T-shape filtered arc deposition system with built-in electrostatic macro-particle trap for DLC film preparation

Masao Kamiya ^{a, b}, Taichiro Yanagita ^a, Hideto Tanoue ^a, Shinichiro Oke ^a, Yoshiyuki Suda ^a, Hirofumi Takikawa ^{a*}, Makoto Taki ^c, Yushi Hasegawa ^c, Takeshi Ishikawa ^d, Haruyuki Yasui ^e

^a *Department of Electrical and Electronic Engineering, Toyohashi University of Technology, Toyohashi, Aichi 441-8580, Japan*

^b *Itoh Optical Industrial Co., Ltd., 3-19 Miyanari, Gamagori, Aichi 443-0041, Japan*

^c *Onward Ceramic Coating Co., Ltd., Wa-13 Yoshihara, Nomi, Ishikawa 929-0111, Japan*

^d *Hitachi Tool Engineering, Ltd., 13-2, Ninomi, Narita, Chiba 286-0825, Japan*

^e *Industrial Research Institute of Ishikawa, 2-1, Kuratsuki, Kanazawa, Ishikawa 929-8203, Japan*

** Corresponding Author*

Abstract

The T-shape filtered arc deposition system (T-FAD) is a powerful tool to prepare high-quality diamond-like carbon (DLC) films. Most macro-particles (droplets) emitted from the graphite cathode are caught at the extension duct of the droplet catcher or collector facing the cathode, and then the clean plasma bent 90 degrees is transported toward the substrate. However, further droplet reduction is still required in order to realize a higher quality film without droplet adhesion. In the present study, T-FAD was evolved by employing an electrostatic droplet trap (ES-trap). A cylindrical ES-trap was placed in the extension duct part of the T-shape duct of an electromagnetic plasma transportation and droplet filter. The ion current at the exit of the T-filter duct and the current flowing to the ES-trap were measured as a function of the ES-trap bias voltage for various positions of the ES-trap. The deposition rate and number of droplets were also measured. As a result, it was found that the optimum voltage of the ES-trap was +35 V and that it was better to place the ES-trap closer to the plasma beam in order to obtain fewer droplets on the film without an excessive decrease in the deposition rate. In the optimum condition, the number of droplets on the DLC film prepared with ES-trap was reduced to 1/3 of that without the ES-trap.

Keywords: DLC film; T-shape filtered arc deposition (T-FAD); Droplet reduction; Electrostatic trap (ES-trap)

1. Introduction

A cathodic arc discharge appearing in a vacuum has been employed in industrial manufacturing processes to coat protective or decorative films, and is one common physical vapor deposition technique. In most cases, metal nitride films have been supplied by this method. Metals, alloys, oxides, and carbides are also possible. Much research and development has been carried out in this field [1, 2]. However, the cathodic arc has a problem in that the macro-particles, called droplets, which are of submicron to tens of microns in size, are emitted from the cathode spot and the droplets adhere to the film and sometimes deteriorate the film quality from the perspectives of homogeneity, surface flatness, and trigger for film delamination. The most efficient method to overcome the droplet problem in cathodic arc deposition is to employ a filtered arc technique. The cathodic arc plasma is transported to the process position located out-of-sight from the cathode by a magnetic field [1-4]. Such are sometimes called filtered arc deposition (FAD) systems.

One of the FAD applications is to prepare a diamond-like carbon (DLC) film. The hard and high-density DLC film is attractive for use as a read/write magnetic head in hard disk drives [5, 6] and high temperature molds [7] especially for lenses [8, 9], which require high-precision surfaces. The authors have developed a unique T-shape filtered arc deposition (T-FAD) system [10], which can prepare various kinds of DLC films [11, 12]. Unlike other FADs, T-FAD has a droplet collection part facing the cathode, where the droplets are caught. However, the droplets still exist on the DLC film surface. Further reduction of number of droplets is required. Thus, in the present study, the electrostatic trap (ES-trap) placed in the droplet collection duct of the T-shape filter was designed to reduce the number of droplets adhered to the DLC film. The performance of the ES-trap was examined as a function of its position and bias voltage, from the viewpoints of ion current,

deposition rate, and droplet reduction.

2. Experimental details

Inaba *et al.* have attempted to use a thick ring-type electrical filter between the double-bend filter duct and the process chamber, namely, in the path of plasma transportation to the substrate [13-15]. As the plasma beam passes through the ring filter biased at higher voltage than plasma potential, some of the charge droplets were caught. However, in this case, the path of the plasma beam becomes so long that some of the ions are lost. In the present investigation, the electrostatic trap was located so that the plasma path did not become elongated.

