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Stationary scanning x-ray source based on carbon nanotube field emitters

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We report a field emission x-ray source that can generate a scanning x-ray beam to image an object from multiple projection angles without mechanical motion. The key component of the device is a gated carbon nanotube field emission cathode with an array of electron emitting pixels that are individually addressable via a metal–oxide–semiconductor field effect transistor-based electronic circuit. The characteristics of this x-ray source are measured and its imaging capability is demonstrated. The device can potentially lead to a fast data acquisition rate for laminography and tomosynthesis with a simplified experimental setup. © *2005 American Institute of Physics.* [DOI: 10.1063/1.1923750]

X-ray radiation is used today in a wide range of imaging applications including diagnostic medical imaging and security and industrial inspection. In conventional radiography, the transmitted x-ray beam projects a three-dimensional (3D) object onto a two-dimensional (2D) plane, a process that loses the resolution along the beam direction.[1] The computed tomography (CT) technique enables the reconstruction of a 3D image of an object by collecting hundreds of 2D projection images from different projection angles.[1] Limited-angle tomographic techniques including tomosynthesis[2] and laminography[3] have also been developed for applications where only limited numbers of image planes are required and/or the total x-ray dosage needs to be minimized. These include the inspection of microelectronics, such as printed computer boards (PCBs) and for breast imaging. In most of the current tomographic scanners, a single x-ray tube is mechanically rotated around an object to collect the multiple projection images required for reconstruction, a process that limits the data acquisition rate and complicates system design.

To improve the imaging speed, several x-ray sources have been proposed and some developed. One is the electromagnetically scanned x-ray source used in the ultrafast electron-beam CT scanner[4] and some PCB inspection systems. In this case, an electromagnetic field steers the electron beam to different spots on the anode to produce a scanning x-ray beam,[5,6] very much like the design of a cathode-ray tube. Such x-ray sources are in general large, costly, and have a limited range of viewing angles due to the difficulty in steering the high-energy electron beam. An alternative method to generate a scanning x-ray beam is to use as many cathodes as the number of x-ray focal points required, where each cathode sends an electron beam to the corresponding focal point only. The design of a multibeam x-ray source with multiple *thermionic* cathodes was disclosed in the patent literature,[7] but the actual device has not been reported, due to difficulties of packaging and programming the thermionic cathode array.

X-ray sources using field emission cathodes have several intrinsic advantages over the thermionic x-ray tubes, including low operating temperature, instantaneous response time, and potential for miniaturization. Field emission x-ray tubes using carbon nanotube (CNT) emitters[8–12] have recently been demonstrated to have significantly improved properties compared to those using metal tips[13,14] and diamond.[15] Several groups have recently disclosed the concept of multibeam x-ray source based on field emitter arrays.[8,16–18] The design can, in principle, significantly reduce the size, and increase the range of viewing angles and the spatial resolution. Here, we report a step toward experimental realization of the multibeam field emission x-ray source (MBFEX).

The MBFEX source is comprised of a field emission cathode with a linear array of five gated CNT emitting pixels, focusing electrodes, and a molybdenum target in the reflection mode, as illustrated in Fig. 1(a). The entire setup was housed in a vacuum chamber with a 4 in. diameter Be window at a base pressure of 10^{-7} Torr. Detailed structure of each individual x-ray unit is shown in Fig. 1(b). The CNT film was deposited on the metal substrate by electrophoresis[19] using CNTs synthesized at Xintek. All of the gate electrodes were electrically connected. An active electrostatic focusing electrode was placed between the gate electrode and the anode for each pixel. The electron beam is focused into a focus area on the target with an electrical potential (V_f) applied to the focusing electrode, as we have reported previously.[12] Each emitting pixel was connected to the drain of an *n*-channel metal–oxide–semiconductor field effect transistor (MOSFET), the source of which was grounded. The gate of the MOSFET was connected to the output of a digital input/output board which can provide a 5 V dc voltage signal.

