High-energy negative ion beam obtained from pulsed inductively coupled plasma for charge-free etching process

O. V. Vozniy and G. Y. Yeom

Additional information on Appl. Phys. Lett.

High-energy negative ion beam obtained from pulsed inductively coupled plasma for charge-free etching process

O. V. Vozniy[a)] and G. Y. Yeom[b)]

Sungkyunkwan Advanced Institute of Nano Technology, Sungkyunkwan University, Jangan-Gu Chunchun-Dong 300, Suwon, Kyunggi-Do 440-746, South Korea

Negative ions in conventional inductively coupled plasma are often more chemically active than positive ions (for example, in CF_4 or SF_6 plasmas), but inconveniently they are trapped inside the sheath and cannot be used for high-energy surface etching in sources with a grid-type acceleration system. In this work we describe a method of positive and negative ion extraction that allows the energy and flux of oppositely charged particles to be varied independently. Then by scattering the ions off from a metal surface, it is possible to form a high-energy beam of neutrals from the negative ions by using the low-energy positive component of the beam current for better charge compensation. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3152763]

A high-density ion source derived from an inductively coupled plasma is a useful tool in the fabrication of devices for use in large-scale integrated circuits.[1] A disadvantage of the technique is that charge-induced damage,[2,3] such as side-wall etching, the creation of trenches, and changes in the layered material's electrical structure, can cause irreversible changes in the device properties. In order to avoid or to compensate for the non-uniform accumulation of positive and negative charges near the treated surface,[4] a number of low-damage processes have been proposed.[5–7] The most promising of these processes uses high-energy (10–1000 eV) beams of fast atoms and radicals for surface treatment.[8–10] The advantage of this method compared with the others is that the beam charge neutralization occurs away from the sample. In the continuous mode only the positive ions can be extracted from the generally electropositive plasma, while the negative ions, such as Cl^-, F^-, and O^-, whose presence at the surface can significantly accelerate the etching process, remain inside the source because of sheath formation near the extraction electrode.

It is possible to extract the negative ions from a pulse-time modulated plasma during the afterglow periods at the point when the sheath collapses to near zero. This time $t = t_0$ at which this collapse occurs is given by the formula[11,12]

$$\frac{n_-(t_0)}{n_e(t_0)} = \left(\frac{M_+}{2\pi m_e}\right)^{1/2}. \tag{1}$$

Here n_- and n_e are the negative ion and electron densities and M_+ and m_e are the positive ion and electron masses. As the electron temperature decreases during the plasma-off time, the density of negative ions becomes larger because the attachment cross section of the electrons to positive ions and neutral radicals increases. If the magnitude of $dn_-/dt = K_{att}n_e n_a - K_{rec}n_+ n_-$ is larger than zero, where K_{att} and K_{rec} are the electron attachment and positive-negative recombination rate constants, respectively, and n_a is the gas density, then negative ions are able to escape the discharge volume with low energy and then be accelerated with a dc or radio-frequency (rf) bias applied to the sample.[13] Electrodeless ex-

traction is the simplest method for negative ion beam formation, but this does not allow for the control of a number of source output parameters, such as the negative ion energy at the source outlet, the ratio of negative ions to positive ions, or the beam angular distribution.

This letter reports on a different method of negative beam formation that has potential application to neutral-beam etching. In particular, we obtain a flux of fast neutral atoms with narrow energy and angular distribution from an initially negative ion beam which is extracted from the discharge volume with energy of 10–500 eV and then neutralized. By increasing the pulse frequency of the antenna voltage to 20 kHz and applying a synchronized bipolar potential to the accelerating electrodes, it is possible to produce a high-density negative ion beam whose energy level is determined by the amplitude of the extraction potential. During the discharge, a positive potential is applied to the extraction electrode and a negative potential to the focusing electrode. In the afterglow period, these potentials are switched, allowing high-energy negative ions to escape the source. The lower and upper limits of the bipolar extraction potential on the two electrodes can be varied independently, so that the ratio of negative ions to positive ions in the resulting beam can be adjusted from 0% to 100%.

