J. Plasma Physics (2006), *vol.* 72, *part* 6, *pp.* 873–876. © 2006 Cambridge University Press
doi:10.1017/S0022377806005642 Printed in the United Kingdom

Ponderomotive effects in an electromagnetic accelerator

Y. N. TOLMACHEV[1], WONTAEK PARK[1], V. N. VOLYNETS[1], V. G. PASHKOVSKY[1] and JINWOO YOO[2]

[1]Mechatronics and Manufacturing Technology Center, Samsung Electronics Co., Ltd, 416 Maetan-3Dong, Suwon-City 443-742, Korea

[2]Nano Fabrication Center, Samsung Advanced Institute of Technology, Kihung-Eup, Yongin-City 449-712, Korea

(Received 2 July 2005 and accepted 9 February 2006)

Abstract. An inductive coupled plasma (ICP) source of a new type for dry etching has been developed. It is driven by a planar inductive coil, which is placed at the top of the channel formed by two coaxial dielectric cylinders. At low pressure, the radial component of the radiofrequency (RF) magnetic field causes a ponderomotive force acting on the electrons directed towards the bottom of the channel. Charge separation gives rise to an ambipolar electric field, which retards electrons and accelerates ions. The source represents an electrodeless electromagnetic accelerator (EMA) and can create an axially directed flux of ions. EMA has been modeled as an axisymmetric ICP discharge in argon gas based on experimental data of the plasma density and electron temperature profile. The magnetic field and RF current densities obtained have been used for calculation of the Lorentz force acting on the electrons and ambipolar plasma potential. Simulations of electron trajectories show that electrons are trapped in the EMA channel and make a number of oscillations before leaving the channel. The ponderomotive potential produces acceleration of the ions in the channel up to 13–16 eV.

1. Introduction

An inductive coupled plasma (ICP) source of a new type for dry etching has been recently developed (Volynets et al. 2006). It operates at a frequency of 2 MHz and is driven by a planar inductive coil, which is placed at the top of the annular channel formed by two coaxial quartz cylinders (Fig. 1(a)). At low pressures the radial component of the radiofrequency (RF) magnetic field causes a strong ponderomotive force (Chen 1974; Sydorenko et al. 2005) acting on electrons and directed towards the exit from the channel to the main chamber. Charge separation resulting from this force gives rise to an ambipolar electric field, which retards electrons and accelerates ions. The source represents an electrodeless electromagnetic accelerator (EMA) and can create an axially directed flux of energetic ions due to the ponderomotive effect. The ponderomotive force on a unit volume of plasma in a time-varying inhomogeneous RF field calculated from the equation $F_{\mathrm{p}} = -(\varepsilon_0\omega_{\mathrm{p}}^2/4\omega^2)\nabla E^2$ (Gaponov and Miller 1958) usually gives much higher values of the plasma potential than those obtained from the experiment (Sydorenko et al.

https://doi.org/10.1017/S0022377806005642 Published online by Cambridge University Press

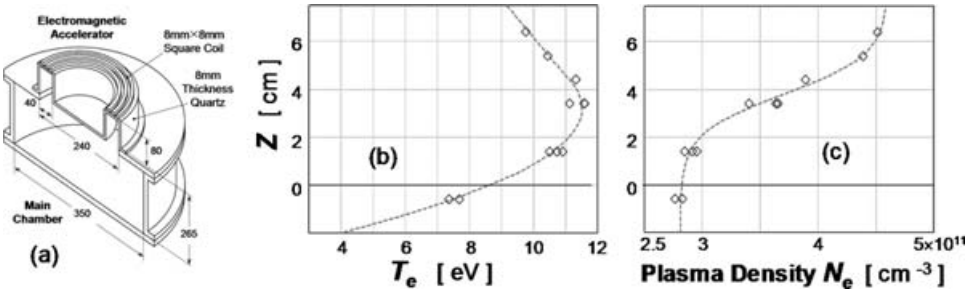


Figure 1. (a) Schematic drawing of the EMA. (b) Experimental electron temperature and (c) plasma density profiles along the EMA channel at a pressure of 1.25 m Torr and a RF coil current of 37.5 A. $Z = 0$ corresponds to the boundary of the EMA and main chamber.

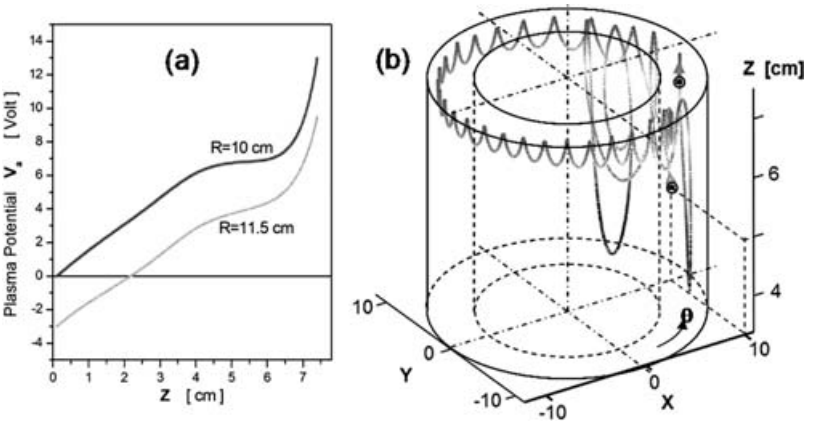


Figure 2. (a) Profile of the plasma potential V_a along the EMA channel. (b) Typical trajectory of an electron in the EMA channel starting from $Z = 5$ cm.

