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Patterned free-standing diamond field emitters for iarge area field emission display applications

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Abstract – Using micro-wells on the Mo substrate, we could obtain various tubular-volcano-types of free-standing diamond field emitters by depositing a diamond film, detaching the film, and turning the film upside down. The field emission characteristics of these structures were investigated as a function of size, shape and the number density of the tubular-volcano-type diamond field emitters. The field emission characteristics, especially the current density, were greatly enhanced with increasing the number density of the tubular-volcano-type diamond field emitters on the Mo substrate. Based on these results, we suggest that the reduction of the well size can give better field emission characteristics by the increase in the number density of the tubular-volcano-type diamond field emitters. Finally, we suggest the feasibility of fabricating a large-area field emission display using our patterned tubular-volcano-type free-standing diamond field emitters.

I. Introduction

The size of spindt-type field emission displays (FED) [1], which are made of metal tips, is limited by the size of the equipment to deposit/etch metals. Recently, we have reported the possibility of large-area displays using the growth side (the as-grown surface of the film) of free-standing diamond films (FSDF) [2]. Furthermore, the field emitter based on diamond could have excellent field emission characteristics such as low turn-on voltage, high current density, and chemical inertness [3-5].

To practically apply diamond films for FED, the achievement of electron emission uniformity over a large area is essential. The uniformity of field emission might be achieved by eliminating morphology imperfections at the field emitter surface. However, voids and nondiamond carbon phases usually form at the interface between Si substrates and films, so it is hard to get uniform field emission characteristics from FSDF. Recently, we succeeded in removing morphology imperfections at the interface between the films and the Mo substrates [6]. Consequently, we could expect a good surface morphology at the field emitter and the enhancement of the electron emission uniformity. Furthermore, we could easily separate FSDF from the Mo substrate, because of the large difference in thermal expansion coefficients between diamond and Mo substrate [7].

To improve both the field emission characteristics and the emission uniformity of diamond films, patterning the diamond films, for example, making tip- or volcano-type ones, has been regarded as a promising method [8-10]. For fabricating a patterned FSDF suitable for a large area FED, we engraved well-type grooves on the Mo substrate. At the substrate side (the interfacial surface of the film detached from the Mo substrate), we could obtain a patterned FSDF in a tubular-volcano-type by depositing a diamond film on the engraved Mo substrate, detaching the film, and turning the film upside down, as we reported before [2]. We here investigated the field emission characteristics as a function of the shape, size, and the number density of the well-type grooves on the Mo substrate. Detailed processes and a potential application of FSDF for large-area FED are presented.

II. Experimental

Diamond films were deposited onto the Mo substrate in a conventional-type microwave-plasma-enhanced chemical vapor deposition (MPECVD; ASTeX 5 kW) system (see Fig. 1). Polycrystalline

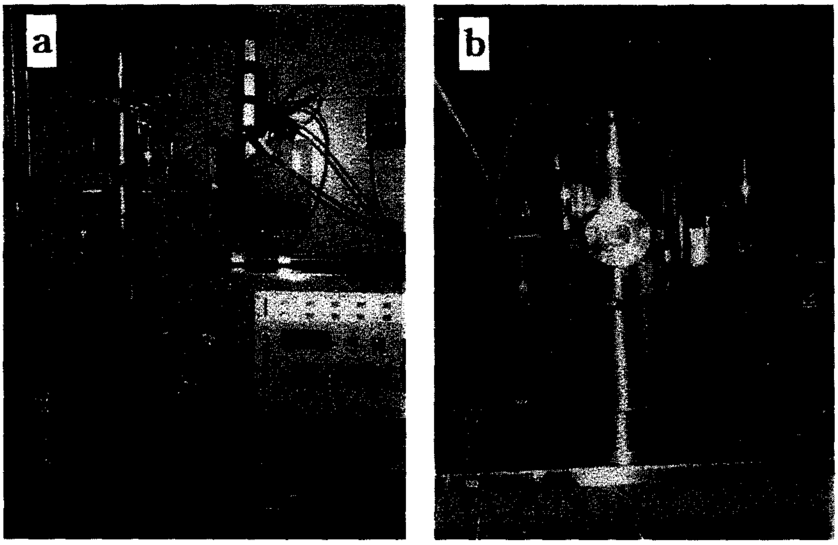

Fig. 1. (a) Microwave-plasma-enhanced chemical vapor deposition system, and (b) the plasma reaction chamber used for this study.