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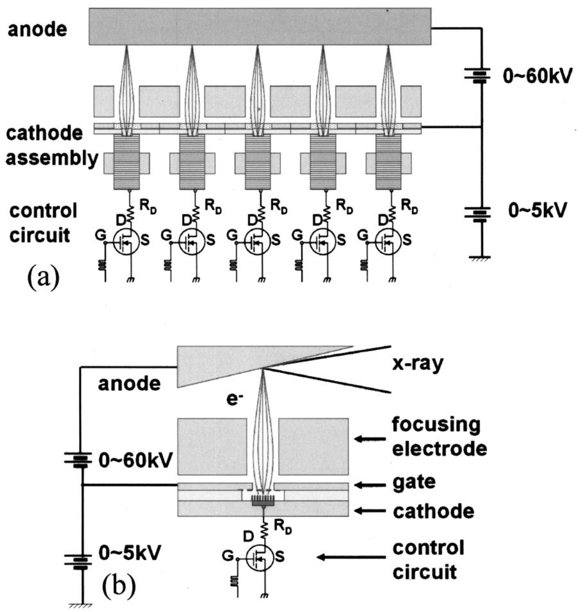

FIG. 1. (a) A schematic of the multibeam x-ray source with a field emission cathode that contains five emitting pixels and a molybdenum target at 10^{-7} Torr pressure. The pixels were evenly spaced with a center-to-center spacing of 1.27 cm. Each pixel is capable of emitting 1 mA current. The anode voltage is set at 40 kV. The gate voltage varies depending on the flux required. Switching the x-ray beam from each pixel is controlled by sweeping a 0–5 V dc pulse through the MOSFET. (b) Each emitting pixel is comprised of 1.5 mm diameter CNT film coated on a metal disk, a 150 μm thick dielectric spacer, an extraction gate, and a focusing electrode.

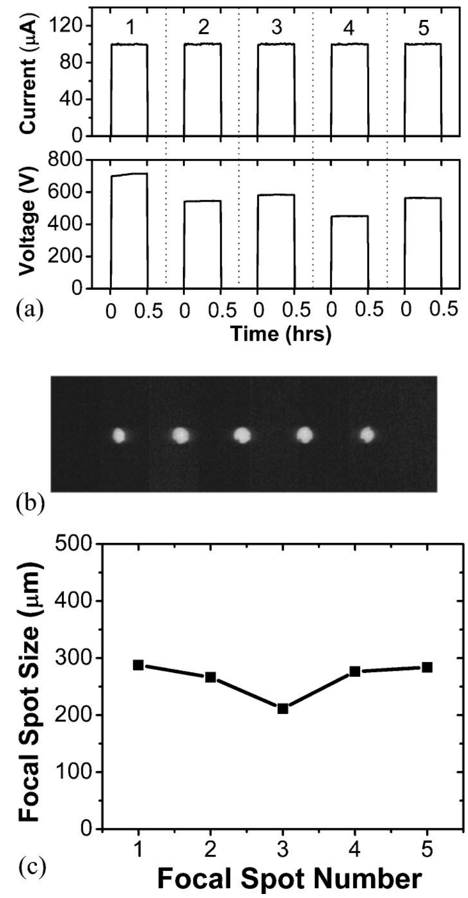

FIG. 2. (a) Experimentally measured cathode current from the five pixels recorded over a 30 min period under the constant current mode using 100% duty cycle. The set cathode current was 100 μA and the anode voltage was 40 kV. (b) Pin-hole measurement showed five evenly spaced focal spots on the target. (c) The focal spot size was determined based on the European Standard EN 12543-5 (Ref. 20). All of the five focal spots are in the range between 200 μm to 300 μm in diameter under same focusing voltge V_f =900 V.

The field emission characteristics of the individual pixels were measured under the triode mode in the x-ray chamber. The measured threshold field for 1 mA/cm^2 current density is between 2.3–3.1 V/μm. Cathode current density of ~1 A/cm^2 was achieved at higher fields. To minimize the current fluctuation and decay, and to reduce pixel to pixel variation, an electrical compensation loop was incorporated into each pixel to automatically adjust the gate voltage to maintain a constant preset cathode current. Fig. 2(a) shows the experimentally measured cathode currents and the corresponding gate voltages from the five pixels recorded over 30 min period under the constant current mode (100% duty cycle). The set cathode current was 100 μA with anode voltage V_a=40 kV. No arcing was observed after initial conditioning.

