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ABSTRACTS

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Steady-State Direct-Current (DC) Plasma Immersion Ion Implantation (PIII) for Planar Samples

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Plasma immersion ion implantation (PIII) has been demonstrated to be an excellent technique in many microelectronics applications, e.g. fabrication of silicon-on-insulator (SOI), formation of shallow junctions, etc. However, high-voltage PIII (above 100kV) is very difficult because under a high sample bias voltage, the plasma sheath is quite thick thereby requiring a large vacuum chamber and the required high-voltage power modulator is also prohibitively expensive. We have recently conducted theoretical and experimental studies to extend the implantation energy without the need of a big vacuum chamber or a power modulator. Ions are implanted using a grounded conducting grid positioned on top of the wafer stage The grounded grid that is made of a compatible material to avoid contamination stops the propagation of the plasma sheath and divides the vacuum into two zones. Ions are formed in the plasma sustained by an external plasma source above the grid and are accelerated through the lower zone to be implanted into the sample biased by only a DC power supply. By numerically simulating the ion paths by the particle-in-cell (PIC) method, it is observed that the ion paths are optimized for certain implant geometry. In this configuration, the directional angle of the acceleration vector does not depend on the mass and charge state of the ions and the ratios of the partial differentials of the scalar potential ϕ along the radial and longitudinal direction remain constant for different applied voltage. The retained dose and impact energy uniformity on the wafer is totally determined by the ratio of the radius of wafer stage r, the radius of chamber R, the distance between the wafer stage and the grid H, and the thickness of the wafer stage D. Our results suggest that the best ratio of r : R : H : D be 1 : 4 : 2.5 : 2, i.e., a disk shape chamber. We will also present our experimental data in this paper.

In addition to retaining the large area and parallel processing advantages of plasma immersion ion implantation (PIII), this technique allows the implantation energy to be extended far beyond the current limit of PIII as the technique obviates the use of the power modulator which not only limits the implantation energy but also is the most expensive and technologically complex hardware component in a PIII system.

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Steady-State, Direct-Current (DC) Plasma Immersion Ion Implantation (PIII) for Planar Samples

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Abstract – **A new direct current (DC) plasma immersion ion implantation (PIII) technique by using a grounded conduction grid positioned between the plasma source and sample chuck is described in this paper. DC-PIII is simulated employing the particle–in–cell (PIC) method. Our simulation shows that the ion paths do not change with the negative voltage applied to the wafer stage as well as the mass and charge states of the ions. The ion dose and impact energy uniformity is determined by the internal ratio between the r (radius of sample platen), R (radius of vacuum chamber), H (distance between the grid and bottom of the vacuum chamber), and D (thickness of sample platen). Our simulation suggests that the best ratio is r:R:H:D=1:4:2.5:2. Our experimental results show that high voltage DC-PIII can be realized by using a conducting grid in a conventional PIII system.**

I. INTRODUCTION

Plasma immersion ion implantation (PIII) has been demonstrated to be an excellent technique in many microelectronics applications such as fabrication of silicon-on-insulator (SOI) and formation of shallow junctions [1]. In the fabrication of SOI, PIII is an efficient and economical approach to implant a high dose of hydrogen or oxygen into a silicon wafer, and as the implantation time is independent of the wafer diameter, it is more appealing for larger wafers. The entire surface of the wafer stage is implanted in traditional PIII, but for planar samples such as silicon wafers, ions implanted into the side and bottom of the sample chuck are wasted and cause undesirable effects such as sample heating and sputtered contamination. In addition, traditional pulse-mode PIII at a high voltage (above 100kV) is very difficult because under a high sample bias voltage, the plasma sheath is quite thick thereby requiring a large vacuum chamber [2,3], and the required high-voltage power modulator is also prohibitively expensive.

We have recently conducted theoretical and experimental studies to decrease the wasted ions and extend the implantation energy without the need of a big vacuum chamber or a power modulator. Ions are implanted using a grounded conducting grid positioned on top of the wafer stage (Fig. 1). The grounded grid, which is made of a compatible material to avoid contamination, stops the propagation of the plasma sheath and divides the vacuum into two zones.

