Title
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Journal
Applied Physics Letters, 76(21)

Author
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Publication Date
2000-04-11

LBNL-45457
Preprint

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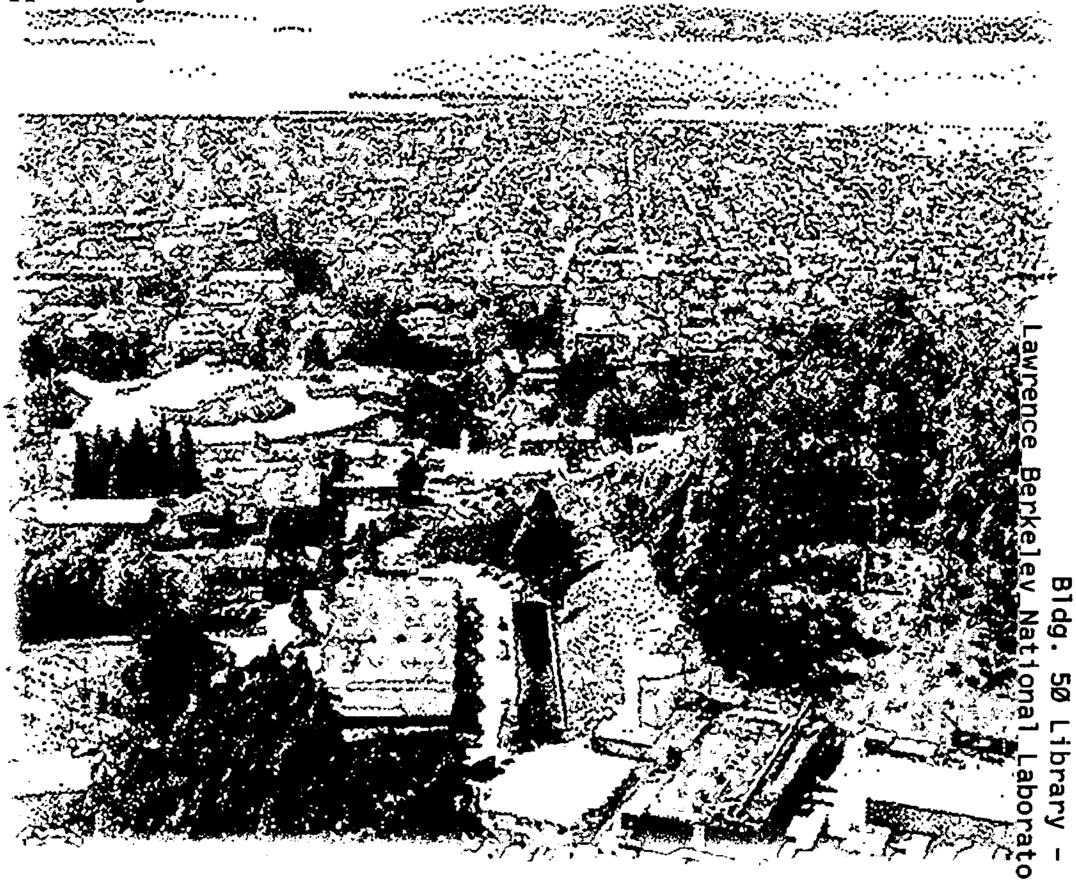
April 2000

Submitted to
Applied Physics Letters



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LBNL-45457

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This work was supported in part by the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

PLASMA DRIFT AND NON-UNIFORMITY EFFECTS IN PLASMA IMMERSION ION IMPLANTATION

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Abstract

Measurements of the ion current collected by a substrate biased to high-voltage have been carried out in plasma immersion ion implantation with a filtered vacuum arc plasma source. The vacuum arc plasma jet is characterized by its spatial non-uniformity and high ion drift velocity. In order to investigate these effects we placed the substrate at various distances from the source exit-plane and at various angles with respect to the jet streaming direction. We have found that the ion saturation current increases with applied 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 increases with decreasing angle of the substrate with respect to the plasma stream. A model was developed for the sheath expansion in a non-uniform plasma with substantial ion drift velocity. We find that non-uniformity and high drift velocity lead to a decrease in sheath thickness. In a non-uniform plasma, the ion saturation current increases with applied voltage. The predictions of the model were found to be in good agreement with experiment.

