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METAL VAPOR VACUUM ARC ION SOURCES

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ABSTRACT

We have developed a family of metal vapor vacuum arc (MEVVA) high current metal ion sources. The sources were initially developed for the production of high current beams of metal ions for heavy ion synchrotron injection for basic nuclear physics research; more recently they have also been used for metal ion implantation. A number of different embodiments of the source have been developed for these specific applications. Presently the sources operate in a pulsed mode, with pulse width of order 1 ms and repetition rate up to 100 pps. Beam extraction voltage is up to 100 kV, and since the ions produced in the vacuum arc plasma are in general multiply ionized the ion energy is up to several hundred keV. Beam current is up to several Amperes peak and around 10 mA time averaged delivered onto target. Nearly all of the solid metals of the Periodic Table have been used to produce beam. A number of novel features have been incorporated into the sources, including multiple cathodes and the ability to switch between up to 18 separate cathode materials simply and quickly, and a broad beam source version as well as miniature versions. Here we review the source designs and their performance.

INTRODUCTION

The MEVVA ion source is a recently developed source in which a metal vapor vacuum arc is used as the means for generating the plasma medium from which ions are formed into an energetic ion beam. The key features of this kind of ion source, that distinguish it and that make it of interest for several different applications, are the very high beam currents of metal ions that can be produced. With this source pulsed beam currents of over 1 Ampere of metallic ions have been produced from a wide range of solid electrode materials.

The production of ions by the metal vapor vacuum arc plasma has been investigated by a number of authors for at least the last two decades [1-9]. One of the earliest attempts to incorporate the arc as the method of plasma production for use in an ion source is the work done as part of the Manhattan Project in World War II; however, this work was not pursued [10]. Revutskii et al [11], in 1968, investigated a cylindrically symmetric arc geometry; their configuration employed ion extraction through a hole in the cathode, and this work also seems to have not been pursued. More recently, sources of this kind have been investigated by Adler and Picraux at Sandia [12], Humphries and coworkers at New Mexico [13-14], Spaedtke and coworkers at Darmstadt [15-16], Zhang and co-workers at Beijing [17], and Ryabchikov at Tomsk [18], as well as by us as described here. These recent versions have produced impressive results.

To-date we have designed, constructed and operated a total of five different sources, MEVVAs I through V, as well as two different versions of miniaturized sources, MicroMEVVAs I and II. These different sources all have their different characteristics and performance parameters. We describe here the design and operation of these sources, and outline the applications to which they have been put.

DESCRIPTION OF THE SOURCES

The metal vapor vacuum arc is a prolific and efficient generator of dense metal plasma from a solid cathode material. A carrier gas is not required, and the metal plasma is created in the vacuum ambient. We have made use of a cylindrically-symmetric configuration of the geometry initially studied by Gilmour and Lockwood [19] and the LBL design has drawn upon this work. The quasi-neutral plasma that is created at the cathode spots on the front surface of the cathode plumes away from the cathode toward the anode; some of the plasma flows through a hole in the anode toward a set of extractor grids, where the ion component is separated from the plasma and the ion beam generated. The plasma consists entirely of material evolved from the cathode, since this is where the cathode spots are located. The plasma plume may be magnetically ducted, and the plasma size and density can to some extent be controlled.

Source Design

Several versions of the MEVVA concept have been developed at Lawrence Berkeley Laboratory (LBL). The basic philosophy and the general design features are exemplified by the MEVVA IIb source version, a schematic of which is shown in Figure 1. A portion of the plasma created at the cathode flows through a central hole in the anode, of diameter about 1 cm, and through a drift space of several centimeters to the extraction grids. Coolant is carried to the cathode and anode regions for heat removal. The cathode is a simple cylindrical plug of the material of interest, and is surrounded coaxially by a trigger electrode, separated from it by a thin (about 1 mm thick) alumina insulator. Since only the front surface of the cathode is eroded by the vacuum arc, it is not essential that the entire mass of the cathode be fabricated from the element required; thus the front surface of the cathode may be a thin wafer only several mm thick that has been secured to, for example, a stainless steel 'cathode mounting slug'. A magnetic field may be established in the arc region by a small field coil; the field is not necessary for the source operation, but serves to increase the efficiency (ratio of beam current to arc current) with which the source operates. The field can be varied up to several hundred Gauss; the effect of this field on the transport of the metal plasma generated at the cathode to the extractor grids has been studied in detail [20]. The ion beam formation electrodes ("extractor") configuration is a multi-aperture, accel-decel design. In the MEVVA IIb, the three grids are fabricated from about 0.030-inch thick stainless steel and have anywhere from 7 to 200 individual extraction holes, each of diameter in the range 1 to 5 mm.

