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Magnetron sputtering on large scale substrates: an overview on the state of the art

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Abstract

In the last 15 years sputter deposition of thin films on large area substrates has enjoyed a steady growth. On the one hand, sputtering is gaining more and more market share in applications that in earlier times have been dominated by evaporation techniques. On the other hand, completely new markets have grown, which would not have been realized without the existence of sputtering (e.g. microelectronics, flat panel displays). Some of the reasons for this development are:

(1) the ability to deposit all kinds of metals including high-melting metals, binary, ternary and multicomponent alloys and compounds with precise control of film composition and structure;
(2) the ability to deposit metal oxides, metal nitrides, metal carbides, etc. with precise control of the layer stoichiometry;
(3) the extremely high thickness uniformity of Δd, less than 2%, that can be realized for example for glass panes of 3.2×6 m size.

In the late 1980's and the beginning of the 1990's, a handful of basically different approaches have been made in order to enhance further the performance of sputter magnetrons for large scale applications.

This paper gives an overview of the state of the art of magnetron sputtering for large scale applications, covering the well-proven conventional planar magnetron, as well as those solutions that have grown in the last few years and right now are themselves on the point of being state of the art. © 1997 Elsevier Science S.A.

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1. Introduction

1.1. Development of magnetron sputtering technology

In 1935 F.M. Penning proposed to enhance the plasma density of a glow discharge by means of a magnetic field [1]. Then it took nearly 40 years until the planar magnetron with a closed loop tunnel of magnetic field lines was invented by J.S. Chapin in 1974 [2]. Only half a decade later, in the early 1980s, magnetron sputtering technology had already been scaled up to a substrate width of 3 m. The further development in the 1980s was characterized by incremental improvements such as optimization of the shape of the magnetic field and the development of power supplies with higher throughput and better stability.

In the late 1980s and early 1990s a handful of basically new magnetron systems have been developed, which created a quantum leap in deposition rate and process stability (see Sections 4 and 5).

1.2. Advantages of magnetron sputtering

The deposition rates, achievable with magnetron sputter cathodes are typically one order of magnitude lower than the deposition rates of thermal evaporation (max. 100 nm/s for sputtering of aluminum, typically 1000 nm/s for aluminum evaporation). Nevertheless, sputter deposition of thin films on large area substrates has enjoyed a steady growth over the last 15 years. This is due to the following major advantages of magnetron sputtering:

(1) High thickness uniformity ($\Delta d \leq 2\%$) for coating width ≥ 3 m.
(2) High stability of deposition rate and layer properties for >100 h uninterrupted production.
(3) Good reproducibility of layer properties from day to day and from month to month.
(4) Good adhesion and high density of deposited film.
(5) Ability to deposit all kinds of metals including high melting point metals, metal alloys and compounds with precise control on film composition.
(6) Ability to deposit metal oxides, nitrides, carbides, etc. with precise control of layer stoichiometry.

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2. The basics of magnetron sputtering

A lot of books are covering the topic of magnetron sputtering with great comprehensiveness. Among the most helpful ones are the books of Vossen and Kern [3], Wasa and Hayakawa [4], Bunshah [5], Chapman [6] and Chen [7]. In this section we will only have a very brief look into the basics of magnetron sputtering.

Sputtering is playing billiards on an atomic scale. Positive ions of a glow discharge are accelerated towards the "target" and by momentum transfer via a collision cascade, neutral target atoms are ejected (Figs. 1 and 2). The deposition rate of a sputter process is proportional to the current and is proportional to the discharge voltage as well:

Deposition rate = const. · U · I

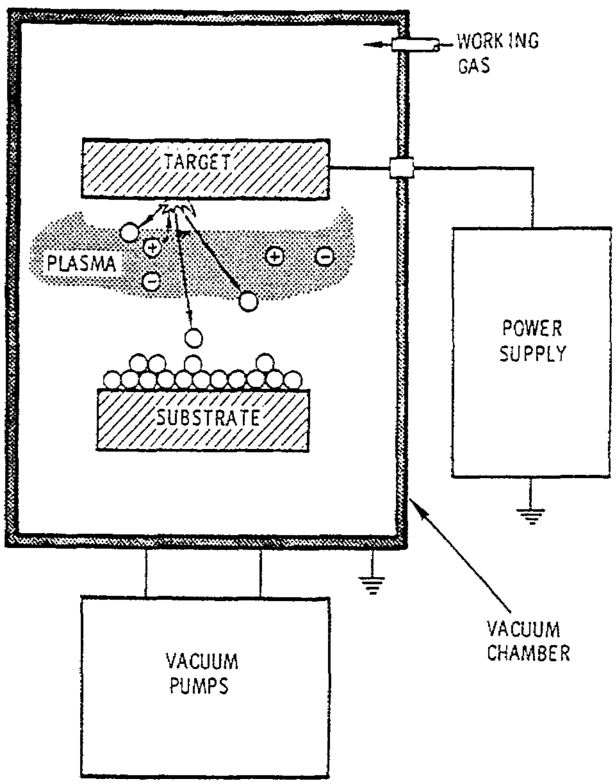

Fig. 1. Schematic representation of a parallel-plate diode sputtering system, Ref. [5], p. 251.

