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Modulate the deposition rate through changing the combination of frequency and pulse width at constant duty cycle

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ABSTRACT

Due to the large degree of ionization of the sputtered flux and high quality film fabrication, high power pulsed magnetron sputtering (HPPMS) is widely used. However, compared with DC sputtering, low deposition rate is probably the drawback of the HPPMS technique and restricts its application. In order to increase the deposition rate of HPPMS, different combinations of frequency and pulse width at a constant duty cycle were used to modulate the deposition rate of the Ti film. The results showed that wider pulse width would be more effective than increasing frequency on improving titanium deposition rate for a constant duty cycle. The pulse width also would affect the power utilization ratio. Especially for a high duty cycle of 4.8% and 5.6%, a wider pulse was favorable to make full use of power on film deposition, resulting in a higher normalized static deposition rate. Meanwhile, with increase in pulse width for a constant duty cycle, adatom mobility and the deposition rate increased, contributing to growth of crystallite size and higher surface roughness of Ti thin films.

1. Introduction

As a promising physical vapor deposition (PVD) technology, magnetron sputtering is widely used in surface engineering area. Nevertheless, the degree of ionization of the sputtered particles is relatively low and this will decrease possibility in controlling the microstructure, phases, and chemical composition of the growing films [1]. In order to generate a highly ionized sputtered vapor, high power pulsed magnetron sputtering (HPPMS) have been put forward by Dr. V. Kouznetsov in 1999 [2]. For high power pulsed magnetron sputtering (HPPMS), high power is pulsed at low duty cycle to avoid substrate overheating and it can provide ionized flux for deposition [3]. Meanwhile, the film deposited by HPPMS has dense film structure, good mechanical properties and better adhesion than that deposited by directed current magnetron sputtering (dcMS). Furthermore, complex-shaped tools can be coated with better thickness uniformity and high deposition rate on surfaces oriented non-parallel to the target [4,5] by HPPMS. These advantages are generally associated with a large degree of ionization of the HPPMS sputtered flux. Unfortunately, due to the self-sputtering [6–8] and the low sputtering yield [9] at high power, the deposition rate of HPPMS is in a range of 15% to 90% to dcMS at the same average power [10]. From the view of the industry application, low deposition rate is probably the largest drawback of the HPPMS technique [11]. As the important parameter of HPPMS, pulse width together with frequency contributes to determine the duty cycle, which has a strong influence on the deposition rate. Konstantinidis [12], Bagcivan [13] and Jing [14] found that the deposition rate increased with the pulse width at a constant frequency. Chang [15], West [16] and Yin [17] observed that the deposition rate also increased with frequency increasing at a constant pulse width. But all these studies were based on changing the duty cycle through controlling frequency or pulse width to modulate the average power. The increase of average power would induce the deposition rate increase. But this tactics cannot be considered as a good method for improving deposition rate just through increasing duty cycle. An excessive duty cycle may cause heavy load of power and excessive high temperature of target. Hence, in order to increase deposition rate at a constant duty cycle and average power, the power of target should be make full use of for film deposition. From a practical point of view, it is hard to avoid the wastage of energy, such as the heat consumption of target. The normalized static deposition rate has been used to assess the power utilization ratio on film deposition, which is defined as the thickness of deposited film per time and power [9]. It is also influenced by the pulsing characteristics of the HPPMS discharge. In this paper, different combinations of frequency and pulse width at a constant duty cycle were used to modulate the deposition rate of the Ti film, and the effect of different combinations of frequency and pulse width on deposition rate, the normalized static deposition rate and film quality was studied in detail.

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2. Experimental details

The titanium film was deposited on Si (100) wafer by a closed-field unbalanced magnetron sputtering system (shown in Fig. 1), which was equipped with four rectangular shaped unbalanced magnetrons and a high power pulsed power supply [14]. The cathode was operated by a pulsed power supply delivered by Chengdu Pulsetech Electrical (HPS-450D, China). During the deposition, only the target D (125 * 150 mm^2) was used as shown in Fig. 1. Si (100) wafer was mounted on a substrate holder with a target to substrate distance of 60 mm. The argon flow rate was uniformly 60 sccm, which was controlled by a mass flow controller. The substrate bias voltage was set to −50 V, which was controlled by a dc bias power supply. The deposition time was 10 min. A constant HPPMS voltage 800 V was used at different constant duty cycles. The peak current density was 0.747 A/cm^2 and the peak power density was about 0.213 kW/cm^2. Different combinations of frequency and pulse width at a constant duty cycle were set, and the duty cycle was regulated ranging from 2.4%–5.6%, which were shown in Table 1.

