

MINIATURE X-RAY TUBES UTILIZING CARBON-NANOTUBE-BASED CATHODES

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ABSTRACT

The electron field-emission properties of carbon nanotubes enable the fabrication of cold cathodes for a variety of vacuum device applications. The utilization of these cathodes is an attractive alternative for the replacement of thermionic or hot cathodes for generating X-rays. Miniature X-ray tubes have been fabricated using triode-style carbon nanotube-based cathodes. In this paper we report the results of characterization studies, such as beam current dependence on the control gate voltage. Also, results on focal spot measurements and electron-beam modeling allow the possibility of reducing focused spot sizes. Driving gate voltages below 1000 volts for easy pulsing has been achieved, and the extended lifetime data suggests that a regulated power supply would be ideal for a constant AC operation mode. The 1mm focal spot size achieved so far is suitable for most XRF applications.

INTRODUCTION

A new X-ray tube design utilizing carbon nanotube (CNTs) cold cathodes may be a significant advance in X-ray technology development and could lead to portable and miniature X-ray sources for medical and industrial applications.

CNT is a new carbon allotrope that was discovered over ten years ago [1]. Because of the unique chemical bonding and the perfect tubular geometry, it has many unique properties [2] such as atomically sharp tips and large aspect ratios ($>10^3$). As a result, CNTs have larger field enhancement factors and, thus, lower threshold fields for emission than conventional emitters such as the Spindt-type tips fabricated by lithography [3]. Due to the field-emission nature of this cold cathode, the energy spread is about 0.5eV and the spatial spread angle in a parallel direction to the electrical field is smaller than 5° . It has been shown that the field emission turn-on field of CNTs is significantly lower than the values reported for other electron emissive materials (Table 1).

Cathode Material	Threshold Field (V/ μm) for 10 mA/cm ²
Mo tips	50-100
Si tips	50-100
p-type diamond	160
Defective CVD diamond	30-120
Amorphous diamond	20-40
Cesium-coated diamond	20-30
Graphite powders	10-20
Nano-diamond	3-5 (unstable > 30 mA/cm ²)
Carbon Nanotubes	1-2 (stable >4000mA/cm²)

Table 1. Threshold fields for various cathode materials and some CNT emission characteristics.

The CNTs are capable of delivering stable high currents—a stable emission current of $>1\mu\text{A}$ has been observed from an individual single-wall carbon nanotube (SWNT) [4]—and reaching an emission current density greater than $1\text{A}/\text{cm}^2$ from a macroscopic cathode [5]. These properties make the CNTs attractive electron-field emitters for technological applications. The potential of using CNTs as the cold cathodes has been demonstrated in devices such as the field-emission flat panel displays (FEDs) [6], lighting elements [7], and discharge tubes for over-voltage protection [8].

The novel CNT cold cathode generates room temperature emission and controllable output currents and repetition rates [9]. In contrast, conventional thermionic cathodes are limited by a slow response time, high power consumption, and high operating temperature (up to 1000°C) that substantially decrease the average lifetime of X-ray filaments. The imaging resolution in typical diagnostic X-ray machines is also limited because the distribution of electrons is random. In this paper we report results on the development of carbon-nanotube-based miniature X-ray tubes.

MINIATURE X-RAY TUBES

The miniaturization of XRF instrumentation created a need for a compact, portable, battery-powered X-ray tube. In 2001 MOXTEK introduced a miniature X-ray tube designed to address the needs of handheld XRF [10,11]. This tube was designed to be a transmission-target, end-window configuration in order to provide very close anode-to-sample coupling. Refer to Figure 1 for details of the interior construction of the tube. To provide for battery operation of the tube the cathode includes a thermionic filament that was designed for very low power consumption, requiring typically only 0.2 watt input power to produce $100\mu\text{A}$ of emission current. There is a circular focusing aperture to restrict the electron beam to a central cone. The anode is a sputtered film on the back of the beryllium exit window.

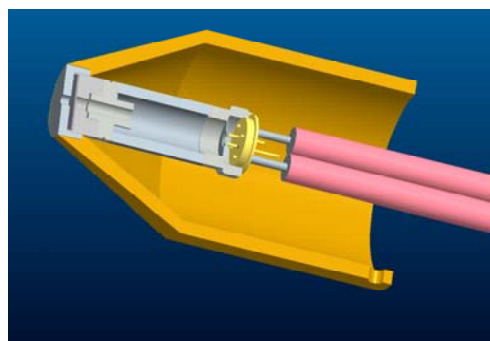


Figure 1. Cross-section of a transmission target X-ray tube.

