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Effect of duty cycle on plasma parameters in the pulsed dc magnetron argon discharge

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The time-resolved probe measurements of the plasma parameters and the electron energy distribution function are carried out in a unipolar pulsed dc magnetron argon discharge. The cathode target is driven by the 20 kHz midfrequency unipolar dc pulses at three operating modes, such as constant voltage, constant power, and constant current with the duty cycles ranging from 10% to 90%. It is observed that as the duty cycle is reduced, the electron temperature averaged during the pulse-on period rapidly increases irrespective of the operating mode although the average electron density strongly depends on the operating mode. The comparison of the measured electron energy distribution functions shows that the electron heating during the pulse-on period becomes efficient in the pulse operation with short duty cycle, which is closely related to the deep penetration of the high-voltage sheath into the bulk during the pulse-on period. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1946900]

Pulsed dc magnetron sputtering technology has been developed in the last 10 years as a useful tool for the deposition of high-quality dielectric thin films.[1,2] Typically, these sputtering sources are operated in the frequency range from 10 to 100 kHz and the duty cycles from 50% to 90% with two operation methods of the unipolar and bipolar modes. Some experimental observations of the temporal behavior of plasma parameters have been carried out.[3–5] These time-resolved measurements have shown that the pulse operation can give rise to the increase in the flux and energy of the ions incident at the substrate, the increases of the average electron temperature and density over the cycle, and the possibility of the existence of the energetic beam-like electrons during the pulse-on period.[3]

More recently, there has been concern about the pulse operation with high voltage (few kilovolts) and short pulse period (less than a few microseconds) due to the possibilities of higher ionization rate of sputtered atoms and the improved target utilization and film quality.[4–7] In this work, time-resolved measurements of the plasma parameters and the electron energy distribution function (EEDF) at the vicinity of the substrate under the experimental conditions of various duty cycles from 10 to 90%, and three operating modes are presented. In particular, we focus on the changes of the average electron temperature and the electron energy distribution function as the duty cycle is reduced such that the cathode is driven by the pulse with a very short duration.

The detailed configuration of the type II unbalanced planar magnetron chamber can be easily found elsewhere.[8,9] Argon was used as the discharge gas and the operating pressure of 3 mTorr was kept throughout this study. A cylindrical Langmuir probe, which is a tungsten wire of 0.05 mm in radius and 2 mm in length, was located on the discharge axis at a distance of 70 mm from the target.[8,9] For time-resolved measurements of probe$I$-V characteristics, the boxcar sampling technique was used with a commercially available probe data acquisition system (Plasmart Ltd. SLP2000®). This acquisition system has a minimum time resolution of 100 ns (trigger delay jitter less than 50 ns) and a maximum sampling rate of 50 kS/s. For the triggering of the boxcar electronics, a trigger signal from the pulse power supply was fed into it. In this experiment, the sampling time of 1 μs was adopted for saving the acquisition time and the averaging of 200 times was carried out for each probe bias in order to improve the signal-to-noise ratio. The probe voltage was swept in a range from −90 V to +10 V and the 1024 data points were recorded resulting in a complete I-V characteristic. The electron energy distribution functions were determined using the well-known Druyvesteyn method. The second derivatives of the probe characteristics were obtained by numerically differentiating the measured I-V curves. The plasma parameters such as the electron density and the effective electron temperature were obtained from the resulting EEDFs.[9] The initial time $t=0$ was chosen as the time when the cathode voltage turns on. The cathode target was driven by the 20 kHz unipolar pulse through a pulsed dc power supply with the various duty cycles ranging from 10% to 90% in three operating modes such as the constant-voltage mode (V-mode), constant-power mode (P-mode), and constant-current mode (C-mode). Each operating mode is defined as follows:

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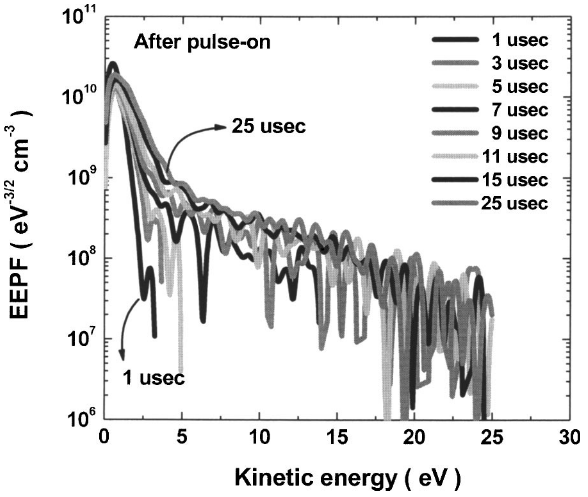

FIG. 1. Temporal evolution of the EEPF during the pulse-on period after initiating the pulse with the driving frequency of 20 kHz and the duty cycle of 50%.

$$V_{\mathrm{cavg}} \equiv \frac{1}{\tau_{\mathrm{on}}}\int_0^{\tau_{\mathrm{on}}} V_c(t)dt = \text{constant}, \quad \text{in V-mode},$$

$$P_{\mathrm{cavg}} \equiv \frac{1}{\tau_{\mathrm{period}}}\int_0^{\tau_{\mathrm{period}}} \mathrm{P}_c(t)dt = \text{constant}, \quad \text{in P-mode},$$

$$I_{\mathrm{cavg}} \equiv \frac{1}{\tau_{\mathrm{period}}}\int_0^{\tau_{\mathrm{period}}} I_c(t)dt = \text{constant}, \quad \text{in C-mode}, \tag{1}$$

where $V_c(t)$, $P_c(t)$, and $I_c(t)$ are the instantaneous cathode voltage, power, and current, respectively, and τ_{period} $(=\tau_{\mathrm{on}}+\tau_{\mathrm{off}})$ is the periodic time of the pulse. Here $V_{\mathrm{cavg}}=-350$ V, $P_{\mathrm{cavg}}=100$ W, and $I_{\mathrm{cavg}}=0.3$ A.

Figure 1 shows the temporal evolution of the electron energy probability function (EEPF) during the pulse-on period when the cathode is driven with the duty cycle of 50% at the constant voltage mode. Initially, the EEPF exhibits a Maxwellian distribution with the low-energy electrons less than 2 eV. We can find that the high-energy electron tail rapidly grow up as time goes on after the pulse-on and then the EEPF exhibits a bi-Maxwellian distribution consisting of two electron groups over the pulse-on period. As elucidated through our previous works in dc magnetron discharge,[8,9] the high-energy electron tail consists of the electrons that are produced near the racetrack zone on the cathode and which drift to the anode.

Figure 2 shows the waveforms of the cathode voltages and currents for each duty cycle in three operating modes. While the maximum cathode voltage at the pulse-on phase rapidly increases in the constant-power and -current modes as the duty cycle is reduced, it is almost constant in the constant-voltage mode. In addition, the cathode current at the pulse-on phase rapidly increases in the constant-power and -current modes with reducing the duty cycle, but it decreases in the constant-voltage mode. The peaks of the cathode currents during the pulse-on and -off periods, which may be caused by the instantaneous ion and electron flows to the cathode due to the sudden evolution and collapse of the high-voltage cathode sheath are observable.