Ions are formed in the plasma sustained by an external plasma source above the grid, accelerated through the lower zone, and implanted into the wafer biased by only a DC power supply. We name this method steady-state, direct-current plasma immersion ion implantation (DC-PIII). It has a number of advantages compared to traditional pulse-mode PIII. The cost of the equipment is greatly reduced as the expensive high voltage modulator can be substituted by a DC power supply. There is no plasma under the conducting grid in DC-PIII facilitating high voltage insulation of the wafer stage, and so the impact energy can be raised. The process is also more mono-energetic than in pulse-mode PIII because there are no voltage pulse rise and fall times to be concerned with. The power and time efficiency are also improved, and the sample cooling system can be simplified or even dispensed as ions only impact the top surface of the wafer without the effects of distribution capacity [4]. In this paper, we will describe our simulation and preliminary experimental data acquired in this novel operation mode.

II. SIMULATION RESULTS

The potential above the grid is the plasma potential, whereas the potential below the grid is influenced by the negative DC voltage applied to the wafer stage. It can be solved by Laplace's equation in cylindrical coordinates:

$$\frac{\partial^2 \phi}{\partial r^2} + \frac{1}{r}\frac{\partial \phi}{\partial r} + \frac{\partial^2 \phi}{\partial z^2} = 0 \qquad (1)$$

where ϕ is the potential, r is the radial distance from the center, and z is the longitudinal distance. It is assumed that the space charge density is approximately equal to below the grid during DC-PIII. In the ideal situation, the electric field is built up before the generation of the plasma. That is, there is initially no plasma inside the lower part. The secondary electrons created during implantation are immediately

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absorbed by the chamber walls and grounded grid as they are light and energetic. The diffusion rate relative to the electric field strength is too small to gather the ions and change the potential. Eq. (1) can be solved by the finite difference method [5]. The ion motion is governed by Newton's equations of motion in cylindrical coordinates [5]:

$$v_i^r(f) = v_i^r(I) - \frac{q}{M}\frac{\partial \phi}{\partial r}t \tag{2a}$$

$$v_i^z(f) = v_i^z(I) - \frac{q}{M}\frac{\partial \phi}{\partial z}t \tag{2b}$$

$$\Delta r = v_i^r(I)t - \frac{1}{2}\frac{q}{M}\frac{\partial \phi}{\partial r}t^2 \tag{3a}$$

$$\Delta z = v_i^z(I)t - \frac{1}{2}\frac{q}{M}\frac{\partial \phi}{\partial z}t^2 \tag{3b}$$

where M is the ion mass, q is the ion charge, and $v_i^r(f)$, $v_i^r(I)$, $v_i^z(f)$, and, $v_i^z(I)$ are the initial and final velocities of the ion at time step t, respectively. The wafer stage (D = 0.056m and r = 0.081) is supported by a thin metal rod (0.3m long and 0.004m in radius) and connected to the high power voltage supply. The vacuum chamber radius is R = 0.381m, and the distance between the top of the wafer stage and the grid, H, can be varied.

Our simulation results show that the ion paths do not change with the negative voltage applied to the wafer stage, mass, and charge states of the ions, provided that their initial velocity is small compared to the electric field. The ion path of O^+ particles at H = 70cm and H = 30cm are depicted in Figs. 2a and 2b. The applied voltage is –70kV and the initial velocity of the particles is zero. Fig. 2a reveals that some of the particles will pass through the mid-plane and get implanted into the other half of the wafer stage. At H = 70cm, the ions will focus onto the center of the wafer stage.

The ion path is determined by the velocity vector that in turn changes with the acceleration vector created by the force field in space. As shown in Eq. (2), the acceleration vector can be written as:

$$\vec{a} = \left(-\frac{q}{M}\frac{\partial \phi}{\partial r}\right)\hat{r} + \left(-\frac{q}{M}\frac{\partial \phi}{\partial z}\right)\hat{k} \tag{4}$$

The directional angle θ of the vector $\vec{a}$ is:

$$\theta = \tan^{-1}\left(\left. -\frac{q}{M}\frac{\partial \phi}{\partial z} \middle/ -\frac{q}{M}\frac{\partial \phi}{\partial r} \right. \right) = \tan^{-1}\left(\left. \frac{\partial \phi}{\partial z} \middle/ \frac{\partial \phi}{\partial r} \right. \right) \tag{5a}$$

Hence, the directional angle does not depend on the charge state and mass of the ions. The ratio of the partial differential of the scalar potential ϕ along the radial and longitudinal directions remains constant for different values of ϕ. It follows that the directional angle θ of the accelerating force field is totally determined by the local field structure of the lower part of the chamber. Therefore, if the ions are placed at the same starting position with zero initial velocity, they will pass through the same local field path. The amplitude A of the acceleration indeed will vary with the charge state, ion mass, and applied voltage:

$$A = \frac{q}{M}\sqrt{\left(\frac{\partial \phi}{\partial r}\right)^2 + \left(\frac{\partial \phi}{\partial z}\right)^2} \tag{5b}$$