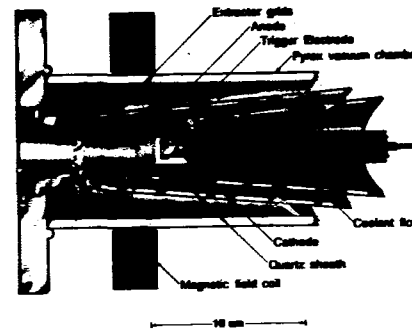

Fig. 1 Outline of the MEVVA ion source. The embodiment shown is that of MEVVA IIb. (CBB 862-1326A)

Source Operation

The source is operated in a pulsed mode with a pulse length typically in the range 0.1 - 5 msec and a repetition rate of up to about 100 pps depending on the mean power dissipation. Pulsed operation is not an inherent limitation of this kind of ion source, but has evolved because of the low duty cycle pulsed nature of the synchrotron for which the sources were initially designed and because of our power supply limitations.

The main parts of the electrical system are the extractor power supply, the arc power supply, and the trigger generator. Up to 100 kV dc is applied across the extractor grids, and extractor current is drawn when arc current is supplied to generate the metal plasma. The arc is initiated by a trigger pulse applied between the ion source trigger electrode and the cathode, at a level of order 10 kV and of some microseconds duration. The arc current is supplied by an LC pulse line of impedance typically an Ohm or so, or by a transistor switched high current power supply; typically the arc current is 100 - 200 A. A simplified schematic of the electrical circuitry used is shown in Figure 2.

MEVVA II: This is the version that has been used to describe the basic MEVVA design and performance, above, and that is shown schematically in Figure 1. The fully-assembled MEVVA IIb device is shown on the left in Figure 3. This is a single-cathode embodiment with a maximum extraction voltage of around 70 kV and an extractor diameter of 2 cm, which can readily produce a beam current of several hundred milliamperes in typical operation. The source has been described in more detail in refs [21-23].

MEVVA III: This embodiment is about the size of a closed fist. Its arc and extractor components are similar to those of the MEVVA II, and the source can deliver pulsed beams of hundreds of milliamperes. It resides entirely within the vacuum chamber, and because the cooling is quite minimal, so the average power dissipation capability is modest also - ie, the duty cycle is limited.

MEVVA IV: This version incorporates a number of novel features, the most significant of which is a multi-cathode design. A circular cathode assembly houses an array of 16 separate cathodes, and can be rotated so as to position any one of the 16 cathodes into the firing position. The rotation can be done rapidly and while under high vacuum. With this multiple cathode source, the operational time (time for which the source can operate continuously before it is necessary to replace the cathodes) is increased by a factor of 16, or alternatively, different cathode materials can be installed and the beam species switched simply and swiftly. The source operates at an extraction voltage of up to 100 kV. Note that this high extraction voltage, in conjunction with the fact that in general the ion species produced are multiply ionized with mean charge state up to Q = 3 (see below), means that the mean ion energy can be up to about 300 keV. This source is shown on the right in Figure 3; see [21,24] for more details.

That beams can be produced from 16 different cathode materials in a single experimental run is quite an advantageous operational feature, and makes possible a range of experiments that would otherwise be difficult or impossible. Characteristics of a wide range of beam species can be compared while maintaining the same experimental conditions.

