

Improved planar radio frequency inductively coupled plasma configuration in plasma immersion ion implantation

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Plasmas with higher density and better uniformity are produced using an improved planar radio frequency (rf) inductively coupled plasma configuration in plasma immersion ion implantation (PIII). An axial magnetic field is produced by external electromagnetic coils outside the discharge chamber. The rf power can be effectively absorbed by the plasma in the vicinity of the electron gyrofrequency due to the enhanced resonant absorption of electromagnetic waves in the whistler wave range, which can propagate nearly along the magnetic field lines thus greatly increases the plasma density. The plasma is confined by a longitudinal multipolar cusp magnetic field made of permanent magnets outside the process chamber. It can improve the plasma uniformity without significantly affecting the ion density. The plasma density can be increased from 3×10^9 to $1 \times 10^{10} \text{ cm}^{-3}$ employing an axial magnetic field of several Gauss at 1000 W rf power and 5×10^{-4} Torr gas pressure. The nonuniformity of the plasma density is less than 10% and can be achieved in a process chamber with a diameter of 600 mm. Since the plasma generation and process chambers are separate, plasma extinction due to the plasma sheath touching the chamber wall in high-energy PIII can be avoided. Hence, low-pressure, high-energy, and high-uniformity ion implantation can be accomplished using this setup. © 2003 American Institute of Physics. [DOI: 10.1063/1.1568559]

I. INTRODUCTION

Inductively coupled plasmas have been widely used for thin film deposition and etching in the microelectronics and optics industry due to their low-pressure and high plasma density.^{1–8} Although a high plasma density at low pressure can also be achieved with electron cyclotron resonance (ECR) source,^{9,10} helicon wave source,¹¹ and helicon resonators,¹² the inductively coupled plasma has several advantages. It has a greater scalability and wider operating window. It is, thus, relatively easy to scale to large diameter samples without significant increase in the hardware complexity and cost while retaining the advantage of high plasma density. Inductively coupled plasmas are particularly useful in low-energy and high-dose plasma immersion ion implantation (PIII) experiments.¹³

The trend towards large-area materials processing especially in the microelectronics and optics industry is propelling large-area plasma developments. Processes using different inductively coupled plasma sources have been designed to produce large-area, high-density, and high-uniformity plasmas for plasma etching in microelectronics^{14–16} as well as surface modification utilizing PIII.¹⁷ The application of external magnetic field to inductively coupled plasmas is known to improve the ionization and power absorption efficiency at low pressure in small aspect ratio ($L/R < 1$ for cylindrical geometry).¹⁶ An end-launched flat-spiral helicon plasma source was investigated,¹⁸ in which 13.56 MHz rf

power was coupled into a helicon mode with the application of a weak external magnetic field. In most of these processes, the plasma discharge and materials processing are conducted in the same vacuum chamber. This makes high-energy, low-pressure PIII difficult due to plasma extinction when the plasma sheath reaches the chamber wall.

In this article, we present an enhanced magnetized radio frequency inductively coupled PIII setup and process utilizing a separate plasma discharge chamber and processing chamber, in which an external axial magnetic field introduced into the plasma discharge region enhances the absorption of rf power in the magnetized plasma. In our previous work,¹⁹ we conducted a preliminary study on the effects of magnetic field on the pulse waveforms in a rf inductively coupled plasma. In this article, we report on our improved hardware that yields higher density and better uniformity for plasma immersion ion implantation. We also investigated the effects of the external axial magnetic field on the rf power absorption and plasma density profiles. The effects of the axial magnetic field and multipolar cusp magnetic field on the characteristics of plasma as well as the damping mechanisms of rf power were probed. A Langmuir probe was employed to characterize the electron saturation current and plasma density. Using the setup, high-uniformity hydrogen PIII into 150 mm silicon wafers was demonstrated.

