Deposition Processes Utilizing a New Filtered Cathodic Arc Source

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ABSTRACT

A newly developed, commercially available cathodic arc source and macroparticle filter combination makes new arc deposition processes possible on a production scale. The source, its operating characteristics and its output are described briefly. Basic processes utilizing the filtered source to make hard, amorphous carbon films, a-C, are presented. The output of the filtered source, with a carbon cathode, is an intense plasma containing mostly C+ for the ionic component. Results previously obtained at the laboratory scale were confirmed which establish a relationship between substrate bias, and therefore C+ ion bombardment energy, and film hardness and stress. The trend is that the hardest a-C films (up to 80 GPa) are produced in the low, 0 to 50 eV, C+ ion energy range while higher energies produce films that are less hard, but also have less stress, so that they can be made quite thick (10 µm). Data needed for scale up of filtered arc a-C processes is presented. Plasma beam rastering in one dimension has been demonstrated and gives film thickness uniformities of 5% over a 10 x 3 cm area and 10% over a 14 x 4 cm area. The data has allowed development of 30 x 30 cm uniform rastering capability. Carbon throughput to the film has been measured to be up to .15 $\mu m \cdot m^2$/hr for 117 A arc current giving a non-rastered deposition rate of 16,000 Å/min over a 2 cm diameter spot. Rastered and non-rastered deposition spot shapes were measured and the divergence of the plasma column was characterized. Net carbon loss from the expanding plasma column is observed when downstream magnetic fields are not controlled.

INTRODUCTION

The cold cathode arc phenomenon provides a unique and useful technique for simultaneously vaporizing, ionizing and accelerating solid material from a cathode for deposition elsewhere[1]. Cold cathode arcing is mediated by arc spots on the cathode, which move laterally about on the face of the cathode in a random fashion, giving rise to the name sometimes used, random arcs. The entire current of the arc, which may be 50 to 500 or more amperes[2], flows through one or more of these cathode spots which causes intense local heating and therefore vaporization. Ionization and acceleration of the vaporized atoms occurs in the space in front of the cathode by a complex process thought to involve a region of positive space charge from which positive ions are repelled[3]. In this manner positive ions of the cathode material are accelerated to 10 to 100 eV kinetic energy even though the cathode is at a negative potential. For vacuum arc deposition usage, these ions and a portion of the electron current emitted from the cathode are directed in the form of a plasma beyond the cathode-anode gap towards a substrate using a suitably shaped anode and magnetic fields with 0.01 T order of magnitude strength. Droplets or fragments of the cathode surface are also ejected by the violent local heating at the moving spots and accompany the ions downstream away from the cathode. These droplets or fragments are called macroparticles, and may become incorporated into any film deposited from the vaporized and ionized material emitted from the cathode. Carbon arcs (graphite cathodes) are especially bad in this respect so smooth films can only be achieved if effort is taken to remove these macroparticles. A filter based on "plasma-optics"[4,5] was used to remove macroparticles and is described in subsequent sections.

The advantages of filtered cathodic arc deposition are numerous compared, for example, with electron beam evaporation or magnetron sputtering. The arc vaporization process itself provides vaporization on the order of .1 g/min per 100 A of arc current with virtually no scale up limit and approximately 70% to 90% of this is both atomized and ionized, depending on the cathode material[6]. The arcing is done with safe, low voltages of 20 to 40 volts. Almost any conductive material can be so vaporized directly from solid form, often eliminating the need to use toxic, chemically unstable gases. Waste or stray cathode material deposits are solids that can be recovered and recycled. The ionization and the acceleration of the ions that is native to cold cathode arc vaporization can be very valuable for formation of high quality thin films.

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Low energy (20 to 500 eV) ion bombardment of the surface of a growing film during deposition is known as ion assisted deposition (IAD) and provides densification of the film due to enhanced mobility of the depositing species caused by the ion impacts. IAD also may impart improved stability and durability to a film and allow control of film stress and stoichiometry. With cathode arc deposition, one has control of the ion impact energy by biasing the substrate negatively to further accelerate or positively to retard the ion kinetic energy relative to the native ion kinetic energy for the arc, which is 15 to 90 eV depending upon cathode material. Alloys generally retain their composition upon vaporization and deposition onto a substrate and a wide variety of compounds may be deposited by chemically reacting the arc plasma or depositing film with the appropriate gas. A wide variety of compounds may be deposited by chemically reacting the arc plasma or depositing film with the appropriate gas.

