Growth Rate of Titanium Thin Film by High-Power Pulsed Sputtering (HPPS) Penning Discharge Plasma with the Inner Electrode

Kingo Azuma, Toru Higuchi, Yusuke Inoue

Department of Electrical Engineering and Computer Sciences, University of Hyogo, 2167 Shosha, Himeji, Hyogo, Japan

E-mail: easter11_azuma@mem.iee.or.jp

Abstract. High-power pulsed sputtering (HPPS) penning discharge is featured that the plasma is generated at a narrow gap consisting of a pair of cathodes as sputtering target in parallel each other. The magnetic field is provided by setting a set of permanent magnets behind the targets and the electric field is parallel to the magnetic field. The conventional HPPS penning plasma source is disadvantage in a narrow pressure range on the plasma production, and in particular, the lower limit of the pressure is 2 Pa or higher. This problem has been solved by setting an electrically-grounded electrode at the central region of the plasma source. The lower limit of plasma generation is lowered to about 0.5 Pa. In the case of titanium target, titanium films are deposited on the collector electrode for an HPPS Penning discharge in the presence of the inner electrode, and the deposition rate is 16 nm/min at argon gas pressure of 0.5 Pa, where the peak power is 15 kW at power consumption of about 310 W.

1. Introduction

The sputtering deposition is one of the technologies that cover the surface of a substrate with functional thin film. It is known as the deposition process to able to form dense thin film. Especially a magnetron sputtering process has high deposition rate. However, improvements of film quality and adhesion are horny issues for the magnetron sputtering because the ionization rate of the sputtering particles is very low. These problems may be cleared up by a high power pulsed sputtering (HPPS) discharge. HPPS glows produce high density metallic ion species, and the thin film physical vapor deposition coating using these plasmas is emerging technologies both to improve tribological characteristics and to control film structure.

There are two major categories of HPPS discharge plasma by the relation of direction of an electric field and a magnetic field. One is HPPS magnetron discharge plasma [1], the other is HPPS penning discharge plasma [2]. At the magnetron discharge, an electric field and a magnetic field intersect perpendicularly in the ion sheath. In general, HPPS discharge means HPPS magnetron discharge, because the magnetron electrode is commonly used in the sphere of the hard coatings. One of the weak points of metal coating by HPPS magnetron discharge is to generate reflected high energy neutrals. These arise from ions bombarding a surface in a low-pressure environment [3]. These have a bad influence on the film quality on workpieces in many cases [4]. HPPS penning discharge technology can control generation of particles. It is largely based on configuration of target electrodes.

HPPS penning discharge is featured that the plasma is generated at a space consisting of a pair of cathodes as sputtering target in parallel each other [2]. The chamber wall works as an anode to collect electrons. The electric field is parallel to the magnetic field at the narrow gap. The magnetic field is provided by setting a set of permanent magnets behind the targets. Energetic argon ions accelerated by a voltage difference between the cathode and the plasma bombard the target to sputter metallic species, which are mixed in the plasma and ionized. Second emission electrons from the target are even strongly ionized metallic particles. The reflected high energy neutrals is trapped the narrow space. Therefore these rarely reach the workpieces.

The plasma density of HPPS penning discharge plasma is as high as 10^{18} m^{-3} due to high power consumption on the order of 100 kW [5]. The fraction of titanium ions is about 70% [6]. However, the HPPS source is disadvantage in a narrow pressure range on the plasma production, and in particular, the lower limit of the pressure is 2 Pa or higher. This problem has been solved by setting an electrically-grounded rod (inner electrode) at the central region of the plasma source.

2. The experimental setup

A HPPS penning discharge plasma source is configured a pair of cathode targets, permanent magnets, U-type magnetic yoke and inner electrode. The cathode targets have the same potential. A magnetic field is created by a set of permanent magnets installed behind the targets. The magnetic field is oriented perpendicular to the targets. When a pulsed voltage is applied to the targets and initial plasma is ignited in the narrow gap, the electric field in the ion sheath of target electrodes is parallel to the magnetic field. Thus, the plasma is a kind of Penning discharge [7].

HPPS plasma was generated at the gap formed by a pair of parallel targets. The surface area of each target was 12 cm^2 (length: 60 mm and height: 20 mm). The gap length was 10 mm, and the target material was titanium. A magnetic field was oriented perpendicular to the targets, at strength of approximately 0.3 T at the target surface. The inner electrode is inserted into the center void of the magnetic yoke. It is grounded. The gap distance of the inner electrode and the yoke is 2 mm.

