gekennzeichnet, dass** die ferner eine Anodenanordnung neben dem Substrathalter umfasst.

**37.** Kammer gemäß Anspruch 36, **dadurch gekennzeichnet, dass** die Kammer ferner eine Abschirmung aufweist, die einen Prozessbereich zwischen der Quelle und dem Substratträger begrenzt und elektrisch potentialfrei ist oder auf einem anodischen Potential liegt, und bevorzugt auf negativerem Potential als die Anode ist.

**38.** Kammer gemäß Anspruch 36, **dadurch gekennzeichnet, dass** die Anode hinter einer Abschirmanordnung und in Bezug auf das Verarbeitungsvolumen versteckt ist.

**39.** Kammer gemäß einem der Ansprüche 36 bis 38, **dadurch gekennzeichnet, dass** die Kammer ferner mindestens eine Spule mit einer zu der Sputteroberfläche der Quelle senkrechten Spulenachse umfasst.

**40.** Kammer gemäß einem der Ansprüche 35 bis 39, **dadurch gekennzeichnet, dass** der Substratträger elektrisch potentialfrei ist oder mit einem vorbestimmten Biaspotential verbindbar ist.

## Revendications

1. Procédé pour fabriquer des substrats avec une surface traitée au plasma sous vide, comprenant les étapes qui consistent :

    - à prévoir une cible (1) avec une surface de cible (3) ;
    - à prévoir au moins un substrat qui est placé à une certaine distance et en face de ladite surface de cible et qui présente une surface de substrat ;
    - à générer dans le volume situé entre la surface de cible et la surface de substrat un dessin de champ magnétique

        a) d'un dessin de champ de magnétron ($F_M$) qui forme une boucle fermée, considéré dans le sens dirigé vers la surface de pulvérisation cathodique et, considéré parallèlement à celle-ci, qui forme un arc en forme de tunnel d'une zone extérieure ($A_o$) d'un premier pôle magnétique vers une zone intérieure ($A_i$) d'un second pôle magnétique, ladite zone intérieure étant limitée par rapport à la zone extérieure par un lieu fermé (L') de composante zéro de champ magnétique perpendiculairement à la surface cible ;
        b) d'un dessin de champ de longue distance déséquilibré ($F_{AU}$) qui est généré asymétriquement grâce à l'augmentation du flux magnétique le long d'une zone distincte de la zone extérieure par rapport au flux magnétique le long de la zone intérieure et par rapport au reste de la zone extérieure, le champ de longue distance qui atteint la surface du substrat a une composante du champ magnétique parallèle à la surface du substrat d'au moins 0,1 Gauss ;

    - à générer une décharge de plasma dans le dessin de champ magnétique ;
    - à traiter par plasma la surface du substrat balayant le dessin de champ asymétriquement déséquilibré le long du substrat, **caractérisée par** effectuer ledit balayage par déplacer ladite zone distincte le long de la zone extérieure.

2. Procédé selon la revendication 1, la surface de cible étant une surface de pulvérisation cathodique, et le traitement au plasma étant une enduction par pulvérisation cathodique.

3. Procédé selon la revendication 1, selon lequel la composante de champ magnétique parallèlement à la surface de substrat est choisie entre 1 et 20 Gauss.

4. Procédé selon la revendication 1, comprenant par ailleurs le recouvrement de plus de 60 % de la surface de cible avec le dessin de champ de magnétron en forme de tunnel.

5. Procédé selon la revendication 4, recouvrant plus de 85 % de la surface de cible avec le dessin de champ de magnétron en forme de tunnel.

6. Procédé selon la revendication 1, comprenant par ailleurs la production du dessin de champ asymétriquement déséquilibré en augmentant de manière non homogène la densité de flux magnétique le long de la zone extérieure par rapport à la densité de flux magnétique globalement homogène le long de la zone intérieure.

7. Procédé selon la revendication 6, comprenant par ailleurs à perturber l'homogénéité de la densité de flux magnétique augmenté, en appliquant localement un champ magnétique supplémentaire le long de la zone extérieure.

8. Procédé selon la revendication 7, comprenant la production du champ magnétique supplémentaire à l'aide d'au moins un aimant permanent et/ou électro-aimant.

9. Procédé selon l'une des revendications 1 à 8, comprenant par ailleurs le balayage du dessin de champ de magnétron et du dessin de champ déséquilibré le long du substrat.

10. Procédé selon l'une des revendications 1 à 9, comprenant par ailleurs l'étape qui consiste à produire le balayage grâce à un déplacement circulaire du dessin de champ magnétique déséquilibré autour d'un axe perpendiculaire à la surface de cible.

11. Procédé selon l'une des revendications 1 à 10, comprenant par ailleurs l'étape qui consiste à produire le balayage en déplaçant le dessin de champ de magnétron et le dessin de champ déséquilibré autour d'un axe perpendiculaire à la surface de cible et décalé par rapport à un centre géométrique de la zone intérieure.

**12.** Procédé selon l'une des revendications 1 à 11, comprenant par ailleurs l'étape qui consiste à générer la boucle du dessin de champ de magnétron suivant une forme circulaire autour d'un axe central de boucle.

**13.** Procédé selon l'une des revendications 1 à 12, comprenant par ailleurs l'étape qui consiste à générer à l'aide du dessin de champ déséquilibré asymétriquement une zone de densité de plasma maximum près de la périphérie de la surface de substrat et à balayer ce maximum près et le long de ladite périphérie.

**14.** Procédé selon la revendication 7, comprenant par ailleurs le réglage de l'uniformité de la densité de courant ionique à la surface de substrat à l'aide du réglage du champ magnétique supplémentaire.

**15.** Procédé selon la revendication 7, comprenant par ailleurs la production du champ magnétique supplémentaire à l'aide d'au moins une bobine produisant un champ magnétique globalement parallèle à la surface de cible.

**16.** Procédé selon la revendication 15, la production du balayage comprenant l'alimentation de ladite au moins une bobine avec un courant alternatif.

**17.** Procédé selon la revendication 15, qui prévoit par ailleurs que plus d'une bobine produisent respectivement des champs magnétiques dans des directions différentes, la production du balayage comprenant l'application de courants alternatifs aux bobines.

**18.** Procédé selon l'une des revendications 1 à 17, selon lequel il est prévu par ailleurs plus d'un substrat.

**19.** Procédé selon la revendication 18, comprenant par ailleurs l'étape qui consiste à choisir que le substrat soit circulaire ou que les substrats soient disposés à l'intérieur d'une zone circulaire, et comprenant le balayage du dessin de champ déséquilibré autour d'un axe central du substrat ou de la zone.

