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Extraction of a nearly monoenergetic ion beam using a pulsed plasma

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A nearly monoenergetic ion beam was extracted from a capacitively coupled pulsed Ar plasma. The electron temperature decayed rapidly in the afterglow, resulting in uniform plasma potential, and minimal energy spread for ions extracted in the afterglow. Ion energy was controlled by a dc bias on a ring electrode surrounding the plasma. Langmuir probe measurements indicated that this bias simply raised the plasma potential without heating the electrons in the afterglow. A rejection grid downstream of the plasma allowed ions to pass only during a selected time window in the afterglow. The energy spread was 3.4 eV full width at half maximum for a peak ion beam energy of 102.0 eV. This energy spread is about an order of magnitude narrower than the beam extracted from the continuous plasma. © *2005 American Institute of Physics*. [DOI: 10.1063/1.2001129]

Precise control of the ion energy distribution (IED) is important in a variety of thin-film etching and deposition applications.[1] In plasma processing, for example, etch rate and selectivity depend sensitively on ion bombardment energy, especially for near-threshold processes. The IED is determined by the difference in potential between the plasma and the substrate, as well as ion collisions with the background neutral gas. For radio-frequency (rf) plasmas, commonly employed in semiconductor manufacturing, the dependence of IED on control parameters has been studied extensively.[2,3] For collisionless ion flow, the ion energy spread depends critically on the ion transit time through the sheath and the sheath potential wave form. Wang and Wendt[4] reported a method to control the ion bombardment energy by applying a nonsinusoidal bias wave form on the substrate electrode, designed to result in a narrow energy spread. Coburn and Kay[5] as well as Smith and Overzet[6] showed that ion energy can be controlled by inserting a separate electrode into the plasma, and biasing that electrode to control the plasma potential. This technique has also been used to control the energy of ions and the resulting energetic neutrals in neutral beam sources.[7,8]

In all of these experiments, ions were extracted from a continuous-wave plasma. Under such conditions, however, even when the sheath potential wave form is designed to yield a narrow IED, the ion energy spread is limited by the *spatial* variation of the plasma potential. This in turn is proportional to the electron temperature, T_e.[9] Thus, the energy of ions entering the sheath depends on *where* the ion was born, and the spread of the resulting IED should be of the order of T_e. A way to further sharpen the IED is to extract ions from a plasma of very low T_e. In this work, an ion beam was extracted from the afterglow of a pulsed plasma. The electron temperature decays drastically in the afterglow, with only a moderate drop in the ion density. A separate biased electrode was used to control the plasma potential and the energy of the extracted beam.

Power at 13.56 MHz was delivered to a 4 in. diameter nickel target electrode. A capacitively coupled Ar plasma formed between the powered electrode and a grounded extraction grid (Fig. 1). A 4.4 in. inner diameter 0.3 in. high, 0.1 in. thick stainless-steel ring (acceleration ring) was placed around the discharge region to raise the plasma potential (V_p) and push positive ions out of the plasma. Ions were extracted through a 0.3 in. diameter, 127 μm thick, 21% open area stainless-steel extraction grid at ground potential. The hole diameter was 142 μm on the side of the grid facing the plasma, and tapered to 160 μm on the opposite side. A 90% transmittance nickel wire woven mesh (rejection grid) was suspended 1.5 in. underneath the extraction grid to periodically screen out unwanted ions. The discharge pressure was 10 mTorr and the region downstream of the extraction grid was differentially pumped to 2×10^{-5} Torr to avoid collisions of the extracted ions with background gas. After exiting the plasma, ions drifted ~25 in. before reaching an ion energy analyzer. The ion energy analyzer composed of three stainless-steel grids (each 72% transparent) and a current collector. The top grid was grounded, and the middle grid was swept from 0 to 150 V (referenced to ground potential) at 0.5 V intervals. The bottom grid was biased at −20 V to repel electrons coming from the plasma and suppress any secondary electrons emitted from the 1 in. diameter current collector. The resolution [full width at half maximum (FWHM)] of the ion energy analyzer was estimated to