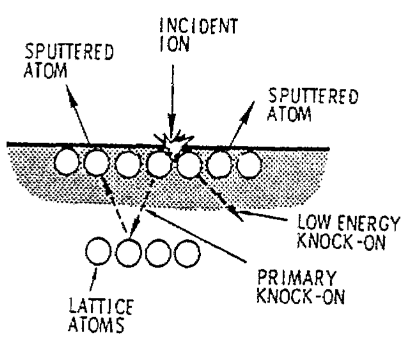

Fig. 2. Schematic diagram showing momentum exchange processes that occur during sputtering, Ref. [5], p. 264.

As the discharge characteristic of a "diode" has a very high steepness (Fig. 3), the achievable deposition rate is limited by high-voltage problems. The necessary insulation distance in an ambient atmosphere is growing to impractical values for voltages above 1 kV.

In a magnetron cathode the plasma electrons are confined by a magnetic field. This results in a higher charge carrier density in the plasma, which in turn results in a lower discharge voltage. Three rows of permanent magnets with alternating polarity, which are positioned behind the target, create tunnel-like lines of magnetic field (Fig. 4). By closing the tunnel of magnetic field lines as indicated in the upper part of Fig. 4, an endless tunnel of magnetic field lines is created. This ensures a very effective plasma confinement, resulting in a small increase in the discharge voltage over a wide range of discharge current. Hence the deposition rate of a magnetron cathode can be raised by increasing the discharge current at moderate discharge voltages of typically 400–800 V.

3. The workhorse: the rectangular planar magnetron

3.1. Mechanical and electrical set-up

3.1.1. Cathode

Three rows of permanent magnets with alternating polarity are either mounted inside a housing of soft iron (Fig. 5) or inside a non-ferromagnetic housing, which is surrounded by a dark space shielding. The cathode width typically is 10 to 30 cm. The cathode length ranges between 0.5 and 3.5 m. The target is mounted in good thermal contact to the backing plate by screwing, clamping or soldering. The backing plate in turn is in good thermal contact to a — preferably closed — water cooling circuit.

3.1.2. Anode

Either the whole vacuum chamber is used as anode (see Fig. 1) or the anode is built of metal rods or metal bars, which are positioned near to the cathode (Fig. 5).

3.1.3. D.C. power supply

The D.C. power supplies typically cover the voltage range from 0 to 1000 V and can provide between 5 and 120 kW, depending on the application.

