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August 1996
Presented at the
10th International Conference on Ion Beam Modification of Materials,
Alburquerque, NM,
September 1–6, 1996,
and to be published in
the Proceedings

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This work was supported in part by the Director, Office of Energy Research, of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098, and by the Electric Power Research Institute under Award Number 8042-03.

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Ref No. 272

HIGH ENERGY IMPLANTATION WITH HIGH-CHARGE-STATE IONS IN A VACUUM ARC ION IMPLANTER

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Abstract

Ion implantation energy can in principal be increased by increasing the charge states of the ions produced by the ion source rather than by increasing the implanter operating voltage, providing an important savings in cost and size of the implanter. In some recent work we have shown that the charge states of metal ions produced in a vacuum arc ion source can be elevated by a strong magnetic field. In general, the effect of both high arc current and high magnetic field is to push the distribution to higher charge states – the mean ion charge state is increased and new high charge states are formed. The effect is significant for implantation application – the mean ion energy can be about doubled without change in extraction voltage. Here we describe the ion source modifications, the results of time-of-flight measurements of ion charge state distributions, and discuss the use and implications of this technique as a means for doing metal ion implantation in the multi-hundreds of keV ion energy range.

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1. Introduction

Metal ion beams formed by a vacuum arc ion source [1-3] have been used to carry out ion implantation for an increasingly diverse range of surface modification applications [4]. The charge state distributions of the metal ions produced in vacuum arc plasmas and formed into beams in vacuum arc ion sources generally contain ionization states from Q = 1+ to about 5+, with a mean charge state Q = 1+ to 3+, depending on the metal used [3,5]. Since the ion energy is equal to the extraction voltage multiplied by the charge state ($E_i = Q_i V_{extr}$), the beam energy spectrum consists of several discrete peaks at multiples of the extraction voltage with a mean of several times the extraction voltage. An upper limit to the extraction voltage is set by the available electrical system and ion source design, and it is difficult to operate conveniently at voltages much over 100 kV. There would be advantage therefore in having upward control over the ion charge states. The ion energy could then be increased by increasing the charge state rather than by increasing the implanter operating voltage, providing a savings in cost and size of the implantation facility.

Experiments by a number of workers have shown that vacuum arc ion source performance can be modified in several different ways by the application of a magnetic field to the arc region in which the plasma is formed [6-13]. In particular, the ion charge states can be increased by a magnetic field of one to several kilogauss. We have explored the charge state distribution of ions produced in a vacuum arc ion source, with and without magnetic field and as a function of magnetic field, for many different metallic elements [14,15].

Here we outline the ion source modifications and summarize the ion charge state distribution measurements made. The significance of this mode of operation to high energy ion implantation is discussed.

2. Experimental

A multi-cathode vacuum arc ion sources was modified to include a magnetic field established by a small, pulsed field coil mounted inside the anode region near the cathode, producing a field of about 17 Gauss/amp. The coil was powered either by an additional external power supply or by configuring the arc power supply to serve a dual purpose (arc discharge plus field coil in series). The magnetic field is more-or-less confined to the cathode-anode region and there is little influence of the field on the ion extraction and beam formation process. The coil and the field volume are small, simplifying both the ion source modifications needed and the electrical power requirements. A schematic of the ion source with the coil in place is shown in Figure 1. In this modification of the source the internal cylindrical surface of the coil mandrill serves as arc anode. The charge state distribution of the extracted ion beam was measured by a time-of-flight system [16]. Background gas pressure was in the 10^{-6} Torr range.

3. Results and Discussion

Typical results obtained are shown in Figure 2. Here the TOF charge state spectra (electrical current into a Faraday cup) for an aluminum ion beam is shown for the case of no applied magnetic field and for an applied field of strength 3.75 kG; the arc current was 220 A in both cases. The peaks present in the spectrum are from Al^{+}, Al^{2+} and Al^{3+}, and the mean charge state (referred to particle current) is 1.7 for B = 0 and 2.4 for B = 3.75 kG. (Note that for beams of multiply charged ions it is important to distinguish between electrical current i_e and particle current i_p, since $i_p = i_e/Q$; a Faraday cup measures electrical current, but for ion implantation work it is the particle current that is important). With magnetic field the triply-ionized Al^{3+} component increases greatly while the singly ionized Al^{+} component is reduced almost to zero, and in terms of implantation

energy, the aluminum ion energy component at $3V_{extr}$ now dominates.

