東北大学機関リポジトリ
TOUR
Tohoku University Repository

Energy distribution and formation mechanism of fast atoms in a fast atom beam

著者	桑野　博喜
journal or publication title	Journal of applied physics
volume	72
number	1
page range	13-17
year	1992
URL	http://hdl.handle.net/10097/35250

doi: 10.1063/1.352173

Energy distribution and formation mechanism of fast atoms in a fast atom beam

Fusao Shimokawa and Hiroki Kuwano
NTT Interdisciplinary Research Laboratories, Nippon Telegraph and Telephone Corporation, Musashino-shi 3-9-11, Tokyo 180, Japan

(Received 17 October 1991; accepted for publication 19 March 1992)

The energy distribution of fast atoms produced by modifying a McIlraith-type fast atom beam (FAB) source is measured using a retarding-field energy analyzer coupled with an ionization chamber. The energy distribution mainly depends on the gas pressure of the FAB source. When the gas pressure is low, the main energy distribution peak coincides with the discharge voltage, so the acceleration energy of the ions is retained when they become fast atoms. When the gas pressure is high, the peak energy appears at about 25% of the discharge voltage and has a broader spectrum. The energy distribution is almost completely independent of the discharge voltage, discharge current, and the geometry of the source anode. The fast atoms are mainly produced by resonant charge-transfer collisions inside the source. These collisions are dominant over electron-ion recombinations for FAB formation.

I. INTRODUCTION

A fast atom beam (FAB) is defined as energetic neutral particles ranging in energy from a few electron volts to several thousand electron volts. FAB bombardment can be used instead of ion-beam bombardment in sputter deposition,[1,2] etching,[3,4] and surface analysis.[5] Using neutral particles has the important advantage that the processing is independent of the material's conductivity, since the specimen surface does not become charged.[1–4] FAB techniques are also better for forming fine patterns because there is little repulsion between particles in the beam, which causes beam spreading in an ion beam. Furthermore, an FAB source does not need a hot filament to induce plasma and it has a long operational lifetime when used with reactive gases.[6]

The fundamental characteristics of an FAB source, such as beam current, beam neutralization, and energy distribution, are critical in many applications. However, there have been few reports in this area[7,8] and no one has measured the energy distribution of the energetic neutral particles emitted by an FAB source.[9]

This paper reports the energy distribution of the fast atoms and residual ions in a beam emitted by an FAB source, measured using a retarding-field energy analyzer coupled with an ionizer. Possible mechanisms for the formation of energetic neutral particles are also discussed.

II. EXPERIMENTAL PROCEDURES

A. FAB source

The FAB source used for this experiment is schematically shown in Fig. 1. It consists of a ring anode, deflectors, and a tubular cathode 70 mm long and 40 mm in diameter. The anode is almost exactly in the middle of the tubular cathode. The deflectors are outside one end of the cathode, which has a beam-emitting aperture 5 mm in diameter. The other end has an inlet for introducing the gas molecules that will become the energetic neutral beam. An axial magnctic field of about 500 G is applied to the cathode.

When a positive high voltage is applied to the ring anode, cold-cathode discharge occurs between the anode and cathode. Electrons produced during the glow discharge oscillate at a high-frequency backward and forward through the ring anode (Barkhausen–Kurtz oscillation).[10] The axial magnetic field increases the path length of the electrons by making them travel in a helix about the axis. A large number of ions are produced when these electrons collide with the gas molecules. These ions are then accelerated towards the ends of the cathode. Most of these ions are converted into fast atoms via two processes: the ions are neutralized in resonant charge-transfer collisions with gas molecules, or recombine with low-energy electrons near the cathode ends. The fast atoms thus produced are emitted through the aperture in one end of the cathode. Most of the residual ions passing through the aperture are removed by the deflectors, leaving a pure beam of fast atoms.

B. Energy analyzer

The energy analyzer, schematically shown in Fig. 2, consists of an ionization chamber, retarding electrodes, and a Faraday cup. The two mesh electrodes used as retarding electrodes produce a uniform electric field with about 80%–90% transparency. The analyzer is completely surrounded by a grounded screen to exclude any stray charged particles.

