ELSEVIER

Physics Letters A 277 (2000) 42–46

PHYSICS LETTERS A

www.elsevier.nl/locate/pla

Modeling of the relationship between implantation parameters and implantation dose during plasma immersion ion implantation

Xiubo Tian, Paul K. Chu *

Department of Physics and Materials Science, City University of Hong Kong, 83 Tat Chee Avenue, Kowloon, Hong Kong, China

Received 17 July 2000; received in revised form 19 September 2000; accepted 3 October 2000
Communicated by M. Porkolab

Abstract

Plasma immersion ion implantation (PIII) has attracted wide interests since it emulates conventional ion-beam ion implantation (IBII) in niche applications. For instance, the technique has very high throughput, the implantation time is independent of the sample size, and samples with an irregular shape can be implanted without complex beam scanning or sample manipulation. However, unlike conventional ion-beam ion implantation (IBII), prediction of the implantation dose and consequent process optimization are very difficult without extensive experiments since the incident ion flux is related to the implantation parameters such as accelerating voltage, pulse duration, and so on in a complex manner. Even though individual parameters have been investigated, there has not been a unified and user-friendly model to numerically predict the implantation dose under different plasma and processing conditions. In this letter, we present a one-dimensional analytical model to simulate the effects of parameter variations on the incident ion dose and to predict the implantation dose. The derived model is quite simple and applicable to planar targets such as silicon wafers. It will be an invaluable tool to process engineers in microelectronics working on silicon-on-insulator (SOI) formation by PIII and plasma doping.

PACS: 61.72; 81.70.J; 81.65; 52.75.R
Keywords: Plasma immersion ion implantation; Implantation dose; Modeling; Silicon processing

---

Plasma immersion ion implantation (PIII) has been shown to be an effective surface modification and materials fabrication technique [1]. It emulates conventional ion-beam ion implantation (IBII) in a number of areas. For example, it has high sample throughput (high current density) and it is a parallel processing technique in that the implantation time is independent of the wafer size, making it more attractive for larger samples, such as 300 mm silicon wafers. It also circumvents the line-of-sight restriction imposed by IBII. Typical commercial applications of PIII include metal strengthening [2] and semiconductor processing, e.g., SPIMOX (separation by plasma implantation of oxygen) [3–7] and PIII/ion-cut [8–13]. In PIII, accurate knowledge of the incident ion dose is very critical to the success of the process. For instance, in the PIII/ion-cut technique, a proper number of hydrogen ions on the order of 5×10^{16} cm^{-2} must be implanted. An insufficient ion dose cannot produce effective coalescence of the microcavities and consequent uniform exfoliation of the surface layer [14]. How-

---

[*] Corresponding author. Tel.: (+852)-27887724, fax: (+852)-27889549 or (+852)-27887830.
E-mail address: paul.chu@cityu.edu.hk (P.K. Chu).

0375-9601/00/$ – see front matter
PII: S0375-9601(00)00673-3

ever, an overdose causes premature surface blistering leading to the failure of ion-cut. Unfortunately, accurate modeling and prediction of the implantation dose in PIII is quite difficult because it is a complicated function of inter-related processing conditions such as plasma density, pulse duration, acceleration voltage, ion mass, and ion charge state, and the same dose can be obtained using different sets of implantation parameters [15]. This complicated situation thus makes process optimization difficult without extensive experiments. Up to now, even though individual processing parameters have been investigated using theoretical simulations employing the Child–Langmuir law [16–18], plasma fluid model [19,20], and particle-in-cell (PIC) codes [21,22], a simple and user-friendly analytical model describing the effects of these inter-related parameters on the implantation dose is not available to process engineers for process optimization. In this letter, we present a one-dimensional analytical model to effectively predict the effects of parameter variations on the incident ion dose for planar specimens such as silicon wafers.

