A carbon nanotube field emission multipixel x-ray array source for microradiotherapy application

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The authors report a carbon nanotube (CNT) field emission multipixel x-ray array source for microradiotherapy for cancer research. The developed multipixel x-ray array source has 50 individually controllable pixels and it has several distinct advantages over other irradiation source including high-temporal resolution (millisecond level), the ability to electronically shape the form, and intensity distribution of the radiation fields. The x-ray array was generated by a CNT cathode array (5×10) chip with electron field emission. A dose rate on the order of >1.2 Gy/min per x-ray pixel beam is achieved at the center of the irradiated volume. The measured dose rate is in good agreement with the Monte Carlo simulation result. © 2011 American Institute of Physics.

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Today, many cancer patients receive state-of-the-art radiotherapy in which the radiation dose distribution is highly conformal around the tumor and normal tissue around the tumor is largely spared.¹ However, traditional research irradiators such as the cesium irradiator and x-ray irradiators lack many of the capabilities found in today's clinical practice, such as spatial resolution and temporal resolution. Recent advances in both genetically engineered mouse modeling and cancer biomarkers promise better preclinical studies to understand human cancers and cancer biomarkers.² These and other advances in cancer research demand new research tools with high spatial and temporal resolution for preclinical study before clinical trials. For small animal irradiation, there is a need for high-resolution and image-guided microradiotherapy (micro-RT) technology that can deliver radiation treatment similar to human radiotherapy but at mouse scales. Currently, there are several micro-RT systems developed in different research laboratories using Ir-192 isotope³ or conventional x-ray tubes⁴ as the radiation sources.

We have proposed a multipixel x-ray beam array micro-RT system that is capable of electronic field shaping and intensity modulation. None of the existing micro-RT systems are capable of intensity-modulated treatment at a mouse scale. The enabling technology for this multipixel x-ray system is the carbon nanotube (CNT) field emission technology. Instead of a single radiation source design that has been used in practically all existing x-ray systems for imaging and therapy, the multipixel x-ray tube proposed contains 50 individually addressable cathodes that each produces a pixel x-ray beam via a multipixel x-ray beam array collimator. Our group has developed several CNT field emission based radiographic imaging devices for cancer research, clinical application,⁵⁻⁷ and electron beam single cell irradiation.⁸

However, the application of the technology to produce the dose and dose rate at therapeutic levels has a unique set of technical challenges that require further exploration.⁸ For instance, unlike imaging devices, radiotherapy device design must be dosimetrically driven and requires a multipixel x-ray array source with a higher dose rate generated by an individually addressable cathode array chip. However, no such x-ray source has been developed.

Several techniques have been developed for fabrication of patterned CNT field emission cathode array, including direct growth by chemical vapor deposition,⁹ screen printing,¹⁰ and the combined photolithography and electrophoretic deposition (EPD) method developed in our laboratory.¹¹ Each method has its own advantages and disadvantages. Our method is a liquid phase and room temperature deposition process that when combined with photolithography enables deposition of preformed CNTs on device surfaces with precise control of the location and pattern. In this letter, we used the EPD method to fabricate an individually addressable CNT cathode array for a multipixel x-ray array source which is composed of a CNT field emission cathode chip, gate electrode, focusing electrode, transmission anode (tungsten target), and collimator. The x-ray source has a high temporal resolution (millisecond level) and the pixels can be individually addressable.

The optimal dimension of the cathode chip was determined by Monte Carlo (MC) simulation on the resulting micro-RT dosimetry and other physical constraints. Few walled CNTs with an average tube diameter of 10 nm and tube length of ~ 10 μm were used for cathode fabrication. A 3 in. highly doped p-type Si wafer with ≥ 5 μm thick dielectric layer of SiO_2 (or glass plate) was used as the cathode chip substrate. The cathode chip fabrication is a two-step process as follows: first a Cr/Cu electrical contact was fabricated on a Si/ SiO_2 substrate using photolithography; and second the CNTs were selectively deposited on 1 mm diam-

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FIG. 1. (Color online) (a) Image of a completed 5×10 pixel cathode chip; (b) schematic illustration of the structure of an individual cathode; (c) a typical SEM image of CNTs in pixel cathode; and (d) schematic illustration of the EPD setup.

eter predefined Cr/Cu contact dots using a combined photolithography/electrophoresis technique. Figure 1(a) shows a completed cathode chip with a 5×10 multipixel cathode array. Figure 1(b) presents the schematic diagram of the cathode structure of an individual pixel in the chip. The black dots are the Cr/Cu contact coated with the CNTs. They can be individually addressed with the lines (with bright color) through the external circuit. Prior to CNT deposition, a glass interlayer was deposited on the Cr/Cu dots to enhance the adhesion between the CNTs and the substrate. Figure 1(d) shows the setup of the EPD process. The thickness and density of the nanotube film can be controlled by the current, deposition time, and the concentration of the nanotube suspension during the EPD process.¹² After the CNT deposition, the chip was annealed at 480°C for 30 min to melt the glass interlayer and fix CNTs on the substrate, and taped twice to remove the loosely bounded CNT emitters and make more

FIG. 2. (Color online) I-V curve from one individual pixel cathode. Inset: (a) image of the prototype multipixel x-ray array source; and (b) the corresponding Fowler-Nordheim plot.

