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X-ray tube based on carbon nanotube field emitter for low dose mini C-arm fluoroscopy

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ABSTRACT

We designed and developed the vacuum sealed x-ray tube based on carbon nanotube(CNT) field emitter for mobile medical x-ray devices and also design the test bed for CNT x-ray tube. The CNT was synthesized by chemical vapor deposition(CVD) method on a metal alloy substrate. The grown CNT is assembled with a gate and a focuser and then combined into an electron gun(e-gun) through a brazing process. The the e-gun had an aging process inside the vacuum chamber. As a result of aging, the CNT e-gun was able to generate anode current of 1.5 mA at electric field of about 4 V/µm, and field emission current was also stabilized. After the aging process, the e-gun was brazed into a ceramic X-ray tube inside a high-temperature furnace at a vacuum degree of E^{-06} torr and vacuum sealed. Field emission characteristic was measured using this X-ray tube and compared with an e-gun, and almost similar results were obtained. Incase of X-ray tube, we applied a higher electric field while controlling the current at 500ms intervals through pulse driving. As a result, X-ray images of human teeth were successfully acquired using CNT X-ray tubes.

Keywords: Carbon nanotube, Field emission, X-ray tube, Mini C-arm fluoroscopy

1. INTRODUCTION

Despite the risk of exposure to radiation from the use of medical devices, the use of medical x-rays in medical fields is inevitable. Various methods have been attempted to reduce radiation exposure during medical practice, mainly suggesting shielding the radiation or improving the image quality with a lower dose as a solution[1]. In order to reduce the radiation exposure, one method may be to increase the efficiency of the X-ray source by avoiding unnecessary driving. X-ray systems using carbon nanotubes as a source have many possibilities[2]. Materials that emit electrons from field emission have been studied in various ways. Among them, carbon nanotubes (CNTs) are particularly advantageous for field emission due to their large aspect ratio and stability[3]. Unlike a filament that generates unnecessary electrons during the heating process, in a field emission method tube current can be controlled by an electric field, allowing more precise electron control[4]. Such precise electronic control has the effect of reducing unnecessary X-ray emission. In addition, the advantage of CNT emitters compared to commercial filament emitters is that CNT emitters can be made into various shapes through etching or catalytic patterning[5], compared to filaments that are difficult to make various shapes. Therefore, it is possible to design and create a shape optimization for obtaining an X-ray image or a shape optimized for electron emission. One of the advantages of CNT is that it has a very stable and robust structure. However, CNT is not a perfect material. CNTs get easily decomposed and damaged by oxygen at high temperatures[6]. Since electron emission and generation of X-rays cause a high temperature environment inside the tube, it is important to seal the tube in sufficient vacuum when making CNT X-ray tubes.

In this study, CNTs were grown on a metal alloy substrate and used as an electron emission source. Using this emitter, the electron gun(e-gun) including the focuser and the gate structure was brazed and its field emission characteristics were analyzed to confirm whether sufficient current could be obtained for X-ray acquisition. Also, the X-ray image was acquired with e-gun. The aged e-gun was brazed into a tube in a vacuum environment. It was confirmed that the X-ray tube showed a field emission characteristic even if it was not inside the vacuum chamber. In addition, it was able to stably apply a high electric field with fast on/off switching and as a result, the X-ray tube generated enough emission

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current required for mobile x-ray devices. Moreover, this fast switching can reduce unnecessary radiation while taking X-ray images. Finally, X-ray images were successfully obtained from a test bed including a high voltage source and a X-ray detector.