Changing the duty cycle of the cathode pulse at three operating modes, the time-resolved probe measurements were carried out and the results are presented in Fig. 3, in which the variations of the average electron density N_{eavg} and temperature T_{eavg} against the duty cycle are shown. Here, the average electron density and temperature are defined as

$$N_{\mathrm{eavg}} = \frac{1}{\tau_{\mathrm{on}}}\int_0^{\tau_{\mathrm{on}}} N_e(t)dt, \quad T_{\mathrm{eavg}} = \frac{1}{\tau_{\mathrm{on}}}\int_0^{\tau_{\mathrm{on}}} T_e(t)dt, \tag{2}$$

where τ_{on} is the pulse-on duration. Obviously, it can be found that T_{eavg} increases at all of the operating modes as the duty cycle is reduced. Especially, it changes exponentially at the duty cycles less than 30%. On the other hand, the variation trend of N_{eavg} strongly depends on the operating mode. Although N_{eavg} decreases with reducing the duty cycle at the

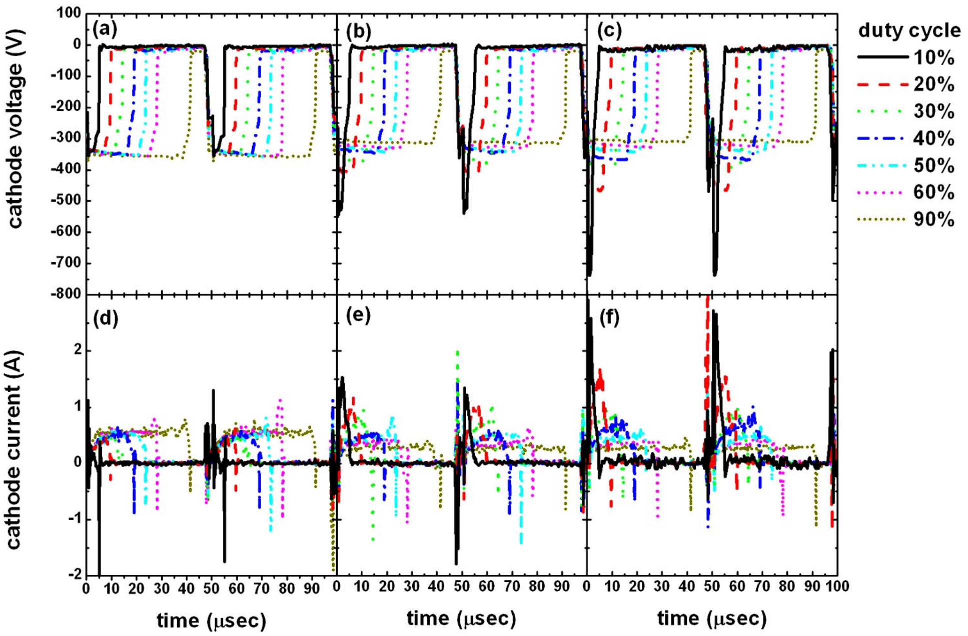

FIG. 2. (Color online). The wave forms of the cathode voltages [(a), (b), (c)] and currents [(d), (e), (f)] for each duty cycle in the constant-voltage [(a), (d)], -power [(b), (e)], and -current [(c), (f)] modes.

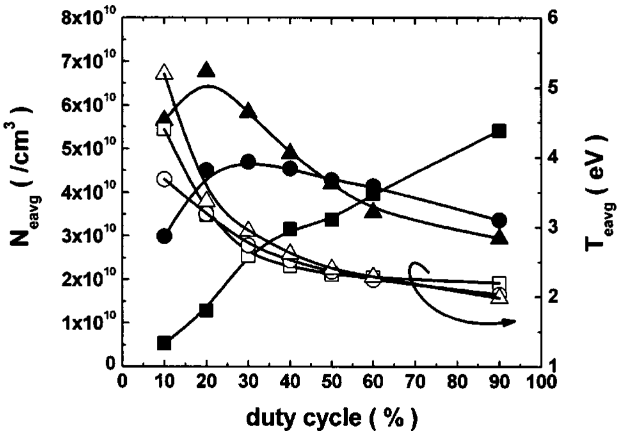

FIG. 3. The variations of the average electron density (closed symbols) and the average electron temperature against the duty cycle in three operating modes: the V-mode (rectangular symbols), the P-mode (circular symbols), and the C- mode (triangular symbols).

constant-voltage mode, it shows the increasing trend with reducing the duty cycle at the constant-power and -current modes. N_{eavg} in a pulsed discharge with short duty cycle is even higher than that in a dc discharge.