Thus, by varying the charge state of the ion and applied voltage, the impact energy can be altered, and by varying the ion mass, the final velocity of the ion can be changed. However, if the ions have a large initial drift velocity compared to the maximum velocity created by the applied voltage, they will pass through a different local field structure. In this situation, the ion paths will vary with the charge state, ion mass, and applied voltage. The ion path of the O^+ and O^{2+} particles with initial downward drift velocity $2.4468\text{x}10^5$ m/sec (equal to 5 keV impact energy of oxygen ions) are displayed in Figs. 2c and 2d for H = 30cm and applied voltage = –70kV. As shown, a portion of the ions passes through the wafer stage and is implanted into the supporting rod.

The dose and energy uniformity along the implanted wafer are important issues in semiconductor applications. The uniformity of the ion dose on the wafer depends on two factors, uniformity of the incident ion current and impact angle. Previous studies [6] have shown that the PIII ion dose is higher at the edge of the wafer stage when the impact angle is away from normal up to 45°. Therefore, although the depth profile is shallower at the edge, the ion dose is higher. In DC-PIII, the implantation area is totally determined by the ratio of the radius of wafer stage r, radius of the vacuum chamber R, distance between the wafer stage and grid H, and thickness of the wafer stage D. The projected area from the grid to the wafer stage determines the incident dose into the wafer. Actually, the smaller H is, the closer is the ratio of the projected area to the implanted area to 1 and the better is the incident dose uniformity. However, the shorter the distance between the anode (grid) and cathode (wafer stage), the higher is the electric field that may lead to breakdown at high implantation voltage. The impact angle at the edge can be made normal by changing the thickness of the wafer stage. A thicker wafer stage can smooth out the electric field at the edge. In PIII, the ions are accelerated from the ion sheath and the ion incident angle is dominated by the spherical shape of the ion sheath. Our results show that the retained dose and impact energy in DC-PIII can be made much more uniform by choosing the suitable internal dimensions of the lower part. Our simulation suggests that the best ratio is $r : R : H : D = 1 : 4 : 2.5 : 2$, that is, a disk shape chamber instead of the conventional cylindrical chamber is preferred.

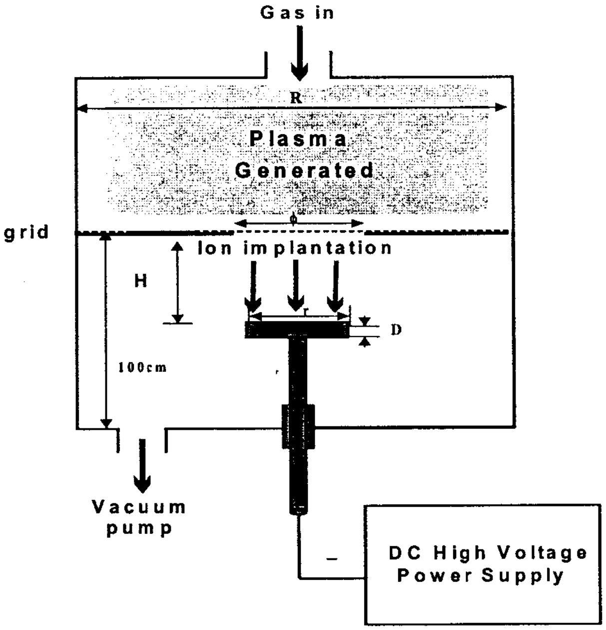

Fig. 1: Schematic diagram of DC-PIII system in the City University of Hong Kong, R=76cm, r=16.2cm, D=5.6cm, H and ϕ can be varied. The plasma is generated by four RF coils (ICP).