Filtering the arc brings further benefits. All but the ionized component of the vapor is removed, so essentially 100% of the material reaching the substrate is in the form of ions. Most filter designs also collimate the plasma column coming off of the cathode, creating a highly directional deposition that can be used for filling of trenches and vias or for pattern transfer by photoresist liftoff techniques. The filtered, directional deposition also confines the deposited material to the substrate area, leaving the remainder of the substrate chamber substantially free of incidental coatings. To give a sense of the cleanliness this allows, a viewport downstream of the filter placed parallel to the arc column within inches of it remains clean for dozens of hours of arc on-time. The filter also isolates the substrate from the heat and radiation of the arc which permits coatings to be applied to heat-sensitive or delicate substrates. These benefits of filtered arc deposition are difficult to achieve with electron beam evaporation or magnetron sputtering. Moreover the simplicity, cheapness, ruggedness and reliability of arcs are unmatched by the other two techniques except possibly in the most simplistic implementation.

The purpose of this study is to investigate several other characteristics of filtered cathodic arc deposition which must be shown to be manageable before this technology can be applied widely in commercial coating applications. These are area of uniform deposition coverage, total volume or mass throughput of cathode material to the coating, consumption and replenishment of cathode material, maintenance and cleaning intervals and procedures and detailed evaluation of macroparticle trapping efficiency of the filter. With the exception of the latter issue, we succeed in this article to demonstrate commercial viability of filtered cathodic arc deposition for high quality films. With respect to macroparticle transport, we see a many-fold reduction in particulates, but we do not reach a firm conclusion here due to unsuitability of the overall deposition facility for evaluation of particle contamination.

EXPERIMENTAL

The filtered cathodic arc source subsystem used in the present study was the model CAF-38 manufactured by Commonwealth Scientific Corporation and is based upon a patented "knee" filter design[7] which has been reported upon in brief previously[8]. The source is depicted in Fig. 1. The cathode consists of a shaped, pressed graphite cathode charge which is tightly clamped to a water-cooled stainless steel pedestal. For the work reported upon here, the active end of the charge was a 19 mm diameter right cylinder. The water-cooled anode was located downstream some distance allowing a rotary mechanical striker of conventional type to reach the face of the cathode charge to strike the arc, then swing out of the way of the discharge. These components were immersed in a generally solenoidal magnetic field with shape and field strength designed to direct a large portion of the arc plasma to the entrance of the filter duct while allowing the excess electron current to go to the anode. The arc current was maintained at 117 A giving an arc voltage of ~ 26 v. An electrically-isolated thermocouple inserted into a bore in the cathode charge near the base recorded temperatures of 250 to 300 °C after a typical 3 minute run.

The macroparticle filter consisted of a 45° bent tube with a step up in diameter from 152 mm to 203 mm O. D. at the bend. Numerous ring baffles with beveled inner edges formed the primary entrapment surfaces for macroparticles. The baffle set was designed so that not only was there no line-of-sight from the anode-cathode region to the substrate but also there was no "single bounce" trajectory by which a macroparticle could reach the substrate from the arc gap region. Upstream and downstream solenoidal magnet coils were located on either side of the 45° bend in such a way that lines of magnetic flux can jump the gap between the open ends of the coils and create a bent solenoidal field in that region. All fields were between 0.01 and 0.04 T (100 to 400 Gauss). In operation, electrons emitted from and repelled away from the cathode by its negative potential are confined to a cylindrical column near the axis of the filter duct by the magnetic field as they travel from the cathode through the duct to the substrate region. The carbon + ions, also emitted with some velocity from the arc gap, are attracted by electrostatic forces to the column of negative space charge formed by the confined electrons and thereby stay near axis also and are able to make the 45° bend.

