Pulsed Mode Reactive Magnetron Sputtering

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Chapter 1

Introduction

Sputtering is a subclass of PVD - Physical Vapor Deposition, which is an essential process in manufacturing integrated circuits, photovoltaic modules, specialized optical and mechanical equipment. It is a process used for the creation of extremely thin (even down to atomic) coating layers on different surfaces in order to achieve better physical, chemical, optical or electrical characteristics than those of the coated material itself. Among others, the use of this technique allows the formation of transparent but also conducting layers, which are essential in optics. The process essentially consists of the removal of material from one or more target surfaces and their deposition onto a surface that is required to have improved characteristics, also known as the substrate. This removal process is accomplished with the help of high energy noble gas ions which bombard the surface of the target due to the presence of an electric field. With the addition of a magnet behind the target one can achieve magnetron sputtering, greatly increasing the ionization efficiency and the sputtering yield.

With the introduction of one or more reactive gases into the vacuum chamber, reactive magnetron sputtering is achieved, which allows the formation of different compounds like oxides and nitrides. Reactive magnetron sputtering has been extensively studied and modeled in the past few decades.

There are several approaches and technologies used for magnetron sputtering, such as DC (direct current) sputtering, pulsed DC sputtering, AC (alternating current) sputtering, HiPIMS (high power impulse magnetron sputtering) and RF (radio frequency) sputtering. All of the different coating techniques mentioned require highly specialized operating environments in order to function correctly [3]. The creation of a high vacuum environment (pressure in the range of a few Pascals) is mandatory. At such low pressures, different metals begin to evaporate, hindering the insertion of any nonspecialized equipment into the sputtering chamber. Simple questions as measuring the total or partial pressure inside the chamber become ever more difficult, requiring special processes to be put in place and the indirect calculation of the desired quantity from the gathered data. In situations like these, the use of a state identification algorithm becomes favored. From the control perspective, the system quickly becomes complex when one simply attempts to count the number of inputs, outputs and their non-linear cross coupled effect on each other. Each of the magnetron sputtering processes sets particular challenges from the point of view of modeling.

Chapter 2

Theses

2.1 Thesis 1

I developed a graphical identification method suitable for determining the main parameters of the Berg Model so that they can be used for fine-tuning a control algorithm.

In order to find the parameters α_c, α_t, η_M and η_G, I consider the derivative of the function $q_{in}(p)$, derive its extrema and identify negligible terms in different pressure ranges so that the simplifications result in straightforward parameter identification methods [4]. An excerpt of the process (pages 35-41 of the manuscript) can be seen in Fig. 2.1 as I simplify (2.1) to (2.2).

$$q_{in} = \underbrace{Sp}_{q_p} + \underbrace{M_{O_2} K \alpha_t A_t f_1(p)}_{q_{G_1}} + \underbrace{M_{O_2} K \alpha_c A_c f_2(p)}_{q_{G_2}}, \tag{2.1}$$

$$q_{in}^* \cong \underbrace{Sp}_{q_p} + \underbrace{M_{O_2} A_t \eta_G J}_{q_{G_1}^*} + \underbrace{M_{O_2} A_c \frac{\eta_G \eta_M J^2}{\alpha_t K K_a p}}_{q_{G_2}^*} \tag{2.2}$$

The parameter identification of the classical macroscopic reactive magnetron sputtering model is feasible using both analytical and graphical methods. Simplification of the analytically determined gas flow-pressure relation is possible in both the metallic and the poisoned operation modes in order to provide a support for the graphical determination of the reactive gas sticking coefficient on the condensation surface (α_c) and of the sputtering yield of compound

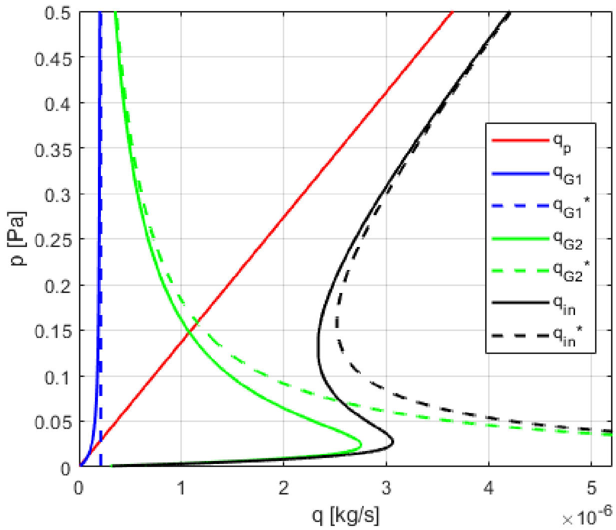

Figure 2.1: The terms of (2.1) and their approximations according to (2.2).