**20.** Procédé selon l'une des revendications 1 à 19, comprenant par ailleurs le réglage du courant d'ions à la surface de substrat grâce au réglage de la composante de champ magnétique perpendiculaire à la surface de substrat.

**21.** Procédé selon la revendication 20, comprenant l'étape qui consiste à guider un courant d'électrons dans le plasma globalement perpendiculaire à la surface de cible vers la surface de substrat.

**22.** Procédé selon l'une des revendications 1 à 21, comprenant l'étape d'alimentation du plasma par une tension d'alimentation pulsatoire.

**23.** Procédé selon la revendication 22, comprenant la sélection de la fréquence f de la pulsation pour que

$$5\ \text{kHz} \leq f \leq 500\ \text{kHz},$$

et de préférence pour que

$$100\ \text{kHz} \leq f \leq 200\ \text{kHz}.$$

**24.** Procédé selon l'une des revendications 22 ou 23, comprenant par ailleurs la sélection d'un cycle de fonctionnement de la tension pulsatoire pour qu'elle ait 1 % à 99 % (inclus) de temps de repos et pour qu'elle ait de préférence 35 % à 50 % (inclus) de temps de repos.

**25.** Procédé selon l'une des revendications 1 à 24, comprenant par ailleurs l'établissement, dans la chambre à vide, d'une pression totale p d'au maximum $10^{-1}$ Pa, de préférence

$$10^{-2}\ \text{Pa} \leq p \leq 5 \times 10^{-2}\ \text{Pa}.$$

**26.** Procédé selon l'une des revendications 1 à 25, comprenant par ailleurs la polarisation du substrat avec une puissance de fréquence Rf.

**27.** Procédé selon la revendication 26, comprenant par ailleurs le réglage de l'énergie du bombardement ionique de la surface du substrat grâce à un réglage de ladite puissance Rf.

**28.** Procédé selon l'une des revendications 1 à 27, comprenant par ailleurs l'étape qui consiste à prévoir que ladite cible à une surface de pulvérisation cathodique de Ti ou de Ta ou de Cu.

**29.** Source de magnétron comprenant

- une cible (1) avec une surface de cible (3) et une surface opposée ;
- un arrangement magnétique prés de ladite surface opposée et comprenant :
  - au moins un premier sous-arrangement magnétique (5) ;
  - au moins un deuxième sous-arrangement magnétique (7, 7a) ;
  - le premier sous-arrangement magnétique ayant une première zone dirigée vers la surface opposée et présentant une polarité magnétique ;
  - le deuxième sous-arrangement magnétique ayant une seconde zone dirigée vers la surface opposée et présentant l'autre polarité magnétique ;
  - la seconde zone formant une boucle autour de la première zone et à une certaine distance de celle-ci ;
  - la première zone produisant un premier flux magnétique ($F_M$) à travers la surface de cible ;
  - la seconde zone produisant un deuxième flux magnétique ($F_U$) à travers la surface de cible ;
  - le deuxième flux magnétique étant supérieur au premier, et par ailleurs
  - comprenant un troisième sous-arrangement magnétique (7b) qui produit un troisième flux magnétique superposé sur le deuxième flux magnétique à travers la surface de pulvérisation cathodique, ce qui donne un flux magnétique résultant ($F_{AU}$) le long d'une zone distincte de la seconde zone, qui est supérieur au deuxième flux magnétique le long du reste de ladite seconde zone, produisant ainsi un champ magnétique déséquilibré, asymétrique, de longue distance,

**caractérisée par** un arrangement de balayage apte à déplacer le troisième sous-ensemble magnétique par rapport à la seconde zone et le long de celle-ci.

**30.** Source selon la revendication 29, dans laquelle la seconde zone décrit une boucle autour d'un axe central de boucle, le dispositif de balayage comprenant un mécanisme d'entraînement qui déplace le troisième sous-ensemble magnétique autour de l'axe central de boucle.

**31.** Source selon l'une des revendications 29 ou 30, dans laquelle la seconde zone décrit une boucle autour d'un axe de boucle central, le dispositif de balayage comprend un mécanisme d'entraînement qui déplace le deuxième sous-arrangement magnétique autour d'un axe de rotation décalé par rapport à l'axe central de boucle.

**32.** Source selon la revendication 31, dans laquelle l'axe de boucle central, l'axe de rotation et le troisième sous-arrangement magnétique sont globalement alignés dans le sens radial à partir de l'axe de rotation.

**33.** Source selon l'une des revendications 29 à 32, comprenant par ailleurs un écran magnétique mobile par rapport au deuxième flux magnétique, pour que ce deuxième flux magnétique soit réparti irrégulièrement le long de la seconde zone.

**34.** Source selon l'une des revendications 29 à 33, dans laquelle la boucle est circulaire autour d'un axe central de boucle.

**35.** Chambre de traitement par magnétron comprenant une source de magnétron selon l'une des revendications 29 à 34 et un porte-substrat disposé loin et en face de la surface de cible de la source de magnétron.

**36.** Chambre selon la revendication 35, comprenant un dispositif à anode près du support de substrat.

**37.** Chambre selon la revendication 36, comprenant un écran qui confine une zone de traitement entre la source et le porte-substrat et qui est électriquement flottant ou à un potentiel anodique, de préférence à un potentiel plus négatif que l'anode.

**38.** Chambre selon la revendication 36, dans laquelle l'anode est cachée derrière un dispositif à écran et par rapport au volume de traitement.

**39.** Chambre selon l'une des revendications 36 à 38, comprenant par ailleurs au moins une bobine avec un axe de bobine perpendiculaire à la surface de pulvérisation cathodique de la source.

**40.** Chambre selon l'une des revendications 35 à 39, dans laquelle le porte-substrat est électriquement flottant ou apte à être relié à un potentiel de polarisation prédéterminé.