Figure 1 shows the source of energetic neutrals, as well as the potential distribution in the vicinity of its electrodes. To generate a high-density (10^{13} cm^{-3}) inductively coupled plasma inside a quartz chamber, pulsed rf power from an ENI A1000 amplifier was delivered to a three-turn antenna through a π-type matching network. The pulsing frequency was determined by a Hewlett Packard 8657B signal generator, which generated 13.56 MHz low-voltage pulses interrupted by control signals V_{ref} from an external function generator. Ion extraction was performed by a system of grid electrodes. The extraction voltage V_1 determined the plasma potential during the discharge and, consequently, the energy of the positive ions.[14] The degree of beam alignment was controlled by the negative component of the voltage V_2 on the focusing electrode.[15] Potentials V_1 and V_2 were kept in opposing phases in order to provide favorable conditions for the extraction of positive ions during the discharge and of negative ions during the afterglow. A hidden analytical quad-

a)Electronic mail: oleksiy@skku.edu.
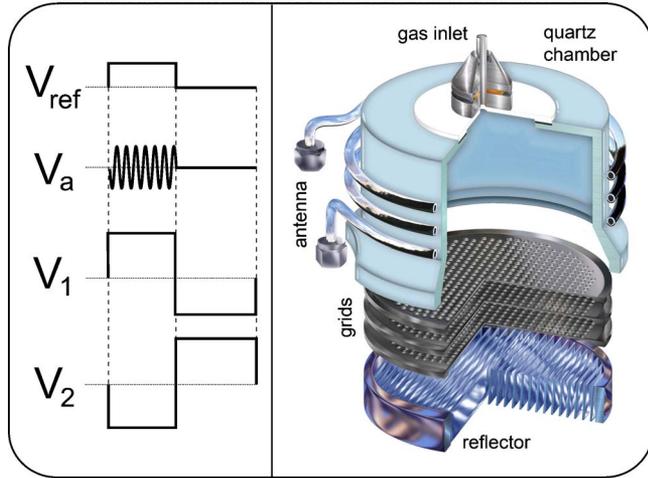b)Electronic mail: gyyeom@skku.edu.

94, 231502-1

FIG. 1. (Color online) The source of high-energy neutrals derived from inductively coupled plasma and voltage distribution on antenna and extraction electrodes. V_{ref} is the synchronizing signal.

FIG. 2. Energy distribution of O^- and O_2^- ions, indicating a high-energy beam formation with an increase in modulation frequency.

rupole mass spectrometer with an integrated energy analyzer was used to study the ion energy distribution and the beam composition. We directed the resulting beam of negative and positive ions, which had been produced in the required proportion, to a set of polished metal plates, where a beam of neutrals was formed during scattering under a grazing angle of 5° due to Auger and resonant neutralizations.

Although 97% of the scattering ions are neutralized, the remaining flux of charged ions does not significantly charge the sample surface, because it consists of oppositely charged particles whose ratio can be controlled by the magnitude of the focusing potential. It is possible to achieve a significant level of beam charge compensation before the ions collide with the reflector when equal currents of negative and positive ions averaged over time are generated.

The pulsing frequency, which determines the periods of negative and positive ion extraction, must on the one hand be high enough to avoid negative ion depletion at the afterglow but on the other hand must not exceed the limit beyond which the electron temperature cannot drop to the required level for the electron attachment. As our experiments showed, when the pulsing frequency was set to 20 kHz a large number of negative ions remained in the plasma until the next discharge. At lower frequencies, however, negative ions left the source before the afterglow period ended.