1. Introduction

Plasma immersion ion implantation (piii) is a technology used to modify material surface properties[1]. By repetitively applying negative high-voltage bias pulses to the substrate, ions are extracted from the plasma, accelerated across the high voltage sheath and implanted into the surface. A related kind of surface modification has been developed based on the use of vacuum arc generated metal plasma[2-4]. This technique incorporates both surface deposition of plasma and sub-surface ion implantation, with energetic ion implantation occurring during the voltage-on part of the substrate pulse-biasing and deposition occurring during the voltage-off part of the cycle.

Application of negative bias to the substrate immersed in the plasma leads to sheath formation near the substrate. Firstly, an ion matrix sheath is established on a timescale of about the inverse electron plasma frequency. Then the ions respond on a timescale of about the inverse ion plasma frequency. During this time the high voltage plasma sheath propagates into the plasma at about the ion acoustic speed.

The vacuum arc plasma has some specific properties which may affect the sheath structure near the target. The ions in the vacuum arc plasma jet have a supersonic velocity, which can significantly affect the sheath expansion. Also, the plasma density along the plasma jet is non-uniform[5], which may lead to plasma density increase at the sheath edge.

In this paper we present results of experimental measurements of ion saturation current in piii using a filtered vacuum arc plasma source. In order to investigate the effects of plasma density non-uniformity and high ion drift velocity we placed the substrate at different distances from the source exit plane and at various angles with respect to the plasma stream. We have developed a model of the sheath expansion into the non-uniform plasma in vacuum arc plasma immersion ion implantation. We present here a comparison of the predictions of the model with the experimental data, and a qualitative explanation of the observed experimental effects.

2. Experimental details and results

A simplified schematic of the experimental set up is shown in Fig. 1. A vacuum arc plasma gun with titanium cathode was driven with an arc current of 100 A in pulses of 500 microseconds duration and with repetition rate of 1 pulse per second. The negative bias pulse was of magnitude up to –8 kV. The titanium plasma was injected into a 90° curved magnetic duct in order to separate out macroparticles (cathode debris)[6]. The substrate plate was located downstream of the duct at a location that was varied from 5 to 35 cm from the duct exit plane. The substrate angle with respect to the plasma stream was varied from 90° (substrate normal to the plasma flow direction) to 30° (substrate oblique to the plasma flow).

The measured ion saturation current collected by the substrate as a function of distance from the duct exit, with substrate bias voltage as a parameter, is shown in Fig. 2. One can see that the ion current increases with applied voltage and decreases with distance from the duct exit.

The influence of the angle of the substrate with respect to the plasma stream is shown in Figs. 3a - 3c for different bias voltages. It can be seen that generally the substrate current is high for the case of small angle of incidence. The effect of increasing ion current with decreasing angle of incidence is more pronounced for the case of high bias voltage. We have summarized these results as shown in Fig. 4. The maximal effect of increasing ion current with decreasing angle of incidence is seen to be a factor of 1.6 for the case when the substrate is placed 25 cm from the duct exit.

The experiments thus show that the ion saturation current increases with applied voltage and that this effect depends upon the angle of the substrate with respect to the plasma stream and the distance of the substrate from the plasma duct exit. We also found that the ion current is high for the case of small angle of substrate with respect to the plasma stream. In order to explain the observed effect, a model of sheath formation in front of a substrate immersed in a non-uniform drifting plasma is now developed.

3. Model and comparison with experiment

We consider a planar substrate which is immersed in a non-uniform plasma with density distribution n(x), where x is the coordinate directed normal to the substrate as shown in Fig. 5. In this section we briefly outline a model of sheath formation for this case. The model described here is a development of the basic model of plasma immersion ion implantation as formulated by Lieberman[7-8]. More details about this model can be found in ref. 9 .

