A miniature x-ray tube

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A miniature x-ray tube is described. The tube is made of Kovar, inside which a grounded target is located close to a field-electron emitter consisting of aligned carbon nanofibers, which continues to work for around 100 h in the 10⁻⁶ Pa region unless arcing is induced between the electrodes. The resolution of the contact x-ray images provided by the tube would be impossible using the existing techniques of conventional x-ray radiography, whether the sample is biological or nonbiological.

Field-electron emission (FE) refers to the extraction of electrons from a noninsulating solid surface through electron tunneling. The tunneling process is exponentially affected by the chemical state of the emitter surface. This implies that, for their wide applications, FE emitters must be robust in non-ultrahigh vacuum where the interaction is unavoidable between the emitter and residual gases. The so-called catalytically induced carbon nanotubes, or “carbon nanofibers” (CNFs), well satisfy this requirement, and numerous attempts have been reported on the application of CNFs to electron-beam tools, typically flat-panel displays.

In FE x-ray radiography (XR), field-emitted electrons bombard the metallic target to generate x rays. The potential benefits of a FE x-ray source are exciting, since it could serve to miniaturize the entire tube structure. A so-called “miniature x-ray tube” (MXT) of the kind could provide a finely focused electron beam and hence x-ray images with an ultrahigh resolution, paving the way to new frontiers in medicine and microelectronics. This possibility has consistently encouraged us to develop FE-MXTs. Here we report on the design and performance of an FE-MXT system.

A critical issue in developing a MXT is how to devise a tiny electron source that can be built into a tube. In a preceding article, we demonstrated that CNFs were promising as an electron source in FE-XR. They continuously emitted electrons for 80 min or so in a non-ultrahigh vacuum ambiance of 2 × 10⁻⁷ Torr, providing high-resolution x-ray images. These CNFs were grown on a nickel overcoat sputter-deposited on a tungsten (W) wire. Recently, we noticed that palladium (Pd) induces the growth of CNFs. As confirmed by auxiliary experiments at 2 × 10⁻⁶ Pa, these Pd-induced CNFs continued to field-emit electrons of 15–40 μA for around 100 h, with no discernible decline in intensity. Further prolonging the emitter operation resulted in a very slow decrease in electron current, and the emitter ceased to emit electrons after around 200 h. This finding was the technical basis for our MXT.

The principle of preparing an electron emitter was to grow CNFs on one end of a Pd wire. In brief, a Pd wire 1 mm in diameter and ~2 mm in length was vertically spot-welded on a tantalum wire (see the drawing inset in Fig. 1). CNFs were then made to grow at the mechanically polished upper end of the spot-welded Pd wire through the chemical vapor deposition (CVD) described elsewhere in detail. The CNFs thus grown were always topped with a strongly faceted single crystal of Pd (see the transmission electron microscope image inset). After CVD, the Pd wire was carefully detached from the tantalum wire to serve as the electron emitter in the MXT.

Figure 2(a) shows a cross-sectional drawing of our MXT. The x-ray tube, 10 mm in diameter, was machined out from a Kovar rod. Inside the tube, the target and the emitter were equipped at an interval of ~2 mm. The target was a W rod 2 mm in diameter with a hemispherical surface, half embedded in a copper rod [see the encircled enlargement in Fig. 2(a)]. The CNF substrate, or the Pd wire, was sheathed in a stainless steel tube, with its tip slightly protruding [see the rectangle in Fig. 2(a)]. In this tube design, rough electron focusing was automatically achieved since the grounded tube wall deflected the obliquely emitted electrons toward the target. The open end of the stainless steel tube also served to slightly converge the electron beam coming out from the emitter. The target potential and the emitted electron current were positive 30 kV and 50 μA, respectively, at their maximum level, corresponding to the maximum power of 1.5 W.

FIG. 1. Scanning electron image of CNFs grown on the conically shaped tip of a Pd wire. Insets show the emitter-support in CVD and the transmission electron image of a Pd crystallite atop a CNF. The surface of the Pd crystallite was covered with a thin layer of graphite. Electrons are thought to be emitted from such Pd crystallites.
Operating the tube beyond this wattage caused overheating of the target. Figure 2(b) is a schematic drawing of the x-ray producing circuit. The RL coupling between the target and the power supply was arranged to prevent a current surge. The main pumping was done with a V acIon pump that lowered the tube pressure to \(2 \times 10^{-6}\) Pa via a mild bake-out with the aid of ribbon heaters.

