LIQUID CRYSTALS

Electric fields line up graphene oxide

The macroscopic alignment of dilute dispersions of graphene oxide can be controlled, with extremely large optical sensitivity, through the application of weak electric fields.

Ju Young Kim and Sang Ouk Kim

Alignment in liquid crystals originates from the entropic interactions among the anisotropic constituents[1]. Such orientational ordering is generally switchable by external stimuli, such as induced flow, or magnetic or electric fields (electric fields are widely employed for the optical switching of liquid-crystal displays (LCDs)). This is the case for solvent dispersions of carbon nanotubes or graphene[2,3]. For graphene oxide (GO)[4] — a chemically modified graphene produced by oxidative exfoliation of graphite[5] — however, electric fields have been ineffective at ordering GO flakes; indeed, instead of causing liquid-crystal alignment, conventional direct-current fields raise GO's electrophoretic drift and reduction at the electrodes. Reporting in *Nature Materials*, Jang-Kun Song and colleagues now show that efficient electric-field switching of GO liquid crystals is indeed possible in low-concentration dispersions (0.05 vol%), and demonstrate a prototype of a GO LCD[6].

Song and collaborators observed that flow or high-frequency (1 kHz to 1 MHz) alternating-current electric fields induced liquid crystallinity in GO dispersions at concentrations low enough for the dispersion to be isotropic when the field is off. Aqueous dispersions of GO are known to form liquid-crystalline phases, and thus birefringent (Schlieren) textures, at concentrations below 1.0 vol% (ref. 4) because of its high aspect ratio (approaching 10,000 for exfoliated GO monolayers), and because the basal planes and edges in GO flakes are functionalized with hydrophilic oxygen-containing functional groups, which facilitate the spontaneous dispersion of the flakes in water or other polar solvents (Fig. 1a).

Conventional LCDs take advantage of the orientational transition from surface-induced to electric-field-induced alignment (Fig. 1b, left). However, the electric-field switching of GO liquid crystals demonstrated by Song and co-authors occurs through a direct transition from an isotropic to a highly aligned liquid-crystalline phase (Fig. 1b, right). Notably, the dependence of the optical birefringence on the electric field, which is represented by the Kerr coefficient, was measured to be 1.8×10^{-5} mV^{-2}, possibly the highest value ever reported for a molecular liquid crystal. Such a high Kerr coefficient stems from the synergistic effect of the large polarizability anisotropy of GO and Onsager's excluded-volume effect for liquid-crystal ordering (liquid-crystal alignment increases translational entropy at the expense of rotational entropy). Indeed, because of GO's high shape anisotropy and the electrical double layer formed at its surfaces (aqueous dispersions of GO are negatively charged as a result of the presence of oxygen functional groups on the surfaces of the flakes), GO's polarizability along the direction of the flake's plane is greatly enhanced when the external electric field is switched on. The collective alignment of GO flakes occurring at low concentrations also contributes to the large Kerr coefficient.

Another notable point of Song and co-authors' GO LCDs is their low power consumption for optical switching. GO LCDs with large Kerr coefficients could be operated with only 5 V mm^{-1} of electric potential, three orders of magnitude lower than the typical values for conventional LCDs. Still, several issues remain to be solved before GO LCDs can be used in commercial devices. Most importantly, response times are slow. As mentioned by the authors, relaxation times were longer when the voltage was switched off. Considering that conventional LCDs operate at 60–80 Hz, there is a lot of room for improvement. Another issue is GO's long-term stability, as GO flakes may undergo thermal reduction or other chemical modification, particularly at high temperatures or in corrosive operating conditions.

Moreover, the Kerr coefficient could be further increased. As GO's shape anisotropy and surface charge are directly related to the Kerr coefficient, the coefficient could be enhanced by producing larger flakes and by altering their chemical functionalization. GO flakes with larger Kerr coefficients would lead to faster relaxation times, of relevance to applications in optical communication, nonlinear optics and laser technology, for example.

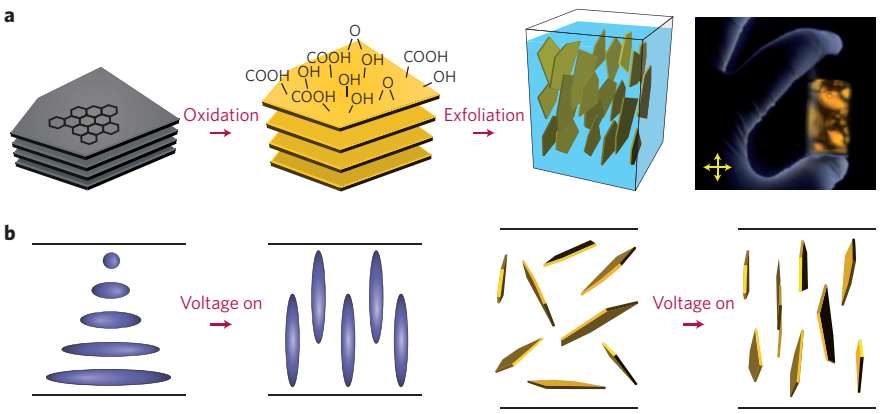

Figure 1 | Graphene oxide liquid-crystal formation and electric-field switching. **a**, Left: Graphite oxide powder, which can be produced by chemical oxidation of graphite, spontaneously exfoliates into monolayer GO sheets in water because of the hydrophilic oxygen-containing groups at its basal planes and edges. Right: At low concentrations, GO flakes between crossed polarizers (whose direction is indicated by the arrows) show birefringent textures, indicating liquid-crystalline ordering[4]. **b**, Left: In a conventional LCD, the surface-induced orientation of a small-molecule liquid crystal under confinement is switched by an electric field. Right: The electric-field induced orientation of GO liquid crystals occurs at a very low GO concentration (0.05 vol%), where the dispersion is isotropic and the interflake interactions are sufficiently small[6].