When a negative voltage is applied to a substrate immersed in a plasma, electrons are repelled from the substrate, leading to positive sheath formation. The ions are then accelerated toward the substrate by the electric field of the sheath. In the one-dimensional case the ion current density can be calculated according to the Child law,

$$j = \frac{4}{9}\varepsilon(\frac{2e}{m_i})^{1/2}\frac{U^{3/2}}{s^2} \qquad (1)$$

where j is the ion current density, U is the voltage across the sheath, s is the sheath thickness, and m_i is the ion mass. On the other hand the ion current at the plasma-sheath interface is due to a drift velocity v and the uncovering of ions by the moving sheath edge:

$$j = Z_i en(x)(\mathrm{v} + \frac{ds}{dt}) \qquad (2)$$

where n(x) is the plasma density distribution in front of the target. The plasma density distribution in the vacuum arc plasma jet may be approximated by the function[5]:

$$n(x) = \frac{n_o x_o^2}{x^2} \qquad (3)$$

where x_o is the characteristic length for plasma density change. The steady-state sheath thickness (ds/dt = 0), obtained from the general solution of Eqs. (1) - (3), has the following form:

$$s = x_o \frac{\sqrt{\beta} - 1}{\beta - 1} \qquad \beta > 1$$

$$(4)$$

$$s = x_o \frac{\sqrt{\beta} + 1}{1 - \beta} \qquad \beta < 1$$

where the parameter β is given by

$$\beta = \frac{n_o x_o^2 Z_i e v}{\frac{4}{9}\varepsilon\left(\frac{2Z_i e}{m_i}\right)^{1/2} U^{3/2}} \qquad (5)$$

In the filtered vacuum arc plasma configuration employed by us, at the filter exit plane the plasma jet is characterized by a density $n_o = 10^{17} - 10^{18}\ m^{-3}$ at $x_o = 0.01$ m (see ref. 5 and references therein). Thus the parameter β can be estimated as $4 \times 10^6\ M/U^{3/2}$, where M is the Mach number, defined by $M = v/c_s$, where c_s is the sound speed.

The sheath thickness calculated from Eq. 4 as a function of applied bias voltage is shown in Fig. 6, with angle of the substrate with respect to the plasma stream as a parameter, for the case $n_o = 10^{17}\ m^{-3}$, $v = 1.1 \times 10^4$ m/s [10] and $x_o = 0.01$ m. One can see that the sheath thickness increases with bias voltage, but nevertheless remains small compared to typical plasma dimensions. It was found also that the sheath thickness is large for the case when the angle of the substrate with respect to the plasma streaming velocity is small.

In a non-uniform plasma, the increase in sheath thickness leads to an increase in ion saturation current because the ion current is determined by the plasma density at the plasma-sheath interface. This effect is shown in Fig. 7, with angle of the plasma stream with respect to the substrate as a parameter. For comparison the experimental results are also shown. One can see that both the theoretical prediction and the experimental results show an increase in the ion current with increasing applied voltage and with decreasing substrate-plasma stream angle. We find generally good agreement between the model and experiment.

4. Discussion

(Michael: I can't think of anything more to say here. Possibly we might simply replace this section with a concluding sentence / paragraph, above. The paper might then possibly be short enough to go to APL rather than JAP; but of course JAP is perfectly fine too.)

Acknowledgements

One of the authors (MK) gratefully acknowledges the financial support of the Fulbright and the Welch Fellowship Programs. This work was supported in part by the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

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Figure Captions

Figure 1. Schematic of the experimental configuration.

Figure 2. Measured substrate ion saturation current as a function of distance from the duct exit plane, with applied voltage as a parameter. $\alpha = 90°$.

Figure 3. Measured substrate ion saturation current as a function of distance from the duct exit plane, with angle between plasma stream and substrate as a parameter.
a) V = -2 kV; b) V = -4 kV; c) V = -6 kV.

Figure 4. Normalized substrate ion saturation current as a function of angle between plasma stream and substrate, with distance from the duct exit plane as a parameter.

Figure 5. Schematic of the configuration used for the sheath model.

Figure 6. Sheath thickness as a function of applied voltage with angle between plasma stream and substrate as a parameter.

Figure 7. Normalized ion implantation current density *vs* substrate bias voltage, with angle between plasma stream and substrate as a parameter.
Experimental data: squares – 50°; triangles – 30°.

