A high-current pulsed cathodic vacuum arc plasma source

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Cathodic vacuum arcs (CVAs) are well established as a method for producing metal plasmas for thin film deposition and as a source of metal ions. Fundamental differences exist between direct current (dc) and pulsed CVAs. We present here results of our investigations into the design and construction of a high-current center-triggered pulsed CVA. Power supply design based on electrolytic capacitors is discussed and optimized based on obtaining the most effective utilization of the cathode material. Anode configuration is also discussed with respect to the optimization of the electron collection capability. Type I and II cathode spots are observed and discussed with respect to cathode surface contamination. An unfiltered deposition rate of 1.7 nm per pulse, at a distance of 100 mm from the source, has been demonstrated. Instantaneous plasma densities in excess of $1\times10^{19}\,\mathrm{m}^{-3}$ are observed after magnetic filtering. Time averaged densities an order of magnitude greater than common dc arc densities have been demonstrated, limited by pulse repetition rate and filter efficiency. [DOI: 10.1063/1.1614851]

I. INTRODUCTION

Continuous operation [direct current (dc)] cathodic arcs have been studied extensively within the School of Physics at the University of Sydney. Pulsed cathodic vacuum arcs (CVAs) generally have a higher current and plasma density and also provide a more stable and reproducible plasma density than their dc counterparts. If a high repetition frequency can be achieved the deposition rate of pulsed CVAs is equal to or greater than that of dc arcs with a concomitant reduction in the rate of macroparticle formation. The development of the pulsed arc system described here was undertaken with the purpose of producing ultrathin films and multilayers, and studying sheath dynamics during plasma-based ion implantation (PBII). When producing ultrathin (<10 nm) metallic and ceramic films, precise control over the deposition parameters is required. Our filtered dc arcs, operating at currents around 100 A, exhibit density fluctuations on a millisecond time scale due to arc spot instabilities, and also on a time scale of a few seconds due to variations in the degree of plasma coupling to the magnetic macroparticle filter. Reproducible production of ultrathin films is extremely difficult under these conditions. In contrast, a pulsed vacuum arc can provide a highly reproducible plasma density during each pulse, the profile of which closely follows that of the arc current. Calibration of the amount of material deposited per pulse allows the nominal film thickness to be precisely controlled by simply counting the number of arc pulses. Reproducible plasma densities have allowed the study of sheath dynamics during PBII to be compared with theoretical predictions.[1]

II. SYSTEM DESIGN

The design of our pulsed arc sources is based on that presented by Siemroth *et al.*[2] for a high current pulsed vacuum arc (HCA). A fundamental difference is the increase in cathode diameter, representing an increase in the scalability of the system, which is important for commercial applications. Cathodes are 50 mm diameter disks (compared to around 20 mm diameter in Siemroth's HCA) with a small hole in the center for the trigger electrode. A tube of copper is coaxially located around the cathode to act as an anode. The trigger is a tungsten wire inserted into an insulating sleeve made of alumina. A high voltage pulse applied between the trigger wire and the cathode by a triggering circuit causes a flash over to occur across the insulator, which ignites an arc that burns between the anode and cathode. Metal plasma is created from the cathode material and expands outward from the cathode surface with a high velocity. A 90° curved solenoid made from copper tubing is located at the exit of the anode and electrically connected in series with the cathode and anode to act as a magnetic macroparticle filter. Cathode, anode, and filter can be water cooled to allow a high pulse repetition frequency. A schematic of the anode, cathode, trigger, and power supply is shown in Fig. 1.