2005). The purpose of our study was a direct calculation of the ponderomotive effect in the EMA channel using experimental data of the plasma density and electron temperature obtained with a double Langmuir probe (Fig. 1(b) and (c)). The plasma was modelled as a conducting medium with complex electrical conductivity

$$\sigma = \frac{e^2 N_e}{m_e} \cdot \frac{1}{\nu_{eff} + j\omega}.$$

Magnetic and electric field distributions in the plasma were calculated from the vector potential using a finite element method (FEM) for solving field equations (Jin 2002).

2. Results of the simulation

Integration of the RF power density over the volume of the EMA and then comparing it with the experimentally determined value of the RF power (1200 W) absorbed by the plasma allowed us to estimate the effective collisional frequency $\nu_{eff} = 1.1 \times 10^7\ s^{-1}$. The calculated RF fields allowed us to obtain the time averaged ambipolar electric field E_a using the equation $E_a = -(eN_e)^{-1}(\nabla(kN_eT_e) + \langle J \times B \rangle)$ (Sydorenko et al. 2005). The plasma potential profile shown in Fig. 2(a) was determined by

https://doi.org/10.1017/S0022377806005642 Published online by Cambridge University Press

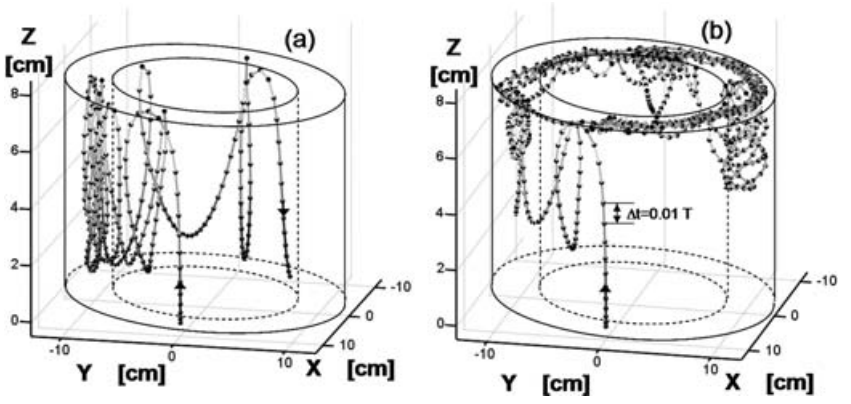


Figure 3. (a) Collisionless and (b) collisional trajectories of an electron in the EMA.

integration of this field. The calculated plasma potential provides acceleration of ions in the EMA up to 13–16 eV. The trajectory of an electron travelling in the EMA during four periods of the RF field is shown in Fig. 2(b).

From this trajectory we see that electrons can be trapped in the channel being isolated from the main chamber. This may account for the experimentally observed (Volynets et al. 2006) high gradient of the electron temperature along the EMA channel.

The trajectory of an electron starting from the exit of the channel towards the top and travelling without collisions during 3.37 periods of the RF field is shown in Fig. 3(a). We see that the electron finally escapes from the channel. However, the total path of electron is 1.82 m and we cannot neglect collisions with neutral atoms. According to our estimations, based on literature cross-section data, the electron mean free path for our conditions is practically constant and is equal to 62 cm.

The collisional trajectory of an electron traveling during 9.2 periods of the RF field is shown in Fig. 3(b). Now the electron does not leave the channel and is completely trapped in the skin layer of the RF field. The total path of electron is 5.73 m and although the EMA channel width is equal to 4 cm, which is much less than electron mean free path, a number of collisions with neutral atoms may occur along the trajectory.

3. Conclusions

Magnetic and electric fields in plasma can be calculated from experimentally measured plasma parameters. The effective collisional frequency, which determines the electrical conductivity of the plasma, can be estimated from the calculation of the total RF power deposited in the plasma. The ponderomotive effect of the Lorentz force and the electron pressure gradient create an ambipolar electric field, which may provide ion acceleration up to 13–16 eV in the axial direction. In combined magnetic and electric fields, the electrons can be trapped in the EMA channel and travel along very complicated trajectories, specularly reflecting from the sheaths and being periodically repelled and accelerated by the ambipolar electric field. Electrons may undergo a number of reflections before they leave the channel. This may cause additional charge separation in the channel and additional electric

https://doi.org/10.1017/S0022377806005642 Published online by Cambridge University Press

fields in the axial direction, which can make some corrections in our calculations. The collisions increase the residence time of electrons in the EMA channel, thus enhancing the electron trapping effect.

References

Chen, F. F. 1974 In: *Introduction to Plasma Physics*. New York: Plenum., p. 305.
Gaponov, E. V. and Miller, M. E. 1958 *Sov. Phys. JETP* **25**, 952.
Jin, J. 2002 *The Finite Element Method in Electromagnetics*. New York: Wiley.
Sydorenko, D. Y. et al. 2005 *Phys. Plasmas* **12**, 033503.
Pashkovsky, V. G. et al. 2005 In: *Proceedings of the 27th ICPIG*.
Volynets, V. N. et al. 2005 In: *Proceedings of the 27th ICPIG*.

https://doi.org/10.1017/S0022377806005642 Published online by Cambridge University Press