The x-ray focal spots from the five pixels on the cathode were recorded by pinhole measurements and are shown in Fig. 2(b). Due to the large diameter (>1 mm) of the pinhole used in the experiment, the actual focal spot sizes cannot be extracted from the image. However, it does show that the five focal spots are evenly spaced on the target surface. The noncircular shape of the spots on each end is due to the oblique projection angle of the corresponding pixel. The focal spot sizes were determined by measuring the radiographs and analyzing the intensity distribution of a thin metal wire in two orthogonal directions.[20] The measured actual focal spots (diameter on the anode) are plotted in Fig. 3(c) for the focusing voltages V_f=900 V. A demagnification factor of 5–7.5 was obtained.

To generate x-ray radiation, a constant dc voltage (40–60 kVp) was applied to the anode and a variable dc voltage (<1 kV) was applied to the gate electrodes. The MOSFET circuit, as illustrated in Fig. 1, was used to switch the emission current on and off from the individual pixels. To activate a pixel, a 5 V signal was applied to open the channel of the corresponding MOSFET such that the pixel formed a complete electrical circuit with the gate electrode. Electrons were emitted from this activated pixel when V_g was larger than the critical field for emission. They were accelerated by the V_a and bombarded on a directly opposing area on the anode to produce x-ray radiations. The other pixels would not emit electrons because of the open circuit. To generate a scanning x-ray beam from different origins on the target, a pulsed controlling signal with a predetermined pulse width was swept across the individual MOSFETs. At each point, the channel was "opened" to generate an electron beam from the particular pixel which produced an x-ray beam from the corresponding focal point on the target.

Projection images of a phantom placed 15 cm away from the anode were recorded from different projection angles using this MBFEX source. The phantom was a blade from a surgical scalpel placed behind a metal rod. V_a was fixed at 40 kV. A digital area x-ray detector (Hamamatsu C7921) running at 16 frames/s was used to record the image. The phantom-to-detector distance was 10 cm. The five pixels were turned on sequentially for 5 s each by sweeping a 5 V pulse signal with 5 s pulse width through the MOSFETs. The gate voltage was adjusted automatically to main-

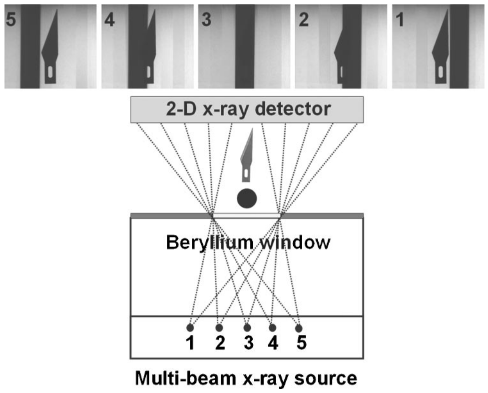

FIG. 3. Five projection images of the same blade-metal rod phantom from different viewing angles were taken by the MBFEX. The digital 2D x-ray image sensor (Hamamatsu C7921) has a 1056×1056 photodiode array with 50×50 μm pixel size. It was operated at 16 frames per second (fps) with 4×4 binning. The imaging conditions are: 40 kVp, 25 μA cathode current, and 5 s exposure time. The source to object distance is 15 cm and the blade is placed close to the x-ray detector.

tain a 25 μA cathode current from each pixel. The detector was on during the entire process. Figure 3 shows the five projection images of the object phantom formed by the x-ray beams from the five focal points. As expected, the blade is invisible in the central projection image (Image 3), but clearly visible from other projection angles due to the spatial extension of the focal spots. Here, the acquisition time is only determined by the required x-ray exposure time since no mechanical motion is needed and the electrical switching time is negligible.

Another set of projection images of a circuit board was taken to demonstrate potential for laminography and tomosynthesis applications. In Fig. 4(a), we showed one of the five projection images of the circuit board with overlapping circuit planes. Five projection images were processed using a simple add and subtract algorithm developed for multilayer tomosynthesis.[2] After the tomosynthesis two images with different focusing planes—shown in Figs. 4(b) and 4(c)—clearly reveal different layered structures. In Fig. 4(c), the thick wire—shown in the Fig. 4(a)—was removed and structures underneath that wire clearly showed up. However, here we only have limited geometrical resolution in the direction of x-ray beam, called axial resolution, due to the fact that there are only five scanning beams providing limited viewing angle. The axial resolution can be further improved with increasing projection angle and number of directions.

