Proceedings of the International Conference
Nanomaterials: Applications and Properties
Vol. **3** No 1, 01PISERE03(4pp) (2014)

Deposition of Uniform Vacuum Arc Coatings by Use of Magnetic Traps for Plasma Electrons

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(Received 30 April 2014; published online 29 August 2014)

Deposition of uniform coatings in the vacuum arc deposition setup has been investigated. A control unit consisted of two electromagnetic coils installed under substrate of 400 mm dia. exposed to the plasma flux at a distance of 325 mm from the plasma duct exit. The unit generated the magnetic field of various configurations to create a system of the magnetic traps for plasma electrons, which effectively influences the motion of the plasma ions. Superposition of different operation modes of the control unit allows obtaining a uniform distribution of the processing ion flux. TiN coatings were deposited onto cutting inserts placed at different locations on the substrate, by use of the uniform distribution, and SEM technique was used to characterize surfaces of the coatings. The SEM images confirmed the deposition of the uniform coatings along the substrate surface with diameter of 320 mm. This method may be suitable for deposition of uniform coatings from the ion flux extracted from the plasma sources with guiding magnetic field, over the large substrates.

Keywords: DC discharges; Ion-assisted Deposition; Process control.

PACS number: 52.77.-j

1. INTRODUCTION

Control of ion current directed toward the particular area of a substrate, along with the control of ion energy and gas flow, greatly influences the formation of the preferable texture and composition and, hence, physical, mechanical, tribological and chemical properties of the surface [1]. Ability to control a density distribution of the ion fluxes along the substrate processed by plasma is necessary feature of modern plasma reactors to obtain required micro- and nanostructures [2,3]. One of the challenges of plasma-processing technology is maintaining the uniformity [4] to process a wafer with sizes exceeding 300 mm evenly from center to edge. Another challenge is to affect the growing film quality by varying the ion current density to the particular area of the wafer [5,6,7,8].

The electromagnetic focusing of the plasma flux was found to be very effective in transporting the plasma from cathode of a vacuum arc source [9,10,11]. It was shown that the use of two electromagnet coils can be very useful for controlling the ion current density distribution on the large substrates (up to 400 mm dia.) [12,13]. The influence of the ion current density to the structure and workability of TiN coatings deposited on the cutting inserts was also demonstrated [14].

In that paper a deposition of the uniform coating to the surface area of 320 mm dia. is shown by using the early developed method of control of ion density distribution by magnetic traps for plasma electrons [13] and determined limits for the ion current density that are acceptable for the formation of serviceable TiN coatings on a surface of cutting tool inserts [14]. The results of the work can be used in deposition of the vacuum-arc coatings to the large substrates (over than 300 mm dia.)

2. EXPERIMENTAL PART

The experimental setup is shown schematically in Fig. 1. It consists of a vacuum arc plasma source, two additional electromagnetic coils with ferromagnetic cores, and a planar probe for measuring the radial distribution of axial component of the ion flux. The plasma source was fitted with a water-cooled truncated cone-shaped titanium cathode and tubular water-cooled anode. The cathode cone was 60 mm long with a 50 mm diameter upper surface and the base diameter of 60 mm. The anode had a 210 mm inner diameter and a length of 200 mm. A guiding coil was mounted on the anode, so the anode was used as a plasma duct. The plasma source was mounted on a flange of a 500 mm diameter, 500 mm long cylindrical vacuum chamber. The dc arc current, $I_a = 110$ A, was applied between the cathode and the anode, which was grounded. Focusing and guiding coils generated an axial magnetic field in the plasma source.