In PIII of planar samples, the plasma sheath is flat only away from the sample holder edge [8] as shown schematically in Fig. 1. However, if the sample platen is sufficiently bigger than the wafer, we can ignore the edge effects and describe the sheath dynamics using the Child–Langmuir law. In a typical PIII process, the sheath voltage is always greater than the electron temperature, and we can assume that a quasi-static Child–Langmuir law sheath exists at all time and the ion current is spatially constant within the sheath. The implantation ion current J_i, can thus be described using the Child–Langmuir law. For a voltage V_a across a collisionless sheath of thickness S, the current is

$$J_i = \frac{4}{9}\varepsilon_0\left(\frac{2q}{M}\right)^{1/2}\frac{V_a^{3/2}}{S^2}, \tag{1}$$

where ε_0 is the free-space permittivity, q is the ion charge, and M is the ion mass.

In our dynamic sheath model, it is assumed that the ion current, J_i, arises from the ions within the moving sheath. Therefore,

$$J_i = qn_0\frac{ds}{dt}, \tag{2}$$

where n_0 is the plasma density. Combining Eqs. (1) and (2) and integrating the resulting equation, the time-dependent dynamics can be described as [16–18]

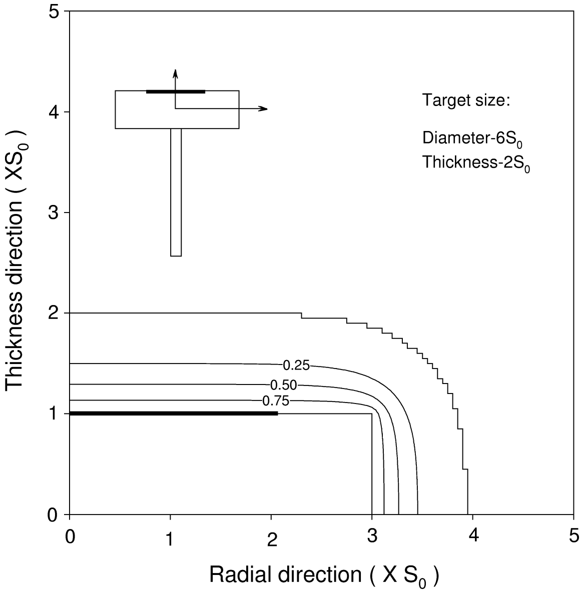

Fig. 1. Initial plasma sheath and potential around the sample platen. The electric field is rounded near the corner, but is flat on the sample provided the sample is sufficiently smaller than the sample stage.

$$S_{(t)} = S_0\left(\frac{2}{3}\omega_{pi}t_p + 1\right)^{1/3}, \tag{3}$$

where $\omega_{pi} = u_0/S_0$ is the ion plasma frequency, $S_0 = \sqrt{2\varepsilon_0 V_0/qn_0}$ is the ion-matrix sheath thickness, and $u_0 = \sqrt{2qV_0/m}$ is the characteristic ion velocity. Hence, the incident ion dose deposited onto a unit area in a single pulse is

$$D = n_0 S_t. \tag{4}$$

The total deposited ion dose within a certain duration, t, is

$$D_{\text{total}} = n_0 S_t f t, \tag{5}$$

where f is the pulsing frequency. Consequently,

$$D_{\text{total}} = tfn_0^{1/2}V_0^{1/2}(2\varepsilon_0)^{1/2}q^{-1/2} \times\left[\frac{2}{3}\left(\frac{n_0q^2}{\varepsilon_0 m}\right)^{1/2}t_p + 1\right]^{1/3}. \tag{6}$$

For a typical set of implantation parameters,

$$\beta = \frac{2}{3}\left(\frac{n_0q^2}{\varepsilon_0 m}\right)^{1/2}t_p \gg 1,$$

