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MAGNETRON SPUTTERING

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Sputtering, once no more than a scientific curiosity, is increasingly widely used to produce thin coatings. Magnetron sputtering, in particular, shows how the application of simple physical principles has led to a successful commercial technology.

There are several physical vapour deposition methods for producing coatings in a vacuum environment and these can be separated into two main groups: (i) those involving thermal evaporation techniques, where material is heated in vacuum until its vapour pressure is greater than the ambient pressure, and (ii) those involving ionic sputtering methods, where high-energy ions strike a solid and knock off atoms from the surface. Ionic sputtering techniques include diode sputtering, ion-beam sputtering and magnetron sputtering.

We are specifically concerned here with cathodic sputtering techniques where the ions are derived from a plasma in a low-pressure gas between two electrodes. Sputtering as a phenomenon was first observed back in the 1850s but remained a scientific curiosity until around the 1940s when diode sputtering was first used to any significant extent as a commercial coating process.

However, diode sputtering suffers from very low deposition rates and in many applications was too slow to make the process economic and was only used in applications where the special benefits of sputtered films were justified. Then in the mid-1970s a magnetically enhanced variant of diode sputtering emerged and this became known as magnetron sputtering.

Magnetron sputtering is a high-rate vacuum coating technique for depositing metals, alloys and compounds onto a wide range of materials with thicknesses up to about 5 μm. It exhibits several important advantages over other vacuum coating techniques and this has led to the development of a number of commercial applications ranging from microelectronics fabrication through to simple decorative coatings.

This article describes the sputtering process, and in particular the magnetron version: how it is achieved, its technological benefits and how the application of simple physical principles has led to a successful commercial process. The discussion begins with the special advantages of magnetron sputtering and is followed by a description of the basic diode sputtering process, progressing to a description of the development of the magnetron principle.

Why magnetron sputtering?

Magnetron sputtering has emerged to complement other vacuum coating techniques such as thermal evaporation and electron-beam evaporation. However these techniques show certain disadvantages. In particular, alloys and refractory metals cause problems because of differences in alloy constituent vapour pressures and their high melting points (the need to run sources very hot thereby affecting your coated articles). In addition compounds can dissociate into their chemical constituents at the low evaporation pressures used. Magnetron sputtering overcomes these problems and has many other advantages.

The primary advantages are (1) high deposition rates, (2) ease of sputtering any metal, alloy or compound, (3) high-purity films, (4) extremely high adhesion of films, (5) excellent coverage of steps and small features, (6) ability to coat heat-sensitive substrates, (7) ease of automation, and (8) excellent uniformity on large-area substrates, e.g. architectural glass. These points will be discussed later but it

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is immediately clear that sputtering is a very powerful technique which can be used in a wide range of applications.

What is sputtering?

Several terms may be met describing the sputtering process – cathodic sputtering, diode sputtering, RF or DC sputtering, ion-beam sputtering, reactive sputtering – but all these are variants of the same physical phenomenon. Sputtering is the process whereby atoms or molecules of a material are ejected from a target by the bombardment of high-energy particles. More significantly, cathodic sputtering is the process discussed here and in this case the bombardment is by positive ions derived from an electrical discharge in a gas. Material is ejected from the target in such a way as to obtain usable quantities of material which can be coated directly onto substrates.

To obtain sputtering as a useful coating process a number of criteria must be met. Firstly, ions of sufficient energy must be created and directed towards the surface of a target to eject atoms from the material (figure 1). Secondly, ejected atoms must be able to move freely towards the object to be coated with little impedance to their movement. This is why sputter coating is a vacuum process: low pressures are required (i) to maintain high ion energies and (ii) to prevent too many atom–gas collisions after ejection from the target. The concept of mean free path (MFP) is useful here. This is the average distance that atoms can travel without colliding with another gas atom.

Figure 2 shows how MFP varies with pressure and it can be seen that in order to obtain relatively unimpeded travel through a gas it is necessary to operate at pressures of 1 Pa (10^{-2} mbar) or better. Above this pressure material undergoes many gas collisions and deposition rates are very low. Material can also be deflected straight back onto the target and this reduces deposition rates further. Unfortunately the need to operate at low pressure contrasts with the process required to produce the bombarding ions, namely that of plasma generation.

All cathodic processes require a plasma or glow discharge in order to work. The plasma may be generated by DC or RF power. The simplest system uses DC which will now be described (RF systems will be described later). Figure 3 shows the typical behaviour of conduction of electricity in a gas at low pressure. Region A is the regime required for sputtering: here current densities are sufficiently high ($\sim$1 mA cm^{-2}) to make sputtering useful. This situation can relatively easily degenerate into an arc where voltage drops to very low values and the current density rises rapidly. Sputtering power supplies must be specially designed to cope with this eventuality.

