

DEVELOPMENT OF A C-BAND RF GUN WITH A CONIFEROUS-TREE-TYPE CARBON NANOSTRUCTURE FIELD EMISSION CATHODE*

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Abstract

Recently, coniferous formed carbon nano-structure (CCNS) as a field emission cold cathode has been developed. Tips of it have a nanometer-size tubular structure that becomes thicker on the substrate side. Owing to this configuration, the CCNS is considered to be more stable in high electric fields than carbon nanotubes. Characteristic of the field emission of the CCNS under an electrostatic field was revealed in the previous study. We have developed a C-band RF gun to reveal characteristic for a RF field. An important quantity for the field emission cathode which is called field enhancement factor was measured as 894 ± 54 by applying the electric field from 20 to 30 MV/m. This value is lower than that obtained by an electrostatic field up to 7.4 MV/m. Reduction of the enhancement factor was due to the destruction of tips of the CCNS by a high electric field.

INTRODUCTION

We have fabricated a C-band RF gun which used a field emission cathode of coniferous-tree-type carbon nano-structure (CCNS) cathode. Aim of it is a development of a tabletop size high-energy x-ray source and a terahertz radiation source.

If a wavelength of emitted radiation is longer than a bunch length of an electron beam, each radiation is coherently enhanced. Terahertz radiation is coherently enhanced by using the sub-picosecond electron beam. Electrons are emitted only in the restricted phase by the field emission. This characteristic is suitable for the generation of the short pulsed electron beam. Generation of the short pulsed electron beam in the range from sub-picosecond to picosecond is usually achieved by a photocathode and a short-pulsed laser system. If the picosecond electron beam can be generated via a field emission, it contributes to a miniaturization of the equipment.

We use the CCNS as a field emission cathode. Appearance of the CCNS cathode is shown in Fig. 1. The CCNS is deposited on a stainless steel substrate with the diameter of 6 mm by plasma-enhanced chemical vapor deposition. A detailed method is described in Ref. [1]. The CCNS has a following structure, which a graphene sheet composed of carbon has a coniferous form, and the tip has a nanometer-size tubular structure that becomes thicker on the substrate side [1]. A lot of studies concerning the field emission characteristics of carbon nanotubes (CNT) are carried out. CNT is a uniform diameter from the substrate side to the tip. On the other hand, the CCNS has the similar tip shape as CNT and becomes thicker towards the substrate side. Owing to this

structure, the CCNS is considered to be more stable in high electric fields than CNT. In the previous study using the electrostatic field, it was found that a field emission current was 1.6 mA at the electric field of 7.4 MV/m, current density was 200 mA/cm², and field enhancement factor was 1562 [1]. In this proceedings, we report the first measurement of the field emission properties of the CCNS under the RF field.

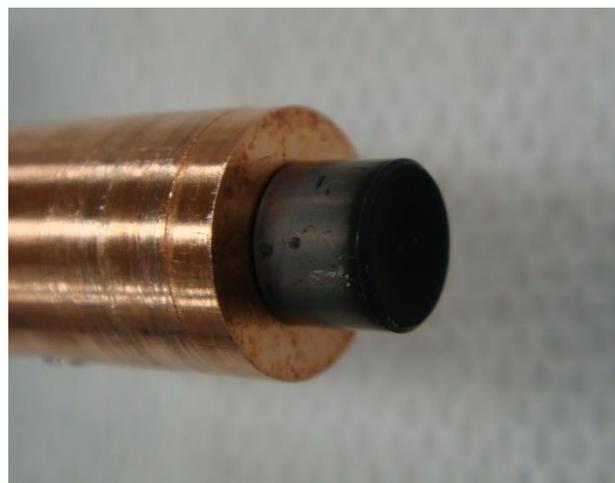


Figure 1: Appearance of CCNS cathode. The diameter of the CCNS is 6 mm.

