Design, Construction And Performance Of DC Magnetron
CHAPTER II

DESIGN, CONSTRUCTION AND PERFORMANCE OF DC MAGNETRON

2.1. INTRODUCTION

Different methods are available to prepare thin film. The important methods are evaporation, sputtering, chemical vapour deposition, ion plating, anodisation, electrolytic deposition, electroless deposition, spray pyrolysis, sol gel process, Plasma Enhanced Chemical Vapour Deposition (PECVD), spin coating, Pulsed Laser Deposition (PLD), MOCVD and Molecular Beam Epitaxy (MBE).

In the present investigation, DC magnetron sputtering has been used for the preparation of TiO$_2$ thin films. The process of sputtering is defined as ejection of material from a solid target by bombardment of energetic particles, which can be charged or neutral. However, ions are used for sputtering due to the fact that their energy and direction can be controlled by application of electric and magnetic field. DC voltages are sufficient to sputter conducting targets, but one has to use RF power for insulating targets. Due to continuous charged particle bombardment on the substrate, the adhesion of sputtered film is extremely good in comparison with evaporated films. Sputter deposition has been found to be suitable for many industrial applications and is replacing conventional evaporation techniques. The details of sputter deposition and the transformation of it into an industrial technique are discussed below.

2.2. GLOW DISCHARGE SPUTTERING

Most of the sputtering work reported earlier was done with glow discharge as the source of ions. This is mainly because it provides a large area source of energetic particles, almost all of which can be made to fall on the sputtering target. The process of film
deposition can be broadly explained as a sum of different stages like ion production, ion target interaction, sputtering of the target material, transport of target material to the substrate and film nucleation.

2.3. **Glow Discharge Process**

Glow discharge can be obtained by applying a potential between two electrodes in gaseous atmosphere. Most of the space between the electrodes is filled with a bright glow called negative glow. This glow is the result of the excitation and recombination process in the discharge tube. Adjacent to the cathode is the dark space, which is a sheath of positive space charge. The entire applied potential is dropped across this dark space. The positive column is the neutral plasma. When the two electrodes are brought closer, the positive column shrinks, but the dark space and negative glow are unaffected till the electrodes enter that region. The minimum distance of separation is the twice the dark space length. At distances less than this, the dark space is distorted and then the discharge will extinguish. In the discharge, electrons, ions and neutrals are present. Depending on these charges, the reaction at the cathode will be different from that at the anode.

2.4. **Cathode Reactions**

In the dc sputtering process, the cathode is the target material. The glow discharges sustained mainly because of the secondary electrons ejected from the cathode by the ion bombardment. The ionization process takes place near the cathode surface. When a potential is applied between the anode and the cathode, after a certain potential, the ambient gas breaks down. A large number of ions and electrons are created in the gas. Due to their lighter mass, electrons move faster than the ions. This leaves a positive ion sheath near the cathode. This leads to an increase in ionization current and space charge density. This positive space charge sheath is referred as Crooks dark space. The
thickness of this is inversely proportional to the pressure. The positive ions strike the cathode and give rise to different effects depending on their energy.

2.5. ION – CATHODE INTERACTIONS

The ion – cathode interactions depend basically on the energy of the ions and cathode material. Fig.2.1 shows the following typical possible reactions at the cathode due to ion bombardment [1].

1. The ion may be reflected
2. The impact of the ion may cause the target to eject an electron
3. The ion may get buried in the target, leading to the phenomenon of ion implantation
4. The ion impact may cause some structural rearrangements in the target material
5. The ion impact may set up a serious of collisions between the atoms of target (cascade collision process), possibly leading to the ejection of one of the atoms, the process being called sputtering.

2.6. SPUTTERING AS A DEPOSITION PROCESS

The last part of the above section, i.e., the ejection of target atoms by the bombardment of ions is used for the deposition of thin films. Two different mechanisms have been used to explain the ejection of atoms. Stark [2] explained the sputtering as a result of momentum transfer from the bombarding ion to the atom in the target. This theory was amplified; Kingdon and Langmuir [3] provided the further evidence of its validity. The hot spot evaporation theory that assumes sputtering to be due to very high local temperatures created at the surface by the bombarding ions was postulated by Von Hippel [4]. Here in this theory energy of the ion was taken into account rather their momentum. But this theory was failed when Bariess [5] could not observe anodic sputtering by electrons. Many workers later confirmed momentum transfer theory. According to the
Fig. 2.1. Possible interactions of ions with a solid surface
momentum transfer theory, the sputtering yield depends on the mass of the bombarding ion and its energy also. During sputtering several types of interactions may take place between sputtering ion and sputtered atom. There exists a minimum threshold energy required for sputtering. It can be seen that the yield decreases at very high energies mainly due to deep penetration of ions into the target. Also sputtering yield depends on the mass of the bombarding ion, with xenon giving maximum yield. Though these models explain the sputtering mechanism, in practice one has to consider that the sputtering target becomes a mixture of original target material and the bombarding species embedded in it. This may lead to errors in calculation of sputtering yield data [6].