Considering a plasma in a low-pressure gas (figure 4) we find the tube appears to be divided into several regions. The main regions of interest for sputtering use are the cathode dark space and the positive glow. During stable conduction conditions electrons are emitted from the cathode. These are accelerated towards the positive electrode and when they have sufficient energy to ionise the gas molecules a glow appears characteristic of energy-level transitions in that gas. The positive gas ions formed then move towards the cathode and impinge on its surface. As a result of ion impact, secondary electrons and sputtered atoms are created. The electrons lead to further gas ionisation and atoms are sputtered away from the surface.

As the accelerated electrons soon lose their energy in ionising collisions most of the applied voltage in a sputtering system appears across the cathode dark space. If the anode is moved closer to the

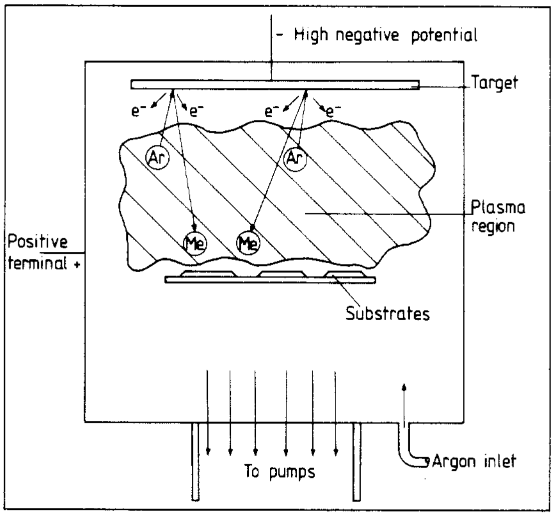
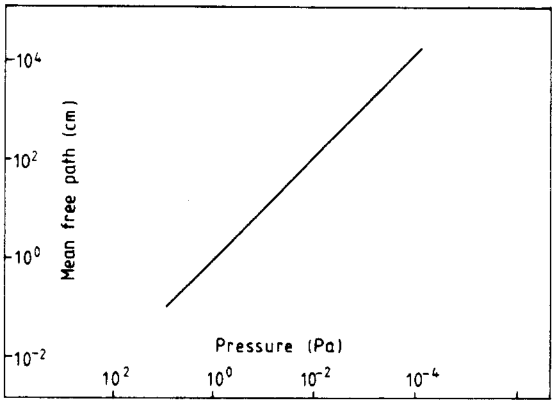
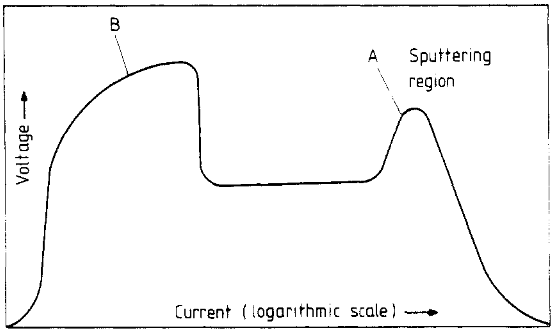


Figure 1. Schematic diagram of DC diode sputtering process chamber.

Figure 2. Typical variation of mean free path with pressure.





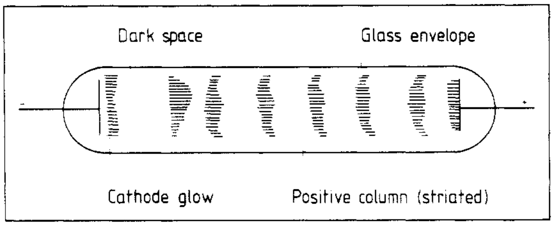


Figure 4. Characteristic appearance of a glow discharge.

Figure 3. Voltage–current characteristics of low-pressure gas.

cathode until it reaches the dark space the plasma extinguishes, ions cease to be produced and sputtering stops. This phenomenon is put to good use in sputtering systems to prevent unwanted sputtering of components held at high voltage, e.g. the electrical connections to the target.

As gas pressure is decreased with a glow discharge the size of the dark space increases due to the larger MFP for electrons, and thus ions are produced far away from the target material where they can be easily lost to chamber walls. Similarly, primary electrons may reach the anode without producing gas ionisation. Therefore the overall ionisation efficiency becomes low. Below approximately 1 Pa the plasma extinguishes and sputtering stops. Unfortunately this happens at pressures where mean free paths are just becoming useful for a coating process.

The solution to this problem is a method of producing more efficient ionisation at these lower pressures and that solution is the magnetron design.

