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# Evolution of electron temperature in low pressure magnetized capacitive plasma

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The evolution of electron temperature in a low pressure magnetized capacitive discharge was investigated under the collisionless electron heating regime. The results showed that while the electron temperature increases monotonously with the magnetic field in previous study [Turner *et al.*, Phys. Rev. Lett. **76**, 2069 (1996)], the electron temperature in our experiment exhibited nonmonotonic evolution behavior with the magnetic field. This nonmonotonic evolution of the electron temperature with the magnetic field was shown to be a combined effect of suppressing electron resonance heating and enhancing collisional heating while increasing the magnetic field. © *2010 American Institute of Physics*. [doi:10.1063/1.3309589]

In the maxwellian electron plasma, the electron temperature is normally governed by the particle ionization balance resulting in $T_e = T_e(pd)$ where $p$ is the gas pressure and $d$ is the characteristic size of the discharge and practically does not depend on the plasma density and discharge power.[1–3] However, in the nonmaxwellian electron plasma which is conventional one in partially ionized plasma, the electron temperature which is represented by an inverse slope of the electron energy distribution in specific energy range $[T_e \propto (\partial f/\partial \epsilon)^{-1}$, $f$ is electron energy distribution functions (EEDFs)] or by an effective electron energy ($T_e = T_{\mathrm{eff}} = 2/3\langle \epsilon \rangle = 2/3 \int \epsilon f d\epsilon / \int f d\epsilon$, where $\epsilon$ is electron kinetic energy) is influenced and determined by specific electron heating/loss mechanisms sustaining the discharge source, which changes depending on the plasma density, discharge power, and pressure. Therefore, to control the electron temperature in processing discharge which means controlling the shape of EEDF, one has to examine first how the electron heating and loss mechanisms (in particular, the electron heating in low pressure discharge, because the loss is not severe in low pressure) are changed by external parameters, such as gas pressure, discharge power, and magnetic fields. Among these external parameters, the magnetic field is known to affect the electron heating and loss processes greatly by changing the electrodynamics in the plasma,[2] thus the magnetic field has been used recently as an additional knob in the plasma processing to control the electron temperature in order to enhance some desirable features of specific plasma sources and processing results.[3,4] Therefore, the magnetic field effect on the electron temperature (EEDFs) is one of the most interesting issues in semiconductor processing recently and many studies have been conducted to understand the effect of magnetic field on the electron temperature and EEDFs.[5–8] However, the application and validation of the results form previous studies that the electron temperature increases with the magnetic field still seems questionable, which will be shown later in Fig. 1.

In this letter, the magnetic field effect on the electron temperature was investigated in a low pressure capacitive discharge where the condition, $\lambda > L$, where $\lambda$ is the electron mean free path and $L$ is the system length. The result shows that the electron temperature of low pressure capacitive discharge evolved nonmonotonically with increasing magnetic field, which is a noticeable result because according to the previous studies, the electron temperature increased with the magnetic field.[5–8] This nonmonotonic change of electron temperature with the magnetic field was shown to be a combined effect from suppressing electron bounce resonance heating and enhancing collisional heating while increasing the magnetic field.

The experiment was performed in a capacitive reactor described in Ref. 9. The EEDFs were measured at gas pressure of 10 mTorr, discharge current of 1 A, gap length of 20 mm by using a rf compensated Langmuir probe.[9] The probe was made of tungsten wire 3 mm long and 0.15 mm in diameter and was placed at the midplane between the discharge electrodes. To acquire the EEDFs, the single

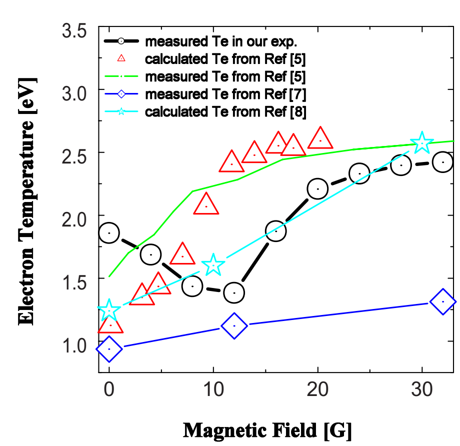


FIG. 1. (Color online) The evolution of electron temperatures ($T_{\mathrm{eff}}$) with magnetic field at a low pressure capacitive discharge (circle: measured $T_{\mathrm{eff}}$ in our experiment, triangle: calculated $T_{\mathrm{eff}}$ in Ref. 5, dot: measured $T_{\mathrm{eff}}$ in Ref. 5, diamond: measured $T_{\mathrm{eff}}$ in Ref. 7, star: calculated $T_{\mathrm{eff}}$ in Ref. 8).