FIG. 1

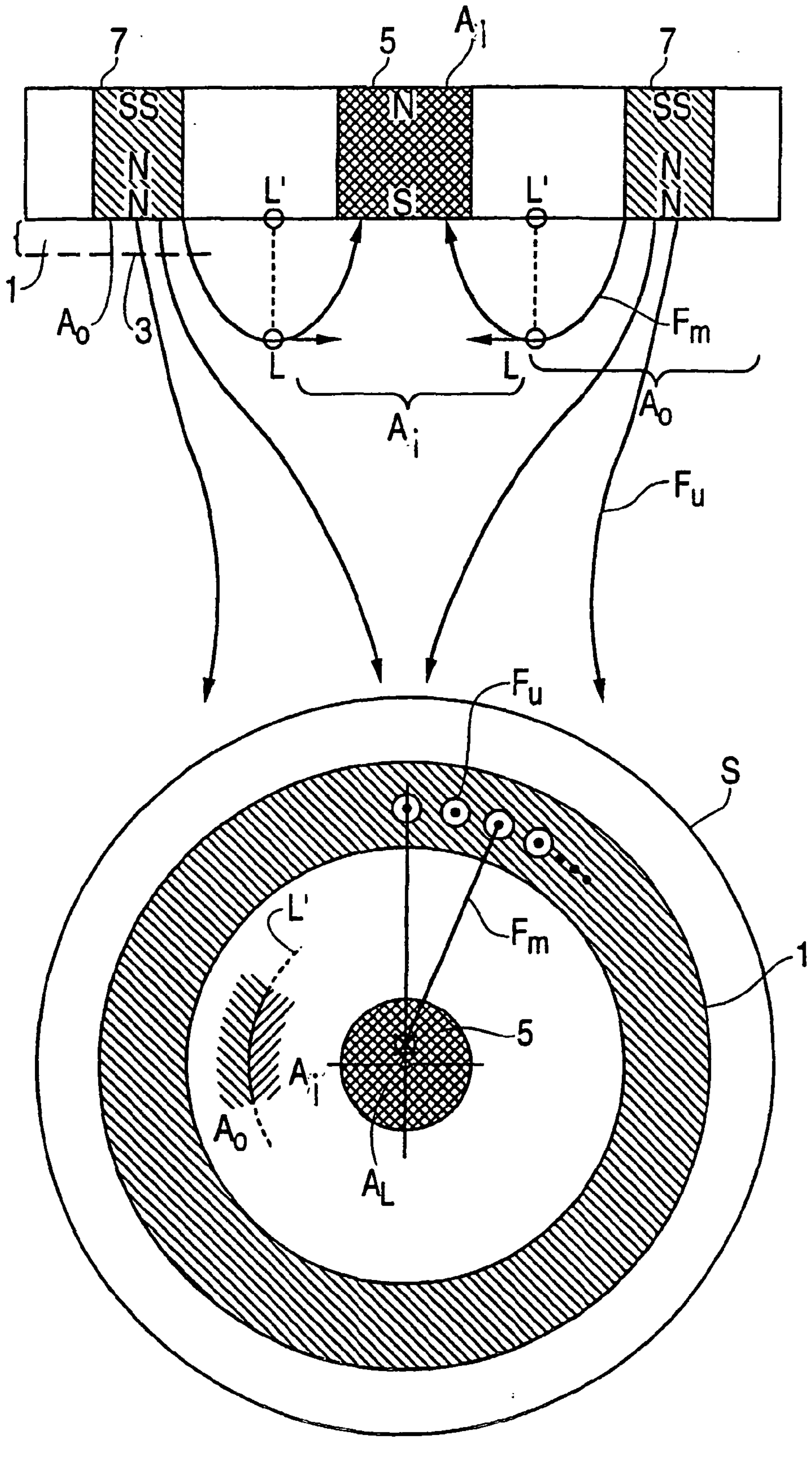


FIG. 2

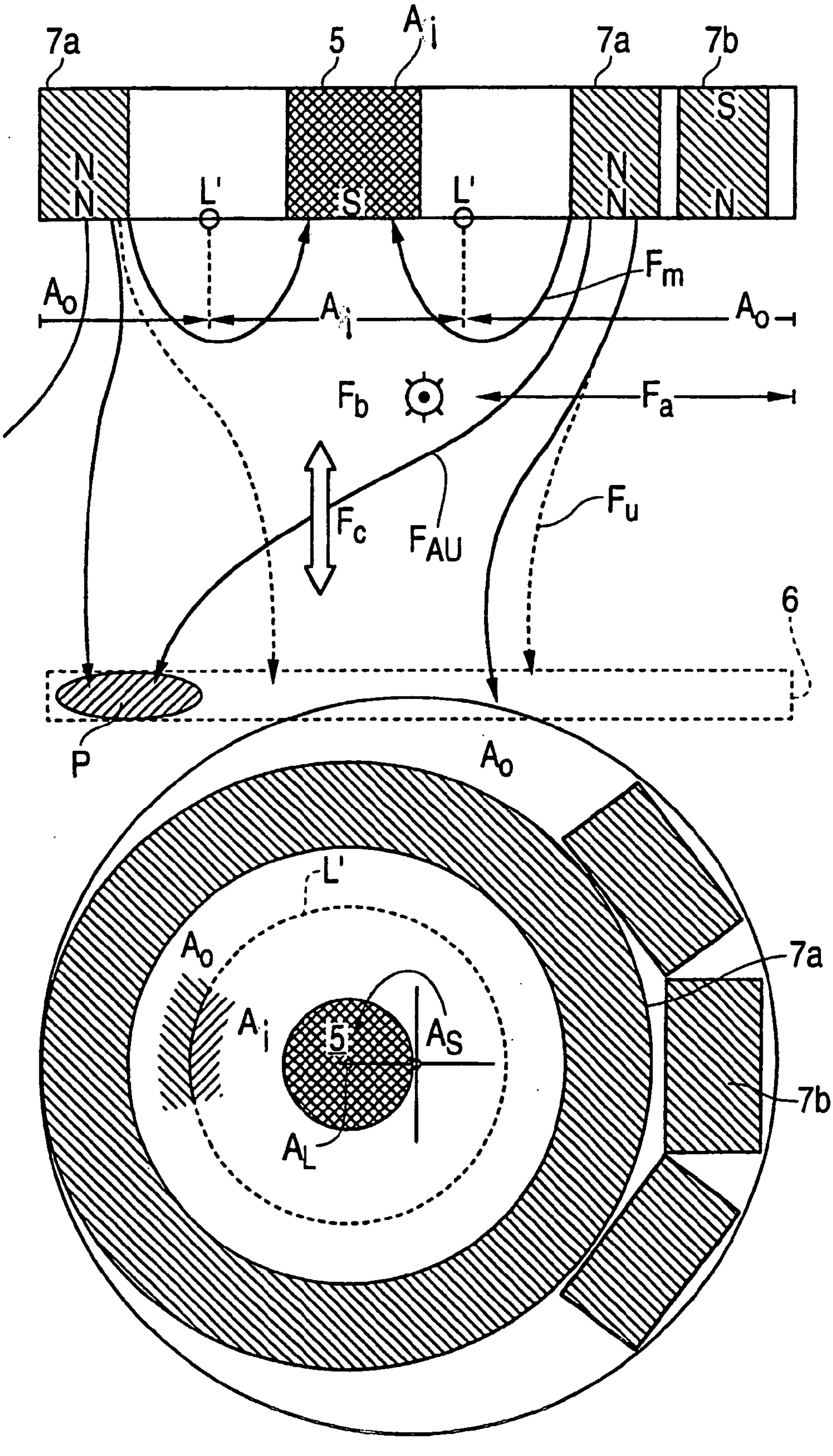

7a
5
$A_i$
7a
7b
N
N
L'
S
L'
N
N
S
N
$F_m$
$A_o$
$A_i$
$A_o$
$F_b$
$F_a$
$F_c$
$F_{AU}$