Energy distributions of the residual ions and fast atoms were measured with the apparatus shown in Fig. 2. When the FAB source deflectors and the ionization chamber are used, the residual ions are removed from the beam, allowing the energy distribution of only the fast atoms to be measured. Some of the fast atoms are ionized in the ionization chamber and then pass into an energy analyzer of the retarding potential type. When the FAB source deflec-

 0021-8979/92/130013-05$04.00 © 1992 American Institute of Physics

Downloaded 15 Oct 2008 to 130.34.135.158. Redistribution subject to AIP license or copyright; see http://jap.aip.org/jap/copyright.jsp

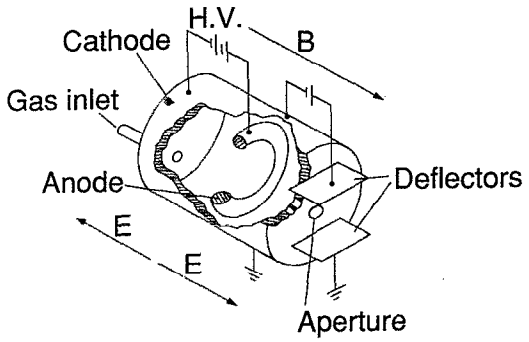

FIG. 1. Schematic diagram of FAB source.

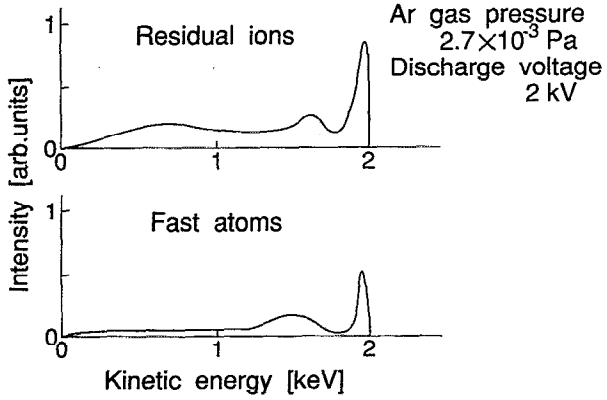

FIG. 3. Energy distributions of residual ions and fast atoms.

tors and the ionization chamber are not used, the energy distribution of the residual ions in the beam can be measured. The beam entering the analyzer contains fast atoms and residual ions. However, since the ionization chamber is not used, the fast atoms are not ionized. Thus, they do not contribute to the current entering the Faraday cup. In this way, the energy distribution of only the residual ions can be measured. Using these two measuring conditions allows us to measure the energy distribution of both residual ions and the fast atoms in the beam emitted from the FAB source. The current in the Faraday cup, i, is recorded with an X-Y recorder as a function of retarding voltage v, and the corresponding energy spectrum is obtained by differentiating the curve $(-di/dv)$.

III. EXPERIMENTAL RESULTS

The energy distributions of the residual ions and fast atoms are compared in Fig. 3. In both cases, the main peak in the energy distribution coincides with the discharge voltage of the FAB source. This suggests that the kinetic energy of the original ions is retained when they become fast atoms. Thus, the fast atom beam is produced by collisions with no energy losses. Therefore, fast atoms are probably formed from resonant charge-transfer collisions and electron-ion recombinations near the beam-emitting aperture. Since the energy distributions of the residual ions and the fast atoms, shown in Fig. 3, are so similar, in the remaining experiments only the ion beam (residual ions in the beam) was measured.

The energy distributions for two different gas pressures are compared in Fig. 4. In both cases, the discharge voltage was about 2.1 kV. For an Ar gas pressure of 2.7×10^{-3} Pa, the beam neutralization coefficient (proportion of energetic neutral particles in the beam) is about 60%, so the beam only contains 40% residual ions and the kinetic energy of the fast atoms is nearly equivalent to the discharge voltage. For a pressure of 8×10^{-2} Pa, on the other hand, the beam neutralization coefficient is 95%. The energy spectrum is broader with a half-width of 600 eV, and the peak appears at about 25% of the discharge voltage. Therefore, the potential distribution inside the FAB source when the gas pressure is high, is very different from when the gas pressure is low, and the number of ions formed in the lower-potential space increases. Furthermore, the kinetic energy of these ions is retained when they become fast atoms.