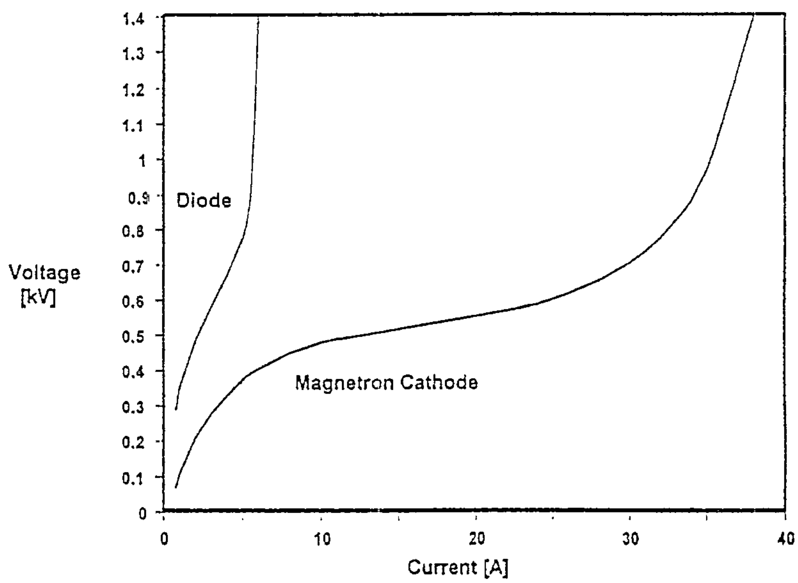

Fig. 3. Discharge characteristics of a diode and of a D.C. magnetron

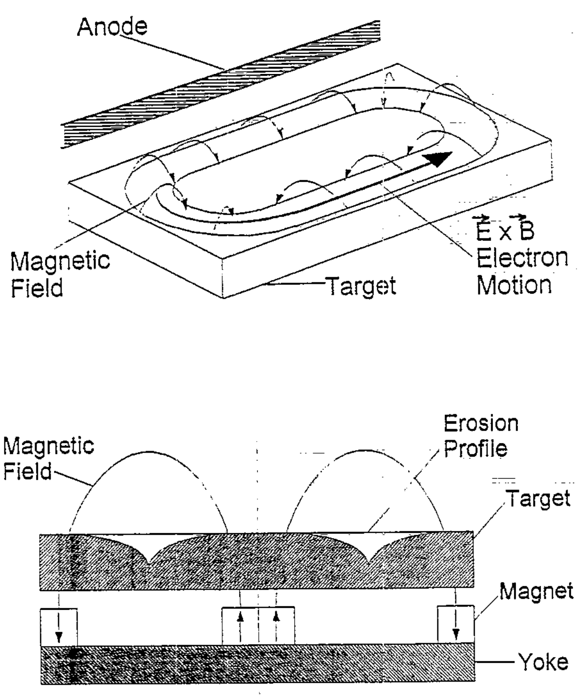

Fig. 4. Schematic view of a rectangular planar magnetron.

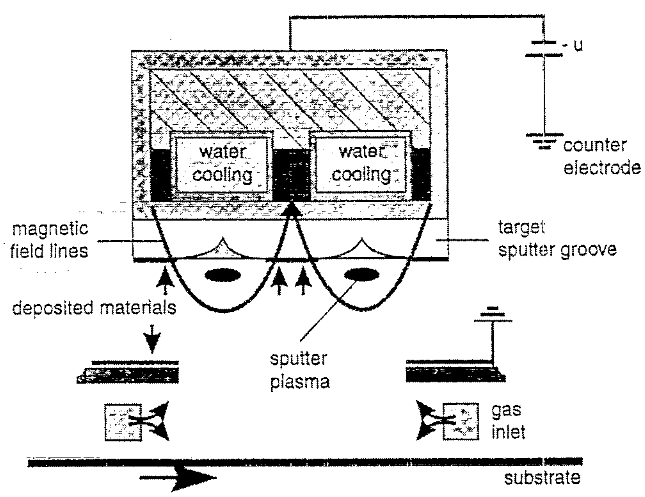

Fig. 5. Cross-sectional view of a sputter chamber.

3.2. Performance data and limitations

Target thickness: Typically 10–20 mm
Limitation: magnetic field decreases with increasing target thickness
Target utilization: Typically 20–25%
Limitation: concentration of plasma by nonuniform magnetic field
Target—substrate distance: Typically 100–140 mm
Deposition rate for metals: depends on material
Limitation: heat load of target in the race track area

Deposition rate for reactive processes: the dynamic deposition rate is expressed in the unit "nm*m/min". This is the layer thickness, measured in nm, with which the substrate is coated, when it passes the magnetron with a velocity of 1 m/min. The static deposition rate is the rate of film growth, measured in nm/s, when the substrate is fixed in front of the magnetron.
SnO_2:
Dynamic rate = 35 nm*m/min. Static rate = 2.1 nm/s.
Limitation: longterm stability decreases with increasing power: arcing
SiO_2:
Dynamic rate = 10 nm*m/min. Static rate = 0.6 nm/s
Limitation: Arcing
Uninterrupted production:
SnO_2: $\leq$ 100 h
Limitation: arcing due to coverage of target rims with

nonconductive layers; plasma instability (flickering of U and I) due to coverage of the anode surface with nonconductive layers ("Disappearing Anode").

4. High rate magnetron for metal layers: interpoles target—hollow magnetron (IPT—HM)

4.1. Features

The IPT—HM [8], which has been developed by Leybold AG, has a race-track shaped target (Fig. 6). The permanent magnets are positioned aside the target instead of behind the target. Pole pieces on top of the permanent magnets create lines of magnetic field with a very low curvature. This allows the plasma to spread all over the target surface. Protruding target rims electrostatically confine the plasma in the direction parallel to the magnetic field. Because of the very wide plasma zone the IPT—hollow magnetron can handle enormously high discharge power. Because of the special design of the magnetic field, very thick targets can be treated with extremely good target utilization (Fig. 7).

