Vacuum 84 (2010) 1368–1371

Contents lists available at ScienceDirect

Vacuum

journal homepage: www.elsevier.com/locate/vacuum

Effect of the target bias voltage during off-pulse period on the impulse magnetron sputtering

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ARTICLE INFO

Article history:
Received 6 July 2009
Received in revised form
7 January 2010
Accepted 7 January 2010

Keywords:
Impulse magnetron sputtering
Bias voltage
After glow plasma diffusion

ABSTRACT

With a high-power impulse magnetron sputtering (HiPIMS) apparatus, it has been studied how the target bias voltage during the off-pulse period affects the stability of the generated plasma. We have prepared an electrical pulse power source which can control the target voltage during the pulse off period, in addition to the pulse voltage, repetition frequency and a duty ratio of the pulse. Time-resolved current-voltage characteristic was monitored by an oscilloscope, and plasma generation behavior was elucidated. With titanium target and at Ar gas pressures of 0.6–5 Pa, pulse-off bias voltage was changed between −300 and +100 V, and the I-V characteristics were recorded. On increasing the negative bias voltage, the time at which the target current began to rise was gradually delayed. And at a certain voltage, the delay suddenly disappeared. This voltage was found to be the sustain voltage of the dc discharge in the same condition. Applying positive bias voltage resulted in a much longer delay. These results suggest that the minimal discharge during the pulse-off period helps the initiation of high-density plasma, while the bias voltage which can not maintain the plasma contrarily hampers it.

1. Introduction

High-power impulse magnetron sputtering (HiPIMS) is a kind of IPVD (Ionized Physical Vapor Deposition) processes and has been attracted attentions recently [1,2]. The concept of the IPVD process is to ionize sputtered particles in a discharge plasma before they reach a substrate. It enables the control of the energy and/or the direction of depositing particles easily by applying bias voltage to the substrate. It has been successfully utilized to the film structure modification, enhancement of side and bottom coverage of the via/trench structure [1]. For efficient ionization of sputtered particles, it is required to prepare a plasma with the electron density of 10^{18}–10^{19} m^3 or higher [2]. By simply applying high electric discharge power to a conventional magnetron sputtering system, it is difficult to achieve this level of high-density plasma because the target cathode is damaged by the thermal load. To overcome this difficulty, the concept of HiPIMS has been proposed. It applies a high power to produce a high-density plasma, for a short period of time with a low repetition frequency. By this, we can produce a required high-density plasma with a sustainable target temperature.

Since HiPIMS is a kind of intermittent discharge, many researchers have been paying attention to the transient property of the plasma formation process after the pulse power is applied to the target cathode. For example, Gudmundsson *et al.* [3] and Alami *et al.* [4] have studied the spatial and temporal properties of HiPIMS plasma by electrostatic probes and discussed evolution and propagation processes of the plasma with their pressure dependences. More recently, Anders *et al.* measured the transient I-V characteristics with a constant voltage pulse applied to the target, and discussed the required periods of time for plasma ignition, cathode sheath formation and the metal plasma generation after the pulse is on [5].

Relating to this discussion, Vašina *et al.* proposed that the application of bias voltage to the target during the pulse-off period could help the prompt generation of high-density plasma after the pulse was on by keeping the minimal discharge during the off period [6]. This kind of bias voltage application is called as the "pre-ionization" and has been reviewed in ref. 2. On the contrary, reversed bias to the pulse voltage has also been reported to have an interesting effect for mid-frequency pulse processes [7]. It raises the potential of after-glow plasma compared to grounded chamber walls (including substrates), so that the raised incident energy of ions to the substrate may affect the growing film structure and other properties.

In this study, we have prepared an electrical pulse power source which can control both pulse-on and pulse-off voltages. The switching of these voltages is achieved by IGBT (Insulated Gate Bipolar Transistor), so that the pulse duration can be controlled as desired. With this apparatus, the transient I-V characteristic can be measured and the effect of pulse-off bias voltage on the plasma

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doi:10.1016/j.vacuum.2010.01.014

formation will be discussed. Especially, the delay of the current rise after the application of pulse-on voltage has been observed and its dependence on the pulse-off voltage is discussed.

2. Experiment

The schematic circuit diagram of the developed custom-built power source (Heiwa Dengen) is given in Fig. 1. It consists of two dc power sources independently switched by respective IGBTs (SEMIKRON SKM200GB176D) to which control signals with reversed polarity are applied. The pulse-on voltage V_p is adjustable between 0 and -1.5 kV, and the pulse-off voltage V_b between 0 and ± 300 V. Note that IGBT works as a diode during the on-state, $V_b = +0$ and $V_b = -0$ cases are different by the rise/decay time.

The generated pulse voltage is then applied to the target through the low-pass filter (161.3 kHz@3db, for the protection of IGBTs and dc power sources from the plasma noise), and applied to the target. In this study, the target current was measured using the current probe (Yokogawa, 701 930) whose cut-off frequency (@3dB) was 10 MHz. Its output and the 1000:1 dropped target voltage were monitored by an oscilloscope (Agilent, DSO3062A) and recorded by a PC connected to it.

Experiments were performed with a conventional magnetron sputter-deposition system. The chamber has a cylinder form with 210 mm in diameter and 250 mm in height. It equips a sputter gun on its symmetric axis which holds a 50 mmφ titanium disk target of 99.9% purity. During the plasma *I-V* measurements in this study, the substrate holder was not introduced, and the distance between the target surface and the upper bound of the chamber was about 150 mm. Therefore, the discharge anode was considered to be the guard electrode around the target.

