PLASMA DISTRIBUTION OF CATHODIC ARC DEPOSITION SYSTEM

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ABSTRACT

The plasma distribution using a cathodic arc plasma source with and without magnetic macroparticle filter has been determined by depositing on a transparent plastic substrate and measuring the film absorption. It was found that the width of the distribution depends on the arc current, and it also depends on the cathode material which leads to a spatial separation of the elements when an alloy cathode is used. By applying a magnetic multicusp field near the exit of the magnetic filter, it was possible to modify the plasma distribution and obtain a flat plasma profile with a constant and homogeneous elemental distribution.

I. INTRODUCTION

Cathodic arc deposition is an established technique for the formation of thin films [1,2]. Cathodic arc plasma sources of various designs can be operated in vacuum for the deposition of metal films[3], films of amorphous hard carbon [4-11] or amorphous semiconductors [12], and in a gaseous atmosphere to form metal oxide [13-16] or metal nitride thin films [14, 17-20]. Cathodic arc deposition is a high rate deposition method because the cathodic arc discharge which is used to transform the cathode material into the plasma state is typically a high-current discharge of one hundred to several hundred amperes, and the ion current, which determines the amount of metal plasma available for deposition, is around 10% of the arc current [21]. This results for certain sources of specific design in deposition rates as high as 3000 Å/s [3]. A problem for cathodic arc deposition is the formation of droplets of the cathode material (solid debris in the case of carbon) along with the plasma. This has been addressed by applying bent magnetic macroparticle filters which separate plasma and particles [5-14, 22-25]. All these filters lead to a certain loss of plasma which is deposited at the filter walls, and effective filters transport about 25% of all ions injected into the filter [25].

The plasma distribution of a cathodic arc deposition system is given by the "natural" plasma distribution of the cathodic arc which is influenced by the anode and cathode geometry, and it can be modified by magnetic fields. The plasma distribution determines the spatial profile of the deposition and is therefore an important parameter for film homogeneity and maximum sample size.

In the present paper we describe a number of experiments investigating the plasma distribution of various deposition systems - plasma source without additional magnetic field, and plasma source with additional magnetic field and with magnetic macroparticle filter. We also demonstrate the successful application of a magnetic multicusp configuration to homogenize and flatten the plasma profile for high quality deposition.

II. CATHODIC ARC DEPOSITION SYSTEMS

For all the experiments described in the following sections we used a pulsed cathodic arc plasma source consisting of a 6 mm diameter cathode surrounded by a cylindrical anode [26]. The discharge was triggered by a high-voltage spark over a ceramic insulator around the cathode. The arc current was 50-300 A, the arc duration 5 ms and the repetition rate 1 Hz. The source could be equipped with a solenoid of 10 turns around the anode to focus the plasma. The arc current was used to feed the solenoid, and the maximum magnetic field at the position of the cathode surface was 75 mT. The source could also be connected to a 90° bent magnetic macroparticle filter which consisted of a free-standing coil of 25 turns with a minor radius of 4 cm and a major radius of 12 cm. The maximum magnetic field in the filter was 50 mT when the solenoid was operated electrically in series with the arc discharge and the focusing solenoid.

A magnetic multicusp arrangement, as is often used in gaseous plasma sources to homogenize and flatten the plasma distribution [27-29], could be attached to the exit of the magnetic macroparticle filter. We explored two different sizes of multicusp "homogenizer". The small multicusp (or "magnetic bucket") consisted of a steel tube of 8 cm length and 13 cm diameter, the large one of 8 cm length and 22 cm diameter to the inside wall of which SmCo magnets were arranged to form a multicusp magnetic field configuration, 10 magnets for the small multicusp, 30 magnets for the large one. Fig. 1 shows the plasma source with solenoid, magnetic macroparticle filter, the large homogenizer, and the substrate location.

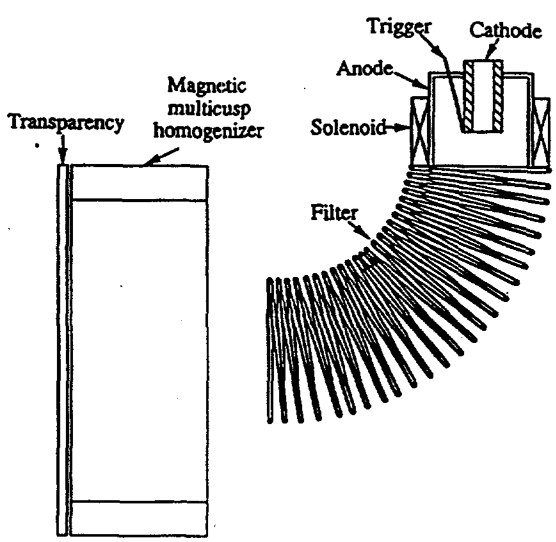

Fig. 1: Deposition arrangement showing the plasma source with focusing solenoid, the magnetic macroparticle filter, the large magnetic multicusp and the substrate (transparency).

