Electron Beam plasma generation for processing and non-equilibrium plasma applications*

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Abstract

Moderate energy electron beams confined by a magnetic field can efficiently produce sheets of dense plasma suitable for processing. 1 cm thick, 60 cm x 60 cm plasmas sheets have been produced with electron density of up to $10^{12}$ cm$^{-3}$ and temperature $\sim$ 1eV. Plasma parameters and extracted particle fluxes have been measured.

1. Introduction

The use of electron beams to ionize a low pressure gas may provide an efficient means to produce large area plasmas for materials processing as well as energize large volumes of gas for non-equilibrium chemistry applications. This technique may also offer better process control than conventional techniques. The Naval Research Laboratory’s Large Area Plasma Processing System (LAPPS) uses a separately generated flux (10’s mA/cm$^2$, 2-4 kV) of electrons to ionize a low pressure (20-100 mTorr) working gas. Such beams have been shown to generate 60x60 cm sheets of high density ($10^{12}$ cm$^{-3}$), cold ($\leq$ 1 eV), plasma[1,2] when confined by a magnetic field, or cubic meters of non-equilibrium gas when injected into a low pressure chamber. This technique offers advantages over conventional plasma sources including: efficient ionization and dissociation of gas mixtures; decoupling of plasma production from system geometry; independent control of the ion and radical fluxes; large area; and low electron temperature. This paper will present experiments measuring plasma parameters and extracted ion fluxes for a LAPPS plasma. Theoretical aspects will be presented in a companion paper [3].

2. Experimental Apparatus

Figure 1 shows a schematic of the LAPPS system. A 20-100 cm wide, 1-cm thick, 2-10 mA/cm$^2$ sheet beam is generated by a pulsed or cw hollow cathode (1). The beam, confined by a 100-250 Gauss magnetic field (2), passes through the processing chamber filled with 20-100 mTorr of gas before being absorbed by a beam dump (3). The sheet plasma (4) coincides with the beam channel. Unmagnetized ions and other products (e.g., free radicals, excited atoms/molecules) leave the plasma and strike the surrounding planar electrodes (5,6).
Capacitively coupled RF bias (7) on an electrode can adjust the ion energy striking the material to be processed (8) or material to be removed for sputtering applications.

Experiments have been performed in various chambers including an acrylic chamber used for optical and microwave diagnostic access and aluminum or stainless UHV-compatible chambers for detailed plasma diagnostics and processing tests. The chambers were filled with 20-100 mTorr of argon, nitrogen, oxygen, SF₆, or mixtures of gases. DC current was driven in surrounding arrays of coils to generate a uniform 100-250 Gauss magnetic field.

a. Electron beam sources: Most experiments used a pulsed cathode that generated a 1-cm thick by 15-30 cm wide, 1-3 kV, 2-10 mA/cm², 200-2000 μs duration electron beam. The pulsed cathode consisted of a rectangular channel (1 cm wide, 1.5 cm deep, 15-30 cm long) surrounded by an insulator and a grounded outer shield. Beam electrons were extracted from the cathode surface by secondary emission due to ion bombardment. The cathode was embedded in a 100-250 Gauss magnetic field which also confined the beam electrons as they crossed the chamber. An Insulated Gate Bipolar Transistor (IGBT) switched pulse generator was used to drive the chamber.[4] Sheet beams of up to 60-cm wide and 8 kV have been produced using this type of cathode.[5] The sheet beam was passed through a 1-cm wide stainless steel aperture 5 cm downstream of the cathode. This aperture served as the grounded anode and defined the beam size as it entered the experimental chamber. The beam terminated on a grounded metal beam dump at the far side of the chamber.

Experiments were also performed using a cw e-beam source. This work was performed in anticipation of materials processes that require seconds or minutes of exposure to plasma. A low voltage (300-500 V) hollow cathode discharge was driven between a 10 x 10 x 30 cm stainless steel chamber with a 1-cm wide slot on one side and a matching stainless steel screen covered anode slot. The entire plasma source was isolated from ground by a 1 cm gap and insulator. Electrons were pulled from the discharge plasma through the screen and entered the experimental chamber through a 1-cm grounded extraction slot. The entire system was embedded in a 100-250 Gauss magnetic field. 1-5 kV cw sheet beams of 2-5 mA/cm² were generated using this technique. The beam current could be controlled by the hollow cathode discharge current and was nearly independent of the extraction voltage.

b. Plasma diagnostics: A large fraction of the initial work done on the LAPPS system has focused on diagnosing the plasma and the particle fluxes generated by the plasma. Diagnostics fielded thus far include 1-10 GHz microwave transmission measurements (line integral of plasma density, peak plasma density), Langmuir probes (ion density, plasma potential, electron temperature), emissive probes (plasma potential), biased particle collectors (relative ion flux, ion energy, and temperature), a mass and energy analyzer (ion species, ion energy, relative ion fluxes), optical emission spectroscopy (ion/neutral identification), and beam voltage and current diagnostics (beam parameters). Data from some of these diagnostics will be presented in this paper.