molecules (η_G). Determination of the sputtering yield of the target metal (η_M) and of the reactive gas sticking coefficient on the target surface (α_t) is possible both analytically and by least squares curve fitting, which is the subject of further study.

2.2 Thesis 2

> I have proposed a control structure employing two control loops, that can keep the system stable, that can control the sputtering power, and which leads to stoichiometric film growth on the substrate surface.

I studied the conditions needed for stoichiometric layer growth on the substrate surface using analytical methods. I have shown that there is a monotonic relationship between the target coverage and the partial pressure of the reactive gas. Results from the literature show that the target voltage, along with state estimation, can be used to calculate the target coverage using (2.3) (pages 55-57 of the manuscript). I have combined these findings in a method that facilitates stoichiometric film growth on the substrate surface [5]. The proposed control structure can be seen in Fig. 2.2.

$$\theta_T = \frac{\frac{1}{U_d(I_d,p_{Ar})} - \frac{1}{U_M(I_d,p_{Ar})}}{\frac{1}{U_{MG}(I_d,p_{Ar})} - \frac{1}{U_M(I_d,p_{Ar})}}. \tag{2.3}$$

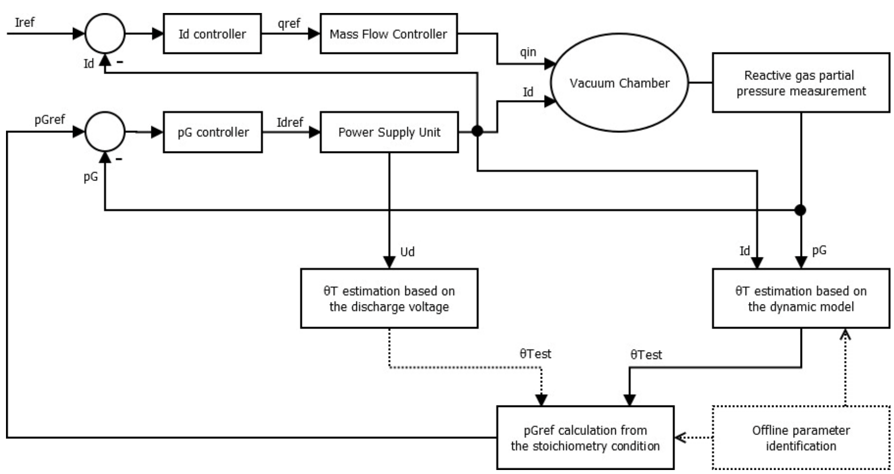

Figure 2.2: The proposed control structure for stoichiometric sputtering.

2.3 Thesis 3

I proposed a new control algorithm and a corresponding control structure that provides stable operation of the process using two continuously supplied reactive gases.

The novelty of the proposed algorithm consists in the extension of reactive magnetron sputtering control algorithms to the two-gas reactive magnetron sputtering process, and the definition of current-dependent monotony domains in the space of the partial pressures. The stoichiometry of the deposited film is influenced by controlling the amount of coverage of the ternary compound TiO_xN_y on the substrate [2].

The question thus raised is to find the subarea of the whole surface, for which this condition is true. Delimiting the region, based on this condition, can best be done by examining the contour plot of the identified surface (Fig. 2.3). Using two lines as shown in Fig. 2.3, it is possible to delimit a region where $\theta_{MG_1G_2} = f(p_{O_2})$ is monotonic (pages 64-68 of the manuscript), for a given pair of p_{N_2} and I values.