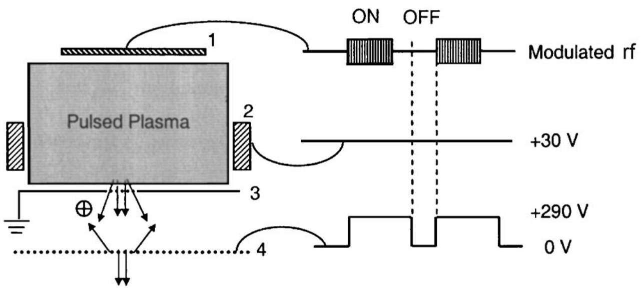

FIG. 1. Schematic of the ion source, showing the configuration of the (1) target electrode, (2) acceleration ring, (3) extraction grid, and (4) rejection grid. The plasma power is modulated at 5 kHz, while the acceleration ring is biased at a fixed potential. The rejection grid downstream of the plasma allows ions to pass during a user-definable window in the afterglow. The extraction grid is grounded.

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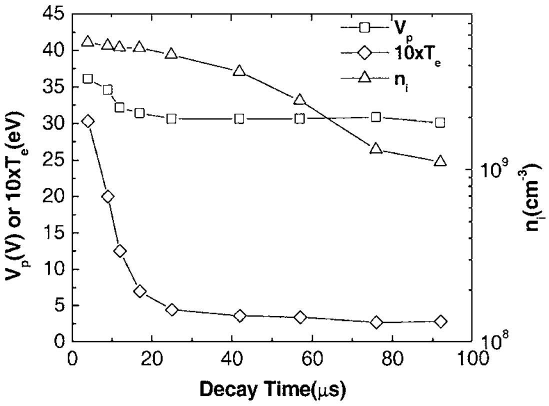

FIG. 2. Evolution of plasma potential, electron temperature, and positive ion density in the afterglow, with +30 V bias (applied continuously) on the acceleration ring. (15.9 mTorr, 5 kHz modulation frequency, 50% duty cycle, 30 W average rf power).

be $\sim 1-2\%$ of the ion energy.[10] Both the sweeping voltage and the collected current were computer controlled using LABVIEW (National Instruments). Time-resolved ion density, plasma potential, and electron temperature were measured by a Langmuir probe (Scientific Systems) that was momentarily positioned near the center of the plasma, 0.8 in. above the extraction grid.

Synchronization of applied signals (see Fig. 1) is central to extracting an ion beam with the desired energy. The plasma was modulated (pulsed) at a frequency of 5 kHz (100 μs ON/100 μs OFF), while the acceleration ring was biased continuously at the desired positive dc voltage (e.g. +30 V in Fig. 1). When the rejection grid was grounded, ions during both the active glow (power ON) and the afterglow (power OFF) were able to reach the ion energy analyzer and a wide IED was obtained. When the rejection grid was biased with a square wave voltage of +290 V (rejects positive ions) during the active glow and the first 12 μs of the afterglow, and 0 V (passes ions) during the late afterglow, only ions extracted from the cold plasma and accelerated across the sheath potential adjacent to the extraction grid are passed to the downstream IED analyzer. Ions extracted later in the afterglow are expected to have a narrow energy spread, since there are no collisions in the sheath and T_e has decayed substantially (see below), resulting in a uniform plasma potential. Consequently, the desired ion energy was set by the voltage applied to the acceleration electrode.

Time-resolved Langmuir probe measurements with a +30 V bias applied on the acceleration ring are shown in Fig. 2. The electron temperature decays rapidly from 3 eV in the active glow to less than 0.5 eV about 30 μs into the afterglow. When the rf power is turned off, the higher-energy electrons initially lose energy mainly by inelastic collisions with the background gas and by diffusion to the walls. Later in the afterglow, when the electron temperature decays, electrons in the high-energy tail of the electron energy distribution function (EEDF) continue to lose energy by diffusion to the wall and by inefficient elastic collisions with the gas. The plasma potential V_p drops in a fashion similar to T_e and reaches about 30 V at 20 μs into the afterglow. In contrast, the ion density (n_i) decreases rather slowly; 57 μs into the afterglow the ion density is 2.5×10^9 cm^{-3}, about one-half of the value at 4 μs after rf power is OFF.