Several different versions of Langmuir probes were used[6,7] The probes were made with thoriated tungsten wire extending beyond an alumina insulator. Independent heating and
discharge cleaning were used to remove surface contaminates from the probe. The current collected by the wire was measured as a function of the probe bias voltage.

An emissive probe was used to independently measure the plasma potential. The probe consisted of a loop of the 10-mil tungsten wire, heated to incandescence by a floating current supply, and biased relative to ground. Emission from the filament determined the plasma potential to within a fraction of a volt.

A cylindrical, retarding-field gridded energy analyzer was used to measure ion flux. A 6.3 mm aperture covered by a 500 line per inch mesh followed by a similar screen with a variable bias voltage (± 50 V) and then a collection electrode set at -90 V. Ions with sufficient energy to pass the variable bias screen were collected by the electrode. The collected current signal was differentiated to give a signal proportional to the ion energy distribution.

Ion flux and energy distributions were measured with a Hiden EQP 300 Plasma Probe that consists of an electrostatic ion-energy analyzer (ESA) in series with a quadrupole mass spectrometer (QMS). The probe was inserted perpendicular to the plasma sheet at varying distances from the beam edge. Ions incident to the electrode entered the differentially pumped EQP through a 100 micron diameter aperture located in the center of the electrode. Time-resolved measurements were achieved by gating the detector output.

3. E-beam generated plasmas

a. Beam measurements: Time resolved measurements from the pulsed electron beam are shown in figure 2. This data comes from the acrylic experimental chamber filled with 75 mtorr nitrogen in a 150 Gauss magnetic field. The 2 kV voltage pulse drove ~ 200 mA of cathode current from the 1 cm x 22 cm cathode. Approximately half of the current was from high energy electrons, giving a beam current density of ~5 mA/cm². Theory predicts electron density n_e ~ 8.5x10¹⁰ cm⁻³ for these conditions. The bottom trace of Figure 2 shows the transmission of a 1.5 GHz modulated microwave beam through the plasma. The microwave system consisted of transmitting and receiving horns on either side of the acrylic chamber aligned perpendicular to the planar sheet. Cutoff of the transmitted signal during the pulse suggests that the plasma density exceeds 5x10¹⁰ cm⁻³, agreeing well with prediction.

b. Plasma density, temperature, floating potential: Figure 3 shows typical I-V curves generated from a Langmuir probe near the axis of the beam. This data was taken in 85 mtorr argon and 120 Gauss magnetic field. In this case a 7.5 GHz microwave beam was cut off by the plasma indicating n_e > 7x10¹¹ cm⁻³. The I-V characteristic
changes little during the pulse but changes rapidly in the afterglow, after the beam has been turned off and the plasma is decaying. The electron collection portion of the curve shifts to the left and drops rapidly when the beam is turned off. The signal indicated a plasma density $n_e = 10^{12} \text{ cm}^{-3}$ during the pulse for these beam parameters in argon, which agrees well with the microwave measurements. The plasma potential is the voltage at which the slope of the I-V curve changes rapidly. During the pulse the plasma potential ranges from 4-8 V with some of the uncertainty caused by probe contamination. When the beam is turned off, the plasma potential falls to <1 V, which is consistent with a rapid decay of the electron temperature.

Likewise the electron saturation current measured at high positive bias drops rapidly after the pulse. This indicates that the plasma density decays rapidly.

The characteristic I-V curves were analyzed using a two-temperature, Maxwellian fitting routine [10]. This routine assumes a $V^{1/2}$ scaling in the ion saturation region and a two-temperature Maxwellian ($\exp(-V/T_e)$) at higher voltages. Variables of the fit are automatically adjusted to minimize the discrepancy between the fit and the data. Figure 4 shows the results for the nitrogen plasma (75 mtorr, 150 Gauss, 800 $\mu$s pulse). The plasma density in this case reaches $n_e = 5\times10^{11} \text{ cm}^{-3}$ after ~150 $\mu$s from the beginning of the pulse.