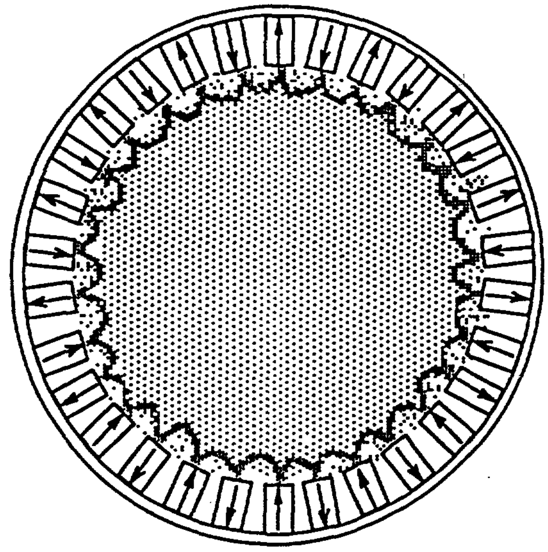

Fig. 2: End view of the large magnetic multicusp with schematic plasma distribution.

Fig. 2 shows an end view of the large homogenizer and schematically the distribution of the plasma in it. The magnets were 2 cm thick, and the region of the strong magnetic field reached about 2.5 cm into the plasma region. This results in an almost field-free inner region for the small multicusp of 4 cm and for the large multicusp of 13 cm diameter.

III. DETERMINATION OF THE DEPOSITION RATE

The deposition rate is proportional to the plasma distribution for cathodic arc discharges because the vacuum arc plasma is fully ionized and the neutral component in the plasma is typically only a few percent [30]. If a magnetic filter is used even this small fraction is removed and only ionized species are emitted from the filter [31]. The deposition profile which is given by the plasma distribution was determined by depositing semitransparent metal films on a transparent substrate (polyester transparency, 125 μm thick). Using a HeNe laser absorption set-up the transmitted light as a function of position was determined. The thickness of the deposited film was determined using the optical constants of the film material and of the dielectric substrate [32]. Assuming a two layer system and taking transmission, absorption and reflection into account, the film thickness was calculated from a numerical solution of the Fresnel equations [33].

The absorption method is a reliable determination of the deposited film thickness if the optical constants don't vary too much over the range of film thickness deposited on the substrate. To test the reliability of this method we have measured for one case the plasma profile by the absorption method and compared it to a measurement of the plasma distribution using a Langmuir probe. A pulsed cathodic arc plasma source with a cobalt cathode was used for deposition on a transparency, and the film thickness was determined by the absorption method. In a second experiment a Langmuir probe with an area of 10 mm^2 at a negative bias voltage of -100 V was used to measure the ion saturation current during the arc discharge. The probe was at the same distance as the transparency (9 cm from the cathode surface) and moved perpendicular to the discharge axis. From the ion saturation current the plasma density profile was calculated. Fig. 3 shows the normalized deposition rate determined by the absorption method (empty dots) and by the probe method (full dots). The agreement is very good.

IV. PLASMA DISTRIBUTION FOR CATHODIC ARC SOURCE

The plasma distribution of a cathodic arc discharge has been investigated by a number of authors. In earlier papers [21, 30, 34-36] the research interest came from the field of vacuum current interrupters, and this origin explains the electrode geometry which was in most cases two disc shaped electrodes opposed to each other. The distribution was determined to be anisotropic, peaked towards the anode, and described by cosine or exponential functions. More recent papers describe systems closer in geometry to cathodic arc deposition devices with annular or cylindrical anodes [26, 37, 38]. A deviation from the cosine distribution was found, and axial magnetic fields are often used to influence the plasma distribution and form a distribution more peaked on the discharge axis.

We have measured the plasma distribution using the absorption method for a number of cathode materials and arc currents. No additional magnetic field was applied, and the substrate (transparency) was at a distance of 9 cm from the cathode surface. Fig. 4 shows the normalized distribution of the deposition for various cathode materials.