Figure 2 shows the energy distribution of O^- and O_2^- ions extracted from the oxygen plasma. In continuous mode (pulsing frequency $f_p=0$) only a low-energy peak was observed, which was attributed to the presence of negative ions with sufficient energy to overcome the sheath potential. The energy of these ions was too low for processing and could not be controlled by the acceleration voltage on the extraction electrode. High-energy O^- and O_2^- ions could be obtained only in the pulsed mode during the afterglow. When the sheath collapsed at approximately 10^{-5} s, the ratio n_-/n_e increased, so, due to diffusion, both negative and positive ions moved toward the extraction grid. There, the positive ions were repelled back to the plasma by the potential difference between the electrodes, while negative ions were accelerated by the same potential toward the source outlet. At higher pulsing frequencies, the number of ions extracted with the controlled energy increased, indicating the presence of a
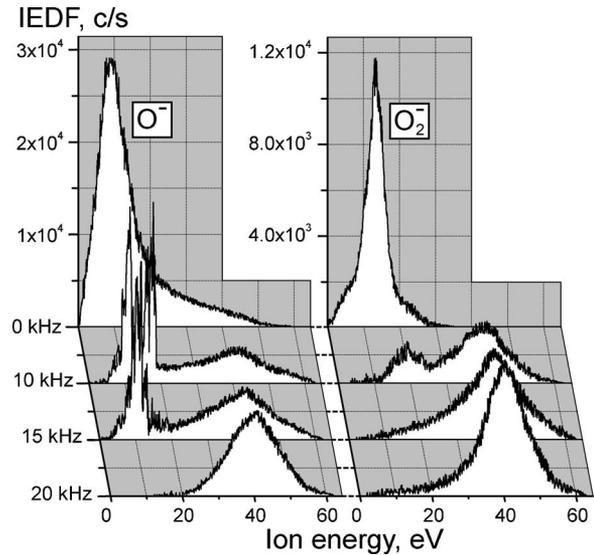
higher negative ion concentration in the source at the time of the next discharge initiation. The intensity of low-energy negative ions, which were generated during the glow, decreased as the pulsing frequency increased, down to a minimum at 20 kHz. Since the number of slow O_2^- ions decreased faster than the number of slow O^- ions, we assumed that the disappearance of the low-energy peak during the increase in pulsing frequency was connected to the fact that the ions required more time to travel through the sheath in order to be extracted.

The coexistence of negative and positive ions allows the total beam charge to be zero, so that the positive and negative charges can nullify each other on the treated surface. Figure 3 shows the resulting ion current measured between the source and the reflector as a function of the beam energy as the modulation frequency was increased from 0 to 20 kHz. For clarity, we kept the acceleration and focusing potentials for the negative ion extraction constant and varied only the positive ion energy from 50 to 200 eV.

Figure 4 shows how the energy profiles of the positive and negative ions extracted from the pulsed plasma changed as the acceleration voltage was increased from 40 to 100 V.
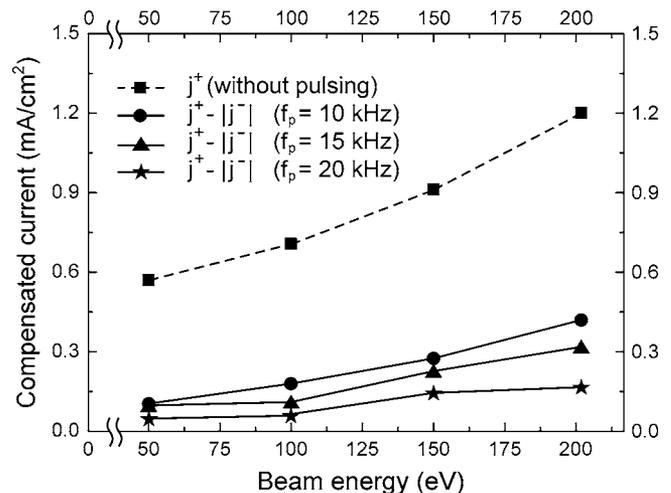

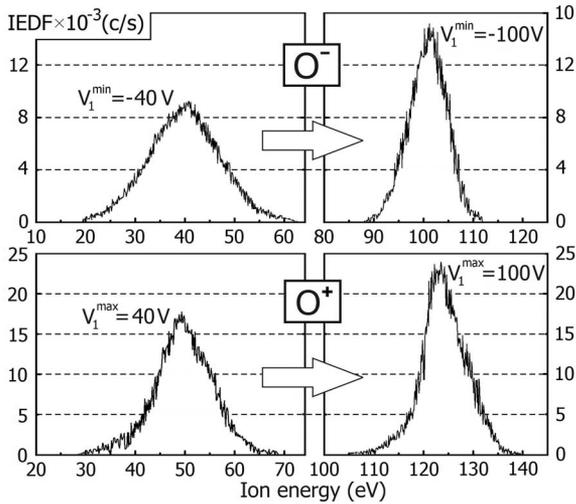FIG. 3. Compensated current as a function of oxygen ion beam energy.

