X-ray generation using carbon-nanofiber-based flexible field emitters

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Journal or publication title: APPLIED PHYSICS LETTERS
Volume: 88
Number: 10
Page range: 103105-1 - 103105-3
Year: 2006
URL: http://id.nii.ac.jp/1476/00005279/
doi: 10.1063/1.2182022

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The following article appeared in Applied physics letters, 88(10), pp. 103105-1 - 103105-3; 2005 and may be found at http://link.aip.org/link/?apl/88/103105

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doi: 10.1063/1.2182022 (http://dx.doi.org/10.1063/1.2182022)
Carbon nanostructures such as carbon nanotube (CNT) and carbon nanofiber (CNF) have been very promising for field emission (FE) electron sources owing to their high aspect ratio and small tip radius. While the potential applications of these materials appears to be limited only by imagination, those better known include cold cathodes for FE displays and other vacuum microelectronic devices. Various articles have documented the excellent field emission properties of these nanostructures. Apart from these low voltage applications, CNT and CNF have also found applications in high voltage devices such as an electron source for x-ray generation. In this letter, we investigated the field emission performance of CNFs grown on flexible polyimide substrates and demonstrated its ability to be used as a high voltage electron source for x-ray generation. Carbon nanofibers were grown on flexible polyimide substrates using an ion-beam sputtering technique. Field emission measurement showed a fairly low threshold voltage of 1.5 V/μm with a current density of 1 μA/cm². The field enhancement factor was determined to be 4400. The emitter showed resilience when exploited as a high voltage electron source for x-ray generation. The x-ray generated by the flexible emitter is capable of delivering fine images of biological samples with superior sharpness, resolution, and contrast. © 2006 American Institute of Physics. [DOI: 10.1063/1.2182022]
ited an initial threshold field of about 1.5 V/µm with a current density of 0.1 µA/cm², which is comparable to CNTs on Si and CNFs on a graphite plate. The value of β thus obtained was about 4400. Figure 3 is a photograph showing the mockup arrangement of the flexible emitter and the copper anode when inside the x-ray tube. The surface of the copper anode was angled approximately 45° to assist x-ray emission. The radius of the emitter curl was approximately 3 mm. Figures 4(a) and 4(b) show the x-ray images of a Bougainvillea flower obtained from the flexible emitter exposed for about 45 s using 13 kV. From the images, it can be clearly seen that the flexible x-ray source produces a high quality picture with high resolution on the biological sample.

The flexible emitter x-ray was able to resolve the fine details in the flower as enlarged in Fig. 4(b), in addition to the veins on the petals as indicated by the two white arrows in Fig. 4(a). The thickness of the vein was ~250 µm. This shows that the flexible emitter is capable of emitting sufficient current to generate the x-ray flux necessary for a high signal to noise ratio even at such a low voltage.

Figure 5 shows the stability measurement of the flexible x-ray source operating at 16 kV as measured by a dosimeter (Ludlum 2241). From the graph, it can be seen that the fluctuation of the x-ray output was low. This suggests that the flexible polyimide based CNFs can have excellent durability for use as high power electron emitter sources. Although the stability is highly dependent on the emission stability of the pulsed power generator, the graph is a good demonstration that the emitter did not degrade even under such a high voltage and current. The same emitter has been tested for x-ray generation for several months and showed no sign of failure. There are no obvious differences in terms of x-ray stability and image quality of a biological sample when the CNFs flexible emitter is used as compared to a CNT emitter (on a tungsten tip) under identical x-ray generation conditions.

This work has demonstrated the viability of using a flexible emitter as an electron source for x-ray application. There could be many possible applications of the flexible emitter, one such potential would be in radiotherapy. Most miniature x-ray tubes for radiotherapy applications used a thin layer of target material coated on the x-ray window. In this transmission mode arrangement, x-ray efficiency is severely lowered as radiation is required to transverse through a thick layer of target material before hitting the targeted organ.
use of beryllium as the window material is not favorable as beryllium is harmful to human beings. Using a flexible emitter would allow us to circumvent these limitations and improve the efficiency of the x ray emitted from the system. As polymers generally have a lower absorption coefficient of the x ray as compared to metals, they made an excellent candidate for this application.

As shown in Fig. 3, the emitter demonstrates sufficient flexibility for it to be curled into a radius of $\sim 3$ mm while still retaining its field emission ability. The use of such a flexible emitter would allow for greater choices of x-ray tube design previously not possible in medical radiotherapy. It would be possible to make an x-ray transparent emitter as the window with a concave target surface to achieve a focused x-ray, thereby reducing the spot size of the x-ray spot. This would allow for more precise radiotherapy treatment rather than the usual diverging x-ray source.

In summary, we have demonstrated an x-ray source using a flexible emitter based on CNFs. The x ray generated at the voltages of 13 keV was sufficient to produce the radiograph image of a Bougainvillea with superior sharpness, resolution, and contrast. The flexible emitter has the potential to be applied in x-ray radiotherapy and radiography applications.

This work was partly supported by the Agency for Science, Technology, and Research of Singapore (Project No. 0221010020), SIMTech Project No. SIMT/04-420009, the Japan Society for the Promotion of Science (JSPS; Grants-in-Aid for Scientific Research B, No. 15360007), and the NITECH 21st Century COE Program “World Ceramics Center for Environmental Harmony.”