$F_u$
6
P
$A_o$
L'
$A_o$
7a
$A_i$
5
$A_S$
7b
$A_L$

FIG. 3

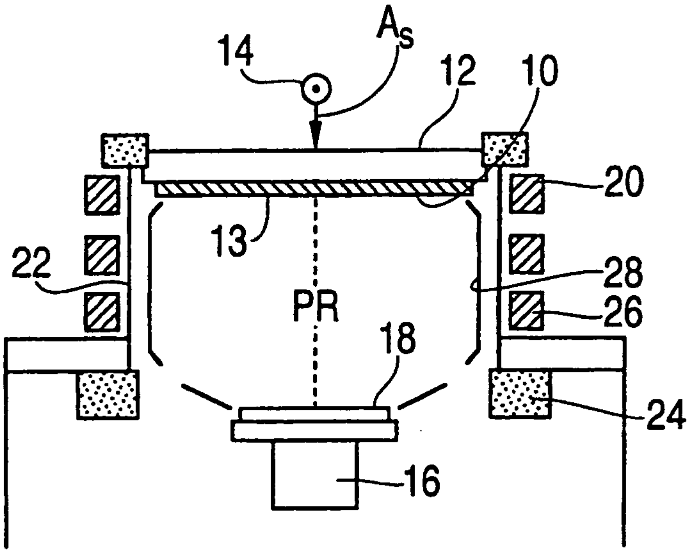


FIG. 4

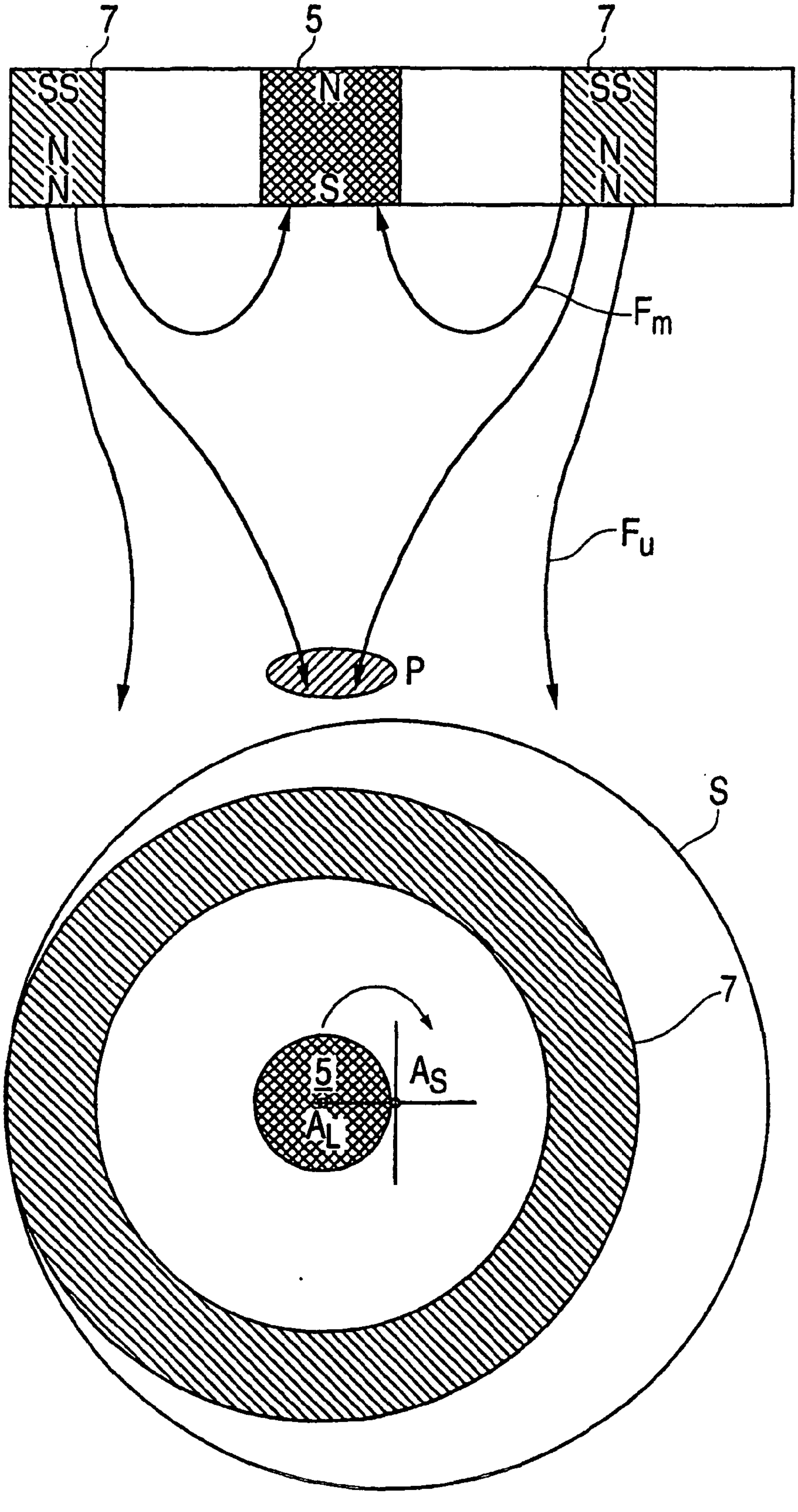
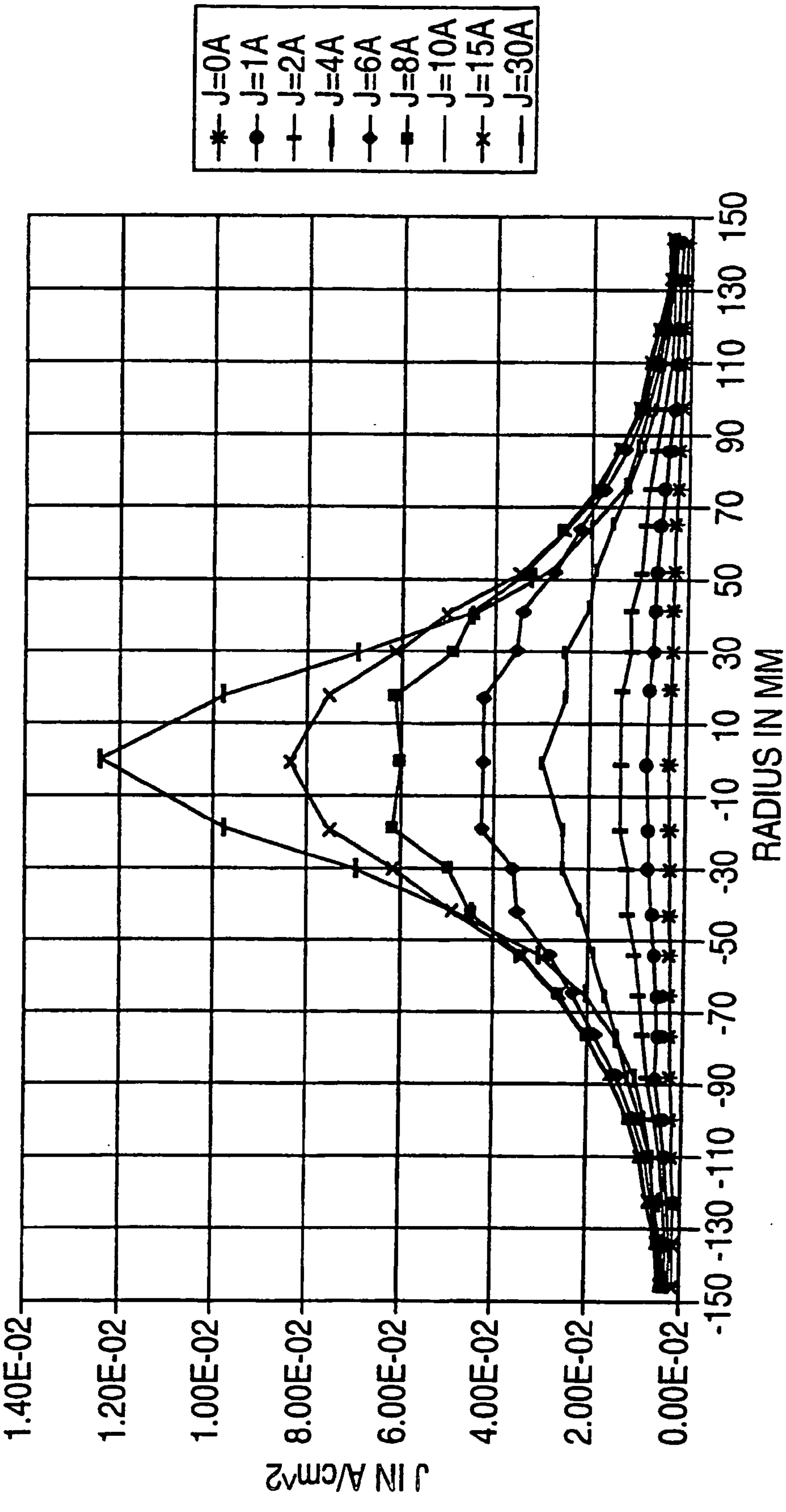