In particular, all N_{eavg} and T_{eavg} show the rapidly increasing trends with reducing the duty cycle in the constant-current mode. T_{eavg} increases from 2 eV with the duty cycle of 90% to 5.5 eV with the duty cycle of 10% and N_{eavg} increases from $3\times10^{10}/\mathrm{cm}^3$ to $5.6\times10^{10}/\mathrm{cm}^3$. Investigating the variation of the EEPF against the duty cycle, we can find out the cause for the increase of T_{eavg} with reducing the duty cycle. The normalized EEPFs, which are well representative of the EEPF characteristics for each duty cycle in the constant current mode (that is, the effective electron temperature is most similar to T_{eavg}) are compared in Fig. 4. It is obviously found that the population of the high-energy tail part of the EEPF increases, but the population of the low-energy electron group decreases as the duty cycles is reduced. We confirmed that this characteristic change of the EEPF with reducing the duty cycle, that is, the increase of the high-energy electrons and the decrease of the low-energy electrons, also occurs in other operating modes.

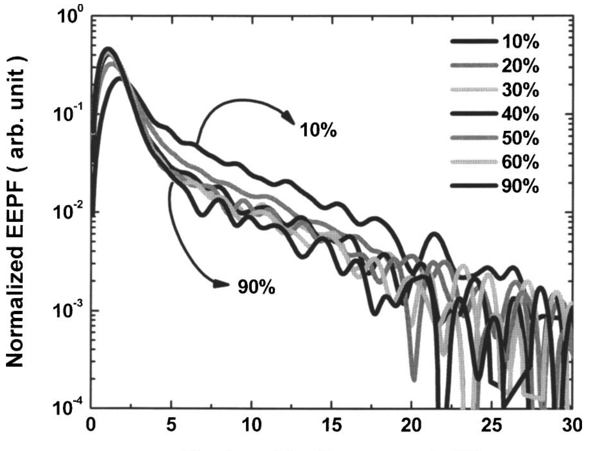

FIG. 4. The comparison of the normalized EEPFs which are measured with changing the duty cycle in the constant current mode. The EEPFs are the representative EEPFs of each operating mode of which the effective electron temperatures are most similar to the average electron temperatures.

As the duty cycle is reduced, the cathode voltage and current, and thus the delivered cathode power, at the pulse-on phase rapidly increase in the constant current and power modes as shown in Fig. 2. In addition, the cathode current as well as the cathode voltage increases with reducing the duty cycle in the constant power mode. Therefore, the cathode sheath can expand more deeply toward the bulk during the pulse-on period with reducing the duty cycle because the electron density is almost same just before the pulse-on in two modes. On the other hand, since the electron density just before the pulse-on becomes lower in the constant voltage mode as the duty cycle is reduced, the cathode sheath can expand more deeply toward the bulk during the pulse-on period with a shorter duty cycle. The deep expansion of the high-voltage cathode sheath reflects the possibility of the enhanced electron heating near the racetrack zone. Consequently, the decrease of the population of the low-energy electrons and the increase of the high-energy tail part of the EEPF at shorter duty cycle make the increase of the electron temperature during the pulse-on duration.

In this work, we investigated the effect of the duty cycle of the cathode pulse on the plasma parameters in the pulsed magnetron discharges of three operating mode. We could observe that as the duty cycle of the pulse is reduced, the average electron temperature rapidly increases irrespective of the operating mode, although the average electron density strongly depends on the operating mode. The measured EEPFs show the decrease of the low-energy electron group and the increase of the high-energy tail part with reducing the duty cycle, which reflects the enhanced electron heating after initiating the pulse with shorter duty cycle. From these results, it is expected that a high-voltage pulse operation with a short duty cycle can produce the high-temperature plasma that yields improved films quality by achieving a high ionization rate of the sputtered atoms.

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