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Dynamics of collisional pulsed planar sheaths

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This paper presents experimental measurements of a high-voltage collisional pulsed sheath. Such high-voltage pulsed sheaths are now commonly used for implanting material surfaces. These laser-induced-fluorescence measurements are used to test the predictive capability of two recent models of pulsed sheaths. It is found that the current models are incomplete and fail to predict accurately the experimental measurements. It is deduced from the data that these models fail primarily because they do not take into account ion production by secondary electrons. This ion production influences both the temporal development of pulsed sheaths and the ion impact energy profile. These influences might be vitally important to some manufacturing processes and so must be included in any accurate model of the system.

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A sheath is an electric field that usually occurs between a plasma and an object. The sheath confines the more mobile species in the plasma and accelerates the less mobile species out of the plasma. For the typical case, in which the electrons are more mobile than the positively charged ions, the electric field points toward the object. This basic problem of plasma flowing into a wall is important, and has been studied since the inception of plasma physics [1].

Many models have been developed to describe sheaths. On the basis of his experimental work, Langmuir was one of the first to model properly plasma sheaths [1]. Other models of sheaths include, for example, the theory of Langmuir probes [2] and models of divertor plates in tokamaks [3]. These models range from simple analytical expressions, such as Child's law [4], to complex kinetic simulations [5]. Models have been used to predict how different physical processes influence sheaths. For example, if the potential at the wall is made to vary in time, then the electric field in the sheath will also vary in time [6–9]. Magnetic fields [10] and collisions [11] can also modify the sheath.

In this paper, we compare two models of collisional pulsed sheaths to each other and to the experimental measurements. Pulsed sheaths have a wide range of uses. These include basic plasma experiments [9,12], e.g., the excitation of ion acoustic waves, and commercial applications [13,14], e.g., plasma source ion implantation (PSII). Considerable interest has been shown in fluid [15] and kinetic [16] models of pulsed sheaths, as well as Child's law types of models [7], because of the recent wide ranging interest in the PSII process. We show here that the sheath edge velocities predicted by the models agree over a wide range of collisionallity. Finally, we compare the predictions of these models to the laser-induced-fluorescence (LIF) measurements of an expanding sheath. This comparison reveals that the previous models of highly collisional pulsed sheaths are incomplete.

LIF was used to measure the expansion of a collisional pulsed sheath in a PSII system. The data shown in Fig. 1 represent experimental data obtained from a collisional high-voltage pulsed sheath. The general layout of the experiment is the same as that in Ref. [17]. In both experiments, LIF was used to provide a measure of the ion density in the region of the plasma-sheath boundary. LIF works through photon excitation of the ions. Once an ion absorbs a laser photon, it decays to a lower energy state producing fluorescence. The strength of the fluorescence is an indication of the number of ions absorbing photons in turn the ion density [17]. The plasma was produced in the same manner as in Ref. [17]. In both, nitrogen plasmas were produced with heated tungsten filaments, having discharge currents of 2 A and discharge voltages of −125 V. To increase the plasma density and

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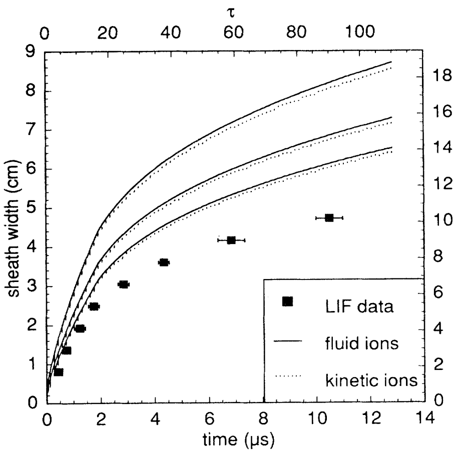

FIG. 1. Experimental data compared to the predictions of both the fluid and kinetic models. It is seen that the models do not provide a good fit with the experimental data. It is likely that this is due to ion production in the sheath, for which the models do not account. The top and bottom curves for each of the simulations are error bars that result from the uncertainty in the measured plasma density. This figure gives the sheath width and time in both "real" units (right and top) as well as in nondimensionalized units (left and bottom).