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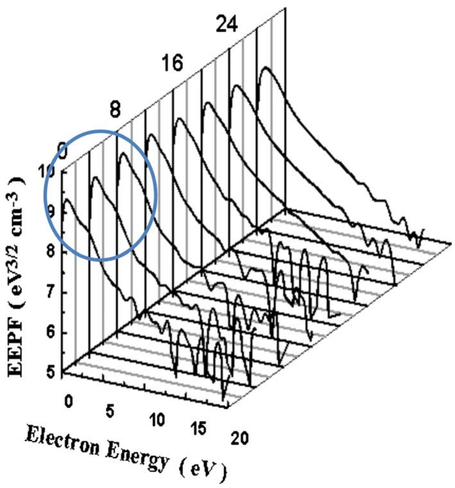


FIG. 2. (Color online) Measured EEPFs for various magnetic fields at 10 mTorr, 1 A, and 2 cm gap.

Langmuir Probe System of SLP2000 (PLASMART.INC) was used.[10] The probe sweep was done at 30 Hz and the measured $I_e''$ is proportional to the electron energy probability functions (EEPFs) $f_e(\epsilon)$ and related to the EEDF $g_e(\epsilon)=\epsilon^{1/2}f_e(\epsilon)$ as follows:[4]

$$g_e(\epsilon) = \frac{2m_e}{e^2A}\left(\frac{2\epsilon}{m_e}\right)^{1/2} I_e''(\epsilon), \quad \epsilon = -eV_b, \tag{1}$$

where $e$, $m_e$, $A$, $I_e$, and $V_b$ are electron charge, mass, probe area, probe electron current, and probe voltage referenced to the plasma potential, respectively. Electron density ($n_e$) and effective electron temperature ($T_{eff}$) can be calculated from the EEPF $f_e(\epsilon)$.[4]

The magnetic field effect on the (effective) electron temperature ($T_{eff}$) in a low pressure discharge has been reported in previous studies.[3–8] Normally, it has been known that the electron temperature increases with the magnetic field in low pressure capacitive discharge because of the enhancement of collisional electron heating and the suppression of collisionless electron heating,[5,6] as shown in Fig. 1. As shown in Fig. 1 (see circle symbol data), however, our result shows that the effective electron temperature ($T_{eff}$) abruptly decreased with magnetic field up to 12 G, but after passing 12 G, the electron temperature starts to increase with the magnetic field. Because the increase in electron temperature above the 12 G can be explained by the previous result, the enhancement of collisional electron heating by magnetic field,[5,6] it can be concluded that this nonmonotonic evolution of electron temperature can be due to the fact that magnetic field effectively cools down the electron temperature below a 12 G regime (by suppressing an electron heating process in the discharge regime).

The cooling down of the electron temperature and the suppression of electron heating are clearly shown in the EEPFs. The EEPFs with various magnetic fields (0–32 G) corresponding to the electron temperature of Fig. 1 are shown in Fig. 2. In the absence of the transverse magnetic field (0 G) of Fig. 2, the bimaxwellian EEPF with a plateau in the low-energy region (1–3 eV) which reflects the presence of a strong heating mechanism for the electrons in the low energy range is observed, and makes the electron temperature somewhat higher than that of conventional capacitive discharge as shown in Fig. 1 (which revealed as electron bounce resonance).[11] However, as the magnetic field increases, the plateau indicating a strong electron heating gradually becomes obscure and finally disappears in the EEPF above 12 G, resulting in the electron temperature decrease with magnetic field up to 12 G, as shown in Fig. 1.

The underlying physics on the disappearance of the plateau and the decrease in electron temperature with the magnetic field below 12 G in Figs. 1 and 2 can be understood by considering the evolution mechanism of a plateau under the transverse magnetic field. The mechanism causing the plateau in the EEPF is known for the electron bounce resonance occurring when electrons bounce in the electrostatic potential field with the same frequency as the driving rf frequency.[11–17] The electron bounce resonance can be explained as follows: low-energy electrons in the bulk plasma are typically inefficiently heated due to their low collisionality and the weak rf electric field present in the bulk, so that the distribution of the low energy electron group of the low pressure capacitive discharge normally exhibits low electron temperature. However, when the gas pressure is low enough to satisfy the condition ($\Omega > \nu_c$, where $\Omega$ is the bounce frequency of electron and $\nu_c$ is e-n collision frequency, respectively), electrons can bounce in the ambipolar potential wall completing more than one round trip before undergoing a collision with the neutrals. Under that condition, the electrons that satisfy the resonance condition ($\omega_0 = 2\pi n\Omega = \omega$, where $n$ is an integer and $\omega$ is an angular driving frequency) interact coherently with the oscillating rf bulk electric field. Therefore, these electrons can accumulate the energy kicks gained in subsequent interactions with rf bulk electric field and diffuse in energy space toward higher energy, an effective electron heating arises, even if small rf bulk electric field.[11–13] As a result of (collisionless) resonance heating, the EEPF of 0 G in Fig. 1 shows the bimaxwellian distribution with a plateau in the low energy electron group. However, if the magnetic field transverse to the bulk electric field increases from 0 G, the electrons start to experience gyromotion bouncing inside the electrostatic potential well, thus, their bounce frequency and bounce resonance condition can be changed from these of 0 G. If the Lorentz force ($F_L$) from the static B-field is compared with or larger than the electron static force ($F_{ES}$) of ambipolar potential, the periodic motion of electrons under the electrostatic potential can be changed noticeably by the magnetic field. Indeed, from a crude estimation, it is shown that a few Gauss of magnetic field ($B \sim 1.45$ G) is enough to change the bounce motion of electron, $F_{ES} \le F_L \to 2eT_e/L_p \le ev_eB$, (assuming that $L_p/2 = 1$ cm, $T_e = 1$ eV where $L_p$ is a plasma bulk length and $v_e$ is a thermal speed for electrons of energy 1 eV). Therefore, the electron bounce motion starts to be influenced by even small magnetic field and the bounce resonance condition (frequency) is also changed.