C-BAND RF GUN

Appearance of the C-band RF gun is shown in Fig. 2. The detailed structure is described in Ref. [2]. This C-band RF gun is a single cell cavity, which the radius and length are 21.6 mm and 16.1 mm, respectively. RF power is inputted from a magnetron (New Japan Radio Co., Ltd. M1602). A four-port circulator, a directional coupler, and a pressurization window are connected between the magnetron and the C-band RF gun. Forward and reflected

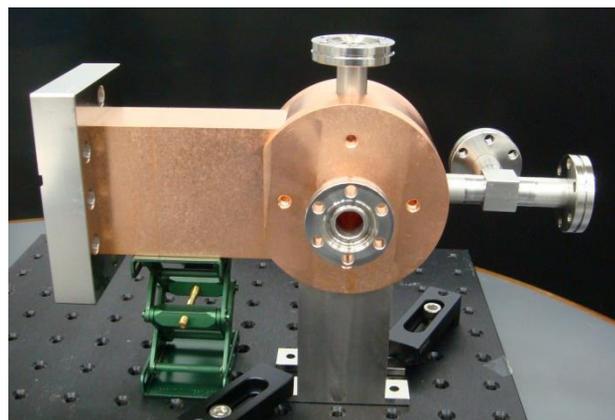


Figure 2: Appearance of the C-band RF gun.

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RF power and waveform are measured by the directional coupler. Parameters of the magnetron are follows: frequency, 5.25 ~ 5.4 GHz; maximum peak power, 600 kW; pulse duration, 2 ~ 2.5 μ s; Duty cycle, 0.001; pulse voltage, 27 kV; Peak anode current, 40 A, respectively.

To evaluate the field emission property of the CCNS, we have to exactly evaluate an electric field distribution induced in the cavity. The electric field on the cathode surface is evaluated by a perturbation method, which a small metallic bead is pushed into a cavity, and described as [3]

$$E = \sqrt{\frac{|\Delta f|}{f_0^2} \frac{P_0 Q_0}{2\epsilon\pi^2 r^3}}. \quad (1)$$

Here, Δf is the frequency shift when the metallic bead with the radius of r is pushed near cathode surface, f_0 is the resonant frequency of the cavity without the bead, P_0 is the power dissipation in the cavity, Q_0 is the unloaded quality factor of the cavity, and ϵ is the vacuum permittivity ($\epsilon_0=8.85 \times 10^{-12}$ F/m), respectively. Δf and f_0 are measured with a network analyser.

We have evaluated P_0 and Q_0 by measuring the ratio between an input power to the cavity, P_i , and a reflected power from the cavity, P_r . The ratio between P_i and P_r is described as [4]

$$\frac{P_r}{P_i} = \left\{ \left(1 - \exp\left(-\frac{t}{t_f}\right) \right) \frac{2\beta_c}{1 + \beta_c} - 1 \right\}^2. \quad (2)$$

Here, t_f is the filling time of the cavity and β_c is the coupling factor between the cavity and the external circuit, respectively. The unloaded quality factor is described as

$$Q_0 = \pi f_0 (1 + \beta_c) t_f. \quad (3)$$

The power dissipation in the cavity is described as

$$P_0 = \frac{4\beta_c}{(1 + \beta_c)^2} P_i. \quad (4)$$

When a stainless steel spherical bead with the radius of 0.794 mm was pushed into near cathode surface, the frequency shift was evaluated as $\Delta f = 3.68$ MHz and the resonant frequency f_0 was 5357.398 MHz. The coupling factor and the filling time were evaluated as $\beta_c = 14.0 \pm$

0.5, $t_f = 45 \pm 10$ ns by fitting the Eq. (2) to the measured waveform of the ratio between P_i and P_r . Therefore, $Q_0 = 11300 \pm 2500$, and $P_0 = 25 \pm 2$ kW when the input power is 100 kW. Consequently, the electric field is calculated as 20 ± 4 MV/m when the input power is 100 kW.

MEASUREMENT OF FIELD EMISSION CURRENT

Field emission current was measured by connected an insulation flange to the C-band RF gun. Current flowing the insulation flange was measured with a picoammeter (Keithley, 6487).

When the electric field is of the form $E \sin 2\pi f_0 t$, the average field emission current density, I (A/cm²), is described as [5]

$$I = 0.57 \times 10^{4.52\phi - 0.5} \frac{(\beta E)^{2.5}}{\phi^{1.75}} \times \exp\left(-6.53 \times 10^3 \frac{\phi^{3/2}}{\beta E}\right). \quad (5)$$

Here, ϕ is the work function in eV ($\phi = 5$ eV), β is the enhancement factor, and E is the amplitude of the surface field in MV/m, respectively. The enhancement factor can be obtained by plotting $\ln(I/E^{2.5})$ versus $1/E$ (Fowler-Nordheim plot) as follows

