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N. L. SIGOURNAY ET AL

3,576,729

SPUTTERING METHODS AND APPARATUS

Filed May 31, 1968

3 Sheets-Sheet 1

FIG. 1.

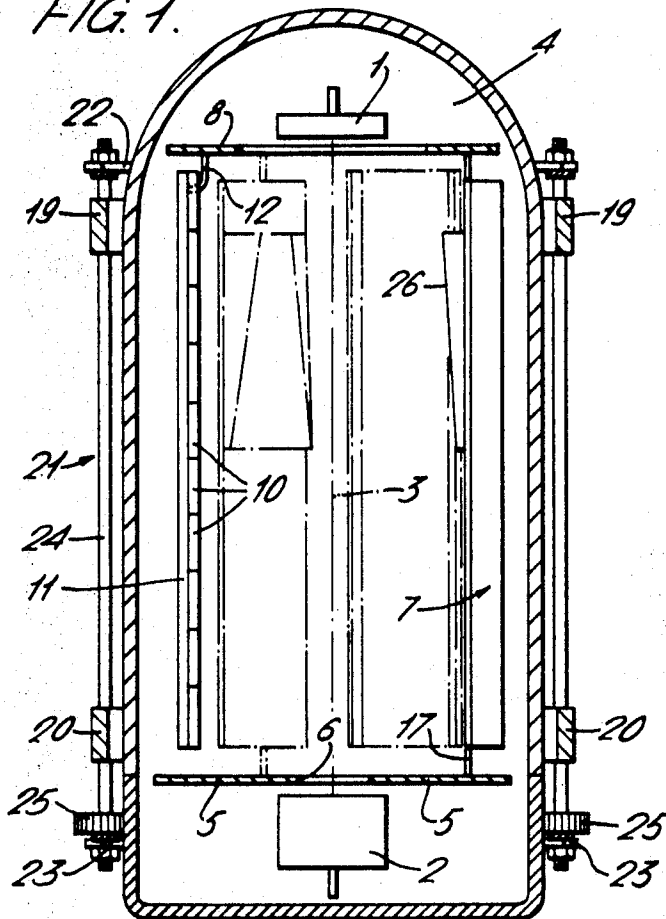
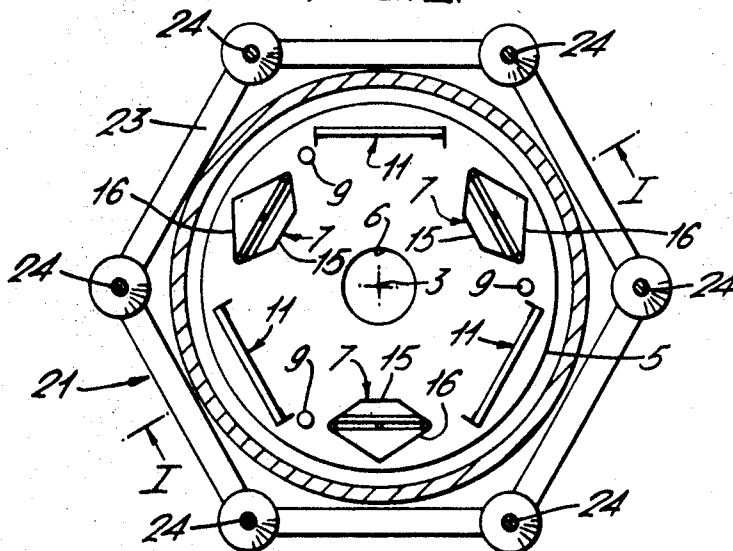


FIG. 2.