The T-FAD system is shown in Fig. 1. A carbon cathodic arc plasma was discharged between a graphite cathode and a stainless anode. The carbon plasma was pulled out from the discharge zone and sent to the T-shape plasma transportation duct (T-duct) and then to the process chamber by a magnetic field generated by several electromagnetic coils. The plasma beam was bent at the T-connection point of the T-duct. Most of the droplets emitted from the cathode spot flew to the expansion duct of the T-duct, facing the cathode, where the droplets were caught and collected. In this way, the droplets were separated from the plasma and clean plasma was transported to the process chamber. The plasma beam scanner was placed in front of the chamber entrance to deposit over a wide area.

In the theoretical mechanism, all droplets would be geometrically removed in the T-FAD. However, in practice, a few droplets still exist on the prepared DLC film, presumably because some droplets are occasionally crushed or broken into smaller pieces when they collide with the T-duct wall. A photograph of a typical example is provided as proof with an explanatory illustration in Fig. 2. If this phenomenon occurs, some pieces of the crushed droplets move toward the substrate.

The ES-trap was a cylindrical aluminum (Al) tube with an outer diameter of 80 mm, length of 85 mm, and thickness of 0.5 mm. The position of the ES-trap was an experimental parameter, as shown

in Fig. 1(b). First, the optimum T-duct bias was obtained without the ES-trap installation. Then, the ion current at the exit of the T-duct and the current flowing to the ES-trap were measured as a function of the ES-trap bias voltage for various positions of the ES-trap. The deposition rate and number of droplets were also measured. The experimental conditions were as follows: base pressure, 0.005 Pa; process pressure, less than 0.01 Pa; arc current, 30 A; bias of ion current monitor, -100 V; T-duct bias, 0 to +30 V; bias of ES-trap, -30 to +30 V; deposition time, 10 min. DLC film was prepared on a silicon (Si) wafer (100) (n-type, 20 mm × 20 mm, thickness $525 \pm 25 \mu\text{m}$, resistivity 2-10 $\Omega\cdot\text{cm}$) with a pulse bias of -500 V (width 20 μs , frequency 10 kHz, duty 20%). The plasma beam was scanned by a magnetic beam scanner in front of the chamber entrance, and the diameter of the obtained coating area was approximately 100 mm. The film thickness was measured with a stylus surface profiler (Veeco, Dektak 3). The droplets were counted in dark field micrographs (magnification, $\times 200$) taken with an optical microscope (Nikon, ECLIPSE ME600).

3. Results and discussion

3.1 T-duct bias

It is well known that plasma transportation efficiency through a magnetic filter duct increases when the appropriate bias voltage is applied to the duct. Prior to using the ES-trap, an experiment to determine the T-duct bias for an arc current of 30 A was carried out. The T-duct current and the ion current I_{IS} at an ion current monitor (stainless-made, 100 mm diameter, backside insulated), which also worked as a mechanical shutter, were measured as a function of the T-duct bias voltage. The optimum bias voltage was reportedly decided as an inflection point in the duct current characteristics [16]. As shown in Fig. 3, the optimum T-duct bias in this case was approximately +16 V, which was in the previously reported range of appropriate voltages for an arc current of 50 A [16]. At a T-duct bias of +16 V, I_{IS} was approximately 140 mA.

3.2 Electrical property of ES-trap and effect on ion current

The ES-trap current I_{EST} as a function of the ES-trap bias voltage for various ES-trap positions is shown in Fig. 4. The shape of the ES-trap current-voltage characteristics was found to be very similar to that of a single electrostatic probe based on the Langmuir theory. Therefore, the characteristics can be interpreted as reported previously in the case of the current-voltage characteristics of the T-duct. The characteristics were divided into 3 regions: ion current saturation region (approximately <10 V), electron current increase region (approximately 10 to 30 V), and electron sheath formation region (approximately >30 V). The absolute value of the current was found to be higher when the ES-trap was located near the plasma beam. The range between 10 to 20 V was considered to be the transition region of the first two regions where the characteristics crossed the line of current 0 A (called current zero-cross region).