Magnetron source

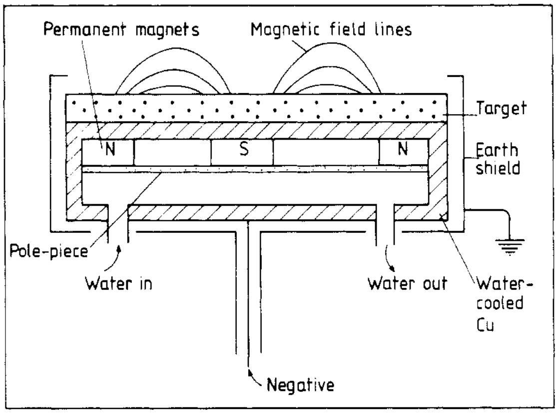
The magnetron uses the principle of applying a specially shaped magnetic field to a diode sputtering target. The principle is that the cathode surface is immersed in a magnetic field such that electron traps are created so that $\boldsymbol{E} \times \boldsymbol{B}$ drift currents close in on themselves. The principle was discovered as far back as the 1930s by Penning but has only been used in the magnetron coating context for about fifteen years.

In essence the operation of a magnetron source relies on the fact that primary and secondary electrons are trapped in a localised region close to the cathode into an endless 'racetrack'. In this manner their chance of experiencing an ionising collision with a gas atom is vastly increased and so the ionisation efficiency is increased too. This causes the impedance of the plasma to drop and the magnetron source operates at much lower voltages than diode systems (500–600 V as compared with several kV). This greater ionisation efficiency leads directly to an increase in ion current density onto the target which is proportional to the erosion rate of the target.

There are several types of magnetron design possible, including post magnetrons, planar magnetrons, S guns etc, but these are only geometric variants of the same physical principle. The common feature is that electron drift is controlled and electrons are trapped. The planar magnetron is a much favoured design because of its physical simplicity and the ability to extend the cathode to virtually any size required. Sources several metres in length can be manufactured. Large cathodes are particularly suited to continuous processing. However, sources are easy to fabricate into circular, rectangular or any complex shape: the only criterion is that an endless racetrack must exist.

It is most straightforward to consider the construction of planar magnetrons. Figure 5 shows a planar magnetron in more detail and figure 6 shows the appearance of three magnetron targets mounted in a vacuum system. Electromagnets or permanent magnets may be used but for simplicity of design permanent magnets are commonly used. These can be of several different possible geometries but the essential feature is that the magnetic field lines form a tunnel shape in front of the target surface. In order to achieve an efficient electron trap, field strengths of a minimum of around 20 mT are used but are frequently much bigger than this.

Figure 5. Simplified schematic diagram of magnetron source.



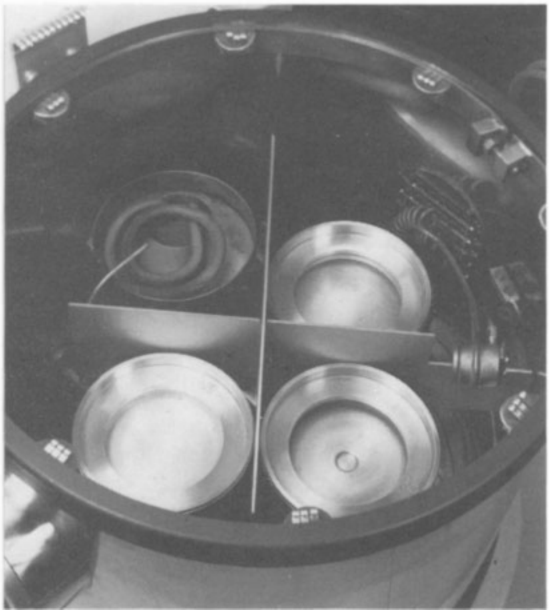


Figure 6. View of three magnetron sources mounted in Edwards ESM100 system.

Figure 7 shows several possible geometries which can be used and the choice will depend on the field strength required and other factors such as efficiency of target utilisation and simplicity of construction. The simplest form of magnet system employs a single high-strength magnet with a ferromagnetic pole-piece to extend the field into the correct shape.

Because the field strength increases the efficiency of electron trapping, high-magnetic-field systems will generally operate at lower pressures, enabling operation well down into the 50 mPa region. Here the process operates with characteristics more like vacuum evaporation, owing to the relatively high mean-free-path length.

