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Effects of target voltage during pulse-off period in pulsed magnetron sputtering on afterglow plasma and deposited film structure

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A B S T R A C T

In this study, we investigated the effect of the target bias voltage during the pulse-off period in the pulsed magnetron sputtering (PMS) of repetition frequency 200 Hz and duty ratio 5–20%. Copper films were deposited by the PMS for Ar gas pressures of 1–5 Pa (with and without the pulse-off target voltage) and compared with those deposited by DC magnetron sputtering (dcMS). The time-averaged power was set to 100 W. Compared to films deposited by dcMS, those deposited by PMS showed smooth surface and a ductile nature. These properties became more evident when the positive pulse-off voltage was applied. To clarify the reason for film structure modification, the plasma was investigated by time resolved Langmuir probe measurement. It was confirmed that electron density was as high as 10^{17} m^{-3} in PMS mode during the pulse-on period. On applying +40 V of pulse-off target voltage, the plasma potential was found to be raised by about 30 V in comparison to the zero voltage case. We suggest that this increase in the plasma potential leads to an increase in impinging energy of Cu ions on the substrate, and modifies the deposited film structure. Though the pulsed plasma we used was in the modest power range, we expect this approach is applicable to high-power impulse sputtering (HiPIMS) mode with high degree of ionization.

1. Introduction

Since the proposal by Kouznetsov and coworkers [1], high-power impulse magnetron sputtering (HiPIMS) has attracted interest not only for academic research but also by the industrial community as a promising candidate to prepare high quality films on low temperature substrates. It is a kind of ionized physical vapor deposition (IPVD) processes and utilizes short high-power pulses with rather low repetition frequency (~1 kHz or lower) to produce high density plasma while avoiding a severe thermal load on a cathode target [2–4]. With the high density plasma, the ionization of sputtered atoms is enhanced which enables the control of energy/direction of the ions as they impinge onto the growing film surface. By this, the film structure can be controlled as well as the bottom/sidewall coverage in grooves on substrate surfaces [1,4,5].

In HiPIMS, the target voltage during the pulse-off period can be an experimental parameter. It has been reported that by applying a negative voltage to sustain minimal discharge during the pulse-off period, the ignition of the high density plasma can be assisted in the following pulse-on period [3,6]. In our previous study, we measured the target *I–V* characteristics of the pulsed magnetron sputtering (PMS) plasma, and found that the behavior of the plasma could be modified by the target voltage during the pulse-off period [7]. Depending on the voltage, the delay of the target current after the pulse voltage changed. When small negative voltage was applied during pulse-off period, the delay gradually increased but suddenly dropped to zero near the plasma sustainment voltage in DC discharge. It was suggested that the minimal plasma kept during the pulse-off period helped the generation of high density plasma in the following pulse. On the other hand, when we applied positive pulse-off voltages, very long delay was observed even at small voltages as low as +10 V.

It was considered that the target voltage during the pulse-off period affected the dissipation behavior of the afterglow plasma. When the plasma gets in touch with an electrode, its charge density profile varies to shield the electric field originating from it. If the voltage of the electrode is positive, due to the difference in mobility of charges of both polarities, the plasma potential is expected to rise. This enhances the ambipolar diffusion of the afterglow plasma, and the plasma tends to disappear promptly.

To exploit the full benefit of the highly-ionized sputtered particles in IPVD, substrates are generally biased negatively to form a potential difference that increases the incident energy of these

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ionized particles. If the plasma potential can be controlled to make it more positive, this substrate bias may become unnecessary. Similar effect has already been reported in mid-frequency pulsed magnetron discharge [8]. Combining this with the high density plasma of HiPIMS, more distinct effect on the film structure can be expected.

We have made a systematic investigation of the effect of the positive pulse-off target voltage on deposited copper film structure in this study. We also made a plasma diagnostics of the PMS plasma with a Langmuir probe to confirm the plasma potential during the pulse-off period as well as other plasma parameters. Copper is an important material for the metallization via sputter deposition, and has been one of main targets in HiPIMS studies [1,9–11]. While these HiPIMS studies utilize very high peak target current above a few tens of amperes for a 2 or 3 inch target which commonly leads to the self-sputtering mode [12], we use a more modest condition in this study to clearly observe the effect of pulse-off voltage. Still, we expect the approach we proposed is applicable to HiPIMS cases.

2. Experiment

The sputter deposition system used in this study was described in detail in our previous paper [7,13]. The chamber is a cylinder of 21 cm in diameter and 25 cm in height. It was evacuated by a turbo molecular pump down to 4 × 10^{-5} Pa. A copper disk target (4N purity) of 5 cm diameter was attached to a sputter gun with slightly unbalanced magnetron configuration. After the evacuation, 20 sccm of argon gas (4.5N) was introduced and the pressure was set to 1–5 Pa by throttling the evacuation valve. As a discharge power source, we applied a custom-built pulse power source (Heiwa Dengen) which equips two independent IGBT semiconductor switches to control both pulse-on and -off voltages [7]. The repetition frequency, duty ratio and the time-averaged power of the applied pulse power in this study were 200 Hz, 5–20% and ~100 W, respectively. "Time averaged" in pulse cases takes both on and off periods into account. Namely, since the repetition frequency was 200 Hz, energy per pulse was set to 0.5 J for average power of 100 W, for example. During pulsed discharge, waveforms of target current and voltage were recorded by an oscilloscope, (Agilent Technologies, DSO 3062A), and time-averaged target power was obtained. During the discharge, we controlled the pulse-on target voltage and set this average power to a desired value. We also used a DC power source (Advanced Energy, MDX-1.5 k) for comparison.

