2D Material Liquid Crystals for Optoelectronics and Photonics

B. Hogan,* E. Kovács,# M. F. Craciun* and A. Balágyi‡

The merging of the materials science paradigm of liquid crystals and 2D materials promises new opportunities for the advancement of the fields of optoelectronics and photonics. In this review, we summarise the development of 2D material liquid crystals by two different methods: dispersion of 2D materials in a liquid crystalline host and the liquid crystal phase arising from dispersed 2D materials in fluid organic solvents. The properties of liquid crystal phases that make them so attractive for optoelectronics and photonics applications are reviewed. The processing of 2D materials also allows for the development of 2D material liquid crystals is also considered. It is implied in the applications of such materials, from the development of films, fibers and membranes to display applications, optoelectronic devices and control of synthetic processes.

Introduction

Two-dimensional (2D) nanocomposite materials with dynamically tunable liquid crystalline properties have recently emerged as a highly promising class of novel functional materials, opening new routes within a wide variety of potential applications from the deposition of highly uniform layers and heterostructures, to novel display technologies. Here, we will introduce the underlying concepts that underpin this recent technological advance; provide an overview of the synthetic routes towards such 2D nanocomposite materials; and review recent advances in the application and applicability of these materials within the fields of optoelectronics and photonics. Since the advent of graphene in 2004,1 there has been an explosion in the investigation of a wide range of atomically thin (two-dimensional) materials. In addition to graphene (exfoliated from graphite), materials that can be reduced to monolayer size have been shown to include: graphene oxide (from graphite oxide); transition metal dichalcogenides (TMDs); for example MoS2, WS2 and MoTe2; and hexagonal boron nitride (h-BN) amongst others. The possibilities for applications of these materials are almost limitless, owing to the diverse properties that they exhibit. However, adoption of these materials in novel optoelectronics and photonics applications is often limited by challenges surrounding the scalability, cost of production processes or limited device tunability. Recently, two paradigms of significant interest for the development of novel functional materials where dynamic reconfigurability is delivered through the exploitation of liquid crystalline properties and 2D materials have emerged. Firstly, 2D material particles can be dispersed in a conventional liquid crystal host.1,2 Alternatively, 2D materials dispersed in specific solvents have been shown to display lyotropic liquid crystalline phases within certain ranges of 2D material concentration.5–10

Liquid crystals

The liquid crystal phase is a phase of matter that exists for a variety of molecules and materials, depending on their geometric and chemical properties, with characteristics intermediate to those of a conventional crystalline solid and a liquid.11 Liquid crystalline phases can be found in a variety of applications through the years (Fig. 1). The liquid crystal phase was initially described by Austrian botanist Friedrich Ranvier in 1888 when looking at the properties of cholesterol derivatives,12 although some credit goes also to Julius Planer, who reported similar observations 27 years prior.23 The new and distinct state of matter was then identified as the “liquid crystal phase” by Otto Lehmann in 1880 and in 1904 the first commercially available LCs were produced by Merck AG.2 Over the following 18 years, scientists established the existence of three distinct liquid crystalline phases (nematic, smectic and cholesteric) but, with no applications of note forthcoming, the study of LCs was halted. For the next 30 years, the scientific community ignored LC materials, considering them as an interesting curiosity. However, following a renaissance in liquid crystal science in the 1950s, the previously curious property has become a ubiquitous part of the modern technology landscape. During the 1950s, the invention of the first cholesteric LC thermometer indicates that LCs can also display important medical and diagnostic applications. Cancer diagnostics and non-destructive material testing methods have been developed in this era of liquid crystal science by 1982, liquid crystals were already being used for state-of-the-art laser devices, and LCs are widely used in medical applications. Computer technology, which has revolutionised scientific research, is one of the most important technological innovations that came in 1965 with the development of the first LC displays (LCDs).6,7 Subsequently, twisted nematic LCDs (1969–1971) advanced the field further. Significant breakthroughs in the evolution of liquid crystal technologies occurred in the 1980–1990s, and LCDs continue to have a profound impact on day-to-day life: the miniaturisation of display technologies facilitated the development of portable PCs, mobile telephones and countless other innovations8–10. Since the start of the new millennium, LCD and recently discovered 2D material LCs have come into demand as optoelectronic and photonic materials.11–15