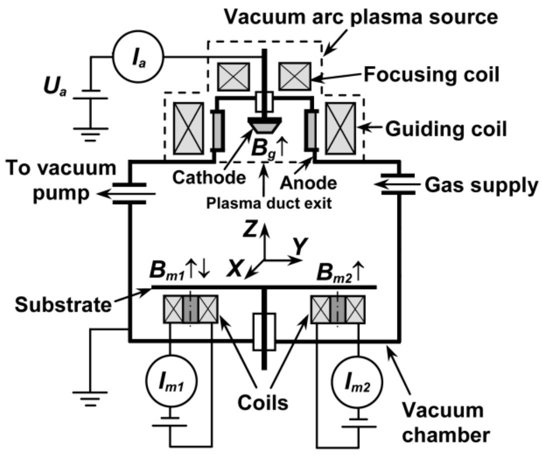

Fig. 1 – Experimental setup

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The focusing magnetic field B_f ($B_f = 0.03$ T at the center of the focusing coil) was used to retain the cathode spots on the front cathode surface. The guiding magnetic field B_g ($B_g = 0.016$ T at the center of the guiding coil) guided the plasma beam towards the substrate. A disk-shaped substrate made of nonmagnetic stainless steel was placed at distance of 325 mm from the plasma duct exit in the vacuum chamber in such a way that substrate and plasma duct (anode) axes of symmetry coincided. The substrate diameter and thickness were 400 mm and 8 mm, correspondingly. Two additional coils with diameter of 100 mm and height of 80 mm (2000 coils on core diameter of 30 mm) were mounted on a holder under the substrate. Axes of symmetry of the coils, substrate and plasma duct where parallel, and the distance between the coils axes was 280 mm. Measured values of magnetic field generated by the additional coil on its axis above the substrate surface shows almost linear dependence on the coil current, with the magnetic field of 0.05 T and 0.19 T for coil currents of 1 A and 4 A, correspondingly. The substrate was under the negative potential relative to the grounded vacuum chamber walls. An automatic gas-supplying system maintained nitrogen pressure of 0.01 Pa. The pressure was measured with a help of the thermocouple vacuum gage and ionization gage.

The planar probe was used to measure the ion current density distribution of the axial plasma current along the substrate surface (x, y axes on Fig. 1). The probe was a ($10\times10\times0.5$ mm^3) current-collecting plate made of polished nonmagnetic stainless steel with a high-temperature insulator on one side [13]. The duration of each experimental run was 2 s. Three operation modes were studied for stationary substrate (i.e. the substrate was not rotating relative to z-axis): a – operation of the vacuum source with the coils 1 and 2 powered off, which gives the initial distribution of the ion current density along the substrate surface; b – coil 1 is powered opposite while coil 2 is powered in line to the coils of the plasma source ($I_{m1} = 2$ A, $I_{m2} = 4$ A), Ref. Fig. 1; c – coil 1 is powered opposite while coil 2 is powered in line to the coils of the plasma source ($I_{m1} = 4$ A, $I_{m2} = 4$ A). Then these modes were superimposed at a ratio of 0.5:0.25:0.25 at the substrate rotation relative to z axis, to obtain a deposition mode. The ratio was selected on a base of calculations according to a developed model [13] to obtain a uniform distribution of the ion current density along the substrate surface.

The deposition mode were applied, when the cutting tool inserts (16×16×5 mm, 79 % TiC + 15 % Ni + 6 % Mo) are placed on the substrate in points with coordinates $r = 0$, 50, 100, and 160 mm to deposit TiN coating on the cutting surfaces ($r^2 = x^2 + y^2$). Before deposition, the inserts were cleaned and heated by ion flux at the bias potential of 1.5 kV for 8 minutes. The deposition time was 9 minutes at nitrogen pressure of 0.05 Pa. At the deposition, the substrate was rotating relative to z-axis (Ref. Fig. 1). After deposition, side surfaces of the cutting inserts were polished, and SEM images of the coating were made to determine the coating thickness and morphology.

3. RESULTS AND DISCUSSION

The dependence of ion current distribution along the substrate on the current of additional coils was studied during stable arc operation.