Mo (99.9%) discs were used for a substrate. The substrates were cleaned with H_2 plasma for 10 minutes at the initial stage of the process. The substrate, placed on the Mo substrate holder, was merely heated by the plasma. The temperature of the substrate surface was estimated to be above 1,000°C. The gas flow and the pressure in the reaction chamber could be precisely controlled by a mass flow controller (MFC; Tylan FC 260) and an automatic pressure controller (MKS 253A), respectively.

The reaction chamber was initially evacuated to 10^{-2} Torr. The pressure and the microwave power were gradually increased from 25 Torr and 500 W to 110 Torr and 4,000 W, respectively. The conditions used for diamond deposition are as follows: methane concentration = 6.0%, oxygen concentration = 0.5%, hydrogen concentration = 93.5%, and total flow rate = 200 sccm. The deposition time was 78 h, giving rise to the film thickness of about 500 μm.

Film morphologies were examined using a scanning electron microscopy, optical microscopy, and a non-contact surface roughness measurement system (WYKO, NT2000). The quality of diamond film was investigated using a micro-Raman spectrometer (Renishaw 3000). Field emission characteristics of FSDF were measured in a diode mode. The pressure inside the vacuum chamber was maintained as low as 10^{-7} Torr during measurements. An indium tin oxide (ITO) glass was used as an anode with a spacing of ~150 μm to the cathode. A silver paste was used as an electrical contact of the diamond film to the voltage source.

III. Results & Discussion

The patterned FSDF could be readily obtained after depositing the diamond film on the engraved Mo substrate and detaching the film from the substrate [2]. To investigate the morphology variation of the film as a function of the well shape and size on the Mo substrate, we initially engraved wells of different shape and size on the Mo substrate. Figs. 2a ~ d show the Mo substrate engraved with wells of different shape and the substrate side of FSDF detached from these substrates. A circular-type well also resulted in a circular-type shape on the substrate side (compare Figs. 2a with b). As shown in Figs. 2c and d, irregular polygon-type well resulted in the identical shape on the substrate side. These results reveal that the shape of the initially engraved well on the Mo substrate may determine the shape of the morphology of the diamond plane on the substrate side. Fig. 3 shows the FSDF on the Mo substrate (Fig. 3a) and the detailed morphologies of the substrate side of FSDF (Fig. 3b). The substrate side shows the patterned morphology as circular-type shapes (see inset of Fig. 3a). As shown in the inset of Fig. 3b, we could observe the light through a circular-type shape of the substrate side, indicating a hole formation at the center area of the circular-type well position on the Mo substrate. We could also observe the protrusion around the edge of the hole (see Fig 4). Despite of the small (or large) well size, we could consistently find the formation of a protru-

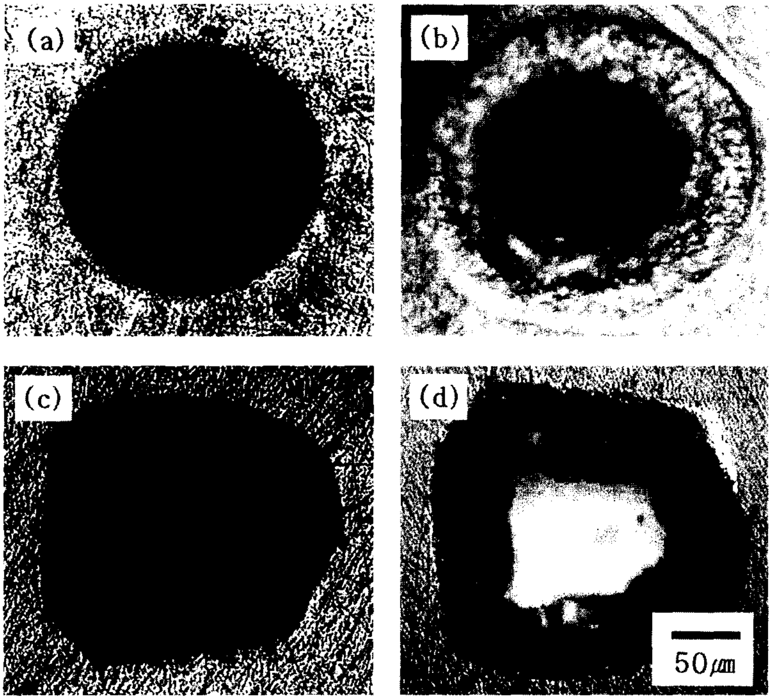

Fig. 2. (a) A Mo substrate engraved with circular-type well, (b) the substrate side of FSDF detached from this substrate, (c) A Mo substrate engraved with irregular polygon-type well, and (d) the substrate side of FSDF detached from this substrate.