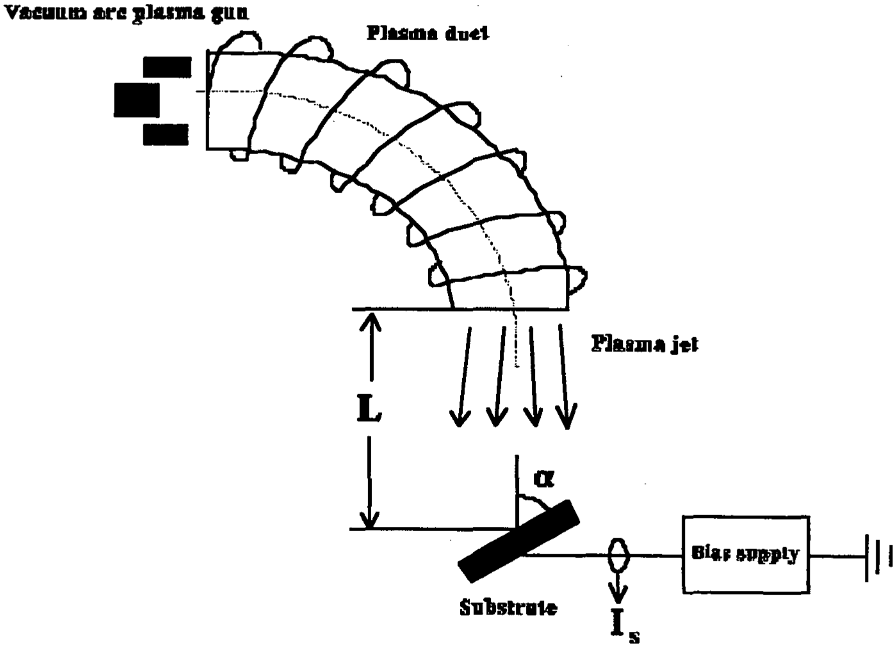
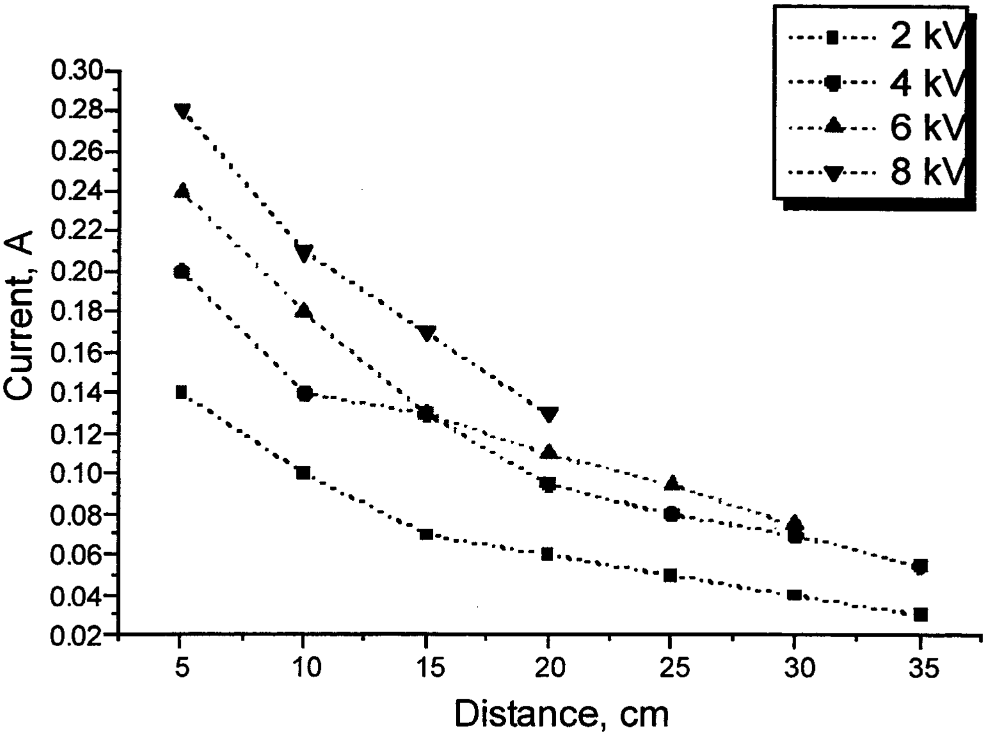


Figure 1. Keidar, Monteiro and Brown, "Plasma drift and non-uniformity effects..."



