DIAMOND MICRO-SCHOTTKY EMITTER WITH AN INTEGRATED HEATING ELEMENT

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ABSTRACT

This paper describes the fabrication and evaluation of a boron-doped diamond micro Schottky emitter for micro-electron sources. We fabricated an emitter tip on the top of the cantilever-type heating element using selective diamond deposition and silicon molding techniques. The fabricated diamond emitter shows high brightness emission pattern of an emitting current of 800 nA with tip-anode (screen) electric field of 0.4 V/μm and tip heating power of 225 mW. This kind of structure can be useful for electron sources with potential advantages of low threshold voltage and long life time stability.

INTRODUCTION

Electron emitter using Schottky effect is widely used for Scanning Electron Microscopy (SEM), Electron beam lithography systems owing to its high emission current, high brightness and long term stability [1]. Especially, various kinds of carbon-based materials, including diamond and carbon nanotubes, have attracted interest in the field of electron emission because they can emit electrons at relatively low applied electric field [2]. Due to the small diameter, high aspect ratio, unique electrical and mechanical properties, carbon nanotubes became a good candidate for electron field emitters. With carbon nanotubes, electrons can be emitted at low electric field because external electric field strongly concentrated at its apex [3]. In the case of diamond, good mechanical hardness, chemical inertness are known to provide resistance against ion bombardment and improve emission stability. Furthermore, negative electron affinity (NEA) of specially pretreated diamond (H-terminated diamond) is believed to be able to emit electron at a low threshold voltage [4].

In this paper, we fabricated boron-doped diamond Schottky emitter with an integrated heating element. It is known that potential barrier with external electric field gets to be lower than that without electric field, called as Schottky effect. For the microelectronic applications, such as SEM or electron beam lithography, Schottky emitter is often used because it can emit highly stable electron beam with a narrow energy width and high brightness [1]. Emitter with external electric field usually needs a periodic tip heating occasionally, known as flash cleaning. This is necessary for removing adsorbed contaminations on the emitter surface. In this work, we demonstrated electron emission with micro diamond Schottky emitter with several advantages in electron emission behaviors of diamond materials. Using the diamond emitter structure with an integrated heating element, we can get a large emission current with high brightness and high stability due to its low threshold electric field. Furthermore, the good mechanical strength of diamond can provide resistance against the ion bombardment. The structure can be mass produced by MEMS technology and can be made in array for multi-electron sources application.

EMITTER STRUCTURE AND FABRICATION

As shown in Fig. 1, diamond Schottky emitter structure consists of 3 layers: the cantilever-type heating element with the diamond tip, Pyrex glass and Aluminum (Al). The cantilever-type heating element and emitter tip was made with boron-doped diamond. By flowing a current through the cantilever, the diamond tip will be heated. The Pyrex glass substrate with feed-through holes was bonded with the diamond cantilever as a support part. Electrical wiring with the diamond layer was formed at the feed-through holes. A thin Al layer was used as an intermediate layer for anodic bonding between diamond layer and the Pyrex glass. In the fabrication, the combination of molding

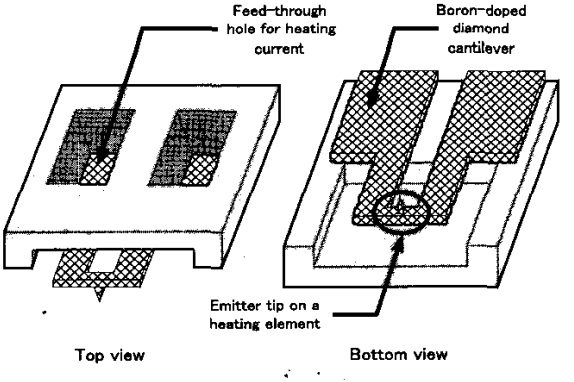

Fig. 1. The structure of diamond Schottky emitter.

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and selective diamond deposition techniques was used for making diamond cantilever with the sharp diamond tip. A p-type (100)-oriented silicon with resistivity of 5-8 Ω·cm was oxidized and oxide was patterned by photolithography. Using this oxide layer as a mask, silicon was anisotropically etched in 20 wt.% KOH etchant at 80 °C to make tip mold. Next, 3 μm-thick boron-doped diamond patterns was selectively deposited on the silicon mold using a Hot-Filament Chemical Vapor Deposition (HF-CVD) [5]. A mixture of methane : hydrogen (1.5%: 98.5%) was introduced into the chamber at a pressure of 5.2 kPa. An additional small amount of vaporized tri-methoxyborane as a boron source was introduced at the same time for Boron doping during the growing. Tungsten filaments were placed above the sample at a distance of 5 mm and heated up to 2000 °C. We used SiO_2 as mask for the selective growth of diamond on the Silicon mold. To ensure the selective growth of diamond, deposition process was carried out as follows. First, the silicon substrate with patterned oxide was treated for diamond nucleation using an ultrasonic agitator with 1 μm diameter of diamond powders. Then oxide layer was slightly etched in a buffered-HF (BHF). At this step, the diamond nucleation on the oxide layer was selectively removed. After growing 30 min., the sample was taken out and the SiO_2 was totally removed. The final growing was done for 10 hours to get diamond patterns with 3 μm-thick on the Silicon mold. Next, Al patterns were formed on the diamond layer by sputtering and following photolithography, which serves as an adhesive intermediate layer for anodic bonding with the Pyres glass [6]. Part of the glass, which corresponds to the upper areas of the cantilever after bonding, was selectively etched in the BHF with a Cr mask layer. Then feed-through holes and narrow grooves were formed on the Pyrex glass substrate by a drilling machine and dicing saw, respectively. The silicon and Pyrex glass was anodically bonded under a voltage of 600 V at 500 °C. Next, the silicon mold was etched-out with an Inductively Coupled Plasma- Reactive Ion Etching (ICP-RIE) using SF_6 gas, and