II. EXPERIMENT

The schematic diagram of the enhanced magnetized rf inductively coupled plasma configuration in PIII is shown in Fig. 1. This equipment consists of a plasma discharge cham-

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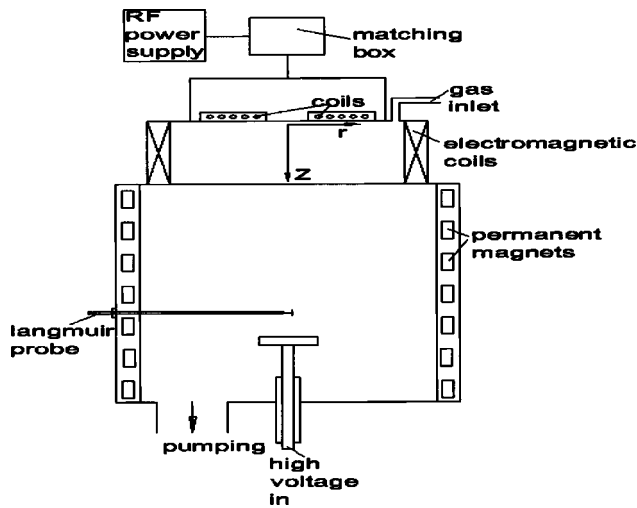


FIG. 1. Schematic diagram of the magnetized rf inductively coupled PIII configuration.

ber ($\phi 600 \text{ mm} \times 300 \text{ mm}$) and materials processing chamber ($\phi 760 \text{ mm} \times 1030 \text{ mm}$), both made of stainless steel and pumped by a turbopump and a mechanical pump. The background pressure is about 7×10^{-6} Torr.

With the increase of the discharge chamber diameter, a spiral planar coil with an increased diameter gives rise to inherent nonuniformity in the magnetic induction field because of the difference between the center and the periphery of the coil.^{20,21} In this work, in order to produce high-density and high-uniformity plasmas, four rf planar inductive coils are placed on four planar quartz windows on top of the plasma discharge region and 13.56 MHz rf power (0–2000 W) is coupled to the plasma via the four pancake inductive antennas through the quartz windows. This setup is different from the end-launched flat-spiral helicon plasma source described in Ref. 18. The four inductive coils are located symmetrically above the plasma discharge region and connected to a matching box. An external axial magnetic field is introduced into the plasma discharge region by external Helmholtz-type electromagnetic coils outside the discharge chamber. The axial magnetic field can be adjusted from 0 to 100 G by changing the coil current I_c . The magnetic bucket confinement scheme has previously been used to improve plasma density uniformity.^{22,23} In our case, the permanent magnets are mounted outside the processing chamber as shown in Fig. 1. Each magnet has a magnetic field of 3 kG at the magnet end surface. A longitudinal multipolar cusp magnetic field is produced to confine the plasma and improve the plasma density.

To investigate the effects of the external axial magnetic field on the characteristics of the rf inductively coupled plasma discharge, the plasma parameters were measured by an electrostatic probe. A two-sided planar circular Langmuir probe made of a thin tantalum disk 2 mm in diameter was swept across the plasma discharge and processing chamber along the axial and longitudinal directions to monitor the electron saturation current and plasma density profile. The plasma density n is obtained from the electron saturation current I_{eo} according to the following relationship:²⁴