The change of the bounce frequency which is influenced by the magnetic field can be easily demonstrated with a simple model of harmonic oscillator of charge particle under the magnetic field assuming that electron is confined in the one-dimensional parabolic potential [$\phi(x) = 1/2\alpha x^2$, where $\alpha$ is a constant], the constant magnetic field ($B$) applies transverse to the electrostatic field, and e-n collisions are neglected. The equations of motion of an electron are expressed as follows:

$$m_e \frac{dv_x}{dt} = -ev_yB - \alpha x, \tag{2}$$

$$m_e \frac{dv_y}{dt} = ev_xB. \tag{3}$$

Solving those equations, one can have the solution of velocity below

$$v_x = v_0 \sin \omega_b t, \tag{4}$$

where $\omega_b = 2\pi\Omega_b = \sqrt{\omega_{ce}^2 + \omega_0^2}$ is the angular bounce frequency electron inside a parabolic potential well under the magnetic field, $\omega_{ce}$ is the angular gyrofrequency and $\omega_0$ is the angular natural electron bounce frequency inside the potential well without the magnetic field. Equation (4) shows that the electrons under the magnetic field perform a harmonic bounce motion with modified bounce frequency ($\omega_b$) instead of the natural bounce frequency ($\omega_0$) and the bounced resonance condition changes from $\omega = \omega_0$ to $\omega = \omega_b$. Because the bounce frequency ($\omega_b$) increases with the magnetic field, to satisfy the resonance condition ($\omega = \omega_b$), the natural bounce frequency ($\omega_0$) should be decreased according to the relation for bounce resonance $\omega_0^2 = \omega^2 - \omega_{ce}^2$. Therefore, at high magnetic field $\omega_{ce} > \omega$, the natural bounce frequency of electrons satisfying the resonance condition is not real, meaning there is no bounce resonance heating of electrons in the plasma. As a result of the disappearance of the resonance heating in the high magnetic field, the electron temperature decreases, obscuring the plateau in the EEPFs with the magnetic field below 12 G.

The critical magnetic field which the bounce resonance condition is completely disappears is expected to be around 4.2 G, because of the relation $0 = \omega^2 - \omega_{ce}^2$. In this point of view, the plateau of EEPFs should disappear above the magnetic field of 4.2 G, and the magnetic field where the electron temperature is at its minimum should be around 4.2 G. However, the magnetic field where the plateau of EEPFs disappears and the electron temperature has a minimum value is around 12 G in our result of Figs. 1 and 2. This discrepancy could be due to gyroradius ($r_L$) effect of electrons. Although the electrons satisfy the condition $\omega_{ce} > \nu_c$, if the gyroradius is larger than the system half length $r_L > L/2$, the electrons see the boundary of plasma and the electrons are not strongly magnetized indeed. In the case of the magnetic field 4 G and electron energy of 2 eV where the plateau is formed, the electron gyroradius is larger than half the length of the plasma bulk $[r_L/(L_p/2) \simeq 1.4 \text{ cm}/0.5 \text{ cm} > 1]$ so that the electron is not strongly influenced by the magnetic field. As a result, the plateau of EEPFs disappears completely and the electron temperature has a minimum value not above 4 G but above 12 G, where the two conditions are satisfied simultaneously $r_L < L/2$, $\omega_{ce} > \nu_c$.

In the case of $\omega_{ce} \gg \omega_0$, which is possible for very low energy electrons at a high magnetic field, the resonance electron heating can take place when the electron gyrofrequency is equal to the driving frequency $\omega_{ce} \sim \omega$ rather than $\omega_0 \sim \omega$, i.e., electron bounce resonance under the magnetic field becomes the electron cyclotron resonance.[17]

The reasons why the previous studies[5,7,8] have not measure this abnormal behavior of electron temperature is that the experimental/simulation condition is not suitable to make at least one collisionless electron bounce motion in the ambipolar potential[11] too high pressure (50 mTorr) and big gap length (>10 cm) for Ref. 7, low pressure (10 mTorr) but big gap length (>7 cm) for Refs. 5 and 8.

Up to now, we focused on explaining the reason why the electron temperature decreases with the magnetic field below 12 G. As mentioned before, because the increase of electron temperature with magnetic field was explained in terms of enhancing electron heating in the bulk,[5,6] it can be concluded that the nonmonotonic evolution of electron temperature with the magnetic field is a combined effect from suppressing the electron bounce resonance heating and enhancing the collisional heating with the magnetic field.

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