A. Cathode spot fundamentals

For commercially applicable thin film deposition purposes a pulsed arc must have a deposition rate comparable to other sources. There are two obvious ways to increase the deposition rate: increase the pulse frequency and increase the arc current. Both these measures are limited by power supply electronics. dc arcs generally operate with an arc current of around 100 A. Depending on the cathode material, these arc currents generally produce between one and three independent arc spots on the cathode surface (an arc spot is a region of extremely high current density where metal plasma production occurs). As the arc current is increased more arc spots are generated on the cathode surface by spot splitting processes, limiting the current per spot to a value primarily dependent on the cathode material. Since each cathode spot is a conduit for a large current it will also be a source of a

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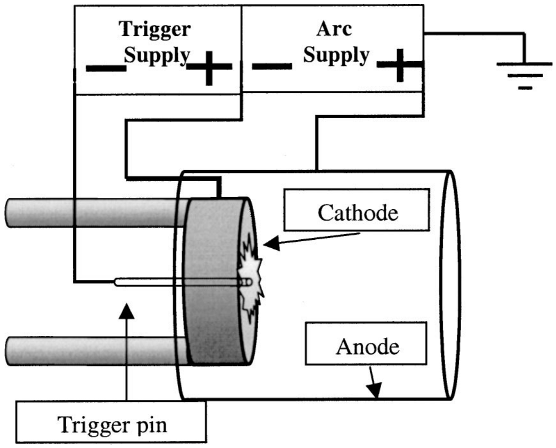

FIG. 1. Schematic of cathodic arc showing central trigger and tubular anode (anode is shown as transparent in this diagram).

radial magnetic field parallel to the cathode surface. Consequently, multiple spots exert retrograde forces on one another.[3] This is observed in images of high current arc traces showing dendritic patterns radiating outward from the point of ignition (Fig. 2).

When a new cathode was installed into the system it was observed that the arc operated in a different mode to that when the cathode had been employed for some time. Review of the literature revealed this to be due to the existence of two types of arc spots, historically labeled type-1, and type-2, arc spots. Type-1 is the term used for arc spots with comparatively high velocity, low brightness and low arc current per spot. Conversely type-2 spots exhibit comparatively low velocity, high brightness and high current per spot.[3,4] Type-1 arc spots are attributed to surface contaminants and adsorbed gases on the cathode surface. Due to their higher velocity and low currents, very little ablation of the cathode material occurs and they are therefore undesirable for the production of metal plasmas. In their original article on the HCA, Siemroth *et al.*[2] present high-speed photographs of arc spots moving radially outward from the point of ignition. Comparing the time period between ignition and when the

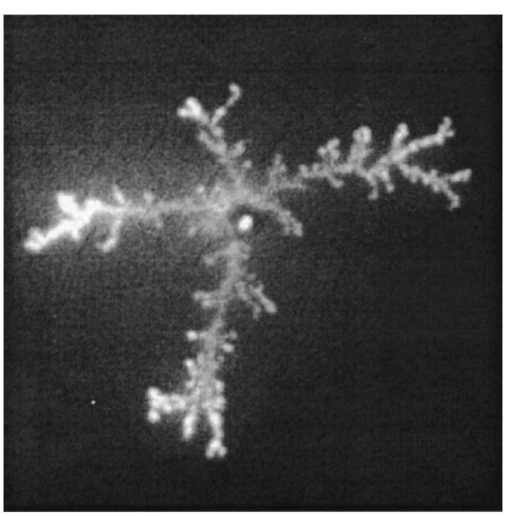

FIG. 2. A typical arc on an aluminum cathode. Exposure time 1 ms, image size 5 cm.