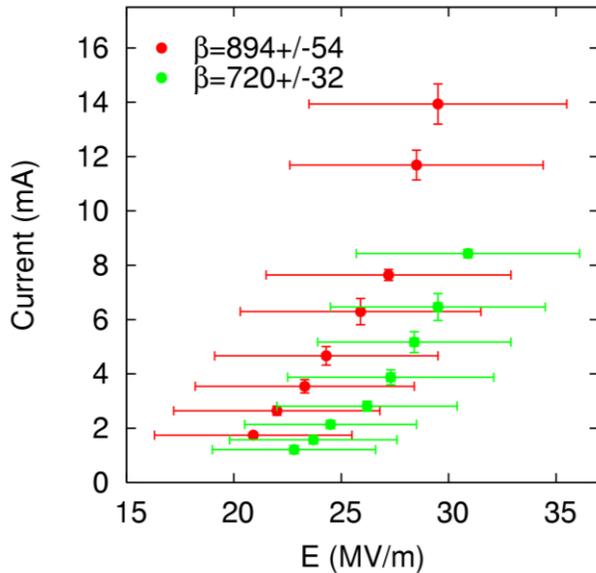


Figure 3: Field emission current from a CCNS measured with a different condition. Red points represent the first measurement of the CCNS. Green ones are second measurement after applying the electric field of 36 MV/m.

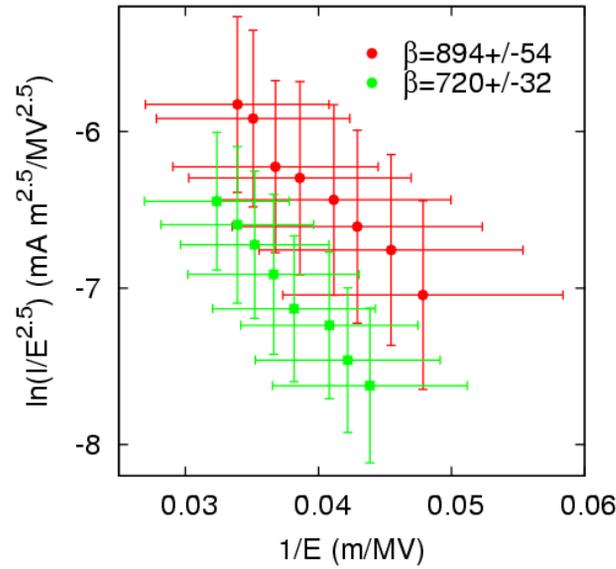


Figure 4: Fowler-Nordheim plot of CCNS.

$$\ln\left(\frac{I}{E^{2.5}}\right) = \ln\left(0.57 \times 10^{4.52\phi-0.5} \frac{\beta^{2.5}}{\phi^{1.75}}\right) - \left(6.53 \times 10^3 \frac{\phi^{3/2}}{\beta}\right) \frac{1}{E} \quad (6)$$

The measured field emission current and Fowler-Nordheim plot are shown in Fig. 4 and 5. The magnetron was operated in the following condition: RF peak power, 110 ~ 310 kW; pulse width, 2 μs; repetition rate, 9.5 Hz; and duty cycle, 1.9×10⁻⁵. The maximum beam current was measured as 14 mA when the electric field was 30 MV/m. Thus, the current density was 50 mA/cm² and the average beam current was 0.27 μA.

The field enhancement factor was evaluated as 894 ± 54 in the initial state (red points in Fig. 3). However, the

field enhancement factor was measured as 1562 for an electrostatic field up to 7.4 MV/m [1]. Reduction of the enhancement factor was due to the destruction of tips of the CCNS by a high electric field. Moreover, we observed further reduction of the enhancement factor, from 894 ± 54 to 720 ± 32 after applying high electric field up to 36 MV/m to the CCNS.

CONCLUSION

Field emission properties of the CCNS was measured with the C-band RF cavity. The field enhancement factor for the RF field was evaluated as 894 ± 54. This value is lower than the value measured with the electrostatic field. Reduction of the enhancement factor was due to the destruction of tips of the CCNS by a high electric field. We also observed the further reduction of the enhancement factor after applying an electric field of 36 MV/m to the CCNS. We found the CCNS can be still remained if the high electric field up to 30 MV/m is instantaneously applied. However, we are performing a detailed analysis to evaluate an actual electric field applying to the CCNS. We are planning to measure the energy distribution of the field emitted electrons. The clear properties of the CCNS will be found after measuring the energy of the electrons.

ACKNOWLEDGMENT

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