Considerations in magnetron design

There are several important features which must be considered in magnetron design. The first is that the cathode must conduct electricity efficiently. In addition a magnetron source is overall inefficient at converting power into sputtered material. Perhaps 80% (or worse) of the power consumed in plasma generation is lost as heat, particularly at the cathode. Cathodes must therefore conduct heat away efficiently and are invariably water cooled to prevent overheating. Cathodes are often constructed of water-cooled solid copper for heat and electricity conduction purposes.

The source must also withstand the pressure differential stresses caused by vacuum operation and, in the case of large magnetrons, quite severe thermal stresses in the target material.

The technological features of considerable interest to the process engineer are the target utilisation, the thickness of target material and film thickness uniformity which may be obtained from the target. All these affect the economics of the process to some degree and can make or break a design.

Target utilisation is defined as

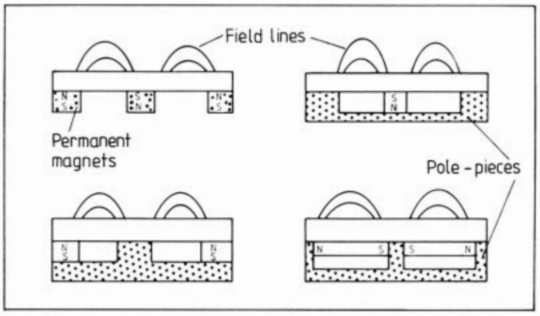
$$\frac{V_o - V_f}{V_o} \times 100\%$$

where V_o is the original volume of the target and V_f is its volume when erosion grooves have just penetrated. In a magnetron design the plasma is localised and concentrated into a region in front of the target. This region has the highest ion current density and it follows that maximum ion bombardment occurs at this point. A characteristic erosion groove is formed as the target wears away (figure 8). Clearly the shape of this groove will determine the target utilisation which can be obtained. The wider this groove is, the better the final utilisation will be. This is of importance where expensive targets are used and also in large machines where dissembly to change targets must occur as infrequently as possible.

The position of maximum erosion corresponds to near $B_v=0$ (when the vertical component of the magnetic field is zero), so the position of this groove can be tailored relatively easily. However, to obtain a wide erosion track it is necessary to have the field lines as parallel to the surface as is practical and yet still maintain an electron trap to prevent loss of electrons at the edge of the target. The simplest magnetic designs are not necessarily the best for this purpose and quite complex systems of magnets and pole-pieces have been devised to improve this behaviour. Some designs have even used moving magnets and variable magnetic fields to increase utilisation. Even so, planar magnetrons seldom have greater than 50% utilisation and figures of 20 to 30% are not uncommon.

Target thickness is significant because for continuous operation on industrial-scale equipment it is necessary to be able to use thick targets to avoid

Figure 7. Examples of possible magnet geometries in planar magnetrons.



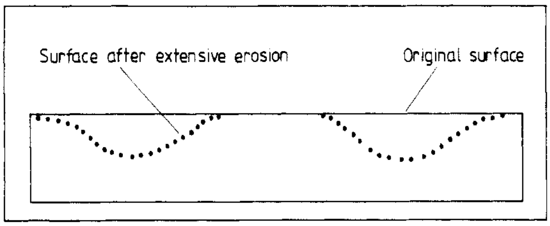


Figure 8. Typical erosion profile of magnetron target (cross section)

changing targets too often. Magnetrons are often operated in load-lock systems where the targets are kept under vacuum at all times in an oxide-free state and this too means that frequent target breakdown to atmosphere is undesirable. It is essential to have a sufficiently strong magnetic field for efficient magnetron operation. As the target becomes thicker the target starts to behave more and more like a diode sputtering source with higher impedance.

Also of major interest to the user is the film thickness uniformity which may be obtained from a source. For a given size of source this will depend on pressure of operation, source–substrate distance, material being sputtered, substrate geometry and motion, and source design. Figure 9 shows the film thickness which can be obtained at several source–substrate distances from the same circular source. The magnetron is acting like a ring source and the best film thickness region will occur at a specific distance. It is of course possible to better this by moving to much larger distances but the trade-off in terms of deposition rate and film purity (due to excessive gas collisions) is too great. Most magnetrons have erosion track widths of a maximum of up to 100mm and so the source–substrate distances used are typically in the region of 30–100mm. This contrasts significantly with evaporative processes where source–substrate distances of 200mm or more are common.

In the case of large rectangular magnetrons the substrates are generally scanned past the targets so the film thickness uniformity is improved by relative motion, and source–substrate distance is less important. Working distances are then dictated by other factors such as heat load to substrates and deposition rate.

Film thickness uniformity may also be improved by using masks which are positioned between the source and the substrate such that some material is intercepted. Masks may be used for static or moving workpieces and can improve distributions significantly.

