Ionized physical vapor deposition (IPVD): Magnetron sputtering discharges

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Abstract. Over the past decade, various magnetron sputtering techniques have appeared that provide a high degree of ionization of the sputtered vapor. Here, ionized physical vapor deposition (IPVD) magnetron sputtering systems are reviewed. The application of a secondary discharge to a magnetron sputtering discharge, either an inductively coupled plasma source (ICP-MS) or a microwave amplified magnetron sputtering, is currently widely used. High power impulse magnetron sputtering (HiPIMS) is a sputtering technique where a high density plasma is created by applying high power pulses at low frequency and low duty cycle to a magnetron sputtering device. Other methods such as the self-sustained sputtering (SSS), and the hollow cathode magnetron (HCM) are discussed as well. Essential to these methods is a high electron density which leads to a high degree of ionization of the sputtered vapor.

1. Introduction
The magnetron sputtering discharge has found widespread use in various coating processes. In a conventional dc magnetron sputtering (dcMS) discharge a small fraction of the sputtered atoms are ionized. The development of ionized physical vapor deposition (IPVD) was initially driven by the need to deposit metal layers and diffusion barriers into trenches or vias of high aspect ratio integrated circuit (IC) structures [1, 2], but has during the past decade found a number of additional applications. When the deposition flux consists of more ions than neutrals the process is referred to as IPVD. If the sputtered vapor is ionized the ion bombardment energy can be controlled by applying a bias voltage to the substrate. This has several advantages: improvement of the film quality, such as density [3] and adhesion [4], especially for substrates of complex shape [5], control of the reactivity, decreasing the deposition temperature [6], and guiding of the deposition material to the desired areas of the substrate [7]. Here the different IPVD-techniques that are based on magnetron sputtering are reviewed. They include addition of a secondary discharge to a conventional magnetron sputtering discharge [2, 8, 9], shaping the target in a particular way [10] and the high power impulse magnetron sputtering discharge (HiPIMS) also referred to as the high power pulsed magnetron sputtering (HPPMS) [11, 12, 13]. A thorough review on IPVD techniques and its applications is given by Helmersson et al. [13].

2. Inductively coupled plasma-magnetron sputtering (ICP-MS)
In order to generate a highly ionized sputtered vapor a non-resonant induction coil is placed parallel to the cathode, in essentially a conventional dcMS apparatus, immersed or adjacent to
the plasma as seen in figure 1 [2]. The inductive coil is generally driven at 13.56 MHz using a 50 Ω rf power supply through a capacitive matching network, coupled to the plasma across a dielectric window [14]. Inductively coupled discharges are commonly operated in the pressure range 1–50 mTorr and applied power 200–1000 W resulting in electron density in the range of $10^{16} - 10^{18}$ m$^{-3}$, which increases linearly with increasing applied rf power. In an ICP-MS the metal atoms are sputtered from the cathode target using dc power and transit the dense plasma, created by the rf coil, where they are ionized. The metal ion fraction of the sputtered vapor increases and saturates as the rf power is increased [2]. The ion flux and the ion energy can be controlled independently by the applied rf power and the substrate bias voltage, respectively.

A global (volume averaged) model study of the plasma parameters and the ionization mechanism in an ICP-MS discharge shows that for electron density of $\sim 10^{18}$ m$^{-3}$, the ionized flux fraction for the sputtered metal is in the range 35 – 80 % and electron impact ionization is the dominant ionization process for the sputtered metal atoms [1]. Thus the dense background plasma is the key to achieve the highly ionized flux fraction.

3. Electron cyclotron resonance magnetron sputtering (ECR-MS)

A supplementary electron cyclotron resonance (ECR) discharge can be used to increase the ionization of the sputtered metal [8, 9]. ECR discharges are typically operated at microwave frequencies (e.g., $\sim 2.45$ GHz) with a strong magnetic field $B$, giving high plasma densities ($10^{17} - 10^{18}$ m$^{-3}$) and are commonly operated at low working pressures (0.1–10 mTorr) [14]. The introduction of a magnetic field leads to a resonance between the applied frequency $\omega$ and the electron cyclotron frequency $\omega_{ce} = eB/m_e$ within the discharge. Due to this cyclotron resonance, the gyrating electrons rotate in phase with the polarized wave launched. Figure 2 is a schematic diagram of the apparatus described by Xu et al. [9]. The two ECR discharge chambers are located at opposite sides of the main processing chamber. The magnetic coils are arranged around the periphery of each of the ECR discharge chambers generating a magnetic field of 875 G to satisfy the ECR condition in both ECR chambers. Thus, a highly ionized plasma is created in the region between the target and the substrate. The ion energy can be controlled by additional substrate bias.