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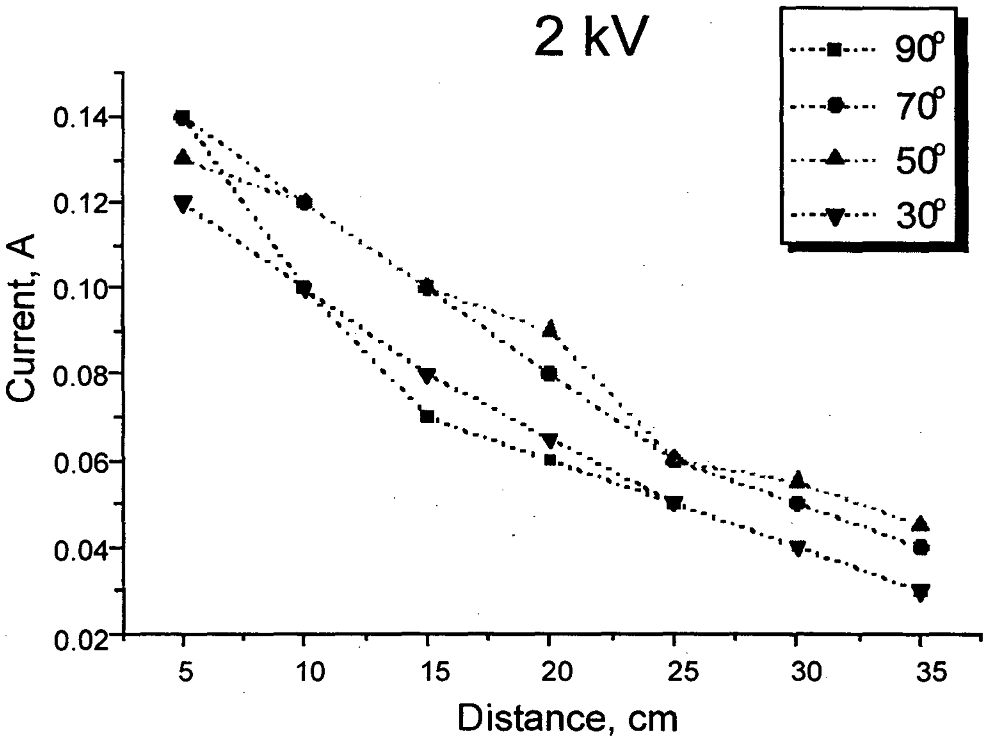

Figure 3a. Keidar, Monteiro and Brown, "Plasma drift and non-uniformity effects..."