The possibility of the existence of a liquid crystal phase stems principally from the geometric structure of the molecules in the material as well as the functional groups present in the molecule. In lyotropic liquid crystals, mesogens are dispersed in a host solvent (typically water but other organic solvents can be used depending on the molecule).2,5 Lyotropic liquid crystals exhibit a liquid crystal phase within a certain range of temperatures but also require a concentration of the active mesogens that falls within a certain range. When an external electric field is then applied to the liquid crystal, the dipole orient along the direction of the field as the electric field exerts a force on the dipole. Some liquid crystal molecules, however, do not form permanent dipole but can still be influenced by an electric field. The shape anisotropy of many liquid crystal mesogens means that they are highly polarisable and as such an applied electric field can induce a dipole by relocating the electron density within the molecule. While not as strong as permanent dipoles, orientation of the induced dipoles with the external field still occurs. The effects of magnetic fields on liquid crystal molecules are analogous to electric fields with the molecules aligning with or against the magnetic field. 2D materials

Whereas, in the past, 2D materials have traditionally been produced by either chemical vapour deposition method or by vapour deposition and exfoliation. More recently, liquid phase exfoliation has attracted significant interest due to the inherent scalability of the process. Liquid phase exfoliation is a method where a bulk material is dispersed in a solvent and then layers are broken apart.16–18 In most cases, the layers are broken apart using ultrasonication where high frequency sound waves are transmitted through the solution.29,30 The sound waves induce the formation of bubbles and cavities between layers which break the layers apart as they expand. However, they also cause strains in the material which cause intralayer cleavage of the particles, reducing the size of the particles obtained after exfoliation. Other than ultrasonication, other methods have been employed for liquid phase exfoliation, including strong acid induced oxidation reactions causing cleavage31 and freezing of water intercalated layered structures where expansion of water as it freezes causes interlayer cleavage32. Following exfoliation, particle sizes of specific sizes can be isolated by centrifugation of the dispersion33,34, solvent induced selective sedimentation35 or by pin-assisted selective sedimentation36 amongst others. Materials of interest for optoelectronics and photonics that can be reduced to few layer or monolayer by means of liquid phase exfoliation encompass a broad range; from graphene and its derivatives to transition metal dichalcogenides (TMDs), metal oxides and hexagonal boron nitride (h-BN) amongst many others. Liquid phase exfoliated 2D materials are of significant interest for the production of 2D material liquid crystal composites as the exfoliating solvent can be used as the fluid host for spontaneous liquid crystal phase self-assembly37,38,39 or to allow combination with conventional liquid crystals.40

Amongst materials discussed further here, graphene can be exfoliated from bulk graphite owing to the weak van der Waals interactions between layers in graphite.41 Graphene is an allotrope of carbon consisting of a two-dimensional hexagonal lattice with a single carbon atom at each vertex. The carbon atoms in graphene are sp2-hybridised in-plane with these sp2 electrons forming three carbon-carbon bonds in the hexagonal lattice which are directed out of the plane. For a graphene sheet these out of plane p orbitals hybridise to form the delocalised π and n bands which are responsible for graphene’s exceptional electronic properties; these electrical properties make graphene a highly significant interest as a material for forming electrical contacts, films and fibers.42