Figure 1. An ICP-MS where a radio-frequency-driven inductively coupled discharge is placed parallel to the cathode in between the cathode and the substrate.

Figure 2. An ECR-MS apparatus, the two ECR discharge chambers are located at the opposite sites of the main processing chamber. A highly ionized plasma is created in the region between the target and the substrate.
4. High power impulse magnetron sputtering (HiPIMS)

A high power unipolar pulse of low frequency and low duty cycle can be applied to the cathode target to create very high plasma density and is referred to as high power impulse magnetron sputtering (HiPIMS). HiPIMS has the advantage of using essentially the conventional magnetron sputtering equipment except for the power supply. The power supply for a high power pulsed magnetron sputtering are usually based on an artificial pulse-forming network and consist of a single or multiple mesh LC networks. Sometimes the plasma is pre-ionized with a dc power supply [15]. An electric circuit diagram illustrating a pulse generator with a pre-ionizer is shown in figure 3. A dc power supply maintains a conventional dc magnetron discharge. The pulse generator consist of a discharge capacitor which is connected to be charged from a charging circuit through a thyristor switch. The capacitor $C_s$ is discharged over the electrodes of the sputtering device through an inductor $L$. The inductance coil is connected in series with the magnetron discharge in order to reduce the rate of current rise. The pulse length is typically 50 – 500 µs and the pulse frequency 1 – 1000 Hz. The high power pulse has a peak cathode voltage in the range 500 – 2000 V which gives peak power densities in the range 1 – 3 kW/cm$^2$ [11, 16]. The exact pulse shape is determined by the load, the discharge formed in the sputtering device, and depends on the gas type and gas pressure [17].

By pulsing the discharge, very high plasma densities ($> 10^{18}$ m$^{-3}$) in the vicinity of the substrate have been reported [17, 18]. Close to full ionization of sputtered metal atoms is achieved during the pulse and ionization fraction higher than 90 % has been reported [19]. A time dependent global (volume averaged) model of the discharge reveals a very high ionization fraction and that electron impact ionization is the dominant process in creating the metal ions [20]. However, there is a drawback, the deposition rate in a HiPIMS discharge is generally found to be lower, a factor of 4–7 lower, than in a conventional dcMS discharge at the same average power. One explanation for the reduction in deposition rate is that the sputtered material is ionized close to the target and the metallic ions can be attracted back to the cathode target [13, 21].

5. Other magnetron sputtering methods

Other methods of creating highly ionized sputtered vapor include shaping the cathode target in a particular way in order to confine the electrons, referred to as hollow cathode magnetron discharge [10, 22]. In a hollow cathode magnetron (HCM), an intense glow discharge forms in a cup-shaped cathode which confines the discharge both physically and electrostatically. The electrons are in an electrostatic mirror which forces them to oscillate until they are lost to

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**Figure 3.** An electric circuit diagram (after Kouznetsov [15]) of a HiPIMS pulse generator with a pre-ionizer. A dc power supply maintains a conventional dcMS discharge. The pulse forming circuit consists of a storage capacitor $C_s$ that is charged through a thyristor switch ($T_2$) from a charging circuit and a trigger circuit discharges the capacitor through a thyristor switch ($T_1$).
the open side or make an ionizing collision. The HCM is capable of operating at an order of magnitude higher power densities than a conventional planar magnetron discharge and can be operated at pressures of a few mTorr, or lower [22]. High-density plasma is generated both in the target region as well as in the vicinity of the substrate, where densities $\sim 5 \times 10^{17} \text{m}^{-3}$ have been reported [10].

Magnetron sputtering without the use of an inert sputtering gas is referred to as self-sustained sputtering (SSS) [23]. Inert gas is used to ignite the plasma, after which the inert gas is removed and the sputtering continues with ions of the sputtered material. The magnetron sputtering discharge is operated at very high power densities, 100–1000 W cm$^{-2}$. The plasma densities are expected to be of the order of $10^{18} \text{m}^{-3}$. The technique is particularly suitable for materials with high self-sputtering yield such as Cu and Ag. The advantages of the SSS technique include a very high sputtering rate, the absence of inert gas particles in the deposited film, as well as low operating pressures ($< 1 \text{mTorr}$).

6. Conclusion
The recent development of IPVD magnetron sputtering technology has been reviewed. Common to all the magnetron sputtering methods discussed is the creation of a high electron density and subsequent electron impact ionization of the sputtered vapor.

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