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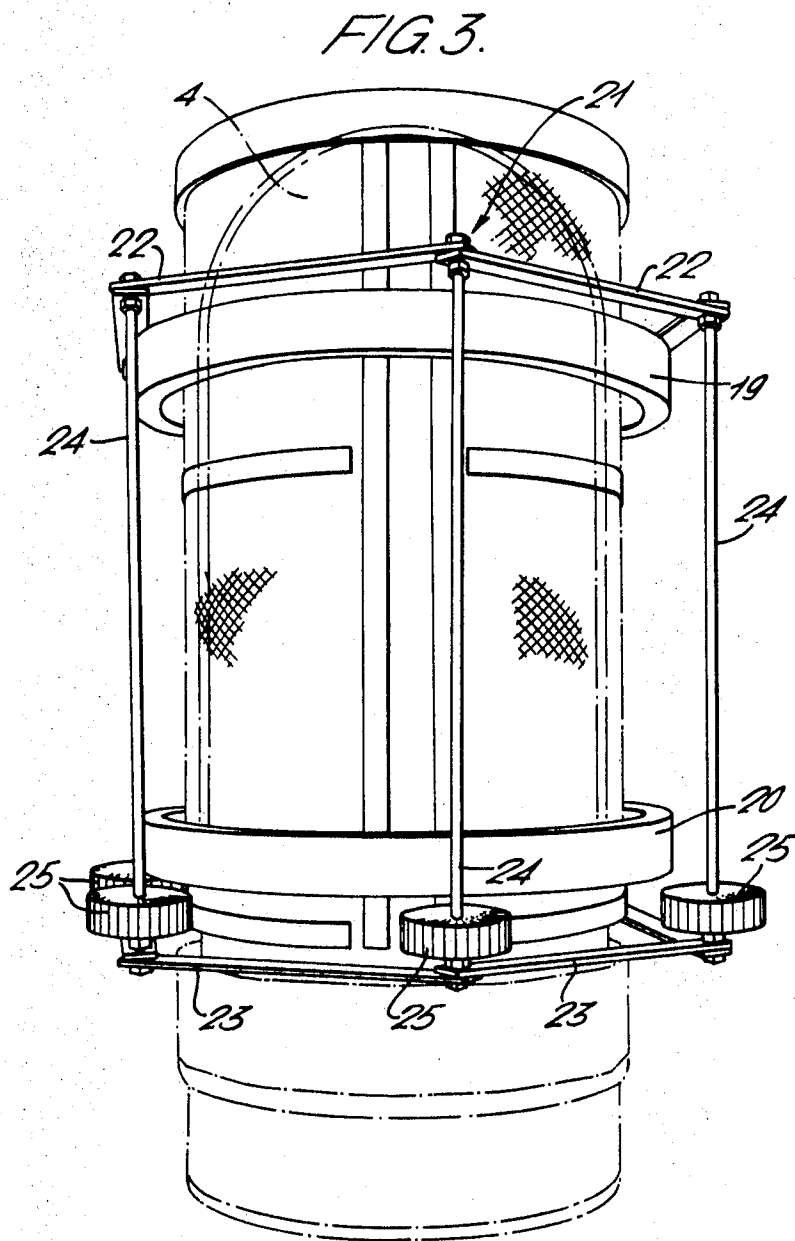
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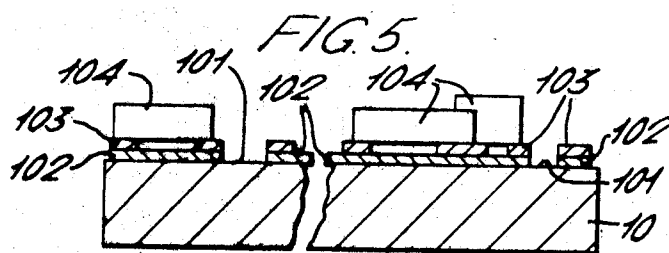
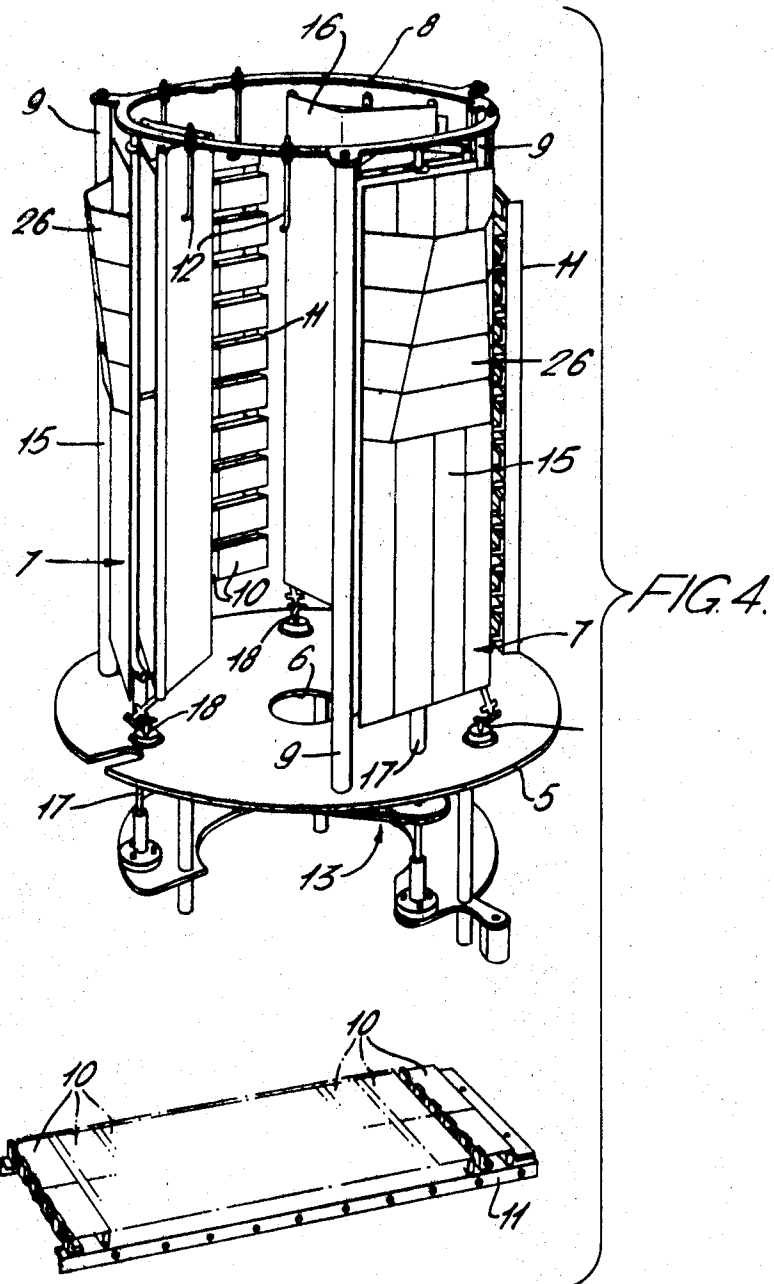
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SPUTTERING METHODS AND APPARATUS