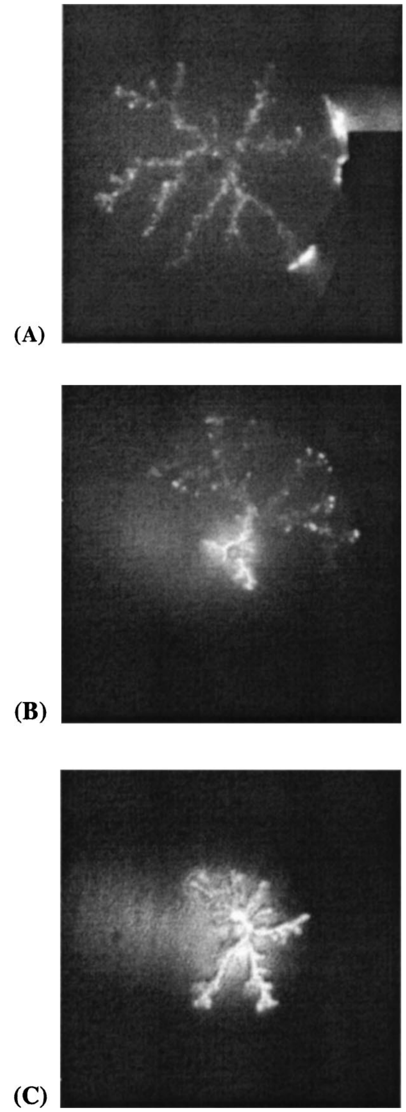

FIG. 3. CCD images of an aluminum cathode showing transition from type-1 spot mode to type-2 mode. Image A is taken 8 pulses after the cathode was inserted into the vacuum system (exposure time 0.2 ms). After 49 pulses (B) the arc begins to operate initially in a type-2 mode before reverting to type-1 as contaminated regions are reached (exposure time 0.3 ms). After 62 pulses the cathode surface has been cleaned of contaminants and the arc is operating purely in type-2 mode (exposure time 1 ms). Image sizes are 6 cm×6 cm.

spots reach the edge of the cathode with other images of arc traces in the same work shows that the arc spots in these high-speed images move at a much faster velocity. We conjecture that type-1 spots are observed in the high-speed photographs and type-2 spots are observed in subsequent images. No such distinction was made by the authors.

Operating the arc for around 100 pulses is sufficient to condition the cathode, removing all surface contaminants by ablating them in the type-1 mode. Subsequent arc pulses operate in a type-2 mode, exhibiting lower spot velocities and higher currents, which operate on the cathode material itself, forming pure metal plasmas. Figure 3 shows a series of three charge coupled device (CCD) images taken after a new cathode was inserted into the system. For the first 40-odd pulses the arc operated in a type-1 mode [Fig. 3(a)], the spot traces reaching the edge of the 51 mm diameter cathode in less than

200 μs. After 49 pulses the arc is observed to be operating initially in a comparatively bright type-2 mode before reverting back to a type-1 mode of operation as the arcs spots encounter contaminated regions of the cathode towards the edges. After 68 pulses the arc is operating entirely in a type-2 mode, exhibiting comparatively slow moving arc spots, which are still within the cathode boundary after 1 ms.

It has been reported recently that the composition of a pulsed vacuum arc plasma operated in an oxygen environment shows a dependence on the arc pulse frequency.[5] This is due to the formation of monolayers of gas on the surface of the cathode. It is recommended that the arc be operated at a frequency high enough to avoid the adsorption of significant amounts of gaseous contaminants to the cathode surface, a value that will depend strongly on the background gas pressure.

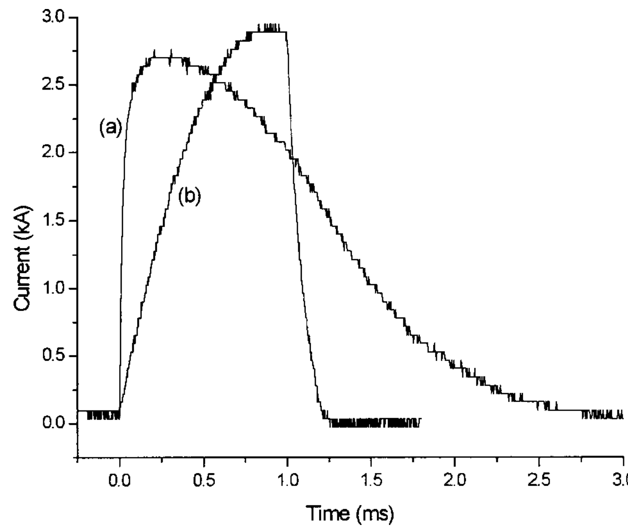

FIG. 4. Comparison of current profiles for the two power supplies we tested, (a) the simple 12 mF, 400 V capacitor bank and (b) the 300 V LC pulse circuit, crowbarred at 1 ms.