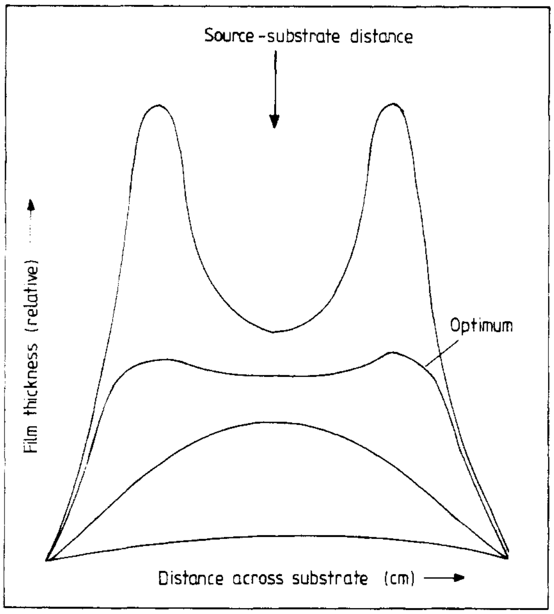
DC magnetron sputtering processes

In the simplest of applications the magnetron is used to deposit metallic materials by DC sputtering. The DC magnetron is the cheapest of magnetron processes because DC power supplies are simpler to manufacture than RF. In the DC mode the target is directly conducting electricity and is subject to I^2R losses and may be operated up to currents of perhaps 70 W cm^{-2} averaged over the target. For 100mm circular magnetrons, power supplies will be capable of delivering up to 5 kW DC into the plasma. This can produce deposition rates on static substrates of several micrometres per minute making this very suitable for high-production-rate processes. The power required is dependent on target size such that large magnetrons may consume up to 50 kW.

Examples of applications are (1) metallising for microelectronic circuits and chip carriers, (2) electrical resistance films, e.g. Ni–Cr for strain gauges, (3) magnetic films (Co, Fe, Co–Pt, Co–Cr, Co–Ni etc) for general magnetic storage devices, floppy discs, tapes and thin-film magnetic heads, (4) opto storage devices, e.g. compact discs and video discs, (5) corrosion-resistant films (Cr–Ni), (6) bonding layers for various purposes, hermetic seals, brazing for leadthroughs, glass fibres, and (7) gas sensors.

In microelectronics fabrication processes sputtering has become the common method of coating because of the ease with which alloys of materials may be processed and because of step coverage. For example it is necessary to produce conductive tracks in direct contact with the silicon wafer and on other layers of SiO_2 and Si_3N_4 formed during the fabrication processes. Sputtering is particularly amenable to producing deposits of about 1µm of aluminium alloy containing a few per cent of silicon or copper.

Figure 9. Variation of film thickness uniformity with source–substrate distance.



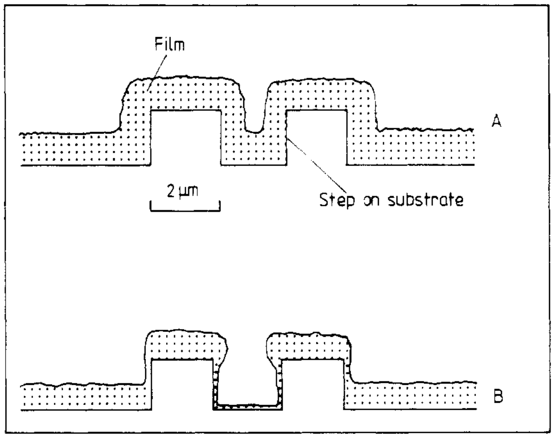


Figure 10. Illustration of step coverage on microcircuit: A, good coverage; B, poor coverage.

This film must have good adhesion, uniformity and 'step coverage'. Step coverage is the ability to coat evenly over microscopic features on the silicon or GaAs wafer (figure 10) which are formed as part of the wafer manufacturing process by photolithographic techniques.

Sputter sources give good coverage by virtue of their source size and because the process is occurring at relatively high pressure where some gaseous diffusional transport of sputtered material occurs. This means that the vapour source does not propagate material in a rectilinear fashion and material has the ability to coat into more difficult geometries without special substrate movement. In electroplating terms the 'throwing power' is considerably enhanced.

Some microelectronic processes use substrate heating and/or biasing to alter the step coverage whilst sputtering. Heating increases the surface diffusion coefficient enabling reorganisation of the growing film and further improvements in step coverage.

Biasing is the application of a voltage to the substrate such that surface bombardment by positive ions occurs on the substrate as well as on the target cathode. This causes resputtering of the depositing layer or at least an increase in surface energy. These effects also control film growth and improve step coverage profile and can eliminate some commonly observed defects such as microcrack formation.