4.2. Performance data and limitations:

Target materials: All metals and metal alloys e.g. Cu, Al, Cr
Target thickness: ≥28 mm
Target width: Up to 320 mm
Target utilization: 55–64%
Max. power density: ≥200 W cm^{-2} (for Cu)

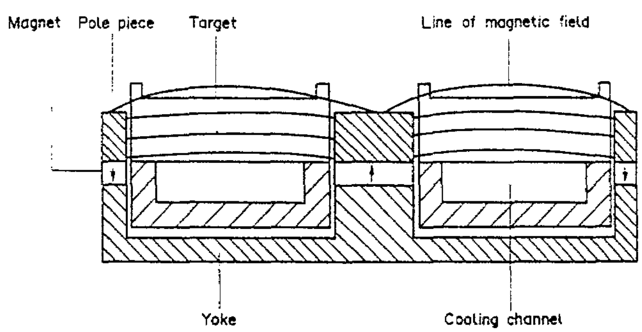

Fig. 6. Interpoles target—hollow magnetron (IPT—HM).

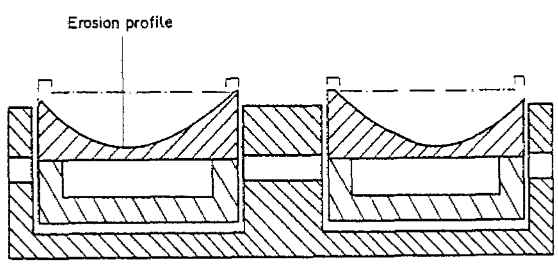

Fig. 7. Erosion profile of IPT—HM. Target utilization = 64%.

Max. deposition rate: 3360 nm*m/min = 200 nm/s for Cu
Max. deposition rate for Cu on web (22 μm polyester): 950 nm*m/min = 57 nm/s
Limitation: thermal damage of substrate

5. High rate magnetrons for metallic and reactive sputtering

5.1. Electromagnetically moved plasma zone: "SpeedMag"

5.1.1. Features

The SpeedMag [9], which has been developed by Leybold AG, is an interpoles target magnetron (IPT) with a planar target and an additional electromagnetic coil on the circumference (Fig. 8). By feeding the coil with a time-dependent current, the constant magnetic field of the permanent magnet is superposed by a time-dependent magnetic field of the coil. This results in a cyclical movement of the plasma zone on the target surface. The benefits are enhanced target utilization and more stability in reactive sputtering, due to the fact that wide zones of redeposition are avoided.

5.1.2. Performance data and limitations

Target thickness: 6–20 mm
Target width: 200 mm
Target utilization: 40–50%
Max. deposition rate for Cr:130 nm*m/min = 7.8 nm/s
Ni:115 nm*m/min = 6.9 nm/s
SnO_2:100 nm*m/min = 6.0 nm/s
TiO_2:30 nm*m/min = 1.8 nm/s
Limitation: long-term stability is limited by redeposition of dielectric films on the target rims and by "disappearing anode".

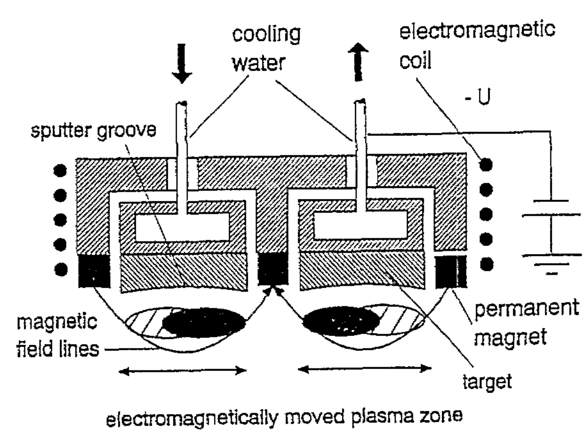

Fig. 8. Cross-sectional view of the special electromatically enhanced magnetron (SpeedMag) cathode with two different positions of the moving plasma zone indicated by full and shaded areas.

5.2. *Cylindrical rotatable magnetron: "C-Mag"*

5.2.1. *Features*

The C-Mag has been introduced by Airco coating technology [10,11]. It has a tubular target which is

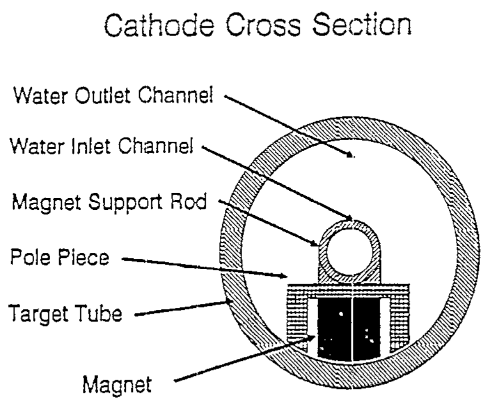

Fig. 9. Cross-symmetry of C-Mag cathode, Ref. [11], p. 251.

rotating around its axis of symmetry (Fig. 9). A stationary set of permanent magnets inside the target tube produces the same closed loop magnetic tunnel as in planar magnetrons. By keeping the magnet arrangement stationary and rotating the target tube, a very high degree of target utilization is achieved.