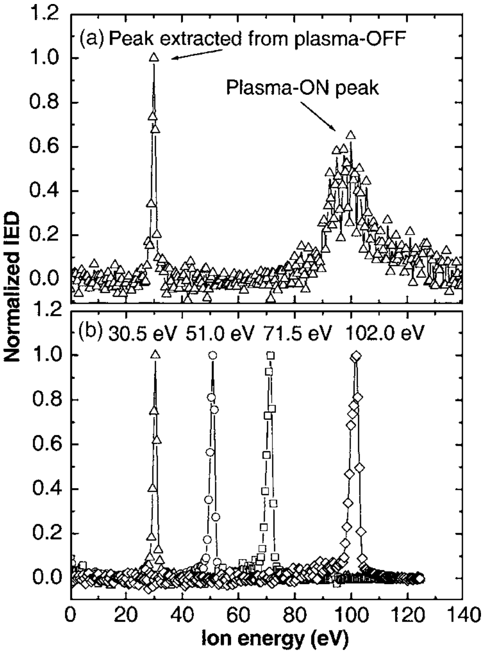

FIG. 3. The normalized IED with (a) the rejection grid grounded and (b) the rejection grid biased late in the afterglow, as shown in Fig. 1. (10 mTorr, 5 kHz modulated frequency, 50% duty cycle, 30 W average rf power). In (a), a 30 V bias was applied continuously to the acceleration ring. In (b), the bias on the ring was 30, 50, 70, and 100 V (each corresponding to a separate experiment).

An important requirement is that the bias applied to the acceleration ring does not reignite the plasma in the afterglow by heating the electrons, as observed in a pulsed chlorine discharge with rf bias on the substrate.[11] The time-resolved current-voltage (*I*-*V*) characteristics with the accelerating ring biased at 0 and +30 V were almost identical. The only difference was that the *I*-*V* curves with the bias on were displaced by +30 V compared to the *I*-*V* curves with no bias. Therefore, the bias on the acceleration ring simply shifts the plasma potential without heating the electrons in the afterglow. This was confirmed by examining the EEDF in the afterglow for the two bias settings. For example, 15 μs into the afterglow, T_e was 0.74 eV and 0.72 eV for 30 and 0 V accelerating ring potentials, respectively. In fact, no electron heating in the afterglow was observed for all values of bias examined, up to 100 V. These results suggest that extraction of a monoenergetic ion beam with energy controlled by the dc bias applied to the acceleration ring is possible in the afterglow.

Fig. 3 shows IEDs measured for the pulsed plasma with a +30V bias continuously applied to the acceleration ring. With the rejection grid grounded [Fig. 3(a)] ions from both the active glow (plasma ON) and afterglow (plasma OFF) reach the ion energy analyzer. The sharp peak at ~30 eV represents ions extracted during the afterglow, with an energy equal to the acceleration voltage. The broad peak at higher energies represents ions exiting the plasma during the active glow. When a high enough positive bias voltage is applied to the rejection grid during the active glow and early afterglow, the high-energy ions are filtered out, leaving only a monoenergetic ion beam to reach the detector during a selected window in the late afterglow (from 12 μs to 100 μs in this case). The beam energy can now be controlled by the potential of the acceleration ring. By setting the acceleration ring to 30, 50, 70, or 100 V (each in separate experiments), sharp IEDs at 30.5, 51.0, 71.5, or 102.0 eV, respectively, were recorded [Fig. 3(b)]. The corresponding FWHM of these distributions is 1.4, 1.9, 2.5, or 3.4 eV. Such sharp peaks reinforce the notion that, even for a 100 eV bias on the acceleration ring, electron heating in the afterglow is not taking place. Similar results were obtained when the acceleration ring was biased only during the afterglow.

In summary, a method has been presented for extracting a nearly monoenergetic ion beam with specified energy using a pulsed plasma. The electron temperature decayed rapidly in the afterglow, resulting in uniform plasma potential, and minimal ion energy spread. An electrode immersed in the plasma was biased to control the ion energy, while a grid downstream of the plasma was used to filter unwanted ions.

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