Graphene oxide is the 2D material produced by the exfoliation of graphite oxide.43 Maximum oxidation of graphite results in a carbon to oxygen ratio between 2.1 and 2.9. Graphite oxide retains the layered structure of graphite but the interlayer spacing is increased and no longer regular for bulk graphite oxide. The oxidation of graphite introduces three types of oxygen containing functional groups to the structure: epoxy bridges (oxygen bridging between two carbons on the surface of a graphite sheet), hydroxyl groups (on either the surface or the edges) and carboxyl groups (on the edges of the graphic sheets).44 Graphene oxide can be exfoliated from bulk graphite oxide analogously to graphene from graphite.45 However, the intercalation of the graphic carbon sheets into oxygenated functional groups results in graphene oxide being more readily exfoliatable. This means that graphene oxide can be exfoliated to few layers and even monolayer in large quantities without the use of...
additional surfactant molecules.\textsuperscript{38,43} Graphene oxide possesses nonlinear optical properties of significant interest for applications in ultrasonic phononics and optoelectronics. The saturable absorber can be used for pulse compression, mode locking and Q-switching of laser systems.\textsuperscript{38,57} The large observed Kerr effect and the related electro-optic effect suggest possibilities in all-optical switching and signal regeneration and hence optical communications devices.\textsuperscript{38,61,62} The nonlinear optical properties of graphene oxide can be tuned by controlling the carbon to oxygen ratio.\textsuperscript{63} The tuning has been achieved by using laser irradiation to reduce the material.

Transition metal dichalcogenides (TMDCs) are a class of material where transition metal atoms are connected by bridging group 14 elements with a stoichiometry of 1:2 to form layers. The layers are held together by weak van der Waals interactions and therefore present an ideal candidate for reduction to few-layer or monolayer materials. Cleavage to monolayer is typically achieved using mechanical exfoliation methods but few-layer material can be readily attained using liquid-phase exfoliation methods. Many different TMDCs have been synthesized. A common example, molybdenum disulfide (MoS\textsubscript{2}), consists of layers of molybdenum atoms bound to six sulfur ligands in a trigonal prismatic coordination sphere.\textsuperscript{64,65} MoS\textsubscript{2} is an indirect bandgap semiconductor with a band gap of 1.23 eV in its bulk form\textsuperscript{65} but the monolayer form has a direct bandgap of 1.8 eV.\textsuperscript{66} So it can be used in switchable transflectors and photodetector devices.\textsuperscript{61} MoS\textsubscript{2} can emit light opening applications in situ light generation devices.\textsuperscript{61,66}

**2D material liquid crystals**

It has been shown that by dispersing nanoparticles or molecules in a liquid crystal host that the ordering of the liquid crystal mesogens can impart ordering to the dispersed particles.\textsuperscript{39,40} The nanoparticles have been shown theoretically and experimentally\textsuperscript{38,40} to align with the discilinations of the liquid crystal due to the energetic favourability of such an alignment. More recently, the imperfection of ordering from a liquid crystal host has also been shown with dispersed 2D material particles.\textsuperscript{41,42} Additionally, dispersions of graphene oxide in water have been shown to have a hydroscopic liquid crystal phase within a specific range of concentrations of dispersed graphene oxide particles (Fig. 3), where the dispersed dislocations of graphene oxide particles are either stacked in the columnar manner typical of discotic liquid crystals or exhibit ordering analogous to a nematic phase.\textsuperscript{21,49} The liquid crystal phase of the graphene oxide dispersions arises due to the competition between the long-range electrostatic repulsion between particles, originating from ionized functional groups at the edges of the particles, and the weak attractive interactions originating from the unoxidized graphite domains on the surface.\textsuperscript{70} The liquid crystallinity is therefore dependent on the particle size; more precisely to the ratio of the surface area to the circumference (and number of layers) as this determines the attractive and repulsive forces.\textsuperscript{68,69} Most dispersions of liquid phase exfoliated graphene oxide will consist of particles of differing sizes and therefore the polydispersity of the particles becomes an important factor.\textsuperscript{71} Additionally, this balance is affected by the degree of oxidation: the carbon to oxygen ratio of the material.\textsuperscript{70} The stability of the liquid crystal phase can also be strongly affected by the ionic content of the solvent as this determines the degree of ionisation of the oxygen containing functional groups on graphene oxide.\textsuperscript{71} The pH of the solvent also affects the critical concentration for the onset of liquid crystalline behaviour.\textsuperscript{21} By tuning these separate parameters, it is possible to observe either a nematic phase or columnar phase of the graphene oxide dispersion (Fig. 4). The different liquid crystalline phases can be observed using photoluminescence measurements as there is a strong polarisation dependence of the photoluminescence for ordered monolayers in graphene oxide dispersions.\textsuperscript{72}