plasma density and stability, the discharges were confined stability, the discharges were confined using a multidipole magnetic "cage." The sheath was pulsed in the same manner as in Ref. [17]. In both, the target was biased to -5 kV. It required 1.9 μs to drive the target to this potential from ground. The target was held at this bias for an additional 11 μs before being allowed to decay back up to ground. The primary difference between this experiment and that in Ref. [17] is that here the neutral pressure was 5.0 mTorr rather than the 0.5 mTorr used before. Thus, the ion mean-free path $\lambda_{\mathrm{mfp}} \approx 0.6$ cm rather than ≈ 6.0 cm. (The value of λ_{mfp} cited here is for relatively low energy ions. At higher energies, λ_{mfp} is much longer [18,19].) In addition, because of the difference in pressure, the plasma parameters are marginally different. In this discharge it was found in the region of interest 3–10 cm above the target, both a cold bulk electron population ($n_{e\,\mathrm{bulk}} = 1.12 \pm 0.58 \times 10^9$ cm^{-3}, $T_{e\,\mathrm{bulk}} = 0.36 \pm 0.01$ eV) and a hot electron population ($n_{e\,\mathrm{hot}} = 1.92 \pm 0.25 \times 10^7$ cm^{-3}, $T_{e\,\mathrm{hot}} = 10.74 \pm 2.88$ eV). In addition, it was found that the plasma and floating potentials were 0.07 ± 0.09 V and -86.76 ± 3.31 V. (All potentials are given relative to the grounded chamber walls.)

Because of a wide spread interest in the PSII process, numerous models of pulsed sheaths have been presented. To test their validity, we compare the predictions of the models to the above experimental data. While both of the models, as tested here, are one dimensional, they can be easily expanded to multidimensional systems [15,16].

The first model tested was the collisional two-fluid model described in Ref. [15]. A number of simplifying assumptions are usually made when one applies this model to sheaths. First, the ions are assumed to be cold. Second, it is assumed that there is no impediment to the flow of electrons to the electrode surface. Third, it is typically assumed that the sheath region is source free. Thus, the ions obey the equation of continuity.

$$\frac{\partial n_i}{\partial t} + \frac{\partial}{\partial x} n_i v_i = 0 \ . \tag{1}$$

Fourth, the ions suffer a collisional drag F_c as they are accelerated to the target and, thus,

$$\begin{aligned}\frac{\partial v_i}{\partial t} + v_i \frac{\partial v_i}{\partial x} &= -\frac{e}{M}\frac{\partial}{\partial x}\phi(x,t) - \frac{F_c}{M} \\ &= -\frac{e}{M}\frac{\partial}{\partial x}\phi(x,t) - \frac{\pi}{2}\frac{|v_i| v_i}{\lambda_{\mathrm{mfp}}} \ .\end{aligned} \tag{2}$$

Here, M is the ion mass, $n_i(x)$, x, and $v_i(x)$ are the ion density, position, and velocity in the sheath, e is the electron charge, t is the time, and $\phi(x,t)$ is the sheath potential. As is typical, in this model λ_{mfp} is assumed to be constant and the equal to the low energy value. As is typical, λ_{mfp} is maximum at low energies; thus, there occurs a slight over estimate of the affect of such collisions. Finally, assuming that the electrons are in thermal equilibrium at a temperature T_e (given in units of energy), Poisson's equation becomes

$$\frac{d^2\phi}{dx^2} = -\frac{e}{\varepsilon_0}\left[n_i - n_0 \exp\left[\frac{e\phi(x,t)}{T_e}\right]\right] , \tag{3}$$

where ε_0 is the permittivity constant and n_0 is the plasma density at the sheath-plasma boundary. These equations can be nondimensionalized,

$$\frac{\partial n}{\partial \tau} + \frac{\partial}{\partial \xi} n u = 0 \ , \tag{1'}$$

$$\frac{\partial u}{\partial \tau} + u\frac{\partial u}{\partial \xi} = \tfrac{1}{2}\frac{\partial \Psi}{\partial \xi} - \alpha |u| u \ , \tag{2'}$$