Fig. 2 (a-c) shows the ion current density distributions, measured by the planar probe, presenting the main features for the discussed configurations. The plots present results of approximation for the experimental data points that are the averages of 10 measurements. The coordinate plane x-y corresponds to the x-y plane shown in Fig. 1, where the substrate center is located at point of $x = 0$, $y = 0$, $z = 0$ and the additional coils are located under the substrate positions of $y = \pm 140$ mm, $x = 0$. A uniform current distribution was assumed over the probe plate. The continuous distributions were obtained to fit the measured values with the error not exceeding 10 % in the points of the probe location. The approximation calculates the value within the range of the measured values for the range between adjacent experimental points. When coils 1 and 2 are not powered, the distribution corresponds to Gaussian-like distribution, as it can be seen from Fig. 2 (a). When coil 1 is powered opposite while coil 2 is powered in line to the focusing and guiding coils of the plasma source, the distribution is changed to complex multi-peaked distributions shown in Fig. 2 (b, c). The influence of the resulting magnetic field to the motion of the ions can be described by use of assumption about formation of the negative space charge regions in the plasma affected by the magnetic field configuration. These regions are formed when generating the magnetic trap with bottle or cusped configuration for the plasma electrons. Within the region, the electrons are confined by the applied magnetic field while the ions are not, so the electron density prevails over the ion density, and the region gains the negative electric space charge. Thus, the ion emitted from the plasma duct exit, is affected by the negative space charge generated in the region of the magnetic trap of plasma electrons. A method of the ion flux control was proposed on a base of the investigation [13]. The essence of the method is creating the magnetic traps for plasma electrons between a plasma source and a substrate to affect the plasma ions via self-consistent electric field generated due to the violation of the plasma quasi-neutrality in the traps. The resulting distributions can be described by a simple model of a particle motion in a central field at the condition that complex area of the magnetic traps can be approximated by a set of spheres [13]. As was shown, combination of the control by magnetic traps with rotation of the substrate allows increasing the number of possible time-averaged distributions of the ion current density over the substrate, and the uniform distribution is available, in particular [12]. The distribution shown in Fig. 2 (d) is a result of calculations and is obtained as a superposition of distributions (a), (b) and (c) at the ratio 0.5:0.22:0.25, and the substrate rotation relative to z axis (Ref. Fig. 1). It can be seen from the Fig. 2 (d), that the superposition allows obtaining a uniform distribution of the ion current density along the substrate surface of about 320 mm dia. with a mean ion current density of 40 A/m^2.

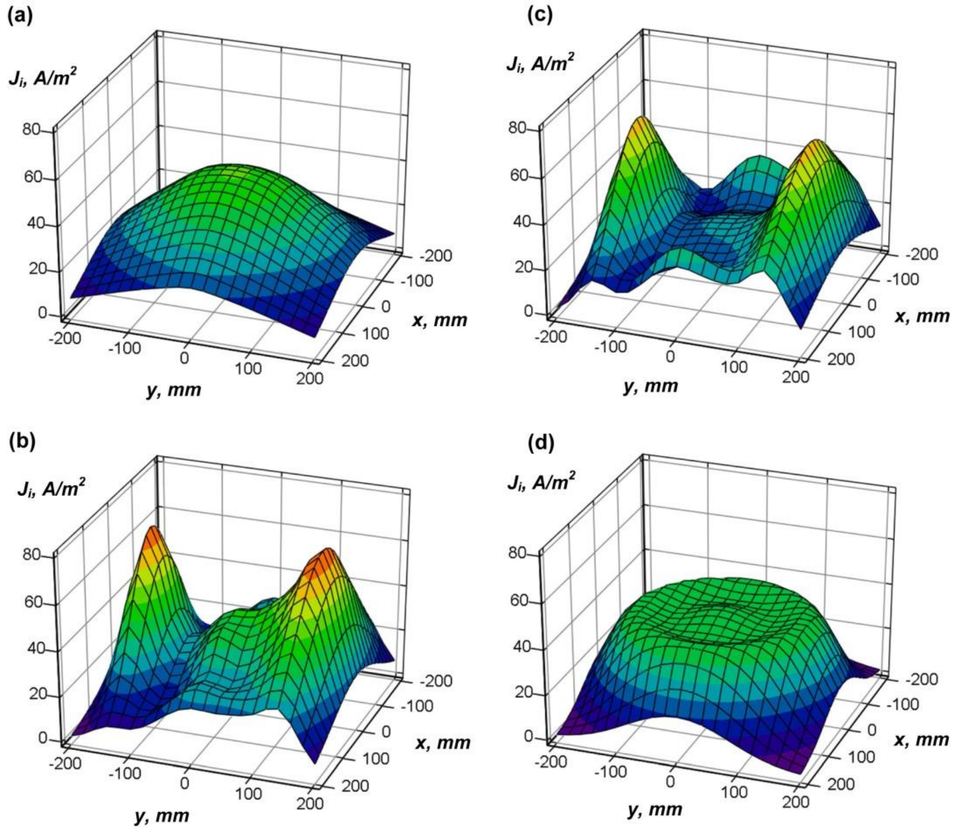

Fig. 2 – Distributions of ion current density along the substrate surface for different powering of the control magnetic coils: a – initial distribution, I_a = 110 A; b – coil 1 is powered opposite while coil 2 is powered in line to the coils of the plasma source (I_{m1} = 2 A, I_{m2} = 4 A), Ref. Fig. 1; c – coil 1 is powered opposite while coil 2 is powered in line to the coils of the plasma source (I_{m1} = 4 A, I_{m2} = 4 A); d – superposition of the distributions (a), (b) and (c) at the ratio of 0.5:0.25:0.25 and the substrate rotation relative to z axis)