The energy distributions for various discharge voltages are compared in Fig. 5. In each case, the main peak occurs at an energy equivalent to 94%–98% of the discharge voltage and the half-widths of the main peaks are all about 100 eV. A much smaller peak appears at about 80%–85% of the discharge voltage, and lower energy peaks at 25%–30% are also just visible in the 1.5 and 2.1 kV spectra. The

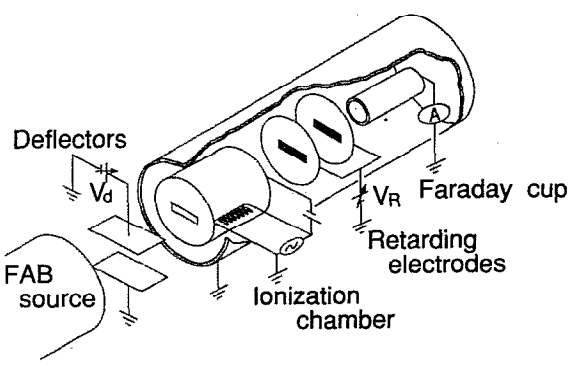

FIG. 2. Schematic diagram of energy analyzer.

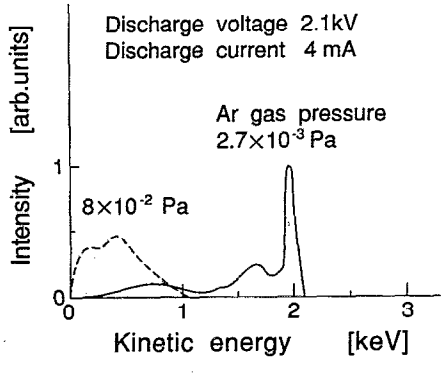

FIG. 4. Energy distribution of fast atoms at two Ar gas pressures.

Downloaded 15 Oct 2008 to 130.34.135.158. Redistribution subject to AIP license or copyright; see http://jap.aip.org/jap/copyright.jsp

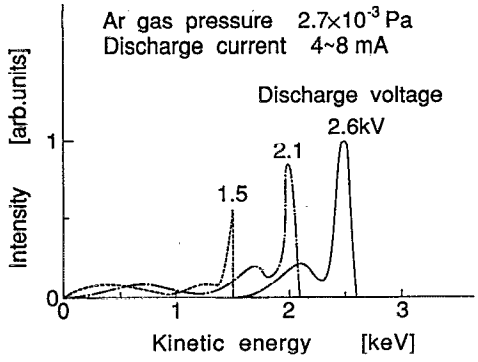

FIG. 5. Energy distribution of fast atoms at various discharge voltages.

ratio of the side peak energy to main peak energy is almost the same in each case. Consequently, the energy distribution of fast atoms is closely related to the potential distribution in the FAB source.

The energy distributions for various discharge currents are compared in Fig. 6, for a constant discharge voltage of 2.1 kV. Clearly, the fast atom intensity is weaker for a smaller discharge current and stronger for a later one. The results show that the number of fast atoms emitted from

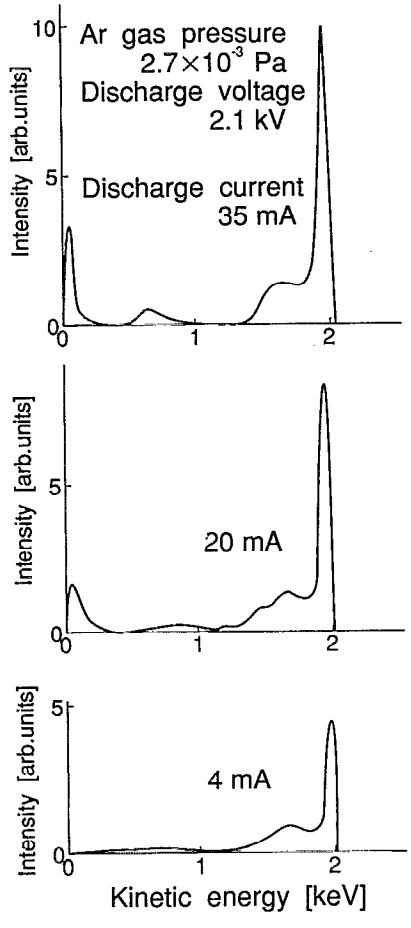

FIG. 6. Energy distribution of fast atoms at various discharge currents.

