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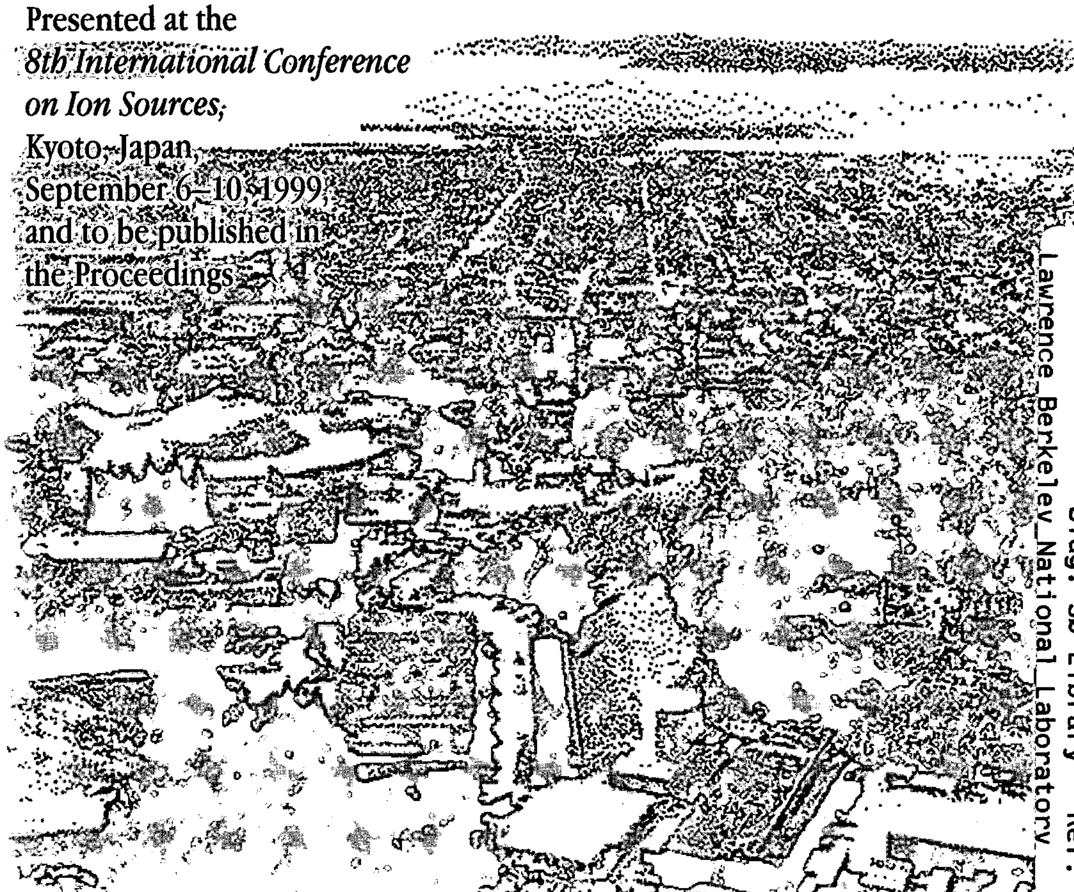

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Abstract

We consider the case of energetic ion beam formation when the ion streaming velocity within the source plasma is substantial, i.e., when the ions have a drift speed (in the positive downstream direction) that is of order of or greater than the ion acoustic speed in the plasma. Some interesting consequences can follow, including the capability of a negatively biased substrate located in the plasma stream to maintain high bias voltage, and of an ion source with no extractor or "conventionally poor" extractor providing a kind of plasma immersion ion implantation mode of operation. Here we summarize the kind of plasma geometry in which this situation can occur, and describe some experimental observations we've made of these effects, with reference to a simple theoretical basis for the mechanism.