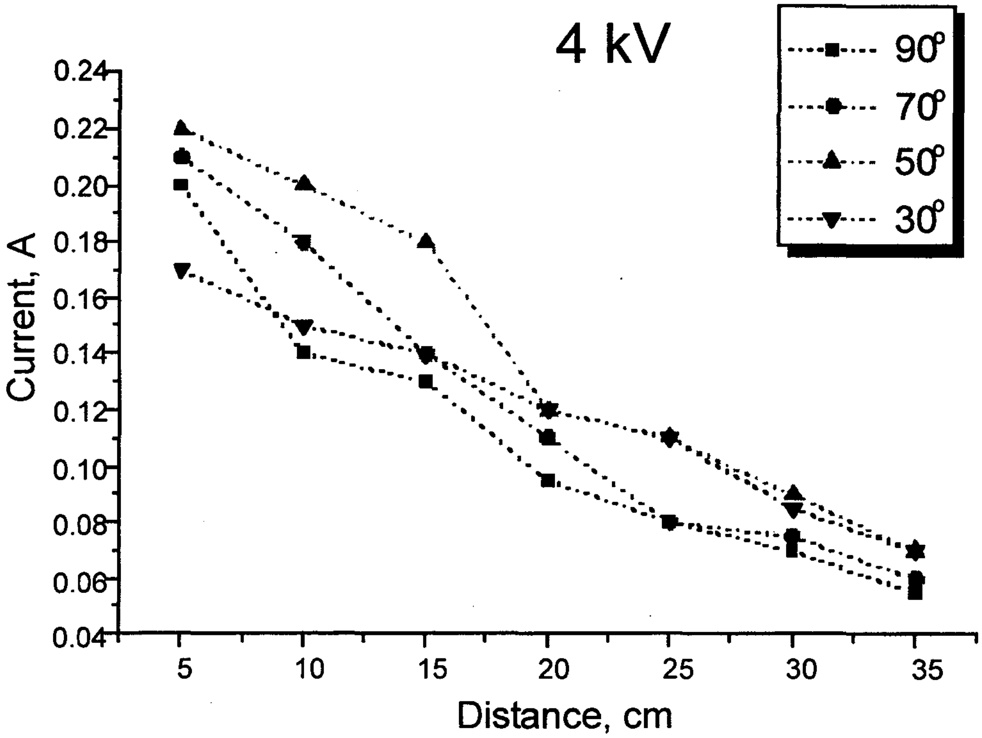

Figure 3b. Keidar, Monteiro and Brown, "Plasma drift and non-uniformity effects..."

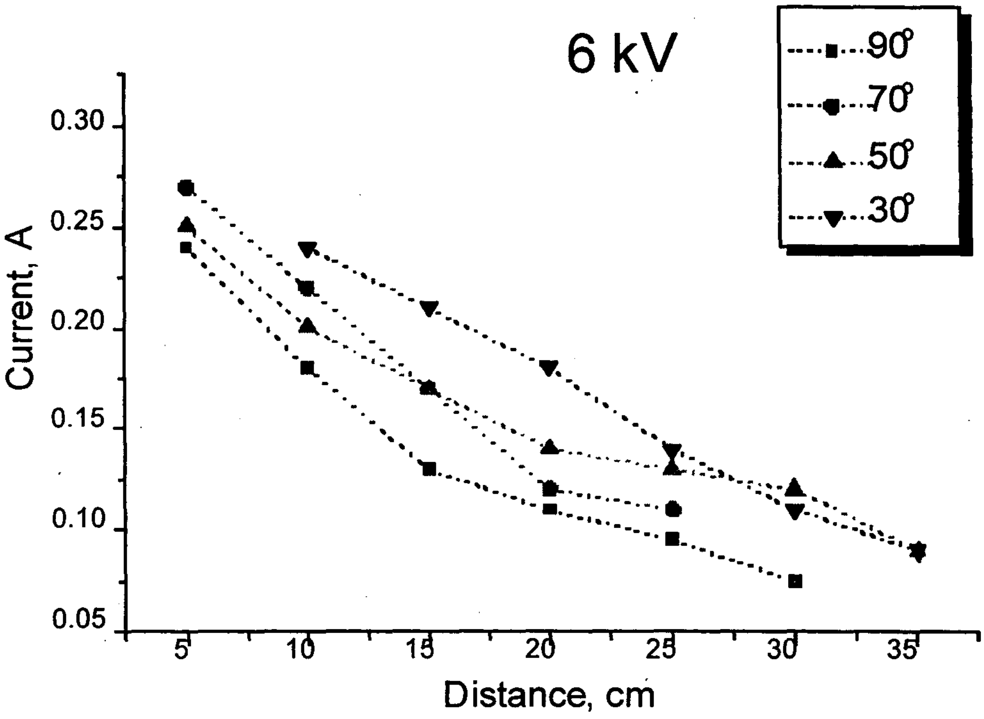

Figure 3ca. Keidar, Monteiro and Brown, "Plasma drift and non-uniformity effects..."