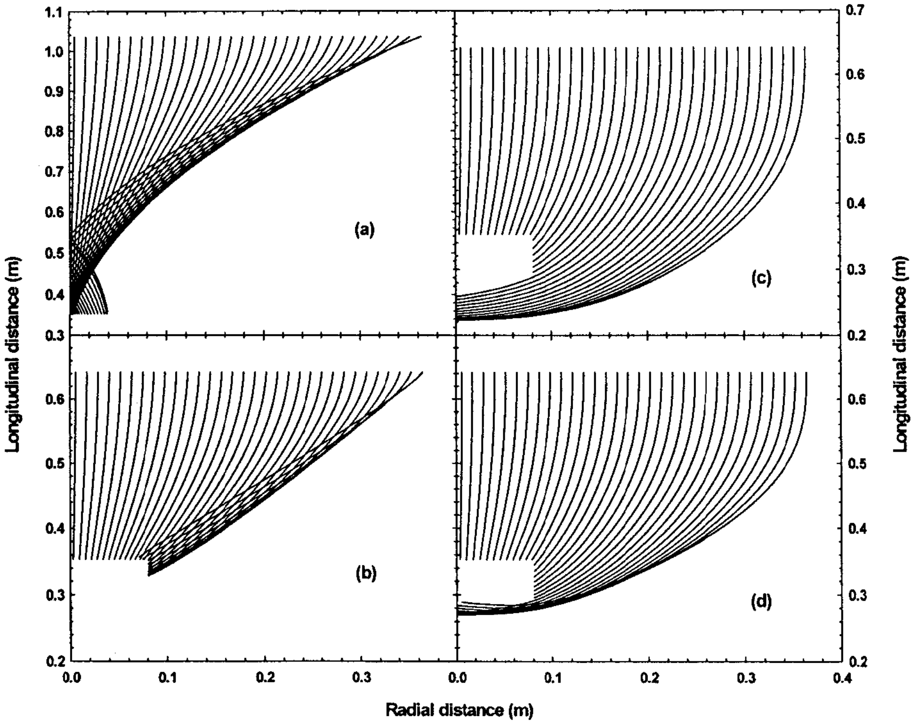

Fig. 2: Trajectories of O^+ *implanting from the grid (top of the field lines) to the wafer stage (bottom of the field lines) at −70kV bias voltage and ϕ=R: (a) H=70cm showing that the ions focus onto the center of the wafer; (b) H=30cm showing that the whole wafer is implanted; (c) an initial downward drift velocity equivalent to 5keV energy is applied and ion trajectories are changed; (d)* O_2^+ *ions with the same velocity as (c) are used and the ion paths become dependent on the charge state at the high initial velocity of the ions.*

III. EXPERIMENTAL RESULTS AND DISCUSSION

The experiments were done in our semiconductor PIII equipment. The basic parameters are displayed in Fig. 1. We measured the I-V curves for different gas pressure, plasma density, and distance between the grid and the wafer stage. In order to investigate the basic phenomena, we used argon plasma generated by using RF-ICP (radio frequency inductively-coupled plasma). Our experiments suggest that the argon gas pressure should be quite low (0.12mtorr-0.5mtorr) in DC-PIII. The distance between the grid and wafer stage *H* is 67cm or 37cm. Different RF power and gas pressure change the plasma density. The plasma density was measured by a Langmuir probe.

Shown in Fig. 3 are three I-V curves when the argon pressure is 0.12mtorr, 0.3mtorr, or 0.5mtorr (*H* is 67cm and RF power is 600W). Three I-V curves when the argon pressure is 0.12mtorr (RF power is 600W or 200W) or 0.31mtorr (RF power is 600W and *H* is 37cm) are shown in Fig. 4. There appears to be no obvious glow discharge under our experimental conditions. The currents depend on the surface area of the plasma sheath, plasma density, secondary electron emission, and Bohm speed, i. e. $I=e\gamma nA_sU_b$ ($U_b=kT_e/2e$). The plasma sheath expanding process is schematically shown in Fig. 5.

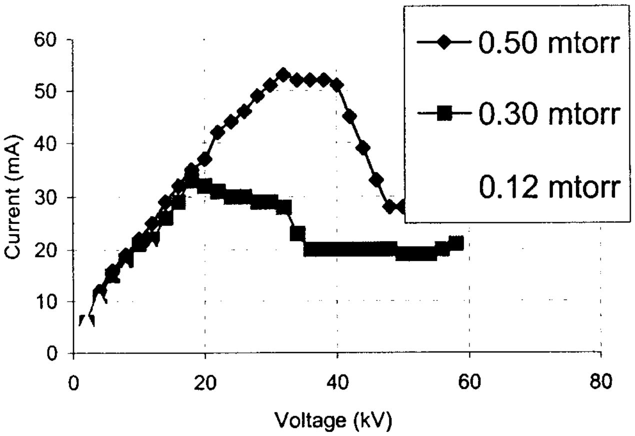

Fig. 3: I-V curves for different argon gas pressures when RF power = 600W, H = 67cm.