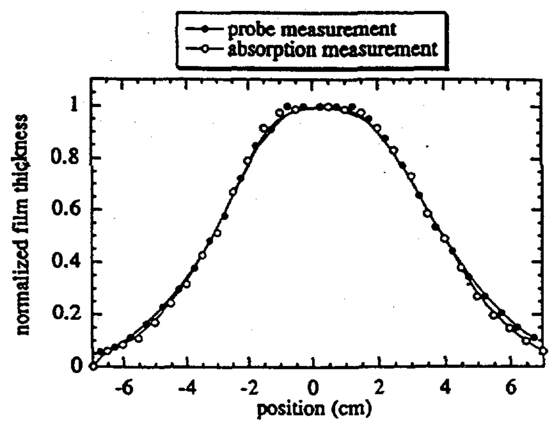

Fig. 3: Normalized film thickness as a function of position in the substrate plane. Co cathode, plasma source without solenoid, filter and multicusp, distance cathode surface - substrate 9 cm, 160 A arc current. The rate was measured using the probe method (full dots) and the absorption method (empty dots).

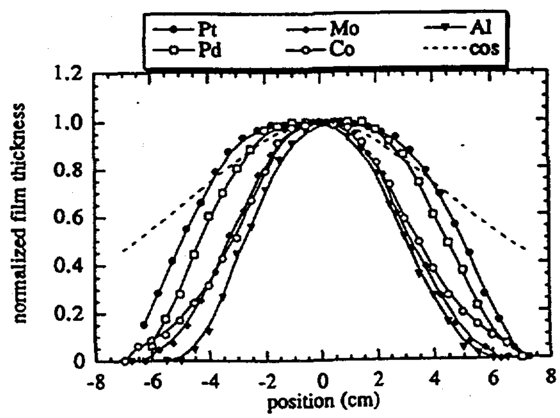

Fig. 4: Normalized distribution of the film thickness for various cathode materials. Plasma source without solenoid, filter and multicusp, distance cathode surface - substrate 9 cm, 160 A arc current. The rate was measured using the absorption method.

We found that the distribution deviates considerably from the cosine, and the full width at half maximum (FWHM) is a function of the cathode material. Fig. 5 shows that the FWHM of the distribution varies considerably with cathode material, and there is a tendency for materials with higher mass to have a broader distribution.

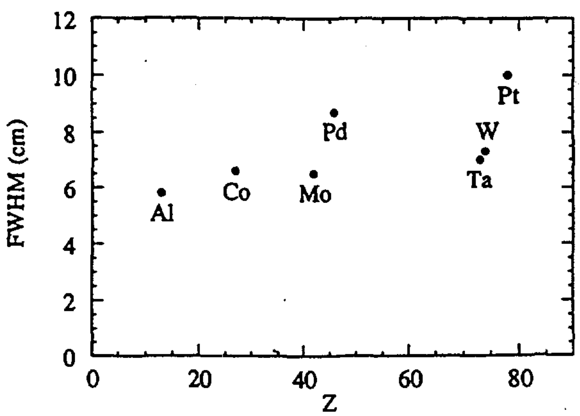

Fig. 5: FWHM of the film thickness profile taken from Fig. 4 for various cathode materials as a function of atomic number.

In another series of experiments we measured the FWHM of the distribution as a function of the discharge current. Fig. 6 shows the FWHM of the distribution for Pt in the current range between 50 and 300 A.

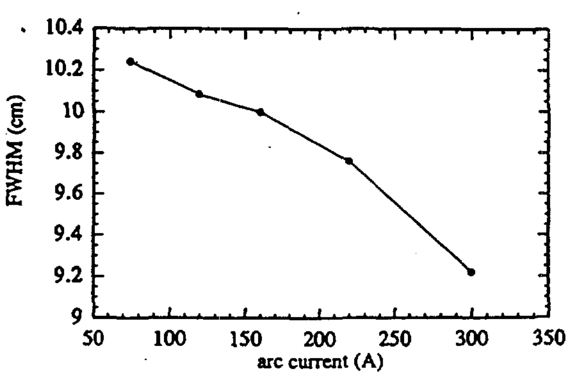

Fig. 6: FWHM of the film thickness profile for a Pt cathode as a function of the arc current. Plasma source without solenoid, filter and multicusp, distance cathode surface - substrate 9 cm. The rate was measured using the absorption method.

