Extraction of ions from the matrix sheath in ablation-plasma ion implantation

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(Received 13 June 2000; accepted for publication 22 November 2000)

A simple one-dimensional theory is presented to assess the implantation of ions from the ion matrix sheath (IMS) in an ablated plasma plume that is approaching a negatively biased substrate. Under the assumption that the plume geometry, the electron and ion density distributions, and the potential distribution are frozen during the IMS extraction, the implanted ion current is calculated as a function of time for various substrate-plume separations. This model accurately recovers Lieberman's classic results when the plume front is initially in contact with the substrate. © *2001 American Institute of Physics.* [DOI: 10.1063/1.1343842]

When an energetic beam (laser or electron beam) hits a target, a plasma plume is generated from the target material.[1,2] This ablated plasma expands roughly at the ion acoustic speed with electron temperature of order a couple eV.[3] It may be used for ion implantation, if a substrate is placed in the path of plasma plume expansion and is negatively biased to a high voltage. We call this process ablation-plasma ion implantation (APII). The bias voltage is turned on when the plume front is at a distance, h, from the substrate. In this letter, we use a simple model to evaluate the implanted ion current as a function of h. The model is a generalization of the conventional plasma immersion ion implantation (PIII),[4–11] which may be considered as the $h=0$ limit.

This work is motivated by several appealing features of APII. For instance, any solid material, including metals and refractories, may be ablated to form the ion source. APII may also operate in a repetitively pulsed mode (10–50 Hz). It requires no toxic gases and is therefore environmentally benign. It has the inherent ability of ion-assisted deposition.

In PIII, the ion implantation consists of two phases,[5,6] the earlier ion matrix sheath (IMS) extraction phase and the subsequent Child-sheath expansion phase. The separation between these two phases occurs at a time roughly equal to $3/\omega_{pi}$ after the bias voltage is turned on, where ω_{pi} is the ion plasma frequency. The IMS extraction phase is of most practical interest. It also allows relatively simple analytical treatments[6,7] that yield excellent agreement with numerical integration of the governing equations. Here, we focus only on IMS extraction for APII, borrowing the crucial features revealed by these PIII models: (1) the electrons can be largely ignored, (2) the results are insensitive to the adoption (or not) of the Bohm velocity for the ion flux, and (3) the implanted ion current density may be reliably evaluated with the electric field approximated by the initial profile, when the IMS is first formed.

The negative bias voltage, $-V_0$, is applied to the substrate when the plasma plume reaches a distance, *h*, from the substrate (Fig. 1). In a very short time scale of order $1/\omega_{pe}$, electrons are expelled, leaving behind the IMS of constant ion density n_0 extending from $x=h$ to $x=s_h+h$, beyond which the plasma is neutral. Let $-\phi_h$ be the potential at $x=h$. The sheath potential ϕ_h and the sheath thickness s_h may be determined in terms of h, n_0, and V_0 under the assumption of vanishing electron temperature:

$$\phi_h/V_0=F(\xi), \tag{1}$$

$$s_h/s_0=\sqrt{F(\xi)}, \tag{2}$$

where

$$s_0=\sqrt{\frac{2\varepsilon_0 V_0}{en_0}}, \tag{3}$$

$$F(\xi)=\xi+1-\sqrt{\xi^2+2\xi}, \tag{4}$$

with $\xi=2(h/s_0)^2$. These equations are derived by noting that the electrostatic field is a negative constant in the vacuum region, $0<x<h$, but linearly increases from $x=h$ to $x=h+s_h$, at which both the electric potential and electric field are zero (Fig. 1). Note that s_0 is simply the IMS width in the conventional PIII where the plasma is in contact with

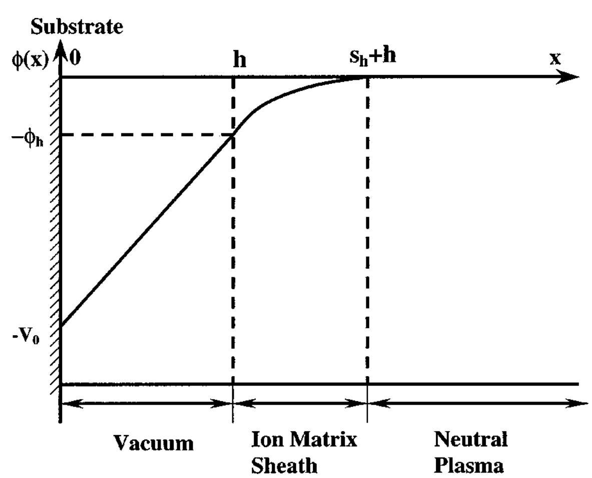

FIG. 1. Model, and the electrostatic potential $\phi(x)$.

