current pulses reduces spatial resolution and increases noise, thereby reducing the overall sensitivity and performance of the mass spectrometer. Hence, it would be preferable to make a direct measurement of the spatial distribution of charged particles impinging on the focal plane.

The utility of delta-doped CCDs as detectors of charged particles was reported in two articles in *NASA Tech Briefs*, Vol. 22, No. 7 (July 1998): "Delta-Doped CCDs as Low-Energy-Particle Detectors" (NPO-20178) on page 48 and "Delta-Doped CCDs for Measuring Energies of Positive Ions" (NPO-20253) on page 50. In the present developmental miniature mass spectrometers, the above mentioned miniaturization and performance advantages contributed by the use of delta-doped CCDs are combined with the advantages afforded by the Mattauch-Herzog design. The Mattauch-Herzog design is a double-focusing spectrometer design involving an electric and a magnetic sector, where the ions of different masses are spatially separated along the focal plane of magnetic sector. A delta-doped CCD at the focal plane measures the signals of all the charged-particle species simultaneously at high sensitivity and high resolution, thereby nearly instantaneously providing a complete, high-quality mass spectrum. The simultaneous nature of the measurement of ions stands in contrast to that of a scanning mass spectrometer, in which abundances of different masses are measured at successive times.

This work was done by Shouleh Nikzad, Todd Jones, April Jewell, and Mahadeva Sinha of Caltech for **NASA's Jet Propulsion Laboratory**. *Further information is contained in a TSP (see page 1).*

In accordance with Public Law 96-517, the contractor has elected to retain title to this invention. Inquiries concerning rights for its commercial use should be addressed to:

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Refer to NPO-41378, volume and number of this NASA Tech Briefs *issue, and the page number.*

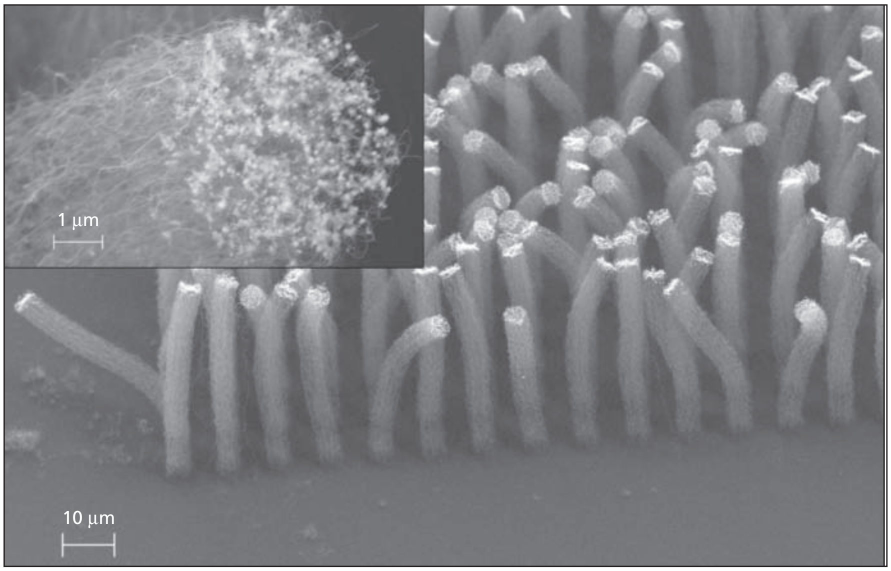
Arrays of Bundles of Carbon Nanotubes as Field Emitters

Area-averaged current densities exceed those of arrays of single nanotubes.

NASA's Jet Propulsion Laboratory, Pasadena, California

Experiments have shown that with suitable choices of critical dimensions, planar arrays of bundles of carbon nanotubes (see figure) can serve as high-current-density field emitter (cold-cathode) electron sources. Whereas some hot-cathode electron sources must be operated at supply potentials of thousands of volts, these cold-cathode sources generate comparable current densities when operated at tens of volts. Consequently, arrays of bundles of carbon nanotubes might prove useful as cold-cathode sources in miniature, lightweight electron-beam devices (e.g., nanoklystrons) soon to be developed.

Prior to the experiments, all reported efforts to develop carbon-nanotube-based field-emission sources had yielded low current densities — from a few hundred microamperes to a few hundred milliamperes per square centimeter. An electrostatic screening effect, in which taller nanotubes screen the shorter ones from participating in field emission, was conjectured to be what restricts the emission of electrons to such low levels. It was further conjectured that the screening effect could be reduced and thus emission levels increased by increasing the spacing between nanotubes to at least by a factor of one to two times the height of the nanotubes. While this change might increase the emission from individual nanotubes, it would decrease the number of nanotubes per unit area and thereby reduce the total possible emission current. Therefore, to maximize the area-averaged current density, it would be necessary to find an optimum combination of nanotube spacing and nanotube height.



This **Scanning Electron Micrograph** shows bundles of carbon nanotubes, each 70 µm high and 5 µm in diameter. The gaps between adjacent bundles are about 5 µm wide. The bundles stand up because their constituent nanotubes support each other. The inset is a magnified image of the top of one bundle, showing individual nanotube tips.

The present concept of using an array of bundles of nanotubes arises partly from the concept of optimizing the spacing and height of field emitters. It also arises partly from the idea that single nanotubes may have short lifetimes as field emitters, whereas bundles of nanotubes could afford redundancy so that the loss of a single nanotube would not significantly reduce the overall field emission.

In preparation for the experiments, planar arrays of bundles of carbon nanotubes having various bundle diameters, bundle heights, and bundle spacings were fabricated. The fabrication process can be summarized as follows: Electron-beam lithography was used to form planar arrays of iron dots having various thicknesses and having diameters and inter-dot spacings corresponding to the desired diameters and spacings of the carbon-nanotube bundles. The dots served as catalysts for the growth of carbon nanotubes: Bundles of multiwalled 20-nm-diameter carbon nanotubes were grown on the iron dots by chemical vapor deposition. The average height of the bundles was 70 ± 2μm. The heights of the bundles were found to depend on the thicknesses of the iron dots. The tallest bundles (112 μm high) were found on iron dots 8 μm thick.

In the experiments, field emission from these arrays was measured in a vacuum chamber by use of a 100-μm-diameter probe anode. The highest nondestructive area-averaged current densities (about 1.5 to 1.8 A/cm^2) were observed on arrays of bundles of 1- to 2-μm diameter and spacings of 5 μm at an applied electric field of about 4.5 V/μm.

This work was done by Harish Manohara and Michael Bronkowski of Caltech for **NASA's Jet Propulsion Laboratory**. *For further information, access the Technical Support Package (TSP)* ***free on-line at www.techbriefs.com/tsp*** *under the Physical Sciences category.*

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