PROCEEDINGS OF THE INTERNATIONAL CONFERENCE NANOMATERIALS: APPLICATIONS AND PROPERTIES
Vol. **1** No 4, 04PITSE01(4pp) (2012)

Control of Ion Density Distribution by Use of Magnetic Traps for Plasma Electrons

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(Received 3 May 2012; published online 17 August 2012)

Method of ion current density control in the vacuum arc deposition setup has been investigated. The control unit consisted of two electromagnetic coils installed under substrate of 400 mm dia. exposed to the plasma flux. A planar probe was used to measure the ion current density distribution along the plasma flux cross-sections at different distances from the plasma duct exit. It was shown that configuration of the resulting magnetic field generated by the control coils and the guiding and focusing coils of the arc source, strongly affects the ion current density distribution. Broad range of ion current density from 25 to 340 A/m^2 was obtained at dependence on the control coils powering, distance from the plasma duct exit and the position along the substrate. This method may be suitable for effective controlling of 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

Nowadays, plasma is widely used in industry for many purposes [1]. Its application extends to surface cleaning and modification, plasma microdischarges and many other rapidly growing areas, such as creating of nanopatterns [2, 3]. Ion current density is one of the main plasma parameters, which should be controlled not only for maintaining uniformity [4] to process a wafer evenly from center to edge, but to influence the formation of high aspect ratio structures, or strongly affect the growing film quality by varying the ion current density to the particular area of the wafer [5, 6, 7, 8].

The most promising way to control ion current density is to use electromagnetic focusing of the plasma flux, which is widely used in transporting the plasma from cathode of a vacuum arc source [9,10,11]. The essence of the method is applying some guiding magnetic field to "magnetize" plasma electrons, which, in turn guide the plasma ions by means of electric field. However, applying additional controlling magnetic field is rather complex problem. This field should not interfere with fields of the source to prevent unstable source operation, but should be strong enough to catch the plasma right near the plasma source exit. At that limitation is reasonable to place the or sources of the controlling magnetic field under the substrate exposed to plasma flux. In this paper we show that the use of two electromagnet coils can be very useful for controlling the ion current density distribution on the large substrates. We investigate the ion current density distribution along the substrate, when magnetic field generated by one of the additional coils placed under the substrate, forms either "bottle" or "cusp" configuration with magnetic field generated by guiding and focusing coils of arc source, whereas magnetic field of another additional coil, forms only "bottle" configuration with magnetic field from arc source [12].

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.

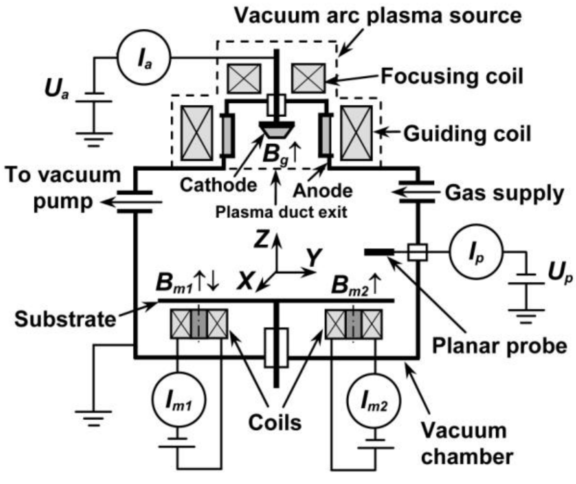

Fig. 1 – Experimental setup

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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 ($B_g = 0.02$ 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 as a function of distance of 150, 230, and 325 mm from the plasma duct exit (along z axis on Fig. 1) and position parallel to the substrate surface over the plasma flux cross section (x, y axes on Fig. 1). The probe was a ($10 \times 10 \times 0.5$ mm^3) current-collecting plate made of polished nonmagnetic stainless steel with a high-temperature insulator on one side. The probe was connected to the power supply via a separate ammeter. When the vacuum arc plasma source was switched on, the voltage drops between the probe and anode was 200 V, so saturated ion current was collected [13]. The duration of each experimental run was 2 s.

3. RESULTS AND DISCUSSION

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

Fig. 2 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, $x = 0$. Plots on Fig. 2 a-d correspond to probe location at distance of 150 mm from plasma duct exit along z axis (Ref. Fig. 1); Fig. 2 e-h correspond to probe location at distance of 230 mm; Fig. 2 k-n correspond to probe location at distance of 325 mm. The configurations, when both additional coils generate magnetic fields aligned with the direction of magnetic field from guiding and focusing coils, are designated as $B_{m1}\uparrow B_g\uparrow B_{m2}\uparrow$. When magnetic field generated by one additional coil (B_{m1}), is directed opposite to the magnetic field of the guiding and focusing coils, and magnetic field generated by another coil (B_{m2}), is aligned with magnetic field of the guiding and focusing coils, the configurations are designated as $B_{m1}\downarrow B_g\uparrow B_{m2}\uparrow$.