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3 Sheets-Sheet 3



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22 Claims

ABSTRACT OF THE DISCLOSURE

Sputter-deposition of superimposed metal films on ceramic substrates in batch-production of microcircuit devices is made by ionic bombardment of successive targets from a plasma created using an electron beam, the bombardment being accompanied by application of a transverse magnetic field rotating about the path of the beam. The substrates are carried between target-assemblies that are rotatable to effect deposition from different targets successively, and the top and bottom films deposited are etched away to form respectively the circuit interconnections and resistive elements of the devices.

This invention relates to methods and apparatus for sputtering of materials.

The invention relates especially to methods and apparatus for deposition of material by sputtering. In sputter-deposition, material is deposited as a result of ionic bombardment of a target, the bombarding ions being directed to the target (normally by means of an electric field) from a plasma. It is common practice to arrange for creation of the plasma by collision of an electron beam with the atoms or molecules of a gaseous atmosphere, the substrate upon which deposition is to take place being then conventionally positioned opposite the target across the electron-beam path. With this arrangement, however, there has been found to be considerable variation in the rate of deposition from one point to another along the path of the beam, and this is of particular disadvantage where an accurately-controlled and uniform deposit-thickness is required; furthermore, it tends to limit unduly the area of substrate, or the number of substrates that can be coated at any one time. These disadvantages are of especial importance in the sputter-deposition of thin metallic film as required in the manufacture of electrical microcircuit devices, since in such devices the thickness of film is required to be uniform across the substrate of the device itself and from one device to another. The disadvantages act also to reduce the rate at which the devices can be manufactured.