CNTs stand up on metal dots. Figure 1(c) shows a typical scanning electron microscope (SEM) image from the fabricated 5×10 multipixel electron cathode array chip. It can be seen that the CNTs are roughly vertically deposited on the substrate with a medium CNT density of 10^7 emitters/ cm^2 .

The electron field emission characteristics of the multipixel cathode chip were studied using the prototype setup of the x-ray source designed for the micro-RT, as shown in inset (a) of Fig. 2. Figure 2 shows the typical emission current (I) versus applied voltage (V) of one individual pixel in the cathode chip. The threshold field is $3.5 \text{ V}/\mu\text{m}$, which, for the purposes of this letter, we define the threshold field as that corresponding to the emission of $10 \mu\text{A}/\text{cm}^2$. No current saturation is observed in the measured range. An emission current of 3.5 mA was achieved at a field of $7.5 \text{ V}/\mu\text{m}$. To verify that the electron emission from the CNT cathode was governed by a field emission process, a Fowler-Nordheim analysis was performed, even though a traditional Fowler-Nordheim theory may not be strictly applicable because of the small radius of the CNTs. According to Fowler-Nordheim theory, the current density J is related to the applied field E by $J = AE^2 \exp(-B\Phi^{3/2}/E)$,¹³ where A and B are parameters weakly dependent on the applied electric field and Φ is the work function of the emitting surface. A proportionality constant β relates the applied voltage V to the resulting electric field E by $E = \beta V$. Ultimately, β can be related to the tip geometry (γ_{tip}) and a field compress factor k ,¹⁴ using $\beta = 1/(k\gamma_{\text{tip}})$. The corresponding Fowler-Nordheim plot of the emitted current versus applied voltage [$\ln(I/V^2)$ versus $1/V$] from our CNT cathode is nearly linear [see Fig. 2, inset (b)], indicating the electron current is governed by field emission. The field emission based electron (x-ray) source can be turned on/off instantly, the temporal resolution is at the millisecond level, higher than other irradiation sources. This ability is one of the advantages of our x-ray array source for micro-RT application.

The emission uniformity was examined using a home-made phosphor screen on ITO glass as an anode. Figure 3(a) shows an image of a 5×10 electron beam array incident on a phosphor screen at an applied voltage of 1400 V . It can be seen that 50 electron beams are roughly uniform.

Individual pixel control is necessary for defining arbitrary beam shapes and intensity distributions. The performance of the individual pixel control was tested for the 5×10 pixel array irradiation source. Figure 3(b) shows an image in which only 17 of the 50 pixel cathodes were ad-

FIG. 3. (Color online) (a) Electron field emission image from a 5×10 pixel CNT cathode array; (b) 17 of 50 pixel electron beams incident on a phosphor screen; (c) corresponding 17 of 50 pixel x-ray beams to a Gafchromic EBT film to form a pattern of “NCI;” and (d) a 5×5 pixel beam array showing the ability of the intensity modulation.

dressed with an applied voltage of 1400 V. It can be seen that electron beams were only observed from the selected 17 cathodes to form an electron pattern of “NCI” (which stands for “National Cancer Institute”), indicating that the cathode chip can individually control each pixel. With the cathode array chip and transmission anode of tungsten, the x-ray beams were produced using the prototype x-ray source in the proposed micro-RT system. Figure 3(c) shows the corresponding dose image delivered to a Gafchromic EBT film. Each x-ray beam size is ~ 2 mm. A dose rate of 1.24 Gy/min at the center of the irradiated object was obtained at an emission current of 3.0 mA. The ability of individual irradiation pixel control is another advantage of the x-ray array source for micro-RT application. It enables the micro-RT to elec-

tronically form arbitrary shapes and intensity distribution of the irradiation field. Figure 3(d) displays the intensity modulation ability of a 5×5 pixel x-ray beam array. Because each of the x-ray pixel beams is individually controlled, the x-ray array source for micro-RT can irradiate any spatial or intensity modulation pattern simply by activating a given subset of the x-ray pixel beams electronically.

We have conducted extensive MC simulation of the micro-RT dosimetry for the multipixel x-ray array source and the micro-RT system.¹⁵ MC simulations track the path of individual radiation particles as they travel through each component of the micro-RT system and deposit radiation dose in the target. The MC simulations indicated that for an emission current of 3.0 mA per pixel beam the x-ray pixel beam is expected to generate a dose rate of 1.2 Gy/min at the center of the irradiation target. This result is in good agreement with the measured result of 1.24 Gy/min.

In conclusion, a CNT field emission multipixel x-ray array source was developed for an x-ray multipixel beam array micro-RT system. The x-ray pixel beams can be individually controlled and each x-ray pixel beam produces a dose rate on the order of >1.2 Gy/min at the center of the irradiated target with a beam size of ~ 2 mm and a temporal resolution of a millisecond level. The developed CNT field emission multipixel x-ray array source provides new capabilities and features for irradiation technology development such as micro-RT for cancer research.

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