Analysis of Failure in Miniature X-ray Tubes with Gated Carbon Nanotube Field Emitters

Jun-Tae Kang, Jae-Woo Kim, Jin-Woo Jeong, Sungyoul Choi, Jeongyong Choi, Seungjoon Ahn, and Yoon-Ho Song

We correlate the failure in miniature X-ray tubes with the field emission gate leakage current of gated carbon nanotube emitters. The miniature X-ray tube, even with a small gate leakage current, exhibits an induced voltage on the gate electrode by the anode bias voltage, resulting in a very unstable operation and finally a failure. The induced gate voltage is apparently caused by charging at the insulating spacer of the miniature X-ray tube through the gate leakage current of the field emission. The gate leakage current could be a criterion for the successful fabrication of miniature X-ray tubes.

Keywords: Carbon nanotube, field emission, triode, miniature X-ray tube, charging.

I. Introduction

Carbon nanotube (CNT) field emitters were studied to achieve an ideal triode property for many applications, such as field emission devices [1], backlight units for liquid crystal displays [2], [3], and X-ray sources [4]-[8]. In particular, miniature X-ray tubes that use CNT field emitters have been studied for portable X-ray spectrometers and for non-destructive X-ray radiography and brachytherapy of cancer [5], [6]. The diode configuration of a field emitter can be easily implemented in the miniature X-ray tube [5], but its controllability is limited because of the coupling of the anode voltage (V_A) and current. Therefore, the triode CNT field emitter with a gate electrode is essential to an intensity-controllable X-ray tube [6]-[8]. It is difficult to configure the gated CNT field emitters because of structural complexity and high gate leakage current. Furthermore, some spatial dispersion of the electron emitted from the gated field emitters would limit a reduction in the diameter of a miniature X-ray tube due to charging at the insulating spacer of the tube.

To reduce charging at the insulating body of the miniature X-ray tube along with a small focal spot, the researchers in [6], [7] proposed using a focusing-functional gate (FFG) structure. The well-developed miniature X-ray tube has successfully displayed very stable and reliable electron and X-ray emissions up to a considerably high V_A. Many vacuum-sealed miniature X-ray tubes, however, have shown an uncontrollable operation and then a failure, requiring an investigation into their failure mechanism. In this letter, we report the failure analysis of the miniature X-ray tubes with the FFG and a criterion for the successful design and fabrication of the miniature X-ray tubes.

II. Experiments

We simulated the FFG structure and fabricated a fully vacuum-sealed miniature X-ray tube that was 6 mm in diameter and 38 mm in length, as shown in Fig. 1. The optimized design of the miniature X-ray tube with FFG was achieved by the electron beam trajectory simulation using a commercial tool. The FFG was designed to be like a coaxial metallic cylinder having different apertures at its ends and to

Manuscript received July 16, 2013; revised Aug. 13, 2013; accepted Aug. 21, 2013.

This work was supported by the MSIP (ETRI R&D program) and MOTIE (Project No.: 10035553), Rep. of Korea.

Jun-Tae Kang (phone: +82 42 860 6293, notation@etri.re.kr) is with the Creative Future Research Laboratory, ETRI, Daejeon, Rep. of Korea, and also with the Department of Physics, Kyungpook National University, Daegu, Rep. of Korea.

Jae-Woo Kim (jwkim0515@etri.re.kr) and Yoon-Ho Song (corresponding author, yhsong@etri.re.kr) are with the Creative Future Research Laboratory, ETRI, Daejeon, Rep. of Korea, and also with the School of Advanced Device Engineering, UST, Daejeon, Rep. of Korea.

Jin-Woo Jeong (jinu@etri.re.kr), Sungyoul Choi (sungyoul@etri.re.kr), and Jeongyong Choi (yongs@etri.re.kr) are with the Creative Future Research Laboratory, ETRI, Daejeon, Rep. of Korea.