I. INTRODUCTION

The formation of energetic ion beams from a plasma by a set of extractor electrodes is more-or-less well understood for the case when the plasma is drift-free, i.e., when the ion drift velocity is small compared to the ion acoustic speed. Most kinds of plasmas are created drift-free, and the usual scenario for ion beam formation prevails. However, the metal plasma formed by a vacuum arc discharge is an exception to this situation, as is also the plasma formed by a high-power focussed laser beam directed upon a solid target. It is possible to add a directed ion drift velocity to plasma created otherwise drift-free, for example by the addition of electric or magnetic features to more conventional kinds of plasma schemes. Consider for example $\boldsymbol{E} \times \boldsymbol{B}$ and $\boldsymbol{j} \times \boldsymbol{B}$ driven drifts, and the magnetic moment driven μgradB force in mirror-confined plasmas. In the case of a plasma with substantial ion drift velocity (ion drift comparable to or greater than the ion acoustic speed), some unexpected consequences can follow, including the ability of a negatively biased substrate located in the plasma stream to maintain high bias voltage, and an ion source with poor extractor design providing an unusual kind of plasma immersion ion implantation (pi^3) mode of operation.

When a negative high voltage potential is applied to an electrode located in the downstream plasma region, firstly an ion matrix sheath (electron-depleted ion layer) is formed on a timescale of order the inverse electron plasma frequency, $t \sim \omega_{pe}^{-1}$, and as the ions respond on a longer timescale, $t > \omega_{pi}^{-1}$, the high voltage sheath propagates into the plasma with a geometry-dependent speed that is of order the ion acoustic speed c_{si} [1,2]. If now the plasma is drifting toward the substrate with an ion drift velocity, u, that is comparable to the ion acoustic speed in the plasma, $u \sim c_{si}$, where $c_{si} = (kT_e/m_i)^{1/2}$, then one would intuitively expect a substantially different behavior, as the sheath propagation speed in the upstream direction is comparable to the plasma drift speed in the downstream direction.

The metal plasma formed by a vacuum arc discharge is created on the cathode surface (at cathode spots) and plumes away from the cathode in a direction normal to the surface with a speed that is typically 1 to 3 cm/μs and is of order the ion acoustic speed in the plasma or up to several times the acoustic speed [3]. The characteristics of vacuum arc plasmas have been investigated and described by a large number of authors [4,5]. Here we consider some effects that can occur due to the streaming plasma in an ion source configuration.

II. EXPERIMENTAL

Our observations were made in several different configurations. We used a vacuum arc plasma gun to produce a dense titanium plasma. The plasma gun and the properties of the plasma formed have been described elsewhere [6,7]. We carried out several different experiments in different configurations and using different experimental hardware. The experiments had to do with observations of the behavior of the drifting vacuum-arc plasma in the presence of high voltage electrodes, and of finding ways to profitably utilize the unusual phenomena encountered. We describe here two important experiments.

A. High voltage substrate in a drifting plasma stream

A vacuum arc plasma gun with a titanium cathode was driven with an arc current of 100 A in pulses of duration varied from 50 μs to 10 ms. The Ti plasma was injected into a 90° magnetic duct [8,9] from which the plasma was allowed to stream into the vacuum chamber. A cylindrical aluminum substrate, 4 cm diameter by 4 cm long and having all well-rounded edges, was located downstream from the duct at a location that could be varied from 5 to 50 cm from the duct exit. The substrate was connected to a 2 μF capacitor that was charged negatively to a voltage that could be varied from 0 to -10 kV; the capacitor was able to adequately maintain the voltage throughout the plasma pulse (up to 10 ms), so that the substrate bias was essentially dc as seen by the plasma. We monitored the time-resolved plasma gun arc current, substrate voltage, and substrate current, as a function of capacitor charging voltage, substrate location and plasma pulse length. A simplified schematic of the experimental set-up is shown in Figure 1.

The behavior of the high voltage electrode in the plasma stream was evident from the monitored electrode voltage and current. Each pulse was either of two very different modes: a breakdown mode typified by rapid current rise and voltage drop; or a well-behaved mode in which the current drawn by the substrate was of magnitude typically 0.1 to 1.0 A and of shape similar to the plasma gun arc current pulse shape. That is, breakdown of the high voltage substrate was very apparent when it occurred, and when there was not breakdown the high voltage substrate drew a current appropriate to the density of the streaming plasma in which it was immersed. After we installed the highly-rounded substrate shape as described above we found only well-behaved performance and no breakdown. Prior to this change we had used a substrate with some pointed edges exposed; in this case we were unable to increase the voltage to above about 3 kV without breakdown occurring, and then only together with rather Herculean efforts in positioning plastic insulators around the vessel walls. We conclude that so long as the substrate is well configured everywhere so as to minimize field enhancement, the substrate can be maintained at high voltage for long times.

