

## DRAFT

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### Field Emission Study of Carbon Nanotubes: High Current Density from Nanotube Bundle Arrays

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#### Abstract

We have investigated the field emission behavior of lithographically patterned bundles of multiwalled carbon nanotubes arranged in a variety of array geometries. Such arrays of nanotube bundles are found to perform significantly better in field emission than arrays of isolated nanotubes or dense, continuous mats of nanotubes, with the field emission performance depending on the bundle diameter and inter-bundle spacing. Arrays of 2- $\mu\text{m}$  diameter nanotube bundles spaced 5  $\mu\text{m}$  apart (edge-to-edge spacing) produced the largest emission densities, routinely giving 1.5 to 1.8  $\text{A}/\text{cm}^2$  at  $\sim 4$   $\text{V}/\mu\text{m}$  electric field, and  $>6$   $\text{A}/\text{cm}^2$  at 20  $\text{V}/\mu\text{m}$ .

Recent work<sup>1-3</sup> has shown that Carbon Nanotubes (CNTs) can have outstanding electrical field emission properties, with high emission currents at low electric field strengths (turn-on voltage as low as 1-3  $\text{V}/\mu\text{m}$  and emission current as high as 0.1 mA from a single nanotube).<sup>4,5</sup> Carbon nanotubes are therefore attractive as cold-cathode field emission sources, especially for applications requiring high current densities (hundreds to thousands of amperes per  $\text{cm}^2$ ) and lightweight packages, such as the recently proposed *nanoklystron*,<sup>6,7</sup> which is a micrometer dimension reflex klystron designed to generate milliwatts of power at terahertz frequencies. As part of our efforts to develop a high current density electron source for a working nanoklystron, we have investigated the field emission behavior of CNT arranged in a variety of geometries. We find that the best field emission behavior is achieved when the CNT are arranged in bundles a few microns in diameter, with the bundles arranged in arrays with an array spacing of several microns. CNT in this arrangement are found to have better field emission properties than either isolated, individual CNT or continuous, dense mats of CNT. We have studied the field emission characteristics of arrays of such CNT bundles, and have optimized field emission with respect to bundle size and separation.

CNT are produced by the decomposition of hydrocarbons over catalytic metal (iron) at elevated temperature. Substrates of Si or  $\text{SiO}_2$  are

lithographically patterned with Fe (10 nm thick), then inserted into a tube furnace for CNT growth. Typical CNT growth conditions are:  $\text{C}_2\text{H}_4$  flow, 380 sccm;  $\text{H}_2$  flow, 190 sccm; total pressure, 200 Torr; Temperature, 650° C; growth time, 15 minutes. CNT grow upon the substrates only in the areas patterned with Fe catalyst. This catalyst was patterned in arrays of circular islands or dots with various diameter (in the range of 0.2 – 5.0 microns) and separation (in the range of 2 – 100 microns). Growth of CNT on the micron-sized dots of catalyst yields micron-sized zones of dense CNT having the appearance of ropes or bundles of nanotubes, separated by a distance equal to the separation of the catalyst dots before CNT growth; Figure 1 shows an example.

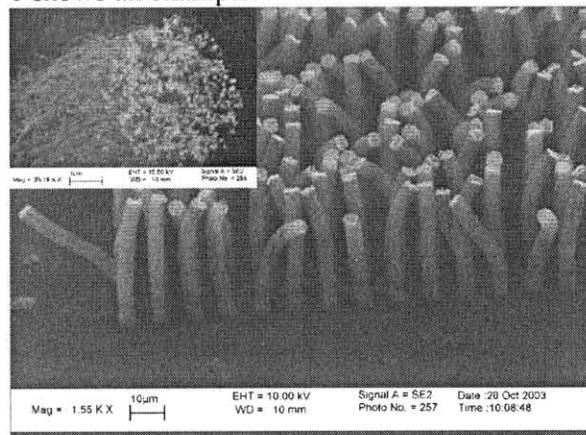


Fig 1. SEM image of CNT bundle array; inset shows one bundle with individual CNT visible.

