Saturated Field Emission from Carbon Nanotubes

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Nanotube field emitters are known to exhibit current saturation at high currents. We have measured energy spectra of the emission from gated carbon nanotube arrays as a function of gate voltage. The distributions show that the saturation occurs mainly at energies near the Fermi level (E_F). This behavior cannot be explained within the assumptions of the usual free-electron theory, even by adjusting the work function.

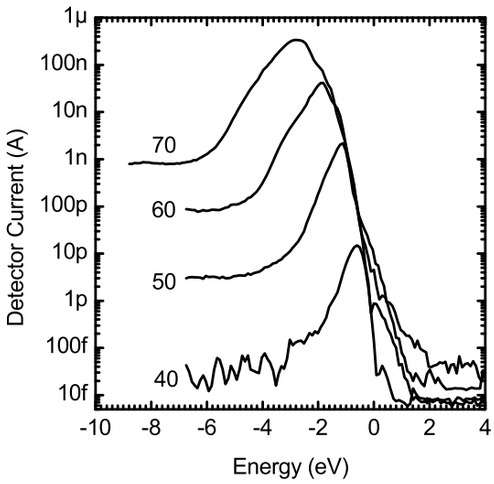
The nanotubes were grown by CVD on bare silicon posts inside gate structures using Ni or Fe catalysts[1]. The spectra are measured after baking the arrays at 600V in UHV, after exposing to water vapor and hydrogen, and while the arrays are held at 600C in UHV.

At low currents, we find the emission spectra are narrow and increase in intensity at all energies (figure 1). However, the intensity does not increase as quickly as theory predicts. At high currents, the emission completely saturates at energies just below E_F. The total current continues to increase, but does not give a straight line when plotted as $\ln(I/V_g^2)$ vs. $1/V_g$. This general behavior is observed under all conditions (at room temperature after baking, at 600C, and after exposure to water vapor (see figures 2 and 3).

The condition of the surface has a substantial effect on both the emission current and the energy distributions. Emission at high currents also seems to have an effect on the surface condition. For example, the spectra are substantially changed by exposure to water vapor, but high current emission causes the spectra to partially revert to the condition observed before exposure.

The saturated behavior of the energy spectra rule out certain effects that might at first seem to explain the non-linear Fowler-Nordheim plots. Poor substrate-nanotube contacts would cause a shift in the entire distribution that increases with emission current. Although some parts of the spectra do shift with emission current (indicating some of the tubes have poor contacts), the main part of the spectra do not shift significantly. The deviation from a linear Fowler-Nordheim plot is more severe when the arrays are heated than after cooling (Figure 3). This result contradicts the idea that the change in the FN slope is related to adsorbed water molecules, suggested previously[2].

We suggest that field penetration (a potential drop within the nanotube locally at the emission site) causes the saturation and broadening in the emission spectra. The energy distribution is broadened because the surface potential changes with position across a single emitting site. The change in potential across the emission site is largest where the emission current density is largest, and thus causes current saturation beginning at the highest energies.



1. David S. Y. Hsu and Jonathan Shaw, Appl. Phys. Lett. 80 p. 118 (2002).
2. Kenneth A. Dean and B. R. Chalamala, Appl. Phys Lett. 76 p. 375 (2000).