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# Alignment of Liquid Crystal / Carbon Nanotube Dispersions for Application in Unconventional Computing

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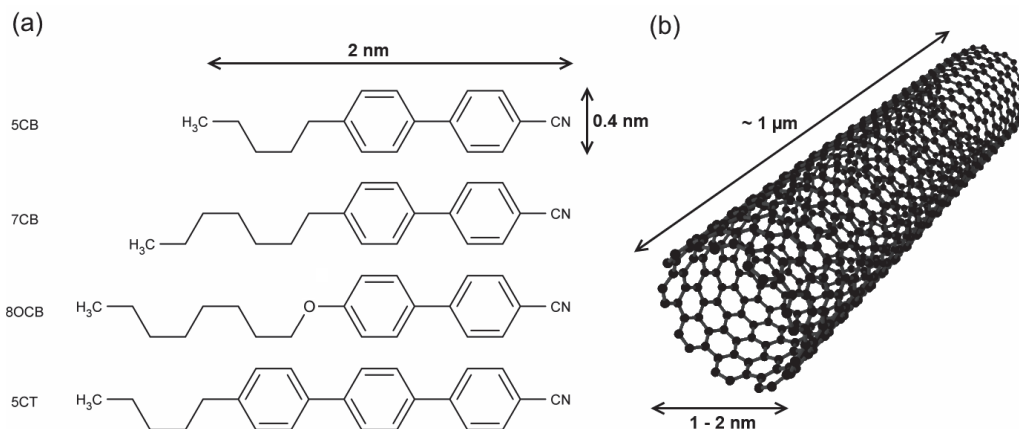
**Abstract.** We demonstrate the manipulation of single-walled carbon nanotube/liquid crystal composites using in-plane electric fields. The conductivity of the materials is shown to be dependant on the application of a DC bias across the electrodes. When the materials are subjected to this in-plane field, it is suggested that the liquid crystals orientate, thereby forcing the SWCNTs to follow in alignment. This process occurs over many seconds, since the SWCNTs are significantly larger in size than the liquid crystals. The opportunity for applying this material to unconventional computing problems is suggested.

**Keywords:** Liquid crystal alignment, carbon nanotubes, unconventional computing

**PACS:** 88.30.rh, 61.30.Gd

## INTRODUCTION

The alignment of single-walled carbon nanotubes (SWCNTs) is an important topic in both science and engineering; the general aim is to improve the electrical or mechanical properties of the material [1]. One reported method to achieve a preferred orientation is by the use of liquid crystals (LCs) [2]. Here, this approach is exploited in order to produce a novel material to perform unconventional computing. Our previous studies, using composites of SWCNT and polymers [3] showed that simple logic gates could be optimized from a disordered material system. This material had a fixed morphology, so the only way to train the network was to exploit non-linearities in the conductivity at different electric field strengths. However, if a liquid material (in this case a SWCNT/LC mixture) is used, it should also be possible to change the morphology of the network and to create or break conducting pathways between different nodes. The majority of reports on the alignment of SWCNTs exploit out-of-plane alignment using conventional liquid crystal cell structures [4, 5, 6, 7]. This work, will instead, explore the in-plane alignment between electrodes in a thin network of SWCNTs and LCs under the influence of DC electric fields.



**FIGURE 1.** (a) Blend of liquid crystal molecules present with in the commercially available E7 and (b) a single walled carbon nanotubes. The approximate dimensions are given to compare the scale of each material.