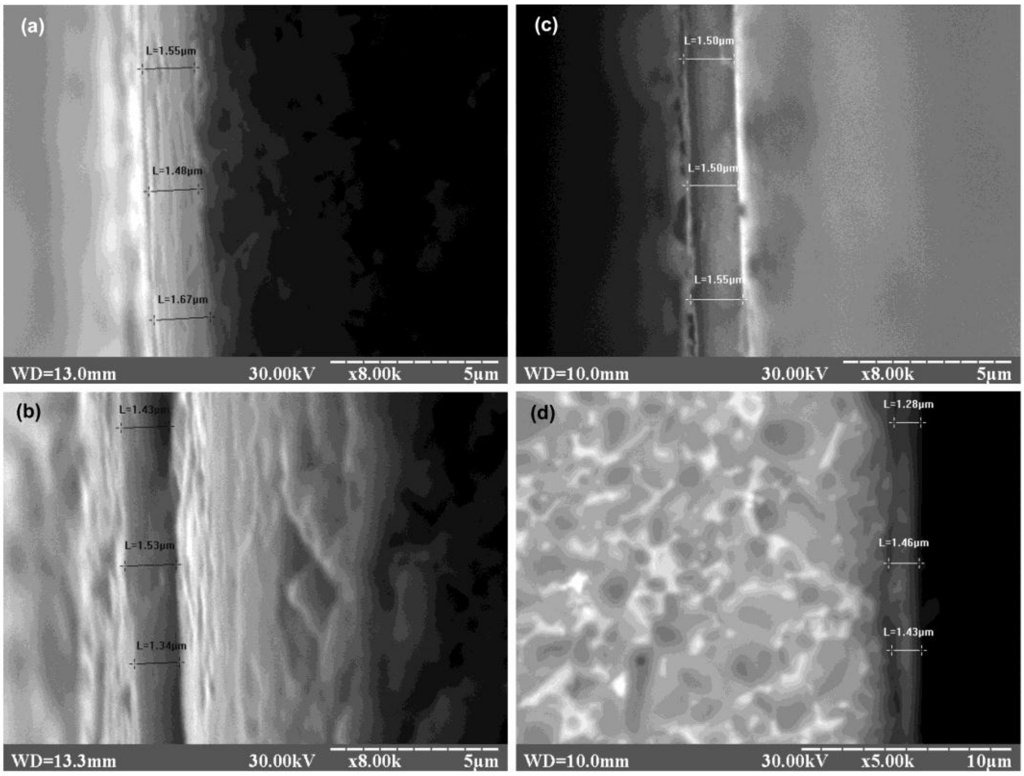

Fig. 3 – SEM images of the coatings deposited on the cutting inserts at different locations along the substrate surface for deposition time t = 9 minutes: a - r = 0 mm; b - r = 50 mm; c - r = 100 mm; d - r = 160 mm

For the cutting inserts, a test by lathe machining of the stainless steel has proven the workability of the coating obtained at the ion current density not less then 30-32 A/m^2, as was shown in our previous work [14]. Thus, the proposed value of 40 A/m^2 is suitable for the formation of wear-proof coatings.

SEM images of the coatings deposited on the cutting inserts at different locations along the substrate surface are shown in Fig. 3. An average coating thickness for the inserts located at $r = 0$, is 1.57 μm; for the inserts located at $r = 50$ mm, $r = 100$ mm, and $r = 160$ mm the corresponding values are 1.43 μm, 1.52 μm, and 1.39 μm. As it can be seen, the coating thickness is about 1.48 μm and is almost the same for the deposition area of 320 mm dia. This result confirmed a strong relation between the density of the processing ion current and coating thickness, as well as a possibility to deposit a uniform coatings along the large substrates by applying the proposed method of magnetic control.

4. CONCLUSION

The results of the work show that magnetic field is a powerful tool to control the distribution of the ion current density and generate the uniform distribution along the substrate, in particular. Two additional electromagnetic coils, placed under a substrate perpendicular to a plasma flux generated by vacuum arc source, affects ion current density distribution over the plasma flux cross section. To de-focus the ion flux extracted from the vacuum-arc plasma source, one of the coils should be powered opposite while another – in line to the coils of the plasma source. Superposition of the initial distribution and distributions obtained at the defocusing, allows generate the uniform distribution along the large substrates with diameter exceeding 300 mm. In practical, the results of this work can be used to deposit the uniform vacuum-arc coatings.

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