# Carbon-Nanotube-Based Electrodes for Biomedical Applications

**Stimuli and responses could be localized to within nanometers.**

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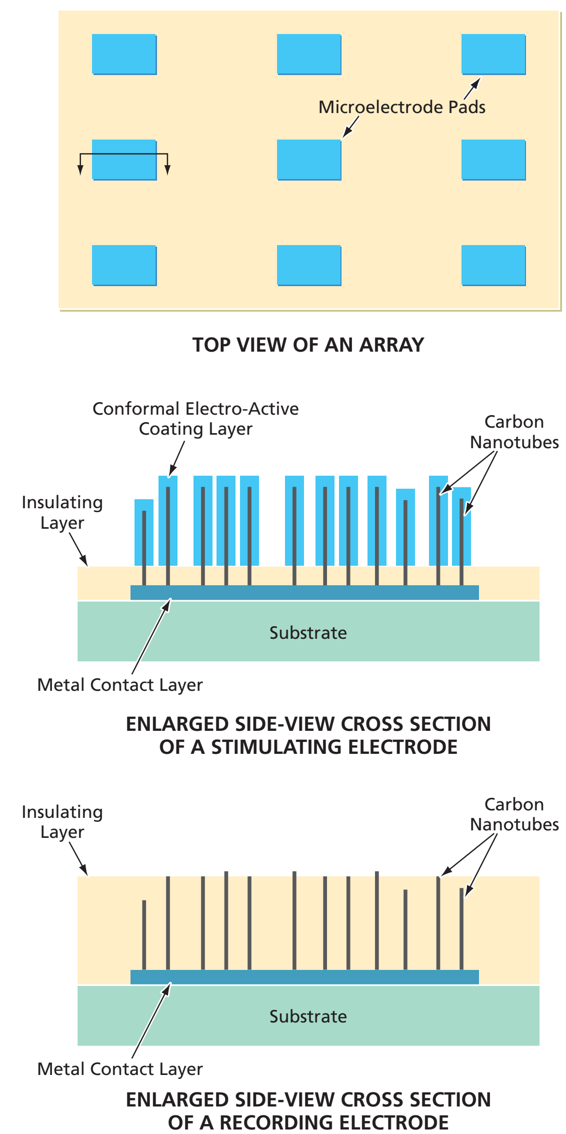
A nanotube array based on vertically aligned nanotubes or carbon nanofibers has been invented for use in localized electrical stimulation and recording of electrical responses in selected regions of an animal body, especially including the brain. There are numerous established, emerging, and potential applications for localized electrical stimulation and/or recording, including treatment of Parkinson's disease, Tourette's syndrome, and chronic pain, and research on electrochemical effects involved in neurotransmission.




**Carbon Nanotubes** connected to metal contact layers would protrude from surfaces of microelectrode pads. In use, the array would be positioned so that at least some nanotubes would be in electrical contact with cell components or intercellular structures of interest.

Carbon-nanotube-based electrodes offer potential advantages over metal macroelectrodes (having diameters of the order of a millimeter) and microelectrodes (having various diameters ranging down to tens of microns) heretofore used in such applications. These advantages include the following:

- Stimuli and responses could be localized at finer scales of spatial and temporal resolution, which is at subcellular level, with fewer disturbances to, and less interference from, adjacent regions.
- There would be less risk of hemorrhage on implantation because nanoelectrode-based probe tips could be configured to be less traumatic.
- Being more biocompatible than are metal electrodes, carbon-nanotube-based electrodes and arrays would be more suitable for long-term or permanent implantation.
- Unlike macro- and microelectrodes, a nanoelectrode could penetrate a cell membrane with minimal disruption. Thus, for example, a nanoelectrode could be used to generate an action potential inside a neuron or in proximity of an active neuron zone. Such stimulation may be much more effective than is extra- or intracellular stimulation via a macro- or microelectrode.
- The large surface area of an array at a micron-scale footprint of non-insulated nanoelectrodes coated with a suitable electrochemically active material containing redox ingredients would make it possible to obtain a pseudocapacitance large enough to dissipate a relatively large amount of electric charge, so that a large stimulation current could be applied at a micron-scale region without exhausting the redox ingredients.
- Carbon nanotube array is more compatible with the three-dimensional network of tissues. Particularly, a better electrical-neural interface can be formed.
- A carbon nanotube array inlaid in insulating materials with only the ends exposed is an extremely sensitive electroanalysis tool that can measure the local neurotransmitter signal at extremely high sensitivity and temporal resolution.

A nanoelectrode array according to the invention (see figure) would include two or more microelectrode pads on an electrically insulating substrate. The sizes of the microelectrode pads and the distances between them could range from as little as about a micron to as large as hundreds of microns, the exact values depending on the intended use. Each microelectrode pad could be electrically addressed, either individually or in combination with one or more other pads for localized stimulation and/or recording. Each microelectrode pad would support either a stimulating or a recording electrode. In either case, the electrode would comprise a subarray of multiple nanoelectrodes in the form of carbon nanotubes electrically connected to, and protruding perpendicularly from, a metal contact layer on an electrically insulating substrate.