It is an object of the present invention to provide a method and apparatus for sputtering of material, that can be used to overcome these disadvantages.

According to one aspect of the present invention a method of sputtering of material by ionic bombardment of a target from a plasma created using a beam of electrons in a gaseous atmosphere, includes the step of applying a magnetic field to act transversely of the path of the electron beam and to vary in direction relative thereto during said bombardment.

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The variation in direction of the field may be achieved by causing rotation of the field about the electron-beam path.

According to another aspect of the present invention apparatus for sputtering of material by ionic bombardment of a target from a plasma created using a beam of electrons in a gaseous atmosphere, includes means for applying a magnetic field to act transversely of the path of the electron beam and to vary in direction relative thereto during said bombardment.

The said means may be electrical means that is energizable from a three-phase supply to provide a magnetic field that rotates about the electron-beam path.

A method and apparatus for deposition of material by sputtering, in accordance with the present invention, will now be described, by way of example, with reference to the accompanying drawings in which:

FIGS. 1 and 2 are simplified sectional representations of the apparatus in elevation and plan respectively, the section of FIG. 1 being taken on the line I—I of FIG. 2;

FIG. 3 is an exterior view of the apparatus;

FIG. 4 is a view of part of the internal structure of the apparatus showing one of the three substrate-carriers of this structure detached; and

FIG. 5 is a representative sectional side-elevation of an electrical microcircuit device manufactured using the method according to the present invention and the apparatus shown in FIGS. 1 to 4.

The method and apparatus to be described with particular reference to FIGS. 1 to 4, are used in batch-production of electrical microcircuit devices of the kind shown in FIG. 5, in which electrically-resistive elements of the circuit, together with electrical circuit-interconnections, are provided in the form of thin metallic film carried by an electrically-insulative substrate.

Referring to FIG. 5, the substrate 10 of the device is a rectangular ceramic plate having, for example, a length of two inches, a width of one inch and a thickness of 0.025 inch, and having a composition which is 95% alumina. An unglazed face 101 of the substrate 10 carries thin-film elements 102 of nickel-chromium alloy that are partially coated with thin-film elements 103 of copper (or other material, such as gold, having a good electrical conductance). The elements 103 provide the electrical circuit-interconnections of the device, whereas the elements 102 where these are left uncoated between the elements 103, provide the electrical resistors of the circuit. Other electrical components 104, such as capacitors and semiconductor devices, are welded, soldered, or otherwise bonded, to the elements 103 so as to be incorporated appropriately in the electrical circuit of the complete device.

The electrical device of FIG. 5 is manufactured by initially depositing two metal films one upon the other on the unglazed face 101 of the ceramic substrate 10, the first film (deposited directly on the face 101) being of an 80%–20% nickel-chromium alloy (such as sold as material V under the trademark "Nichrome") and the second of copper. After deposition of the two films, the substrate 10 is submitted to two etching processes to provide from the two metal films the resistors and circuit-interconnections required. The first etching process affects

the upper film of copper but not the lower film of nickel-chromium alloy, and leaves just those parts of the copper film, the elements 103, required for the pattern of circuit-interconnections of the device. The second etching process affects the lower, nickel-chromium film where this has been exposed by removal of the copper film during the first etching process, and leaves only such parts of the film, the elements 102, that have the exposed areas required to constitute resistors. When the patterned coating of the substrate 10 has been stabilized by baking, electrical circuit components 104 (such as capacitors and semiconductor devices) are then welded, soldered or otherwise bonded, to the copper pattern so as to be incorporated in the electrical circuit and complete the microcircuit device.

The deposition of the metallic films on the ceramic substrate 10 is performed by sputtering, a batch of some sixty substrates being coated in the one operation. It is clearly desirable to ensure that there is uniformity of deposition of each film across the surface of the individual substrates 10 and from one substrate to another in the batch. In particular, the film of nickel-chromium alloy on each substrate is required to be of a uniform thickness to provide an electrical resistance of 200 ohms per square, and the film of copper of a uniform thickness to provide an electrical resistance of 0.1 ohm per square (all square areas of uniform thickness have the same resistance and this applies irrespective of the side-dimension). The sputter-deposition of these films with the requisite uniformity is obtained using the apparatus shown in FIGS. 1 to 4.