Seungjoon Ahn (sjan57@etri.re.kr) is with the Creative Future Research Laboratory, ETRI, Daejeon, Rep. of Korea, and also with the Department of Information Display, Sun Moon University, Asan, Rep. of Korea.

http://dx.doi.org/10.4218/etrij.13.0213.0346

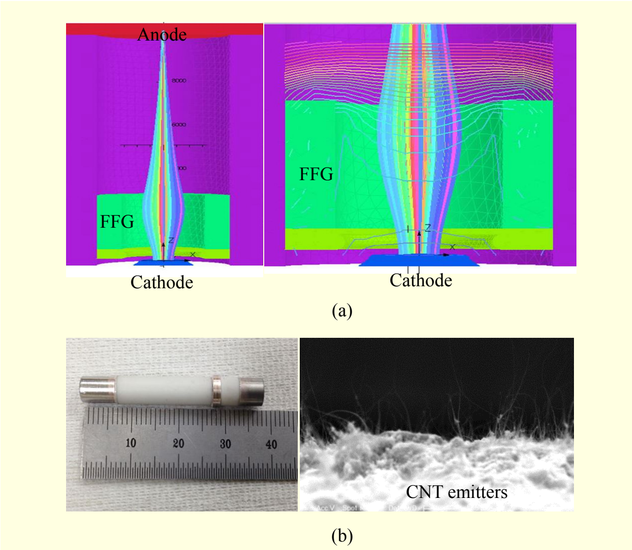

Fig. 1. (a) Simulated electron-beam trajectories for triode CNT emitters with FFG. (b) Optical image of vacuum-sealed miniature X-ray tube and SEM image of CNT emitters on cathode rod.

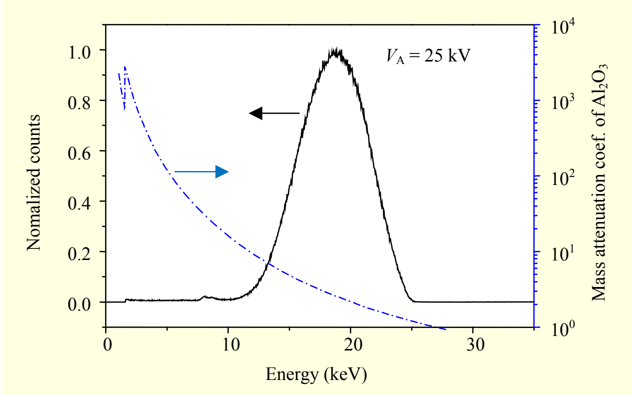

Fig. 2. Energy spectrum of X-rays from vacuum-sealed miniature X-ray tube at V_A of 25 kV and mass attenuation coefficients for photon interactions in Al_2O_3.

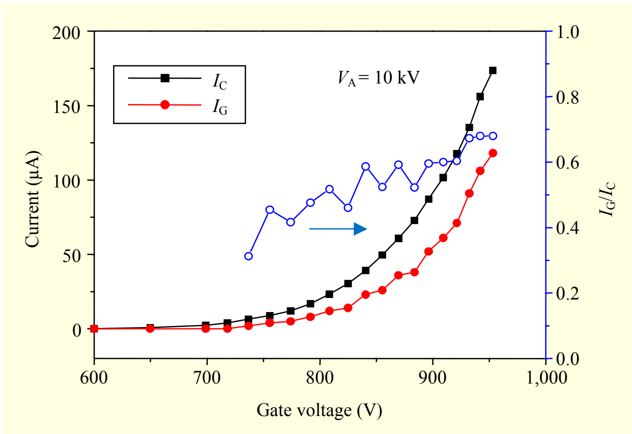

Fig. 3. I_C, I_G, and ratio of I_G with respect to I_C as function of V_G at V_A of 10 kV for unstably operated miniature X-ray tube in pulse mode operation.

focus the electron beams onto the anode target. The detailed configuration and fabrication sequence of the triode miniature X-ray tubes, including the CNT field emitter and the brazing process for vacuum sealing, were described in [6], [7].

Besides the vacuum-sealed miniature X-ray tubes, we fabricated test gated CNT field emitters and measured their instability in a vacuum chamber. In the experiments on the test gated CNT emitters, the configuration of the device and its constituent material, such as the Al_2O_3 ceramic tube used as an insulating spacer, were the same as that in the vacuum-sealed X-ray tubes. The field emission characteristics were measured by the active current control through the cathode electrode [6]-[9] or the direct gate control.