MEVVA V: The MEVVA V is a "broad beam" ion source, retaining also the multiple cathode and high voltage features developed for the MEVVA IV. The extractor grids are 10 cm in diameter. For optimum beam optics, the plasma profile across the extractor aperture is kept relatively uniform by means of a samarium cobalt permanent magnet multipole structure located within a plasma expansion chamber. The multiple cathode feature was retained, and in fact the number of individual cathodes was increased to 18. The cooling of the source was increased and made more efficient, and so also the mean power dissipation capability. The source has been described in more detail in references [24,25] and a photograph of the partially-disassembled source showing the multicathode feature and the large area extractor is shown in Figure 4.

Fig. 3 MEVVA IIb (left), MEVVA IV with corona shield removed (right), and the MicroMEVVA II (foreground). (CBB 881-677)

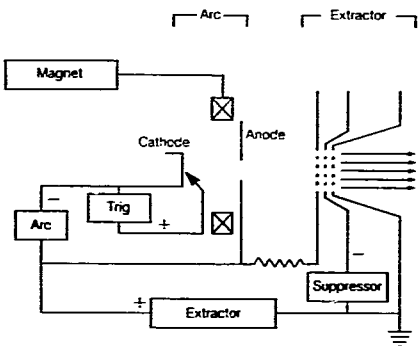

Fig. 2 Schematic of the electrical circuitry used. (XBL 858-9895A)

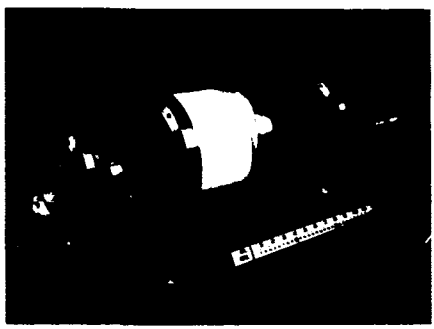

Fig. 4 The MEVVA V ion source, partially disassembled to show the multiple cathode feature (holds 18 separate cathodes) and the large beam formation electrodes. (CBB 892-1174)

MicroMEVVA: Two versions of miniature sources have been made. Both of these sources are of overall length about 10 cm, diameter about 2 cm, and they weigh only about 100 gm. They are fabricated very simply from coaxially fitting stock ceramic and stainless steel tubing. Beam extraction is done in an unsophisticated manner through a single aperture of diameter about 3 mm, and the maximum extraction voltage that can be maintained across the short spacings is about 20 kV. Pulsed beam current is up to 10 or 20 mA. The entire source resides within the vacuum, and the cooling is minimal. The MicroMEVVA II source is shown in the foreground of Figure 3 and has been described in more detail in references [21] and [26].

PERFORMANCE

A schematic of the experimental configuration that has been used for much of the work described here is shown in Figure 5. The facility has been used for testing and development of the various MEVVA ion sources, as well as for carrying out our ion implantation research. In the following, most of the source performance refers to operation with our most recent source, the

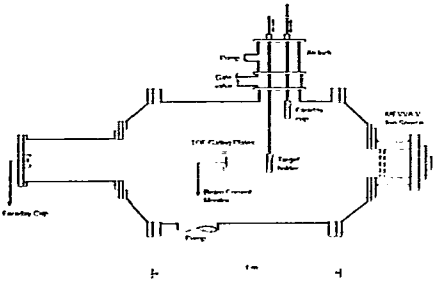

Fig. 5 Schematic of the experimental facility. (XBL 896-7641B)

MEVVA V. Implantation is done in a broad-beam mode, line-of-sight from ion source to target without magnetic charge-to-mass analysis of beam components. The source-to-target distance (ion source extractor grids to target holder) is 65 cm. A magnetically-suppressed Faraday cup with a 5 cm diameter entrance aperture can be inserted into the beam path to monitor the ion beam current density at (or close to) the target location. An example of the ion source beam current performance for the case of a titanium beam is shown in Figure 6. Here the ion beam current density (during the beam pulse) delivered onto target, as measured by the Faraday cup near the target location, is plotted as a function of extraction voltage for a range of different arc currents. The ion current density is up to 20 mA/cm^2. The beam composition can be monitored by means of a time-of-flight charge state diagnostic. This diagnostic is described in a companion paper presented at this conference [27]. An example of the charge state spectra obtained is shown in Figure 7, where an oscillogram of a Ta time-of-flight spectrum is shown. In typical operation the source might be pulsed at a rate of around ten pulses per second. For our standard pulse length of 250 μsec, a repetition rate of 40 pps corresponds to a duty cycle of 1%, and the mean beam current is then 1% of the peak (pulse) beam current. The base vacuum pressure is around 5 x 10^{-7} Torr, and in the low-to-mid 10^{-6} Torr range when operating.