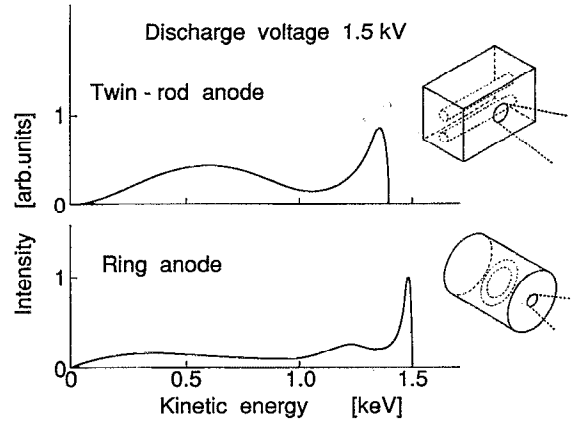

FIG. 7. Energy distribution of fast atoms for two different electrode configurations.

the source increases as the discharge current increases, but the energy distribution of the fast atoms is constant. In addition, a low energy peak is also visible when the discharge current is high, but the reason for this is not yet clear.

The energy distributions are compared in Fig. 7 for different FAB source electrode configurations, for a constant FAB source discharge voltage of 1.5 kV. The energy distributions for a twin-rod anode configuration and a ring anode are similar, indicating that the potential distributions of the source are almost the same.

The energy distributions for various gases (Ar, CF_4, O_2, and O_2/CF_4) are compared in Fig. 8.[9] Since all the main peaks nearly coincide the energy distribution is virtually independent of the type of gas.

IV. DISCUSSION

The results of this study show that the energy distribution of fast atoms produced by an FAB source is almost completely independent of discharge voltage, discharge current, electrode configuration, and the gas. The energy distribution almost entirely depends on the pressure of the gas in the FAB source. Therefore, we next look at the influence of ion-gas collisions on the energy distribution of fast atoms.

In general, when ions reach the boundary between glow and the ion sheath in a source, they have the same kinetic energy as the sheath voltage. These ions are then accelerated toward the beam-emitting aperture and undergo collisions either with or without charge transfer. These collisions have a strong effect on the glow discharge process since they modify the energy distribution of the particles striking the target and substrate.[11] In charge-transfer collisions, the kinetic energy of the ions is retained when they become energetic neutral particles, i.e., fast atoms.[12] Among the charge-transfer collisions, symmetrical resonant charge transfer is the most efficient process.[13] This process has a larger cross section (and thus a larger probability) when its accelerated ions and thermal-energy neutral are the same atomic or molecular species.

Downloaded 15 Oct 2008 to 130.34.135.158. Redistribution subject to AIP license or copyright; see http://jap.aip.org/jap/copyright.jsp

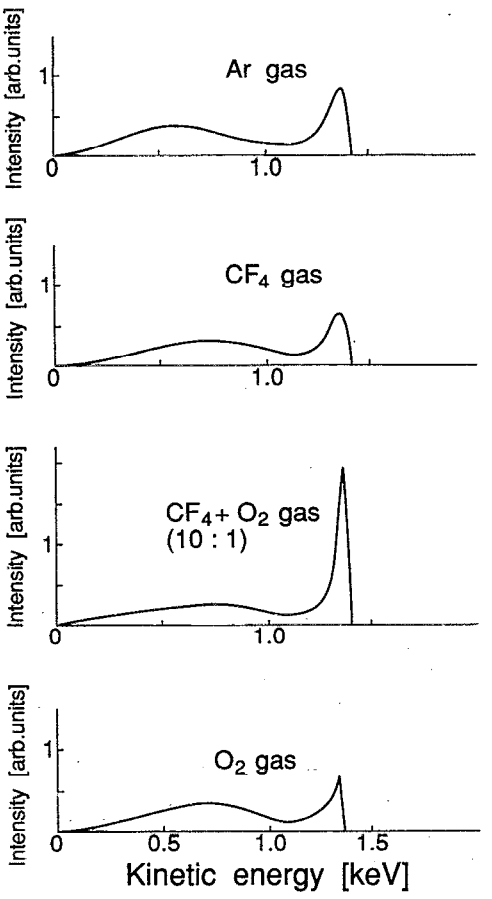

FIG. 8. Energy distribution of fast atoms for various gases.