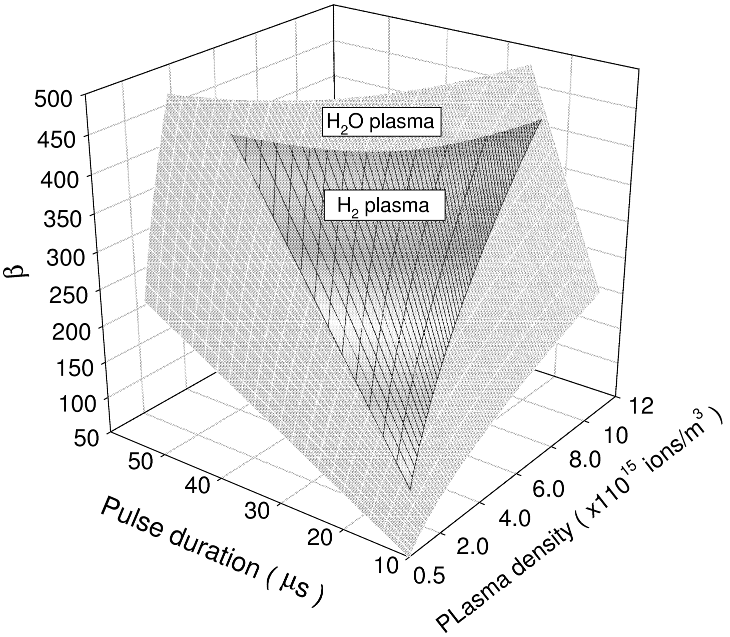

Fig. 2. Relationship of $\beta = \frac{2}{3}\left(\frac{n_0 q^2}{\varepsilon_0 m}\right)^{1/2} t_p$ versus pulse duration and plasma density for H_2 and H_2O plasmas.

as shown in Fig. 2. Therefore, Eq. (6) can be simplified to be:

$$D_{\text{total}} = \left(\frac{2}{3}\right)^{1/3} 2^{1/2} \varepsilon_0^{1/3} t f q^{-1/6} n_0^{2/3} m^{-1/6} \times V_0^{1/2} t_p^{1/3}. \tag{7}$$

Eq. (7) demonstrates the relationship between the incident dose and implantation parameters for a single species (e.g., Ar^+) plasma ion implantation. When there exist more than one species in the plasma (e.g., N_2^+/N^+ or H_2^+/H^+),

$$D_{\text{total}} = \left(\frac{2}{3}\right)^{1/3} 2^{1/2} \varepsilon_0^{1/3} t f q^{-1/6} N_0^{2/3} M^{-1/6} \times V_0^{1/2} t_p^{1/3}, \tag{8}$$

where the effective plasma ion mass, $\sqrt{M} = \sum_{i=1}^{L} A_i \sqrt{m_i}$, L is the number of ion species, A_i is the fraction of the total ion density in the plasma bulk for species i, m_i is the mass of the ith ion, incident atom dose $N_0 = \sum_{i=1}^{m} B_i n_i$, B_i is the atomic number of the ith ion species, n_i is the density of the ith ion species [17].

In the case of a plasma consisting of ions with multiple charge states (e.g., Ti^+, Ti^{2+}),

$$D_{\text{total}} = \left(\frac{2}{3}\right)^{1/3} 2^{1/2} \varepsilon_0^{1/3} t f q^{-1/6} N_1 n_e^{-1/3} M^{-1/6} \times V_0^{1/2} t_p^{1/3}, \tag{9}$$

where the total ion density $N_1 = \sum_{i=1}^{L} n_i$, plasma density $n_e = \sum_{i=1}^{L} C_i n_i$, effective plasma mass $\sqrt{M} = \sum_{i=1}^{L} k_i \sqrt{C_i m_i}$, and C_i is the charge state, the fraction of the total ion density for the ith ion, $k_i = n_i / \sum_{i=1}^{m} C_i n_i$ [18].