$$\frac{d^2\Psi}{d\xi^2} = 2\left[n - \exp\left[\Psi \frac{e\phi_t}{T_e}\right]\right] , \tag{3'}$$

using the parameters found in Ref. [15]. Those parameters are $\Psi = \phi/\phi_t$, where ϕ_t is the maximum target potential; $s_{\mathrm{IM}} = \sqrt{-2\varepsilon_0 \phi_t / e n_0}$ is the ion matrix sheath width at ϕ_t; $\alpha = (\pi/2) s_{\mathrm{IM}} / \lambda_{\mathrm{mfp}}$ is the degree of collisionallity; $n = n_i/n_0$; $u = v_i \sqrt{-M/2e\phi_t}$; $\xi = x/s_{\mathrm{IM}}$; and $\tau = t\omega_{pi} = t\sqrt{e^2 n_0/\varepsilon_0 M}$, where ω_{pi} is the plasma frequency for the ions. For pulses of finite rise time and infinite duration, the only physically important parameters are the degree of collisionallity α and the rise time of the high-voltage pulse [15].

The kinetic model [16] of pulsed sheaths differs from fluid model in two important aspects. First, in the fluid model the ions are assumed to be cold so that the velocity distribution is considered to be a δ function. In comparison, in the kinetic model the velocity distribution is resolved in detail. Second, in the fluid model collisions are added as a resistive drag term. In comparison, in the kinetic model the collisions are added as a reshaping of the velocity distribution. In practice, the velocity is set to zero for that fraction of the ions that suffer a collision during a given time step.

Figure 2 shows that both models predict almost identical sheath widths, $\sigma = x/s_{\rm IM}$, for various α. For these simulations, we used parameters that one would typically find in the PSII process. These parameters were $\phi_t = -10$ kV, $M = 28$ amu (N_2^+), $n_0 = 10^9$ cm^{-3}, $T_e = 1$ eV, and a rise time = 1 μs. After reaching ϕ_t, the target bias was held constant and the simulations were continued for an additional 10 μs. As is indicated by Eqs. (1)–(3), the target was assumed to be an infinite plane. While the differences between the results of the two models are small, Fig. 2 shows that the fluid model consistently predicts that the sheath propagates slightly faster than what is predicted with the kinetic model. Figure 2 shows the percentage difference $[100(\sigma_{\rm fluid} - \sigma_{\rm kinetic})/\sigma_{\rm kinetic}]$ at $\tau = 86.77$ ($t = 11$ μs) that is associated with using the fluid model. (One would expect to see similar differences for the Child's law type of models [7].) One observes two phenomenon in Fig. 3. First, there is a "bump" in the difference in the $0 \leq \alpha \leq 1\pi$ range. It is likely that this is due to the assumption in the fluid model that the ions are cold. Second, the difference increases slowly as α becomes larger. It is likely that this difference is due to either a very minor error in the drag term found in Eq. (2) or different round-off errors in the two distinct codes.

In Fig. 1 we compare the experimentally measured sheath expansion to the predictions of both the fluid and kinetic computer codes. For the experimental data shown here, $\alpha \approx 6.0$. (In comparison, $\alpha \approx 0.25$ for the experimental data in Ref. [17].) Three curves are given for each of the models. The upper and lower curves represent the possible error expected in the predictions of the models, which result from the uncertainty in the experimentally measured plasma parameters.

It is seen that the models, as used previously [15,16], do not accurately predict the observed sheath expansion. There are two phenomena that might account for this error. First, one might wonder is if the observed population of hot electrons might cause such a disagreement. Taking an extreme case, using $T_e = 10.74$ rather than 0.36 eV in the model, one finds that while the plasma-sheath boundary is slightly blurred, the results from the model do not change significantly. Second, one might wonder if plasma production during the high-voltage pulse would account for the large error. In the experiment, approximately five secondary electrons are produced for each ion striking the target [17]. On average, 5–10% [$\approx$(mean-free-path)/(sheath width), Ref. [20]] of these secondaries will result in the production of electron-ion pairs in the sheath. This suggests that the total ion current to the target will be 25–50% above the current from the plasma to the target. This additional current will substantially retard the sheath expansion, as is observed.