2. EXPERIMENTAL DETAIL

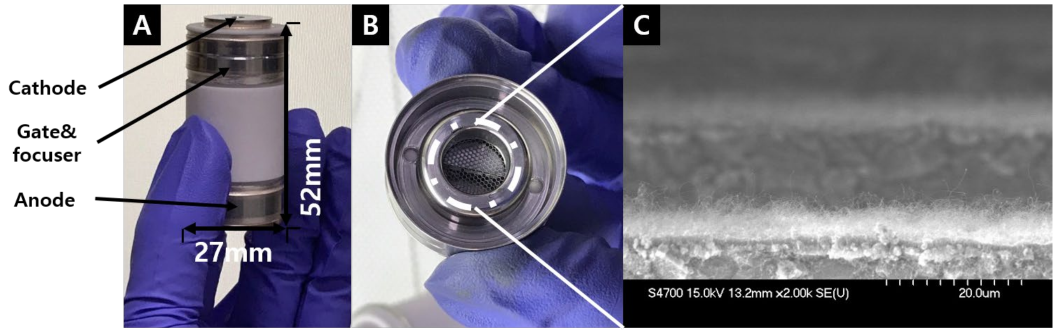

Figure 1. (A) Image of brazed CNT x-ray tube. (B) Image of the e-gun used in the tube. (C) SEM image of CNT emitter.

CNTs were synthesized on a metal alloy substrate, yef-426, consisting of 52% iron, 42% nickel and 6% chromium. The metal alloy substrate was etched into a stripe pattern to reduce the screening effect and improve the emission current. A single strip has 40µm of width and the distance between each strip is 150 µm. Since the metal alloy substrate contains nickel, chromium, and iron, CNTs can grow without adding a catalyst. CNTs were grown using chemical vapor deposition (CVD). The CVD process was carried out for 1 hour by supplying 30 sccm of C_2H_2 and 70 sccm of NH_3 gas at a temperature of 900 °C. Verification of CNT growth was examined through scanning electron microscope (SEM).

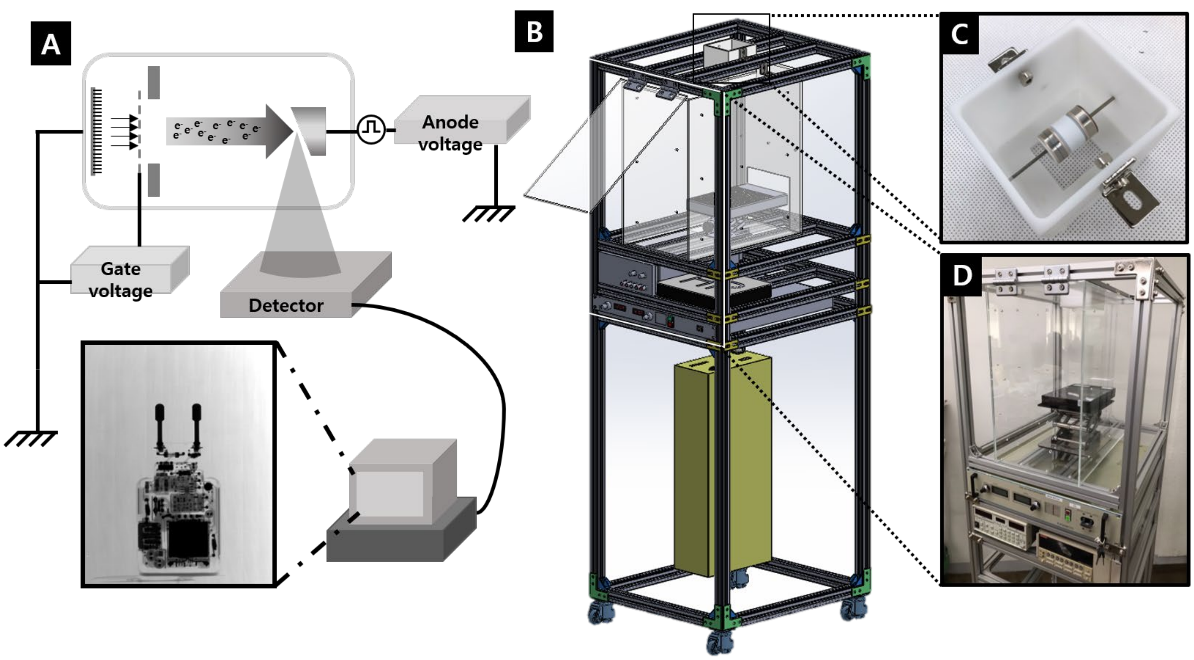

Figure 2. (A) Schematic diagram of CNT x-ray tube test bed. (B) Design of CNT x-ray tube test bed. (C) Image of CNT x-ray tube. (D) Image of CNT x-ray tube test bed.