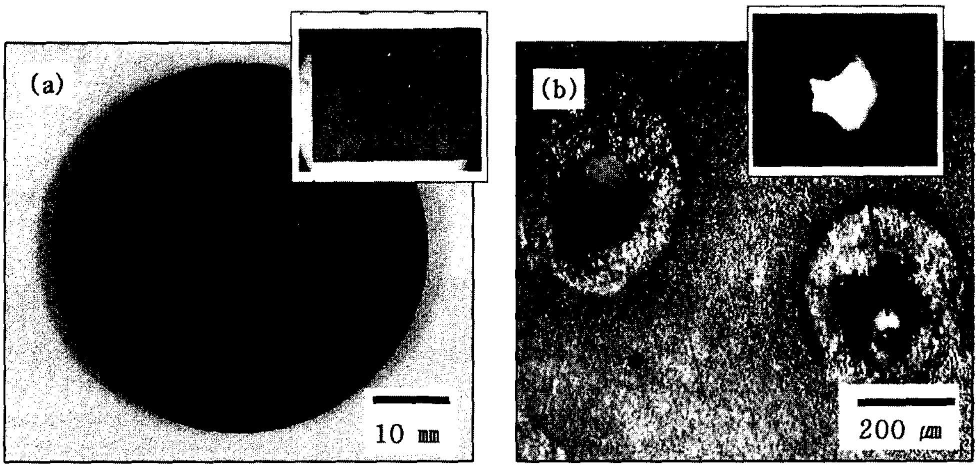

Fig. 3. (a) FSDFs on the MO substrate (inset: the substrate side of FSDF showing the patterned morphology as circular-type shapes) and (b) the detailed morphologies of the substrate side of FSDF having two TV-DFEs. (inset: the light through a circular-type shape of the substrate side).

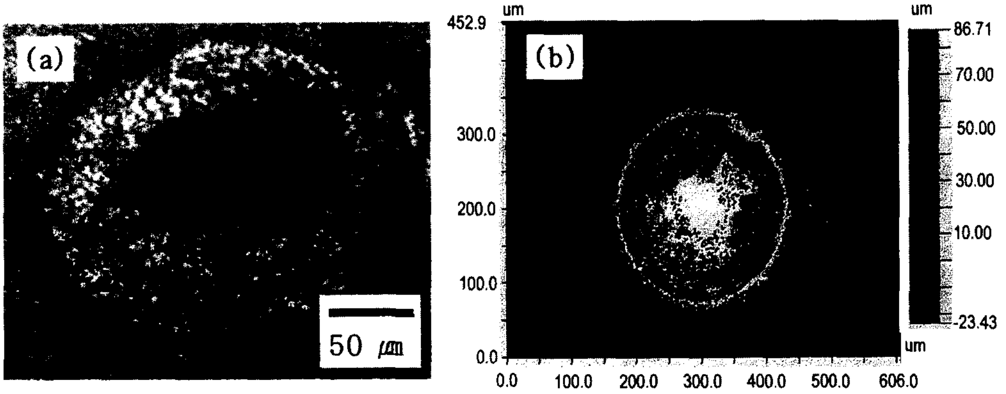

Fig. 4. (a) A TV-DFE and (b) surface morphology of the substrate side of a TV-DFE measured by a noncontact surface roughness measurement system. (White color at the center area indicates the hole formation).

sion around the edge of the hole as high as ~50 µm from the base plane. The protrusion around the edge of the hole may be ascribed to the higher film growth rate around edge area because the edge position can enhance the induced plasma density, compared with the flat position. On the growth side, we found a smaller hole, compared with that on the substrate side. It means that the hole size decreases with increasing the film thickness. Recently, we reported the possibility of crater formation, instead of hole, by the decrease in the inner diameter of hole with increasing the film thickness [11]. This crater shape of FSDF has protrusions on the substrate side and the decreased holes with increasing the film thickness. We refer to this as the tubular-volcano-type diamond field emitter (TV-DFE). A large well requires a thicker diamond film to fabricate a TV-DFE. This means that we can decrease the film deposition time for fabricating TV-DFE by engraving small size wells on the Mo substrate. Furthermore, the reduction of the well size can enhance the number density of the TV-DFE.