B. Arc triggering

Triggering of cathodic arcs is achieved in many ways. Mechanical contact of an electrode, laser ablation, high-voltage flashover, and the so-called "triggerless" triggering technique[6] are all used to provide the initial plasma to trigger an arc between the anode and cathode (essentially close the circuit). For a pulsed system the mechanical method is not viable when high repetition frequencies are required. Laser ablation requires an expensive high power laser. The inventors of the triggerless system suggest that the slow rising current profile in high current arcs is not well suited to providing the required conditions for this method of triggering.[7] Considering these limitations we decided the high-voltage flashover technique was best suited to our requirements.

High-voltage flashover requires the application of a high voltage between two adjacent electrodes; in this case the cathode and a trigger electrode. A commonly quoted method of arranging these electrodes is to coaxially insert one electrode inside the other and separate them by an alumina insulator. Insertion of the cathode electrode inside the trigger was found by Brown *et al.*[8] to improve the triggering reliability when compared to a centrally located trigger electrode. While this may be the case, we have observed in edge-triggered systems the erosion profile to be concentrated at the edge of the cathode due to spot repulsion. For flat disk cathodes, such as ours, this results in an inefficient utilization of cathode material. Considering the aforementioned fundamental characteristic of cathode spot dynamics, namely that multiple arc spots repel one another, we conclude that centrally locating the trigger electrode gives a better erosion profile. In addition, optimization of the arc current can improve the erosion profile, as will be discussed later.

Application of a voltage of around 3 kV for 3 μs between the trigger electrode and the cathode is generally sufficient to initiate the initial plasma required for triggering of the arc. Initially the alumina insulator needs to be coated with a small amount of conductive material. Graphite is a good option. This material is ablated by the trigger pulse and essentially switches on the arc. After a small number of arc pulses the alumina becomes partially coated with cathode material from the arc, replacing the ablated conductive material.

There is a threshold voltage between the anode and cathode, which must be surpassed to achieve reliable triggering of the arc. For our arrangement this voltage is greater than 100 V, however, this depends strongly on the arrangement of the anode and cathode. (Note that this is the "preburn voltage" and should not be confused with the arc operating voltage, which is generally around 50 V.) Under these conditions the triggering reliability exceeds 99.9% for around 10 000 pulses. After such a period the reliability begins to reduce due to a buildup of cathode material on the alumina trigger insulator. By the application of a large power burst (>250 J) through the buildup, a large proportion of it can be ablated from the insulator. In this way we have been able to extend the period of reliable triggering by around 1000 pulses.

C. Anode design

The electron collecting ability of the anode is an important consideration of the arc design. Many variations on the size and shape of the anode exist in the literature, ranging from tubes and rings surrounding the cathode, to rods axially inserted in the center of the cathode.[9] For simplicity and historical continuity with our dc design, we chose a tube of copper slightly larger than the cathode diameter and coaxially located around the cathode. The current collected by the anode is used to produce a magnetic field in a macroparticle filter by connecting the filter in series with the power supply. It is therefore important to insure maximum anode efficiency during operation.

With a macroparticle filter installed we compared the anode efficiency for a number of anode lengths. It was found that the distance the anode extended in front of the cathode surface was crucial in determining the anode effectiveness. Figure 4 shows a comparison of the current collected in the anode when the anode extended 55 and 70 mm in front of the cathode surface. A small change in the anode length shows a large difference in the amount of current collected.

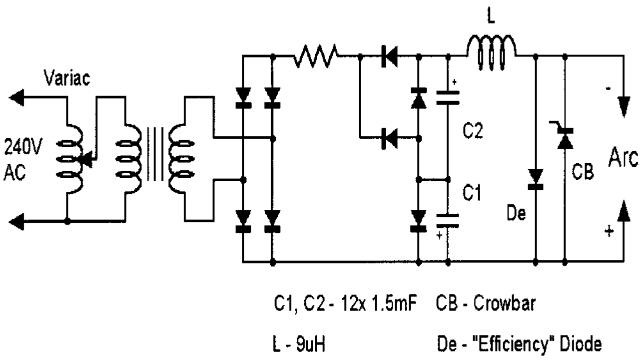

FIG. 5. Circuit diagram of the resonant LC circuit power supply used to drive the arc current. The circuit is based on a design published previously by Siemroth *et al.* (see Ref. 2).