## EXPERIMENTAL

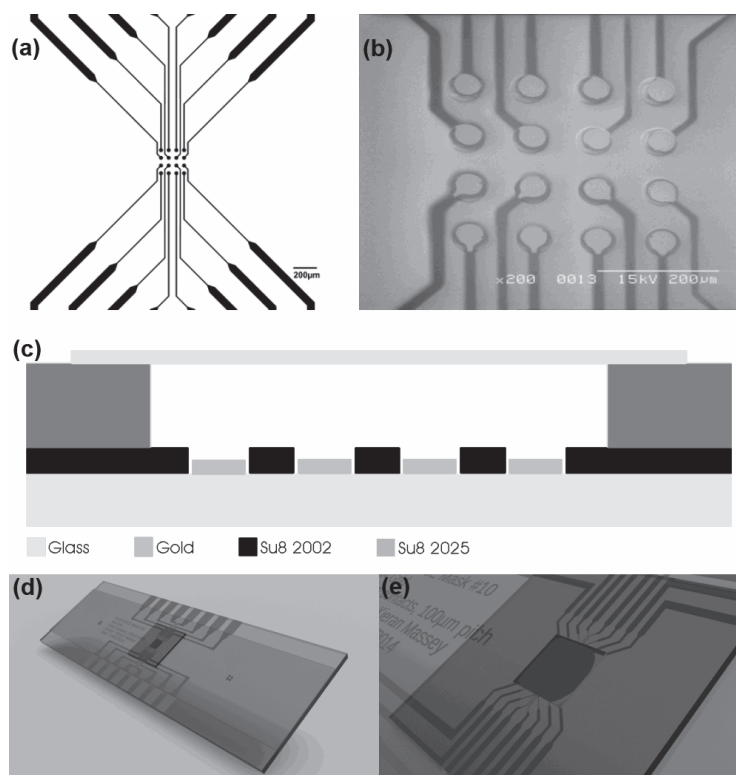
### Material System

The composites used in this work consist of two materials; SWCNTs (electrically conductive) and LCs (insulating). The SWCNTs were HiPCO produced, purchased from Carbon Nanotechnologies Inc. (Houston, TX, USA). The material was used as supplied without any further purification or sorting processes, so contained a mixture of semiconducting and metallic species. The length of the SWCNTs was specified as  $\sim 1 \mu\text{m}$ , significantly shorter than the electrode separation used for all experiments. The liquid crystal, E7, a commercially available blend (Merck, Japan) was used as supplied.

The SWCNTs were mixed with E7 following a simple technique [8] involving 24 h of stirring followed by 5 min of probe sonication at 20 % power (Cole-Palmer, 750 W ultrasonic homogenizer). This created a visually uniform mixture which was stable for many days without showing signs of the SWCNTs precipitating from suspension. Despite this, whenever measurements were carried out, the mixtures were stirred for 12 h to ensure good dispersion and consistent readings.

### Electrodes

To make electrical contact to the materials, gold electrodes were used. These electrodes were arranged in-plane in a  $4 \times 4$  grid pattern, shown in Figure 2(a). The contact pad diameter was  $50 \mu\text{m}$  and the pitch was  $100 \mu\text{m}$ . The contacts were fabricated on glass using conventional etchback photo-lithographic techniques. Next, a layer of SU8 2002 (MicroChem) was spun to a thickness of  $2 \mu\text{m}$  to act as an insulation layer between the electrode tracks and



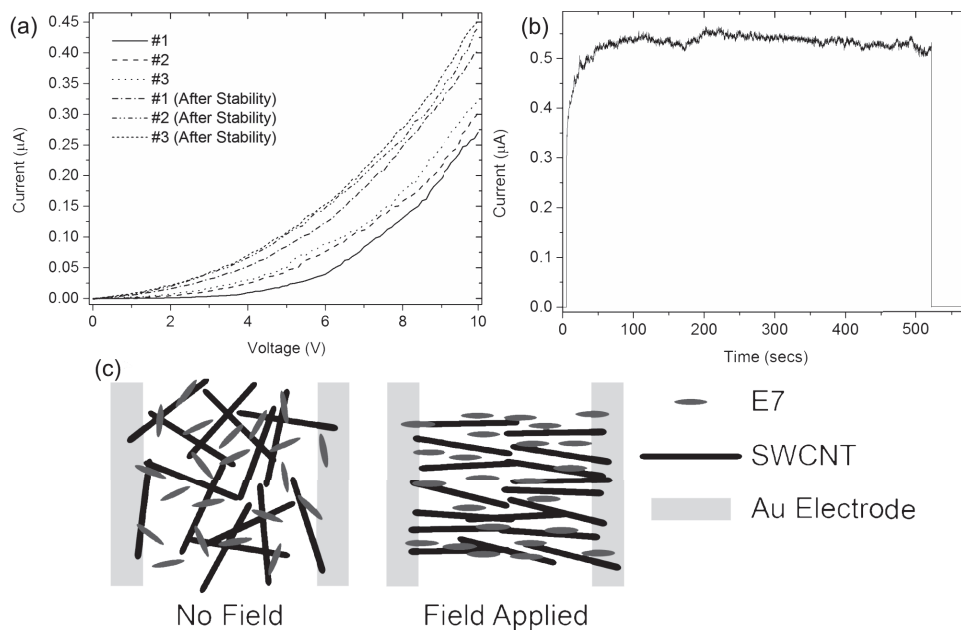
**FIGURE 2.** Fabrication of electrodes. (a) layout of  $4 \times 4$  grid, contact diameter  $50 \mu\text{m}$  and pitch of  $100 \mu\text{m}$ . (b) SEM image showing electrodes with thin (SU8 2002) insulating layer to isolate contact pads. (c) Cross section of structure including LC cell area. (d) and (e) show 3D renders of the complete structure.