III. Results and Discussion

The researchers in [6] observed that the miniature X-ray tube without a gate leakage current exhibited a stable and reliable operation over 250 h in a pulse mode above a V_A of 25 kV. In addition, the energy spectrum of the X-rays was investigated for the miniature X-ray tube [7]. Both in [7] and in this study, the X-ray spectrum was measured by using a commercial spectrometer with a CdTe sensor through the direct ceramic spacer that had no special window for X-rays. Considering some attenuation of X-rays by the 1-mm-thick Al_2O_3 ceramic spacer [10], we found that the measured X-ray spectrum was very much in agreement with the typical spectrum of the W target for a given V_A of 25 kV, as shown in Fig. 2.

The stability and reliability of the CNT field emitters are known to be very dependent upon the vacuum level [11]. Even if the vacuum inside an X-ray tube is well maintained, the operation can be unstable and ultimately fail. A gate leakage of field emission current existed, and was thus measured, in most cases of unstable operation and then failure of the miniature X-ray tube. Figure 3 shows the cathode current (I_C) and gate current (I_G) as a function of the gate voltage (V_G) for the unstably operated miniature X-ray tube in a pulse mode operation with a duty of 50%. The ratio of I_G to I_C is 0.7 at a V_G of about 950 V. Even for the optimally designed miniature X-ray tube, the gate would have a leakage current resulting from the misalignment of the CNT emitter and the gate aperture that occurs during the fabrication process. If a gate leakage current exists, it means that some of the electron beams have diverged from the designed path, providing a charge at the insulating spacer. Furthermore, the scattered electrons from the gate electrode would be directed to the insulating spacer, which would also cause charging [12]. The charging at the insulating

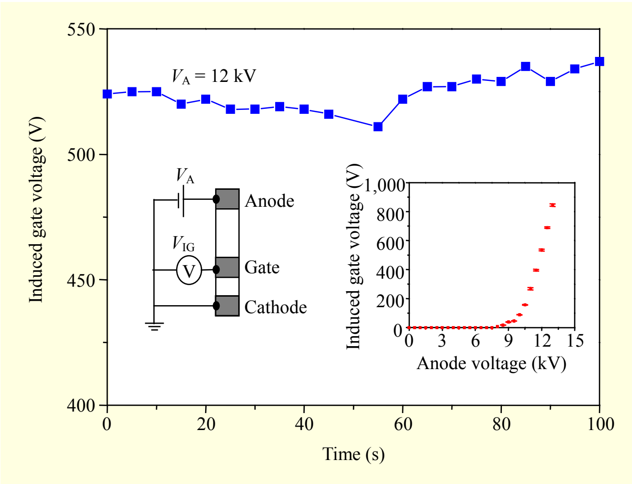

Fig. 4. V_{IG} as function of time at V_A of 12 kV for unstably operated miniature X-ray tube. Inset shows schematic of measurement setup and V_{IG} as function of V_A.

spacer may induce a voltage on the gate electrode unstably, giving uncontrollable coupling between the gate and anode and then a destructive arc.

Just after obtaining the field emission current, we measured the induced gate voltage (V_{IG}) caused by the charging and the coupling between the V_G and various V_A. Figure 4 shows the V_{IG} with time at a V_A of 12 kV and the V_{IG} as a function of the V_A along with the schematic of the measurement setup in the inset. The V_{IG} was measured by using a DC voltage measurement unit of the KEITHLEY 248 system. The cathode was electrically connected to the ground potential during the measurements. As shown in Fig. 4, the V_{IG} fluctuated with time and the V_A increased the V_{IG} through the coupling between the gate and anode after the field emission. The V_{IG} was observed to be very unstable and disappeared gradually after a full relaxation of several tens of hours, suggesting that they originated from the charging of the insulating spacer through the leakage of the field emission current to the gate electrode.

To elucidate the failure mechanism of the triode miniature X-ray tubes, we fabricated test gated CNT field emitters with a laterally misaligned FFG hole and measured their instability caused by the gate leakage current and then the charging at an insulating spacer in a vacuum chamber. The misalignment between the FFG hole and CNT emitter was intentionally designed to induce a gate leakage current to the FFG.