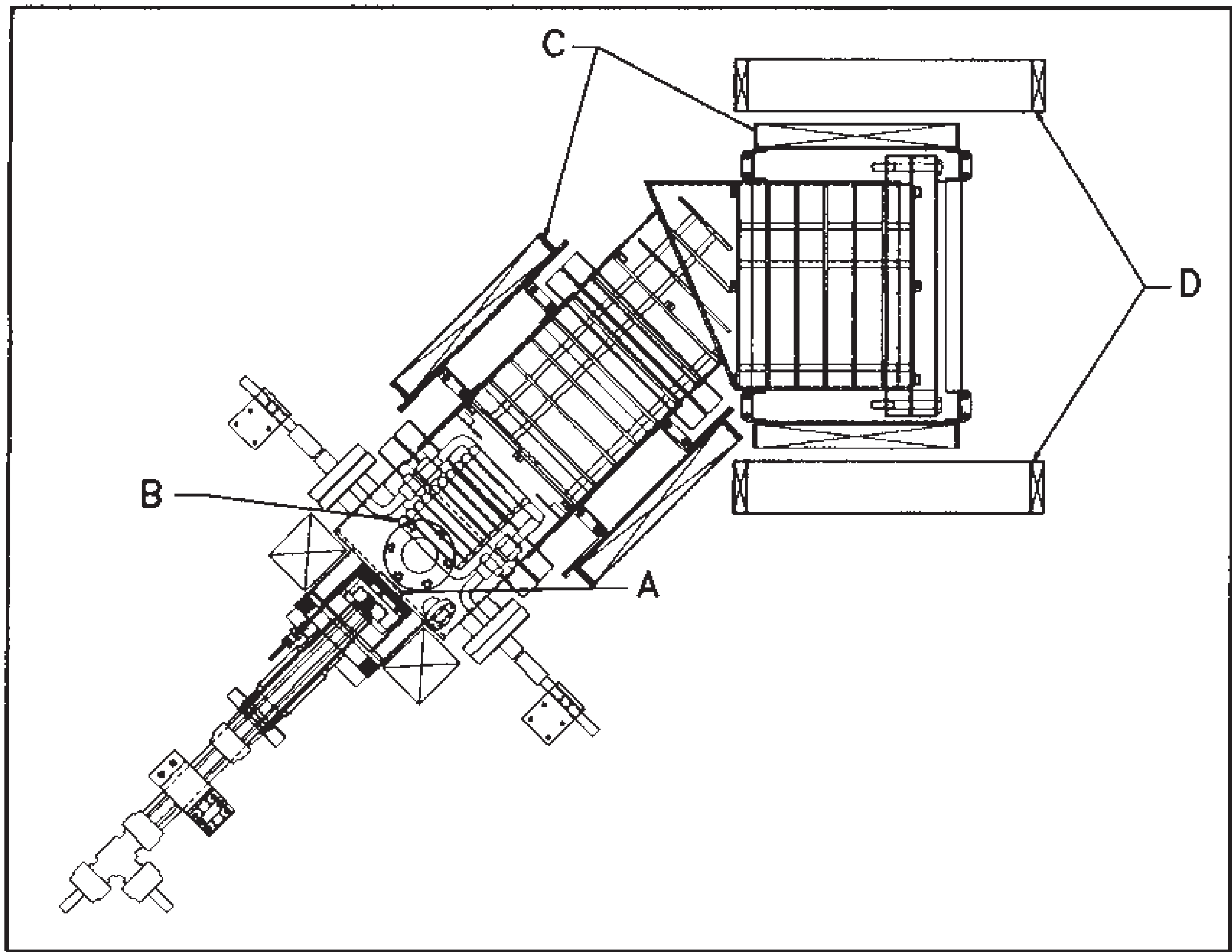

Figure 1. CAF-38 Filtered Cathodic Arc Source. Components - A: Cathode, B: Anode, C: Macroparticle Filter Magnetic Field Coils, D: Raster Magnetic Field Coils

A pair of circular Helmholtz-like raster coils were positioned on either side of the downstream filter coil, with their axis perpendicular to the duct axis. These were energized in series such that their fields reinforced each other and shifted the main fields in the duct which caused a deflection of the plasma column passing through the duct in that region. The deflection fields were on the order of 0.003 to 0.01 T (30 to 100 Gauss). A triangular waveform of 1.8 Hz frequency was used to drive these coils to give a repetitive sweeping type of raster of the plasma column. A newer design has another pair of such coils placed 90° to the first pair to give both X and Y raster.

The source and filter were mounted onto the cylindrical side of an 460 mm (18 in) long by 500 mm (20 in) diameter high vacuum deposition chamber. The chamber was pumped by a 200 mm (8 in) cryopump to a pressure of ~ 3 x 10^{-4} Pa (2 x 10^{-6} Torr) before each deposition run. An electrically isolated substrate mounting plate could be located at several locations to give a number of substrate setback distances, i.e., the distance from the exit end of the downstream filter coil to the plane of the substrate. Good thermal contact was provided between the mounting plate and the back of the substrate, and the plate was massive enough and cool enough before each run that no other cooling was needed. Areas of the mounting plate not exposed to the arc column were covered with Kapton tape. All depositions were done with the arc column at normal incidence to the surface of the substrates, except for the slight angular deviation due to the rastering.

