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Carbon nanotubes as electron source in an x-ray tube

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Field emitters comprised of aligned carbon nanotubes are shown to be promising as a primary electron source in an x-ray tube working in a nonultrahigh vacuum ambience. At a pressure of $2 \times 10^{-7}$ Torr, the nanotube emitters continue to emit electrons for more than 1 h, and yield better resolved x-ray images than do thermionic emitters, independently of whether the sample is biological or nonbiological. The near-uniformity in energy distribution of electrons emitted from carbon nanotubes might be related to the improved image quality in the field-emission mode.

Since its theoretical formulation by Richardson, thermionic emission (TE) has been a key concept in electron-beam techniques. In thermionic electron emission, the solid electron source (i.e., the cathode) is heated above 2000 °C to allow free electrons to escape from the surface. The greatest advantage of this so-called “hot cathode,” usually a heated tungsten (W) filament, is that it works even in nonultrahigh vacuum (non-UHV) ambiances, which contain vast numbers of gaseous molecules. Underlying this is the fact that the gas-impinging rate is inversely proportional to the square root of surface temperature. However, hot cathodes are prone to chemically react with residual water and oxygen to produce tungsten oxides, and get thinner and thinner over a long duration through the sublimation of the oxides. In addition, hot cathodes require a power supply for heating, thus making it difficult to construct a compact electron-beam tool.

It was suggested in the mid-1950s that these disadvantages of hot cathodes may be overcome by replacing them with field emission (FE), or cold, cathodes. Unfortunately, the electron emission from a FE cathode is exponentially affected by the chemical and morphological states of the electron-emitting area, resulting in instability of emitted currents in non-UHV ambiances. This is particularly true of metallic cathodes, which strongly interact with residual gaseous molecules. Thus, no attempt to use field emitters in non-UHV has been of practical significance.

Chemically, carbon is far more stable, and hence more robust in non-UHV, than metals. Indeed, several groups have claimed that carbon nanotubes (CNTs) are promising as multiple field electron sources. Most studies of this kind are directed to the application of CNTs to flat-panel displays, for electrical conduction [Fig. 2(a)]. The tube was pumped down to $\sim 2 \times 10^{-7}$ Torr with the aid of two turbo-molecular pumps. The electron current emitted from the cathode (CNTs) was controlled by manually varying the potential of the counter electrode placed just before the cathode. By replacing the CNTs with a mere W wire (0.3 mm diameter), the tube could also be operated in the TE mode. For some CNT emitters, the intensity of x rays passing through the beryllium (Be) window was measured as a function of target potential, with total electron current as the parameter. Very roughly, the x-ray intensity increased exponentially with the linear increase in target potential [Fig. 1(b)].

Since a major industrial application of XR is the nondestructive inspection of electronic device, we chose a large-scale integrated (LSI) circuit as the first sample. Its x-ray image recorded with a CNT emitter was so sharp as to disclose every gold wire ($\sim 30 \mu m$) across for electrical conduction [Fig. 2(a)]. Because of a low electron current (1.5 mA), the exposure time was as long as 14 min, but the second to fourth imaging could be done by this emitter with no appreciable deterioration in image resolution.

The above LSI was also x-ray imaged in the TE mode, and the result is shown in Fig. 2(b). Compare these x-ray images, and the superiority of the FE mode becomes clear. For example, the arrowhead-indicated lead wires in Fig. 2(a) are missing or barely perceptible in Fig. 2(b). The vast majority of field electrons are emitted through a tunneling process from the Fermi level, which is a function of electronic.

conductivity. The electronic conductivity of CNTs has been predicted to depend on their diameter, as well as their lattice helicity. Thus, field electrons from different tubes with different diameters possess different energies, and hence cause a Fermi level distribution. For our CNT emitters, however, very few prominent tubes well uniform in field-enhancement factor actually emit electrons, so the emission energy distribution should be far more uniform than for thermal electrons. This near uniformity in electron energy might be responsible for an improved image resolution in the FE mode.

For soft samples like plants, the energy of x rays must be lowered to the soft x-ray region. In terms of electron energy, the upper limit for the soft energy region is several keV; a prolonged exposure time is needed for soft x-ray imaging. Unfortunately, the lifetime of our CNT emitters is 60–80 min in $2 \times 10^{-7}$ Torr, making them unable to operate in the true soft x-ray region. (A prolonged application of electric field led to a local removal of the nanotube film from the substrate, whereupon the emitter ceased to work.) This forced us to image biological samples at 10 keV. Figure 3(a) shows a leaf imaged at 10 kV, revealing leaf veins for nutrition transportation. The exposure time was around 1 h, reflecting the robust nature of CNTs in non-UHV. This kind of observation at low energies is completely impossible with metallic cathodes, due to their limited lifetime in non-UHV. It is emphasized that this leaf was snatched from its tree just before imaging and hence was still not dehydrated.

Other biological samples that we examined in the FE mode included insects, each of which presented a clear x-ray image at 20–40 keV.
such current fluctuation, the electron-gun chamber would have to be differentially pumped down to UHV. Also, the electron current could be automatically stabilized in a non-UHV ambience by electronically controlling the counter-electrode potential. The present work may pave the way to these next generations of x-ray technology, which may be termed the "field-emission x-ray radiography."

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