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Towards a Tuneable Thermal Conductivity Material via Low Voltage Ordering of CNT Networks

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Abstract — Traditionally we seal our devices and insulate our houses with static materials that possess no ability to change their insulation value. This inevitably leads to increased energy consumption due to thermal management needs: a device may be required to be cooler or warmer, and an insulating material, of static thermal conductivity, doesn't help in this regard. Here we examine the real-time tuneable thermal conductivity properties of a low-voltage device, consisting of a Carbon Nanotube Network embedded in a gel matrix and sandwiched between custom made electrodes. The operating principle is that the thermal conductivities of disordered networks tend to be insulating, while highly aligned networks become metallic. The thermal conductivity, durability, power consumption and extensibility properties of the device are examined.

I. INTRODUCTION

This work aims to demonstrate the feasibility of a tunable thermal conductivity material. Materials with such a property are highly sought after and intensively researched, particularly in areas where thermal management actively improves efficiency, such as in the automotive sector. Methods which tune thermal conductivities employ various approaches, and may include: variations on the material density [1], atomic intercalations [2], mechanically induced lattice mismatching [3], phononic metamaterials [4] and multilayered graphene [5]. Voltage controlled changes in thermal conductivity at room temperature in a solid-state material has been demonstrated in Lead Zirconate Titanate [6], which was correlated to domain wall density. Recently, magnetic control over thermal conductivity was demonstrated in a carbon fibre loaded ferrofluid, requiring only a moderate magnetic field of approximately 0.01 T to modulate [7]. Electrical control over thermoelectric couples acting as "insulators" has also been demonstrated [8].

It has been previously demonstrated that alignment and disorder in a carbon nanotube network can dramatically modify the thermal conductivity [9], however some counter examples do exist [10]. Here we investigate if this fact can be utilised profitably in a meaningful device. It is often thought that large ac [11] or dc [12] electric fields are required to align CNTs, however with careful balancing of the CNT in suspension and control over the inter-electrode distance, such challenges can be met [13]. We now describe briefly the properties of our chosen CNTs in solution, the thermal characteristics of CNTS, and describe the proposed device and operating principle.

II. CARBON NANOTUBES AND THERMAL CONDUCTIVITY

Nanotubes are known to be excellent thermal conductors along the axial direction, exhibiting a property known as "ballistic conduction" while behaving as insulators radially. Individual SWNTs may have a room-temperature thermal conductivity axially of as much as 3500 $Wm^{-1}K^{-1}$ [14], but this depends on chirality and, interestingly, on sufficient tube length [15,16].

This impressive feat of thermal transport is matched equally by how unimpressive the radial transport is, of approximately 1.52 $Wm^{-1}K^{-1}$, which has been compared to that of ground soil [17]. It is these dual attributes that make CNTs such an attractive option for this application.

III. CARBON NANOTUBE SUSPENSION MATRIX AND ALIGNMENT ELECTRODES

We have previously prepared high density, vertically aligned single walled CNTs arrays on various substrates [13]. Here we prepare a highly uniform (regarding size/chirality) vertically aligned array on silver coated Schott Nexterion glass slides and arrange the electrodes to mirror each other with an inter-electrode distance of approximately 2 μm. The SWNTs are initially de-bundled in an aqueous solution with a low concentration of a surfactant (0.01 % sodium dodecyl sulphate). Angular and polarization-dependent spectroscopy has previously confirmed that the quality of alignment of these nanotube arrays is excellent. The angle of the main axis of the SWNT array can even be arranged to deviate from the surface normal of the substrate.

A key point of the investigation here will depend on the nature of the suspension gel. Ideally, devices would only consume power upon switching, analogous to twisted nematic liquid crystal displays. The suspension-gel density will have to closely mimic the density of the CNTS – otherwise, in the passive state they will tend to bundle and aggregate and ruin the ability to highly realign.

As CNT alignment occurs in applied electric fields, interaction between the nanotubes leads to translation. This is where CNTs form up in a head-to-tail manner to create dynamic percolation paths that bridge the electrodes. This creates conductive CNT filaments bridging an otherwise insulating matrix and has been observed at concentrations as low as 0.002 wt% [18]. The gel-CNT interaction therefore, will be depend sensitively on its density and viscosity and is required to be rigorously investigated to achieve a state which can be switched from ordered to disordered at will.

IV. EXPERIEMENTAL METHODOLOGY

Fig 1. depicts a cross-section of the experimental device, showing the counter electrodes, which have attached to them highly aligned SWNT arrays, while in between is situated the CNT network in its suspension matrix. Displayed is the fully metallic (aligned) state and the insulating, disordered state (bottom).

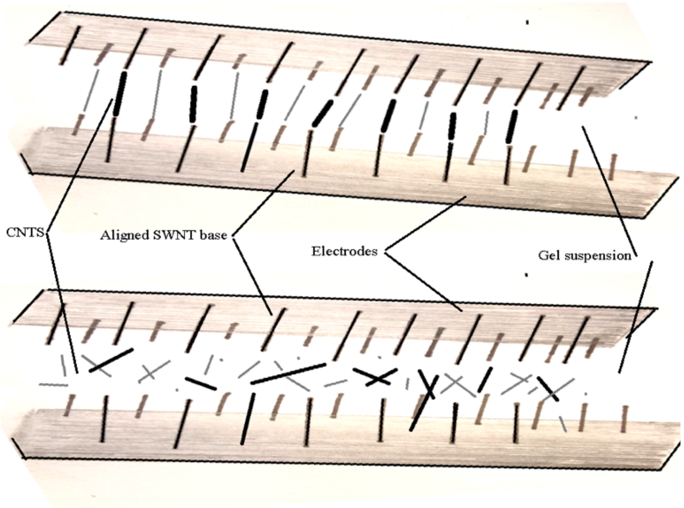

Fig. 1. Cartoon of the experimental apparatus, showing the ordered (top) and disordered states (bottom).

Measurements of the thermal conductivity are carried out by a modified commercial Flat-Plate Thermal Conductivity tester (Vitex) and dynamics investigated with a custom made Time-Domain Thermo-Reflectance (TDTR) pump-probe setup, using an 88-MHz mode-locked Ti:sapphire laser (Kapteyn-Murnane), optical delay stage (Newport) and lockin amplifier (Zurich Instruments).

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