The distribution is more peaked on the discharge axis at higher arc currents. This effect was found also for other cathode materials (Al, Ta). This could be due to the fact that with increasing arc current more plasma is produced and ejected along the discharge axis but due to the geometry of the anode there is a shading effect for plasma emitted to the side.

V. PLASMA DISTRIBUTION FOR CATHODIC ARC SOURCE WITH MAGNETIC MACROPARTICLE FILTER

Magnetic macroparticle filters are typically 90° bent magnetic field arrangements with the magnetic field produced by external solenoids [5, 7, 12, 13, 14, 37], or by solenoids within the vacuum system which can be driven by the arc discharge current itself [6, 25, 26]. Other bending angles have also been tested for macroparticle filtering such as straight filters [4, 6, 39], 20° [9], or 45° [24, 40].

In bent magnetic field arrangements the plasma undergoes complex transport processes best described by a fluid model for a partially magnetized plasma [25, 41]. The models predict a shift of the plasma toward the outer torus wall [41], which has also been observed experimentally [25]. A shift perpendicular to the plane of symmetry has also been found [25], the direction of which changed with the direction of the toroidal magnetic field. Other papers report on a symmetric plasma distribution [5], or a distribution which is shifted toward the inner or outer torus wall depending on the magnetic field strength, and also shifted perpendicular to the plane of symmetry [42]. Possibly, the motion of the plasma column in the filter can be described by a spiral motion, and depending on the geometry, field strength, and plasma properties, all kinds of shifts can be observed.

We have measured the deposition profile using the plasma source with focusing solenoid and attached macroparticle filter. The profile was measured at a distance of 9 cm from the filter exit. Fig. 7 shows, for the examples of Ta and Al depositions at a current of 300 A, that the profiles were shifted to the outer wall of the filter in our case, and that they were asymmetric. We observed the same effect as for the plasma source without solenoid and filter, namely a different width of the plasma distribution for different elements.

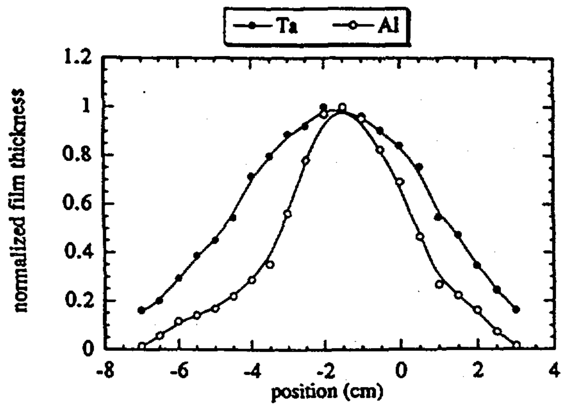

Fig. 7: Normalized film thickness as a function of the position in the substrate plane. Ta (full dots) and Al (empty dots) cathode, plasma source with solenoid and filter. Distance filter exit - substrate 9 cm, 300 A arc current. The rate was measured using the absorption method.

The last observation has an important consequence. The problem of the deviation of the deposition maximum from the filter axis can be solved by simply placing the substrates at the deposition maximum, or by using additional coils at the filter exit to change the position of the deposition maximum. But a different width of the distribution for various elements means that if a deposition is performed using an alloy cathode the different elements will be separated spatially, and a different ratio of the elements will be found at each radial location. We have observed this effect when depositing a film using an alloy cathode of composition $Nd_{1.0}Fe_{7.0}$. The plasma source with solenoid and filter was used, the substrate was a silicon wafer located at a distance of 5 cm from the filter exit, and the arc current was 300 A. The ratio of Nd and Fe in a film of 3000 Å thickness was determined by Rutherford Backscattering Spectrometry (RBS) over a range of 1.5 cm from the sample center. Over this small range the ratio varied from $Nd_{1.0}Fe_{10.0}$ at the center of the sample to $Nd_{1.0}Fe_{9.0}$ at 0.5 cm distance from the center, $Nd_{1.0}Fe_{7.2}$ at 1 cm distance, up to $Nd_{1.0}Fe_{6.7}$ at 1.5 cm distance. The increase of the heavy element Nd toward the edge of the sample reflects the fact that heavier elements have broader distributions.

VI. APPLICATION OF A MAGNETIC MULTICUSP HOMOGENIZER

In order to overcome this problem we have used an approach well known in other domains of plasma physics - the use of a magnetic multicusp field to homogenize the plasma distribution.