The grown CNT emitter was bonded to the cathode electrode and assembled with ceramic for insulation, a gate and a focuser. This e-gun structure is brazed inside the vacuum furnace at 800 °C. After high-temperature brazing, this e-gun electrical aging process was performed inside a vacuum chamber. The brazed e-gun was aged until the fluctuation of field emission current was reduced in the chamber at the vacuum level of E^{-07} torr. After this process, the aged e-gun was sealed with ceramic tube body and anode in a vacuum environment at the level of E^{-07} torr. The material of the tube body was made of ceramic, and the anode was made of tungsten copper alloy. Figure 1 (A) and (B) shows image of brazed vacuum sealed tube and CNT e-gun, respectively. The e-gun consists of a gate, a focuser and an emitter combined with a cathode.

The vacuum tube is mounted on a test bed with a high voltage source and an x-ray detector. The test bed has two kinds of voltage supply. One is a voltage source applied to the gate, and the other is a high voltage source connected to the anode. A device that is capable of on/off switching is included in the circuit to apply the voltage only when the anode voltage is needed. The detector connected to the computer was placed under the tube socket. The schematic diagram of x-ray test bed is shown in Figure 2 (A), and the design of the test bed is shown in Figure 2 (B). Figure 2 (C) and Figure 2 (D) is the image of x-ray tube socket and the test bed. Since it is a vacuum sealed tube, no additional pump is required, but insulating oil or epoxy treatment is required for high voltage experiments. The loaded tube is applied with the same voltage as in the vacuum chamber to confirm that there is no change in performance even after brazing. In addition, the generation of tube current is turned on/off at intervals of 500ms, and it was confirmed that the current was stably generated. Finally, it was confirmed that X-ray images of various objects can be obtained by X-ray detector.

3. RESULTS

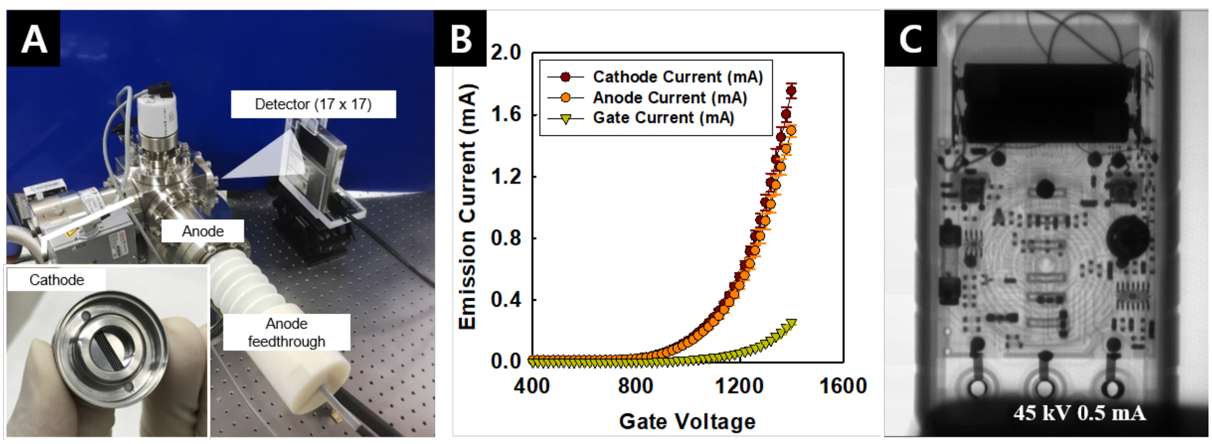

Figure 3. (A) Image of e-gun aging and testing system. (B) Field emission characteristic plot of e-gun. (C) X-ray image of multi meter.