2.7. CONVENTIONAL DC SPUTTERING

In a typical sputtering process for thin film deposition the material to be sputtered as a thin film is made the cathode. The substrate is mounted on another electrode that may be grounded. If left floating, it can acquire certain potential from the plasma during deposition. Some times, the substrate is kept deliberately at some potential and the process is called as bias sputtering. The target is normally shielded at the sides and at the bottom to avoid the undesired sputtering. The cathode dark space decides the spacing between the shield and the target. The shield is kept within the dark space such that sputtering for the sides and back of the target is avoided. Since the target is continuously bombarded with ions, the target must be cooled to avoid the excessive heating. Also since the substrate is bombarded with sputtered atoms, fast electrons and neutrals, it may get heated and has to be cooled. The entire electrode assembly is kept in a vacuum chamber, with provision for gas admittance for sputtering process. When high potential is applied between the electrodes, the target being at negative potential is bombarded by the positive gas ions leading to the ejection of the target atoms, which fly off in random directions. Some of them landing on the substrates condense to form a thin film. The parameters that influence the deposition are the cathode potential and current density of ions on the target, both being functions of the sputtering pressure. The rate of sputtering
depends on the flux of the ions incident on the target and the sputtering yield. The potential applied to the cathode causes a rise in the temperature of the cathode due to the ion bombardment, since more than 90% of the ion energy on the target is lost as heat in the solid material and only about 5% is passed onto secondary particles [7]. At high pressures the ionization is high and hence the rates of sputtering are high, but the rate of deposition of thin film will be very low due to scattering effects.

2.8. Substrate Effects

Some of the sputtered atoms that strike the substrate are condensed and thin film is formed. The stages that govern the normal thin film formation by physical methods (condensation, nucleation, coalescence and continuous film etc.) also appear in sputtering, but the difference is the energy of the sputtered atoms is higher that the evaporated atoms, which in turn improves the adhesion. Along with the sputtered atoms, the substrate is prone to bombardment of contaminants, negative ions, fast electrons, and photons etc. each of which contribute to the substrate reactions. The substrate when left electrically isolated will acquire a negative potential with respect to the ground thus leading to the sputtering of weakly bonded layers of the growing film.

2.9. Problems in DC Sputtering

Though dc sputtering is widely used in depositing thin films of various materials, it has certain inherent disadvantages. The basic disadvantage being that the sputtering target should be conducting; otherwise, a positive space charge is build up on the cathode preventing the sputtering. Also if ‘V’ is the applied potential, not all the sputtered atoms will have this energy, but will have a wide energy distribution because of collision with the atoms. The low deposition rate poses a major problem in depositing thick film using this technique. Operating the process at higher pressure enhances the rate of sputtering but the rates of deposition will be poor. Increasing the cathode potentials at low pressure
leads to a $T^4$ increase in the temperature of the target and a simultaneous increase in the substrate temperature, which plays a dominant role on the morphology and structure of the sputtered films.

2.10. REACTIVE SPUTTERING – BASIC PROCESS

As we discussed earlier, one of the main problems with normal dc sputtering is its inability to sputter insulator target due to accumulation of charges on the target surface. This can be solved by resorting to high frequency sputtering. But still, in this process the stoichiometry of the deposited film deviates from that of the target material. So during deposition a certain amount of reactive gas should be present in the system to achieve stoichiometry. The process of sputtering a material target in the presence of a reactive gas leads to the advantage of controlling the composition of the deposited film to tailor its properties and this process of sputtering is called reactive sputtering. The nature of the reactive gas, its reactivity with the target material and the rate at which the sputtered material atoms reach the substrate decide the composition of the film.