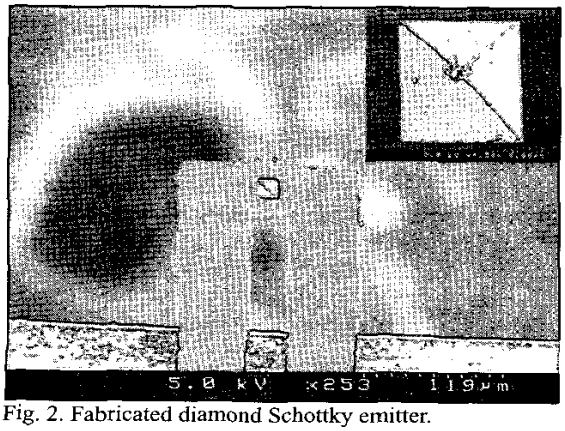

Fig. 2. Fabricated diamond Schottky emitter.

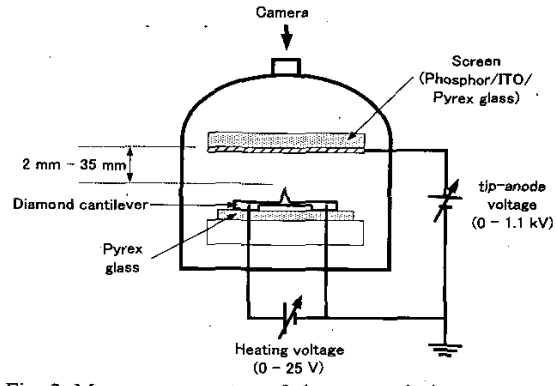

Fig. 3. Measurement setup of electron emission.

cantilever was released. The emitter probes were cut into pieces along the glass grooves and metal wires were glued onto the holes with conductively adhesive bond. Figure 2 shows the fabricated Schottky emitter tip with the cantilever-type heating element.

EVALUATION AND DISCUSSION

Figure 3 shows a schematic view of a setup for electron emission experiment. Emission characteristics of the fabricated diamond Schottky emitter were examined in the vacuum chamber of 2.5×10^{-6} Pa. A phosphorous screen (ZnO, Zn) formed on an ITO coated glass was used as an anode electrode for the emission pattern observation. The distance tip-anode can be manually controlled.

Firstly, electron emission current was measured with changing the tip heating voltage. In this case, the tip-anode voltage and the tip-anode distance were fixed at 1.1 kV and 2 mm, respectively. As shown in Fig. 4, electron emission was started at the heating voltage of 12 V and raised up to 800 nA at 25 V. With the fixed heating voltage of 20 V and tip-anode distance of 2 mm, the emission current as a function of the applied electric field was monitored as shown in Fig. 5, where the electric field was defined as the tip-anode voltage divided by the distance. Figure 5 shows that the

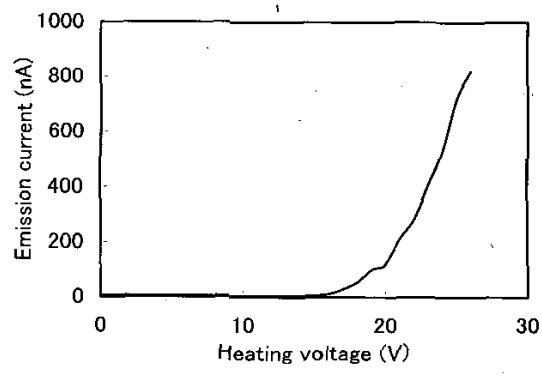

Fig. 4. Emission current as a function of tip heating voltage.