Similarly, this liquid crystal phase has been observed in a range of other organic solvents including acetone, dimethylformamide, ethanol, cyclohexylpyrrolidone and tetrahydrofuran.\textsuperscript{49-60} (Fig. 5). The concentration of particles required to give rise to the liquid crystal phase is different for each solvent, but there is also some discrepancy between the threshold concentrations observed for the same solvent due to the effect of the size, shape and polydispersity of the graphene oxide particles in the solution. A liquid crystal phase has also been observed for graphene exfoliated and dispersed in chlorosulfonic acid.\textsuperscript{45} A similar phase has been observed in other solvents for graphene and small graphitic particles although only with the addition of either stabilising surfactant\textsuperscript{45,73} or polymer coatings.\textsuperscript{69} Dispersions of graphene in water have been reported to show an anisotropy associated with a cholesteric liquid crystal phase.\textsuperscript{74} More recently a liquid crystal phase has been observed for dispersions of molybdenum disulfide at high concentration in water\textsuperscript{75} suggesting the possibility of liquid crystalline phases existing for a far greater range of dispersions of 2D materials.\textsuperscript{76}

**Applications and prospects**

Films, fibers, membranes and inks

The self-assembling nature of liquid crystalline materials has led to the use of graphene oxide dispersions for the formation of well-ordered layers and stacks of 2D materials. Behabtu et al.\textsuperscript{77} demonstrated that graphene spontaneously exfoliates into single-layer graphene in chloroformic acid, and spontaneously forms liquid-crystalline phases at high concentrations. Transparent, conducting films were produced from the liquid crystalline dispersions. Ji et al.\textsuperscript{40} showed that self-assembly of graphene oxide sheets is possible in a wide range of organic solvents. The prepared dispersions were employed to achieve self-assembly layer-by-layer multilayer 3D hybrid architectures comprising SWNTs and GO with promising (Fig.4). More recently, the same group has showed that similar self-assembly can be achieved using liquid crystal dispersions of molybdenum disulfide.\textsuperscript{61} Layers of these materials have been combined to act as membranes for a variety of diverse applications such as photocatalysts,\textsuperscript{78} and improving the mechanical properties of composite materials.\textsuperscript{79}

The more homogenous layers produced from the liquid crystalline dispersions are of significant interest to applications of these nature. The use of liquid crystalline dispersions of graphene oxide to prepare uniform layers has been used as a precursor to forming similar defect structures of graphene through the reduction of the graphene oxide.\textsuperscript{48,80} Akbari et al. demonstrate that the discotic nematic phase of GO can be shear aligned to form highly ordered, continuous films of multi-layered GO on a supporting membrane. The high alignment of the membranes in the phase of the graphene oxide dispersion (Fig. 4). The different liquid crystalline phases can be observed using photoluminescence measurements as there is a strong polarisation dependence of the photoluminescence for ordered monolayers in graphene oxide dispersions.\textsuperscript{72}