The magnetic multicusp is a magnetic field configuration established by alternatively polarized magnets as shown in Fig. 2, which produces a strong field at the border of the multicusp but an almost field-free in the inner region. Diffusion in the plasma leads to a flat plasma profile in the inner region, but transverse diffusion is greatly reduced by the strong magnetic field at edge thus confining the plasma within the multicusp.

We can estimate the diffusion in the plasma by calculating the drift velocity of ions and comparing it to the directed velocity of ions in a vacuum arc plasma. The diffusion in the field-free case is given by the ambipolar diffusion coefficient $\mathscr{D}_a$ which is for ion-ion collisions in the hard sphere approximation [43]

$$\mathscr{D}_a = 2\mathscr{D}_i = \frac{6}{8}\frac{1}{n_i r_i^2}\sqrt{\frac{kT_i}{\pi\, m_i}} \qquad (1)$$

where $\mathscr{D}_i$ is the ion diffusion coefficient, n_i is the ion density, r_i is the ion radius, m_i is the ion mass, T_i is the ion temperature, and k is Boltzman's constant. The plasma density in the magnetic multicusp can be estimated from the deposition rate at the multicusp exit plane and is of order 10^{19} m^{-3}. The ion temperature (not to be confused with the directed ion velocity) is comparable to the electron temperature and is around 1 eV [44, 45]. We assume a ratio of the plasma density of about 2 for the plasma on axis to the plasma at 5 cm distance from axis (see Fig. 4), and can estimate a plasma density gradient over the multicusp radius of 10 m^{-1}. In this case the ion drift velocity v_i^{drift} is [43]

$$v_i^{drift} = -\mathscr{D}_a \frac{\nabla n_i}{n_i} \quad (2)$$

and we obtain for Al ions an approximate value of the drift velocity of v_i^{drift} = 5x10^4 m/s and for Pt ions v_i^{drift} = 2x10^4 m/s. This should be considered only as a rough estimate, but it shows that the drift velocity and directed velocity of ions which is typically 10^4 m/s are of the same order of magnitude and thus a magnetic multicusp with an aspect ratio of about 1 should be long enough to provide a flat plasma profile if the plasma is trapped in the multicusp. We can also estimate the cross-field drift velocity at the border of the multicusp by the Bohm diffusion coefficient [43]

$$\mathscr{D}_{Bohm} = \frac{1}{16}\frac{kT_e}{eB} \quad (3)$$

where T_e is the electron temperature, e the elementary charge, and B the magnetic field strength. Assuming a magnetic field strength of 410 mT (SmCo magnets) and an electron temperature of 1 eV, we obtain ion drift velocities perpendicular to the magnetic field of order 1 m/s. This is four orders of magnitude smaller than the directed ion velocity and drift velocity in the field-free region, and should be sufficient for highly effective confinement of the plasma in the magnetic multicusp interior region.

Fig. 8 shows the deposition profile for a number of elements obtained at the exit plane of the multicusp. The deposition was performed using the plasma source with solenoid, filter and small multicusp in a distance of 6 cm from the filter exit. The profiles are quite different from profiles obtained without multicusp. They are flat over a range of about 4 cm, and they are very similar for all elements.

In order to enlarge the area of homogeneous deposition we used a multicusp with the same length but a larger diameter (22 cm instead of 13 cm) and a larger number of magnets (30 instead of 10).

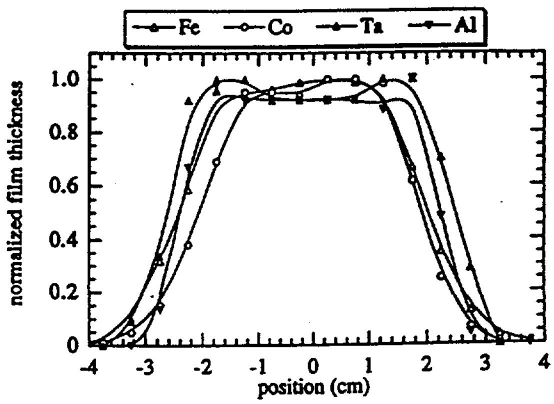

Fig. 8: Normalized film thickness for Fe, Co, Ta, and Al. Plasma source with solenoid, filter and small multicusp, distance filter - multicusp 6 cm, transparency in exit plane of multicusp, 300 A arc current. The rate was measured using the absorption method.

