

low-molecular-weight imide-based liquid crystals, but these compounds contain aliphatic units, which lack the oxidative stability necessary for semiconductor applications.

The generic molecular structure of the wholly aromatic ether-imide compounds of this investigation is a classic “tail-core-tail” structure, which is denoted by the term “calamitic” in the liquid-crystal art. In the generic molecule, the core contains one of four dianhydrides with a *p*-phenylamine at each end. The dianhydrides are pyromellitic dianhydride (PMDA); 1,4,5,8-naphthalenetetracarboxylic dianhydride (NDA); 3,3',4,4'-biphenyltetracarboxylic dianhydride (BPDA), and 3,3',4,4'-oxydiphthalic dianhydride (ODPA). The tails are members of a homologous series of meta-substituted aryl-ethers. Each tail is the para substituent on the *p*-phenylamine (see figure).

This generic molecular structure was chosen for the following reasons: The *p*-

phenylamine functionality increases the length of the core beyond that of the rigid di-imide portion, while the bulky meta-substituted aryl-ether tails have some flexibility. Increasing the numbers of meta-substituted aryl units in the tails reduces melt transition temperatures and increases solubilities. Also, the tails stabilize the molecular orientations necessary for mesophase formation. Aryl-ether flexible tails had not been used previously as flexible tail segments in liquid crystals, and in comparison with alkyl or alkyloxy flexible tails, aryl-ether tails have more breath, which keeps the overall diameters of mesogens more nearly uniform.

In the investigation, monofunctional amines (destined to become tails) were synthesized by various techniques, then combined with the dianhydrides (destined to become the cores) in one-step solution imidization procedures to obtain the desired ether imides. These compounds were examined for tempera-

ture-dependent phase behavior by means of optical microscopy and x-ray diffraction, and cyclic voltammetry was used to characterize redox behavior. Absorption spectroscopic measurements were also performed on dilute solutions of the compounds. Of these compounds, those containing NDA and BPDA in the cores were found to have electron-transport properties suitable for n-type semiconductors. Of all the compounds tested, only one containing NDA in the core clearly exhibited a tendency toward formation of liquid crystals. This is the first example, known at the time of the tests, in which a mesophase was detected in a wholly aromatic ether-imide compound.

This work was done by Erik Weiser and Terry L. St. Clair of Langley Research Center; Theo J. Dingemans (ICASE); Edward T. Samulski and Gene Irene of the University of North Carolina at Chapel Hill. Further information is contained in a TSP (see page 1). LAR-17041-1

Carbon-Nanotube-Carpet Heat-Transfer Pads

The compliance and high longitudinal thermal conductivity of carbon nanotubes are exploited.

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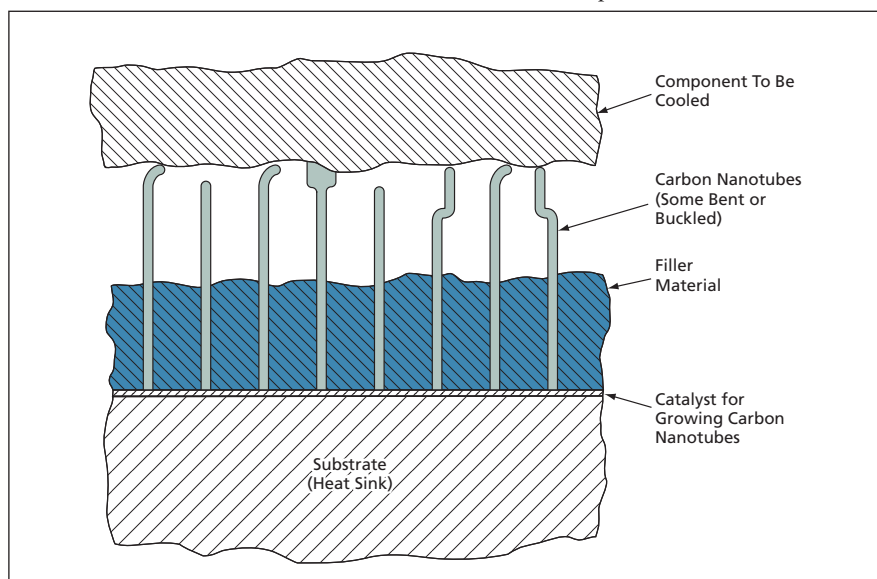
Microscopic thermal-contact pads that include carpetlike arrays of carbon nanotubes have been invented for dissipating heat generated in integrated circuits and similarly sized single electronic components. The need for these or other innovative thermal-contact pads arises because the requisite high thermal conductances cannot be realized by scaling conventional macroscopic thermal-contact pads down to microscopic sizes. Overcoming limitations of conventional thermal-contact materials and components, the carbon-nanotube thermal-contact pads offer the high thermal conductivities needed to accommodate the high local thermal power densities of modern electronic circuits, without need for large clamping pressures, extreme smoothness of surfaces in contact, or gap-filling materials (e.g., thermally conductive greases) to ensure adequate thermal contact. Moreover, unlike some conventional thermal-contact components, these pads are reusable.

The figure depicts a typical pad according to the invention, in contact with a rough surface on an electronic component that is to be cooled. Through reversible bending and buckling of carbon nanotubes at asperities on the rough sur-

face, the pad yields sufficiently, under relatively low contact pressure, that thermal contact is distributed to many locations on the surface to be cooled, including valleys where contact would not ordinarily occur in conventional clamping of rigid surfaces. Hence, the effective thermal-contact

area is greater than that achievable through scaling down of a macroscopic thermal-contact pad.

The extremely high longitudinal thermal conductivities of the carbon nanotubes are utilized to conduct heat away from potential hot spots on the surface to be



Carbon Nanotubes Bend and Buckle to accommodate roughness of the surface of the component to be cooled. The high longitudinal thermal conductivity of carbon nanotubes is exploited to conduct heat into the heat sink.

cooled. The fibers protrude from a layer of a filler material (Cu, Ag, Au, or metal-particle-filled gels), which provides both mechanical support to maintain the carbon nanotubes in alignment and thermal conductivity to enhance the diffusion of concentrated heat from the nanotubes into the larger adjacent volume of a heat sink.

The array of carbon nanotubes, the filler material, and the heat sink are parts of a unitary composite structure that is fabricated as follows:

1. Using techniques that have been reported previously, the array of substan-

tially perpendicularly oriented carbon nanotubes is grown on a metal, silicon, or other suitable thermally conductive substrate that is intended to become the heat sink.

2. By means of chemical vapor deposition, physical vapor deposition, plasma deposition, ion sputtering, electrochemical deposition, or casting from a liquid phase, some or all of the interstitial volume between carbon nanotubes is filled with the aforementioned layer of mechanically supporting, thermally conductive material.

3. To cause the carbon nanotubes to protrude the desired length from the filler material, an outer layer of filler is removed by mechanical polishing, chemical mechanical polishing, wet chemical etching, electrochemical etching, or dry plasma etching.

This work was done by Jun Li of Ames Research Center and Brett A. Cruden and Alan M. Cassel of UARC.

Inquiries concerning rights for the commercial use of this invention should be addressed to the Technology Partnerships Division, Ames Research Center; (650) 604-2954. Refer to ARC-15173-1.