The angular distribution of plasma flow has been reported to approximately follow a cosine distribution with higher currents increasing the percentage of ion emission perpendicular to the cathode surface.[10] Increasing the anode length therefore increases the electron current collected. The magnetic field produced by the filter acts to constrict the flow of the plasma parallel to the cathode surface. Since the current collected by the anode determines the magnetic field strength there is a feedback mechanism that restricts the current collecting ability for shorter anodes and higher currents. The design of the anode is therefore influenced by the incorporation and design of the magnetic filter. Alternatively the filter can be operated from a separate power supply, reducing the constraints on anode collection efficiency but increasing the cost and complexity of the power supply.

D. Power supply

In the early stages of prototyping, our power supply consisted of a simple capacitor bank of between 6 and 12 mF, charged to between 100 and 400 V. This provided current pulses with a fast rise time and a long decaying tail, such as shown in Fig. 4(a). Since the erosion rate is proportional to the arc current a current profile such as this results in an excessively high erosion rate near the center of the cathode where the arc spots are triggered and a very small erosion rate near the circumference of the cathode. In an attempt to even out the erosion profile across the cathode surface, we designed our next prototype power supply based on an oscillating low concentration (LC) circuit such as that used by Siemroth *et al.*,[2] adapted to make it suitable for electrolytic capacitors. Electrolytic capacitors are less expensive for a given capacity than other types, but require a circuit design that will prevent them from being reverse biased. Our power supply utilized 1.5 mF high current discharge electrolytic capacitors manufactured for Lawrence Livermore National Laboratory, California, with a voltage rating of 450 V and instantaneous current rating of 417 A for 1 ms.

A circuit diagram of the power supply is shown in Fig. 5. The "crowbar" is used to short out the plasma and cut the pulse current at a predetermined time during the positive cycle (0°–180°) of the oscillation. If it is cut prior to 90° into the oscillation cycle, a current pulse that rises over almost the entire pulse length is produced, as shown in Fig. 4(b). Cathode spot velocity is primarily determined by the cathode current and the cathode material. Easy adjustment of the capacitor and inductor values within the power supply is possible, allowing tailoring of the oscillation period for different spot velocities. This is especially useful for carbon cathodes where the spot velocity is significantly smaller than that of most metals. The crowbarring time can be adjusted to suit the velocity of the cathode spots so that the maximum coverage of the cathode surface is achieved but the spots do not run over the edge of the cathode surface. The crowbar diverts the current from the plasma but keeps the remaining energy in the circuit. When the current drops to zero the crowbar turns off and the efficiency diode takes over, carrying the entire negative cycle of the current. Efficiency diodes are commonly utilized in high current power supplies.[11] The remaining energy in the circuit is returned to the primary capacitor bank (C1) via the efficiency diode.

We generally limited the peak current to no more than 5 kA to be sure that the system does not overheat. However, during testing we have run the supply with peak currents as high as 10 kA. Deciding on an optimal peak current requires balancing a number of factors. Since the arc current also provides the current for the coils of the curved magnetic filter, it needs to be high enough to ensure good magnetic confinement (i.e., to produce a field of at least a few tens of millitesla), but it cannot be so high that the force on or heat dissipation in the filter coils causes them to deform. High arc currents are advantageous because they generate faster moving arc spots, which produce fewer macroparticles,[2] but unfortunately losses in the power supply scale as the square of the peak current. With these factors in mind we designed the power supply to operate with peak currents in the range of 1–5 kA.