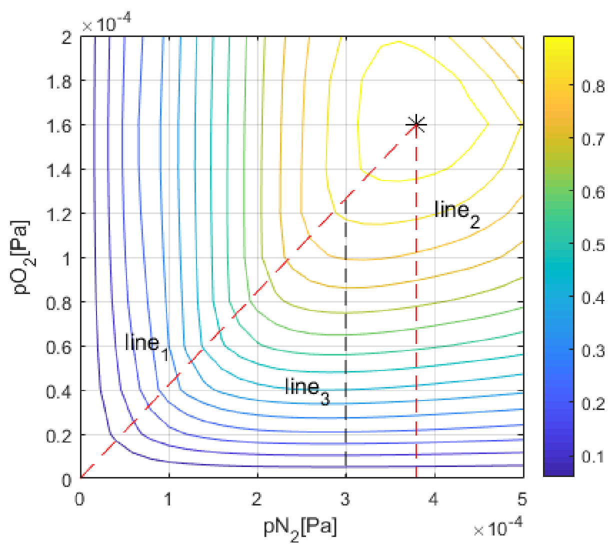

Figure 2.3: The contour plot of the substrate coverage and the lines used to delimit the preferred area.

In order to hold the operating point on the preferred subsurface, a new control algorithm can be formulated:

1. I_{ref} is defined by the technological process
2. $p\hat{N}_2 = m_3 + I_{ref} * m_4$
3. $p_{N_{2reflim}} = m_2 * p\hat{N}_2$
4. p_{N_2} is controlled with I_{disch}
5. I_{disch} is controlled with q_{N_2}
6. $\theta_{MG_1G_{2ref}}$ is defined by the technological process
7. $\theta_{MG_1G_2}$ is controlled with $p_{O_{2_{ref}}}$
8. $p_{O_{2reflim}} = p_{N_2}/m_1$
9. p_{O_2} is controlled with q_{O_2}

The corresponding control structure can be seen in Fig. 2.4.

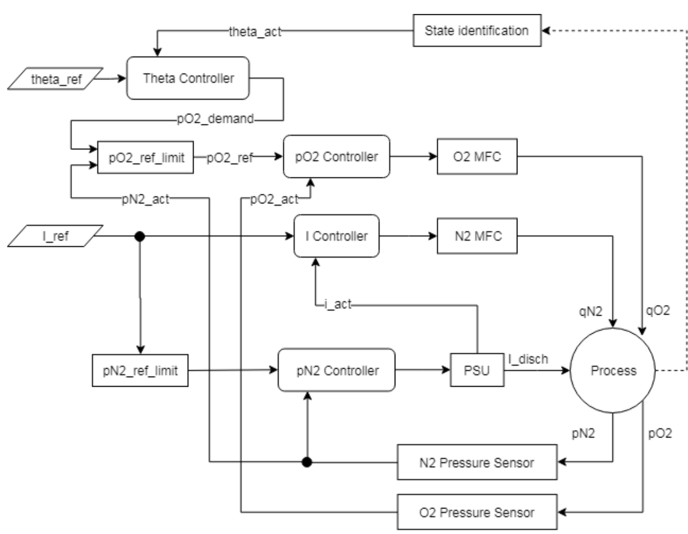

Figure 2.4: Control structure for power and substrate coverage with $\theta_{MG_1G_2}$.

By implementing the proposed limiting algorithms, the trapped state of the target can be avoided. Implementation in engineering practice is conditioned by the successful state-identification of the substrate surface coverage by the desired compound, and fast partial pressure measurement of the two reactive gases.

2.4 Thesis 4

I proposed and built a current controlled power supply that is suitable for use with both high impedance and low impedance loads, characteristic for different states of the plasma in magnetron sputtering applications.

I determined the specific design criteria needed for the implementation of the pulsed mode power supply by taking into account the current-voltage characteristics, the ignition voltage and the current impulse delay for different gases and pressures (Fig. 2.5).