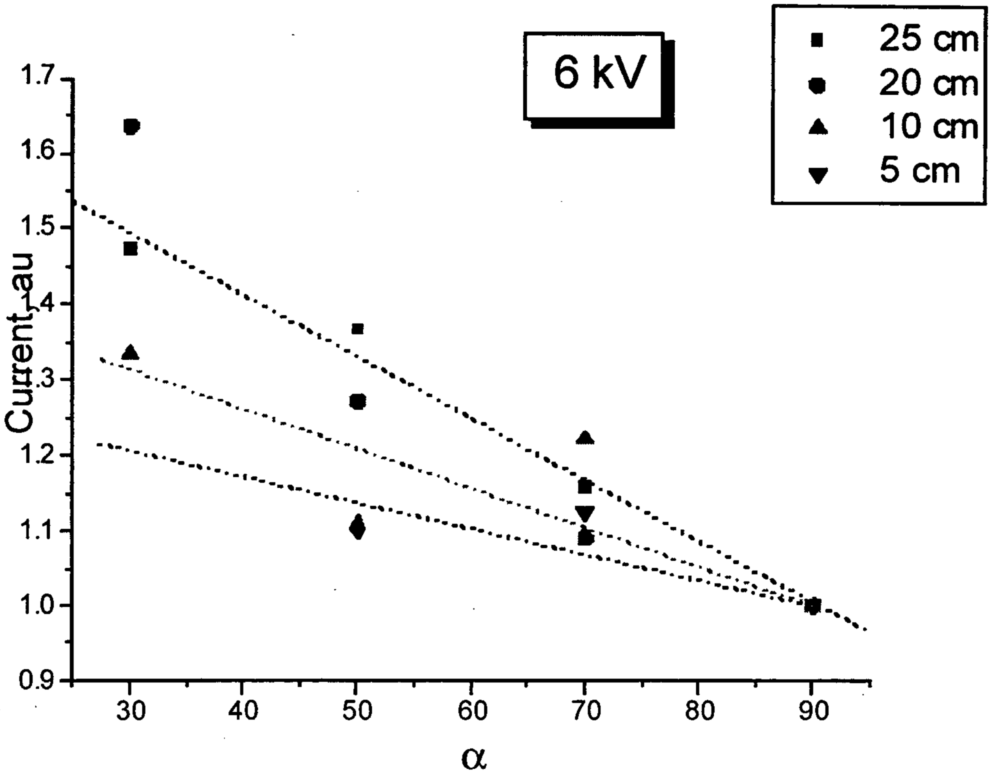

Figure 4. Keidar, Monteiro and Brown, "Plasma drift and non-uniformity effects..."

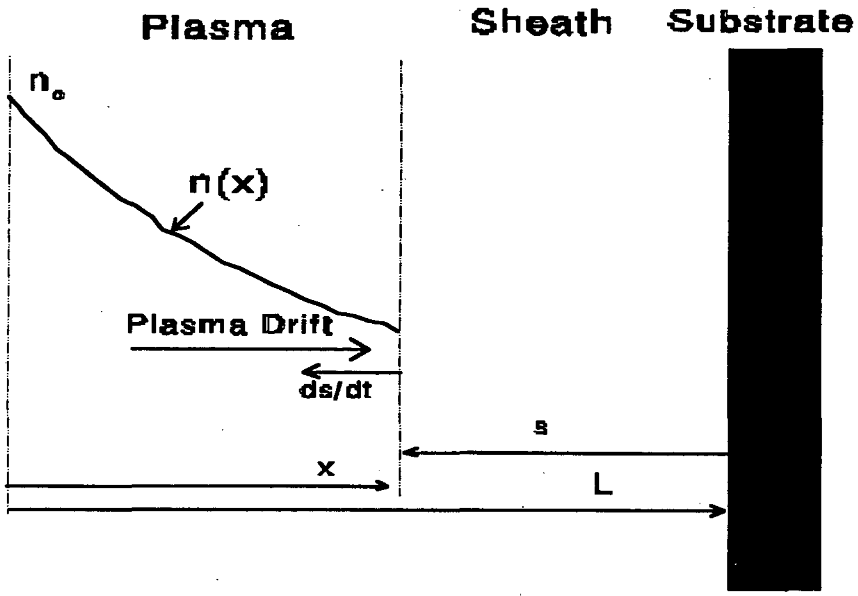

Figure 5. Keidar, Monteiro and Brown, "Plasma drift and non-uniformity effects..."