The ion current at the ion current monitor I_{IS} as a function of ES-trap bias voltage is shown in Fig. 5. It was found that I_{IS} had a peak at +16 V, which was the same value as the T-duct bias. This means that the plasma transportation efficiency was maximized when the ES-trap acted electrically as a part of the wall of the plasma transportation duct. This is supported by the finding that the region for the peak was almost the same as the range of the current zero-cross region of the ES-trap current-voltage characteristics. In the ranges of an ES-trap bias of less than +10 V and more than 25 V, the I_{IS} was not significantly changed. This indicated that the ES-trap did not work as the plasma transportation wall in this range. In detailed observation, it was found that the I_{IS} was higher when the ES-trap position was far from the plasma and the I_{IS} for position 1 in the bias range above +25 V tended to decrease slightly with the bias.

3.3 DLC film deposition

From the results of I_{EST} and I_{IS} in Figs. 4 and 5, we decided to make a film deposition at ES-trap biases of +16 V (same as the T-duct bias), +20 V (electron current increase region), +35 V

(beginning of the electron sheath region), and +45 V for the ES-trap at position 1. The ES-trap position was changed only for the ES-trap bias of +35 V. The resulting film thickness and the number of droplets are listed in Table 1. From these results, the deposition rate was obtained, as shown in Fig. 7. All the deposition rates were lower than that without the ES-trap. However, the decrease was only down 15% in the lowest case. In the case of the ES-trap at position 1, the deposition rate decreased as the ES-trap bias increased. This may have occurred because when the voltage of ES-trap increased, the plasma was disturbed by many electrons attracted to the ES-trap. In the case of an ES-trap bias of +35 V, the deposition rate decreased since the ES-trap position was closer to the plasma beam. This is consistent with the I_{IS} at a ES-trap bias of +35 V for different ES-trap positions, which is shown in Fig. 7, obtained from Fig. 5.

The numbers of droplets per 0.1 mm^2 and per unit film thickness nm obtained from Table 1 are shown in Fig. 8. All the results of the number of droplets with the ES-trap were found to be less than those without ES-trap. In the case of the ES-trap at position 1, the number of droplets decreased with ES-trap bias, and reached the minimum at +35 V. However, at +45 V, the number of droplets was greater than that at +35 V. This is likely because, when the voltage applied to the ES-trap is too high, the ES-trap strongly attracts more droplets from the arc generation zone than usual and/or the droplets which lightly adhered to the duct wall were detached, and then such droplets penetrated the plasma and were transported to the substrate. Moreover, the number of droplets was lower for the ES-trap positions closer to the plasma. The minimum number of droplets was obtained at position 1 and ES-trap bias of +35 V, and the number was 1/3 of that without ES-trap.

4. Conclusions

The present study proposed an advanced technique to reduce the number of droplets adhered to DLC film in a T-shape filtered arc deposition (T-FAD) system. A cylindrical electrostatic trap (ES-trap) was placed in the extension duct of the T-FAD, where the droplets were geometrically

caught. Electrical characteristics of the ES-trap and its influence on the ion current toward the substrate were measured as a function of the position and bias voltage of the ES-trap. The deposition rate of the DLC (a-C) film and the number of droplets were also measured. The principal results can be summarized as follows.

(1) The current-voltage characteristic of the ES-trap is similar to that of a single-electrostatic probe and it is interpreted based on a consideration of Langmuir probe theory.

(2) The ion current towards the substrate has a peak at an ES-trap bias of +16 V, which was the same as the value of the bias voltage of a T-shape magnetic-filter duct and also the value of the voltage of the current zero-cross region of the current-voltage characteristics of the ES-trap. This means that the ES-trap biased at such voltage acted as a part of the plasma transportation duct wall.

(3) A higher deposition rate of DLC (a-C) film and greater droplet reduction efficiency were obtained when the ES-trap was closer to the plasma beam. The droplet reduction efficiency peaked at an ES-trap bias of +35 V. At this bias, the number of droplets was reduced to 1/3 of that without the ES-trap, although the deposition rate decreased approximately only 1/10.

Acknowledgements

This work has been supported in part by the Outstanding Research Project of the Research Center for Future Technology, Toyohashi University of Technology (TUT); the Research Project of the Research Center for Future Vehicle, TUT; the Research Project of the Venture Business Laboratory, TUT; Global COE program “Frontiers of Intelligent Sensing” from the Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan; the Japan Society for the Promotion of Science (JSPS), Core University Programs (JSPS-KOSEF program in the field of “R&D of Advanced Semiconductor” and JSPS-CAS program in the field of “Plasma and Nuclear Fusion”); Osawa Scientific Studies Grant Foundation; Suzuki Foundation; the Die and Molds Technology Promotion Foundation; Practical Application Research; Practical Application Research, Science and

Technology Incubation Program in Advanced Regions, Comprehensive Support Programs for Creation of Regional Innovation, from The Japan Science and Technology Agency (JST); and the Second Stage Knowledge Cluster Project (Tokai Region Nanotechnology Manufacturing Cluster).