If the energy of the arriving ions is to be well controlled by the application of a bias voltage to the substrate it is important that the plasma not only be fully ionized but that the ion charge state distribution (CSD) is well known. Ions with different charges will experience unequal acceleration by the application of a bias to the substrate and subsequently exhibit different kinetic energies upon arrival at the substrate. Oks *et al.*[12] showed that the CSD is affected by both the application of a strong axial magnetic field at the cathode surface, and also by the magnitude of the arc current. For a carbon cathode in the absence of an external magnetic field, currents above 2 kA linearly increase the average charge state. Thus, although high current arcs can provide a high deposition rate and reduced macroparticle content, it is important to consider the effects of the current on the CSD if the ion arrival energy is to be manipulated by an electric bias. This is also true for the application of an axial magnetic field for the purposes of macroparticle filtering and/or cathode spot motion control.

III. OPERATIONAL PERFORMANCE

We have successfully operated the arc with a number of cathode materials, including carbon, aluminum, titanium, silver, and copper. For initial characterization of deposition

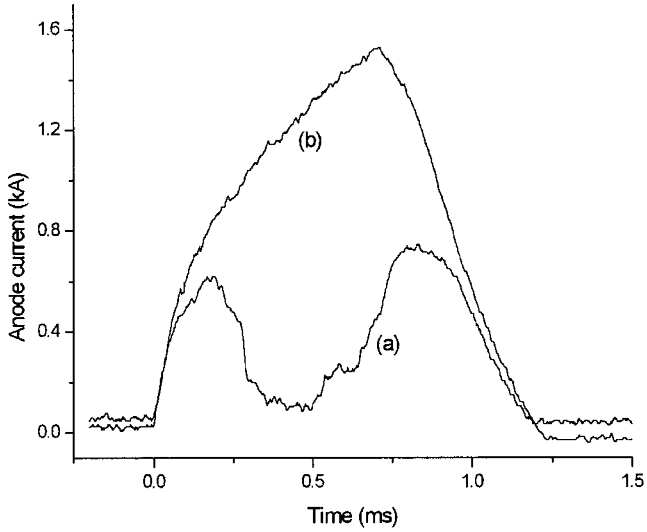

FIG. 6. Comparison of anode currents for different anode lengths. Curve (a) is the current collected by an anode protruding 55 mm past the end of the cathode (b) by an anode protruding 70 mm past the end of the cathode.

rates titanium films were deposited on silicon substrates before and after the macropaticle filter. Deposition rates were measured by determining the final film thickness using a stylus profilometer. At a location 100 mm from the cathode surface, without the macroparticle filter employed, the deposition rate was determined to be 1.7 ($\pm$0.1) nm per arc pulse at a peak arc current of 3 kA (arc bank 210 V). For short operating periods we have successfully operated the system at frequencies as high as 50 Hz. This corresponds to a time averaged deposition rate of 85 $\mathrm{nm\,s^{-1}}$ for titanium. This rate is not large in comparison with a carbon deposition rate of 200 $\mathrm{nm\,s^{-1}}$ from Siemroth's HCA measured 150 mm from the source at a pulse frequency of 300 Hz.[2] At this stage we have not thoroughly investigated the fundamental limits of the pulse frequency for our system. Limits on pulse frequency are set primarily by the heat tolerance of the circuit components.

Deposition rates after the macroparticle filter were significantly lower, at around 0.07 nm per arc pulse. At only 4% of the deposition rate before the filter entrance this represents a significant loss of the plasma available for deposition. With significant instantaneous deposition rates demonstrated in the unfiltered arrangement, macroparticle filter efficiency is the primary limiting factor of the instantaneous deposition rate. Research is ongoing into the optimization of the filter transport efficiency. With the macroparticle filter employed we have used a langmuir probe to measure ion densities greater than $1\times10^{19}\,\mathrm{m^{-3}}$ at the substrate position for a titanium plasma. At 50 Hz the time averaged ion density is around $3\times10^{17}\,\mathrm{m^{-3}}$, which is an order of magnitude greater than the ion densities measured in our dc arcs. Optimized filter arrangements have indicated filter efficiencies as high as 35% (defined as the ratio of the ion density at entry and exit of the filter) for an in-plane 90° magnetic filter.[13] If filter efficiency can be improved in our system to this level then time averaged metal ion densities in excess of $1\times10^{18}\,\mathrm{cm^{-3}}$ can be achieved. (See Fig. 6.)

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