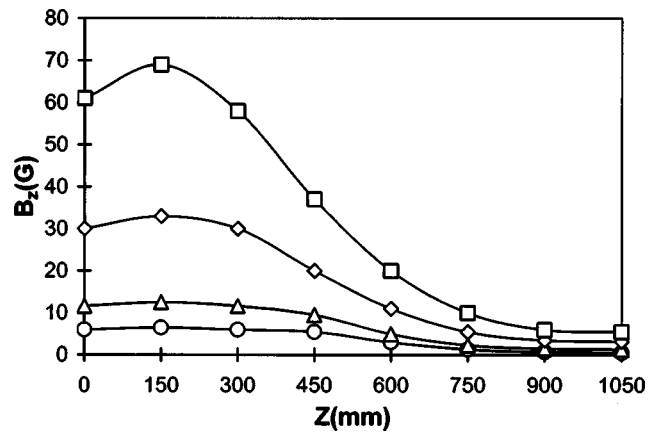


FIG. 2. Axial magnetic field B_z vs z position at $r=0$: ($\square$) $I_c=2$ A, ($\diamond$) $I_c=1$ A, ($\triangle$) $I_c=0.4$ A, and ($\circ$) $I_c=0.2$ A.

$$n = \frac{I_{eo}/(eA)}{[kT_e/(2\pi m_e)]^{1/2}}, \quad (1)$$

where k , A , T_e , and m_e are, respectively, the Boltzmann's constant, area of the probe, electron temperature, and electron mass. The electron temperature is defined by

$$\frac{e}{kT_e} = \frac{d \ln I_e}{d V_p}, \quad (2)$$

where I_e and V_p are the electron current and probe potential, respectively.

To demonstrate the feasibility and improvement as a result of the new configuration, plasma immersion ion implantation was conducted into 150-mm-diam silicon wafers. The wafers were biased by either a high-voltage pulse power supply or dc power supply. Similar to that used in the ion-cut technique for SOI silicon-on-insulator (SOI) synthesis, H_2 was used as the working gas.

III. RESULTS AND DISCUSSION

The magnetic field strengths in the plasma discharge and processing regions are monitored using different magnetic coil current I_c . Cylindrical coordinates are used to locate the position in the plasma discharge and processing chambers. $Z=0$ mm designates the top of plasma discharge chamber as shown in Fig. 1. The axial magnetic field B_z vs Z at different magnetic coil currents is displayed in Fig. 2. It can be observed that B_z decreases along the Z direction in the processing chamber ($Z > 300$ mm). This indicates that plasma transport is due not only to diffusion but also to the ∇B drift and curvature drift arising from the magnetic field gradient and divergent magnetic field configuration in the process chamber.

The electron saturation current and plasma density profile of the hydrogen plasma at different external magnetic fields and pressures are measured using the planar electrostatic probe. The electron saturation currents I_{eo} versus the external magnetic field at different Z positions are displayed in Fig. 3. Here, the rf input power is 1000 W and the pressure is 5×10^{-4} Torr. The electron saturation currents vary with the external magnetic field strength and peaks are seen in all

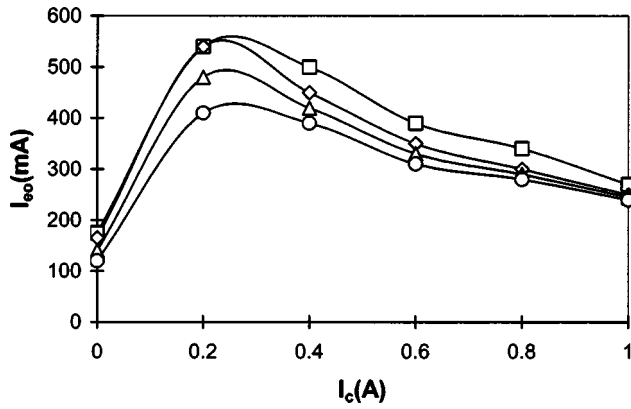


FIG. 3. Electron saturation current vs electromagnetic coil current at $r=0$: ($\square$) $z=450$ mm, ($\diamond$) $z=600$ mm, ($\triangle$) $z=750$ mm, and ($\circ$) $z=900$ mm.

of the curves shown in Fig. 3. The electron temperature T_e versus different external magnetic field trend is illustrated in Fig. 4. The electron temperature decreases with increasing external magnetic field and pressure. This is primarily due to the reduction of radial transport of electrons by the confinement of the external magnetic field and the effective increase in the collisions between the electrons and neutral gases at high pressure.