Figure 1 shows a schematic diagram of the experimental set up. The vacuum chamber had an inner diameter of 310 mm and a height of 300 mm. A pulsed voltage was supplied from the pulsed power source (maximum ratings: current of 100 A, output voltage of –800 V, repetition rate of 5 kHz, and pulse duration of 1-200 μs). The plasma was generated in an argon environment. The argon gas pressure was varied 0.5 Pa to 3 Pa. The applied voltage was –800 V with a repetition rate of 500 Hz. The current through the circuit was regulated by a series resistor, R_S (the maximum rated power of a unit resistor was 300 W).

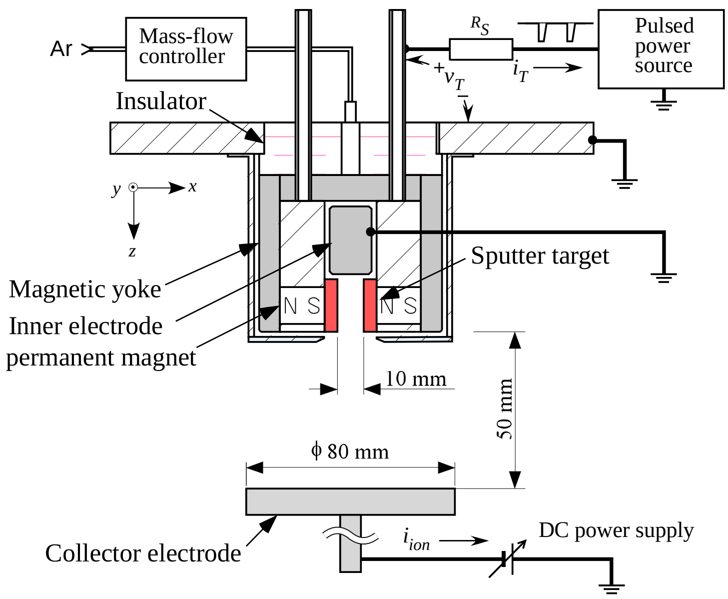

Figure 1. The experimental setup.

The evacuation system consisted of a turbo molecular pump (TMP, 350 L/min) (as the main evacuation device), a mechanical booster pump (MBP) and a rotary pump (RP) (as a backup for the TMP). The inlet gas pressure was controlled by a mass flow controller. The argon gas was introduced from behind the plasma source through a ¼ inch-PFA (Perfluoroalkoxy) tube. The pressure inside of the vacuum chamber was measured using a ceramic capacitance manometer (ULVAC, GM-2001/CCMT-10A, range of measurement: 1.3×10^{-1} to 1.3×10^{3} Pa) and an ionization gauge (ANELVA, MIG-430/MG-2, range of measurement: 10^{-6} to 13 Pa).

The target current, i_T, through the circuit was observed using a current transformer (Pearson type 110A, sensitivity: 0.1 V/A, rise time: 18 ns, observatory bandwidth: 1 Hz-20 MHz). The target voltage, v_T, was observed using a voltage probe (Tektronix, type 5100, rated voltage: DC+AC peak of 2.5 kV, frequency bandwidth: DC-250 MHz). Waveforms were monitored with an oscilloscope (Tektronix, TDS3034B, bandwidth: 300 MHz, maximum sampling rate: 2.5 GS/s).

In order to extract ions from the HPPS plasma, a disc-shaped holder electrode with a diameter of 80 mm was positioned nearby the plasma source. As shown in Figure 3, the distance from the edge of the plasma source was 50 mm. A negative voltage was applied to the collector electrode at –50 V. The measured current is ion current, i_{ion}, because the floating potential of the collector is about –20 V.

3. Results

3.1. Temporal electrical characterisation

Figures 2 (a), (b) and (c) show waveforms of target voltage, v_T, target current, i_T, and ion current, i_{ion}. The pulse duration was 50 μs and the initial target voltage was –800 V. The series resistor, R_S, set in the plasma generation circuit had a resistance of 10 Ω. The source voltage was maintained constant during the plasma generation. Thus, the source voltage is delivered to R_S and the plasma.