5.2.2. *Performance data and limitations*

Target materials: Metals, alloys, Si,···
Limitation: The target has to be manufactured as tube or has to be plasma sprayed onto a supporting tube.
Target utilization: 80%!
Deposition rate: High!
Process stability: Limited
Limitations:
Mechanical stability for 3.5 m target length is critical.
The redeposition problem is solved only on the straight part of the race track, not solved at the ends of the tubular target.
The long-term stability is limited due to the still-existing problem of the "disappearing anode".

5.3. *Dual magnetron sputtering "DMS" and "TwinMag"*

Independent from each other, the Fraunhofer Institut für Elektronenstrahl- und Plasmatechnik (FhG-FEP) in Germany developed an arrangement called "dual magnetron sputtering DMS" [12] and Leybold AG in Germany developed a system named "Twin-Mag" [13].

5.3.1. *Features*

Two planar magnetrons are installed side by side (Fig. 10). A medium-frequency power supply is connected to the two magnetrons in the following manner: In one halfwave one magnetron is the "cathode", the other magnetron is the "anode". In the next halfwave the polarity is changed so that cathode and anode function are changed as well. By the changing of cathode and anode function with a frequency of some 10 kHz the problem of the disappearing anode is solved.

5.3.2. *Performance data and limitations*

Target thickness: 12 mm
Target utilization: 28%
Deposition rate for SiO_2: 40–60 nm*m/min!
Deposition uniformity: $\leq \pm 1.5\%$
Uninterrupted production with deposition rate of 40 nm*m/min for SiO_2: ≥ 300 h!
Limitation: End of target lifetime

6. Summary and conclusions

The 20-year-old rectangular planar magnetron with up to 3.5 m length is still the workhorse for industrial sputter deposition of large area coatings. But the requirements concerning deposition rate, coating costs and process stabilitv are growing more and more; and the performance of the planar magnetron is limited with

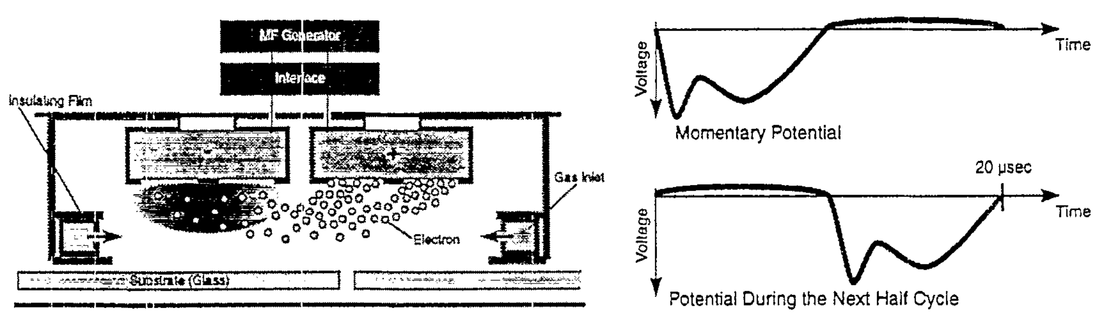

Fig. 10. Operating principle of the TwinMag.

regard to the following items: limited target thickness, target utilization and target lifetime. The deposition rate is limited due to overheating of the target and due to deposition of dielectric films on the target rims which cause arcing. The long term stability is limited due to deposition of dielectric films on the anode ("disappearing anode").

There are very powerful magnetron tools available today, called interpoles target magnetron, SpeedMag, C-Mag and TwinMag. Each of them can overcome some of these limitations. The remaining challenge for the researchers in the field of magnetron sputtering is to develop a magnetron tool that overcomes all of these limitations in one system.

The present work in the field of reactive sputtering seems to concentrate on the improvements of the dual magnetron sputtering and TwinMag systems. On the one hand, these systems have to be qualified for all kinds of reactively sputtered layers, like SnO_2 ZnO, TiO_2. On the other hand, their economic performance has to be optimized. This means that the useable target thickness and the degree of target utilization have to be increased and the investment costs for the hardware have to be decreased. There is a very good chance of reaching these ambitious goals in the near future.

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