FIG. 4. Evolution of the energy profiles for positive and negative ions extracted from the pulsed plasma. Acceleration voltage was increased from 40 to 100 V.

The reason that the beam intensity grow as the potential difference ΔU between the extraction and focusing electrodes increases is explained in Vozniy et al.,[15] which also provides the solution of the ion trajectory equation,

$$\frac{2\Delta U}{1+(y')^2}y'' + E_x y' - E_y = 0. \tag{2}$$

The solution gives the trajectories of the negative and positive ions located close to the x-axis (which is parallel to the axis of the extraction aperture) when ΔU becomes large. Here the y-axis is parallel to the plane of the extraction grid. $E_x(x,y)$ and $E_y(x,y)$ are the components of electric fields $y' = dy/dx$ and $y'' = d^2y/dx^2$.

The average energy of the negative ions is always equal to the extraction grid potential V_1. At the same time, however, the energy of the positive ions is shifted toward higher values because of the influence of the plasma potential V_p. When positive ions travel through the sheath, they gain an additional energy determined by the Bohm criterion

$$\Delta E = e(V_p - V_1) = eT_e \ln\left(\frac{m_i}{2\pi m_e}\right)^{1/2}, \tag{3}$$

where T_e is the electron temperature and m_e and m_i are the electron and ion mass, respectively.

In summary, we extracted negative ions from a low-frequency modulated plasma with the required j^-/j^+ ratio and the specific energy for positive and negative ions by applying a bipolar acceleration potential to the grid electrodes, thereby facilitating a charge-free etching process with increased neutralization efficiency. The resulting beam, with its negative and positive ions of different energies, has a number of advantages for the etching process compared with the conventional sample treatment, as the energetic chemically active negative ions can be used for surface bombardment, and the low-energy positive ions will neutralize the surface charge without damaging the sample.

[1] J. W. Lee, M. W. Devre, B. H. Reelfs, D. Johnson, N. Sasserath, F. Clayton, D. Hays, and S. J. Pearton, J. Vac. Sci. Technol. A **18**, 1220 (2000).
[2] J. Yamamoto, T. Kawasaki, H. Sakaue, S. Shingubara, and Y. Horiike, Thin Solid Films **225**, 124 (1993).
[3] N. Fujiwara, T. Maruyama, and M. Yoneda, Jpn. J. Appl. Phys., Part 1 **35**, 2450 (1996).
[4] J. C. Arnold and H. H. Sawin, J. Appl. Phys. **70**, 5314 (1991).
[5] F. Shimokawa, H. Tanaka, Y. Uenishi, and R. Sawada, J. Appl. Phys. **66**, 2613 (1989).
[6] K. P. Giapis, T. A. Moore, and T. K. Minton, J. Vac. Sci. Technol. A **13**, 959 (1995).
[7] T. Ono, H. Kashima, S. Hiraoka, and K. Suzuki, J. Vac. Sci. Technol. B **9**, 2798 (1991).
[8] S. Panda and D. J. Economou, J. Vac. Sci. Technol. A **19**, 398 (2001).
[9] D. H. Lee, J. W. Bae, S. D. Park, and G. Y. Yeom, Thin Solid Films **398**, 647 (2001).
[10] B. J. Park, K. S. Min, S. D. Park, J. W. Bae, O. Vozniy, and G. Y. Yeom, Solid State Phenom. **124–126**, 275 (2007).
[11] S. Samukawa, Appl. Phys. Lett. **68**, 316 (1996).
[12] M. Lieberman and A. Lichtenberg, *Principles of Plasma Discharges and Material Processing* (Wiley, New York, 2005).
[13] H. Ohtake and S. Samukawa, Appl. Phys. Lett. **68**, 2416 (1996).
[14] K. H. Bai, C. K. Choi, and H. Y. Chang, Plasma Sources Sci. Technol. **13**, 662 (2004).
[15] O. Vozniy, K. Polozhiy, and G. Y. Yeom, J. Appl. Phys. **102**, 083306 (2007).