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Fabrication and Characterization of Individually Controlled Multi-Pixel Carbon Nanotube Cathode Array Chip for Micro-RT Application for Cancer Research

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Abstract

We report here the development of a new carbon nanotube (CNT) field emission multi-pixel cathode array chip, a vital component for the multi-pixel beam x-ray micro-radiotherapy (micro-RT) system under development in our group for cancer research. The CNT field emission cathode array chip has up to 25 (5×5) individually addressable cathode pixels, each 1 mm in diameter and with center-to-center distance of 2 mm. The fabrication is a two-step process: first a Cr/Cu electrical contact was fabricated on Si substrates with a 5 μm SiO_2 dielectric layer using photolithography; and second the CNTs were selectively deposited on 1 mm-diameter predefined Cr/Cu contact dots by using a combined photolithography/electrophoresis deposition technique. The electron pixel beams produced from the multi-pixel array chips are uniform and individually controllable. Each pixel beam is expected to generate a dose rate in the order of 100 cGy/min based on our Monte Carlo simulations.

INTRODUCTION

Today there are several types of small animal imaging systems commercially available including micro-CT, micro-MRI, and micro-CT-PET. However, the development of therapeutic tool for small animal models for cancer research, falls far behind. Currently there are a few groups working on development of micro-radiotherapy (micro-RT) systems using Ir-192 isotope [1] and conventional x-ray sources [2]. We have proposed a carbon nanotube (CNT) field emission based multi-pixel x-ray beam array micro-RT system. The key difference between ours and other micro-RT systems is that arbitrary shaped radiation field is formed by many individually controllable x-ray pixel beams in our system, while fixed-shaped radiation field of other systems is formed by mechanical collimation of a single broad beam. Intensity modulation and gated radiation that would be extremely difficult in other micro-RT systems [1,2] can be achieved by electronic control in our micro-RT system. Once developed we will integrate the micro-RT system with the CNT field emission micro-CT already developed by our group to form a high resolution CT image-guided and intensity-modulated irradiation system at the mouse scale that is analogous to state of the art clinical image-guided radiotherapy system.

CNT field emission technology has been successfully used by our group to develop new radiographic imaging devices to meet the current and future needs in both cancer biology research and clinical application [3–10]. We are applying the same CNT field emission technology to develop the multi-pixel x-ray beam array micro-RT system. One of the key

challenges for this new application is the fabrication of individually addressable multi-pixel CNT cathode array chip with high net emission current and high pixel beam packing density. Several carbon nanotube cathode arrays for flat panel display application were reported [11,12]. However, the net emission current of their cathode arrays was too low. Our group has developed a 9-pixel cathode array before, but the array has a low packing density and CNTs were coated on individual metal substrates that were assembled later into a cathode array [6]. The individual metal substrate assembly approach is not suited for the high packing density and individually addressable CNT cathode array fabrication for the micro-RT system. In this paper, we report the multi-pixel cathode chip fabrication and test of CNT field emission multi-pixel cathode array chips by using a combined photolithography/electrophoresis deposition technique developed by our group [13,14], as well as predicted dose rate for the micro-RT system application based on Monte Carlo simulation.

EXPERIMENT AND DISCUSSION

For the CNT cathode array fabrication we used few walled carbon nanotubes (FWNTs) with an average tube diameter of 10 nm produced by thermal CVD. A 3-inch highly doped *p*-type Si wafer (Silicon Quest International) was served as the cathode chip substrate. In order to fabricate individually addressable multi-pixel CNT cathode array on the substrate, a dielectric layer of SiO₂ was thermally grown on the Si surface. Calculation suggested that a thickness of 5 μ m SiO₂ layer is required to electrically isolate the electrodes (metal contacts) on the SiO₂ layer from the Si substrate. Prior to cathode chip fabrication, the Si/SiO₂ substrates were subjected to a piranha etching/cleaning (H₂SO₄ & H₂O₂) and baking at 200°C for 30 minutes in a conventional oven to obtain maximum process reliability. Figure 1 schematically illustrates the fabrication process of the multi-pixel cathode array chips.