Beam Characteristics

Beam is extracted typically at 50 - 60 kV, and the maximum voltage at which we have operated is 110 kV. Since the ion charge state distribution (see below) contains multiply ionized species with charge state up to about Q = 5+ for some metals and with mean charge state of typically Q = 2+ to 3+, the mean energy of the beam ions produced can be 200 - 300 keV with components as high as

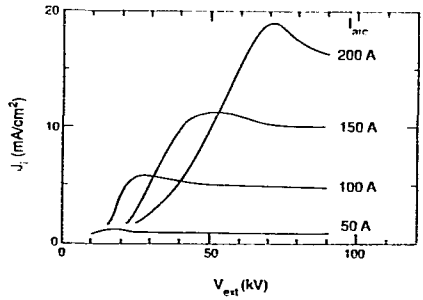

Fig. 6 Peak ion beam current density measured by the Faraday cup at z = 60 cm as a function of ion source extractor voltage, for several different arc currents. Titanium beam. (XBL-904-6340)

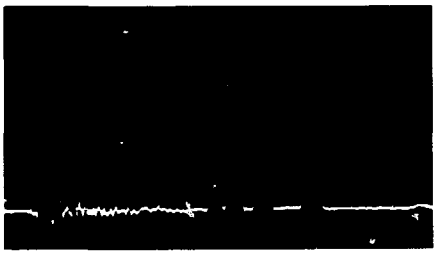

Fig. 7 Time-of-flight charge state spectrum for Ta. The peaks correspond to Q = 1,2,3,4,5 right to left and the maximum is at Q = 3+. (XBB 904-2899)

500 keV. With the MEVVA V, beam current is typically of order 1 Ampere peak delivered onto target, corresponding to a maximum time-averaged current of up to 10 - 20 mA. The record peak current we have produced, and delivered to a downstream target, is 3.5 Amperes. Beam divergence is typically about 3°. Operationally the arc current is varied so as to maximize the beam current measured into the acceptance of the Faraday cup, which occurs when the plasma density is best matched to the extractor parameters; an arc current at or near 100 A is usual.

The ion charge state spectrum is of interest both fundamentally because of its importance to the physics of vacuum arc cathode spots, and also because of its relevance to understanding and predicting specific ion implantations. We have studied the ion charge state distributions quite extensively. Ion spectra have been measured for a wide range of metallic cathode materials, including Li, C, Mg, Al, Si, Ca, Sc, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Ge, Sr, Y, Zr, Nb, Mo, Pd, Ag, Cd, In, Sn, Ba, La, Ce, Pr, Nd, Sm, Gd, Dy, Ho, Er, Yb, Hf, Ta, W, Ir, Pt, Au, Pb, Bi, Th and U [27-29]. We have also investigated the spectra produced by a range of compound and alloy cathode materials, including for example TiC, SiC, UC, PbS, brass, and stainless steel [30]. The compound cathodes produce a beam containing ions of the molecular constituents, and it is interesting to note that beams containing non-metallic elements, like B and S, can be made by using conducting compound electrodes of which the non-metal is a constituent. The ion charge state multiplicity can be as high as 5 or 6 for some

elements and the mean charge state varies from 1 up to about 3. Our charge state distribution studies are presented in a companion paper at this conference [27]. We have proposed a phenomenological fit to the charge state data,

$$\bar{Q}_p = 0.38(T_{BP}/1000) + 1,$$

where $\bar{Q}_p$ is the mean charge state and T_{BP} is the boiling point temperature of the cathode material in °C. This expression fits the data well with the exception of carbon; see [27] for more details.