Figure 3 shows the TOF charge state spectrum for a Mo ion beam for the case of a 3.75 kG magnetic field. Here the dominant peak is Mo^{4+}, and Mo^{5+} is present significantly. The mean charge state, again referred to particle current, is 3.5.

We have measured similar data for many different metallic species for a wide range of magnetic field and arc current [14,15]. In general the effect is large; new high charge state components are created, and the mean charge state increases by a factor of up to as high as 2.5. The measurements show clearly that upward control of the metal ion charge states produced in the vacuum arc ion source can be provided by application of a magnetic field in the kilogauss range. There is a symbiotic effect between high field strength and high arc current; simultaneously increasing both has a greater effect on the charge state distribution than does raising one or the other alone.

These results are significant for implantation application, since the ion energy can be increased without increasing the extraction voltage. The upper limit of extraction voltage depends on the specific ion source design as well as on the available power supply system. We have operated as high as 100 kV [17]. By combining such high voltage operation with the charge state enhancement mechanism described here, metal ion implantation with a vacuum arc ion source implanter can be done at interestingly high energies. For example for the Al and Mo cases described above, the mean implantation energy can be 240 keV (Al) and 350 keV (Mo), with a significant fraction of the implantation at energies of 300 keV (Al) and 500 keV (Mo). Projected ranges [18] at these energies can be quite deep; for example Al at 300 keV has a range in Si of 5000 Å and Mo at 500 keV has a range of 2600 Å.

4. Conclusion

The charge states and hence also the energy of metal ion beams produced by a vacuum arc ion source can be increased by about a factor of two (or more or less, depending on the metal species employed) by a relatively ion source minor modification in which the arc is immersed in a magnetic field of magnitude up to several kilogauss. By operating the source near the high voltage limit of around 100 kV, energy components and mean beam energies of several hundred keV can be obtained. The corresponding range, or implantation depth, of metal ions can be up to several thousand angstroms, depending of course of the metal ion species and the substrate material.

Acknowledgements

That part of this work performed at LBNL was supported by the U.S. Department of Energy, Office of Energy Research, under Contract No. DE-AC03-76SF00098, and by the Electric Power Research Institute under Award Number 8042-03. One of us (EMO) was supported at LBNL by the U.S. ILAB program.

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Figure Captions

Fig. 1 Schematic of the arc region of the modified ion source showing the small, pulsed, magnetic field coil.

Fig. 2 Aluminum ion beam charge state spectrum (electrical current into a Faraday cup) for no applied magnetic field (upper oscillogram) and for an applied field of 3.75 kG (lower oscillogram). Arc current was 220 A, and the TOF timing was near the middle of the ~250 μs duration beam pulse.

Fig. 3 Molybdenum charge state spectrum for B = 3.75 kG, I_{arc} = 220 A.