Deposition runs started with a preliminary DC glow discharge cleaning of the substrate. This was done with the substrate biased -400 v with respect to the chamber walls in 7 Pa (50 mTorr) flowing argon gas, giving 2 to 15 mA of discharge current depending upon size and number of substrates. Preclean time was 3 min. After pumping down again to near ~ 3 x 10^{-4} Pa (2 x 10^{-6} Torr) in about one minute, a bias

of -500 to -1000 v DC was applied to the substrates and the arc was struck. This high voltage bias was maintained for between 6 and 25 sec during which time 0.1 to 1 A of positive ion current was collected on the substrate and mounting plate, depending upon the size and number of substrates exposed. At the end of the high voltage bias duration, a bias of -50 v DC was rapidly switched in without stopping the arc. This lower bias was maintained throughout the remainder of the deposition. Deposition times ranged from 12 sec to several min. The apparent current drawn on the substrate and mounting plate during the lower bias phase was 0.05 to 0.25A. Although no gas was admitted to the system during deposition and full pumping speed was maintained, the pressure in the deposition system rose to approximately 1 x 10^{-3} Pa (1 x 10^{-5} Torr) while the arc was on, as indicated by a Bayard-Alpert type ion gauge not directly exposed to the arc plasma. This is due to gas liberated from the graphite cathode and chamber walls by thermal radiation and ion and electron bombardment. The pressure generally drops during the coating run, and for clean chambers and metallic cathodes, can return to chamber base pressure or even lower due to the gettering effect of some metals.

Deposition runs were coordinated by the CAF-38 Controller provided by the manufacturer. Deposition was started using the automatic striker. A pneumatic rotary actuator swings the striker around to touch the face of the cathode charge until the current drawn by the striker is detected. Very quickly thereafter the direction of rotary actuation is reversed. It is the breaking of the striker contact that causes a spark and ignites the arc. Once the arc current is above a preset threshold, the Controller starts a timer. If the arc extinguishes (which didn't happen during any of the runs reported here with carbon), the current sensor halts the timer. The auto re-strike circuit will strike again, up to five times for each arc outage. Once the arc current is detected again, the timer resumes. When the run timer reaches a preset run duration, the arc power source is turned off. Another timer accumulates the arc-on time between cathode charge changes, allowing the operator to know when to change charges, about every 1.25 hours when using the small charges used in the present study; other larger charges last 3 hours. The controller also turned on and off the arc source cooling water flow and the source and filter magnet coil currents. These were monitored by the Controller via sensors, providing an interlock function to disable the arc power source in event of loss of cooling or magnetic fields. The Controller provided means of setting and reading out the electrical parameters, arc current, arc voltage, magnet coil currents and raster amplitude, as well as reading out the cathode charge temperature.

Deposition runs were performed for the characterization of the deposition thickness distribution in the arc spot on the substrate, for both rastered and non-rastered arc columns. Deposition was done at four substrate setback distances, 14 cm (5.5 in), 26.7 cm (10.5 in), 36.2 cm (14.3 in) and 55.9 cm (22 in), where the setback distance is defined as the distance from the exit end of the exit end of the downstream macroparticle filter magnet coil to the plane of the substrate. First, deposition rate calibration runs were performed and this allowed depositions for the detailed measurements of deposition distribution patterns for to be timed for control of the maximum thickness in the typical pattern to be ~ 1000 Å so that analysis by refractometer would be occurring in a well defined thickness regime. The substrates were polished Si wafers of 100, 150 and 200 mm diameter. Dots or lines of baked photoresist were arrayed over the deposition surfaces of the wafers to assist in thickness measurements. In all cases, the substrates of sufficient size to contain the entire deposition spot. In the cases of 36.2 and 55.9 cm setback with raster, two 150 mm (6 in) diameter wafers were placed flat-to-flat to form a large enough surface to capture the entire deposition pattern. Another series of runs was performed at 36.2 cm setback with raster on a rotating 100 mm (4 in) wafer; several different lateral offsets, spanning 0 to 50 mm, between the center of the plasma column and the center of the wafer were used.

The process chamber and arc source were vented with dry nitrogen as soon as the cathode temperature cooled to 100° C (~ 30 sec) and the substrates were removed. Acetone and lint free wipers were used to remove the photoresist, and film thickness determination was made at a large number of locations on the substrates by both profilometry and microscopic spectrally scanned refractometry, using a Dektak III and a Nanospec, respectively.