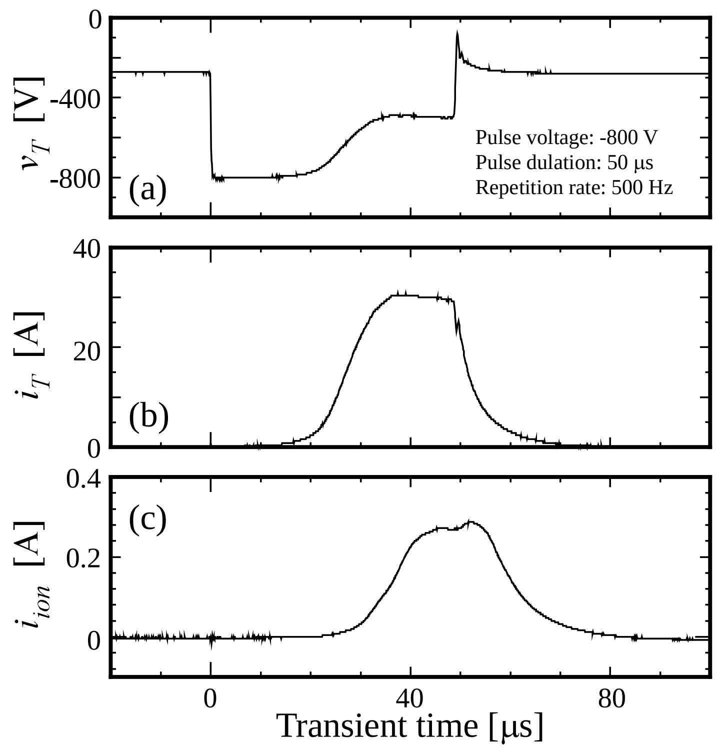

Figure 2. Typical time response of (a) target voltage V_T, (b) target current i_T and (d) ion current i_{ion} on the collector electrode under the ambient argon gas pressure of 0.5 Pa.

Just after a pulse voltage is applied to the target, the voltage shows the initial source voltage, because there is no plasma generation. The voltage begins to decrease after less than a dozen microseconds, which indicates HPPS plasma generation. The target voltage then gradually decreases, followed by a stationary state. Thus, a constant glow voltage is observed after approximately 35 μs.

It is shown in Fig. 4 that the glow voltage and current at 35 μs are approximately −500 V and 30 A, respectively, at a pulse duration of 50 μs. Thus, the instantaneous power consumption is obtained by the product of these values and is approximately 15 kW. Ion current rises later than target current about 10 μs. The peak of ion current appears about 5 μs after a pulse-off time, and is decreased after that. The peak value of ion current is about 290 mA.

3.2. Gas pressure dependence

Figure 3 shows the gas pressure dependence of average power and ion charge. The average power P_{ave} is the value which carried out the time average of the instant electric power $p_T(t)= v_T(t)\times i_T(t)$ supplied to a plasma source, and is denoted by the following formula:

$$P_{ave} = f\int_0^{1/f} p_T(t)dt \qquad (1)$$

where f is the repetition frequency of high-voltage pulses. Average power declined with the fall of gas pressure p. When p was less than 0.7 Pa, the decreasing rate became large greatly at gas pressure. Average powers ware 305 W at p = 2 Pa and 190 W at p = 0.5 Pa.

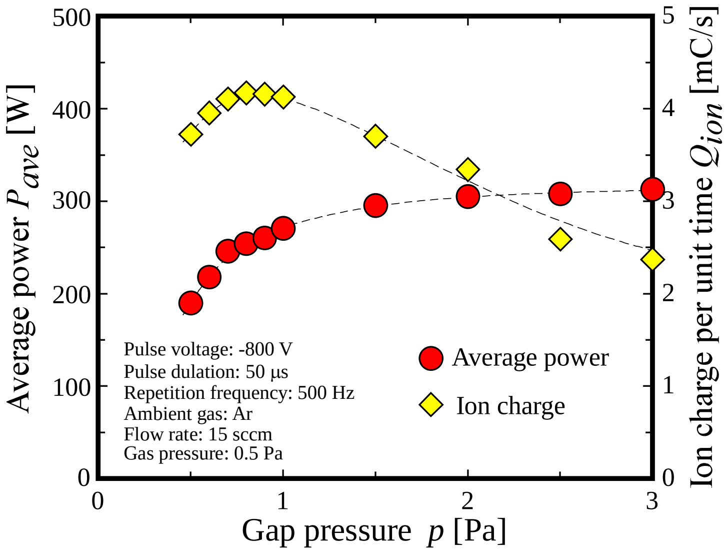

Figure 3. The gas pressure dependence of the average power and the ion charge at the collector electrode.