In a related experiment [10] we placed a flat (and smooth) substrate at various distances from the source exit-plane and at various angles with respect to the plasma jet streaming direction. We found that the ion saturation current increases with applied bias voltage and that this effect depends upon the angle of the substrate with respect to the plasma stream and on the distance of the substrate from the plasma duct exit. We also found that the ion current decreases with decreasing angle between normal to the substrate and the plasma stream. These observations can be explained by a model in which the high ion drift velocity leads to a thinner sheath; the plasma density at the sheath-plasma interface decreases, with a consequent decrease in ion current.

B. High voltage ion implantation using a gridless ion source

The configuration described in the preceding is a plasma immersion configuration. The important departure from the conventional plasma immersion processing set-up is the long (quasi-dc) pulse length. One can also consider a configuration in which the polarities of the plasma source and the substrate are reversed, and instead of a negative high voltage substrate and grounded plasma source, one might use a grounded substrate and a positive high voltage plasma source. In this case the plasma source can be viewed as a gridless ion source. We set up this configuration in our implantation vessel with the plasma source driven by the same electrical system as used for our conventional ion implantation work [7]. The plasma source was biased up to +20 kV or more, in 250 μs pulses at a repetition rate of several pulses per second. We found that breakdown to the grounded chamber wall always occurred, until we provided an insulating barrier (plastic sheet) between the high voltage plasma and the vessel wall. Having done this, we were able to locate the grounded aluminum substrate (ion implantation target) in the high voltage plasma stream and to repetitively pulse the plasma in the same kind of operating mode as used for carrying out "regular" ion implantation. A schematic of the configuration is shown in Figure 2.

For an ion source to form an energetic ion beam from a plasma it is necessary that the extractor grids (beam formation electrodes) be appropriately configured both electrically and geometrically. As the plasma density or the extractor mesh size increases, i.e., as the ratio of extractor grid mesh size (beamlet hole size or wire spacing) to the high voltage sheath thickness becomes larger, the beam optics deteriorates and the beam angular divergence increases. Eventually the sheath thickness becomes smaller than the mesh size and the plasma penetrates the grid. The device then no longer functions as an ion beam generator but rather as a source of streaming plasma that is biased to high potential. This will occur for example if the extractor is made of widely-spaced wires rather than fine mesh. Then, as the plasma streams freely from the high voltage region into the vessel, which is at ground potential, it is probable that breakdown will occur between the high potential plasma and/or plasma generator and the vacuum chamber wall. If the geometry is such that breakdown does not occur, then the plasma can stream toward a distant target where a high voltage sheath will form. The sheath voltage is then dropped not at the extractor but at the target instead. Thus, in the case of improper extraction, although the ion source fails to operate as an energetic ion beam generator, energetic ion bombardment can sometimes nevertheless be achieved by a serendipitous alternative mechanism.

A gridless ion source configuration, or biased plasma gun, with its streaming plasma well-protected against breakdown for example by using a physical or magnetic wall to stop electron flow from the high voltage plasma to surrounding ground-potential material, can thus serve as an alternative approach to the formation of energetic ions.

III. DISCUSSION

The experimental results demonstrate that it is possible to locate an electrode or substrate within a plasma stream, with a high voltage potential difference between the plasma and a well-rounded substrate, for the case of a high density plasma with high drift velocity. This is in fact as expected for the case of a plasma with substantial drift velocity. To show this we examine the equations that govern high voltage sheath formation in a plasma. The current density drawn by a planar substrate is given by

$$j = en(x)\left(u + \frac{dx}{dt}\right) \tag{1}$$

where x is the sheath width, u the directed ion velocity (or the ion sound speed in a stationary plasma), and $n(x)$ the ion density which in the case of a vacuum arc plasma depends strongly on position. The Child-Langmuir law for space charge limited current flow is

$$j = A\frac{V_o^{\frac{3}{2}}}{x^2} \tag{2}$$

where

$$A = \frac{4\varepsilon_0}{9}\left(\frac{2Qe}{M}\right)^{\frac{1}{2}} \tag{3}$$

with M the ion mass, Q the ion charge state, and V_o the voltage difference between the plasma and the substrate. In the steady state (i.e., when the sheath stops growing) we have

$$A\frac{V_o^{\frac{3}{2}}}{x^2} = en(x)u \tag{4}$$

Clearly large $n(x)$ and large u allow for a smaller equilibrium value of x , i.e., a thinner sheath. High directed velocity is a characteristic of the vacuum arc plasma, as is a relatively high density. Both these characteristics can lead to an equilibrium sheath thickness that is confined to the plasma region and that is small compared to the vacuum chamber dimensions. This means that the plasma is not depleted as in the case of sheath expansion throughout the chamber, and thus implantation can continue in a dc mode. It is also necessary that the high voltage sheath width be not too small [11], otherwise breakdown across the sheath can occur as for the case of a substrate with sharp edges.