Zhu and co-workers have shown that the preparation of polyN-isopropylacrylamide/GO nano composite hydrogels with macroscopically oriented LC structures, after polymerisation, can be readily achieved under assistance from a flow-field induced by vacuum degassing. Nanocomposites prepared with a GO concentration of 5.0 mg mL\textsuperscript{-1} exhibit macroscopically aligned LC structures, which endow the gels with anisotropic optical properties. Furthermore, they show that the liquid crystalline structures are not destroyed during swelling in the hydrogels, and hence their behaviour undergoes reversible changes. Additionally, they show that the oriented LC structures in the hydrogels can be permanently maintained after drying the nanocomposite samples. The liquid crystalline properties of such nanocomposites facilitate their applicability to switching in optoelectronic devices.\textsuperscript{81}

Kim et al.\textsuperscript{82} have demonstrated significant improvement of the electro-optic performance of a polymer-stabilized liquid crystalline blue phase using a reduced graphene oxide (RGO) enriched polymer network. The conductivity of the nanocomposite system is increased by the inclusion of the RGO. Furthermore, reductions in the operational voltage (32%), response time (51%) and hysteresis (53%) compared to that of a conventional polymer-stabilized BICLC signify great potential for the use of 2D materials in enhancing novel electro-optic device applications of conventional LC systems.

Recently, Hogan et al.\textsuperscript{83} proposed that by tuning the liquid crystal director by means of an applied field, one could induce the formation of metamaterials for the dispensed 2D material particles as they are repositioned. In particular, they show that nanocomposites of nematic phase liquid crystals with dispersed graphene oxide particles can be integrated with CMOS photonic devices as a back-end process as part of microfluidic systems and that the integrated nanocomposites can be readily controlled by use of either an electric field or laser light to reposition and rearrange the dispersed particles in a novel characterisation method based on Raman spectroscopy to allow determination of the spatial positioning of the integrated 2D material particles, allowing precise monitoring of metamaterial formation.

**Displays**

2D material liquid crystals can be used in back-illuminated liquid crystal display applications as they exhibit electro-optic switching. The Kerr coefficient of graphene oxide liquid crystals observed by Shen et al.\textsuperscript{84} for example, facilitates this application. However, the slow switching times reported by Kim & Kim (Fig. 5) must be considered, although Ahmad et al.\textsuperscript{85} report that this can be improved by approximately an order of magnitude by careful selection of the size of graphene oxide moieties.

More promisingly, 2D material liquid crystals have also been proposed for application in liquid crystal displays—particularly in so-called ‘e-ink’ displays—without requiring the polarising optics typically necessary for these applications.\textsuperscript{86} Hu et al.\textsuperscript{87} demonstrate a process by which graphene oxide liquid crystals can be used for...
reflective displays without the need for polarizing optic(s). By  
using flow-induced mechanical alignment, they prepared graphene  
oxide in different orientational orders and demonstrated that the  
ordered graphene oxide liquid crystals can be used as a rewritable  
display medium. The surface of the graphene oxide liquid crystal  
can be switched from a bright, reflective state to a dark, transmissive  
state using, for a wire to manually draw patterns on the surface.  
They explain that the contrast between the two states arises  
due to the anisotropic response of the flakes due to the inherent  
high aspect ratio of the 2D material.

Quality control  

Inventing the onset of a liquid crystal phase in a dispersion  
of graphene oxide has been used for size selection of the graphene  
oxide particles12. Lee et al introduce a method for facile size selection  
of large-size graphene oxide particles by exploiting liquid  
crystallinity. They state that in a biaxial graphene oxide dispersion  
where both isotropic and liquid crystalline phases are in equilibrium,  
large-size GO flakes (>20 μm) are spontaneously concentrated within  
the liquid crystalline phase. Selectivity of large flakes without the  
need to increase the filtering presents several advantages for photonics  
and optoelectronics applications; primarily larger flakes allow for  
greater uniformity of device characteristics over wider areas and can help  
with the increase of uniformity of deposits.

