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Qualitative model of the magnetron discharge

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ABSTRACT

A simple model of the direct current magnetron discharge is introduced, relating the discharge current I, voltage V, sheath thickness d, plasma density, pressure P, magnetic field and material constants. The model is based on microscopic physics, balancing the generation and loss of ions. After deriving the balance equation $m(d)c(P)\frac{V}{W} = 1/\gamma$, with $m(d)$ a multiplication factor, c(P) a confinement factor, W the effective ionization potential of the sputter gas and γ the ion induced secondary electron emission coefficient, a generic description of the discharge is made. The model is shown to reproduce many experimental results reported in literature, including a minimum voltage and steep I–V characteristics.

1. Introduction

Sputter magnetrons are popular devices used to deposit thin films. These films find a wide range of applications, including as decorative, antireflective, wear resistant or display coatings [1]. Compared to other physical vapor deposition (PVD) methods such as thermal or electron beam evaporation, magnetrons offer facile controllability of the deposition rate. Magnetron sputtering is scalable from lab scale to large area coaters for architectural glass substrates that are multiple meters wide. Another advantage is the non-thermal nature of the sputtered atoms, enabling the engineering of special films.

The basic design of a magnetron is very simple. A schematic cross section is shown in Fig. 1. A metallic cathode, called the target, is mounted in a vacuum chamber. A sputter gas, usually argon, is flowed in the chamber. A set of magnets is fixed under the target. The target is negatively biased and the chamber walls are grounded. This results in a gas discharge. The plasma is centered near the target, where there is a strong magnetic field. Ions produced in the plasma are accelerated towards the negatively biassed target. The interaction of the ion with the target can result in the release of one or multiple target atoms. These move through the chamber and condense on a substrate, forming the desired coating. Because of the large power dissipated during operation of the magnetron, the target and magnets are cooled with water (not shown). Magnetrons have several advantages over sputter glow discharges (without magnetic enhancement), such as lower operating voltages, lower sputter gas pressures and higher deposition rates. Table 1 gives an overview of typical values of parameters in magnetron discharges.

Empirical results of the properties of magnetron discharges have appeared in the scientific literature over the last 30 years. These studies have shown that (a) the discharge current I rises steeply with discharge voltage V [10] [11], (b) the discharge extinguishes (I becomes zero) below a certain minimum voltage V_{min}, where V_{min} depends on the pressure P and magnetic field strength B [10] [11], (c) at low pressures and constant current, V drops with rising pressures, while remaining almost constant at higher pressures [10] [2], (d) the erosion zone of the target widens with decreasing pressure [12] and increasing discharge power [12] [13], (e) the cathode sheath (= space charge region separating the quasi-neutral plasma from the cathode) thickness decreases with increasing V [6], (f) at a fixed I, V can be lowered by introducing an extra ionization source in the discharge chamber [14], (g) the sputter gas [15] and target material [2] influence the I–V.

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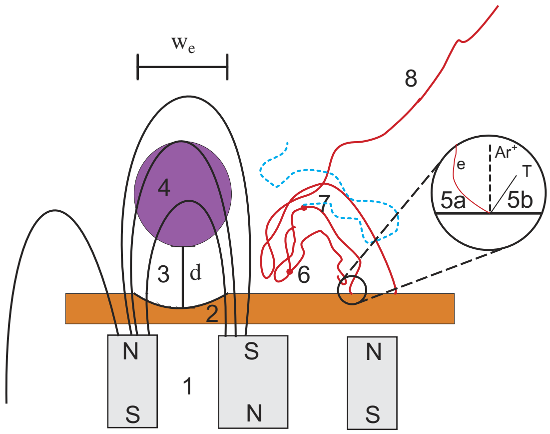

Fig. 1. Schematic cross section of a magnetron with planar target, not to scale. Indicated are the macroscopic observables: (1) the permanent magnets, with north (N) and south (S) pole and field lines indicated, (2) target with erosion groove (racetrack) with width w_e, (3) the sheath, (4) plasma. Right hand side shows microscopic processes relevant to the model: (5) impinging Ar ion, resulting in (a) electron e and (b) sputtered target atom T, (6) energetic electron (full line) causing ionization in the sheath, (7) ionization outside the sheath, emitting a low energetic (dotted line) electron, (8) energetic electron escaping from confinement. The symmetrical situation with all magnetic poles reversed is also possible.