This tube was designed as a replacement for ^{109}Cd radioisotope sources commonly used in handheld XRF instruments. The ^{109}Cd emits primarily the $\text{AgK}\alpha$ line, so silver was chosen for the anode material. The tube has an additional advantage over the isotope sources, as it produces continuum radiation [11].

CNT CATHODES

CNTs have found application in scanning probe microscopy and field emission cold cathodes for visible light, field-emission displays and X-ray generation [5]. Xintek has developed methods to enhance the emission uniformity and stability of the CNT cathodes and carried out extensive systematic studies of their field emission properties, pioneering several methods for integration of CNTs into device structures [6,7,8].

Figure 2 shows a typical current-gate voltage plot. This data was taken by both increasing and decreasing the gate voltage (GV). Throughout the measurement the anode current (AC) to gate current (GC) ratio stays around 1, which means that at this stage of the process approximately half of the cathode current is collected by the gate and the other half by the tube anode. For example, to achieve $20\mu\text{A}$ of AC or GC, a GV of $\sim 340\text{V}$ needs to be applied. Thus, the power consumption on the CNT cathode is substantially less than that of the thermionic cathode. The field emission nature is exhibited when a Fowler-Nordheim (F-N) is used to fit this data, as illustrated in the insert in Figure 2.

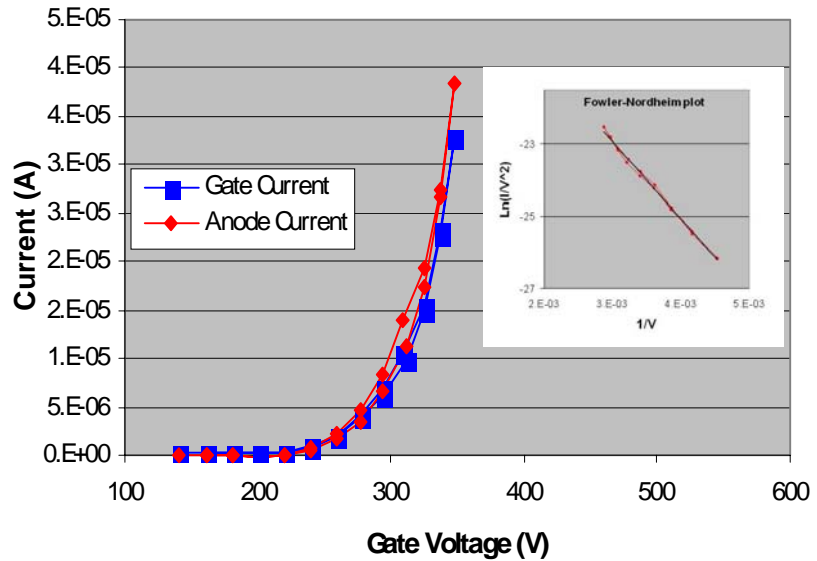


Figure 2. Typical current-gate voltage plot. The insert shows the corresponding F-N fit.

Figure 3 shows pulsed emission current from a typical CNT cathode at a frequency of 20KHz with different duty cycles. The frequency can be controlled by programming the gate voltage through a signal generator. The pulsed current can be further used to produce programmable X-ray radiation at various repetition rates and duty cycles after the electrons are accelerated to bombard the anode. Some X-ray pulses at different frequencies are illustrated in Figure 4.

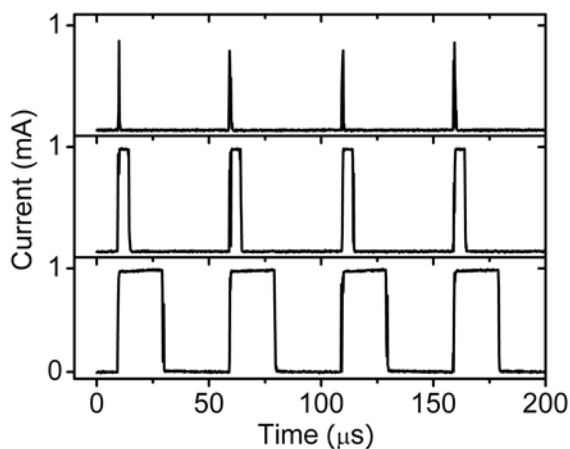


Figure 3. 20 KHz pulsed cathode operation at various duty cycles.