From the test gated CNT field emitters, we also observed a V_{IG} on the FFG electrode by the anode bias voltage after field emission from the CNT emitter with a leakage current to the FFG as in the vacuum-sealed miniature X-ray tube. Figure 5 shows the V_{IG} as a function of the V_A after the field emission of an I_C of around 100 μA at a V_A of 14 kV and the relaxation of V_{IG} with time for the test gated CNT emitters in a vacuum

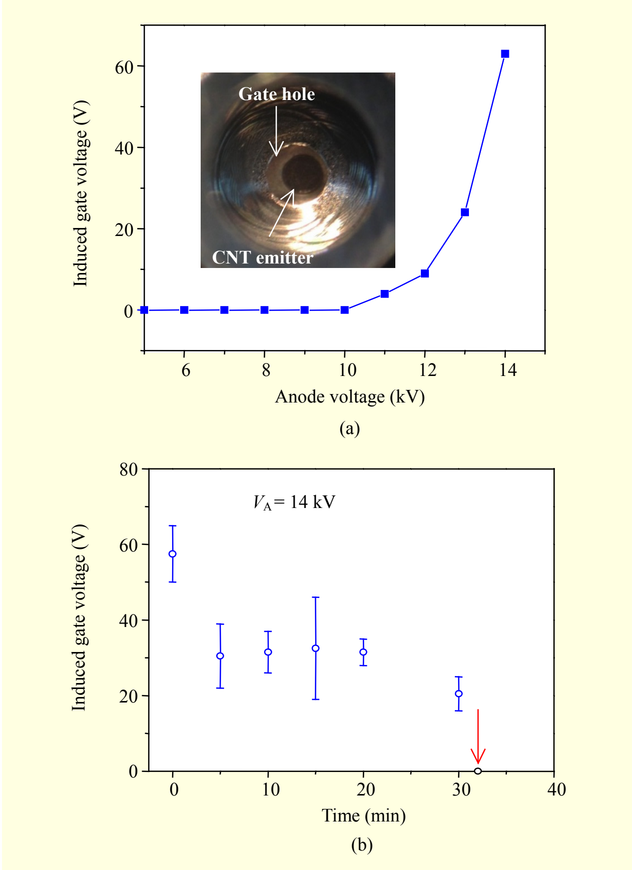

Fig. 5. (a) V_{IG} as function of V_A after field emission of I_C of around 100 μA at a V_A of 14 kV for test gated CNT emitters in vacuum chamber. Inset exhibits photograph image of laterally misaligned FFG hole with CNT field emitter, showing around 17% deviation from concentric point. (b) V_{IG} with time after measurement of V_{IG} and V_A characteristics shown in (a). Measurement procedures are same as those shown in Fig. 4. V_{IG} is pretty unstable and decreases to 0 V after discharging through soft arc at time indicated by arrow.

chamber. As shown in the inset of Fig. 5(a), the CNT field emitter was misaligned with the FFG hole laterally, giving approximately a 17% deviation from the concentric point. The CNT field emitter with a diameter of 0.6 mm was vertically 0.3 mm apart from the FFG hole with a diameter of 1.0 mm. The measurement procedures of the test gated CNT field emitters were the same as those of the vacuum-sealed miniature X-ray tube.

Compared with the vacuum-sealed miniature X-ray tube, the test sample had a lower gate leakage current of about 10% with respect to the I_C. However, it distinctly showed the V_{IG} on the FFG by the anode bias voltage after field emission as the vacuum-sealed miniature X-ray tube. The gate leakage current was larger and the V_{IG} was higher under a constant anode bias voltage. The gate leakage current in the test gated CNT emitters indicated that some of the electrons from the CNT

http://dx.doi.org/10.4218/etrij.13.0213.0346

emitters would diverge from the designed passage, giving a charge at the insulating spacer and then causing the coupling between the FFG and the anode bias voltage.