Figure 1 (C) is the SEM image of synthesized CNTs by CVD process. The CNTs were very dense, and had spaghetti-like shape, with average diameters with tens of nanometer and length of about several micrometers. Since the catalyst is randomly existing in the metal alloy substrate, the CNTs are also have random arrangement. These randomly arranged CNTs have a disadvantage in that field emission efficiency is relatively inferior due to the influence of a local electric field due to a screening effect during emission[7]. However, this etched substrate can compensate for that disadvantage because it provides a gap between the CNT bundles to reduce the screening effect.

Figure 3 (A) is the image of e-gun aging and testing system. The vacuum chamber in which the electron gun is loaded has an electrode connected to the gate power source and a high voltage feed-through connected to the anode power source. In addition to evaluate field emission performance, this system is capable of emitting X-rays as well. During the aging process, the gate voltage was gradually increased by increasing the magnitude of the electric field applied to the CNTs. In this process, long CNTs first emit electrons and are gradually consumed. As a result of the aging process, the length of the CNTs becomes uniform and the emission of electrons from each CNT becomes also uniform[8], so that the load due to field emission is equalized throughout the emitter. Therefore, the emission current is also stabilized. Figure 3 (B) is the field emission characteristic plot that is the curve of emission current depending on gate voltage. The distance between gate and cathode is 370 μm, so the electric field between gate and cathode is 3.78 V/μm when the applied gate voltage is 1400 V. At this electric field, the total cathode current is 1.8 mA and the anode current is 1.5 mA, so the ratio of leakage current is 17%. Figure 3 (C) is the x-ray image of multi meter obtained from e-gun testing system. This image was taken by exposure for 500 ms at a tube current of 0.5 mA and a tube voltage of 45 kV. The distance of source to object is 25 cm. As an anode, the same tungsten embedded copper was as used as in tubes. The PCB board of the multimeter can be viewed through the X-ray image.