The two-temperature fits yielded a cold, dense component (shown in Fig. 4) and a second component with only 30% the density but higher temperature. The density grows slowly over the 800 $\mu$s pulse before decaying in ~100 $\mu$s after the pulse. The electron temperature has a similar profile, reaching 0.35 eV early on and growing slowly to 0.4 eV during the pulse. The temperature decays faster than the density after the pulse. Similar data for an argon plasma gives $n_e = 3\times10^{11} \text{ cm}^{-3}$ and $T_e = 1.2 \text{ eV}$ during the pulse. This data illustrates that beam-generated plasmas can produce high plasma density and low electron temperatures.

Measurements of a nitrogen plasma similar to that illustrated in Fig. 4 using an emissive probe showed a floating potential of ~0.8 V near the center of the plasma. Normally the floating potential is several times the plasma electron temperature. The emissive probe measurement confirmed the low electron temperatures ($T_e \approx 0.35 \text{ eV}$) measured by the Langmuir probes. The emissive probe showed a floating potential of ~1.7 eV for an argon plasma where $T_e$ was = 1.2 eV.

c. Plasma cross section: Figure 5 shows a measurement of the plasma cross section. The figure shows the ion saturation current from a Langmuir probe as a function of distance from the center of a nitrogen plasma sheet. The normalized probe data shows a peaked distribution with ~17 mm full width at half maximum (FWHM). The beam is defined by the 1 cm wide aperture where it enters the experimental region. The gyroradius of a 2 kV electron in a 150 Gauss magnetic field is $r_g = 7 \text{ mm}$.

Figure 4. Electron density and temperature as derived from curve fits to Langmuir probe characteristics.

Figure 5. Plasma distribution cross section.
d. Ion fluxes from the plasma: The EQP 300 was used to measure the ion fluxes coming out of the plasma. Figure 6 shows the O⁺ flux at three different energies as a function of time entering the grounded EQP 100 μm aperture located 1 cm from the edge of the plasma. During the pulse the ion fluxes are relatively constant in time. The distribution of ion energies is due to collisions in the sheath as well as initial ion temperature. When the beam is switched off after 1 ms the ion flux rapidly decays in ~100 μs. This timescale is consistent with a decay dominated by recombination. Similar measurements with an argon plasma, which is diffusion dominated, show a much slower decay lasting ~1 ms.

Figure 7 shows first results of ion flux measurements made using the gridded ion flux probe. This measurement was simpler than using the EQP but could not discriminate between ion species. The figure shows preliminary data for the ion energy distribution for oxygen and argon plasmas with the probe located 1.5 cm from the edge of the plasma. The data was taken near the center of the 1 ms pulse. The probe current was measured as a function of the bias voltage. The two measurements were made with similar beams in 30 mtorr of argon and oxygen in a 150 Gauss magnetic field. The oxygen plasma showed a peak energy of ~1.4 eV while the argon plasma showed a peak at ~2.8 eV. The measured peak energies were slightly higher than the plasma potentials measured with the emissive probe but had similar ratios. The argon ion higher ion energy is consistent with the higher electron temperature measured in Argon.

![Figure 6. Oxygen ion flux measured 1 cm from the plasma.](image)

![Figure 7. Oxygen and argon fluxes measured with a gridded analyzer.](image)

One of the key requirements of a processing plasma is the ability to extract ions at higher energy than the plasma floating potential. Figure 9 shows results of applying rf bias (11 V peak to peak voltage, 13.56 MHz) on an isolated stage close to an argon plasma sheet. The electrode was mounted on the end of the EQP and the rf bias was adjusted to give a de bias voltage on the stage of ~10 V. Ions entering the aperture were mass and energy analyzed with an energy acceptance window of 1 V. The figure shows the Ar⁺ energy spectrum normalized to its peak with and without rf bias. The shift in ion energy with the rf bias is apparent. Ions entering the EQP gain not only the plasma potential, which is ~5 V as seen in

![Figure 8. Argon ion flux measured by the EQP with and without rf bias.](image)
the grounded case, but the $\sim 10$ V dc component of the rf bias. The spread in ion energies is attributed to finite sheath transit time effects and scattering with the background gas. This illustrates that LAPPs is compatible with rf bias and that one could control the ion energy on a processing surface with rf.

4. Summary and Conclusions:

Experiment and theory have shown that E-beams can generate cold $(T_e < 1$ eV), and dense $(n_e \sim 10^{12} \text{ cm}^{-3})$ plasmas in a variety of working gases. This is due to the ionization efficiency of high energy electrons in neutral gas. Ion fluxes can be controlled by gas composition (e.g., diffusion or recombination dominated species), distance between the plasma and the material, and rf bias voltage. Measurements have also confirmed free radical production. Initial materials processing tests have shown anisotropic removal of patterned photo resist. Further processing tests are in progress. Measurements of beam generated plasmas in field free geometries have shown large volume plasma production. Tests of non-equilibrium gas chemistry are underway.

References

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