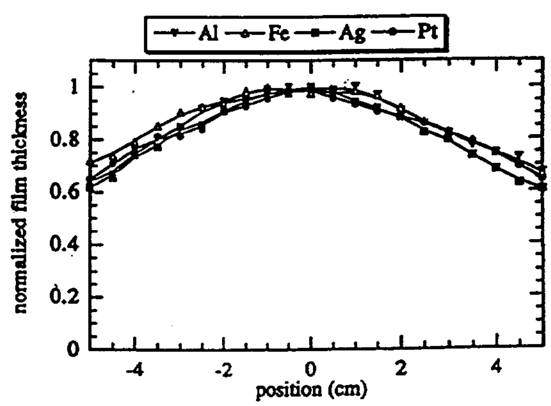

Fig. 9: Normalized film thickness for Fe, Ag, Pt, and Al. Plasma source with solenoid, filter and large multicusp, distance filter - multicusp 6 cm, transparency in exit plane of multicusp, 300 A arc current. The rate was measured using the absorption method.

Fig. 9 shows the profiles for different elements using the plasma source with solenoid, filter and large multicusp. The transparency was at the multicusp exit plane and the multicusp entrance plane at a distance of 6 cm from the filter exit. The discharge current was 300 A. Almost identical profiles were obtained for various elements, but the profiles are not as flat as with the small multicusp. It is probably necessary to use a longer multicusp field region as its diameter is increased so as to produce effective homogenization of the plasma distribution. This observation is in agreement with the estimation above.

When we replaced the SmCo magnets with ferrite magnets which have a much lower field strength, the multicusp had almost no effect and the profile is very close to the profile obtained without multicusp. The maximum field strength at the magnet surface for the SmCo magnets was 430 mT, for the ferrite magnets 40 mT. Fig. 10 shows the profiles for an Fe deposition using the plasma source with solenoid, filter and large multicusp for the two different types of magnet. For comparison the profile after removing the multicusp but leaving the transparency in the same position is shown also.

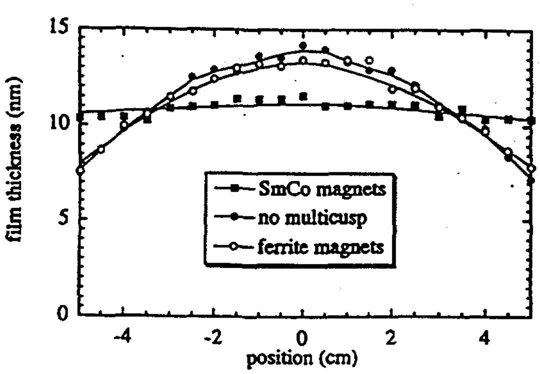

Fig. 10: Normalized film thickness for Fe; plasma source with solenoid, filter and large multicusp with SmCo and ferrite magnets, distance filter - multicusp 6 cm, transparency in exit plane of multicusp, 300 A arc current. For comparison deposition with same set-up but multicusp removed. The rate was measured using the absorption method.

In this case the profiles were not normalized, so as to compare deposition rates. The rate with multicusp is slightly lower in the center because the plasma is spread out over the multicusp diameter. The integrated rate over a substrate diameter of about 15 cm is comparable with and without multicusp.

In order to test the results for the deposition profiles obtained with the magnetic multicusp for an alloy deposition application we have repeated the deposition of a film very similar to the one described in the previous section. An alloy cathode with a composition $Nd_{1.0}Fe_{4.4}$ was used in the plasma source with solenoid, filter and the small magnetic multicusp 5 cm away from the filter exit. The Si wafer substrate was located in the exit plane of the multicusp, and the arc current was 300 A. The film composition of the 1800 Å thick film was determined by RBS over a range of 2.5 cm from the sample center, and the composition was found to vary only between $Nd_{1.0}Fe_{4.4}$ and $Nd_{1.0}Fe_{4.5}$ over this area. This demonstrates the successful application of the multicusp to a film deposition using an alloy cathode.

VII. SUMMARY

The plasma distribution for our cathodic arc plasma source was measured by an absorption method which was demonstrated to be a simple and reliable way of determining the plasma profile. It is more peaked at higher currents which is possibly a geometric effect of our source design. The width of the profile varies with the cathode material, and this effect occurs for the source without and with macroparticle filter. This leads to a spatial separation of the elements when a deposition is performed using an alloy cathode. If the plasma is ejected from the filter into a magnetic multicusp of appropriate design, however, the plasma profiles are flattened and show the same shape for various elements. Depositions using an alloy cathode demonstrated that the compositional homogeneity of the thin film is greatly improved by the application of a magnetic multicusp plasma homogenizer.

ACKNOWLEDGMENTS

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