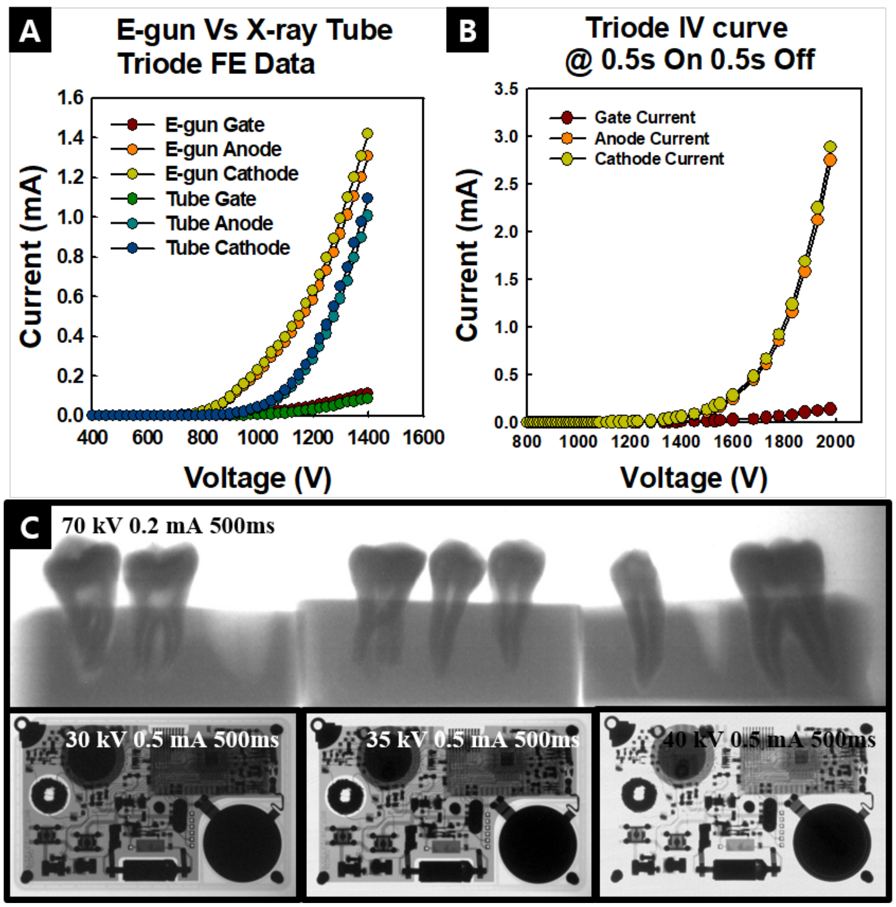

Figure 4. (A) Field emission characteristics of CNT e-gun and CNT x-ray tube. (B) Field emission characteristics of CNT x-ray tube with pulse driving. (C) X-ray image of human teeth and dose meter.

The brazed tube has a small size with length of 52 mm and a width of 27mm and it is shown in Figure 1 (A). The tube is brazed at 800 °C and at the E^{-07} torr vacuum level. The reason for brazing at this temperature is that this temperature is close to the melting point of the filler used for brazing, so that the generation of fumes is minimized, and as a result of brazing, it can be seen that the filler does not spread more than necessary. The brazed tube was applied with a gate voltage of up to 1400 V step by step like an e-gun. The result is shown in Figure 4 (A). From this result, it can be seen that the field emission performance is slightly inferior to that of the electron gun. There are two possible reasons for this.

First, because the vacuum inside the tube is not continuously pumped unlike the chamber, it has a relatively poor degree of vacuum. Secondly, this is because some fume generated as the filler used in the brazing process melted and damaged CNTs. Therefore, more gate voltage had to be applied to obtain sufficient current, and the pulse duty was set to 50% to reduce the load caused from high gate voltage. As a result, we are able to obtain an emission current of 3 mA at a gate voltage of 2 kV. This gate voltage can be converted into an electric field of 5.4 V/μm. This current is the amount of current that can be used as a miniaturized X-ray source that photographs the parts of a human body. Although the current slightly decreased after the brazing process, it was confirmed that it can still generate enough current to be used as an X-ray source.

Figure 4 (C) is the x-ray image of human teeth (upper image) and dosimeter (lower image) obtained from CNT x-ray tube. The human teeth x-ray image is taken at 0.2 mA tube current and 500 ms exposure time, and tube voltage is 70 kV. In order to apply high voltage to the tube, it must be coated with an insulator such as an epoxy material and then processed into a socket shape, but in this experiment, the insulation breakdown caused by foreign substances on the tube surface was eliminated by placing the tube in insulating oil. The structure of the tube and the internal vacuum degree were able to withstand a high voltage of 70 kV without damage. Also, the dose meter image is obtained at 0.5 mA anode current and 500 ms exposure time and anode voltage is changed from 30 kV to 40 kV. From the X-ray image, the shape of the tooth embedded in the gum and the root canal inside the tooth can be confirmed. Also, the x-ray image of dose meter is able to distinguish the circuits and devices of the board most clearly at 35kV, and it is difficult to distinguish them at tube voltages over 40 kV.

4. CONCLUSION

By using CNTs grown directly on a metal substrate as an electron emission source, a sufficient current can be generated to acquire an X-ray image. In addition, we made our own designed electron gun and tube using this emitter and confirmed that our electron gun can produce a current with field emission characteristics in a vacuum, and that it works the same way even if it is made into a tube. We also confirmed that fast switching of on and off through pulse driving is possible to CNT x-ray tube. In addition, through this, it is possible to block the unnecessary current for obtaining an x-ray image, and thus, the possibility of use as a low-dose x-ray source was found. Using this tube, it was confirmed that a current of 3 mA and a pulse drive of 500 ms are possible, which suggests that the tube could be used in several medical devices. And also, that is proved by the x-ray image of circuit board and human teeth can be obtained through a CNT x-ray tube. In particular, it has been miniaturized and does not require additional cooling means, so it is considered to be suitable for small mobile x-ray machines.

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