Referring to FIGS. 1 to 4, the apparatus has an anode 1 and a cathode 2 that are spaced from one another along the longitudinal axis 3 of an air-tight enclosure 4. A metal plate 5, which has a central aperture 6 and is positioned within the enclosure 4 adjacent the cathode 2, carries three elongated target-assemblies 7 that are symmetrically spaced from one another about the axis 3 and each have a length of some sixteen inches and a width of some five inches. The target-assemblies 7 extend parallel to the axis 3 between the plate 5 and a metal ring 8 that is supported adjacent the anode 1 by three glass-insulated rods 9 extending from the plate 5.

The ceramic substrates 10 are loaded in the enclosure 4 on three elongated carriers 11 that each accommodate twenty substrates 10 in two columns of ten and with the faces to be coated exposed. The three carriers 11 are positioned in the spaces between the target-assemblies 7 with the substrates 10 facing inwards and the columns extending substantially parallel to the axis 3. Each carrier 11 is hung on a pair of hooks 12 carried by the ring 8, so as to facilitate loading.

Each target-assembly 7 has two elongated sheet-metal targets 15 and 16, of nickel-chromium alloy and copper respectively, that are insulated electrically from one another by glass. The two targets 15 and 16 are mounted back to back for rotation with one another on a shaft 17 parallel to the axis. The shafts 17 of the three assemblies 7 are interconnected by a chain-drive mechanism 13 (FIG. 4) so that they rotate together from the positions (shown in FIGS. 1 and 2) in which the targets 15 all face inwards, to the positions (shown in FIG. 4) in which the targets 16 all face inwards. Drive for this rotation is obtained from an electric motor (not shown) coupled to the chain-drive mechanism 13 and energized when desired, from outside the enclosure 4. Electrical connection to the inward-facing target 15 or 16 of each assembly 7 is made via a respective one of three spring-contacts 18 (FIG. 4) mounted on the plate 5.

The windings of two toroidal electromagnets 19 and 20 encircle the enclosure 4 adjacent the plate 5 and ring 8 respectively, and the whole is embraced by an aluminium framework 21. The framework 21 comprises two aluminium end-pieces 22 and 23 that are of hexagonal form and encircle the enclosure 4 adjacent the magnets 19 and 20 respectively, and six aluminium rods 24 that inter-

connect the end-pieces 22 and 23 and carry respective toroidal windings 25. The windings 25 are inductively coupled to the closed electrical paths provided by the aluminium framework 21; these paths extend lengthwise of the rods 24 to constitute single-turn secondaries coupled to the windings 25 and adapted to provide a magnetic field acting transversely, and substantially normally, to the electron-beam path along the axis 3.

In operation of the apparatus, the substrates 10 are first loaded on the carriers 11, and the loaded carriers 11 hung on the hooks 12 within the enclosure 4. The enclosure 4 is then sealed and pumped down to a pressure of 2×10^{-6} torr by means of a pump (not shown). Argon gas is then admitted through a valve (not shown), spaced in the enclosure 4 from the vent to the pump, so as to sweep through the enclosure 4 (with the pump still running) to increase the pressure to 3×10^{-3} torr. Under these conditions voltage is applied between the anode 1 and cathode 2 sufficient to strike an arc between them and ensure a clean argon atmosphere within the enclosure 4. No voltage is applied between the cathode 2 and target-assemblies 7 at this time so that ionic bombardment does not take place.

At the end of the cleaning-up process the supply of argon is reduced so that the pressure within the enclosure 4 is thereby reduced to between 8×10^{-4} and 5×10^{-4} torr. The six windings 25 are energized at this time with alternating electric current having a frequency of fifty cycles per second and supplied from a three-phase source, so that the single-turn secondaries provided by the aluminium framework 21 produce a radially-directed magnetic field that rotates about the axis 3.