**FIG. 5**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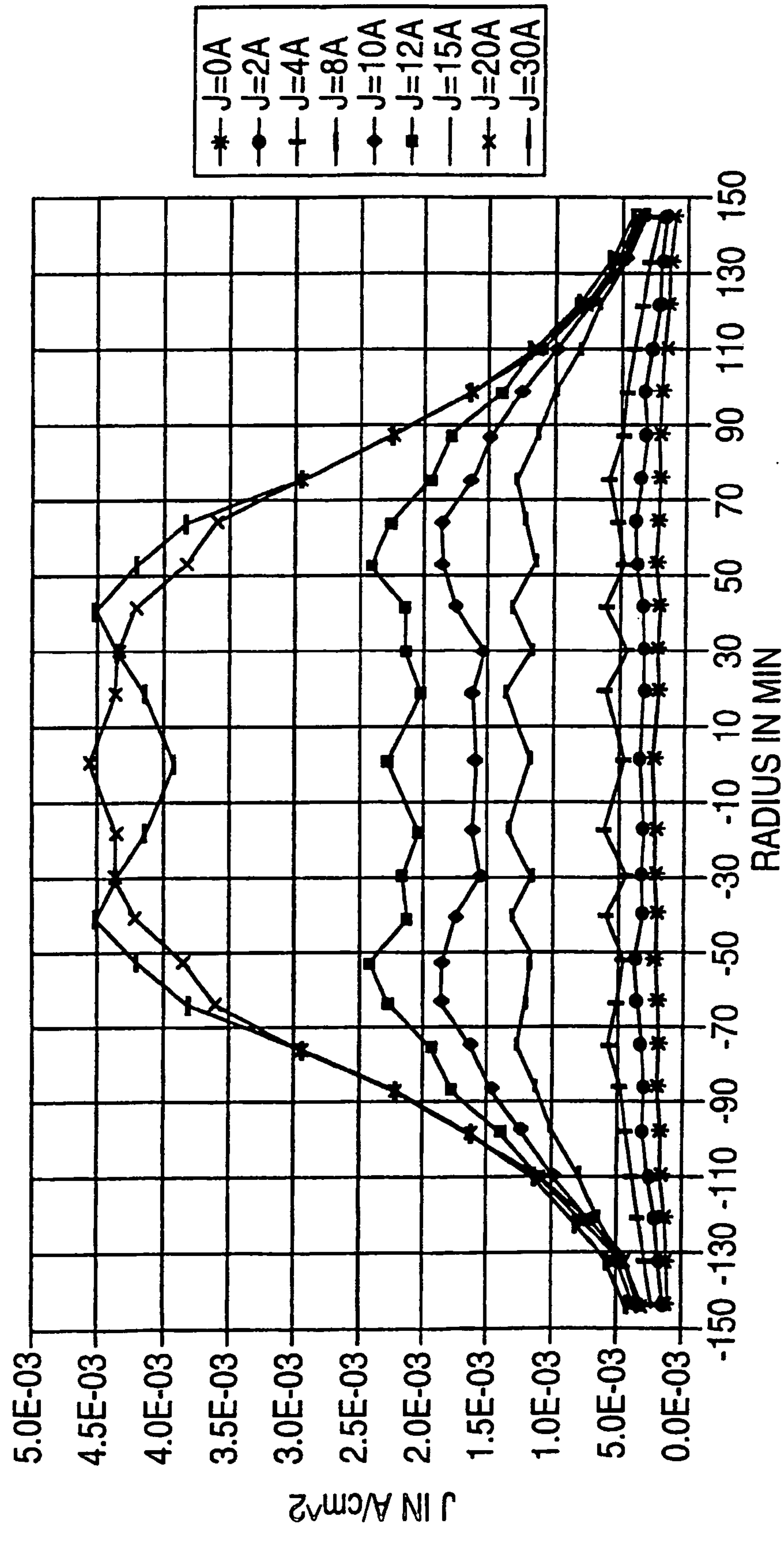
J=1A
J=2A
J=4A
J=6A
J=8A
J=10A
J=15A
J=30A
1.40E-02
1.20E-02
1.00E-02
8.00E-02
6.00E-02
4.00E-02
2.00E-02
0.00E-02
J IN A/cm^2
-150
-130
-110
-90
-70
-50
-30
-10
10
30
50
70
90
110
130
150
RADIUS IN MM