The plasma density is calculated based on the electron saturation current and electron temperature in accordance with Eqs. (1) and (2). The plasma density n versus the external magnetic field at the axial positions is shown in Fig. 5. In our calculation, the rf input power is 1000 W and the vacuum pressure is 5×10^{-4} Torr. First, it is seen that the plasma density will increase when the external magnetic field is applied. This implies that the electron heating mechanism will be affected by the external magnetic field. Meanwhile, peaks can be observed on all the plasma density curves with changing axial magnetic field coupled with the external Helmholtz coil as shown in Fig. 5. Our results show that more rf power is absorbed by the plasma in the vicinity of a certain magnetic field strength, and so a higher plasma density is produced. Curve (3) in Fig. 5 shows that the plasma density can be increased from 3×10^9 cm $^{-3}$ (no external magnetic field) to over 1×10^{10} cm $^{-3}$ using an axial magnetic field of sev-

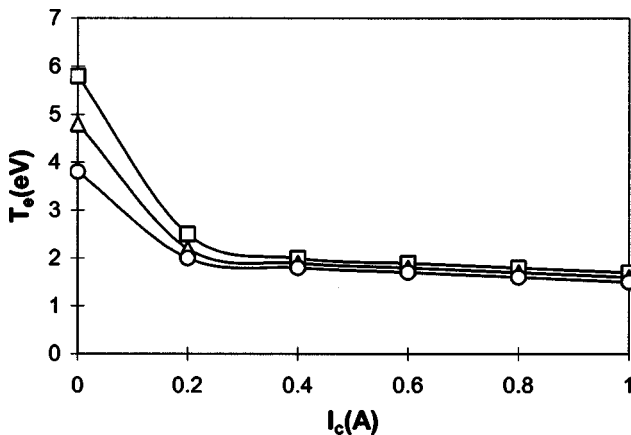


FIG. 4. Electron temperature vs electromagnetic coil current: ($\square$) $p=5 \times 10^{-4}$ Torr, ($\triangle$) 8×10^{-4} Torr, and ($\circ$) 1×10^{-3} Torr.

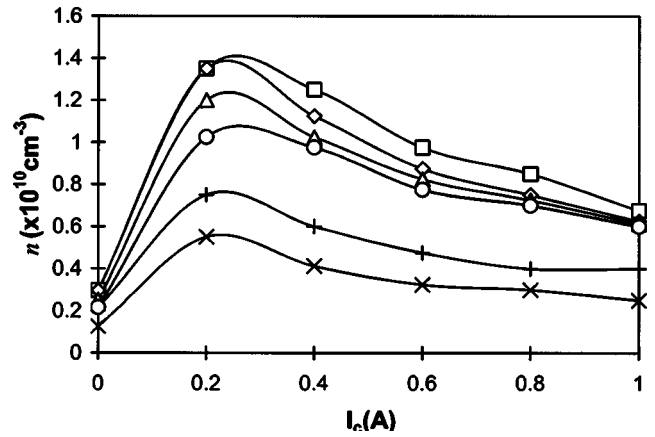


FIG. 5. Plasma density vs external electromagnetic coil current at $r=0$: ($\times$) $z=0$, ($+$) $z=150$ mm, ($\square$) $z=450$ mm, ($\diamond$) $z=600$ mm, ($\triangle$) $z=750$ mm, and ($\circ$) $z=900$ mm.