2.11. DC MAGNETRON SPUTTERING

Some of the problems mentioned above could be solved when the sputtering is associated with a transverse magnetic field. It produces several modifications in the basic process. The required magnetic field can be provided with either the permanent magnets or electromagnets. The magnets are well mated with the target with proper design. This is because of the influence of the magnetic field on the target-generated secondary electrons. The secondary electrons generated are trapped in the magnetic field geometry and they do not bombard the substrate and tend to move in a cycloid path near the target obeying the Lorentz force relation and thus do not contribute to the substrate temperature and radiation damage. Such a process is called DC magnetron sputtering, which is advantageous in the deposition of thin films on low temperature substrates like plastic and surface sensitive MOS devices. In DC magnetron sputtering the ionization efficiency
increases and it enhances the deposition rate. It is a potential process for Industrial applications. Different types of magnetron sources like planar magnetron, cylindrical magnetron and conical magnetrons are developed depending on the need in specific applications.

2.12. Reactive Magnetron Sputtering

In reactive sputtering, thin films of compounds are deposited by sputtering from metallic targets in the presence of a reactive gas usually mixed with the inert working gas. The resulting film in reactive sputtering is either a solid solution alloy of the target metal doped with reactive element, a component or some mixture of the two. Westwood has provided [8] useful way to visualize the conditions required to yield compound films. Sputter rates of metal decreases when compounds formed on the targets. The effect is very much dependent on the reactive gas pressure and the discharge current. Conditioning of the target in pure Argon atmosphere is required to resolve the pure metal surface and desired deposition states. Considerable variation in the composition and properties of reactively sputtered films is possible. Depending on the operation conditions colour changes appear in the film due to variation in the stoichiometry. In the process of compound film formation a small excess of either the metal or the oxygen will not be rejected but will be included in the resultant film material [9]. The question where the compound film formation takes place is essential to understand the reactive sputtering process. Simultaneous conservation of energy and momentum requires the reaction to occur at solid surface, either at the target or at the substrate. At very low reactive gas partial pressure and high target sputtering rate, it is essential that the reaction take place mostly on the substrate. However, when the rate of removal of the material from the target is far less than the rate of arrival of the reactive gas atoms to the target, the compound formation takes place at the target also, which leads to target poisoning [9].
2.13. PHYSICS OF MAGNETRONS

The use of electric field and magnetic field to control the motion of electrons are well known. In a dc glow discharge, the secondary electrons leaving the cathode travel straight to the anode (generally the substrate), taking the shortest path. If it undergoes collisions with the gas molecule during the traverse, ionization results. Due to the high energy of electrons in such a system, the possibility of ionization is less. Most of the electrons bombard the substrate during the film deposition and it results in substrate heating. The introduction of magnetic field confines the electrons to the cathode surface, thereby reducing the substrate heating. The electrons undergo circular motion under the influence of the magnetic field. This leads to an increase in the electron path which in turn results in an increase in ionization efficiency. The radius of gyration is given by

\[ r = \frac{m v \sin \theta}{Be} \]  

(2.1)

where \( m \), \( v \) and \( e \) are the mass, velocity and charge of the electrons, \( B \) is the magnetic field and \( \theta \) is the angle between the magnetic field and electric field. The radius is maximum when the electric and magnetic fields are mutually perpendicular. The electric field in front of the magnetron is greatly altered by the presence of conducting plasma such that the bulk of the applied potential is dropped across a thin region on the surface of the cathode. In magnetrons, this thickness is about 1mm. Generally the radius of gyration as seen from the above equation is larger than the dark space thickness. The electron moving across the applied potential \( P \) gains a velocity \( v \)

\[ v = \sqrt{2qP/m} \]  

(2.2)

The presence of magnetic field causes a circular motion to the electron, described by the first equation and the typical value of the electron path under normal magnetron condition is about 1.5 mm.
One of the major problems in normal direct current (dc) sputtering is the low deposition rate, which leads to longer times of deposition and hence higher probability of contamination during deposition. This process is also resulted in high substrate heating, as most of the input power is not efficiently used. It was shown that only 5% of the incident ion energy is passed onto the secondary electrons [10]. Also high pressure sputtering results in scattering of the sputtered atom back into the target. One of the efficient methods of increasing the ionization at low pressure is by utilizing the magnetic field in conjunction with the electric field. Chapin [11] used this principle in the design of practical magnetron sputtering cathode. Even after three decades, this technique is being continuously refined for the maximum target utilization, high deposition rates and coating uniformity. The theory and practical aspects of magnetrons have been reviewed extensively [12-16]. The main consideration in the present study is to design a magnetron, which has high current efficiency, high erosion area and low substrate heating.