During sputtering the rotating magnetic field is maintained, and direct current is supplied to each of the electromagnets 19 and 20. Initially the target-assemblies 7 are positioned with the targets 15 facing inwards, the targets 15 at this time being maintained, via the contacts 18, at a substantial negative potential with respect to the cathode 2. The anode 1 is maintained at a positive potential with respect to the cathode 2 to set up a plasma-column extending the length of the target-assemblies 7 and the substrate-carriers 11. The currents supplied to energize the magnets 19 and 20 and the coils 25 are adjusted to produce a plasma-column that is of a substantially uniform cylindrical appearance throughout its length with a diameter of some six inches (this adjustment may be made in accordance with prior observations carried out using the apparatus without the target-assemblies 7 and carriers 11). The electromagnets 19 and 20 act to set up an axial magnetic field that provides a measure of focussing of the electron beam from the cathode 2; the electromagnet 20 in this respect appears also to exert a stabilizing effect on the plasma-column.

Once the required deposition of the nickel-chromium alloy of the target 15 has been achieved, drive is applied to the chain-drive mechanism 13 to rotate the target-assemblies 7 to the positions in which the targets 16, rather than the targets 15, face inwards. This automatically transfers to the targets 16 electrical connection via the contacts 18, so that deposition of copper now takes place.

After deposition of the copper film the electrical supplies to the system are switched off and the enclosure 4 is returned to ambient air-pressure. The carriers 11 are then unhooked from the hooks 12 and the coated substrates 10 removed. The substrates 10 are subsequently submitted to an ageing process at a temperature of some one-hundred-and-fifty degrees centigrade.

It has been found with the above method that variation in film thickness across the surface of any one substrate 10 of a batch does not exceed 5%, and it is suspected that much of any variation found arises from surface variation of the substrate 10 itself. Very little variation in thickness of deposited film is also found between one substrate 10 and another in the batch. Between substrates spaced from one another lengthwise of the axis 3, there is a tendency

for the one nearest the cathode 2 to have a thicker film-deposit. With the present apparatus the targets 15 are built up away from the cathode 2 with sheet-metal elements 26 of the nickel-chromium alloy, in an attempt to counteract this tendency. The tendency is, however, to a large extent counteracted by the use of the rotating magnetic field, and it may be found that the combination of the built-up targets 15 with the use of the rotating magnetic field, results in a measure of over-compensation as far as the deposition of the film of nickel-chromium alloy is concerned.

With the method and apparatus described above, very satisfactory and accurately-reproducible results have been achieved using anode- and target-currents of five and 0.5 ampere respectively, the anode 1 and targets 15 or 16 being maintained at potentials with respect to the cathode 2 of seventy-five volts positive and eight-hundred volts negative respectively. The ampere-turns used for the electromagnets 19 and 20 are respectively six-hundred and seventy-five, whereas those for the windings 25 are two-hundred. The deposition of the film of nickel-chromium alloy takes some six to seven minutes, whereas that of copper takes some thirty minutes.

The present invention is applicable to the deposition of electrically non-conductive materials as well as to the deposition of electrically conductive materials. Furthermore, attraction of the ions from the plasma to the target may be effected by means of an alternating electric field (for example of radio-frequency), this technique being applicable especially to those circumstances in which electrically non-conductive materials are to be deposited.

We claim:

1. In a method of sputtering of material by ionic bombardment of a target from a plasma created using a beam of electrons in a gaseous atmosphere, the step of applying a magnetic field to act transversely of the path of the electron beam and to change in angular direction continually about the electron-beam path during said bombardment.

2. A method according to claim 1 including the step of applying another magnetic field to act lengthwise of the electron-beam path.

3. A method according to claim 2 wherein the magnitudes of the two magnetic fields are selected to result together in a plasma-column that is of a substantially uniform cylindrical appearance throughout its length.

4. A method according to claim 1 wherein the gaseous atmosphere has a pressure between 8×10^{-4} and 5×10^{-4} torr.

5. A method according to claim 4 wherein the gaseous atmosphere is of argon.

6. A method according to claim 1 wherein the applied magnetic field is a magnetic field that rotates about the electron-beam path.

7. A method according to claim 1 wherein the magnetic field is applied to act substantially normally to the electron-beam path.