The ion charge quantity per unit time Q_{ion} on the collector electrode is given by the following formula:

$$Q_{ion} = f\int_0^{1/f} i_{ion}(t)dt \qquad (2)$$

Ion charge increased with the decreases of gas pressure, and became the maximum at $p \approx 0.8$ Pa. When p is less than 0.7 Pa, Ion charge Q_{ion} decreased, and Q_{ion} was 3.7 mC/s at p = 0.5 Pa.

While gas pressure becomes low, although average power (as it is called power consumption) decreases, ion current increases. That is, the ion charge per power consumption, Q_{ion}/P_{ave}, increases under low-pressure power. This has suggested that the rate of the metal ions contained in plasma increases.

3.3. Growth rate of titanium film

The silicon substrate was placed on the collector electrode and the titanium thin film was made to deposit for 30 minutes. The thickness of the thin film was measured using a step gauge (VEECO DEKTAK 3 ST AUTO I). Growth rate of the titanium film was determined from film thickness. The relation between the pulse duration of a high-voltage pulse and the growth rate of the titanium film is shown in Fig. 4.

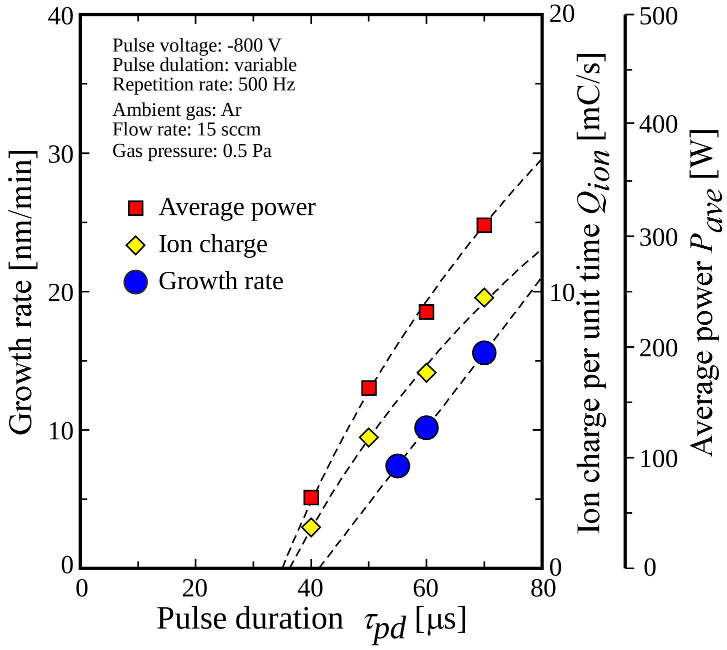

Figure 4. The pulse duration dependence of the average power, the ion charge and the growth rate.

Each of average power, ion charges, and film forming speed increased with the increase in pulse duration. When pulse duration was 70 μs, the average power was 310W, the ion charge is 9.8 mC/s and the growth rate is 16 nm/min. Also, the peak power is 15 kW and peak current is 27 A.

The growth rate increases almost linearly to pulse duration. A fitting analysis has suggested that titanium deposition occurs with the pulse duration for 41 μs or more. On the other hand, the relation between average power and pulse duration has indicated HPPS discharge occurs with the pulse duration of 35 μs or more. In HPPS penning discharge, the metal plasma is produced between a pair of target electrodes. Since the electrons are trapped by the magnetic field and the electric field between target electrodes, plasma is not diffused on the outside of a plasma source if the plasma density does not become high enough. Metal neutrals and ions reach the collector electrode with diffusion of plasma. So, it is thought that the minimum pulse duration required for deposition becomes larger than it for generating HPPS plasma.

4. Conclusion

The HPPS penning discharge plasma source was disadvantage in a narrow pressure range on the plasma production, and in particular, the lower limit of the pressure was 2 Pa or higher. This problem has been solved by setting an electrically-grounded electrode at the central region of the plasma source. According to the results, the lower limit of plasma generation was lowered to about 0.5 Pa with setting the inner electrode. Titanium films were deposited on the collector electrode for an HPPS discharge in the presence of the inner electrode. The deposition rate was about 16 nm/min at argon gas pressure of 0.5 Pa, applied voltage of –800 V, pulse duration of 70 μs and repetition rate of 500 Hz. At this time, the HPPS penning plasma source has target current of 30 A and the peak power of 15 kW and power consumption of 310 W.

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