2.14. DESIGN AND CONSTRUCTION

Fig. 2.2 shows the cathode assembly fabricated in the present study, which consists of a target holder and can accommodate a plane circular target of 110 mm diameter and a flange. The target holder and the flange are fabricated using stainless steel and integrated with water-cooling arrangement. Here in this study, the magnetron are designed in such a way that the magnets are kept under the target plate and are always water-cooled along with the target as shown in the figure. Water at a temperature of 18°C with a flow rate 1.5 l/min is circulated for cooling the target. A soft iron plate is kept behind the magnets in order to minimize the loss of magnetic field. The target has been provided with necessary electrical isolation using Teflon (PTFE). The whole arrangement was fitted with a stainless steel set up, above which a SS tube is brazed. Through this tube water flow tubes and electrical lines are inserted as shown in the diagram. The potential to the target is applied by means of a sufficiently thick copper rod, which is affixed on the top stainless steel plate through Teflon isolations. From there the connection was made to
Fig. 2.2. Schematic diagram of magnetron cathode assembly
the target through a thin cable, which is well isolated. Later, the magnetron assembly is mated to the top plate of the vacuum chamber with the target in sputter down configuration.

In a magnetron design, magnetic field geometry on the target is an important aspect. The positioning of the magnets plays a major role, as it decides the uniformity of the magnetic field on the target and hence the uniformity of the deposition. Solid cylindrical permanent magnets made of Nd Fe B with 13 mm diameter and 10mm thick are used in this present study. The magnets were coated with nickel to minimize the corrosion. The arrangement of the magnets on the back of the target plate is as shown in Fig. 2.3 with the magnet at the center with a pole (N or S) different from the magnets at the edges of the target plate (S or N).

![Fig. 2.3. Arrangements of magnets in the magnetron](image)

In order to understand the extent of ionization near the substrate, it is essential to characterize the sputter cathode in terms of magnetic field geometry near the target and also at the substrate. The field strength at different points is measured using a gauss meter. This helped to understand the description and geometry of the magnetic field in front of the target. Variation of the magnetic field along the radial direction over the target surface is measured and it is shown in Fig. 2.4.
2.15. PERFORMANCE EVALUATION OF THE MAGNETRON CATHODE

PLASMA DIAGNOSTICS OF THE GLOW DISCHARGE

The glow discharge in the sputtering chamber is diagnosed to deduce electron energy and ion density. The well-known technique for plasma diagnostics is the "Langmuir Probe".

2.15.1. LANGMUIR PROBE SET UP

A cylindrical probe is fabricated by concealing a tungsten wire of thickness 0.26 mm in glass capillary with a tip protruding. The length of the probe was 5 mm. It is connected to electrical feed through of the chamber and mounted on a travelling holder. This can be
fitted at different lateral positions on the holder. It can be moved up and down without disturbing the vacuum. This arrangement enables to scan the glow discharge at various axial and radial positions with respect to the target. The bias arrangement consists of a power supply (0 - 30 V) and an ammeter with a commutator to change the polarity. The vacuum chamber body acts as the reference electrode.

![Diagram of Langmuir probe setup](image)

**Fig. 2.5. Experimental set-up of Langmuir probe for plasma analysis**

### 2.15.2. The Langmuir Probe

Due to its simplicity in construction and ease of operation, the Langmuir probe has become a popular technique for plasma diagnostics. Any small electrically conducting object inserted in the plasma acts as a Langmuir probe. The experimental method is the biasing of the probe with respect to the reference electrode and finding the current-
voltage characteristics. The probe characteristics have been analyzed on the basis of collisionless theories for electrons and positive ions collected by the probe [17]. Fig. 2.6. shows a typical I-V characteristic of a single Langmuir probe.

![Graph showing I-V characteristic of a single Langmuir probe]

**Fig. 2.6. Typical I-V characteristic of a single Langmuir probe**

At zero bias potential the probe will record a negative current. This is due to the ion inflow to the probe because of the screening effect in the glow discharge. At a certain positive bias potential $V_F$, the current becomes zero, i.e., the ion current is equal to the electron current. $V_F$ is called the floating potential of the probe. Further increase in the forward bias will lead to the arrival of more electrons and a sharp increase in the current can be observed. When the bias reaches the plasma potential $V_p$, the probe collects most of the electrons in the surroundings. The current reaches a saturation value. In the negatively biased condition the probe will record the ion saturation current.
2.15.3. DETERMINATION OF PLASMA PARAMETERS

Electron temperature ($T_e$)

In the intermediate region of the I-V characteristics curve, both ions and electrons can reach the probe. When the electron current reaches the saturation region the slope of the $\ln(I_e)$-V curve gives the relation,

$$\frac{1}{T_e} = \frac{\delta \ln I_e}{\delta V_p}$$

(2.3)

$T_e$ is the electron temperature, $I_e$ is the current recorded and $V_p$ is the probe potential [18, 19].