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the substrate, i.e., $h=0$. Equations (1) and (2) are shown in Fig. 2. Asymptotically, $F(\xi)$ approaches $1-(2\xi)^{1/2}$ for $\xi \ll 1$, and approaches $1/(2\xi)$ for $\xi \gg 1$.

The ions in IMS are accelerated toward the substrate. We assume that they all have zero initial velocity. Consider an ion initially located at x_0, $h<x_o<h+s_h$. We assume that this ion (or any ion), during its flight to the substrate, is subject to the *same static* field that is formed at the beginning. That is, the electrostatic field is frozen in time. To be consistent with this assumption, we pretend that the ion density, the ion sheath geometry, and the plume front, are also frozen in time. Under these drastic assumptions, the coordinates, $x=\eta(t)$, of this ion obeys the following force law:

$$M_i \frac{d^2\eta(t)}{dt^2} = e\begin{cases} \dfrac{en_0}{\varepsilon_0}[\eta(t)-(h+s_h)], & h<\eta<h+s_h \quad (5a) \\ -\dfrac{V_0-\phi_h}{h}, & 0<\eta<h \quad (5b) \end{cases},$$

subject to the initial condition, $\eta=x_0$ (with $h<x_0<h+s_h$) and $d\eta/dt=0$ at $t=0$. In Eq. (5), M_i is the ion mass (assumed singly charged), and all quantities, except $\eta(t)$, are treated as constants, by the assumption of a *completely time-independent* electric field that is represented by the RHS of Eq. (5) (Fig. 1).

Equation (5a) may easily be solved to yield the time of arrival, t_h, at the vacuum–IMS interface ($\eta=h$), as well as the ion *speed*, v_h, acquired:

$$\cosh(\omega_{pi}t_h)=\frac{s_h}{h+s_h-x_0}, \quad (6)$$

$$v_h=[(h+s_h)-x_0]\omega_{pi}\sinh(\omega_{pi}t_h). \quad (7)$$

Note that t_h is a function of x_0 and that $v_h>0$. Equation (5b) may next be integrated subject to the "initial" condition: $\eta=h$ and $d\eta/dt=-v_h$ at $t=t_h$. This gives the time of flight, t_v, in the vacuum region, $0<x<h$. Upon adding t_h to t_v, we obtain the total flight time, T, given by

$$T=T(x_0)=t_h+\frac{1}{a}(-v_h+\sqrt{v_h^2+2ah}), \quad (8)$$

$$a=\frac{eV_0}{M_ih}[1-F(\xi)]=\omega_{pi}^2 s_0\sqrt{F(\xi)}. \quad (9)$$

Note that a is simply the magnitude of the ion acceleration in the vacuum region. In Eq. (9), the first equality follows from Eqs. (1) and (5b) whereas the second equality follows from Eqs. (3) and (4). Clearly, a depends on V_0, h, n_o, and M_i, but is independent of x_0, whereas T depends on x_0, as explicitly labeled in Eq. (8).

We now calculate the implanted ion current density, $J(T)$, as a function of the arrival time T:

$$J(T)=en_0\times\frac{1}{dT/dx_0}, \quad (10)$$

where $T=T(x_0)$ is given by Eq. (8). In general, there is a one-to-one correspondence between T and x_0. Note, that $J(T)=0$ for $T<T(h)$, since there is no ion impinging onto the substrate prior to the first arrivals from $x_0=h$, the vacuum–IMS interface. Thus, in the plot of the implanted current (Fig. 3), the origin of the time axis represents the arrival time at the substrate by these first ions.

