Streaming metal plasma generation by vacuum arc plasma guns

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We have developed several different embodiments of repetitively pulsed vacuum arc metal plasma gun, including miniature versions, multicathode versions that can produce up to 18 different metal plasma species between which one can switch, and a compact high-duty cycle well-cooled version, as well as a larger dc gun. Plasma guns of this kind can be incorporated into a vacuum arc ion source for the production of high-energy metal ion beams, or used as a plasma source for thin film formation and for metal plasma immersion ion implantation and deposition. The source can also be viewed as a low-energy metal ion source with ion drift velocity in the range 20–200 eV depending on the metal species used. Here we describe the plasma sources that we have developed, the properties of the plasma generated, and summarize their performance and limitations. © *1998 American Institute of Physics.* [S0034-6748(98)55802-9]

I. INTRODUCTION

Metal plasma can be produced in a number of ways, including by ionization of metal vapor formed from an oven, incorporation of sputtered metal into a gaseous plasma, and laser ablation of a metallic target. The vacuum arc is another way. Vacuum arc plasmas have been known and studied for about a century,[1] predating the early work of Debye and Langmuir by some decades. The field has a lot to do with high voltage hold-off in vacuum and high current switchgear; in recent years the field has found application as a metallurgical coatings technology. Reviews of vacuum arc plasma science have been given by Lafferty[2] and more recently by Boxman *et al.*[3] A remarkably complete bibliography, surely containing the entire history of the vacuum arc research literature up to the date of publication, 1990, has been compiled by Miller.[4] Conferences on the subject have been held biennially and the proceedings published in archived journals.[5]

The metal vapor vacuum arc is a copious producer of highly ionized metal plasma. The plasma is created at the cathode spots on the surface of the cathode material, and has an ion streaming energy of order tens to a hundred or so electron volts; the ion drift velocity is typically of order 1 cm/μs. The ions are in general multiply stripped with a charge state spectrum containing components up to about $Q=6+$. The equivalent ion current of the streaming plasma can be up to several amperes or more, and almost all of the solid metals of the Periodic Table can be used as well as alloys and mixtures.

Vacuum arc ion sources have been developed for the production of high current energetic metal ion beams.[6,7] Beams of up to 1 A or more at energies of order 100 keV can be formed from most of the solid metals as well as compounds and alloys. This kind of source has been used for ion implantation and accelerator injection application.

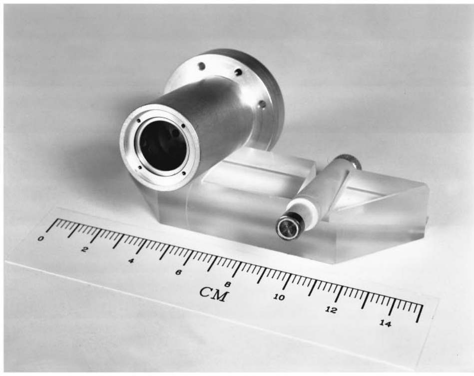
Here we distinguish between energetic ion beams formed by a conventional ion source configuration in which the ions are ''extracted'' from the plasma and accelerated by a beam forming electrode configuration, and a streaming plasma formed by a ''plasma gun.'' We refer to the former as an ion source and the latter as a plasma gun, the term ''gun'' implying that the plasma is formed with a non-negligible forward velocity.

The metal plasma formed by a vacuum arc is created with a substantial streaming velocity—it plumes forward, normal to the cathode, with a drift velocity of about 1–2 cm/μs, corresponding to an ion drift energy of from about 10 eV to about 200 eV depending on the ion mass—and one can thus look on this kind of plasma as a low-energy, high current, fully-space-charge-neutralized, ion beam and on the vacuum arc plasma gun, similarly, as a kind of low-energy ion source.

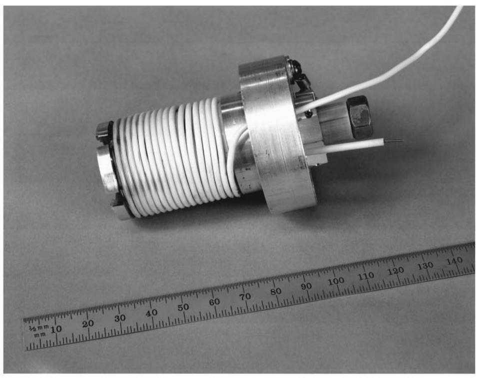
In the following we describe the properties of the plasma produced and some of the vacuum arc plasma gun configurations we have made.