Let N_0 be the number of ions accelerated toward the cathode. Then N, the number of ions that reach the aperture with full energy, is proportional to the probability that the ions will travel a distance, L, without collision. Figure 9 shows N/N_0 [$=\exp(-L/\lambda)$] vs L/λ, where L/λ is the ratio of the cathode sheath thickness to the mean free path of the ions in the source. The mean free path λ for charge transfer between accelerated ions and thermal-energy neutrals is given by

$$\lambda = 1/n\,Q, \tag{1}$$

where n is the density of neutrals (the number per m^3) and Q is the cross section for charge-transfer collision between accelerated ions and thermal-energy neutrals. Given a gas pressure P_0 in pascals, the density of neutral molecules n, is

$$n = 2.47\times 10^{20}\,P_0. \tag{2}$$

The gas pressure of the source, P_0, can be roughly estimated from the gas pressure P_1 in the vacuum chamber, the conductance of the beam-emitting aperture, and the pumping speed. The gas pressures in the source are 0.5 and 15 Pa for chamber pressures P_1 of 2.7×10^{-3} and 8×10^{-2} Pa. From Eqs. (1) and (2), the mean free paths in these two cases are about 40 and 1.4 mm. The cross section Q for charge exchange between Ar ions and Ar neutrals is about 20.0×10^{-20} m^2 at a 1 keV ion energy.[13] Furthermore, in a typical ion source, the sheath thickness L is between 0.1 and 1 mm.[11] In these experiments, we assumed L to be 1.0 mm. For chamber pressures of 2.7×10^{-3} and 8×10^{-2} Pa, L/λ is as indicated in Fig. 9.

When the gas pressure is low ($P_1 = 2.7 \times 10^{-3}$ Pa), the ions rarely collide until they reach the beam-emitting aperture, and ions having almost the same kinetic energy as the discharge voltage are accelerated toward it. Ion neutralization probably occurs near the aperture through charge-transfer collisions with no energy losses, or through the ions recombining with low-energy electrons. When the gas pressure is high (8×10^{-2} Pa), the accelerated ions collide frequently with the gas molecules and lose energy. These charge-transfer collisions and recombinations create fast atoms with lower energy. This hypothesis is confirmed by the experimental results shown in Fig. 4.

Additional experiments were performed to investigate how energetic neutral particles are produced. A filament was attached to the outside of the beam emitting aperture of the FAB source, and we estimated the proportions of the electron-ion recombinations that result from residual ions emitted by the source and from thermal electrons. The beam current density (ion equivalent) and beam neutralization coefficient, both gradually increase as the filament current is increased, as shown in Fig. 10. The neutralization coefficient increases by about 10%; therefore about 10% of the ions in the beam were neutralized as a result of residual ions recombining with thermal electrons emitted by the filament. This suggests that only a small percentage of beam neutralization is due to electron-ion recombination process. Therefore, the high neutralization coefficient (when the filament current is zero, the neutralization coefficient is about 70% for a gas pressure of 3×10^{-2} Pa) of the FAB source suggests that symmetrical resonant charge-transfer collisions are dominant over electron-ion recombinations in the formation of fast atoms in the FAB.

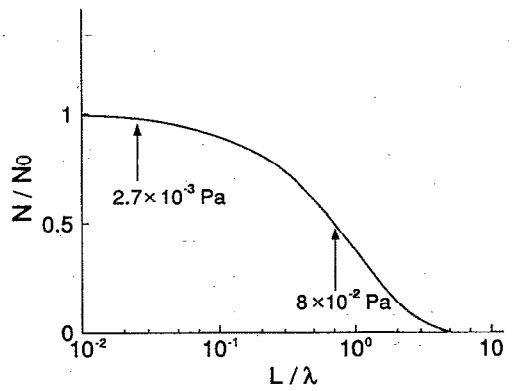

FIG. 9. Proportion of ions that reach the cathode electrode with full energy as function of L/λ.