Microelectronics fabrication machines usually employ a load-lock system where wafers are processed either individually by a circular planar magnetron or scanned past rectangular magnetrons in batches. The choice of machine depends on throughput requirements. The load-lock system ensures that the magnetron surface is not continually cycled up to atmospheric pressure giving longer pumpdown cycles and contamination of the target surface by, e.g. oxygen.

Presputtering or 'conditioning' of targets is required when a sputtering target is first pumped down. During this phase oxides and other surface contaminants such as grease are removed from the surface and deposited onto shutters placed between the target and substrate. This conditioning period is required every time a target sees a contaminating reactive atmosphere and the load-lock system reduces or eliminates this requirement such that targets are instantly ready to 'fire'.

In general, DC magnetron sputtering is therefore eminently suitable for microelectronics fabrication processes where compositional control, step coverage, film uniformity and ease of automation are required.

Magnetic films are another important area for magnetron sputtering. Because the magnetron design relies on the presence of a magnetic field in front of the target it is necessary to use very strong fields and/or thinner targets with magnetic materials. If this is not done the plasma impedance increases and the source operates like a diode source.

Magnetic thin films are used predominantly for read/write storage of data for computer equipment. Storage may be by perpendicular recording, longitudinal recording or magneto-optical recording. Perpendicular recording materials such as Co–Cr have a strong perpendicular columnar isotropy which enables high information density and sharp cut-off between adjacent domain regions. Longitudinal materials have high coercivity and in-plane anisotropy. Ni–Co, Co–P, Co–Pt, Co–Au are examples produced by sputtering.

Magneto-optical discs rely on a reversal of magnetisation direction by heating the surface with a laser beam spot. Materials used have included Gd–Fe, Tb–Fe–Co, Dy–Fe and Tb–Fe and there is considerable interest in this field at the moment. Magneto-optics could well be the major method of information storage in the future and sputtering is the favoured process.

A classic example of the amenability of the sputtering process to large-scale production with entirely automatic machines is for optical storage discs. Video and compact discs have a thin layer (up to 70 nm) of aluminium sputtered onto the surface for reflectivity of the laser signal pick-up. This is done typically in-line or in a single-disc-process system. In either case the target is kept under load-lock conditions such that it is immediately ready to 'fire'. A single circular magnetron is a good configuration for coating individual discs but large machines may have rectangular magnetrons with batches of discs scanning past on linear workholders.

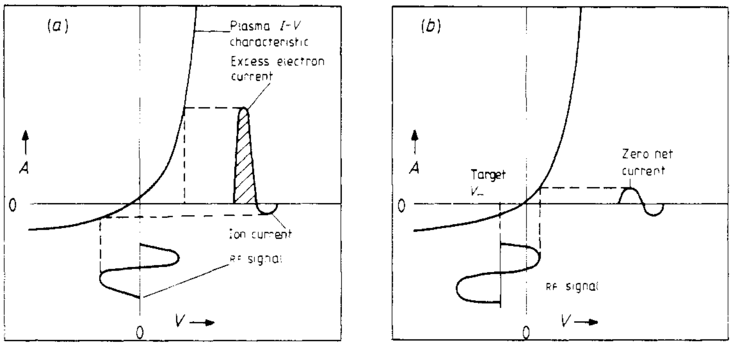


Figure 11. Characteristics of RF plasma (after Butler and Kino 1963); see text below for explanation.

Aluminium has the appropriate high reflectivity of >70% in the required wavelength band of 800–830nm used to detect the optical pits on the disc surface. It also has good adhesion, minimum defect density and economy.

A final example of the use of DC sputtering is for bonding films and other metallurgical films. Sputtered films of Cr, Ti, Ni, Cu and Au have been used successfully to act as a basis for subsequent soldering and brazing treatments onto glass or ceramic substrates. Applications are, for example, bonding of glass fibres into hermetic seals and special electrical leadthrough applications. The sputtered film is particularly suited to this purpose as a result of its very high adhesion to the substrate as compared to evaporative processes. This enables subsequent bonding to be achieved without delamination or interface failure.

DC magnetron sputtering can also be used for general metallurgical films such as corrosion-resistant or decorative coatings and any process where a metallic film is required with good adhesion.

RF magnetron sputtering

DC magnetrons will not work if an insulating target is used, because no current can flow through it. The solution to this problem is to use an alternating current at high frequency. RF sputtering was developed to enable the sputtering of dielectric materials and has the double advantage that it will sputter metals as well.