Plasma potential ($V_p$)

The plasma potential is the value of the probe potential at $E$ where CDE and FE intersect in the I-V curve. This can be found more precisely at the knee of the $\ln I_e$-V curve.

Ion density ($n_i$)

At the negative biased region, the probe repels all the electrons. The $I^2$-V curve in this region will yield the ion density according to the relation [20, 21],

$$n_i^2 = -\left[ \frac{4\pi m_i}{3A^2e^2} \left( \frac{\delta I_i}{\delta V_p} \right)^2 \right]$$

(2.4)

where,

$m_i$ - the ion mass (gas ions)

$A$ – probe area

e - charge on the electron
The Langmuir probe is fixed at the chosen point inside the vacuum chamber and the I-V measurements are taken at the glow discharge parameters (Discharge current: 200 mA, sputtering pressure: \(10^{-3}\) mbar) and shown in Fig. 2.7.

The glow discharge parameters are deduced from the observations. The probe potential is varied from \(-20\) V to \(+20\) V and the corresponding current were noted using an ammeter.

![Fig. 2.7. I-V Characteristics of the Langmuir probe](image)

Fig. 2.7. I-V Characteristics of the Langmuir probe

Fig. 2.8. shows the variation of electron temperature at various positions in the glow discharge. The Langmuir probe is positioned in front of the cathode at a given position. The probe region is selected where the magnetic field is almost uniform. The effect of
the magnetic field is eliminated by placing the probe perpendicular to the field lines. The graph indicates the decrease of electron temperature as the probe is moved away from the cathode. The region nearer the cathode is avoided to minimize the interference of the magnetic field on the probe measurements.

![Graph showing electron temperature versus target-substrate distance](image)

**Fig. 2.8.** Electron temperature versus target-substrate distance

Fig. 2.9. shows the negative particle density variation and ion density variation as a function of oxygen partial pressure at a constant sputtering pressure. The negative particle density increases from $8.61 \times 10^9$ cm$^{-3}$ to a value $10.221 \times 10^9$ cm$^{-3}$ at a critical oxygen partial pressure of $7 \times 10^{-5}$ mbar. It reaches a minimum value of $7.63 \times 10^9$ cm$^{-3}$ at a pressure of $9 \times 10^{-5}$ mbar, before increasing further. The positive ion density also shows a similar behaviour. The behaviour is similar to the variation of cathode potential.
as shown in Fig. 4.1. The critical oxygen pressure at which the target condition changes are also similar to these two figures. The ion density is also determined at different discharge current densities by keeping the other parameters of glow discharge constant.

![Graph showing variation of ion density and electron density with respect to oxygen partial pressure](image)

**Fig. 2.9. Variation of ion density and electron density with respect to Oxygen partial pressure**

### 2.15.4. EFFECT OF GLOW DISCHARGE ON TEMPERATURE OF THE SUBSTRATE

The important effect of glow discharge on the substrate is the heating up of the substrate due to electron bombardment. Temperature measurements are done on a copper substrate of surface area 15 cm², which is thermally isolated from the surroundings. The heat built rate is calculated in electrically floating condition at various sputtering powers for a given distance. The study is also done at various target-substrate distances for a given sputtering power. The heating rate is found to be proportional to the discharge current for a given distance. On varying the distance the heating rate remained constant from the
target for certain distance and then decreased. Figs. 2.10 and 2.11 show the temperature buildup on the substrate.

**Fig. 2.10.** Effect of glow discharge on the temperature of the substrate

**Fig. 2.11.** Temperature build up rate with respect to the discharge current and target-substrate distance

**Fig. 2.10.** Effect of glow discharge on the temperature of the substrate

**Fig. 2.11.** Temperature build up rate with respect to the discharge current and target-substrate distance
SUMMARY

A DC magnetron assembly which can accommodate a 100 mm diameter cathode have been designed and fabricated. The magnetic field profile of the cathode has been studied along the radial direction over the target surface. Langmuir probe was used to study the glow discharge and the plasma parameters such as electron temperature, plasma potential and ion density was evaluated using the relevant formulae and presented. The heat built rate on the substrates during the sputtering was calculated in electrically floating condition at various sputtering powers for a given distance. The study was also done at various target-substrate distances for a given sputtering power. The heating rate was found to be proportional to the discharge current for a given distance. On varying the distance the heating remained constant from the target for certain distance and then decreased.
REFERENCES