8. A method according to claim 1 wherein a plurality of targets are used, and wherein the targets are spaced laterally from the electron-beam path with substrates upon which deposition of the sputtered material is to take place located between them.

9. A method of manufacturing an electrical device, comprising the step of sputter-deposition of metallic film on an electrically-insulative substrate, and a subsequent step of forming electrically-resistive elements of the device by selective removal of parts of the film, the step of sputter-deposition of the metal film on the substrate comprising positioning said substrate adjacent a metal target within an air-tight enclosure, establishing a gaseous atmosphere of reduced pressure within said enclosure, discharging a beam of electrons in said atmosphere to establish a plasma within said enclosure, attracting ions from said plasma to bombard said target, and applying a magnetic field to act transversely of said electron beam and to

vary in angular direction continually about the electron beam path during the bombardment of the target.

10. A method according to claim 9 wherein the material of said target is a nickel-chromium alloy.

11. A method according to claim 9 wherein two films of differing metals are deposited one upon the other on said substrate and both by sputter-deposition, and wherein the substrate is submitted after deposition of both films to two etching processes in succession, a first of the two etching processes providing circuit interconnections of the device from the uppermost of the two films, and the second of the two etching processes providing said electrically-resistive elements from the lowermost film where this is exposed through the uppermost film.

12. A method of sputter-deposition of material on a substrate, comprising the step of positioning the substrate adjacent a target of said material within an air-tight enclosure, the step of establishing a gaseous atmosphere of reduced pressure within said enclosure, the step of discharging a beam of electrons in said atmosphere to establish a plasma within said enclosure, the path of the electrons being displaced from said substrate and target, the step of attracting ions from said plasma to bombard said target, and the step of applying a magnetic field to act substantially normally of said electron-beam path and to rotate relative thereto.

13. In apparatus for sputtering of material by ionic bombardment of a target from a plasma created using a beam of electrons in a gaseous atmosphere, means for applying a magnetic field to act transversely of the path of the electron beam and to vary in angular direction continually about the electron beam path during said bombardment.

14. Apparatus according to claim 13 wherein said means is means for applying a magnetic field to rotate about the electron-beam path.

15. Apparatus according to claim 14 wherein said means is electrical means that is energizable from a three-phase electrical supply to provide a magnetic field that rotates about the electron-beam path.

16. Apparatus according to claim 13 wherein the applied magnetic field acts substantially normally to the electron-beam path.

17. Apparatus according to claim 13 including a plurality of targets spaced from one another around said electron-beam path, and means for mounting substrates upon which deposition of the sputtered material is to take place in positions between the targets around said path.

18. Apparatus for sputter-deposition of material on a plurality of substrates, comprising an air-tight enclosure, an anode within said enclosure, a cathode within said enclosure for emitting electrons along a predetermined path towards said anode, a plurality of elongated target-assemblies for carrying targets of said material, means within said enclosure for mounting said target-assemblies spaced from one another around said path and extending lengthwise thereof within said enclosure, a plurality of carriers for carrying the substrates within said enclosure, means for mounting said substrate-carriers around said path in positions between the target-assemblies, and electromagnetic means mounted externally of said enclosure, said electromagnetic means being means that is energizable to provide a magnetic field acting within said enclosure substantially normally of said path and rotating relative thereto.

19. Apparatus according to claim 18 wherein each target-assembly carries a set of targets of different materials mounted to face in differing directions from the respective target-assembly, and wherein said means mounting the target-assemblies within said enclosure is rotatable means that is operable to bring any selected one of the set of targets carried by each individual target-assembly to face inwardly towards said path.

20. Apparatus according to claim 18 wherein a toroidal

electromagnet encircles the enclosure adjacent the cathode.

21. Apparatus according to claim 20 wherein a second toroidal electromagnet encircles the enclosure adjacent the anode.:

22. Apparatus according to claim 18 wherein said electromagnetic means comprises two metal end-pieces that encircle said enclosure at positions spaced apart lengthwise of said path, metal members interconnecting the two end-pieces at positions spaced apart around said path, and toroidal electrical windings carried by said metal members respectively.

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