In the case of a stimulating electrode, the protruding portions of the carbon nanotubes would be treated to deposit a thin electro-active coating layer that would impart the desired amount of pseudocapacitance. Depending on the application, the exposed surface of the metal contact layer between the nanoelectrodes would be coated with an electrically insulating material (e.g., silica or a nonconductive polymer), or with an electrically conductive or electro-active polymer.

In the case of a recording electrode, it is desirable to minimize the size of the electrically exposed portion of each carbon nanotube so as to maximize the degree of localization and to minimize noise (thereby maximizing sensitivity). Therefore, an insulating layer would be deposited to sufficient thickness that only the tip(s) of the longest carbon nanotube(s) would protrude.

The term carbon nanotube here covers a general class of carbon materials, including multi-walled carbon nanotubes (MWCNTs) and nanofibers (CNFs). These nanostructured carbon materials have physical and chemical properties that make them especially suitable for use as nanoelectrodes according to this invention. Well-aligned arrays of MWCNTs/CNFs have been grown by plasma-enhanced chemical vapor deposition on metal lines that have been pre-patterned by use of lithographic techniques. A previously published "bottom-up" scheme for fabricating an array of MWCNTs/CNFs that protrude from metal lines embedded in an $SiO_2$ matrix has been adopted as the basis of a scheme for fabricating nanoelectrode arrays according to the invention. The fabrication processes involved in these schemes are compatible with those used in manufacturing semiconductor devices. Hence, it should be possible to fabricate the nanoelectrode arrays at relatively low cost.

*This work was done by Jun Li and M. Meyyappan of Ames Research Center and Russell Andrews, an Ames associate.*

*Inquiries concerning rights for the commercial use of this invention should be addressed to the Ames Innovative Partnerships Office at (650) 604-2954. Refer to ARC-15062-1.*

# Compact Directional Microwave Antenna for Localized Heating

## Heating is concentrated on one side.

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A directional, catheter-sized cylindrical antenna has been developed for localized delivery of microwave radiation for heating (and thus killing) diseased tissue without excessively heating nearby healthy tissue. By "localized" is meant that the antenna radiates much more in a selected azimuthal direction than in the opposite radial direction, so that it heats tissue much more on one side than it does on the opposite side. This antenna can be inserted using either a catheter or a syringe. A 2.4-mm prototype was tested, although smaller antennas are possible.

Prior compact, cylindrical antennas designed for therapeutic localized hyperthermia do not exhibit such directionality; that is, they radiate in approximately axisymmetric patterns. Prior directional antennas designed for the same purpose have been, variously, (1) too large to fit within catheters or (2) too large, after deployment from catheters, to fit within the confines of most human organs. In contrast, the present antenna offers a high degree of directionality and is compact enough to be useable as a catheter in some applications.

The antenna design is a hybrid of monopole-antenna and transmission-line design elements. The antenna (see Figure 1) is formed from an open-ended coplanar waveguide in which the gap between the middle conductor strip and the two outer (ground) conductor strips tapers from (1) a smaller value more characteristic of a transmission line to (2) a larger value more characteristic of a leaky transmission line or an antenna. The coplanar waveguide is wrapped around a polytetrafluoroethylene (PTFE) tube, and its abutting edges are soldered together to form the

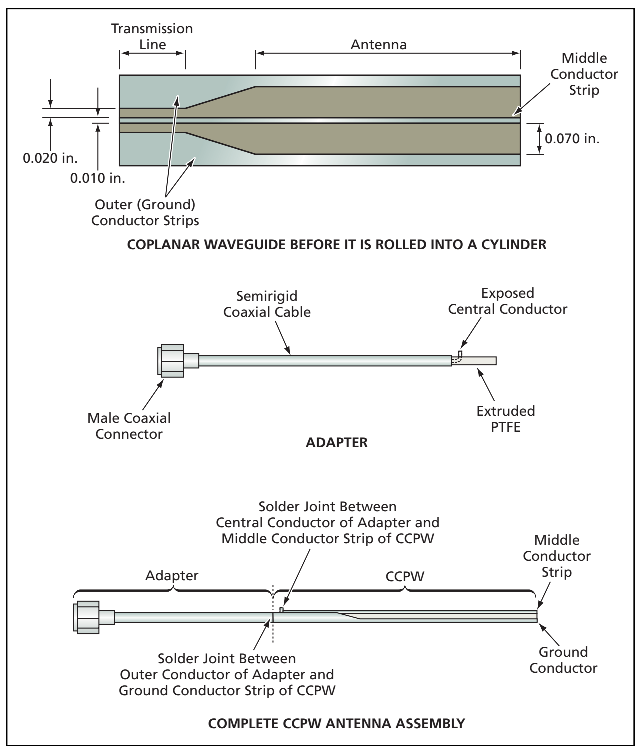


Figure 1. A **Coplanar Waveguide With a Taper** is rolled into a cylinder and joined with a coaxial-cable adapter to form a narrow antenna that radiates predominantly to one side.