The cathode chip fabrication is a two-step process: first a Cr/Cu electrical contact was fabricated on Si/SiO₂ substrate, see figure 1a–g. SU-8 photoresist was used in the UV photolithography. The metal layers of Cr and Cu with a thickness of 20 nm and 300 nm respectively were prepared by using a sputtering system (PVD 75, Kurt J. Lesker Company). Second, the CNTs were selectively deposited on 1 mm-diameter predefined Cr/Cu contact dots using a combined photolithography/electrophoresis deposition technique [14], see figure 1h–l. A series of cathode chip samples were fabricated. Figure 2 shows a typical completed cathode chip with a 5 × 5 multi-pixel cathode array. The black dots at the center of the chip are CNT cathodes with a diameter of 1 mm. The center to center distance of the CNT cathodes is 2 mm. The yellow lines and dots are the electrical connections to the external circuit for individual controlling. The CNT deposition by electrophoresis deposition technique is the key step in the chip fabrication. The thickness and the density of the nanotube films were controlled by the current, deposition time and the concentration of the nanotube suspension during electrophoresis deposition process. After the CNT deposition, the chip was annealed at 480 °C for 30 min and taped twice to remove the loosely bounded CNT bundles and make more CNTs stand up on the cathode. In order to avoid damaging the CNT cathodes, during the taping process, the tape needs to be removed gently after it totally covered the CNT cathode dots in the multi-pixel cathode chip.

The electron field emission uniformity of the multi-pixel cathode chips was measured at room temperature in a vacuum chamber using a parallel plate diode geometry with an anode to cathode distance of 200 μ m by a glass spacer. The anode was a home-made phosphor screen on ITO glass. A programmable (LabView) high voltage supply (A Keithley Model 248) applied voltage to the anode. The vacuum chamber pressure was $\sim 3 \times 10^{-7}$ Torr at the beginning of each test, so the resulting electric field was assumed to be linear across the vacuum space. A series of multi-pixel cathode chips were tested. The field emission images

were captured at the anode during testing by using a digital camera. Figure 3a shows a typical emission image of a 5×5 cathode array chip sample at an applied voltage of 1200 V. It can be seen that 25 electron beams are uniform. The uniform electron beams are important for the generation of uniform x-ray beams for radiotherapy.

The ability of the individual controlling of the 5×5 pixel cathode array chips were tested under the same experimental conditions as the testing of the electron field emission uniformity. Figure 3b shows an image which only 6 cathodes in the 5×5 pixel cathode chip were applied voltage of 1200 V. It can be seen that 6 electron beams were only observed from the selected 6 cathodes, indicating that this cathode chip can be well individually controlled for each pixel. This ability can provide our proposed CNT field emission micro-RT to electronically form arbitrary shape and radiation intensity distribution of small radiation field, which is crucial for high-resolution small animal irradiation.

Net emission current from each cathode pixel is an important issue for micro-RT application as it is proportional to radiation dose rate [15]. The net emission current of a single pixel CNT cathode in the 5×5 cathode array chip was examined in the same vacuum chamber with a diode arrangement with an anode to cathode distance of 325 μm . A stainless steel plate was served as the anode. Figure 4 shows the typical emission current (I) versus applied voltage (V) of one individual cathode pixel in the 5×5 pixel CNT cathode array chip.

From figure 4, it can be seen that no current saturation is observed in the measured range. The highest emission current achieved in this sequence of runs was 2.3 mA at electric field of 6.2 V/ μm . Monte Carlo simulations indicated that for an emission current of 2.3 mA per pixel beam the x-ray pixel beam is expected to generate a dose rate of 100 cGy/min at the center of mouse under the micro-RT irradiation. This dose rate is acceptable for the micro-RT application.

CONCLUSIONS

In conclusion, a carbon nanotube (CNT) field emission multi-pixel cathode array chip was developed for the x-ray multi-pixel beam array micro-radiotherapy (micro-RT) system. The chip fabrication is a two-step process: first a Cr/Cu electrical contact was fabricated on Si substrates with a 5 μm SiO_2 dielectric layer using photolithography; and second CNTs were selectively deposited on 1 mm-diameter predefined Cr/Cu contact dots by using a combined photolithography/electrophoresis deposition technique. The electron beams can be individually controlled and each pixel can produce an emission current of 2.3 mA, which is expected to generate a dose rate in the order of 100 cGy/min per pixel beam based on Monte Carlo simulations.

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Figure 1. Schematic illustration showing the fabrication process of the multi-pixel cathode array chips by using a combined photolithography/electrophoresis deposition (EPD) technique.

Figure 2.
Image of a completed 5×5 pixel cathode array chip.

Figure 3.

(a) Electron field emission image from a 5×5 pixel CNT cathode array chip at an applied voltage of 1200 V; And (b) testing for individual controlling showing 6 electron beams from a 5×5 pixel cathode array chip at an applied voltage of 1200 V.

Figure 4.
I-V curve from one individual cathode pixel in a 5×5 pixel CNT cathode array chip.