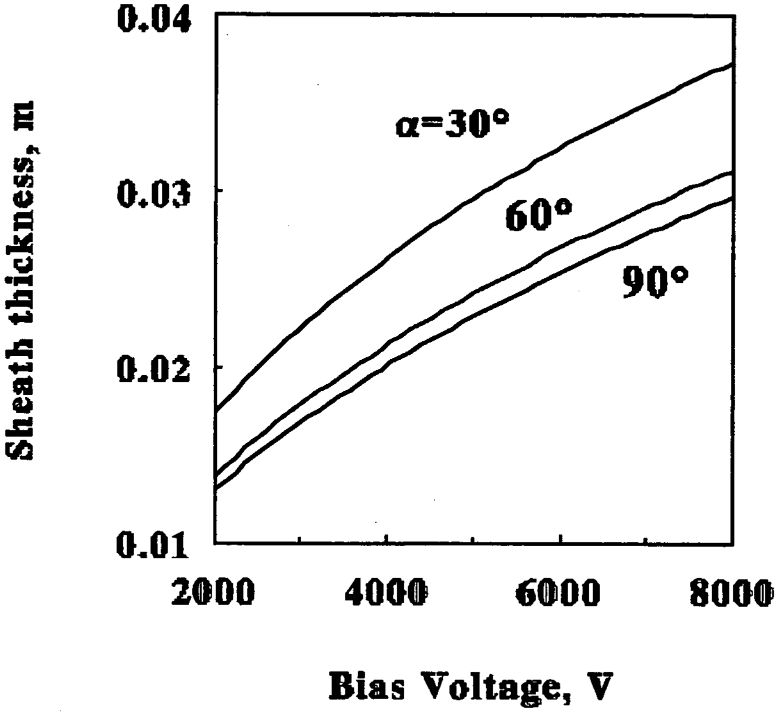

Figure 6. Keidar, Monteiro and Brown, "Plasma drift and non-uniformity effects..."

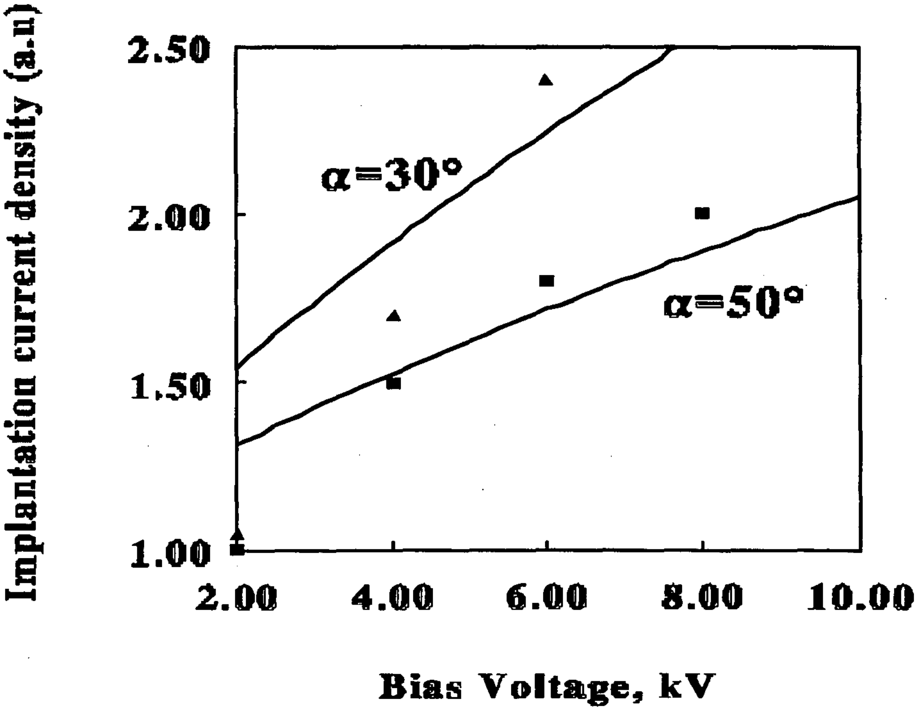

Figure 7. Keidar, Monteiro and Brown, "Plasma drift and non-uniformity effects..."

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Prepared for the U.S. Department of Energy under Contract No. DE-AC03-76SF00098