Routine maintenance consisted of replacing the carbon cathode charge every 1.25 hours of arc-on time and performing a brief cleaning procedure at that time. As stated before, the deposition chamber walls stayed clean except for regions and fixtures directly exposed to the arc column; at this time these areas of the deposition chamber were wiped and particulates removed with a vacuum cleaner. While the cathode port was opened, a vacuum cleaner nozzle was placed in the port opening and allowed to operate for 30 sec to clear any carbon powder accumulations. Other than this, the filter was never cleaned and showed no sign of degradation of performance. The filter has been designed so that gravity will cause any powder to accumulate in harmless places where it can be removed with a vacuum cleaner.

RESULTS

The arc performed stably, by arc standards, with no arc extinguishing events occurring during the reported runs. The arc plasma column was an intense blue color, probably attributable to emissions from excited C^+ ions. The raster motion of the arc column was easily visible.

Carbon films were obtained on the substrates in circular spots, or in elongated spots when 1-dimensional raster had been applied. The carbon films were very hard, dense, smooth, electrically insulating and adherent to the substrates. It is presumed, based on our previous work[9], and that of others[10,11], that the material we deposited is "amorphous diamond", also referred to as tetrahedrally amorphous carbon (TAC) or hard a-C (the "a" signifying "amorphous"). Correlation between the Dektak and the Nanospec thickness readings required us to assign a refractive index of 2.5 to 2.6, which is in agreement with published values for a-D, TAC and hard a-C. Interference fringes on the deposition patterns allowed a quick visual estimation of film thickness.

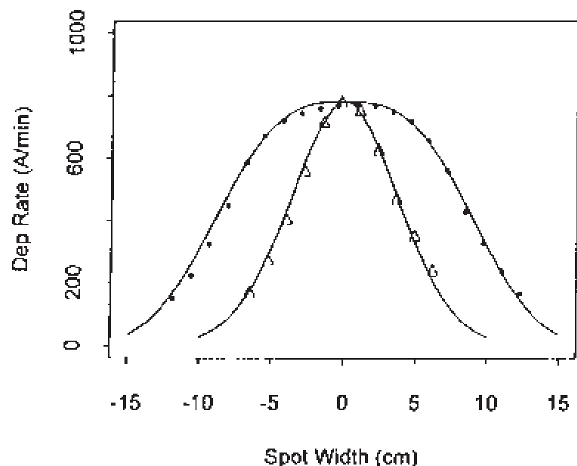

Figure 2. Carbon Deposition Spot Profile at 36.2 cm Substrate Setback.

The arc deposition spot size and shape as a function of setback distance of the substrate are important parameters for coating applications requiring uniform film thickness. Figure 2 shows the 1-dimensionally rastered deposition spot profile obtained at 36.2 cm (14.3 in) substrate setback. The profile is expressed in terms of deposition rate as a function of position in the spot. The non-rastered, circular spot had the same profile as the non-rastered axis of the rastered spot, but the peak deposition rate went up to 1530 Å/min versus 780 Å/min with raster. Similar data was obtained at each of the four setback distances used, as shown in Table I. The full width at half maximum (FWHM) deposition rate of the deposit spots are given along with the deposition rate at the peak, R_{max}.

Table I
Deposition spot width and max deposition rate as a function of setback.

	Non-raster		Raster	
Setback (cm)	FWHM (cm)	R_{max} (Å/min)	FWHM (cm)	R_{max} (Å/min)
14	3.4	16000	N/A	N/A
26.7	6.1	4030	13.9	2080
36.2	7.8	1530	18.2	780
55.9	12.5	390	27.1	245

The smooth curves shown in Figure I were obtained by approximately fitting the deposition patterns to functions of the form:

$R(r) \sim R_{max} \cdot \exp(-|r|^n / r_0^n)$ (Eqn. 1)

where R(r) is the deposition rate at r distance away from the center of the spot, R_{max} is the peak deposition rate in the deposit spot, r_0 is characteristic of the width of the spot and n is an exponent ranging from 1.7 to 3. For rastered deposits,

$R(x,y) \sim R_{max} \cdot \exp(-|x|^n / x_0^n) \cdot \exp(-|y|^m / y_0^m)$ (Eqn. 2)

with similar definitions to Eqn 1. Table II gives the parameters for fitting the present data, R_{max} being obtained from Table I.

Table II
Fitting parameters describing deposit spot shape.