It is instructive to compare the time-evolution of the sheath for plasmas with and without ion drift velocity toward the substrate. The calculations are based on equating the current drawn by a growing sheath to the Child-Langmuir space charge limited current (as above)

$$n\left(u + \frac{dx}{dt}\right) = \frac{4\varepsilon_o}{9}\left(\frac{2Q}{eM}\right)^{1/2} \frac{V_o^{3/2}}{x^2} \quad (5)$$

where n is 0.6 of the bulk density for a non-drifting plasma to account for the pre-sheath. The results of the calculation are shown in Figure 3. The solid curves are for the case an ion drift velocity of 2 cm/μs, and the dashed curves are for ions entering the sheath at the ion sound speed. The three sets of curves correspond to the plasma densities 10^{10}, 10^{11} and 10^{12} cm^{-3}, from top to bottom. All curves were calculated for the case of a spatially homogenous titanium plasma with electron temperature of 3 eV and an applied substrate bias of -20 kV. In each case the curve for the drifting plasma grows to a sheath thickness of less than half that for the stationary plasma. The effect of density is also important and an increase in plasma density by a factor of ten results in the sheath thickness being reduced by about a factor of three. The significance of these curves is in the observation that a high voltage *stationary* sheath forms for the case of a streaming plasma – the configuration can remain in equilibrium indefinitely, with the rate of plasma replenishment sufficient that the plasma is not depleted. This is what we observe in the experiments. A similar situation would also exist for the case of a high plasma density and/or very large chamber, providing that the plasma generation rate was sufficiently high and breakdown did not occur across the sheath.

We have reported on some experiments showing that a substrate biased to high negative voltage can be located within a high-density plasma stream with high drift velocity for long periods of time. This behavior can be explained by the equations for sheath evolution in a plasma with high ion drift velocity. The effects described have bearing on gridless ion source operation, and offer the prospect for a new mode of plasma immersion ion implantation in which the need for repetitively pulsed biasing of the substrate is avoided.

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11. We are grateful to Andre Anders for pointing out this condition.

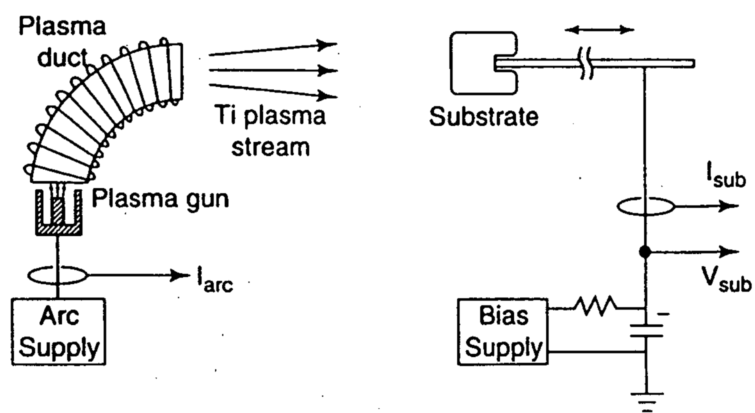
FIGURE CAPTIONS

Fig. 1 Simplified schematic of the configuration used for the first experiment. The substrate is biased to high negative voltage and immersed in a streaming titanium plasma formed at ground potential.

Fig. 2 Simplified schematic of the configuration used for the second experiment. The substrate is grounded and immersed in a streaming titanium plasma formed at high positive potential.

Fig. 3 Sheath evolution for a plasma with (solid curves) and without (dashed curves) ion drift velocity toward the substrate.

Ti plasma with ion drift velocity 2 cm/μs and electron temperature 3 eV. Substrate bias is –20 kV. The three sets of curves are for plasma densities of 10^{10}, 10^{11} and 10^{12} cm^{-3}, top to bottom.