eral gauss at 1000 W rf power and 5×10^{-4} Torr pressure. Although the exact damping mechanism involved in our system is not investigated, noncollisional power absorption such as Landau damping at low pressure and cyclotron resonance damping of the whistler wave in the plasma via the interaction of the whistler waves with the magnetized cold plasma may play some roles.^{18,25} The phenomenon is expected based on the dispersion relation of the R wave in magnetized cold plasmas:²⁶

$$n^2 = \frac{c^2 k^2}{\omega^2} = 1 - \frac{\omega_{pe}^2}{\omega(\omega + i\nu_{en} - \omega_{ce} \cos \theta)}, \quad (3)$$

where ω , ω_p , ω_{ce} , c , and ν_{en} are, respectively, wave frequency, plasma frequency, gyrofrequency, speed of light and electron-neutral collisional frequency, $n = ck/\omega$ is the index of refraction of wave. $k = 2\pi/\lambda$ is the wave number, θ is the angle between the total wave vector with the external magnetic field. The wave number can also be expressed as $k^2 = k_{\parallel}^2 + k_{\perp}^2$, $k_{\parallel}$ and $k_{\perp}$ are, respectively, the wave numbers parallel and perpendicular to the magnetic field, so that $\cos \theta = k_{\parallel}/k$. In our experiments, the neutral gas pressure is about 5×10^{-4} Torr. The electron-neutral collisional frequency is very small. So, it can be treated as the collisionless cold plasmas. Moreover, the plasma frequency is substantially higher than the electron gyrofrequency. For the frequency of whistler waves in our experiments, $\omega_{ci} \ll \omega \ll \omega_{ce} \ll \omega_{pe}$, the dispersion relation [Eq. (3)] may be changed to the following approximated form:

$$k^2 = \frac{\omega_{pe}^2 \omega}{c^2 (\omega_{ce} \cos \theta - \omega)}. \quad (4)$$

For the helicon mode whistler wave propagated along the axial direction, the radial wave number $k_{\perp}$ is generally fixed by the chamber radius R :

$$k_{\perp} = \frac{3.83}{R}. \quad (5)$$

In our experiments, the chamber radius is 30 cm. The axial wavelength is a function of static magnetic field and the average electron density²⁷

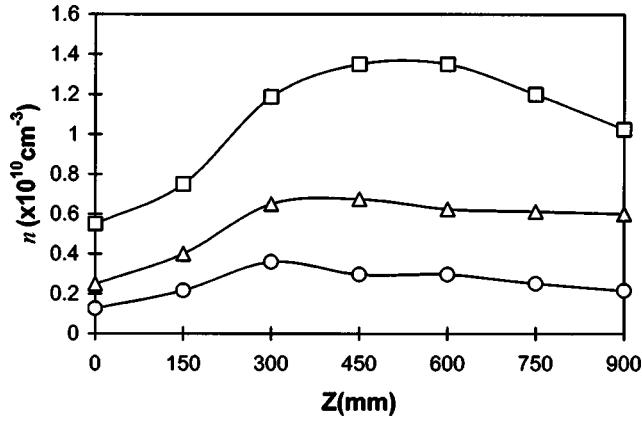


FIG. 6. Axial plasma density profile at $r=0$: (○) $I_c=0$ A, (△) $I_c=1$ A, and (□) $I_c=0.2$ A.

$$\lambda_{\parallel} = \frac{7.6 \times 10^6}{R} \left(\frac{B}{n_e} \right)^{0.63}, \quad (6)$$

where R is the chamber radius with cm, B is the magnetic field with gauss and n_e is the average electron density with cm^{-3} . Therefore, the axial wave number $k_{\parallel} = 2\pi/\lambda_{\parallel}$ can be deduced from Eq. (6). With low static magnetic field (several gauss) and electron density of 10^{10} cm^{-3} , $k_{\parallel} \gg k_{\perp}$. So that $k_{\parallel} \approx k$ and $\cos \theta \approx 1$. Therefore, the total wave number of helicon wave propagating along the axial direction has a solution as follows:

$$k = \frac{\omega_{pe}}{c} \sqrt{\frac{\omega}{\omega_{ce} - \omega}}. \quad (7)$$