	Non-raster		Raster	
Setback (cm)	x_0 or r_0 (cm)	n	y_0 (cm)	m
14	2.1	1.7	N/A	N/A
26.7	3.8	1.7	7.4	2.8
36.2	4.8	1.8	10.3	3.0
55.9	7.5	2.0	15.3	3.0

It is important to note that we are not ascribing physical significance to the functions describing the spot shape; they are merely analytical representations that are helpful for analysis.

Uniformity of the thickness of the film in the arc deposit spots can be seen to good only near the center of the

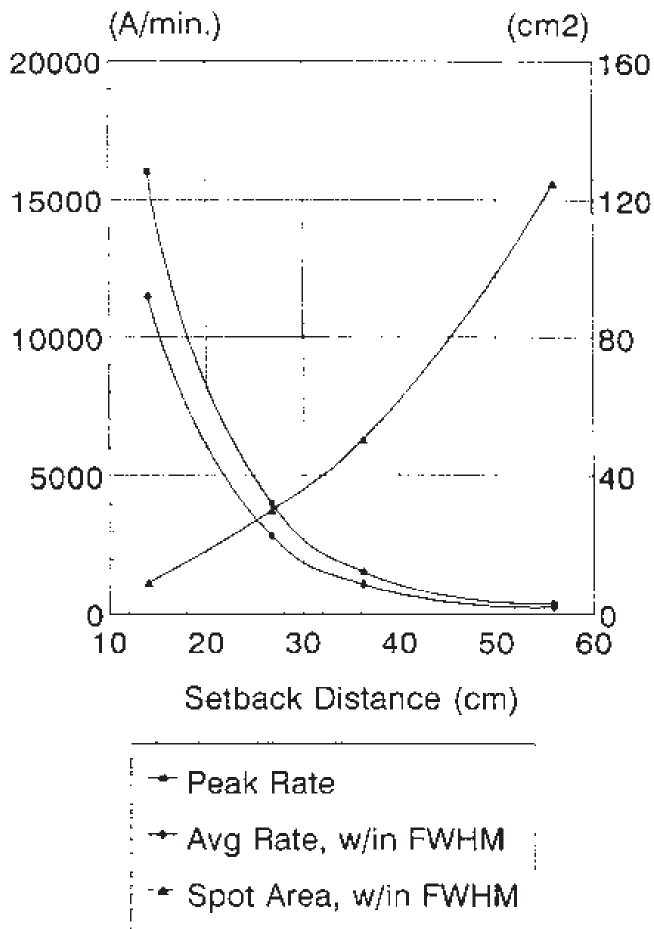

Figure 3. Non-rastered Deposition Rate and FWHM Spot Size as a Function of Substrate Setback.

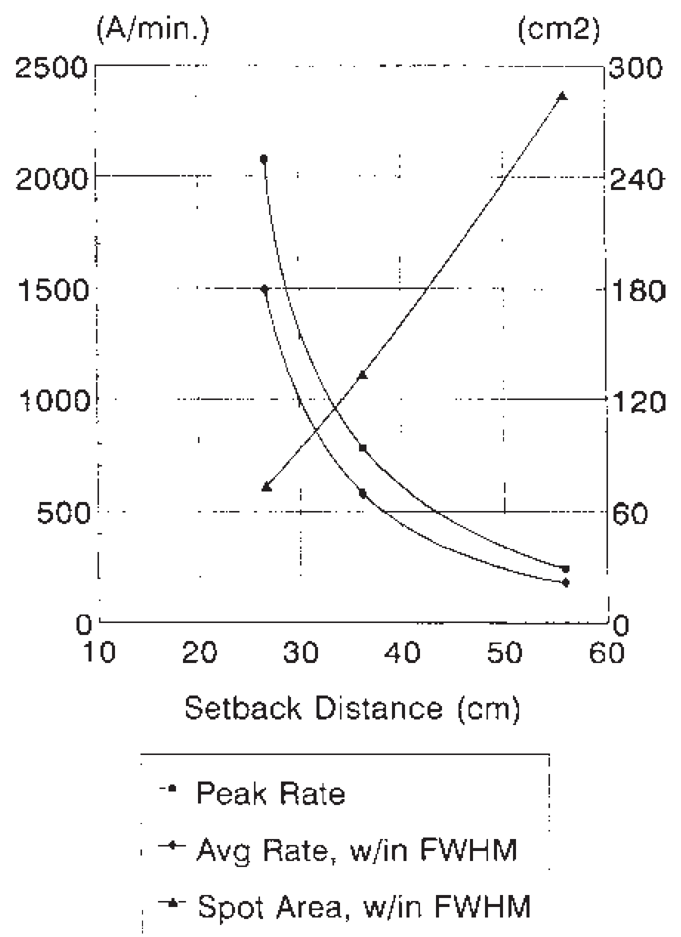

Figure 4. Rastered Deposition Rate and FWHM Spot Size as a Function of Substrate Setback.