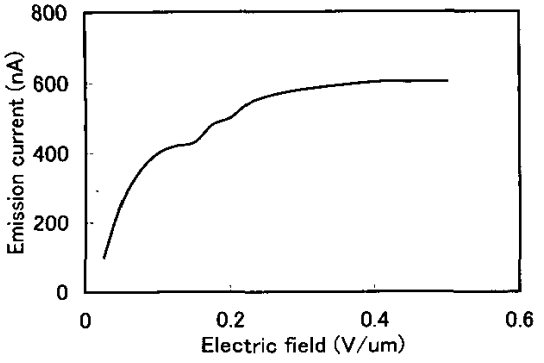

Fig. 5. Emission current as a function of the applied electric field, where electric field was defined as the tip-anode voltage divided by the distance.

electron emission current is saturated at about 600 nA for the electric field of 0.4 V/μm. Obviously, the trend of the curve shown in Fig. 5 is different from the field emission characteristic which is known to follow the Fowler-Nordheim relation [7]. The emission characteristic shown in Fig. 5 can be explained with Schottky emission model. Schottky emission current is known to follow the equation (1) [8].

$$J = AT^2 \cdot \exp\{-\phi/(K_B \cdot T)\} \cdot \exp\{\sqrt{(e^3 \cdot F)}\} \qquad (1)$$

where A is the thermionic emission constant of 1.2×10^6 $[A/(m^2 \cdot K^2)]$ which is not dependent on materials, ϕ is the work function, K_B is Boltzmann constant and F is the applied electric field. In the calculation of the emission current, measured data in Fig. 5 was used, the work function of the boron-doped diamond was considered as 4.2 eV [9] and the emitter tip temperature was also used as a variable. Figure 6 shows the result of this calculation with assuming the emitter temperature at 862 ± 10 °C. It is seen that the

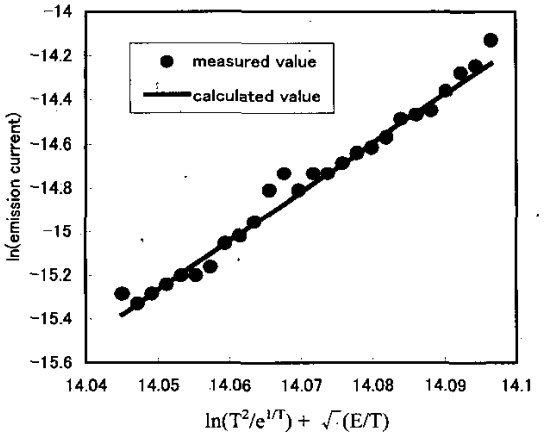

Fig. 6. Comparison of the calculated Schottky emission current assuming emission tip temperature variation with measured result.

Fig. 7. Electron emission pattern at the tip-anode distance of 2 mm (spot size ~ 1 mm) (a) and 35 mm (b).

trend of measured and calculated values was well matched.

Electron emission patterns of the Schottky emitter were observed on the anode screen. Fig. 7 (a), (b) show electron emission patterns with the tip-anode voltage of 1.1 kV and tip heating voltage of 25 V at tip-anode distance of 2 mm and 35 mm, respectively. The spot size of about 1 mm at the distance of 2 mm showed that the electron beam was emitted with approximately 30° cone angle. In order to examine the emission stability of the fabricated emitter, we monitored the emission current for about 50 hrs. as shown in Fig. 7. For the first 8 hours, the tip-anode voltage was 700 V, the tip-anode distance was 2 mm and the tip heating voltage was 20 V. During this interval, emission current fluctuated within ± 20 % range. After that, the tip-anode voltage and tip heating voltage were set at 1 kV and 25 V, respectively. As seen in the figure, there was a big overshooting after changing the condition. It can be thought that the heating of emitter tip removes the microscopic particles adsorbed on the emitter surface at low electric field and induces the large emission current [10]. We can see the emission current decline with the shape of step and become more stable after ward. Though we have no idea about the exact

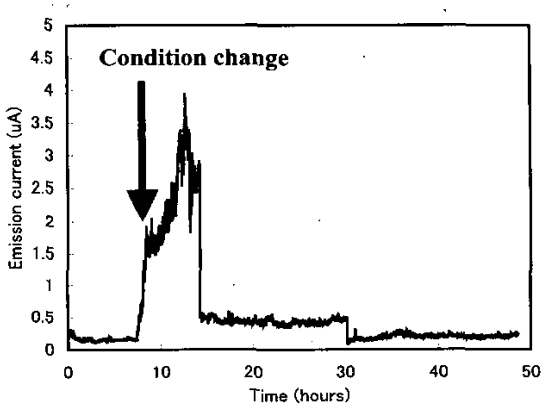

Fig. 8. Long term stability of the diamond electron emitter. With the condition for emission, tip-anode distance of 2 mm, tip-anode voltage of 700 V and heating voltage of 20 V was used until 8 hrs. After that, the tip-anode voltage and the heating voltage was changed to 1 kV and 25 V, respectively.

reason of this trend, it is assumed to be related with chemical modification on the diamond surface at high temperature, which was originated from oxidization, adsorbed materials or chamber contaminations.

SUMMARY

A boron-dope diamond electron Schottky emitter was fabricated and characterized. The emitter was mass produced with selective diamond deposition and silicon molding techniques. The fabricated diamond emitter provided emission current of 800 nA at as low as 0.4 V/μm electric field. The emission characteristic was well fitted with Schottky emission model with assuming the emitter temperature at 862 ± 10 °C. During about 50 hrs monitoring of emission current, there was step-like decline which was considered to come from diamond surface modification.

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