With this sputtering system, three types of experiments were conducted. In all of these three experiments, the distance from the target surface to (holders/probe end) was set to 50 mm. At first, the deposition rate was measured with quartz crystal microbalance (QCM) attached to a holder 8.4 cm in diameter [13]. Secondly, copper film was deposited on HF treated low resistivity n-Si (111) substrates. In this case, average power was set to 100 W and films were deposited for 15 min. Substrates were fixed tightly to a water-cooled copper block substrate holder with folded Al foil in between to enhance the thermal contact. Deposited films were observed with secondary electron microscope (JEOL, JSM-6510). A part of the sample was cleaved from the backside of the Si substrate and cross sectional image of the film was obtained. Thirdly, a Langmuir probe of 10 mm length and 0.38 mm diameter (Scientific systems, SmartProbe) was introduced to perform plasma diagnostics. The measurement system was driven in a boxcar mode triggered by a TTL signal from the pulse power source at the beginning of the

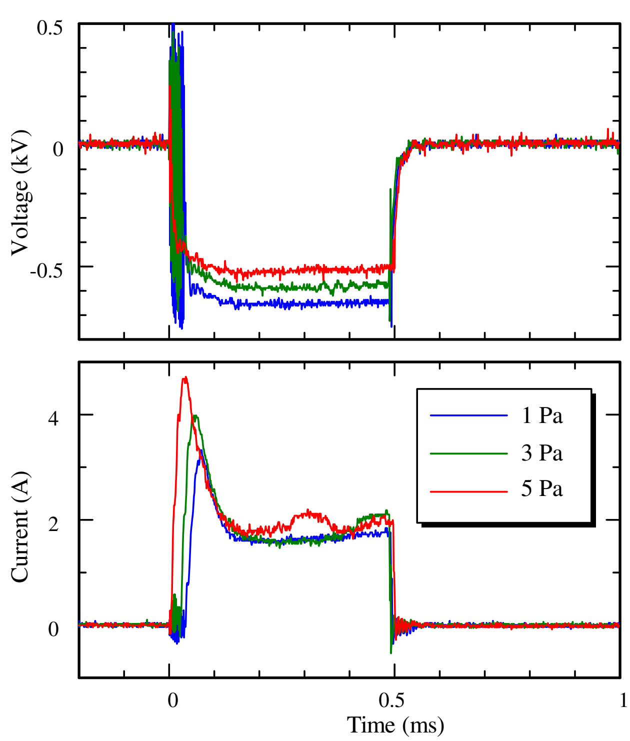

Fig. 1. Voltage and current waveforms at 1–5 Pa (average power 100 W, repetition frequency 200 Hz, duty ratio 10%, pulse-off target voltage $V_b = 0$).

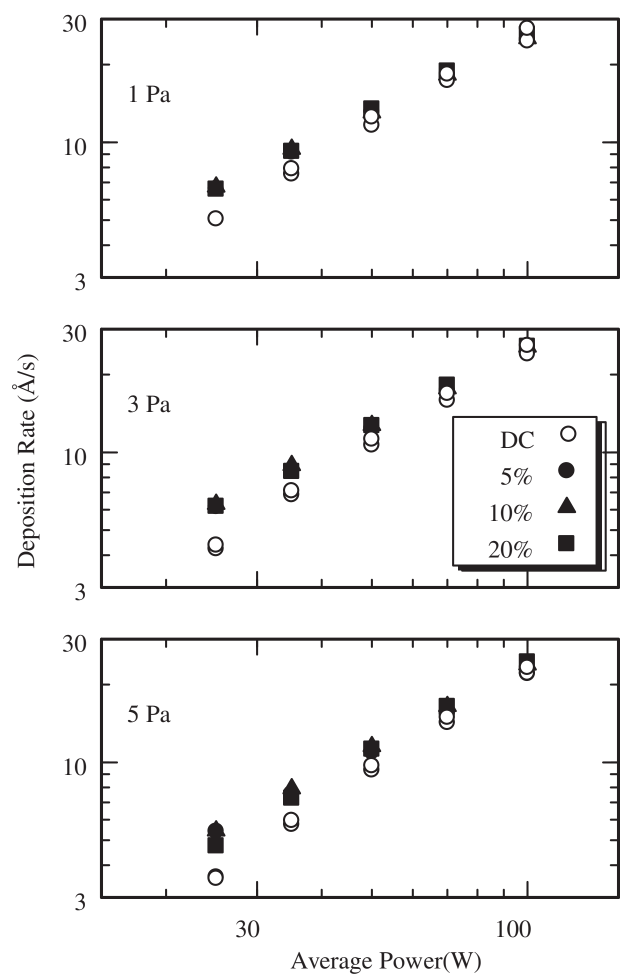

Fig. 2. Power dependence of deposition rate for DC and pulse (duty 5%, 10%, 20%) power sources.