Eq. (7) illustrates that the incident dose in a single pulse has a different sensitivity to each implantation parameter, and this phenomenon is different from that encountered in IBII. In the latter case, the implantation dose is linearly proportional to the implantation pulse duration/pulsing frequency in the pulsing mode or the total implantation time in the direct-current (DC) mode. More importantly, it is independent of the implantation voltage, ion mass, or ion charge state. Thus, process control, experimental design, and process simulation are quite straightforward. On the other hand, in

PBII, many parameters are nonlinearly related to implantation dose, as indicated by Eqs. (7)–(9), making dose prediction and process optimization difficult.

In PIII processes, plasma parameters such as density, species, and charge states vary considerably with the type of plasma source. Owing to the absence of an ion filtering mechanism in PIII, all ions in the surrounding plasma are implanted into the samples when a negative potential is applied to them. Varying the plasma density has a complicated influence on the incident dose. For example, when the plasma density is higher, it seems that incident ion flux will increase correspondingly. Actually, the ion flux will increase not as described by Eq. (7). When the plasma excitation power of plasma sources is increased, the plasma density goes up. Meanwhile, the atomic ion density also increases [23] and the mean ion charge state may also go up, especially in a metal ion plasma [24]. Consequently, the equivalent ion mass decreases in a single charge-state plasma (e.g., nitrogen plasma) leading to an increase in the incident ion flux and ion dose. That is to say, when the plasma density increases, the incident ion flux rises due to not only the density difference but also the change in the ion charge and mass. This interaction can be used to explain the difference in the ion flux variation when the plasma density from different gas species changes. In the case of multiple-charge state plasmas, N_1, n_e, M may be affected by a slight change in the plasma parameters leading to unintuitive relationship as shown in Eq. (9). For instance, if the plasma density is constant, increasing the fraction of multiple-charge state ions will decrease N_1 and M thereby resulting in a lower incident ion flux.

The implantation voltage has a different influence on the incident dose than IBII. In IBII, the implantation voltage only affects the in-depth distribution of the implanted species, mainly the projected range and straggle. In PIII, both the penetration depth and incident dose rate are changed by the implantation voltage. The pulse duration and pulsing frequency are the two parameters normally adjusted to meet the processing requirements. The incident dose is linearly proportional to the pulsing frequency similar to that encountered in IBII, but not the pulse duration. For instance, to maintain the same incident dose, the pulse duration must be increased by eight times if the pulsing frequency decreases by 50%. Hence, engineers who are familiar with IBII may design inappropriate processes without an easy-to-use model such as the one stipulated in this article.

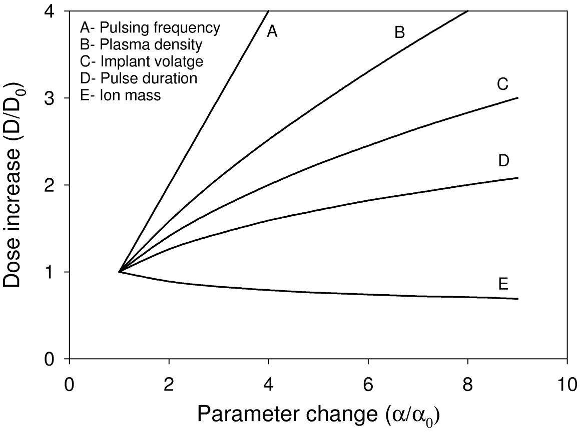

Fig. 3. Implantation dose variation with different processing parameters.

In this Letter, we present the relationship between implantation parameters and incident dose in plasma immersion ion implantation of planar samples. The derived analytical equation is effective and simple to use to process engineers. Our model demonstrates that PIII is a very complicated implantation process compared to conventional ion-beam ion implantation. The incident dose is most sensitive to variations in the pulsing frequency and total implantation time, followed by the plasma density, implantation voltage, and pulse duration. Since the numerical power of every variant is less than one, the implantation dose is much more sensitive to initial parameter changes as illustrated in Fig. 3.

Acknowledgements

This work was jointly supported by grants from the Hong Kong Research Grants Council (CERG #9040412 or CityU 1003/99E and #9040498 or CityU 1032/00E) as well as City University of Hong Kong (SRG #7001028).