When the right coil (Coil 2, $B_g\uparrow B_{m2}\uparrow$, Ref. Fig. 1) is powered only, the plasma flux is contracted. The most interesting feature of the configuration is the ion jet extracted from the mainstream and directed toward the powered coil (Ref. Fig. 2 b, f, l). The maximum ion current density is increased by 1.4 times from 240 A/m^2 (Fig. 2 a) to 340 A/m^2 (Fig. 2 b) for distance 150 mm, maximum is located at $y = 0$; by 1.3 times from 92 A/m^2 (Fig. 2 e) to 117 A/m^2 (Fig. 2 f) – for distance 230 mm, maximum is located at $y \approx 0$ mm. The maximum ion current density of the mainstream is increased by 1.5 times from 50 A/m^2 (Fig. 2 k) to 75 A/m^2 (Fig. 2 l) for distance 325 mm, and maximum of the extracted ion jet distribution (of about 75 A/m^2) is located at $y \approx 120$ mm. It should be noted that the arc current is decreased for this configuration from 110 A (for $B_g\uparrow$ configuration) to 100 A for the coil current $I_{m2} = 4$ A.

Two ion jets are extracted from the mainstream and directed toward the additional coils, when they are powered simultaneously ($B_{m1}\uparrow B_g\uparrow B_{m2}\uparrow$, Ref. Fig. 2 c, g, m). Influence of the magnetic cusp formed between the additional coils, and two magnetic bottles between the coils and plasma duct exit, to the ion flux density distribution is supposed. The cusp is located right above the substrate center. Thus, plasma propagates from the arc source to three main sinks: two magnetic mirrors above the coil cores and the magnetic cusp between them.

The maximum ion current density is increased by 1.3 times from 240 A/m^2 (Fig. 2 a) to 320 A/m^2 (Fig. 2 c) for distance 150 mm, maximum is located at $y = 0$; by 2 times from 92 A/m^2 (Fig. 2 e) to 183 A/m^2 (Fig. 2 g) for distance 230 mm, maximum is located at $y = 0$. Three maximums of the ion current distribution are located at $x = 0$, $y = 0$ and $y = \pm 110$ mm for distance 325 mm. The ion current density is increased by 2 times from 50 A/m^2 (Fig. 2 k) to 100 A/m^2 for the central maximum ($y = 0$), and by 3 times from 40 A/m^2 to 117 A/m^2 for the side maximums ($y = \pm 110$ mm), Ref. Fig. 2 k and Fig. 2 m. The arc current is decreased from 110 A to 95 A, when the both coils are powered with the current of 4 A simultaneously.

When the coils are powered oppositely ($B_{m1}\downarrow B_g\uparrow B_{m2}\uparrow$ configuration), the substrate center area is prevented from penetration of the ion flux extracted from the arc source, Ref. Fig. 2 d, h, n. The magnetic bottle formed between the additional coils near the substrate surface is supposed to be the reason. The ion flux propagates from the arc source to the substrate edge with focusing toward the magnetic mirrors above the additional coil cores.

The maximum ion current density is increased by 1.25 times from 240 A/m^2 (Fig. 2 a) to 300 A/m^2 (Fig. 2 l) for distance 150 mm, maximum is located at $y = 0$. The maximum ion current density is decreased by 0.8 times from 92 A/m^2 (Fig. 2 e) to 75 A/m^2 (Fig. 2 h) for distance 230 mm, maximum is located at $y = 10$ mm. The ion current density is decreased significantly at the substrate center as compared to the configuration without additional magnetic fields – by 2 times from 50 A/m^2 (Fig. 2 k) to 25 A/m^2 (Fig. 2 n) for distance 325 mm. Local maximums are located at $x = 0$, $y = \pm 140$ mm, where the