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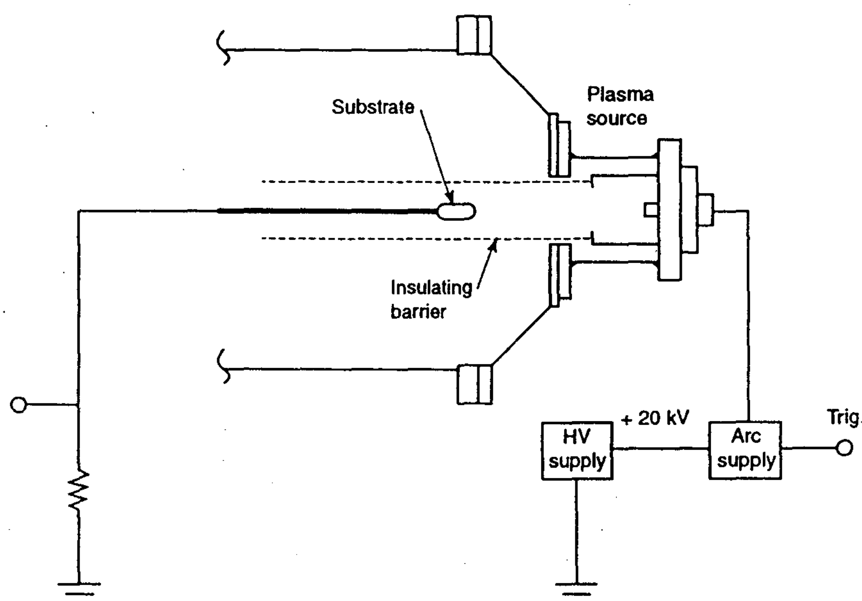
RCI FIG 1



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RSI Fig 2

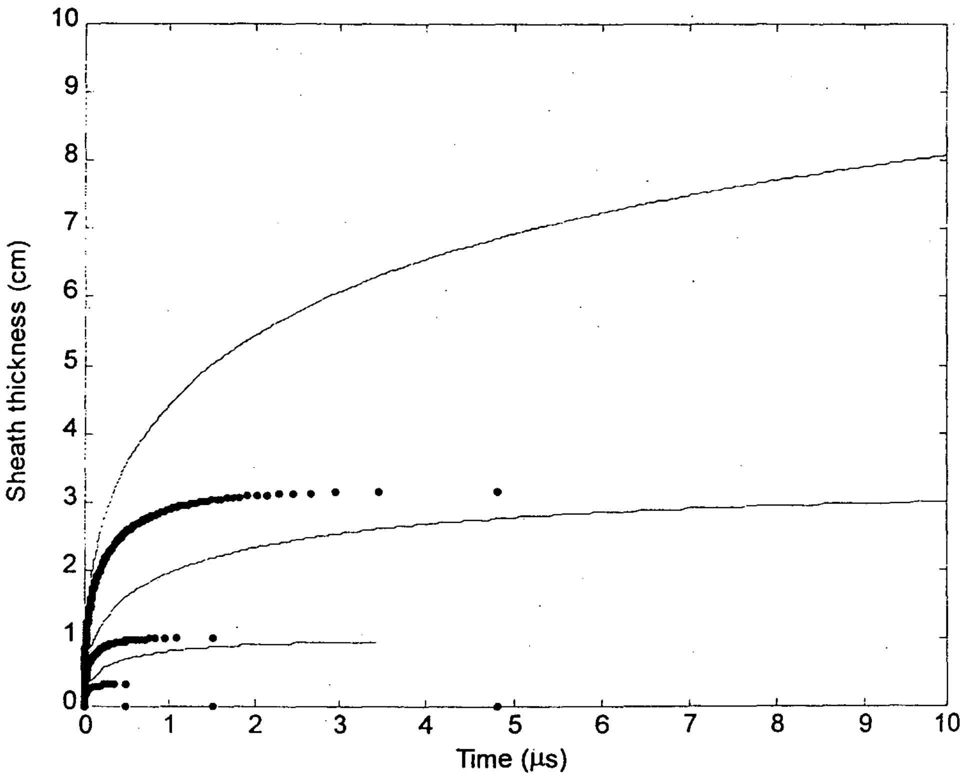

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Fig. 3

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