Since the V_{IG} was caused by the charging at the insulating spacer, the relaxation of the V_{IG} would proceed very irregularly and unstably in a vacuum. As shown in Fig. 5(b), the V_{IG} was pretty unstable and decreased to 0 V after discharging through a soft arc at the time indicated by the arrow. In some cases, the relaxation was simply achieved by venting the vacuum chamber, discharging the insulating spacer through air. These results imply that the V_{IG} on the FFG observed in both the test sample and the vacuum-sealed miniature X-ray tube is related with the charging at the insulating spacer. Furthermore, the V_{IG} and gate leakage current can be used to monitor and estimate the charging through a quantitative modeling.

IV. Conclusion

Even a small gate leakage current in the triode miniature X-ray tubes with CNT field emitters gave rise to the V_{IG} on the gate electrode by the anode bias voltage, resulting in unstable operation and then failure. From the experiments on the test gated CNT field emitters in a vacuum chamber, the V_{IG} on the gate electrode disappeared by a full relaxation of the sample for several tens of minutes with the discharging event or by venting the vacuum chamber. As a result, the instability and failure in the triode miniature X-ray tubes is attributed to the charging at the insulating spacer through the leakage of field emission current to the gate electrode. We could consider the gate leakage current with its related V_{IG} as a criterion for the successful design and fabrication of triode miniature X-ray tubes.

References

[1] Y.S. Choi et al., “An Under-gate Triode Structure Field Emission Display with Carbon Nanotube Emitters,” *Diamond Relat. Mater.*, vol. 10, no. 9-10, Sept.-Oct. 2001, pp. 1705-1708.

[2] Y.C. Choi et al., “The High Contrast Ratio and Fast Response Time of a Liquid Crystal Display Lit by a Carbon Nanotube Field Emission Backlight Unit,” *Nanotechnol.*, vol. 19, no. 23, May 2008, pp. 235306-235310.

[3] Y.-H. Song, J.-W. Jeong, and D.-J Kim, “CNT-Based FEL for BLU in LCD,” *Carbon Nanotube and Related Field Emitters: Fundamentals and Applications*, Y. Saito, Ed., Weinheim, Germany: Wiley-VCH, 2010, pp. 343-371.

[4] F. Okuyama, “Miniature X-ray Tubes,” *Carbon Nanotube and Related Field Emitters: Fundamentals and Applications*, Y. Saito, Ed., Weinheim, Germany: Wiley-VCH, 2010, pp. 401-416.

[5] S.H. Heo et al., “A Vacuum-Sealed Miniature X-ray Tube Based on Carbon Nanotube Field Emitters,” *Nanoscale Res. Lett.*, vol. 7, no. 258, May 2012, pp. 258-262.

[6] J.-W. Jeong et al., “A Digital Miniature X-ray Tube with a High-Density Triode Carbon Nanotube Field Emitter,” *Appl. Phys. Lett.*, vol. 102, no. 2, Jan. 2013, pp. 023504-023507.

[7] J.-T. Kang et al., “Analysis of CNT Emitter-Based Miniature X-ray Tubes for Stable and Reliable Operation,” *Proc. of IVNC*, 2013.

[8] J.-W. Jeong et al., “A Vacuum-Sealed Compact X-ray Tube Based on Focused Carbon Nanotube Field-Emission Electrons,” *Nanotechnol.*, vol. 24, no. 8, Feb. 2013, pp. 085201-085208.

[9] Y.-H. Song et al., “Active-Matrix Field Emission Display with Amorphous Silicon Thin-Film Transistors and Mo-Tip Field Emitter Arrays,” *ETRI J.*, vol. 24, no. 4, Aug. 2002, pp. 290-298.

[10] C.T. Chantler et al., *X-ray Form Factor, Attenuation, and Scattering Tables*, NIST, US Department of Commerce, 2001, accessed July 16, 2013. http://www.nist.gov/pml/data/ffast/index.cfm

[11] A. Haga et al., “A Miniature X-ray Tube,” *Appl. Phys. Lett.*, vol. 84, no. 12, Mar. 2004, pp. 2208-2210.

[12] H. Hao et al., “Secondary Electron Emission in a Triode Carbon Nanotube Feld Emission Display and Its Influence on the Image Quality,” *Carbon*, vol. 50, no. 11, Sept. 2012, pp. 4203-4208.