II. VACUUM ARC PLASMA CHARACTERISTICS

The metal plasma formed in a vacuum arc is created at micron-size regions on the cathode, and the arc current, which is typically several hundred amperes for the sources described here, is concentrated at a small number of such cathode spots. The plasma plumes away from the spot at which it is formed in a manner similar in some respects to a laser-produced plasma. Although the physics of plasma formation at the spots is not completely understood, many features are well known. For example, a minimum arc current is needed in order to keep the spot alive. Typically this current is of order several tens of amperes, depending on the cathode material used; if the arc current is reduced below this minimum value, the arc simply extinguishes. Also, as the arc current is increased the number of spots increases so as to maintain about the same current per spot. These characteristics of vacuum arc behavior lead to a fundamental similarity between all kinds of vacuum arc ion sources—the geometric details change, but the underlying plasma physics remains much the same.

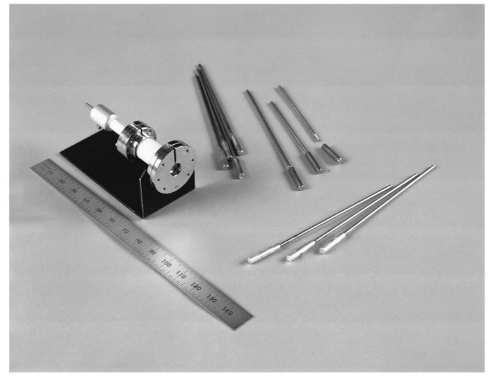


(a)

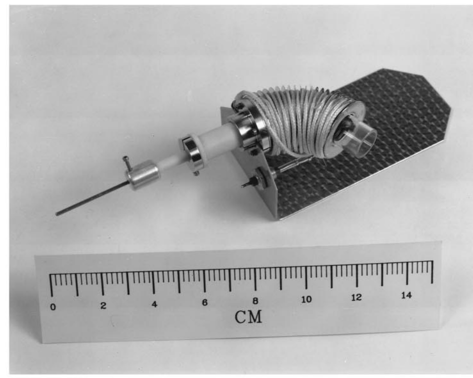


(b)

FIG. 1. (a) Minigun metal plasma source, with cathode assembly removed from anode; (b) assembled minigun with anode solenoid added.



(a)



(b)

FIG. 2. (a) Microgun metal plasma source with extra cathodes shown; (b) microgun with added macroparticle filter.

The following summarizes in general form some of the plasma parameters typical of the plasma guns described here; (see Refs. 2, 3, and 7 for more detail). In keeping with the philosophy of this article of viewing the plasma produced by vacuum arc plasma guns as a kind of highly neutralized, low-energy ion beam, we adopt the terminology as conventionally used in describing ion sources:

Ion current: The ion current i_{ion} produced by the vacuum arc is quite generally close to 10% of the arc current i_{arc}, for all metal species and arc current. For an efficient gun design, perhaps half of this might be delivered from the gun ''barrel.'' Since the arc current is typically 100–300 A the ion current can be of order 10 A, and it is clear that this kind of ion generator is indeed a high current source.

Ion energy: There are no ion beam formation electrodes (''extractor grids'') in the gun, and the ion energy is the ion drift energy as determined by the physics of the cathode spots. The vacuum arc ion drift velocity is know to lie in the approximate range 1–2 cm/μs, corresponding to an ion streaming energy E_i in the range 10–200 eV depending on ion mass. Note that this is a directed energy, not temperature; the ion temperature is low, about one to several electron volts.

Ion charge states: The ions are in general multiply stripped with charge states Q from $1+$ up to about $6+$, depending on the metal species used.[8] There is a spectrum of charge states with mean from $1+$ to about $3+$.

''*Macroparticles*'': At the cathode spots, cathode material is converted into metal plasma, neutral gas, and solid cathode debris called ''macroparticles''—metallic globules that are ejected from the cathode in the molten state and rapidly solidify; they are typically of diameter in the range 0.1–10 μm. Macroparticle generation is observed to be less for cathode materials of higher melting point, and there also is a natural separation because the plasma flux is peaked in the direction normal to the cathode surface while the macroparticle flux is peaked close to parallel to the cathode surface. We typically incorporate a magnetic duct[9] into our gun configurations, thereby producing metal plasma streams that are free of macroparticles, as well as of vapor and neutral atoms. The plasma exiting the magnetic duct filter is fully ionized.

