Available online at www.sciencedirect.com
SCIENCE DIRECT®
Thin Solid Films 513 (2006) 1–24
thin solid films
www.elsevier.com/locate/tsf

Review
Ionized physical vapor deposition (IPVD): A review of technology and applications

Ulf Helmersson [a,*], Martina Lattemann [a], Johan Bohlmark [a], Arutiun P. Ehiasarian [b], Jon Tomas Gudmundsson [c]

[a] *IFM Materials Science, Linköping University, SE-581 83 Linköping, Sweden*
[b] *Materials and Engineering Research Institute, Sheffield Hallam University, Howard St, Sheffield, S1 1WB, UK*
[c] *Department of Electrical and Computer Engineering, University of Iceland, Reykjavik, Iceland and Science Institute, University of Iceland, Reykjavik, Iceland*

Available online 30 May 2006

Abstract

In plasma-based deposition processing, the importance of low-energy ion bombardment during thin film growth can hardly be exaggerated. Ion bombardment is an important physical tool available to materials scientists in the design of new materials and new structures. Glow discharges and in particular, the magnetron sputtering discharge have the advantage that the ions of the discharge are abundantly available to the deposition process. However, the ion chemistry is usually dominated by the ions of the inert sputtering gas while ions of the sputtered material are rare. Over the last few years, various ionized sputtering techniques have appeared that can achieve a high degree of ionization of the sputtered atoms, often up to 50% but in some cases as much as approximately 90%. This opens a complete new perspective in the engineering and design of new thin film materials. The development and application of magnetron sputtering systems for ionized physical vapor deposition (IPVD) is reviewed. The application of a secondary discharge, inductively coupled plasma magnetron sputtering (ICP-MS) and microwave amplified magnetron sputtering, is discussed as well as the high power impulse magnetron sputtering (HIPIMS), the self-sustained sputtering (SSS) magnetron, and the hollow cathode magnetron (HCM) sputtering discharges. Furthermore, filtered arc-deposition is discussed due to its importance as an IPVD technique. Examples of the importance of the IPVD-techniques for growth of thin films with improved adhesion, improved microstructures, improved coverage of complex shaped substrates, and increased reactivity with higher deposition rate in reactive processes are reviewed.

Keywords: Ionized physical vapor deposition; Sputtering; Plasma processing and deposition; Arc-evaporation

Contents

* Corresponding author. Tel.: +46 13 281685.
E-mail address: ulfhe@ifm.liu.se (U. Helmersson).

0040-6090/$ - see front matter
doi:10.1016/j.tsf.2006.03.033

1. Introduction

Deposition of thin films by physical vapor deposition (PVD) techniques has found widespread use in many industrial sectors. State of the art magnetron sputtering processes allow the deposition of metals, alloys, ceramic, and polymer thin films onto a wide range of substrate materials. Therefore, it is used for a wide field of coating applications for, e.g., metal-working industry, biomedical applications, and optical or electrical components. There is an increasing demand for coatings with tailored and enhanced properties such as high hardness, wear and corrosion resistance, low friction, and specific optical or electrical properties as well as decorative colors and often complex combinations of those properties are requested. For high-quality coating on temperature-sensitive substrates such as polymers, there is room for improvements using versatile PVD techniques. Furthermore, magnetron sputtering offers the possibility to synthesize materials outside thermodynamic equilibrium. Thus, it enables the deposition of metastable phases. The field of applications includes integrated circuit (IC) manufacturing applications such as the formation of diffusion barriers, and adhesion and seed layers on the side and bottom of high aspect ratio vias and trenches. With the fast development of the microelectronics industry in which the circuit dimensions shrink steadily, increasing the aspect ratio, successful coverage using magnetron sputtering becomes increasingly more challenging. The increased requirements on coating materials and the synthesis technique as well as the opening of new fields, therefore drive the development of enhanced deposition techniques allowing direct control of the sputtered flux and further decrease in the deposition temperature, by enhancing the adatom mobility through the momentum transfer to the film, and an increased chemical reactivity. Glow discharge methods like magnetron sputtering have the advantage that the ions of the discharge are abundantly available to the deposition process. However, the ions available are mainly the ions of the inert sputtering gas and ions of the sputtered material are rare. Over the last few years various ionized sputtering techniques have appeared that can achieve a high degree of ionization of the sputtered atoms.

This review is focused on the recent development of ionized PVD (IPVD) processes and applications. When the deposition flux consists of more ions than neutrals or $\Gamma_{M^+} > \Gamma_M$ the process is referred to as IPVD [1]. The development of IPVD-techniques was initially mainly driven by the need to deposit metal layers and diffusion barriers into trenches or vias of high aspect ratio IC structures [2–5], but has during the past years found a number of additional areas where beneficial properties are observed. The motion of neutral atoms is difficult to control but ions can be collimated by an electric field. A thin positively charged layer called sheath is formed near surfaces immersed in a plasma. The ions that enter the sheath region are thus accelerated towards the substrate and collimated due to the electric field across the sheath. Furthermore, the ion bombardment energy can be controlled by applying a bias voltage to the substrate. Because of the collimation, the ions may reach the bottom of deep narrow trenches or vias, while a neutral flux will tend to deposit on the upper part of sidewalls leaving the bottom with very little film coverage and possibly a void formation at the bottom of the trench. Thus, IPVD enhances step coverage, both bottom and lower sidewall coverage. Furthermore, ionizing the sputtered vapor has several advantages: improvement of the film quality, such as density and adhesion, especially for substrates of complex shape [6,7], control of the reactivity, extending the metallic sputtering mode regime [8–10], decreasing the deposition temperature [11], and guiding of the deposition material to the desired areas of the substrate [12].

Many different IPVD-techniques are available today. This review focuses on the fundamental aspects of ionization, on magnetron sputtering techniques and, in particular, the high power impulse magnetron sputtering discharge (HIPIMS). A non-sputtering IPVD-technique is also included in this review, which is cathodic arc deposition. The importance of the IPVD-techniques for the growth of thin films is demonstrated with examples of improved adhesion, improved microstructures, improved coverage of complex shaped substrates, increased reactivity and higher deposition rate in reactive processes.

2. Metal ionization — a simple model

Processing plasmas consist of both charged and neutral particles, and are generally referred to as weakly ionized plasmas [13]. In such a plasma, collisions of the charged particles with neutral gas atoms are of great significance and ionization of neutrals sustains the plasma in steady state. The plasma is characterized by the density and temperature of each specie and the electrons are usually not in thermal equilibrium with the neutral species and ions. These discharges are electrically driven and the applied power preferentially heats the more mobile electrons. Therefore, the electron temperature T_e can be significantly higher than the ion temperature. In a