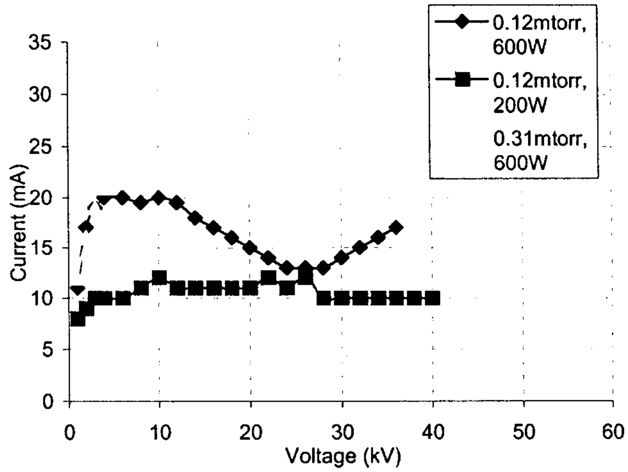

Fig. 4: I-V curves for different argon gas pressures and RF powers when H = 37cm

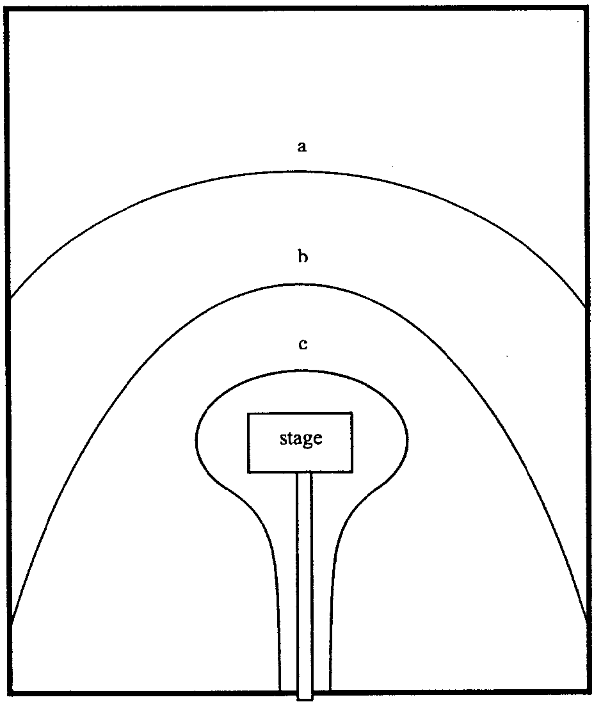

Fig. 5: Schematic of the sheath evolution with voltage in DC-PIII, V(a)<V(b)<V(c).

Since kT_e is almost constant, γ increases with the voltage in the low voltage regime. The plasma density is highest directly above the wafer stage in a down-stream plasma system, and the speed of the sheath propagation diminishes when the density of the plasma increases. Therefore, the time when the current reaches steady-state is longer with increasing argon pressure or RF power. The process can be envisaged as follows. In the beginning, the sheath area and γ become large with increasing voltage, and so the current increases. The sheath propagation becomes slower because the density is larger near the grid. Finally, the sheath area decreases and the sheath stops at the grid with further increase in the voltage. The current only depends on the plasma density. The linear relationship of the steady-state current versus the plasma density is depicted in Fig. 6. We have also found that the secondary electron emission coefficient γ does not vary much at high voltage. The breakdown voltage is observed to increase with H.

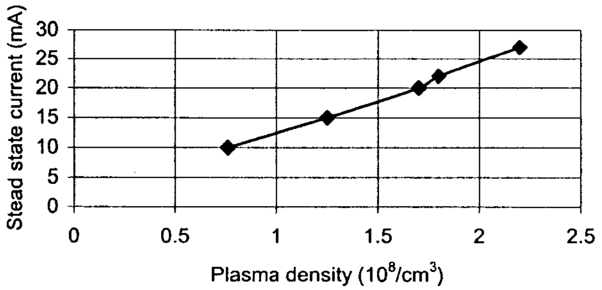

Fig. 6: Linear relationship of the steady-state current versus plasma density.

IV. CONCLUSION

High voltage DCPIII can be realized by using a conducting grid in a conventional PIII system. It is preferable to operate at low gas pressure for high voltage, for example, lower than 0.1mtorr. A more powerful plasma source such as an electron cyclotron resonance (ECR) source will increase the efficiency.

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