III. PLASMA GUN PERFORMANCE

We have made a number of different plasma gun embodiments, including small, pulsed, ''thumb-size'' versions and a large dc version. The difference between the sources is primarily in the duty cycle at which they can be operated, and the plasma produced is always much the same independent of gun size and is dependent only on the arc current and cathode material. The essential features of the source are shown clearly in the ''minigun,'' Fig. 1. Figure 1(a) shows the cathode assembly (cathode, trigger insulator, and trigger ring) removed from the cylindrical anode, and Fig. 1(b) shows the assembled gun with a simple solenoid wound on the anode (slotted to allow field penetration) to add some

FIG. 3. dc gun with 5-cm-diam cathode.

forward focusing to the plasma stream. In the gun variant shown the triggering is via a high voltage spark discharge applied to the small ring electrode surrounding the cathode; we have developed some alternative triggering mechanisms, that have been fully described elsewhere.[10] The minigun can operate at pulse lengths of up to ~10 ms and duty cycle up to ~1% without cathode overheating.

Figure 2(a) shows a ''microgun,'' assembled and with a number of interchangeable cathodes shown also; Fig. 2(b) shows the same gun with an attached macroparticle filter (bent solenoid wound on a vacuum bellows as a form). Maximum pulse length and duty cycle are around 1 ms and <1%, respectively. The gun and the electronics to support it are both particularly simple and straightforward. On the other end of the spectrum, a large dc source is shown in Fig. 3, with water-cooled anode removed from the electromechanically triggered, water-cooled, 5-cm-diam titanium cathode. Finally, the most recent addition to our plasma gun family is shown in Fig. 4. We have operated this ''minibrute'' gun at pulse lengths of up to ~100 ms and duty cycle up to 10%; longer pulse length and duty cycle seem possible. Both cathode and anode are water cooled, and the electrode material is a 2.5 cm (one inch) length of 1.25 cm (half inch) diameter rod that can be easily changed (it is attached to the threaded end of a cooled copper holder). A small solenoid around the anode region helps to increase the forward plasma ejection.

All of the guns have been used in our laboratory. They operate reliably and for long periods. For the most part we have used them for materials synthesis work (thin film deposition), but their simplicity and compact design offer a convenient laboratory tool for a potentially wide range of experimental applications.

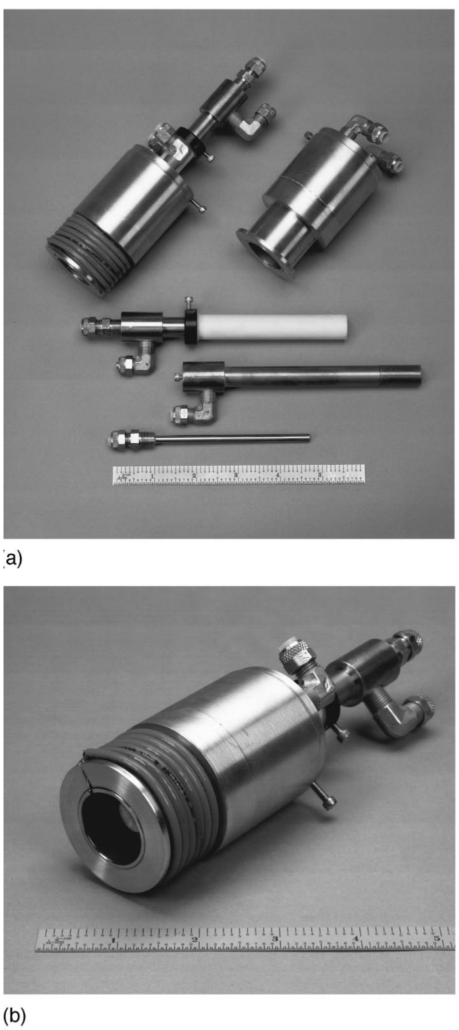


FIG. 4. ''Minibrute'' gun, (a) partially disassembled; (b) assembled.

ACKNOWLEDGMENT

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[5] See the Special Issues on Vacuum Discharge Plasmas in IEEE Trans. Plasma Sci. These issues contain selected papers from the biennial International Symposia on Discharges and Electrical Insulation in Vacuum. (usually in the October issues in odd-numbered years).
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