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Electron emission characteristics of needle type semiconductor diamond electron emitters by pulsed bias operation and X-ray generation

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ABSTRACT

Electron emission characteristics of needle-type semiconductor diamond electron emitters with pulsed bias operation were evaluated. An X-ray generation experiment was performed. Fowler–Nordheim plotting confirmed that field emission completely governed the electron emission. Maximum emission current of 4.2 mA was achieved using an n-type diamond needle. The needle tip, with area smaller than 1 μm^2, had estimated electron emission density greater than 4.2×10^5 A/cm^2. The effective emission area obtained from the Fowler–Nordheim plot was several 10^{-13} cm^2. For adopting and emission area of 1×10^{-12} cm^2, the estimated electron emission density was higher than 4.2×10^9 A/cm^2. Furthermore, the average emission current was 0.5–0.6 mA. This large electron emission was continued for several seconds and repeatable. A threshold electric field existed for electron emission higher than 50 kV/mm; pulsed electron emissions of less than 30 ms were created by slow triangular waveform shaped bias voltage supplied at frequencies of 5–10 Hz. An improved vacuum level and pulsed bias operation prevented damage to diamond electron emitters and steady electron emission better than with thermoelectronic emission and high bias voltage supply in DC mode; continuous X-ray generation of 1 h was achieved.

1. Introduction

Diamond has superior thermal conductivity, high tolerance to sputtering, high mechanical strength, and equal or near-negative electron affinity [1–4]. For those reasons, diamond is expected to be a durable electron emitter. Moreover, fabrication of extremely sharp diamond needles of the order of several nanometers at the tip has been achieved using photolithography and ion beam etching [5–7].

However, a strong competitor for diamond has been developed: carbon nanotubes (CNTs) [8–10]. In fact, CNTs with a large area can be synthesized more easily than diamond. Furthermore, CNTs can emit electrons at room temperature through field emission. Therefore, CNTs are applicable to vacuum light-emitting devices, etc. Endurance for long-term operation remains as a problem to be solved.

Diamond electron emitters have been applied to some industrial production that can use the advantages of diamond described above. One typical case is an electron lithography system for the semiconductor industry. In this case, a semiconductor diamond electron emitter is operated at temperatures of 400–500 °C. This lower operational temperature engenders small energy dispersion [11] and fine spatial resolution. For all other applications, a similar developmental strategy is required for diamond.

An X-ray source is one application of electron emitters. X-ray sources are widely used in industrial nondestructive measurement systems, medical diagnostic systems, etc. In the relevant literature, few diamond-application reports are available, such as one describing a miniature X-ray source using a microfabrication technique [12,13].

Diamond has advantages of high tolerance to sputtering and documented microfabrication techniques. As an X-ray source, a promising diamond electron emitter application relies on these advantages of diamond: a microfocus X-ray inspection system, which is useful for high-density circuit boards and similar objects. This system requires a small geometrical size of an X-ray source to achieve higher spatial resolution. For general purposes, an X-ray source size of a few micrometers is required. In addition, for a high spatial resolution system, an X-ray source size of a hundred nanometers is required.

For further improvement of microfocus X-ray inspection systems, a smaller and brighter X-ray source is necessary; this requirement suits a diamond electron emitter well. For that reason, a needle-type semiconductor diamond electron emitter was applied as an X-ray source by the authors in a previous study [14]. X-rays were generated by a needle-type semiconductor electron emitter with thermoelectronic emission and a DC high voltage supplying up to 50 kV. However, damage to the electron emitter occurred when using a discharge caused by residual gas in the chamber. In this paper, vacuum level

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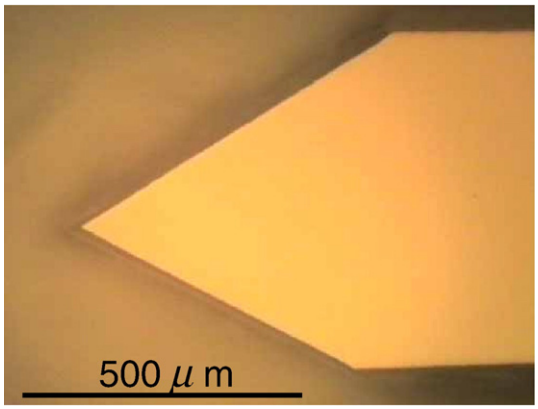

Fig. 1. An example of needle type diamond electron emitters obtained by an optical microscope.

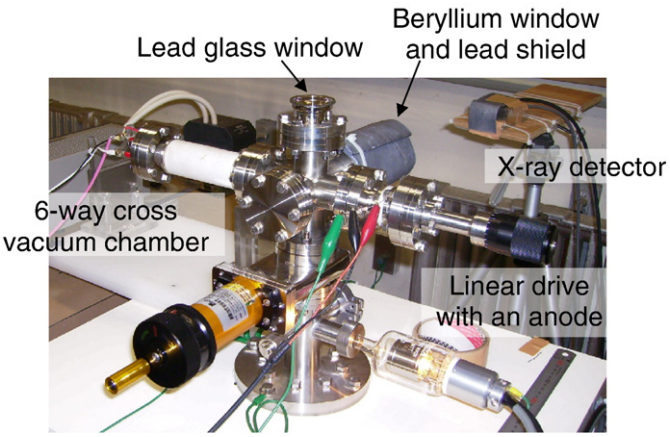

Fig. 2. The 6-way cross vacuum chamber and other apparatus of diamond electron emitter evaluation system.

improvement and pulsed bias operation aimed at steady electron emission and X-ray generation are described.