Theoretical efforts to describe the magnetron have only yielded partial models for some characteristics of the discharge, e. g. [10] [11] [16] [17] [18]. The goal of this paper is to demonstrate that the complex, experimentally established relations between the interdependent physical variables can be disentangled and understood by examining the microscopic physics. The relations between selected pairs of observable quantities as summarized above fit into a general framework. This approach should help users of magnetrons to predict the influence of control parameters on their deposition process. The simple model might aid the construction and interpretation of advanced computer simulations.

In Section 2, the model is developed and checked with basic physics. In Section 3, the experimental properties of magnetrons are reviewed. Comments are made on how to adapt the formalism to other setups. The figures in this paper are meant to demonstrate particular phenomena and are not to scale.

2. Model description

The model is constructed taking into account several fundamental constraints and mechanisms, introduced in different subsections.

2.1. Plasma and sheath

Charges moving perpendicular to the direction of a magnetic field, gyrate around the magnetic field lines with the Larmor radius r_L. This depends on the magnetic field strength B, charge q, velocity v and mass m of the particle: $r_L = mv/qB$. Table 1 shows that the Larmor radius of electrons in magnetrons is small, while that of ions is large compared to the height of the plasma above the target. The electrons in a magnetron discharge are 'magnetized', their motion is strongly influenced by the magnetic field.

When a plasma is in contact with a charged wall, a sheath develops. This is a region of non-zero net charge density, resulting in a current. The density of thermalized electrons in the sheath follows a Boltzmann distribution (z denotes height above the target, $n_{e,\,0}$ is the electron density in the quasi-neutral plasma where $n_{e,\,0} \approx n_i$):

$$n_e(z) = n_{e,0} e^{-eV(z)/k_B T_e}. \qquad (1)$$

For typical values of V and T_e in magnetrons (see Table 1), the density of electrons in the sheath is very small.

The Poisson equation

$$\nabla^2 V = \frac{-qn_i + en_e}{\epsilon_0}, \qquad (2)$$

where q is the ion charge, can be solved exactly under the approximation of a collisionless sheath of ions ($n_e = 0$). The result is the Child–Langmuir law

$$J = \frac{4}{9}\epsilon_0 \left(\frac{2q}{M}\right)^{1/2} \frac{V^{3/2}}{d^2}, \qquad (3)$$

which relates the ion current density J, ion charge q, ion mass M and sheath potential. What will be developed further is a way to eliminate the unknown sheath thickness d and to include the

Table 1
Typical values of quantities and physical constants.

Quantity	Symbol	Magnitude	Units	Reference	Remarks
Discharge voltage	V	300–500	V	[2]	
Current density	J	10–100	mA/cm^2	[3]	
Magnetic field strength	B	200–1200	Gauss	[2]	1 Gauss = 10^{-4} Tesla
Ion density	n_i	10^{10}–10^{11}	cm^{-3}	[4] [5]	
Sheath thickness	d	0.3–1.0	mm	[6]	
Ar pressure	P	0.1–1	Pa	[3]	
Ar density	n_{Ar}	10^{14}	cm^{-3}		Corresponds to 0.39 Pa at $T = 25\,^\circ$C according to the ideal gas law $P = n_{Ar} k_B T$
Electron velocity (300 eV)	v	1.0×10^7	m/s		Calculated from kinetic energy E$_k$: $v = \sqrt{\frac{2E_k}{m_e}}$
Ionization cross section of Ar	σ_i	1.9×10^{-16}	cm^2	[7]	At electron energy 300 eV
Total electron scattering cross section of Ar	σ	5×10^{-16}	cm^2	[7]	At electron energy 300 eV
Mean free path	λ	20	cm		$\lambda = \frac{1}{n\sigma}$, $n_{Ar} = 10^{14}$ cm^{-3}, 300 eV
Ionization potential of Ar	U	15.6	V	[8]	
Effective ionization potential of Ar	W	30	V	[8] [3]	Nearly constant for dc magnetrons [8]
Boltzmann constant	k_B	1.3×10^{-23}	J/K	[8]	
Electron volt	eV	1.9×10^{-19}	J	[8]	
Electron temperature	T_e	2–5	eV/k_B	[4] [5]	
Electron charge	e	1.6×10^{-19}	C	[8]	
Electron mass	m_e	9.1×10^{-31}	kg	[8]	
Argon atom mass	m_{Ar}	6.63×10^{-26}	kg	[8]	
Vacuum permittivity	ϵ_0	8.85×10^{-12}	F/m	[8]	
IISEE coefficient	γ	0.1	–	[9]	Depends on target material and sputter gas [2]
Larmor radius electron	$r_{L,e}$	1.2	mm		Kinetic energy 300 eV, B = 500 Gauss
Larmor radius ion	$r_{L,i}$	32	cm		Kinetic energy 300 eV, B = 500 Gauss