GO liquid crystals also have prospects for the fabrication of functional materials with tailored morphologies. It is well known that flow-assisted alignment of linear polymeric liquid crystals is used in the production of highly oriented superstrong aramid fibres[7]. Macroscopic alignment of two-dimensional GO flakes may generate quasiparallel carbon networks with extremely large specific surface areas. These structures can be exploited in, for example, electrodes for energy-storage devices, separation membranes, molecular absorbers and composites[8,9]. Moreover, the morphological manipulation of GO can be exploited in conjunction with other low-dimensional materials, such as quantum dots, nanowires and two-dimensional metal chalcogenides. A judicious combination of semi-metallic graphene with these low-dimensional semiconducting nanomaterials may provide nanoscale heterojunction structures for energy harvesting or catalysis. ❐

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SUPERCONDUCTIVITY

Squeezing out the current

In spite of their promise, practical applications of high-temperature cuprate superconductors have been hard to come by. The development of a method to fabricate round wires of the cuprate system Bi-2212 may begin to change this.

Joseph V. Minervini

Although high-temperature superconductivity (HTS) was discovered almost three decades ago[1], the widespread applications originally foreseen for it have, in broad terms at least, yet to be achieved. At present, conventional low-temperature superconductors such as the ductile alloy NbTi (ref. 2) and its brittle cousin Nb_3Sn dominate the commercial market for applications such as magnetic resonance imaging systems, as well as for scientific applications in high-energy and nuclear physics, most commonly for accelerator dipoles, quadrupoles and detector magnets, with the Large Hadron Collider at the European Organization for Nuclear Research being a notable example[3].

Cuprate superconductors such as $(Bi,Pb)_2Sr_2Ca_2Cu_3O_{10-x}$ (Bi-2223) and $REBa_2Cu_3O_{7-x}$ (REBCO) have only just started to be used for power grid technologies such as power transmission lines, fault current limiters, and motors and generators, but mostly as demonstration projects[4,5] emphasizing their potential for operation in the 20–65 K temperature range. Writing in *Nature Materials*, David Larbalestier and colleagues report a significant step for improving the performance and practicality of the cuprate system $Bi_2Sr_2CaCu_2O_{8-x}$ (Bi-2212), by fabricating isotropic round wires of it[6].

The widespread deployment of HTS-based conductors and magnet systems has so far been hampered by their high cost and laborious fabrication process, as well as difficulties in achieving uniformly high critical currents over large length scales. This is partly because Bi-2223 and REBCO can be fabricated only as thin, flat tapes in which grain boundary alignment plays a dominant role in determining their ability to carry large currents. This structure not only limits efficiency in material use, it also increases magnet fabrication complexity, especially if large currents are required from numerous tapes in a single conductor or cable. Figure 1 illustrates the typical cross-sectional shapes and internal superconducting filament layout in practical engineering use at present.

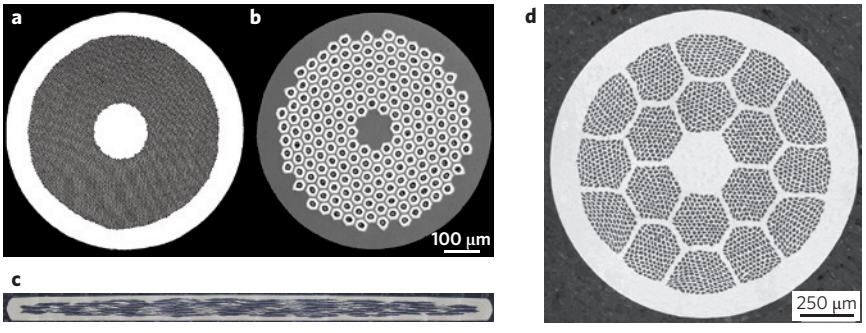

Figure 1 | Examples of different forms of superconducting wire. **a**, Round wire made of NbTi filaments embedded in a copper stabilizer. **b**, Round wire consisting of Nb_3Sn conductor. **c**, Cross-section of Bi-2223 power cable tape. The tape is roughly 0.2 × 4 mm wide. **d**, Round wire Bi-2212 multifilamentary conductor. Figures reproduced from: **a**–**c**, ref. 5, © 2001 NPG; **d**, ref. 7, courtesy of Jianyi Jiang of National High Magnetic Field Laboratory, and the wire manufactured by Oxford Superconducting Technology.

Larbalestier *et al.* describe a method for processing round wires of Bi-2212 to increase both its superconductor current density, J_c, and the engineering current density, J_e. They do this by means of a very high overpressure process during the heat treatment of the material, to increase the density of the melted Bi-2212 powder and close gas bubbles formed during the procedure. This results in significantly improved grain interconnectivity and enhances end-to-end transport current flow. Intriguingly, this remains the case even in the presence of high-aspect grain boundaries, indicating that internal bubble formation during melting is a significant impediment to current flow.

This process can bring the engineering current density of Bi-2212 wires to a level exceeding that of the low-temperature metallic superconductors such as NbTi and Nb_3Sn, and even the REBCO tape conductors. Clearly, the round geometry