It may be shown that the governing equations for the ions, Eqs. (5)–(10), may be conveniently nondimensionalized using $1/\omega_{pi}$ for the time scale and s_0 for the spatial scale. From these two fundamental scales, we may construct the velocity scale $u_0=\omega_{pi}s_0$, the acceleration scale $\omega_{pi}^2 s_0$, and the voltage scale V_0. Note that Eqs. (1), (2), and (9) are already written in these scales. If we further normalize the current density by en_0u_0, and use a bar to denote all normalized quantities, e.g.,

$$\overline{t_h}=\omega_{pi}t_h, \quad \overline{T}=\omega_{pi}T, \quad \overline{x_0}=x_0/s_0, \quad \overline{v_h}=v_h/u_0, \quad \overline{J}=J/en_0u_0, \quad \text{etc.}, \quad (11)$$

we may readily verify from Eqs. (6)–(10) that the various quantities listed in Eq. (11) depend only on two normalized variables: h/s_0 (or ξ) and x_0/s_0 [or $\overline{T}$ from Eq. (8)]. Figure 3 plots the normalized current density for various values of

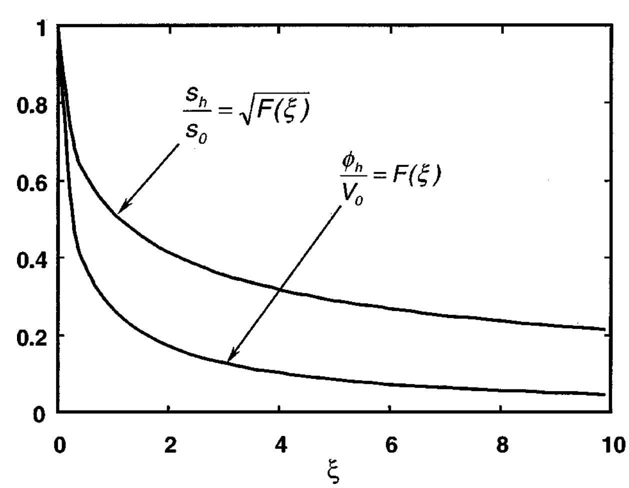

FIG. 2. Normalized sheath potential (ϕ_h/V_0) and the normalized sheath width (s_h/s_0) as a function of $\xi=2(h/s_0)^2$.

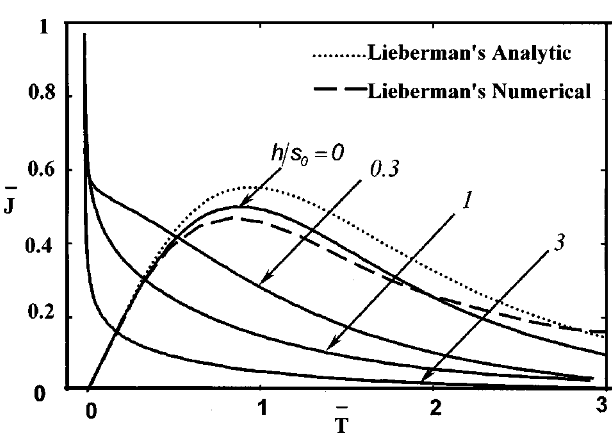

FIG. 3. Normalized implanted ion current density (J/en_0u_0) as a function of normalized time ($\omega_{pi}t$), measured from the moment of impact of the first implanted ions, for various plume-substrate separation (h/s_0). Also shown are Lieberman's numerical results (dashed curve) and analytic results (dotted curve) for the PIII limit, $h=0$.

h/s_0; the origin of the time axis designates the arrival time of the first ions, as explained toward the end of the preceding paragraph.

From Fig. 3, we see that APII always yields a total ion dose less than PIII (the $h=0$ case), for the same bias voltage on the substrate and for the same plasma density. The total APII dose is within a factor of 2 of the total PIII dose if $h < s_0$. For $h/s_0 \gg 1$, the dose becomes small as the IMS thickness becomes small [Eq. (2) for $\xi \gg 1$]. In this limit, one may prove from Eqs. (8) and (10) that J approaches en_0u_0 when the ions first strike the substrate, as expected intuitively.