## FIG. 6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J=4A
J=8A
J=10A
J=12A
J=15A
J=20A
J=30A
J IN A/cm^2
5.0E-03
4.5E-03
4.0E-03
3.5E-03
3.0E-03
2.5E-03
2.0E-03
1.5E-03
1.0E-03
5.0E-03
0.0E-03
RADIUS IN MIN
-150
-130
-110
-90
-70
-50
-30
-10
10
30
50
70
90
110
130
150

FIG. 7

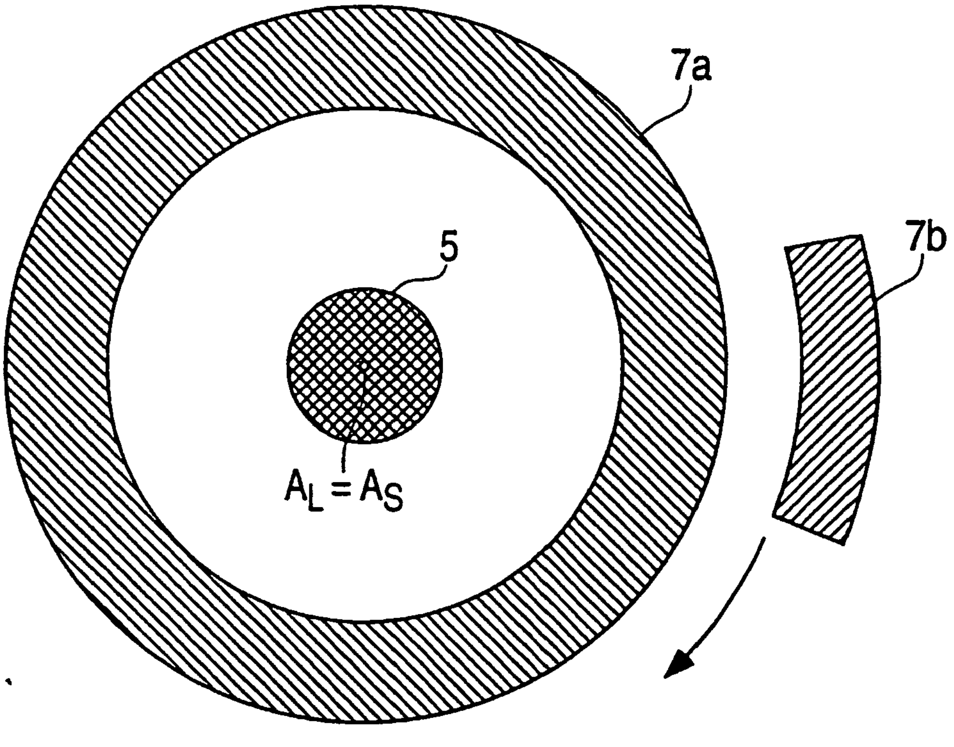


FIG. 8

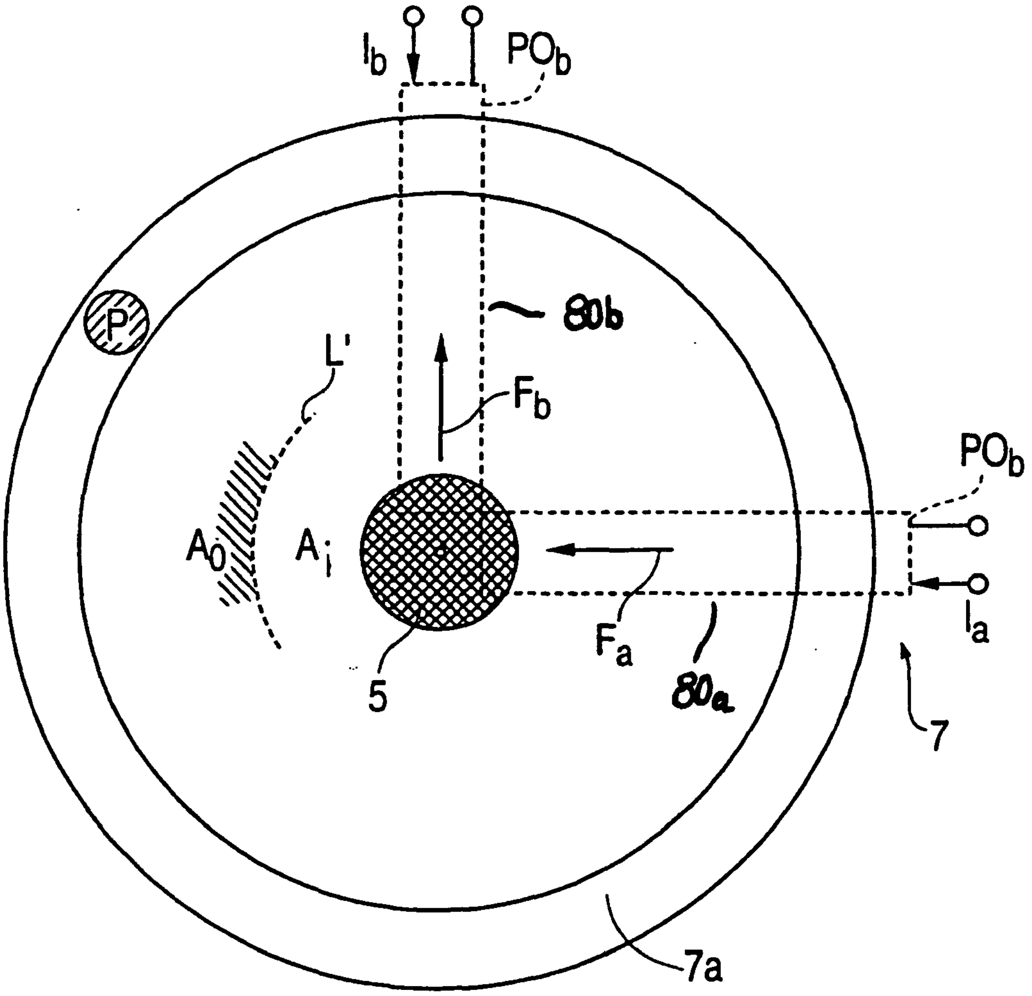