the material under test. This layer was patterned via lithography with holes over each electrode pad; an SEM image of the isolated gold electrodes is shown in Figure 2(b). A second layer of SU8 2025 (MicroChem) was spun over the substrate to a thickness of 25  $\mu\text{m}$  and this had a 5 mm square region patterned over the electrode area to act as a container for the liquid crystal. A cross section of the structure is shown in Figure 2(c), including a glass coverslip placed on top of the structure to contain the LC/SWCNT material. A 3D render of the complete architecture, including material contained in the cell is given in Figure 2(d,e) to help visualise the device. Connections were made to the gold electrodes using gold probes in a custom designed probe station. Measurements were made using a Keithley 2635A sourcemeter running on custom Matlab software.

## RESULTS AND DISCUSSION

To characterize the materials, simple current versus voltage sweeps were performed. The devices contained a large number of electrodes (16 in total), but for this work one adjacent pair was used. These devices have been designed with computation in mind (discussed in the further work section) hence the great number of contacts.

Figure 3(a) shows a current versus voltage sweep before and after a long-term stability measurement. The time for each sweep was approximately 30 s, a relatively short period of time when compared with the current versus time stability measurement. On the virgin sample (before the stability measurement) the three consecutive cycles show an increase in current with each sweep. The sample was then subjected to a fixed voltage (10 V) and the current was measured over a period of 500 s; this is shown in Figure 3(b). The current is approximately 0.25  $\mu\text{A}$  when the bias is applied after 5 s, this then rises to around 0.55  $\mu\text{A}$  and saturates at 75 s. When the bias is removed and the I-V sweeps are performed again (labelled “after stability”) the current on the first sweep is higher than that before the stability measurement, showing that the conductivity of the material has been changed permanently with the application of the fixed voltage. Again, with successive sweeps a small increase in maximum conductivity is observed; however it should be noted that the maximum current recorded is about 0.45  $\mu\text{A}$ , lower than the saturation current during the stability measurement. This indicates that, despite the change in conductivity observed after the application of a voltage, there is some relaxation of the material. We suggest that the liquid crystals present within the composite are helping to align the SWCNTs, resulting in the increased conductivity. Figure 3(c) shows the suggested alignment process. Before the field



**FIGURE 3.** (a) Current versus voltage for encapsulated LC/SWCNT composites before and after, (b) a current versus time stability measurement. (c) Schematic of suggested alignment within the material.

is applied the liquid crystal molecules and SWCNTs have no preferential alignment direction. In this state there will be few, if any, conducting pathways between the two electrodes. When an electric field of suitable strength is applied ( $1 \times 10^5 \text{ V m}^{-1}$ ) the liquid crystals will quickly align in the direction of the electric field between the electrodes. This, in turn, will exert a force on the SWCNTs, causing them to align in the direction of the liquid crystal. Due to the size difference between the LC molecules and SWCNTs (with the LC molecules being much shorter, Figure 1) the alignment of the SWCNTs is likely to be much slower. This is shown in the stability measurements, where it takes several seconds for the maximum current to be reached.

## CONCLUSIONS

This work shows that the conductivity of SWCNT/LC composites can be influenced with the aid of a suitably strong electric field applied in plane to the materials. Before applying an electric field the conductivity is very low. When an electric field is applied the conductivity of the composite increases as SWCNTs are forced into alignment. The response time of the composite material is much longer than that of liquid crystals on their own due to the size difference between the LC molecules and SWCNTs.

## FURTHER WORK

These materials have shown conductivity that is dependant on the magnitude and duration duration of the applied voltage. They also exhibit some relaxation after the voltage is removed, suggesting that the properties can be influenced and changed repeated times with success application of different voltages and pulse lengths. These SWCNT/LC composites offer more opportunities for training under computer evolution than the fixed polymer/SWCNT films previously studied [3]. With this knowledge, the aim of the NASCENCE project is to exploit this material for use in unconventional computing.

## ACKNOWLEDGMENTS

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