High Temperature Gradient in a Conductor: Carbon Nanotube Forest under the "Heat Trap" Condition

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Thermoelectric devices represent a promising direction for clean electricity generation from waste heat. The critical challenge to such energy systems lies within the material: to achieve a high ZT, the thermoelectric figure of merit, the material must possess a low thermal conductivity and high electrical conductivity. However, this does not happen in regular conductors. Phonon-glass electron-crystal materials such as clathrates and skutterudites are viewed as prime candidates for thermoelectric generators[1] as these complex crystal structures are able to maintain a high temperature gradient across the thermoelectric module without greatly impeding electron flow. In this work, we reveal a different approach by demonstrating a high temperature gradient in a nanomaterial widely known for its exceptional conductivity.

Carbon nanotubes (CNTs) are well known to be good conductors for both electrons and phonons. However, despite past studies on the thermal properties of CNTs[2,3] , the experimental investigation of their thermal behavior at high temperatures has been lacking. Our group has recently reported that a localized high-temperature region can be achieved on the sidewall of a CNT forest as a result of illumination by a low-power laser beam[4]. Here, we report on the CNTs' response in this "Heat Trap" regime and the temperature profiles achieved. Under a laser intensity of ~ 19.1 W/mm^2, the local temperature easily reaches more than 1500K at the center of the laser beam, with a longitudinal temperature gradient exceeding 1200K/mm, orders of magnitude higher than typically achievable in metals. Figure 1 portrays the incandescent glow of the hot spot on a CNT forest with macroscopic dimensions, as well as the temperature profile obtained using a high-spatial-resolution thermographic camera. Under similar conditions, we did not measure any significant temperature rise/gradient on a bulk tungsten surface, reinforcing the idea that the observed behavior is special. We believe that this Heat Trap effect has its roots in the highly anisotropic nature of the nanotube forest (which consists of long, vertically-aligned nanotubes) and their strongly negative temperature dependence of thermal conductivity.

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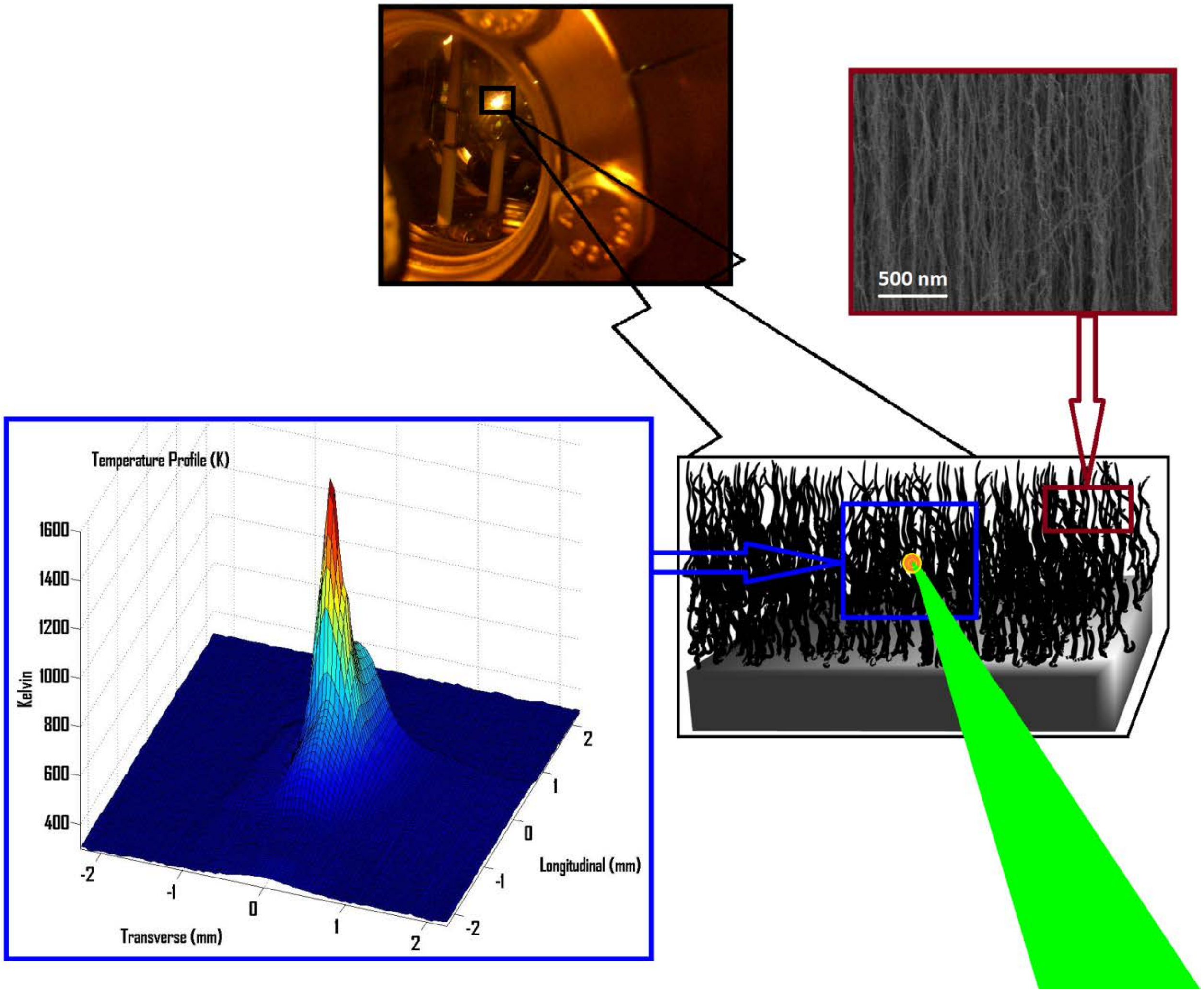

Figure 1: CNT forests grown using catalytic chemical vapor deposition were placed in vacuum (~10^{-6} torr) and illuminated with 532-nm and 514-nm continuous-wave laser sources. The temperature profile was characterized by a thermographic camera through a broadband antireflection-coated viewport, allowing a spectral transparency of greater than 99.5% over the sensitivity range of the camera at the incident angle. Upper left: photo of the experimental apparatus through an optical filter blocking the respective laser line. Upper right: scanning electron micrograph of a CNT forest. The Heat Trap region can be clearly observed because of its bright incandescent glow. Lower left: two-dimensional thermal map obtained with 150 mW of laser power (estimated spot radius ~ 50 µm) illuminating the sidewall of the forest. The orientation of the CNTs is along the axis labeled “Longitudinal”.