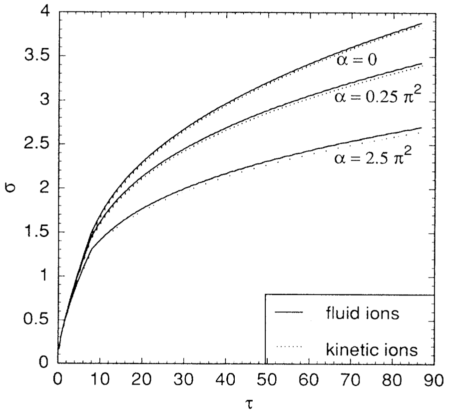

FIG. 2. The time evolving sheath width σ for various degrees of collisionallity α for the fluid and kinetic ion models. Note that the time τ as well as σ and α are given in nondimensional units. Notice that the fluid model always predicts a slightly wider sheath than the kinetic model. The parameters used for the results shown here are typical of those used to model the PSII process.

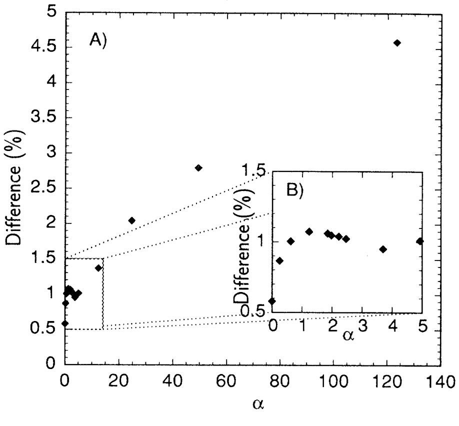

FIG. 3. The percentage difference between the results of the fluid model and the kinetic model at $\tau = 86.77$.

By adding a source to the model, we greatly improve the accuracy of the predictions. In Fig. 4 we compare the LIF data to the results of fluid simulations with and without an ion source. In both simulations we use the experimentally measured plasma parameters. In the simulation with a source, we also assume that each ion striking the target produces five secondary electrons [17]. These secondaries are assumed to pass through the simulated region once and have a mean-free path for ionization of 20 cm. After each time step, the "fluid elements" used in the simulation are slowed and the density is adjusted to approximate the additional ions produced by these secondaries. Furthermore, it is assumed that the mean-free path is constant and the source is evenly distributed across the simulated region. It is seen in Fig. 4 that the resulting ionization greatly slows the sheath expansion. The slowing found with the simulation is an overestimate because the electron's mean-free path changes with energy [20] and the number of secondaries produced is a function [21] of the ion energy. The mean-free path used here is correct only for those electrons having 60–240 eV, e.g., still inside the sheath. At other energies the mean-free path is slightly longer [20], resulting in less ion production. Likewise, the number of secondaries is appropriate only for ions with 5-keV ener-

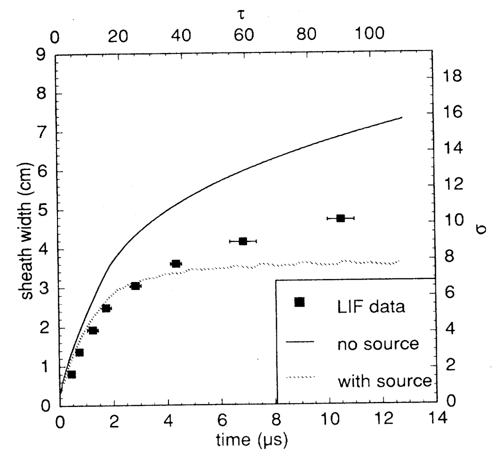

FIG. 4. Experimental data compared to the predictions of the fluid model with and without an ion source.

gy. Ions striking the target at lower energies will produce slightly fewer secondaries, again resulting in less ion production. The combination of these processes will cause the slowing of the sheath to be diminished, which is consistent with the results shown in Fig. 4. Thus, we believe that an accurate model of the ionization produced by the secondaries will lead to an accurate prediction of the sheath speed. This, however, is beyond the scope of the current work.