For field emission measurements, CNT bundle arrays were grown in the pattern shown in figure 2. Dots with various diameters were written in arrays of size  $0.5 \text{ mm} \times 20 \text{ mm}$ . Six such arrays were written for each dot size, with six different edge-to-edge spacing between dots, as shown. The measurements were conducted in a diode mode using a tungsten probe anode of  $100\text{-}\mu\text{m}$  tip diameter. The probe was scanned in Y-direction, and emission values were collected every  $50 \mu\text{m}$ . (The X,Y scan coordinate convention is shown in Figure 2). Three lateral scans across the arrays were conducted at three different longitudinal locations (in X) separated by at least  $1 \text{ mm}$ . The measurement field was  $\sim 3 \text{ V}/\mu\text{m}$ . The vacuum during measurement was maintained below  $5 \times 10^{-7} \text{ Torr}$ .

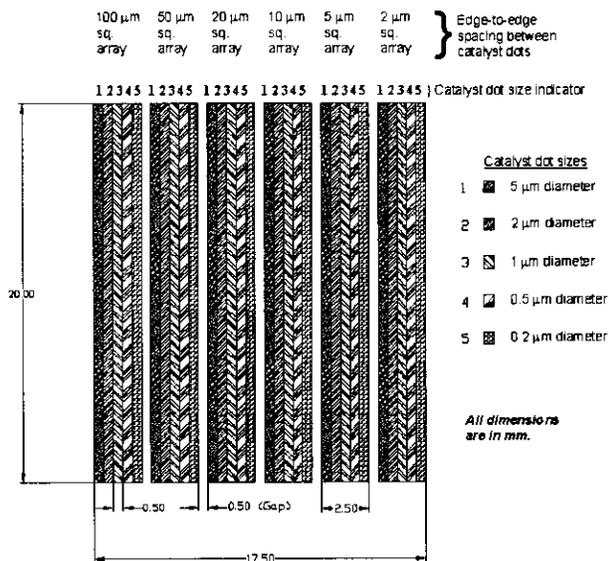


Fig 2. Schematic of an array layout of dots of iron catalyst from which CNT are grown.

The results of field emission current as a function of nanotube bundle diameters and inter-bundle spacing are shown in Figure 3. We observed substantial variation in emission with varying array spacing and the nanotube bundle diameter. Maximum emission was observed in the arrays with  $5 \mu\text{m}$  edge-to-edge spacing, while almost no emission was observed for the arrays of spacing  $50 \mu\text{m}$  and  $100 \mu\text{m}$ .

The maximum emission current density observed was given by CNT bundles with

diameter  $1 - 2 \text{ microns}$  and edge-to-edge bundle array spacing of  $5 \text{ microns}$ . Such bundle arrays routinely gave  $1.5 \text{ to } 1.8 \text{ A}/\text{cm}^2$  emission densities at  $\sim 4 \text{ V}/\mu\text{m}$  field and  $>6 \text{ A}/\text{cm}^2$  at  $20 \text{ V}/\mu\text{m}$ . To the best of our knowledge, these are the highest current densities observed at such low fields. These observed current densities were much greater than the densities observed using either isolated single CNT (arranged in arrays with similar spacing) or dense mats of CNT grown from continuous Fe catalyst films.

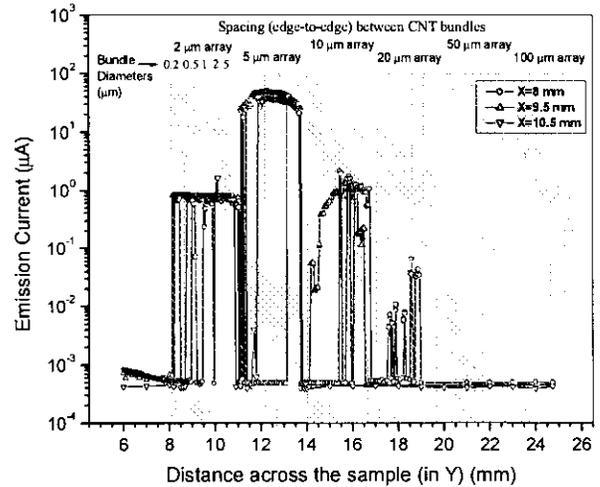


Fig 3. Field emission current from CNT bundle arrays as a function of array spacing and bundle diameter. The topmost labels refer to edge-to-edge CNT bundle spacing.

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