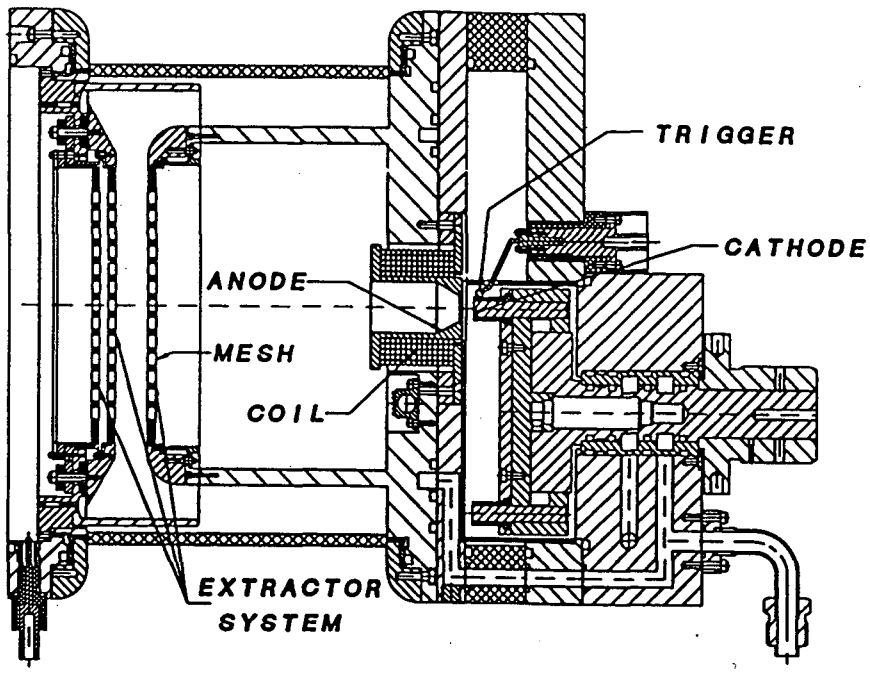

Figure 1

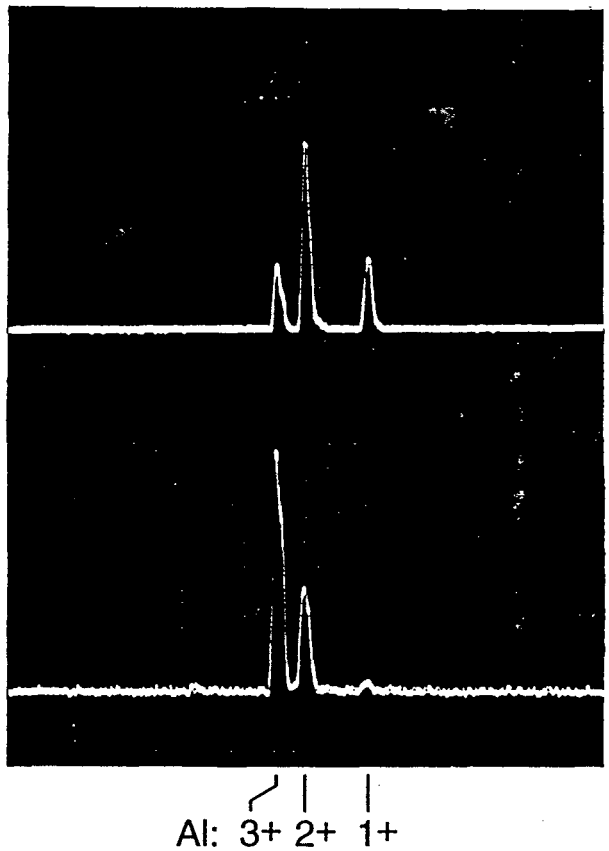

Figure 2

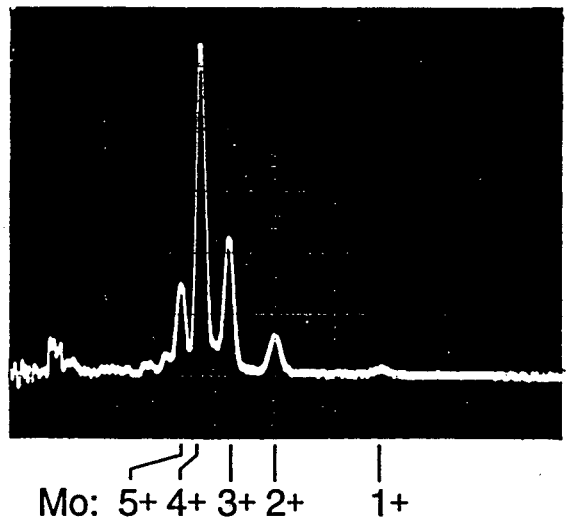

Figure 3

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