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DISCOVERY OF CARBON NANOTHERMOMETER

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Carbon nanotubes (CNTs) are novel materials [1] and can have numerous potential applications in various fields. Here we report a thermal application supported by sufficient evidences and a quantitative analysis: a CNT filled with a continuous one-dimensional (1D) liquid gallium (Ga) column having a length up to ~10 μm and a diameter of ~75 nm can serve as a nanothermometer for a micro-environment.[2] This application is premised on a study of the basic thermal expansion of the filling 1D nanoscale liquid Ga, which equals that of Ga in macroscopic state. Why the surface effect, which generally affects certain properties of materials when materials become of nanoscale, e.g. emission of photoluminance and melting point, does not have a function in the thermal expansion property of 1D nanoscale liquid Ga with 75 nm diameter, required an explanation. Our research quantitatively gave such an explanation and analysis in terms of thermo-dynamic concepts.[3] The result showed that the effect obviously plays a role in expansion by influencing Ga column inner pressure when the diameter decreases to below 5 nm, and suggested that the coefficient can be directly used for the calibration of a given nanothermometer with a diameter larger than 10 nm.

We have also synthesized Indium-filled carbon nanotubes *via* a simple chemical vapor deposition [4, 5] as CNTs containing Ga. The carbon nanotubes had diameters of 100-200 nm and length of ~10 μm. The melting and expansion behavior of the indium in carbon nanotubes were investigated in an analytical transmission electron microscope. It was found that the indium's melting and expansion behavior were different from that in a macroscopic state. The melting behavior was explained using a particular equation developed for a nanoscale indium column. The analysis of the expansion behavior allows us to clarify the problems of indium filling usage in carbon-nanotube-based nanothermometer.

The gallium- or indium-filled CNTs were synthesized in a vertical radio-frequency furnace as described in Ref. 18. The furnace consists of a clear fused–quartz tube of 50 cm in length, 12 cm in diameter and 0.25 cm in thickness. The fused–quartz tube contains an inductively heated cylinder of high purity graphite, which is 7 cm in length, 4.5 cm in outer diameter and 3.5 cm in inner diameter. An uncovered graphite C crucible, which is ~2 cm in diameter and ~2 cm in height, was put in the cylinder. In the C crucible, the reactant was a homogenous mixture of (Ga_2O_3) In_2O_3 and pure

amorphous active carbon (AAC) in the weight ratio of 7.8:1 (11.6:1). The C cylinder had a C fiber coat and an outlet C pipe on its top. Pure flowing N_2 gas was introduced into the furnace. The reactant was heated at 1,360°C for 1-2 hours. After the experiment, the reactant in the C crucible disappeared, while some materials were deposited on the inner surface of the outlet pipe. The materials were collected and analyzed by high resolution transmission electron microscope (HRTEM, JEM-3000F) equipped with an x-ray energy dispersive spectrometer (EDS). A TEM specimen of the deposited materials was heated in the microscope using a Gatan heating system (Hot Stage Power Supply, Model 628-0500).

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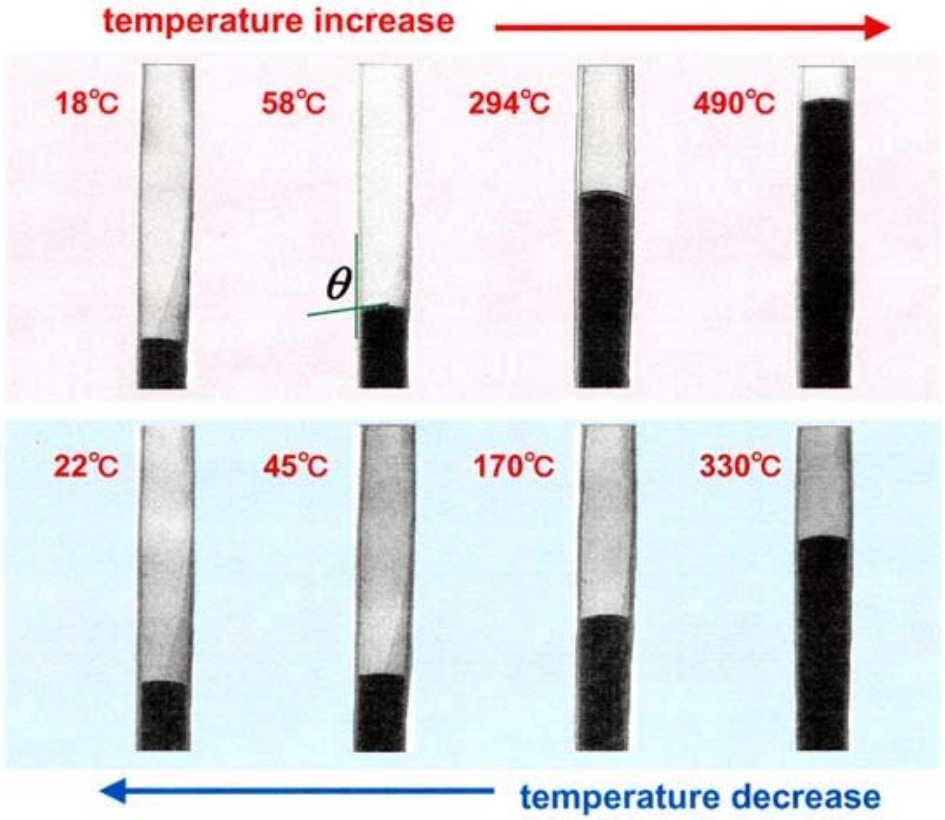

Figure 1 Morphologies of a Ga tip when the temperature rises from 18°C (a), via 58°C(b) and 294°C (c), to 490°C (d), and the morphologies when the temperature drops, *via* 330°C (e), 170°C (f) and 45°C (g) to 22 °C (h). The arrow bar is 75 nm.

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