FIG. 9

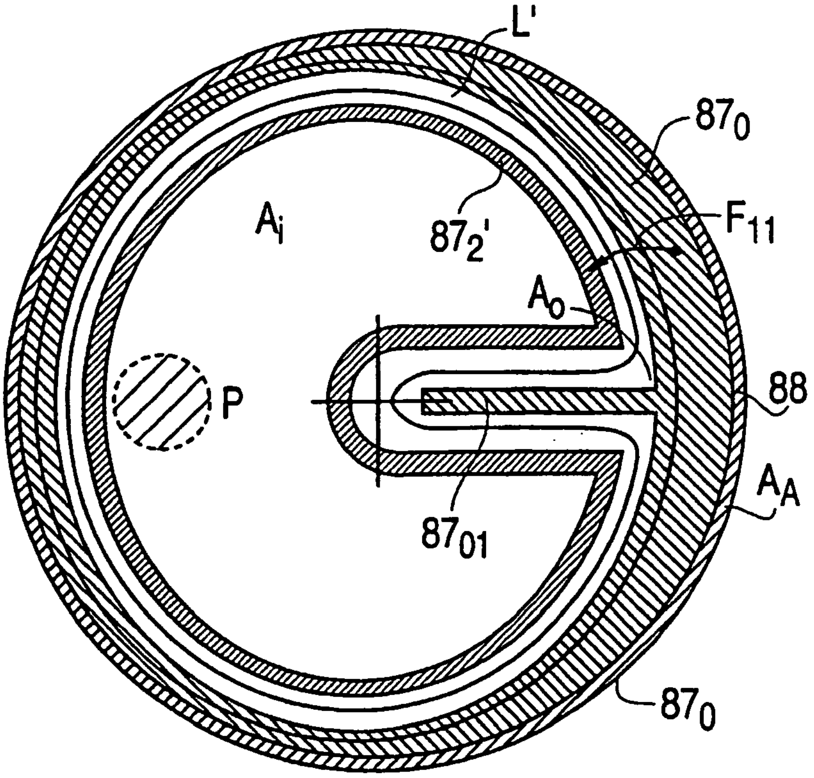


FIG. 10

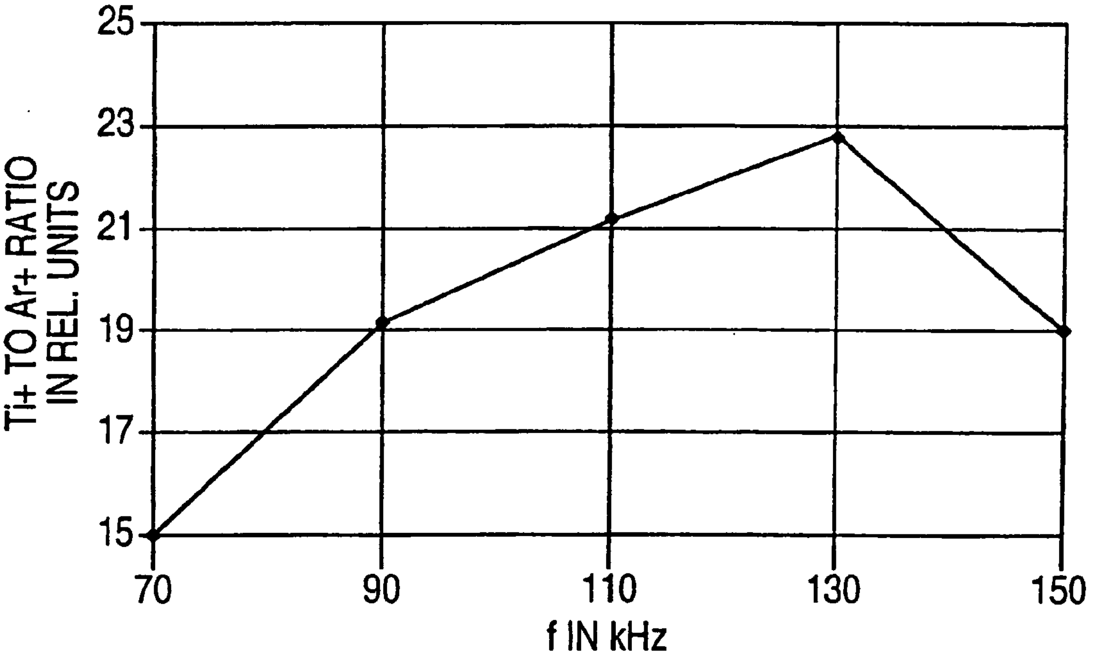

25
23
21
19
17
15
Ti+ TO Ar+ RATIO
IN REL. UNITS
70
90
110
130
150
f IN kHz

FIG. 11

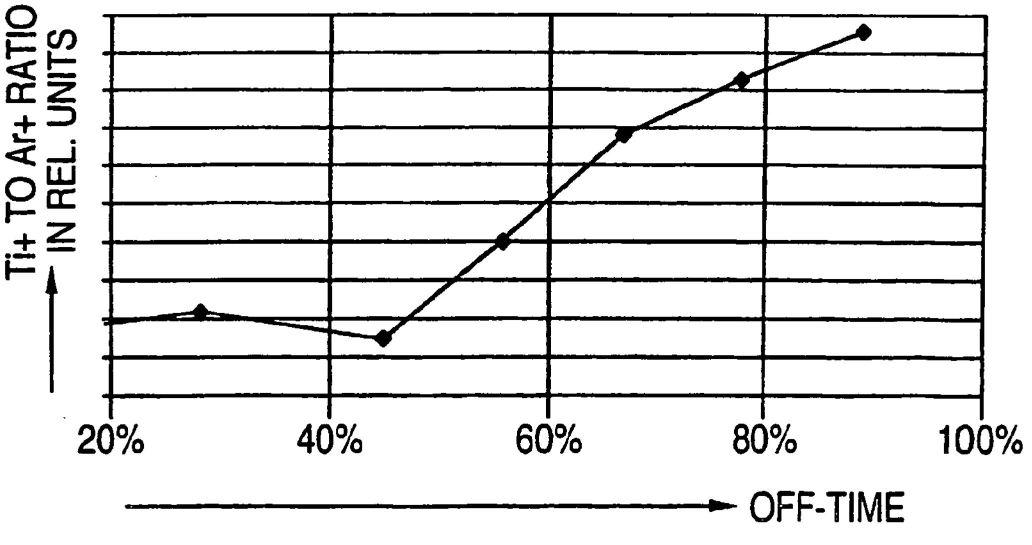
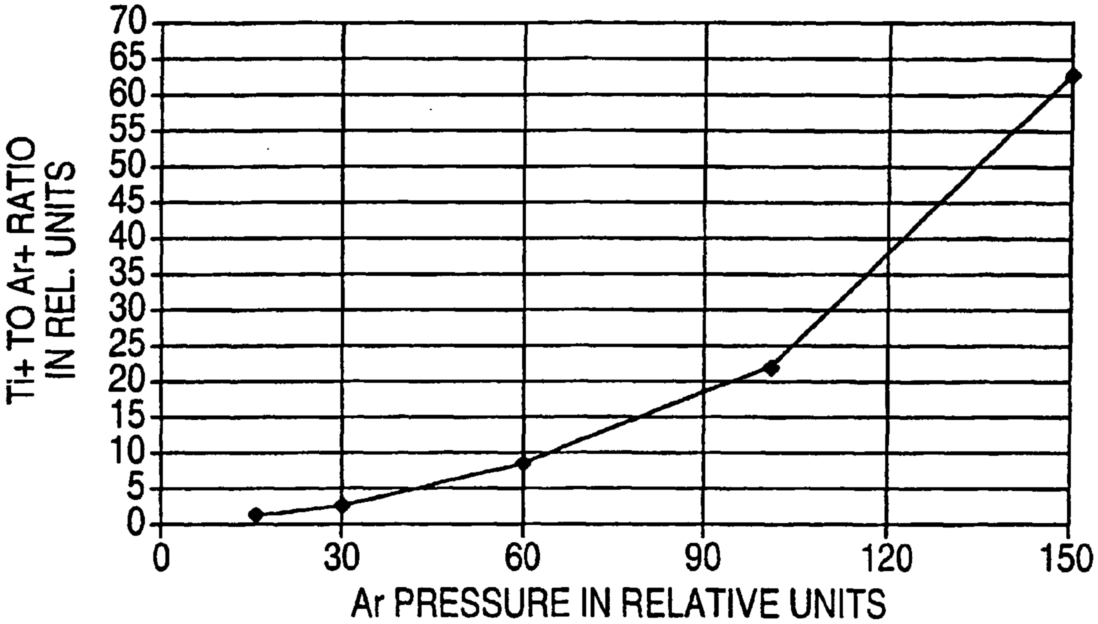
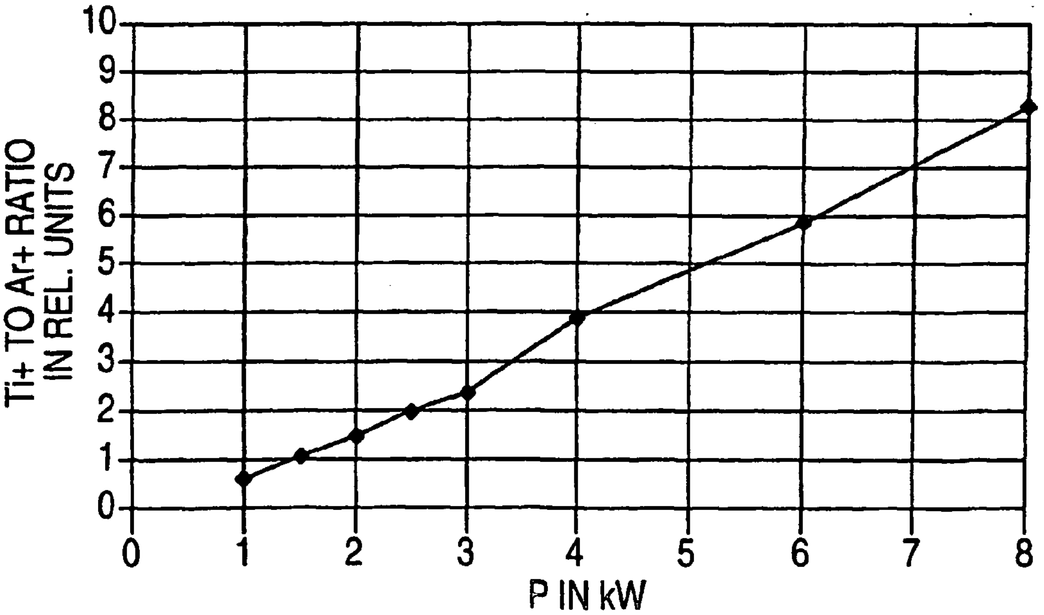

Ti+ TO Ar+ RATIO
IN REL. UNITS
20%
40%
60%
80%
100%
OFF-TIME

FIG. 12



Ti+ TO Ar+ RATIO IN REL. UNITS
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0
0
30
60
90
120
150
Ar PRESSURE IN RELATIVE UNITS

FIG. 13



Ti+ TO Ar+ RATIO IN REL. UNITS
10
9
8
7
6
5
4
3
2
1
0
0
1
2
3
4
5
6
7
8
P IN kW

## REFERENCES CITED IN THE DESCRIPTION

### Patent documents cited in the description

- US 6352629 B **[0002] [0011] [0052]**
- US 6491801 A **[0012]**