Previously, we demonstrated the enhancement of field emission characteristics of TV-DFE, compared with the flat-type diamond field emitter [2]. We here investigated the field emission characteristics of TV-DFE as a function of shape, size and the number density of TV-DFE. The field emission characteristics were investigated in terms of the turn-on voltage, which is defined as $d^2I/dV^2 = 0$, and

Table 1. Turn-on voltages and the emission currents of FSDFs as a function of the shape, the size and the number density of TV-DFEs

TV-DFE Shape, Size and Number density Field Emission Characteristics	Different shape of TVDFE at similar size (0.2mm in diameter)			Different size of circular-type TVDFE (unit = mm, in diameter)				Different number density of circular-type TVDFE (unit = × ea/cm^2)				
	□ square	○ square	⬡ Polygon	0.2	0.5	1.0	2.0	9	25	49	100	144
Turn-on Voltages (V/µm)	10.2 (±0.3)	10.5 (±0.2)	10.7 (±0.2)	10.5 (±0.2)	10.3 (±0.5)	10.8 (±0.3)	10.1 (±0.2)	25.0 (±0.5)	17.2 (±0.7)	16.3 (±0.8)	11.3 (±0.5)	10.5 (±0.2)
Emission currents at 1.4 kV (µA)	61.5 (±0.7)	60.0 (±0.5)	58.2 (±0.8)	60.0 (±0.5)	58.4 (±0.2)	57.7 (±0.6)	59.8 (±0.7)	1.2 (±0.6)	1.0 (±0.9)	3.2 (±0.7)	10.2 (±0.9)	60.0 (±0.5)

the current at the constant induced bias voltage (1.4 kV). We found the decrease in the turn-on voltage as well as the increase in the emission current with increasing the number density of TV-DFE (see Table 1). These results reveal that a film having the higher number density of TV-DFE possesses better field emission characteristics. We also investigated the field emission characteristics as a function of the shape and the size of TV-DFE. On the whole, we did not find any distinctive variation in field emission characteristics as functions of the shape and the size of TV-DFE (see Table 1). These results reveal that the field emission characteristics of the film depend only on the number density of TV-DFE, regardless of the shape and the size of TV-DFE. The reason for these results seems to be due to the ratio of the protrusion area of TV-DFE on FSDF. The different shape of TV-DFE could not strongly affect the protrusion area of TV-DFE on FSDF. For the size of TV-DFE, the increase of the size of TV-DFE should decrease the number density of TV-DFE on FSDF. Therefore, the protrusion area of the large size of TV-DFE would be identical with the original size of TV-DFE. On the other hand, the increase in the number density of TV-DFE could enhance the protrusion area of TV-DFE on FSDF.

To apply this film to a large area outdoor display, we suggest the method as follows. When one is going to use this FSDF as one pixel of cathode, 196,608 pieces of FSDF are needed to fabricate a color display of 256 × 256 resolution. At this experiment, only 20 pieces of FSDF were obtained in one growth cycle, therefore 9,830 deposition cycles are needed to obtain sufficient pieces of FSDF. This is too expensive process to be commercialized. However, if we use 10 substrate, we could obtain 12,500 pieces of FSDF, having 2×2 mm^2 size and 100 μm thick, just in one growth cycle under the optimum growth condition. Then we can reduce the deposition time by ~1/15 and achieve the reasonable production cost for FED. In addition, we suggest the feasibility of fabricating a large-area outdoor display such as the electric billboard using our FSDF. If FSDF can be manufactured in large volume using the present method, we can readily make independent field emission component cells. Therefore, we can easily control the display size via the combination of the independent field emission component cells. Fig. 5 shows a model for the electric billboard using a proposed FSDF.

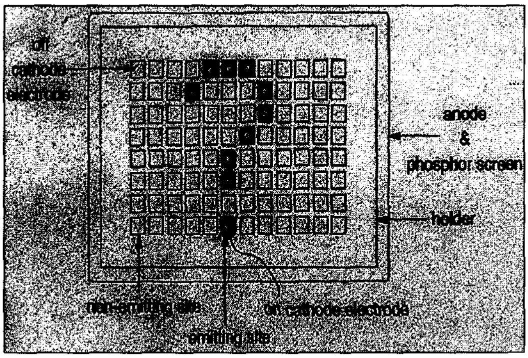

Fig. 5. A scheme of an electric billboard built from FSDFs having TV-DFEs.

IV. Conclusions

The reduction of the well size can enhance the number density of the TV-DFE, giving better field emission characteristics. The enhancement of field emission characteristics with the increase of the number density of TV-DFE seems to be due to the increase of the protrusion area of TV-DFE on FSDF. We suggest that FSDF having TV-DFE might be practically applied to a large-area out door display, such as electric billboard.

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