As $\omega \rightarrow \omega_{ce}$, $k \rightarrow \infty$, and so that the wavelength $\lambda \rightarrow 0$. Note that resonance is achieved at $\omega = \omega_{ce}$. The external magnetic field is $B = \omega_{ce} m/e$. The resonant magnetic field B_0 for 13.56 MHz rf is about 4.8 G, which is the same as our experimental result for hydrogen plasma at 1000 W rf power and 5×10^{-4} Torr pressure. As shown in Fig. 5, the plasma density peaks in the vicinity of $I_c = 0.2$ A. The axial magnetic field at $I_c = 0.2$ A is about 2–7 G in the discharge and process chambers as shown by curve (1) in Fig. 2. This implies that the absorption of rf power is enhanced by the external magnetic field and the maximum rf power absorption occurs in the vicinity of the gyrofrequency. The axial plasma density profile is described in Fig. 6. The axial plasma density in the process chamber is larger than that in the discharge chamber in the presence of the external magnetic field. The largest plasma density occurs between $Z = 450$ mm and $Z = 600$ mm [curve (3) in Fig. 6]. It can also be seen that the axial magnetic field B_z varies from 6 to 3 G between $Z = 450$ mm and $Z = 600$ mm [curve (1) in Fig. 2]. Hence, enhanced resonant absorption occurs in the processing chamber between $Z = 450$ mm and $Z = 600$ mm where the axial magnetic field is close to the resonance magnetic field. This may be because the right-hand polarized (RHP) whistler wave can propagate in an overly dense plasma^{28,29} where the plasma electron density n_e is greater than the critical density n_c . For a radio frequency $f = 13.56$ MHz, n_c is approximately equal to $2.3 \times 10^6 \text{ cm}^{-3}$. The RHP wave is launched from the high-field side of the discharge chamber where the magnetic field B is

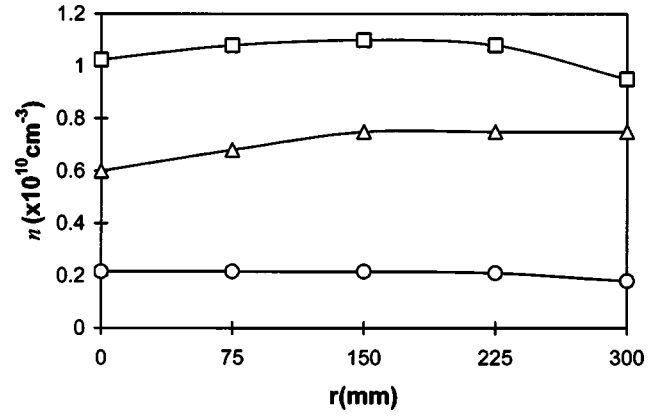


FIG. 7. Radial plasma density profile at $z=900$ mm: (○) $I_c=0$ A, (△) $I_c=1$ A, and (□) $I_c=0.2$ A.

greater than the resonance field B_0 and propagates along the magnetic field lines to the resonant region where enhanced resonant absorption occurs. This result indicates that the huge jump of plasma density in the axial position is mainly due to the electron cyclotron resonance damping in the vicinity of gyrofrequency.

The plasma produced in the discharge chamber is transported to the process chamber by diffusion, ∇B drift, and curvature drift. The multipolar cusp magnetic field around the process chamber reduces the loss of plasma to the process chamber wall and improves the plasma uniformity. The radial plasma density profile is exhibited in Fig. 7. The non-uniformity of the radial plasma density is less than 10% in a 600-mm-diam process chamber above the sample holder. The pulse current wave form of hydrogen PIII into the 150 mm silicon wafer is depicted in Fig. 8. The maximum value of the ion current can be achieved in the vicinity of the resonant frequency using a 0.2 A coil current, which is good agreement with the ion density profile measured in our experiments. The hydrogen concentration across the 150-mm-diam silicon wafer is measured by elastic recoil analysis (ERA) in a Rutherford backscattering spectrometer (RBS). The normalized implant dose profile displayed in Fig. 9