The system was evacuated with a turbo molecular pump as low as 4×10^{-5} Pa. Then 20 sccm of Ar gas was introduced, and by throttling the evacuation valve, the gas pressure was set to 0.6–5 Pa, which was monitored by a capacitance manometer (MKS Baratron 626). After that, the target power was applied and the plasma discharge was generated. In this study, the pulse repetition frequency and the duty ratio of the pulse were fixed to 200 Hz and 10%, respectively.

In a part of the experiment, the plasma discharge was generated with a dc power source (Advanced Energy, MDX-1.5 k) to determine the sustainment voltage of the dc plasma at each gas pressure.

3. Results and discussion

The current-voltage (I_p-V_p) characteristics of the discharge measured behind the IGBT switch are shown in Fig. 2. It can be considered as the time averaged (including both pulse on and off periods) *I-V* characteristics of the discharge. Note that the V_p actually had a negative polarity compared to the chamber ground, and the horizontal axis of Fig. 2 is an absolute value. In this pressure region, the discharge started at the lower V_p and the current increased more steeply as the gas pressure increased. As described in the Experimental section, $V_b = +0$ and $V_b = -0$ cases are not identical with our power source, so the results for both cases are plotted in the Fig. 2. The I_p-V_p curve did not strongly depend on this polarity, but at higher pressures, the $V_b = +0$ case resulted in slightly larger I_p.

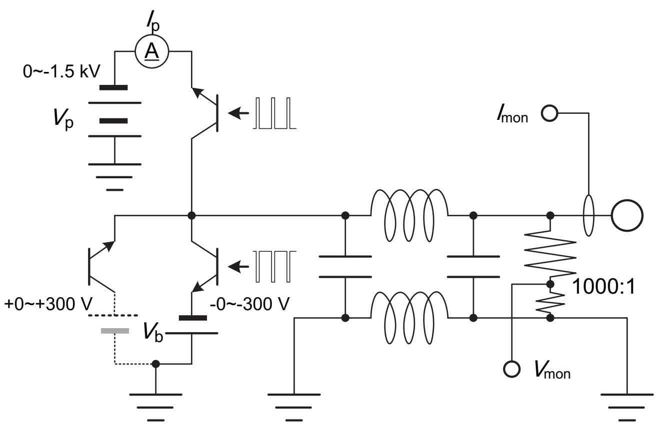

Fig. 1. Pulse power source with controllable bias voltage.

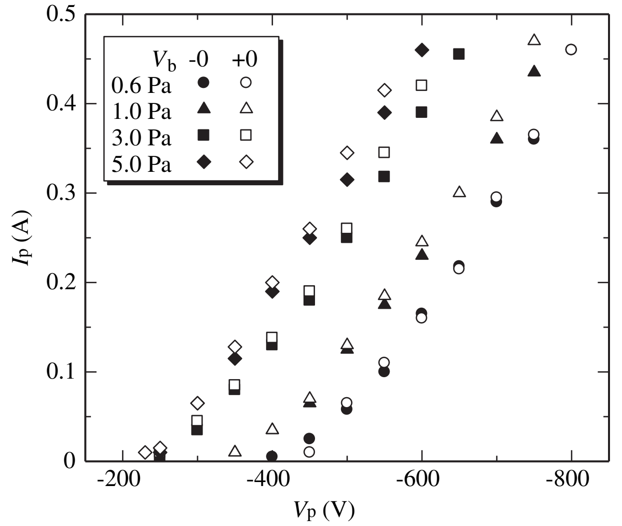

Fig. 2. Time averaged I-V characteristics measured behind the IGBT.

After the discharge conditions were confirmed, time-resolved target voltage and current waveforms were monitored with the oscilloscope. Fig. 3 shows typical target voltage waveforms measured at V_{mon} in Fig. 1. The gas pressure was 0.6 Pa and V_p was -500 V. The voltage of -500 V was reached after several tens of μs, and was kept until 500 μs at which IGBTs were switched. After that, the target voltage behaved quite differently by the polarity of V_b. It quickly reached to the set value for $V_b \geq 0$, while for $V_b \leq 0$ it showed a much longer decay time after it once promptly dropped to ∼∼250 V. For $V_b = -0$ case, the target voltage reached to 0 V with a few ms. For $V_b < 0$, the target voltage also decayed with a similar manner and pinned at the set value. We consider that it is due to the polarity of the IGBT. Once the plasma is extinguished (at -250 V, see the later discussion) in the $V_b \leq 0$ circuit, the negative target voltage cannot be released through the IGBT, so it have to obey much slower CR decay.

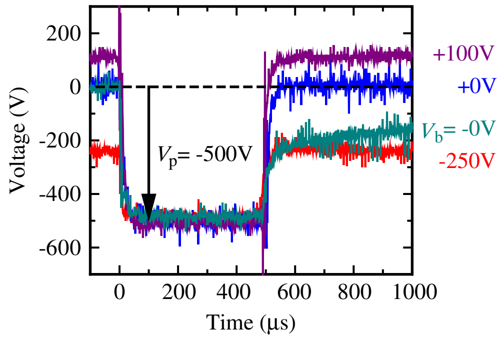

Fig. 3. Pulse voltage waveforms at 0.6 Pa.