Finally, let us check the adequacy of our much simplified model, which assumes completely static quantities in Eq. (5), against the well-known analytic results of Lieberman[5,6] in the $h=0$ (PIII) limit. In this limit, $T=t_h$ from Eq. (8), and $s_h=s_0$ by definition [Fig. 1, or Eq. (2)]. Equation (6) then becomes

$$\cosh(\overline{T}) = \frac{1}{1-\overline{x_0}}. \tag{12}$$

Upon substituting Eq. (12) into Eq. (10), we obtain the normalized ion current density:

$$\overline{J}(\overline{T}) \equiv \frac{J}{en_0u_0} = \frac{d\overline{x_0}}{d\overline{T}} = \frac{\sinh(\overline{T})}{\cosh^2(\overline{T})}. \tag{13}$$

Equation (13) is the $h=0$ curve in Fig. 3. There we see that it is an excellent approximation to Lieberman's numerical solution[5,6] for the major portion of IMS extraction.

Let us now justify the assumption of a static plume for IMS extraction. The time scale for IMS depletion is of order C/ω_{pi} where C is in the single digits according to Fig. 3. Over that time scale, the plume moves a distance of order $\Delta h = Cu_p/\omega_{pi}$ where u_p is the plume-front velocity which typically corresponds to a couple of eV of ion kinetic energy.[1–3] The fractional change of the geometry, measured by $\Delta h/s_0$, is then of order Cu_p/u_0, a quantity much less than unity if V_0 is in the kV range or higher. Thus, during IMS extraction, the plume may be treated as static.

In conclusion, we have used a very simple analytic model to evaluate the implantation of ion matrix sheath of an ablated plasma plume that is approaching a substrate. Figure 3 provides an immediate assessment of APII, for a general ion species, ion density, bias voltage ($>$kV), and plume-substrate separation. The approximate model bypasses many theoretical and practical issues, such as Bohm and Child sheaths,[5,12–14] and electrical breakdown,[15,16] all of which may become important in the long time behavior. Detailed modeling and experiments on APII will be required to address these issues.

This work was supported by NSF, Grant No. CTS-9907106.

[1] R. M. Gilgenbach, S. Kovaleski, J. S. Lash, L. K. Ang, and Y. Y. Lau, IEEE Trans. Plasma Sci. **27**, 150 (1999).
[2] S. Kovaleski, R. M. Gilgenbach, L. K. Ang, Y. Y. Lau, and J. S. Lash, Appl. Surf. Sci. **127–129**, 947 (1998).
[3] R. M. Gilgenbach and P. L. G. Ventzek, Appl. Phys. Lett. **58**, 1597 (1991).
[4] J. R. Conrad, J. L. Radke, R. A. Dodd, F. L. Worzala, and N. C. Tran, J. Appl. Phys. **62**, 4591 (1987).
[5] M. A. Lieberman and A. J. Lichtenberg, *Principles of Plasma Discharges and Material Processing* (Wiley, New York, 1994), Chap. 6.4.
[6] M. A. Lieberman, J. Appl. Phys. **66**, 2926 (1989).
[7] K.-U. Riemann and Th. Daube, J. Appl. Phys. **86**, 1202 (1999).
[8] V. Vahedi, M. A. Lieberman, M. V. Alves, J. P. Verboncoeur, and C. K. Birdsall, J. Appl. Phys. **69**, 2008 (1991).
[9] P. K. Chu, S. Qin, C. Chan, N. W. Cheung, and L. A. Larson, Mater. Sci. Eng., R. **17**, 207 (1996).
[10] N. W. Cheung, Chem. Phys. **46**, 132 (1996); P. K. Chu, N. W. Cheung, and C. Chan, Semicond. Int. **6**, 165 (1996).
[11] D. T. K. Kwok, P. K. Chu, B. P. Wood, and C. Chan, J. Appl. Phys. **86**, 1817 (1999).
[12] K.-U. Riemann, J. Phys. D **24**, 493 (1991).
[13] N. Hershkowitz, L. Oksuz, A. M. Hala, and M. A. Khedr, IEEE International Conference Plasma Science, Conference Record (New Orleans, LA, 2000), p. 227.
[14] S. Masamune and K. Yukimura, Rev. Sci. Instrum. **71**, 1187 (2000).
[15] I. G. Brown, O. R. Monteiro, and M. M. M. Bilek, Appl. Phys. Lett. **74**, 2426 (1999).
[16] A. Anders, Appl. Phys. Lett. **76**, 28 (2000).