When RF power is applied to a target it must be capacitively coupled such that a DC sheath potential is able to develop on the surface of the target. At the high frequency typically used for RF sputtering (~13.56 MHz) ions and electrons have vastly different mobilities in the fluctuating field. This means they physically move different distances during each half cycle. The plasma *I–V* characteristics are as shown in figure 11(*a*) where an excess electron current is produced due to this difference in mobility. However in a capacitively coupled system no net charge can be transferred so the electrode biases negatively to compensate (figure 11(*b*)) such that a DC negative voltage is produced on the cathode surface. Because it is capacitively coupled the electrode surface need not be a conductor and can be an insulating material such as a ceramic or polymer.

Because a DC voltage is present, surface ion bombardment still occurs as with DC magnetron sputtering and so it is possible to sputter ceramic or insulating materials as well as metallic materials. However RF sputtering requires an impedance matching network to ensure that the maximum power is absorbed into the plasma. This, plus the higher complexity of RF generators means that RF sputtering equipment is more expensive to purchase than a DC magnetron. Nevertheless RF sputtering is essential for sputtering nonconducting materials so the increased cost is totally justified.

The use of RF sputtering enables virtually any material to be sputtered. Ionic and covalent compounds and even polymers may be sputtered away at rates depending on their particular sputtering yield. There are certain limitations which must be considered however. Firstly dielectric materials are often difficult to fabricate and to obtain large targets can be a problem. Secondly there are certain limitations to sputtering of ceramics. Magnetron sputtering does put a significant heat load on the target surface and owing to the uneven nature of the ion bombardment the heat flow varies across the surface. Many ceramic materials have very low thermal conductivity and coupled with a low intrinsic shock resistance this means that excessive heating causes catastrophic failure. Hence when sputtering ceramics the power levels usually have to be much less than for DC magnetron sputtering.

Power levels of $10\,W\,cm^{-2}$ as opposed to $70\,W\,cm^{-2}$ are a guide to the differences required. The difference is also noted in the sputtering yield which for covalent and ionic compounds is generally much less than for metallic materials. The sputtering yield is defined as the number of atoms ejected from a target surface per incident ion. Dielectrics can have sputtering yields only 10% of metals.

This means that RF sputtering deposition rates for nonconductors are very much lower than for DC magnetron sputtering thanks to power and yield limitations. However sputtering of compounds is still an attractive process and has found favour in many applications. Examples are superconductive films, dielectric films for semiconductors, passivating and insulating films, wear-resistant and hard coatings, dielectric films for optics, polymeric films, transparent conducting films, integrated optic films, solar and energy-related films. The field of coatings which can be applied is so extensive that it is difficult to describe them all. It is however clear that an RF sputtering system will enable the sputtering of both metallic and nonconducting materials which opens up a huge range of possibilities in coating research and production.

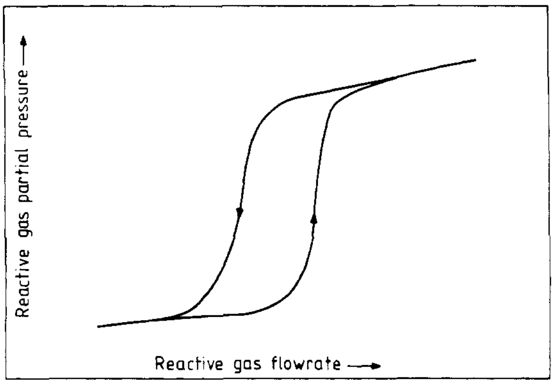
Superconducting materials exhibit a sudden transition to virtually zero resistivity at a characteristic temperature called the critical temperature. Recently huge interest in this field has been produced as reported critical temperatures have 'soared' to above liquid-nitrogen temperatures. Superconducting films such as NbN, Si_3N_4 and mixed oxide compositions can be conveniently prepared by sputtering from fixed composition targets or by using sector-type cathodes to vary composition or by co-sputtering. The preparation of thin films enables layers of the appropriate composition to be prepared for direct placement in a cryostat for resistivity measurements, speeding up the research process. At the moment sputtering is an important research tool in this area.

Wear-resistant coatings can be deposited by RF magnetron sputtering from compound targets or by reactive sputtering (see below). Materials such as WC, Si_3N_4, Al_2O_3, TiN can all be sputtered to give very adherent hard coatings of thicknesses up to several micrometres. Frequently substrates such as tool steels or cemented carbides will be heated during the process to increase surface diffusion. Bias power (RF or DC) onto substrates may also be used to control film properties.

Applications include cutting tools, drills etc, dies and punches, wire guides, tape heads and watch cases. Presently sputtering competes with CVD (chemical vapour deposition) and PECVD (plasma-enhanced CVD) for some of these types of coatings.