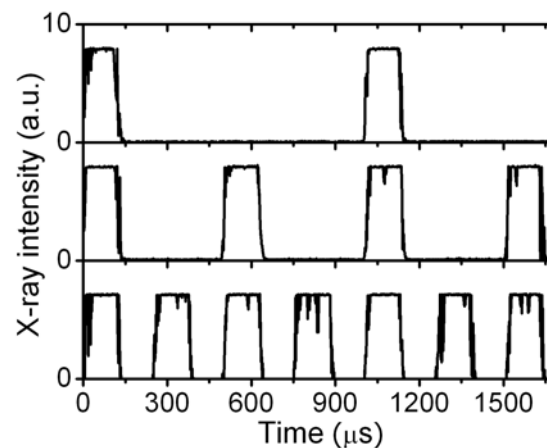


Figure 4. X-ray pulses with flexible width and repetition rate can be readily achieved by programming the gate voltage.

CNT CATHODE INTEGRATION INTO MINIATURE X-RAY TUBES

The CNT cathode has been integrated into the standard miniature X-ray tube envelope utilizing its basic design and dimensions as described in a previous section. The CNT films were deposited onto TO-5 headers used for standard filament X-ray tubes. The CNT cathode configuration essentially consists of a CNT-film support (a TO-5 header) and an electrically insulated gate on top of the CNT emitter on which a voltage (GV) is applied for extracting the electrons—the cathode current from the emitter. Those electrons either make it through the gate to the tube anode or are collected by the cathode gate, contributing to the anode current (AC) and the gate current (GC), respectively (Figure 5).

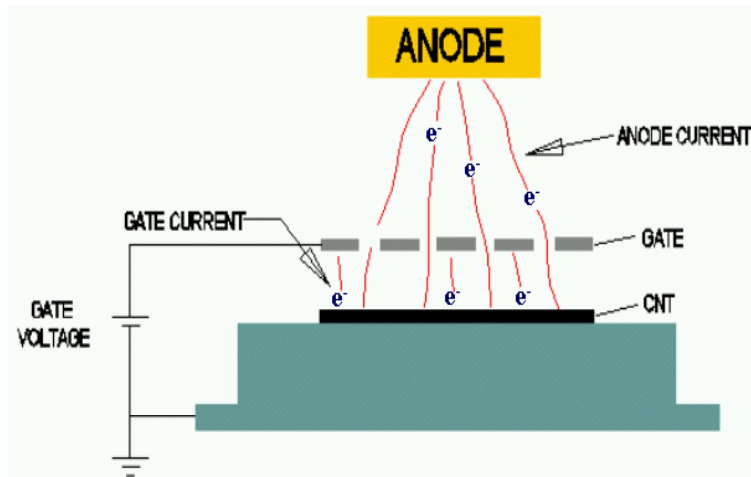


Figure 5. CNT cathode configuration

Extended continuous operation. A CNT tube has been continuously operated for over 700 hours. The GV was adjusted to maintain an AC of $20\mu\text{A}$, as illustrated in Figure 6. The initial and final GVs were 360V and 670V, respectively. The initial GC was around $20\mu\text{A}$ for the first 270 hours and, then, it stayed approximately constant during the last 400 hours of operation. It is

important to note that the increase in GV was more accentuated during the initial time than for the last 120 hours of operation. The GV becomes more stable thereafter. This data suggests that the use of a regulated AC power supply with GV below 1000V would be ideal for maintaining constant a given AC, despite GV variations during the tube lifetime operation.

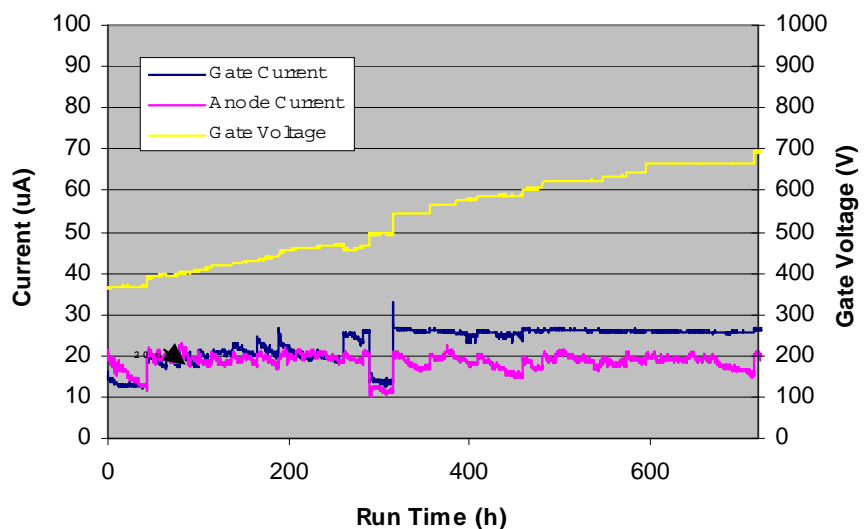


Figure 6. Extended CNT operation. The gate voltage has been manually adjusted to achieve $\sim 20\mu\text{A}$ of anode current.