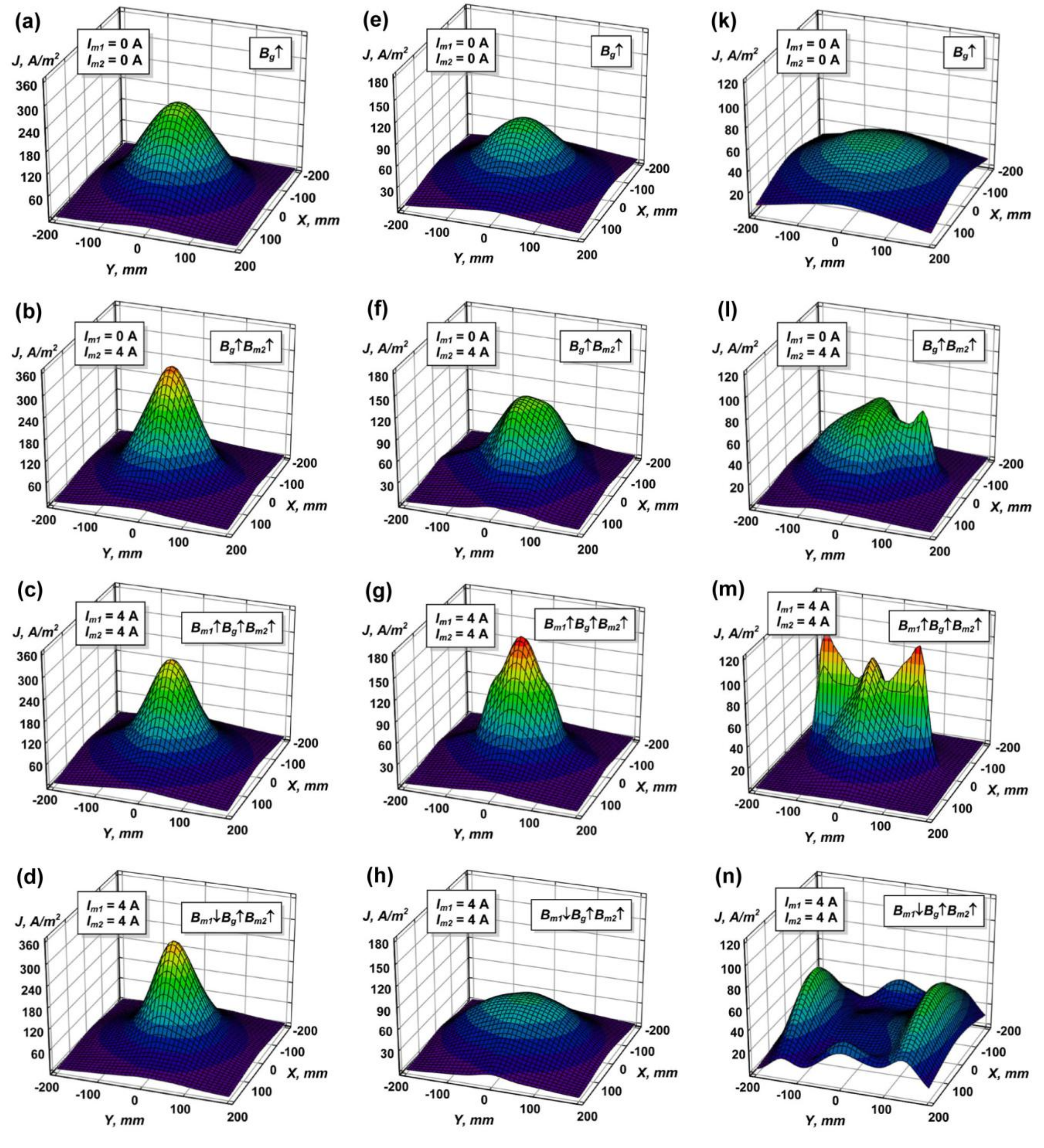

Fig. 3 – Ion current density distribution as a function of coordinate along the substrate surface for probe location at distance of 150 mm (a – d), 230 mm (e – h), 325 mm (k – n) from the plasma duct exit for configurations of resulting magnetic field: a, e, k – $B_g\uparrow$; b, f, l - $B_g\uparrow B_{m2}\uparrow$, $I_{m2} = 4$ A; c, g, m – $B_{m1}\uparrow B_g\uparrow B_{m2}\uparrow$, $I_{m1} = I_{m2} = 4$ A; d, h, n - $B_{m1}\downarrow B_g\uparrow B_{m2}\uparrow$, $I_{m1} = I_{m2} = 4$ A

ion current density is increased by 2 times and reaches 67 A/m², as well as at $x = \pm 180$ mm, $y = 0$, where the ion current density is increased by 1.5 times and reaches 37 A/m². The arc current is almost unchanged for this configuration.

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 can be proposed on a base of the investigation. 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.

4. CONCLUSION

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. Two main possibilities are revealed: focusing of plasma flux towards the substrate center with decreasing the plasma losses to the vacuum chamber walls; and guiding the plasma flux towards the cores of the additional coils installed under the substrate.

At the focusing, the axial ion current density above substrate center was increased by 1.3 to 3 times at dependence on the position above the substrate, as compared to the setup without the additional coils. However, presence of the additional magnetic fields aligned with direction of the magnetic field of the vacuum arc source, influences the arc source operation, and the arc current is decreased up to about 14 %.

At the de-focusing, the axial ion current density above substrate center was decreased up to 2 times as compared to the maximum of the distribution measured right above the substrate, at distance of 325 mm from the plasma duct exit. Presence of the additional magnetic field directed opposite to the magnetic field of the arc source, remove the influence to the arc source operation of the additional magnetic field aligned with the magnetic field of the arc source, and the arc current stays unchanged.

In practical, the results of this work can be used to control the ion flux extracted from various types of plasma reactors, where the magnetic field is used to guide the plasma from a source to a substrate: arc sources, unbalanced magnetrons, ECR and helicon wave sources. Thus, the practical application may be expanded to various plasma processing technologies including thin film deposition, surface layer modifications and growth of nanostructures.

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