During sputtering, the target current $I(t)$ and voltage $V(t)$ were measured by a digital oscilloscope (Tektronix, model TDS-220) with a current monitor (Pearson, Model 411) and a voltage probe (Tektronix, model P-5100), respectively. In the experiments, we focused on the consumed electrical power $P(t)$:

$$P(t) = V(t) \times I(t), \tag{1}$$

where $V(t)$ and $I(t)$ were the time-dependent discharge voltage and current, respectively. The energy E_D consumed in the HPPMS glow plasma was calculated by

$$E_D = \int_0^\tau P(t)dt, \tag{2}$$

where τ was the pulse width. The average consumed power P_{ave}, the pulse power P_{mean} and the charge Q which was equal to the integral of current in a pulse were calculated as follows:

$$P_{ave} = f \times E_D = f\int_0^\tau V(t)I(t)dt, \tag{3}$$

$$P_{mean} = \frac{E_D}{\tau} = \frac{1}{\tau}\int_0^\tau V(t)I(t)dt, \tag{4}$$

$$Q = \int_0^\tau I(t)dt. \tag{5}$$

In order to investigate the plasma composition of the discharge at different duty cycles, optical emission spectroscopy (OES) measurements (Avantes, AvaSpec-2048-7-USB2) were performed. The optical fiber connected with the spectrometer through an optical feedthrough was located on the top of the vacuum chamber. In addition, the probe of the optical fiber was faced to the cathode surface. The light emission was investigated simultaneously in the spectral range of 250 nm to 500 nm. The measured spectra were analyzed by spectrum analyzer (Avantes, AvaLIBS-Specline-AMS). The film thickness was measured using a surface profiler (AMBIOS model XP-2, USA). The Ti films were characterized by XRD (PHILIPS, PW3040,) with Cu Kα radiation for the phase identification, grain size measurement and texture analysis. The scan rate was 1° min^{-1} and the scan range was from 30° to 50°. The surface morphology of the Ti films was studied using AFM (Asylum Research, USA) operated in semi-contact (tapping) mode.

Table 1
The combinations of frequency and pulse width at a constant duty cycle (2.4%, 3.2%, 4.8% or 5.4%)

Frequency and pulse width	Duty cycle	Pulse power (kW)	Average power (W)	Discharge pressure (Pa)	Thickness (nm)
400 Hz, 60 μs	2.4%	33.9	813.8	1.0	205.9
240 Hz, 100 μs		39.7	952.1	1.0	234.8
400 Hz, 80 μs	3.2%	38.3	1225.8	1.1	364.0
320 Hz, 100 μs		41.1	1315.3	1.0	303.6
400 Hz, 120 μs	4.8%	42.1	2033.4	1.1	701.8
480 Hz, 100 μs		42.4	2021.4	1.1	609.1
400 Hz, 140 μs	5.6%	44.3	2483.4	1.1	886.3
560 Hz, 100 μs		41.8	2341.3	1.1	728.0

3. Results and discussion

Different combinations of frequency and pulse width at a constant duty cycle were set to prepare the Ti film, and the duty cycle was set ranging from 2.4%–5.6%. The detail experiment parameters are shown in Table 1. The target voltage and the current through the circuit during the film deposition are shown in Fig. 2. It is interesting to note that the shapes of all the target voltage at different duty cycles are square pulse. The target voltage shows a source voltage 800 V at the beginning of the pulse, and it is followed by an abrupt decrease to steady state about 400 V after 15 μs. The abrupt decrease of the voltage may be due to the limiting resistor R1 in HPPMS system shown in Fig. 1 and this limiting resistor shares voltage during sputtering. The low steady voltage may attract less metal ions back to target and reduce the effect of self-sputtering. For the discharge current at different duty cycles, after the onset of pulse, the discharge current increases rapidly to the maximum value approximately 140 A at about 60 μs, and then tends to be stable. It is found that the duration of the current at stabilization regime depends on the length of pulse width, which is further associated with the regime of stationary plasma and this will be discussed later. Once the

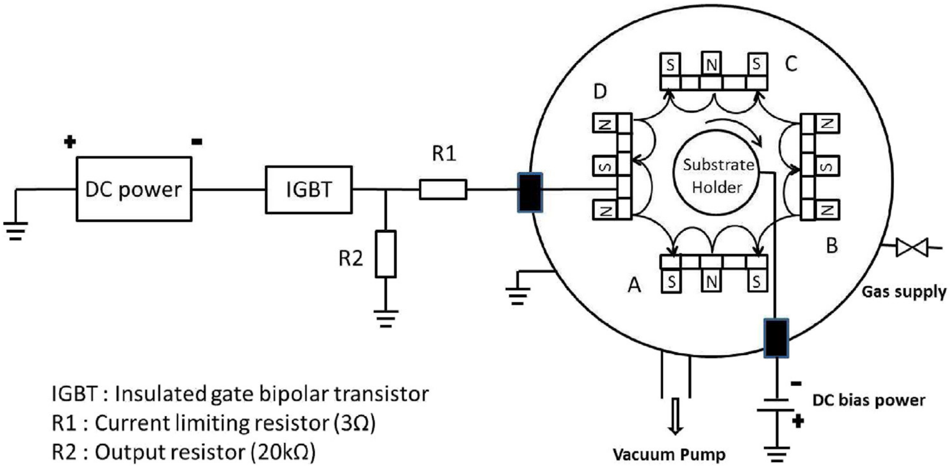

Fig. 1. The schematic configuration of the HPPMS [13].