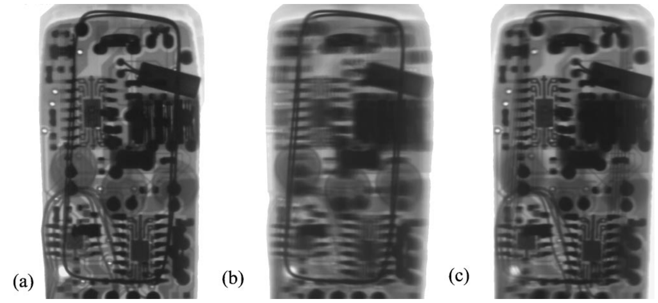

FIG. 4. (a) The projection image of a circuit board which is a superimposed image of several overlapped circuit planes. (b) and (c) Two tomosynthesis images showed different layers of the circuit board. It is very clear that the original thick wire on the top layer of the circuit board was removed in (c). Limited axial resolution is due to the fact that there are only five scanning beams providing limited viewing angle.

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[1] W. R. Hendee and E. R. Ritenour, *Medical Imaging Physics*, 4th ed. (Wiley-Liss, New York, 2002).
[2] J. T. Dobbins III and D. J. Godfrey, Phys. Med. Biol. **48**, R65 (2003).
[3] T. D. Moore, D. Vanderstraeten, and P. M. Forssell, IEEE Trans. Compon., Hybrids, Manuf. Technol. **25**, 224 (2002).
[4] D. P. Boyd and C. Haugland, Med. Imaging Technol. **11**, 578 (1993).
[5] P. Bowles, E. Duff, and D. D. Thayer, U.S. Patent No. 5,594,770 (January 14, 1997).
[6] B. D. Baker, R. L. Corey, J. A. Adams, and E. W. Ross, U.S. Patent No. 4,926,452 (May 15, 1990).
[7] H. T. Morgan, U.S. Patent No. 6,125,167 (September 26, 2000).
[8] O. Zhou and J. P. Lu, U.S. Patent No. 6,553,096 (April 22, 2003).
[9] O. Zhou and J. P. Lu, U.S. Patent No. 6,850,595 (February 1, 2005).
[10] G. Z. Yue, Q. Qiu, B. Gao, Y. Cheng, J. Zhang, H. Shimoda, S. Chang, J. P. Lu, and O. Zhou, Appl. Phys. Lett. **81**, 355 (2002).
[11] H. Sugie, M. Tanemura, V. Filip, K. Iwata, K. Takahashi, and F. Okuyama, Appl. Phys. Lett. **78**, 2578 (2001).
[12] Y. Cheng, J. Zhang, Y. Z. Lee, B. Gao, S. Dike, W. Lin, J. P. Lu, and O. Zhou, Rev. Sci. Instrum. **75**, 3264 (2004).
[13] F. M. Charbonnier, J. P. Barbour, and W. P. Dyke, Radiology **117**, 165 (1974).
[14] G. S. Hallenbeck, Radiology **117**, 1 (1974).
[15] C. Ribbing, P. Rangsten, and K. Hjort, Diamond Relat. Mater. **11**, 1 (2002).
[16] B. M. Dunham, J. S. Price, C. R. Wilson, and D. Snyder, U.S. Patent No. 6,385,292 (May 7, 2002).
[17] O. Zhou, J. P. Lu, and Q. Qiu, U.S. Patent No. 6,876,724 (April 5, 2005).
[18] Q. Qiu, J. P. Lu, and O. Zhou, U.S. Patent Application No. 20040240616 (December 2, 2004).
[19] B. Gao, G. Z. Yue, Q. Qiu, Y. Cheng, H. Shimoda, L. Fleming, and O. Zhou, Adv. Mater. (Weinheim, Ger.) **13**, 1770 (2001).
[20] European Committee for Standardization, EN 12543-5: 1999 E, Brussels, 1999.