Cathode lifetime is limited by cathode erosion [31] and is up to around one million shots per cathode depending on the arc current and pulse length; thereafter triggering becomes erratic and difficult. There is normally no significant deterioration in either the trigger or the trigger insulator. Since there are 18 cathodes in a single MEVVA V cathode assembly, the source can be operated steadily for many days before it is necessary to vent the source to atmospheric to replace the cathodes. Soft materials like Li, Sn and Pb tend to have a shorter lifetime due to plating over of the cathode/trigger insulator, but this depends on the arc current.

The maximum duty cycle at which the source can be operated is determined by several factors, the main one of which, for us, is the limitation set by the electronics, including the trigger generator, arc supply and extractor supply; heat removal from the arc region is also a concern. Our electronics limits us at present to about 1%.

DISCUSSION

The purpose for which the source was initially developed was as an injector of high current, heavy metal ion beams into the LBL heavy ion synchrotron [32], and a MEVVA IV source is presently being commissioned into operation for this purpose [33]. Similar work is underway at GSI/Darmstadt, W. Germany [34].

Another field of application for which the source is particularly well suited is high dose metal ion implantation, and our research has developed in this direction. The implantation facility that we have set up has been used for exploratory research for a variety of different ion implantation applications, including semiconductor, superconductor, and metallurgical applications. We have performed implantations of uranium and thorium into silicon for some quite fundamental studies of diffusion [35,36] and into III-V compounds for luminescence studies [37], of tungsten and palladium into silicon for some novel work related to selective CVD [38], and of iridium into silicon for studies of buried conducting layers [39]. We have carried out some work to demonstrate 'fine tuning' of the composition of the new high-Tc superconductors, in this way improving the low temperature resistance characteristics significantly [40]. The application for which the facility is best suited, however, is for metallurgical surface modification, and we have developed some implantation programs to explore this field [41].

We point out that as well as the intense ion beam that is produced, there can also be a component of micron-size solid droplets ("macroparticles") [42,43] in the beam, which might in some situations be a disadvantage. The macroparticle contamination is observed to be less for cathode materials of higher melting point, and there is a natural separation of the wanted plasma flux from the unwanted macroparticle flux by virtue of the fact that the plasma flux is peaked in the direction normal to the cathode surface while the macroparticle flux is peaked in a direction close to parallel to the cathode surface. It should be possible to completely remove the macroparticle fraction from the plasma, either by using an appropriate geometry or by adapting a magnetic filter [44,45] within the plasma region of the ion source. The magnitude of the macroparticle flux is dependent upon a large number of operational parameters, such as arc current, pulse length, cathode material, source-to-target distance, among others. We plan to carry out a series of measurements to explore this issue.

The low duty cycle pulsed operation of the source described here is not an inherent limiting characteristic of the MEVVA technology, but is simply a legacy from its accelerator-based lineage: a dc version capable of delivering Amperes of metal ion beam current has been tested and is in development.

CONCLUSIONS

The metal vapor vacuum arc provides a discharge mechanism for the efficient production of highly ionized dense metal plasma, and this metal plasma formation mechanism can be harnessed to make a high current metal ion source. We have developed a series of such sources. These sources, which we have called the MEVVA ion sources as an acronym for the plasma formation mechanism, are distinguished by the very high current of metal ions that can be produced. The ion charge state species produced are in general multiply ionized. The ion current that is available for extraction from the ion source can be as high as about 5% of the current employed to drive the vacuum arc; we have measured a plasma ion current at the location of the extractor and available for extraction as high as 20 Amperes [20]. The maximum voltage at which we have extracted beam is 110 kV, and the maximum beam current formed and delivered onto a downstream target is 3.5 Amperes. In typical operation and without stressing the source operation, a beam of approximately 1 Ampere peak ion beam current, or 10 mA time-averaged beam current, can be produced with an extraction voltage of 50 - 75 kV, corresponding to a mean energy of beam ions of approximately 150 - 200 keV. The beam current produced by this kind of ion source is an increase of several orders of magnitude over what has previously been available from more conventional metal ion sources.

ACKNOWLEDGEMENTS

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