References

[1] J.R. Conrad, J.L. Radtke, R.A. Dodd, F.J. Worzala, N.C. Tran, J. Appl. Phys. 2 (1987) 4951.

[2] J. Tendys, I.J. Donnelly, M.J. Kenny, J.T.A. Pollock, Appl. Phys. Lett. 53 (1988) 2143.
[3] J.B. Liu, S. Iyer, C.M. Hu, N.W. Cheung, R. Gronsky, J. Min, P.K. Chu, Appl. Phys. Lett. 67 (1995) 2361.
[4] J. Min, P.K. Chu, Y.C. Cheng, J. Liu, S.S. Iyer, N.W. Cheung, Surf. Coatings Technol. 85 (1–2) (1996) 60.
[5] P.K. Chu, N.W. Cheung, C. Chan, Semiconductor Int. 6 (1996) 165.
[6] X. Lu, S.S.K. Iyer, J.B. Liu, C.M. Hu, N.W. Cheung, J. Min, P.K. Chu, Appl. Phys. Lett. 70 (13) (1997) 1748.
[7] S.S.K. Iyer, X. Lu, J.B. Liu, J. Min, Z. Fan, P. Chu, C.M. Hu, N.W. Cheung, IEEE Trans. Plasma Sci. 25 (5) (1997) 1128.
[8] Z. Fan, P.K. Chu, C. Chan, N.W. Cheung, Appl. Phys. Lett. 73 (1998) 202.
[9] P.K. Chu, X. Lu, S.S.K. Iyer, N.W. Cheung, Solid State Technol. 40 (5) (1997) S9.
[10] X. Lu, N.W. Cheung, M.D. Strathman, P.K. Chu, B. Doyle, Appl. Phys. Lett. 71 (13) (1997) 1804.
[11] X. Lu, S.S.K. Iyer, C.M. Hu, N.W. Cheung, J. Min, Z.N. Fan, P.K. Chu, Appl. Phys. Lett. 71 (19) (1997) 2767.
[12] P.K. Chu, S. Qin, C. Chan, N.W. Cheung, P.K. Ko, IEEE Trans. Plasma Sci. 26 (1) (1998) 79.
[13] Z. Fan, Q.C. Chen, P.K. Chu, C. Chan, IEEE Trans. Plasma Sci. 26 (6) (1998) 1661.
[14] P.K. Chu, N.W. Cheung, Mater. Chem. Phys. 57 (1) (1998) 1.
[15] C. Blawert, B.L. Mordike, G.A. Collins, K.T. Short, J. Tendys, Surf. Coatings Technol. 103/104 (1998) 240.
[16] M.A. Lieberman, J. Appl. Phys. 66 (1989) 2926.
[17] P.K. Chu, S. Qin, C. Chan, N.W. Cheung, L.A. Larson, Mater. Sci. Eng. Reports 17 (6–7) (1996) 207.
[18] S. Qin, C. Chan, Z. Jin, J. Appl. Phys. 79 (1996) 3432.
[19] G.A. Emmert, M.A. Henry, J. Appl. Phys. 71 (1992) 113.
[20] X.B. Tian, Z.M. Zeng, X.C. Zeng, B.Y. Tang, P.K. Chu, J. Appl. Phys., in press.
[21] T.E. Sheridan, T.K. Kwok, P.K. Chu, Appl. Phys. Lett. 72 (1998) 826.
[22] D.T.K. Kwok, P.K. Chu, B.P. Wood, C. Chan, J. Appl. Phys. 86 (1999) 1817.
[23] B.Y. Tang, R.P. Fetherston, M. Shamim, R.A. Breun, A. Chen, J.R. Conrad, J. Appl. Phys. 73 (1993) 4176.
[24] A.S. Bugaev, E.M. Oks, G.Y. Yushkov, I.G. Brown, in: Proc. IEEE Int. Conf. Plasma Sci., June 20–24, 1999, p. 269.