deposition spot At the largest setback distance, 55.9 cm, and with rastering in one dimension, film thickness uniformity of 5% was found only over a 10 x 3 cm area and uniformity of 10% was found over a 14 x 4 cm area. Rotating a 100 mm diameter wafer about its center in the rastered plasma column at 36.2 cm setback gave only ~ 15% uniformity at best.

Integrating the deposition rate or deposit thickness under the curves typified by Figure 2 out to the half maximum, then dividing by the area this covers allowed us to calculate the average deposition rate over that area. This is shown as a function of setback distance in Figures 3 and 4 for non-rastered and rastered plasma columns, respectively.

Integration of the local film thickness times the area element over the area of the deposition distribution out to near zero deposit thickness gave the total volume of the film in the deposit spot. Dividing this by the duration of the deposition run in each case gave the volumn rate of carbon deposition, a representation of the total mass throughput rate of the arc source and filter. This is expressed in units of $\mu m \cdot m^2 \cdot hr^{-1}$ for both non-rastered and rastered cases as a function of setback distance in Figure 5.

DISCUSSION

We have characterized a particular configuration of the CAF-38 filtered cathodic arc source with special regard for its output characteristics at the deposition substrate. The deposition patterns and rates will change somewhat if the configuration or operating parameters of the source are changed. With this source, some of the adjustable parameters are: arc current, magnetic field strengths, cathode-anode gap length, along-axis location of solenoidal magnetic coils, along-axis location of the raster coils, cathode charge diameter and others. Varying these parameters has modest yet significant effects upon the spatial aspects of the deposition. However, we decided to characterize in detail one particular configuration in order to demonstrate how it may be done and to show that adequate information can be obtained for a process

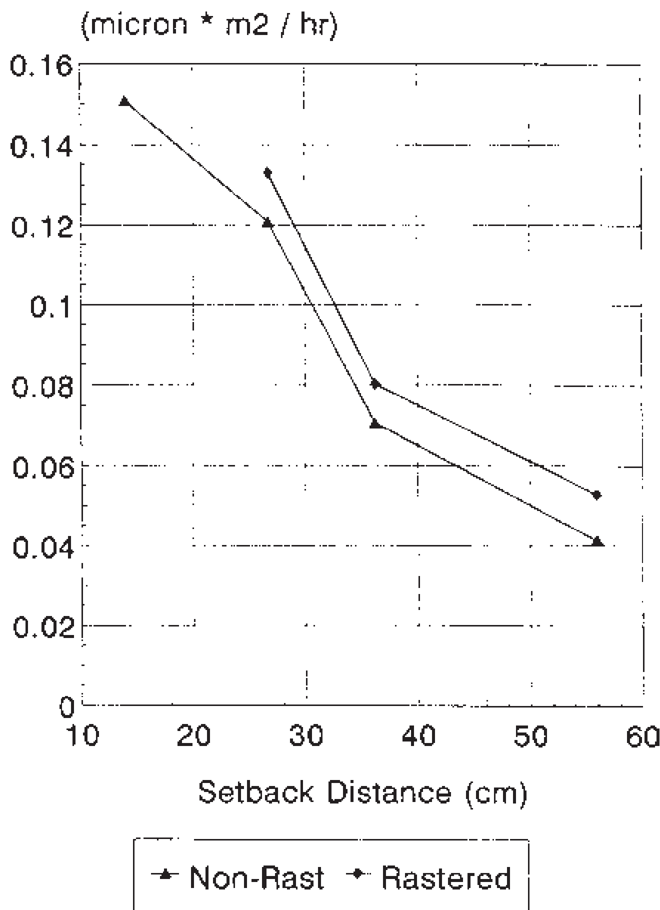

Figure 5. Volumetric Deposition Rate for Carbon as a Function of Substrate Setback.

engineer to evaluate filtered arc coating for any given application.