Downloaded 15 Oct 2008 to 130.34.135.158. Redistribution subject to AIP license or copyright; see http://jap.aip.org/jap/copyright.jsp

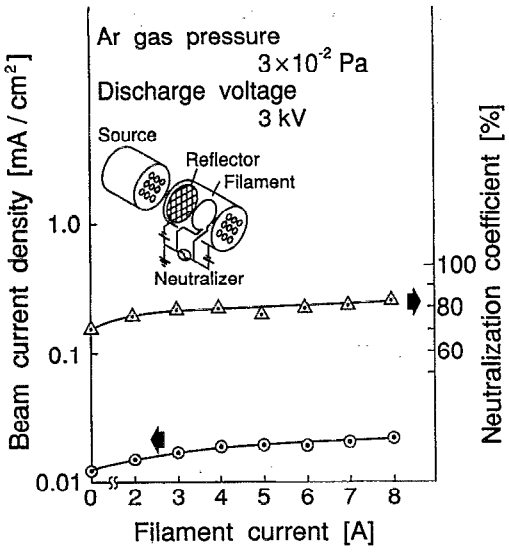

FIG. 10. Dependence of beam current density (ion equivalent) and beam neutralization coefficient (proportion of energetic neutral particles in beam) on filament current. The increase in neutralization coefficient corresponds to an increase in the proportion of electron-ion recombination in the fast atom formation.

V. CONCLUSION

The energy distribution of fast atoms in an FAB is almost completely independent of the discharge voltage, discharge current, electrode configuration, and gas. It depends almost entirely on the gas pressure of the FAB source. When the gas pressure is low ($L < \lambda$), the main peak of the distribution coincides with the discharge voltage. This suggests that the fast atoms are formed by both charge transfer collisions and by the accelerated ions recombining with low-energy electrons near the beam-emitting aperture of the FAB source. When the gas pressure is high ($L > \lambda$), the peak energy level is about 25% of the discharge voltage and has a broader spectrum. Fast atoms are mainly formed by charge-transfer collisions, which are dominant over electron-ion recombination.

ACKNOWLEDGMENT

The authors would like to thank Kazutoshi Nagai for his encouragement and valuable discussions.

[1] H. Kuwano and K. Nagai, J. Vac. Sci. Technol. A **3**, 1809 (1985).
[2] F. Shimokawa, H. Kuwano, and K. Nagai, *Proceedings of the 9th Symposium on Ion Sources and Ion-Assisted Technology*, edited by T. Takagi (Institute of Electrical Engineers of Japan, Tokyo, 1985), p. 467.
[3] H. Kuwano and F. Shimokawa, J. Vac. Sci. Technol. B **6**, 1565 (1988).
[4] F. Shimokawa, H. Tanaka, Y. Uenishi, and R. Sawada, J. Appl. Phys. **66**, 2613 (1989).
[5] H. Kuwano and K. Nagai, *Ion Mass Spectrometry, SIMS IV*, edited by A. Benninghoven, J. Okano, R. Shimizu, and H. W. Werner (Springer, Berlin, 1984), p. 448.
[6] P. J. Revell and A. C. Evans, Thin Solid Films **86**, 117 (1981).
[7] J. Franks, J. Vac. Sci. Technol. **16**, 181 (1979).
[8] M. Khorossany and R. K. Fitch, Vacuum **27**, 159 (1977).
[9] F. Shimokawa, H. Kuwano, and K. Nagai, *Proceedings of the 10th Symposium on Ion Sources and Ion-Assisted Technology*, edited by T. Takagi (Institute of Electrical Engineers of Japan, Tokyo, 1986), p. 101.
[10] A. H. McIlraith, Nature (London) **212**, 1422 (1966).
[11] B. N. Chapman, *Glow Discharge Process* (Wiley, New York, 1980).
[12] J. Richards, Vacuum **34**, 599 (1984).
[13] R. S. Robinson, J. Vac. Sci. Technol. **16**, 185 (1979).

Downloaded 15 Oct 2008 to 130.34.135.158. Redistribution subject to AIP license or copyright; see http://jap.aip.org/jap/copyright.jsp