Passivating and insulating films and electrical resistance are another major area of application. Films of SiO_2, Al_2O_3, Ta_2O_5 are used in microelectronic fabrication processes and in the fabrication of strain gauges where an insulating sputtered film of SiO_2 or glass separates the resistance element from the base support. Films of Ni–Cr can be sputtered to form highly adherent strain-gauge elements.

Figure. 12. Hysteresis loop in reactive sputtering.



Reactive sputtering

Many of the dielectric materials which can be sputtered by RF from compound targets can also be sputtered by DC magnetron sputtering but in a reactive gas atmosphere. Argon gas is introduced as the carrier gas but small quantities of a second reactive gas are introduced into the chamber. The gas may be any gas which will react with the target atoms to form the desired compound. Oxygen and nitrogen are commonly used but methane, H_2S and other gases may be used so long as the reaction byproducts can be appropriately handled.

The desired compound is formed both at the magnetron surface and at the substrate, depending on power and surface reactivity. By controlling the reactive gas flowrate it is possible to control the stoichiometry of the growing film.

Reactive deposition is a cheaper alternative to RF magnetron sputtering of compounds because DC power supplies are cheaper and target materials are cheaper. The process suffers from one important drawback, namely target 'poisoning'. Figure 12 shows the hysteresis curve obtained when a metal target is sputtered in a reactive gas. As the reactive gas flowrate is increased a sudden transition occurs where the compound forms on the surface of the target. The sputtering rate drops and the partial pressure of reactive gas increases ensuring even further target 'poisoning'.

Frequently the conditions required to obtain a suitable stoichiometric compound on the surface are at the knee of the hysteresis curve and so the process is carried out in an essentially unstable condition. Very careful control of gas flow is thus required and sputtering equipment must often be specially designed for reactive sputtering processes.

The main areas of application of reactive sputtering are hard coatings, wear-resistant coatings, energy-related coatings and transparent conducting films. Hard materials such as TiN are used for wear-resistant applications, such as tools and dies, and decorative coatings such as watch cases where the characteristic gold colour and hardness make an ideal combination of properties. These are often sputtered reactively from titanium targets with N_2–Ar atmosphere. Substrates are often biased to enhance reactivity at the surface and to produce the correct colour of film.

Energy-related coatings such as are applied to architectural glass consist of multilayers of dielectrics such as SnO_2 or ZnO with intermediate Ag or Al layers. SnO_2 is sputtered reactively from large rectangular magnetrons and glass is scanned past the targets to form very even coatings. These low-emissivity coatings are used to increase the thermal efficiency of window glass.

Similarly conducting thin films of In–Sn oxide are produced by reactive sputtering. These transparent films find application in LCD displays, electromagnetic interference (EMI) shielding, heated screens for vehicles and aircraft and in solar collector panels. This is a very large area of use for reactive sputtering.

Commercial magnetron systems

Owing to the flexibility of magnetron design, coating systems can be made to suit specific processes. Magnetron systems are made in widely varying formats from small laboratory research machines (figure 13) through to large architectural-glass coating machines taking up hundreds of square feet of space. This is reflected in the price range which may vary from about £20 000 to £10 000 000. Large systems are invariably specially designed and constructed and are commissioned with specialist staff. Research-scale machines are usually standard products delivered off-the-shelf to customer specifications.

Machines vary considerably depending on the process used. They may be diffusion-pumped, turbo-pumped or cryopumped. They may have multi-gas control systems suitable for reactive sputtering and large systems will usually be controlled and sequenced by vacuum process controllers. These can control all the functions of a vacuum system and cycle the pumps ready for the process. Once the chamber is ready the process sequence can also be controlled by computer with feedback from a rate and thickness monitor. This can sense the rate of deposition and hold it at a predetermined level until the required thickness is obtained.

In this way the sputtering process cycles can be 'one button' operations, enabling unskilled personnel to operate the machines. The operator merely has to load in substances and occasionally change the targets when they erode away. Magnetron sputtering is therefore an ideal process for producing high-quality and reproducible coatings on a commercial scale.

Figure 13. Research-size sputtering unit (Edwards ESM100).

Summary

The advent of magnetron sputtering has opened up a huge area of thin-film coating applications. The great benefits of high deposition rate, excellent adhesion, high-purity deposits and the ability to coat difficult materials have brought magnetron sputtering into a leading position in the coating field. An examination of many new products and processes still at the R and D phase indicates that magnetron sputtering is frequently the preferred technique and this trend looks set to continue.

The process itself is continually developing with better and more efficient sources and simpler designs. Modern automation techniques enable production-scale equipment to be produced with ease of operation. What was a scientific curiosity is now an exciting process, a prime example of physics in action.

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Further reading

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