To model properly a typical PSII environment, one must consider initial plasma conditions, multidimensional effects, ion-neutral collisions, and ion production in the sheath. The first three requirements have been discussed elsewhere [17]. To our knowledge, however, the complexities associated with ion production in pulsed sheaths have not been addressed. We believe that the effects of such sources are important. The presence of such a source will result in a larger population of ions striking the target at energies well below $e\phi_t$. In some manufacturing processes these slower ions might be important [22]. Under such conditions, a kinetic model will be required to accurately predict the impact velocity profile. Finally, by examining the appropriate cross sections, one finds that the mean-free paths found in this experiment are not very different from those found for most of the gases used in PSII processing systems. Thus, if one has a system in which either ion-neutral collisions or ion production might be occurring in the sheath, then one should also consider the possibility of the other process occurring.

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[1] *The Collected Works of Irving Langmuir,* edited by C. Guy Suits (Pergamon, New York, 1961), Vol. 4, pp. 1–98.

[2] F. F. Chen, in *Plasma Diagnostic Techniques,* edited by Richard H. Huddlestone and Stanley L. Leonard (Academic, New York, 1965), pp. 113–200.

[3] Allen H. Boozer, Phys. Fluids **19**, 1210 (1976).

[4] C. D. Child, Phys. Rev. **32**, 492 (1911).

[5] R. J. Procassini, C. K. Birdsall, and E. C. Morse, Phys. Fluids B **2**, 3191 (1990).

[6] Michael A. Lieberman, IEEE Trans. Plasma Sci. **16**, 638 (1988).

[7] Michael A. Lieberman, J. Appl. Phys. **65**, 4186 (1989).

[8] G. A. Emmert and M. A. Henry, J. Appl. Phys. **71**, 113 (1992).

[9] M. Widner, I. Alexeff, W. D. Jones, and K. E. Lonngren, Phys. Fluids **13**, 2532 (1970).

[10] Peter L. Auer, Phys. Fluids **26**, 1212 (1981).

[11] T. E. Sheridan and J. Goree, Phys. Fluids B **3**, 2796 (1991).

[12] I. Alexeff, W. D. Jones, K. E. Lonngren, and David Montgomery, Phys. Fluids **12**, 345 (1969).

[13] E. C. Jones and N. W. Cheung, IEEE Electron. Device Lett. **ED-14**, 444 (1993).

[14] J. R. Conrad, J. L. Radke, R. A. Dodd, F. J. Worzala, and N. C. Tran, J. Appl. Phys. **62**, 4591 (1987).

[15] T. E. Sheridan and M. J. Goeckner, J. Appl. Phys. (to be published).

[16] E. R. Keiter, W. N. G. Hitchon, and M. J. Goeckner, Phys. Plasmas **1**, 3709 (1994).

[17] M. J. Goeckner, Shamim M. Malik, J. R. Conrad, and R. A. Breun, Phys. Plasmas **1**, 1064 (1994).

[18] Sanborn C. Brown, *Basic Data of Plasma Physics, 1966* (MIT Press, London, 1967), p. 63.

[19] E. W. McDananiel and E. Mason, *The Mobility and Diffusion of Ions in Gases* (Wiley, New York, 1973), p. 289.

[20] E. Krishnakumar and S. K. Srivastava, J. Phys. B **23**, 1893 (1990).

[21] M. M. Shamim, J. T. Scheuer, R. P. Fetherston, and J. R. Conrad, J. Appl. Phys. **70**, 4756 (1991).

[22] L. Zhang, J. L. Shohet, R. R. Speth, D. Dallmann, M. J. Goeckner, J. R. Booske, K. Shenai, P. Rissman, J. B. Kruger, J. E. Turner, E. Perez-Albuerne, S. Lee, and N. Meyyapan, Appl. Phys. Lett. **65**, 962 (1994).