The CAF-38 arc source and filter were used with no extra magnetic confinement of the arc plasma column as it reached the deposition region, and this allowed the plasma column to diverge as it traveled through the deposition chamber, as shown in Tables I and II and Figures 3 and 4. Even with this divergence and a moderate amplitude of raster, good uniformity could only be obtained over small areas, by commercial and industrial standards. However, the plasma column retained its shape during rastering, indicating that higher raster amplitude can be applied without disrupting the basic operation principle. The results show that 1-dimensional raster is not sufficient for coating large areas uniformly but confirm that 2-dimensional rastering at higher deflection amplitudes will yield good uniformity. A raster amplifier and coils capable of 30 x 30 cm area of uniform raster are coming on line as this goes to press.

A striking loss of carbon throughput to the depositing film was observed as substrate setback distance was increased, as shown in Figure 5. This is due to the loss of magnetic confinement of the electrons in the plasma column after the column exits the downstream filter coil. Some of the C^+ ions follow the electrons, which are diverging off axis, and are not collected on the film. Experience has shown, not reported here, that this divergence can be controlled with the addition of magnetic coils in and around the deposition chamber. 3-dimensional magnetic modeling software has been used successfully to tailor the fields to achieve several improvements. It appears to be better to raster a confined beam than to attempt to achieve uniformity via divergence. The data here show that arc spot size can be evaluated at any setback distance, and the new raster amplifier allows the number of magnetic deflection steps in the "slow" raster axis to be varied between 1 and 16, which enables one to tailor the overlap of adjacent "fast" axis sweeps to achieve very good uniformity. The overlapping of spots or "fast" axis sweeps is easily modeled with existing beam density summing software developed by the authors.

The acceptance of cathodic-arc sources into production environments requires, in addition to producing high-quality coatings, that they operate in a reproducible manner, with minimal supervision. The control circuitry used in this work provides the safety interlocks, run timing and automatic restrike that allows unsupervised operation of the arc source. Also, arc sources must be scaleable to large areas, addressed above, and high rates and have sufficient cathode lifetimes.

For the present study, the CAF-38 was operated at 33% of it rated arc power (the source is rated for 350 A continuous duty). Coating rates in arc sources are approximately proportional to the arc current over a large range of currents. However, the fraction of cathode material eroded in the form of macroparticles and neutrals increases as the arc current increases, so there is a trade-off between rate and efficient use of the cathode material. This can be mitigated to some extent by vigorous cooling of the cathode, but multiple cathodes may prove an easier alternative.

The areas that are the focus of our continuing efforts are the elimination of all macroparticles from the substrate area and the increase in cathode lifetime. Macroparticles are only a problem in cases where the particulates leave the cathode in a solid form. Carbon is about the worst in this respect, as it has no low-pressure liquid phase. These solid particles bounce many times within the chamber, making the design of baffles in the filter more difficult. However, there have been several reports that clean films have been produced by cathodic arc sources, even from carbon. Low melting point materials such as copper require only line-of-sight blocking between

cathode and substrate to eliminate macroparticle contamination.

Increasing cathode lifetime may not be essential in research environments, but is essential for economic success in production environments. The cathode lifetime is determined by several factors, the most important being initial mass and arc current. The cathode mass available for use can be increased by either making the cathode larger in diameter, or making a rod-feed system. Larger diameter cathodes generally necessitate larger diameter ducting in the filter, which increases its length and lowers its ion transport efficiency, which partially offsets the advantage of more cathode mass. A rod-feed system retains the advantage of keeping the arc near the center of the chamber (allowing a small diameter filter), but adds the complexity of motion within a vacuum chamber. Along with the coating and macroparticles potentially fouling the moving parts, there must be good thermal and electrical contact to the cathode in order to dissipate the kilowatt-level heat loads and handle the 100 A currents without melting or welding moving parts. Graphite has an advantage for a rod feed in that less of the arc power is deposited in the cathode in the case of carbon compared with other materials. Also, graphite does not weld to itself, so it may be possible to construct a rod feed specifically for carbon. Other materials are more difficult, especially those with low thermal conductivity and high chemical reactivity such as titanium. We are presently exploring the advantages of both solutions.

CONCLUSIONS

Cathodic arc sources produce metallic ion beams of unequaled current, but require careful design to effectively utilize them. We have demonstrated here that most of the technical barriers to utilizing filtered arc sources for routine commercial coating have been or can readily be surmounted. Control of downstream divergence and 2-dimensional rastering of the arc plasma column are the likeliest pathway to coating large areas with full throughput of coating material. The issues of obtaining higher throughput, long cathode charge lifetime and macroparticle free coatings are being worked on and appear tractable. The source described here provides a means to explore the advantages of arc produced coatings without worrying about the details of the source operation.

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