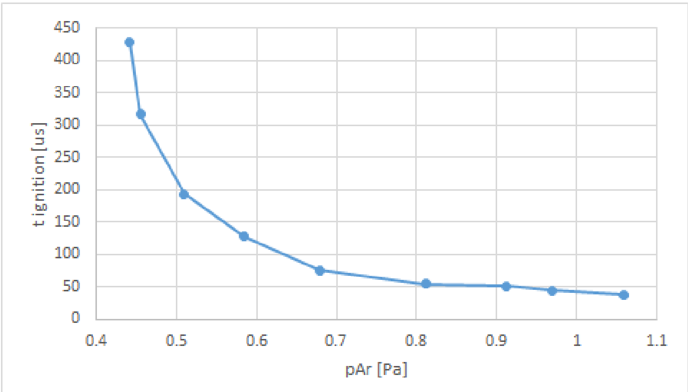

Figure 2.5: The delay of the discharge current pulse versus the chamber pressure measured in the presence of argon gas at $q_{Ar} = 6$ sccm.

The presented converter has been built and tested on a vacuum chamber (pages 81-86 of the manuscript) where it has been demonstrated to be suitable for plasma ignition and current control of the glow discharge, providing a straightforward approach for arc handling [1].

2.5 Thesis 5

I implemented a simple behavioral model in pSpice and have demonstrated that it is suitable for the qualitative reproduction of measurement results associated with physical phenomena characteristic for the pulsed magnetron discharge.

In order to study the interaction between the power electronic converter and the sputtering chamber in pulsed discharge mode, I proposed a behavioral model implemented in pSpice. The proposed converter topology resembles the "chopper" pulser with inductive energy storage. Its topology, along with a behavioral model of the magnetron discharge, is shown in Fig. 2.6 (and detailed on pages 94-96 of the manuscript). I used a chain of transient voltage suppressor (TVS) diodes to limit the CE voltage of the IGBT transistor represented in Fig. 2.6 by the ideal switch S1.

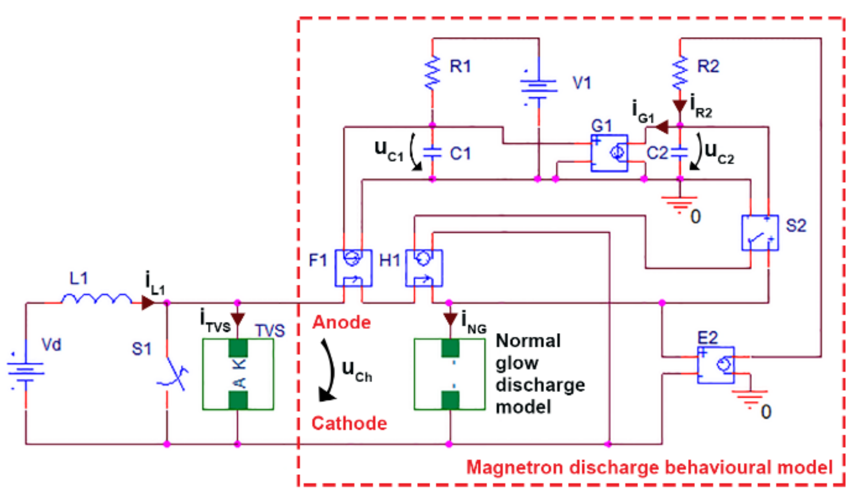

Figure 2.6: Simplified diagram of the behavioral model of the magnetron discharge supplied by a pulse generator with inductive energy storage.

Despite the complex behavior of the plasma in pulsed mode, assuming abnormal discharge mode, the converter-discharge interaction can be reproduced acceptably well for converter dimensioning purposes [6].

Chapter 3

Potential applications and broader impact

The following bullet points further emphasize the practical relevance of the Theses:

1. In Figure 3.3 there is block tasked with calculating the prescribed p_G according to the stoichiometry condition. This is a non-trivial task and the broader impact is having a direct equation to be able to determine this, namely Equation 3.4.

2. The potential implication of Thesis 2 is achieving a sputtering process that has higher yield than it would otherwise have, at the same time achieving stoichiometry without unwanted poisoning.

3. Thesis 3 has direct implications in the formation of a homogeneous thin film of a ternary compound (i.e. TiO_xN_y) using two continuously pumped reactive gases.

4. Thesis 4 covers pulsed mode sputtering, which is already widespread and facilitates not only higher energy levels but also deals with the unwanted buildup of charge carriers that lead to arcing.

5. The design of a power electronics converter for sputtering applications is a non-trivial task. Thesis 5 provides a method that directly addresses the question of component dimensioning of a converter.

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