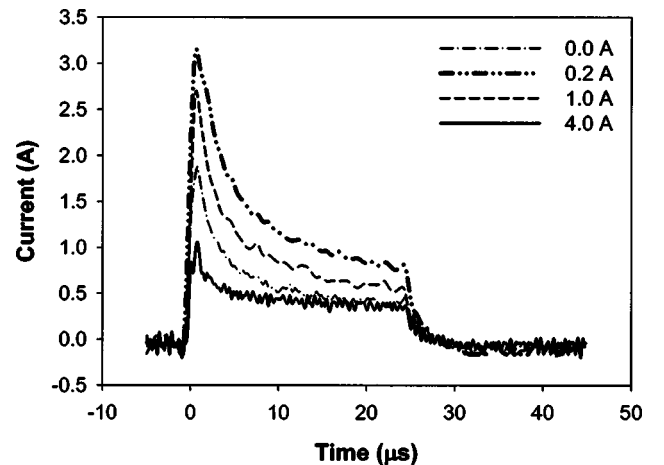


FIG. 8. Pulse current wave forms for different magnetic coil currents at rf power of 1000 W, pulse voltage of 25 kV, and hydrogen pressure of 5.0×10^{-4} Torr.

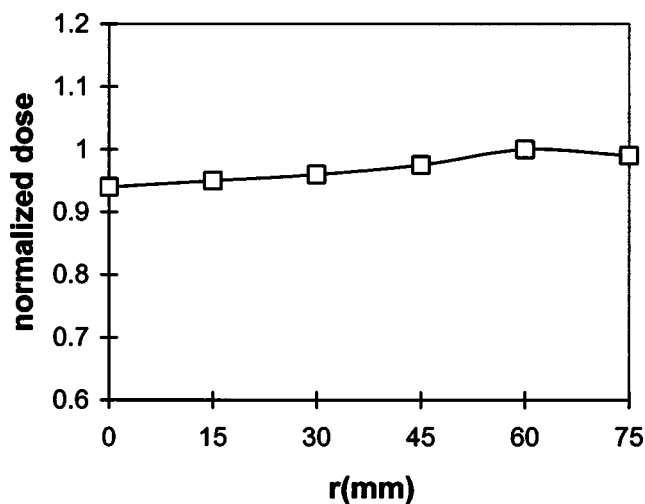


FIG. 9. Normalized hydrogen concentration across the 150-mm-diam silicon wafer implanted at 25 kV.

shows that the lateral nonuniformity of the H concentration across the radius of the silicon wafer is less than 5%.

In summary, an improved planar radio frequency inductively coupled plasma configuration for plasma immersion ion implantation is reported. The effects of the axial magnetic field and multipolar cusp magnetic field on the plasma parameters and ion implantation current are investigated. The rf power can be effectively absorbed by the plasma in the vicinity of electron gyrofrequency due to enhanced resonant absorption of the electromagnetic waves in the whistler wave range, which can propagate nearly along the magnetic field lines to greatly enhance the plasma density. The separation of the discharge chamber and process chamber enables high-energy, low-pressure PIII. The plasma transport is achieved not only by diffusion but also by the ∇B drift and curvature drift due to the magnetic field gradient and the divergent magnetic field configuration in the process chamber. Meanwhile, the plasma density uniformity in the process chamber can be improved by diffusion and plasma confinement by the multipolar cusp magnetic field. The plasma density can be increased from $3 \times 10^9 \text{ cm}^{-3}$ to over $1 \times 10^{10} \text{ cm}^{-3}$ by employing an axial magnetic field of several gauss at 1000 W rf power and 5×10^{-4} Torr pressure. The nonuniformity of the plasma density in a 600 mm process chamber is observed to be less than 10%. Our results show that low-pressure, high-energy, and high-uniformity ion implantation can be accomplished using this process.

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