Pulsed operation. The CNT tube has also been continuously operated in a pulsed mode. Figure 7 shows data taken at 1KHz with a 25% duty cycle, a GC of $33\mu\text{A}$, and a GV of 600V.

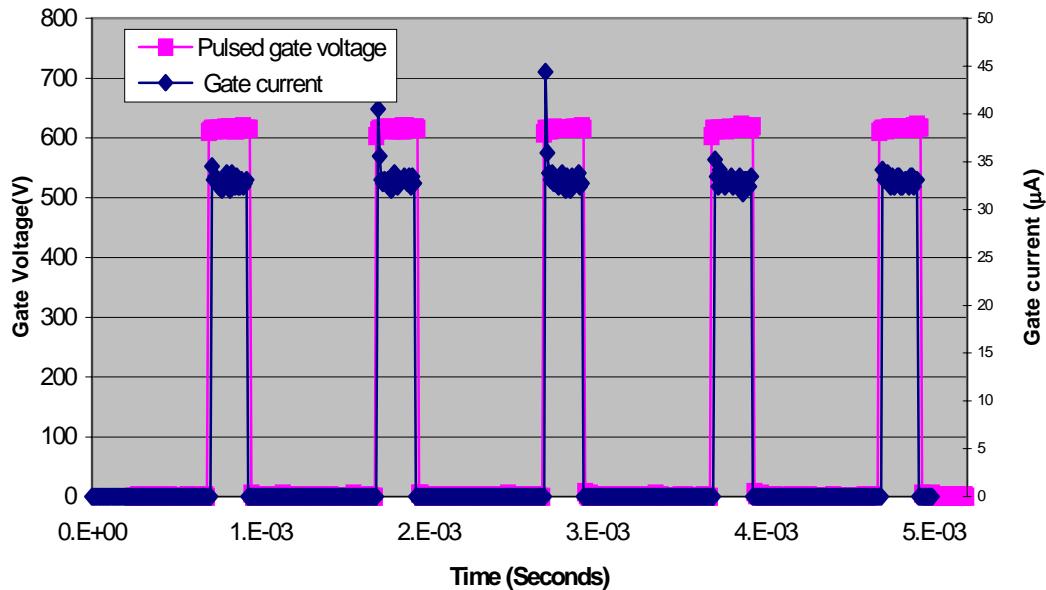


Figure 7. Pulsed operation of a CNT X-ray tube.

Focal spot characterization. Figure 8 shows the focal spot for a CNT X-ray tube with a passive-focusing optic and a large-opening cathode gate. Figure 9 portrays the result using passive optics with an adjusted focal length and a small-opening cathode gate. The images on the right-hand side of each pair are computational results, closely resembling the experimental results on the left. Validation of experimental results through modeling of this kind enables optical design to progress toward the goal of minimizing spot size for CNT-based X-ray devices [13]. Nevertheless, focal spot sizes achieved so far ($\sim 1\text{mm}$) are suitable for most XRF applications.

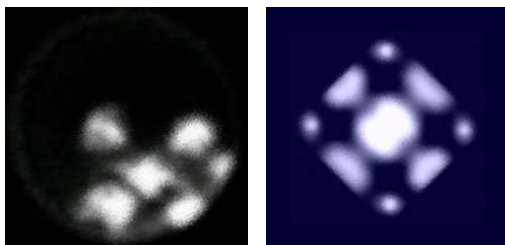


Figure 8. Experimental and computational spot images of a CNT X-ray tube with a large gate opening.

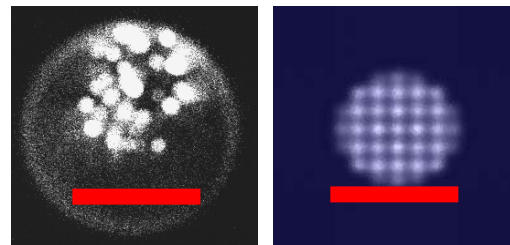


Figure 9. Experimental and computational spot images of a CNT X-ray tube with a small gate opening.

SUMMARY AND CONCLUSIONS

CNT cathodes have been successfully incorporated into miniature X-ray tubes. The CNTs offer unique advantages for a new generation of X-ray tubes, namely: low power consumption, long lifetime (testing still in progress), and pulse capability. Driving gate voltages below 1000 volts for easy pulsing has been achieved, and the extended lifetest data suggests that a regulated power supply would be ideal for a constant AC operation mode. The 1mm focal spot size achieved so far is suitable for most XRF applications. The use of electron-beam modeling tools allows the possibility of reducing focused spot sizes.

ACKNOWLEDGEMENTS

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