References

- [1] R. L. Boxman, D. M. Sanders, P. J. Martin (Eds.), Handbook of Vacuum Arc Science and Technology -Fundamentals and Applications-, Noyes Publications, Park Ridge, NJ, 1995.
- [2] A. Anders, Cathodic arcs, Springer, 2008.
- [3] H. Takikawa, H. Tongue, IEEE Trans. Plasma Sci. 35 (2007) 992.
- [4] A. Anders, Surf. Coat. Technol. 120/121 (1999) 319.
- [5] P. Siemroth, J. Berthold, B. Petereit, H.-H. Schneider, H. Hilgers, Surf. Coat. Technol. 188/189 (2004) 684.
- [6] C. Casiraghi, J. Robertson, A. C. Ferrari, Mater. Today 10 (2007) 44.
- [7] J. Choi, S. Miyagawa, S. Nakao, M. Ikeyama, Y. Miyagawa, Diam. Relat. Mater. 15 (2006) 948.
- [8] H. Ohmori, K. Katahira, J. Komotori, M. Mizutani, F. Maehama, M. Iwaki, CIRP Annals – Manuf. Technol. 54 (2005) 511
- [9] H. Ishizuka, T. Takachi, H. Ozaki, T. Mikami, M. Tsujioka, M. Takahashi, K. Ogata, The surface properties of a high precision glass lens mold prepared by nano-flat DLC films, Nissin Electric Review, 53 (2008) 9 (in Japanese).
- [10] H. Takikawa, K. Izumi, R. Miyano, T. Sakakibara, Surf. Coat. Technol. 163/164 (2003) 368.
- [11] H. Tanoue, H. Hikosaka, Y. Iwasaki, H. Takikawa, T. Sakakibara, H. Hasegawa, IEEE Trans. Plasma Sci. 35 (2007) 1014.
- [12] M. Kamiya, H. Tanoue, H. Takikawa, M. Taki, Y. Hasegawa, M. Kumagai, Vacuum 83 (2009) 510.

- [13] H. Inaba, K. Furusawa, S. Hirano, S. Sasaki, S. Todoroki, M. Yamasaki, M. Endou, Jpn. J. Appl. Phys. 42 (2003) 2824.
- [14] H. Inaba, in: N. Ohtake (Ed.), Application and Technology of DLC Films, CMC Publishing, Tokyo, 2007, p. 117 (in Japanese).
- [15] H. Inaba, S. Sasaki, S. Hirano, K. Furusawa, M. Yamasaka, A. Amatatsu, X. Shi, Japanese Patent No. 3860954, 7 July, 2000; US Patent No. 6875326.
- [16] Y. Iwasaki, S. Minamisawa, H. Takikawa, T. Sakakibara, H. Hasegawa, Vacuum, 80 (2006) 1266.

Table 1 Experimental conditions and results of DLC preparation (deposition time, 10 min).

No	ES-trap position	ES-trap bias (V)	Film thickness (nm)	Number of droplets ($0.1 \text{ mm}^2 \cdot 10 \text{ min}$) ⁻¹
#1	Non trap	Non trap	186	49
#2	1	16	180	43
#3	1	20	172	30
#4	1	35	165	15
#5	1	45	160	27
#6	2	35	171	29
#7	3	35	176	43

Figure captions

Fig. 1. T-shape filtered arc deposition (T-FAD) system; (a) overall diagrammatic illustration and (b) details around electrostatic trap (ES-trap).

Fig. 2. Photograph and illustration of droplet crushed on T-duct wall.

Fig. 3. Variation of T-duct current and ion current at ion current monitor I_{IS} against T-duct bias voltage when ES-trap was not placed in T-FAD (arc current, 30 A).

Fig. 4. Current-voltage characteristics of ES-trap at different ES-trap positions.

Fig. 5. Characteristics of ion current I_{IS} vs. ES-trap bias voltage for different ES-trap positions.

Fig. 6. Deposition rate of DLC film as a function of ES-trap bias at ES-trap position 1 and for various ES-trap positions at ES-trap bias +35 V.

Fig. 7. Ion current I_{IS} at ES-trap bias +35 V for different ES-trap positions.

Fig. 8. Number of droplets on unit thickness of DLC film as a function of ES-trap bias at ES-trap position 1 and for various ES-trap positions at ES-trap bias +35 V.

Fig. 1 (a)

Fig. 1 (b)

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig.8