2. Experimental

2.1. Needle type semiconductor diamond electron emitters

Simple needle type diamond electron emitters fabricated by Sumitomo Electric Industries, Ltd. were used. Fig. 1 shows an example of needle type diamond electron emitters obtained by an optical microscope. The diamond electron emitters were made of type Ib diamond single crystals grown using a high-pressure and a high-temperature synthesis method; a typical size was ca. 0.6×0.6×2.5 mm. A needle tip was shaped as a trigonal pyramid or wedge [11]. An n-type or p-type semiconductor diamond layer was fabricated on a (111) surface of the needle using the chemical vapor deposition method. Table 1 portrays a summary of electron emitters used in this study.

Sample #1 achieved maximum emission current of 550 μA under the following experimental conditions: 5×10^{-5} Pa vacuum environment, 80 mm cathode–anode distance, 500 °C emitter temperature, with a supplied bias voltage of less than 10 kV in DC mode. After large electron emission of several seconds, the emission current dropped suddenly; it became several microamperes. After this experiment, the electron emitter tip was observed using an optical microscope: it had become completely flat. It had probably been destroyed by discharge from interaction between the emitted electrons and residual gas at high density. In addition, the possibility of damage caused by Joule heating was evaluated because n-type semiconductor diamond had high resistivity of several hundred ohm-centimeters at room temperature [11]. However, a simple thermal transport calculation implied no harmful rise of temperature at the tip.

Samples #2, #3 and #4 were new with sharp tips. Tip areas of samples #3 and #4 were smaller than 1 μm^2; they were observed using a laser microscope. In addition, a conventional tungsten filament was used for comparison.

Table 1
Electron emitters used in this study

I.D.	Type	Remark
Sample #1	n-type diamond needle, 0.6×0.6×2.5 mm	Damaged trigonal pyramid shape tip
Sample #2	n-type diamond needle, 0.6×0.6×2.5 mm	Wedge shape tip
Sample #3	n-type diamond needle, 0.6×0.6×2.5 mm	Trigonal pyramid shape tip
Sample #4	p-type diamond needle, 0.6×0.6×2.5 mm	Trigonal pyramid shape tip
Tungsten	tungsten filament, ϕ0.1 mm	Conventional thermal electron emitter

2.2. Evaluation system

The evaluation system [14] used for diamond electron emitters was remodeled for pulsed bias experiments. This system consisted of a 6-way-cross stainless steel vacuum chamber with a beryllium window and lead glass windows, a small turbo molecular pump (UTM-50; Ulvac), and a 10 kV high-voltage AC/DC amplifier (HVA4321; NF Corp.). This amplifier supplied high-voltage pulse waveforms to the cathode according to input waveforms generated using a function generator (AFG3101; Tektronix Inc.). The 6-way cross stainless vacuum chamber had 35 mm inner diameter; vacuum of 3×10^{-6} Pa was achieved. An insulating transformer was set between the 6-way cross stainless vacuum chamber and an electron emitter stage. A needle-type semiconductor diamond electron emitter was fixed in the vacuum chamber using metal nippers. Then a high voltage of −10 kV at maximum was applied in pulsed bias operation. An anode electrode connected with a linear drive was set at a distance between 0.2 and 15 mm from the cathode; the anode was grounded through a digital or an analog oscilloscope. Fig. 2 shows a picture of the 6-way cross vacuum chamber and other apparatus. For current measurements, a copper anode was adopted. A tungsten anode was used for the X-ray generation experiment. Fig. 3 portrays a schematic drawing of the measurement system. A CdZnTe semiconductor detector (XR-111T-CZT; Amptek Inc.) and a multi-channel analyzer (MCA2100; Labo Inc.) were used for X-ray measurements.

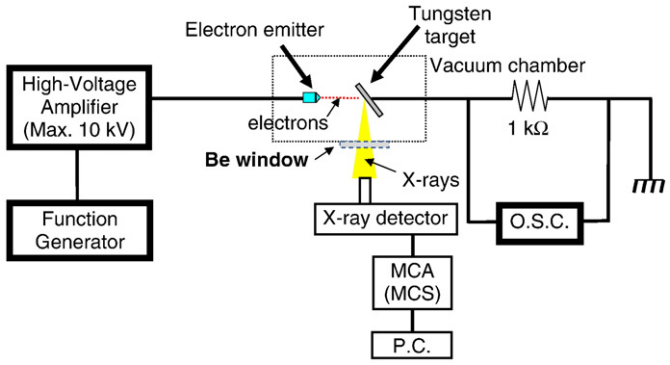

Fig. 3. Schematic drawing of the evaluation system for semiconductor diamond electron emitters with pulsed bias operation. A semiconductor radiation detector was used for X-ray measurement.