Although the electron current fluctuated at an amplitude of \(7\%–8\%\) at a fixed target potential, the current–voltage \((I–V)\) characteristics exhibited little change unless arcing took place between the emitter and the target. At pressures in the \(10^{-6}\) Pa region, an appreciable current fluctuation is generally unavoidable independent of emitter material, primarily because of the interaction of the emitter tip with residual gases. The fluctuations \(7\%–8\%\) for the present emitters were comparable to those for other types of nanofiber emitters operated under similar conditions (cf. Ref. 5). Arcing was prone to take place when target potential was increased too quickly, so the potential increase must be as slow as possible. After arcing, the electron current was well stabilized within the above range as long as the potential was kept constant. The first arcing never destroyed the entire cathode. Perhaps, a limited number of CNFs were damaged upon arcing, with the surviving ones contributing to electron emission.

Electrons emitted at the stabilized level always gave rise to a linear Fowler–Nordheim (FN) plot, as typically illustrated in Fig. 2(c). Strictly speaking, the FN plot holds for electron tunneling. For practical cases, \(J\) and \(E\) are replaced by \(J\) (total current) and \(V\) (applied voltage), respectively, leading to the FN plot of \(\log J/V^2\) vs \(1/V\). The linear FN curve in Fig. 2(c) proves that the electrons that produced x rays were field-emitted.

The energy spectra of x rays radiated from the target were recorded with a silicon detector (Röntec 2001) placed just outside the beryllium window. (This detector enables us to display an x-ray spectrum on PC screen.) Above 15 kV, the spectra exhibited intense \(L_\alpha\) and \(L_g\) signals, involving no characteristic signal from copper (data not shown); most electrons discharged from the emitter might have arrived at the target, despite its small dimension and the closeness of the target and emitter. When lowering the target potential to 10 kV or less, the spectra were exclusively comprised of a continuous signal due to bremsstrahlung.

An important application of XR is the nondestructive inspection of electronic devices, or LSIs. Since the circuit patterns of LSIs are too fine to be resolved with conventional x rays, the major role of XR in this field is to inspect the quality of the electrical connections. Shown in Fig. 3(a) is an x-ray image of an LSI memory recorded at an electron energy of 15 kV. The image is very clear, resembling a photographic image of an artistic pattern. As seen in Fig. 3(b), the respective lead wires (about 20 \(\mu m\) in diameter) and their welded spots have been perfectly resolved. Moreover, no distortion is recognized in the image, and the geometry of the imaged areas and their contrasts are perfectly symmetrical with respect to the image’s center.

Figure 4(a) shows a carpus excised from the carcass of a mouse imaged by XR, in which the joint structures are clearly observed at the end of the claw digits. The photographically enlarged image in Fig. 4(b) reveals balloon-like soft tissues (see arrows). These might be the so-called “footbeat absorber” feature characteristic of quadrupeds.

The tip dimension, number density, and average length of CNFs, together with the tip–anode distance, critically affects current density \((A/cm^2)\). The linearity of the FN plot assures that the electron emission is due to electron tunneling. For practical cases, \(J\) and \(E\) are replaced by \(J\) (total current) and \(V\) (applied voltage), respectively, leading to the FN plot of \(\log J/V^2\) vs \(1/V\). The linear FN curve in Fig. 2(c) proves that the electrons that produced x rays were field-emitted.
ffect the average electric field on the cathode and hence the \( I - V \) characteristics. (FE current exponentially depends on the electric field.) Currently, we have no method to control these parameters. In the present MXT prototype, therefore, the electron-emission characteristics differed from emitter to emitter. For the diode structure, the electron emission is directly governed by the target potential, which has to be regulated to control the electron current. This inevitably leads to a change in electron energy. A means of controlling the electron current without changing the electron energy would be to place a gate electrode just before the emitter. Thus, the control of the gate potential would keep the electron current at a desired level while fixing the electron energy, irrespective of the emitter’s intrinsic quality. Moreover, the feedback control of the gate potential would dramatically reduce the current fluctuation.

The prime cause of FE emitter destruction is sputtering. Specifically, a positively charged ion bombards the surface of an electron emitter to produce an atomically small protrusion thereon. Since the electric field is concentrated on such a tiny protrusion, the electron emission is dramatically enhanced from the protrusion, resulting in a meltdown of the emitter through excessive Joule heating. This means in turn that a steep current increase would generally precede emitter breakdown. The feedback circuit could sense the commencement of such a sudden current increase, then lower the gate potential to stabilize the current. Our next concern is thus to construct a triode-type MXT with a built-in field emitter. The hurdle to be cleared will be how to install a micro-gate electrode within the MXT.

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