Outlook  

2D materials encompass a fascinating range of diverse  
properties with a myriad of possible applications in optoelectronics  
and photonics. The development of liquid crystalline nanoparticle  
composites material incorporating 2D materials represents a significant  
advantage in the opportunities for integration and exploitation of  
2D materials within these fields. However, there remain a large number  
of questions that demand further investigation before 2D material  
liquid crystals can find wider application. Primarily, there remain  
many candidate materials for which a liquid crystal phase is  
theoretically possible but not yet shown; the discovery of further  
liquid material liquid crystals would broaden the range of utilisable  
properties available. Similarly to that observed for graphene oxide,  
observation of this liquid crystallinity should require a combination  
of careful solvent selection, tuning of the 2D material particle sizes  
and control of the concentration of the particles. Additionally, the  
use of the different molecular systems may be necessary to stabilise the  
liquid crystalline phase of the dispersions by maximising the aligning forces  
acting on the dispersed particles. However, this raises the additional  
question of the exploration- both theoretical and experimental- of  
the conditions required for the existence of the liquid crystal phase,  
an area in which little work has far been explored for the specific  
systems of interest here. A significant part of such work remains to  
be done in the comparison of the different synthetic routes towards  
the LC phase, and how the synthesis can affect the observed  
properties.

Additionally, dispersion of 2D materials in  

cellular liquid crystal host fluids presents superb new possibilities in  

optofluidic systems; from light generation to dynamic sensing  
applications. This is owing to the dramatic improvements that can be  
observed in the operational parameters of the nanocomposite  
systems in comparison to the conventional LC systems currently  
used in optoelectronics and photonics. Such nanocomposites do not  
only improve properties such as switching times and threshold voltages,  
but can also add further functionality, for example by metastructuring of nanoparticle dispersions. For these  
nanocomposite systems, the most important advances to be made  
are in the fundamental understanding of the basis for improvements  
in their intrinsic properties; and in the exploration of predicting  
metastructuring as well as experimental observation.

Overall, the existence of liquid crystal phase 2D material  
dispersions presents fantastic opportunities in the exploration of  
new optoelectronic and photonic systems, allowing newly  
high-scalable production processes for thin film integration and  

tagging techniques amongst others applications.

Acknowledgements  

We acknowledge financial support from the Engineering  
and Physical Sciences Research Council (EPSRC) of the United  
Kingdom via the EPSRC Centre for Doctoral Training in  
Electromagnetic Metamaterials (Grant No. EP/L015331/1)  
and via Grant Nos. EP/P033610/1 and EP/P004238/1.

References  

K. S. Novoselov, A. K. Geim, S. V. Morozov, D. Jiang, Y.  
Zhang, S. V. Dubonos, I. V. Grigorieva and A. A.  

S. U. Mu, S. Hu, Y. Zhao, Y. Liu, D. He and W. Yang,  

B. T. Hogan, S. A. Dyakov, L. Brennan, S. Younese, T.  
Perova, Y. G. Guryko and A. Balandin,  


C. Zakr, C. Blanc, E. Grelet, C. Zamora-Ledezma, N. Puech,  

S. Chandrasekhar, Liquid Crystals, Cambridge University  

P. G. de Gennes and J. Prost, The Physics of Liquid Crystals,  


G. T. Shuk, D. Murn, M. H. H. Samali and H. Schmieder,  

2003, 13, 1531–1540.

T. Zhang, S. Li, X. Zhang, J. H. Li, B. Ge, F. Wang,  
M. Liu, J. G. Lu and D. C. Marcano, J. Phys. Chem. B,  
2010, 114, 12779–12786.

J. J. H. Chacon, G. A. G. Nogueira, A. A. M. Freitas,  
M. D. S. Carrilho, J. M. Tour and R. S. Ruoff,  
Figure 1: Timeline of the history of liquid crystal phase applications, from their discovery to the present day. 1888: The LC phase was first reported by Friedrich Reinitzer (Image reproduced with permission from Mitov, ChemPhysChem, 2014© (©2014 Wiley-VCH)). 1950-1959: the development of the first cholesteric phase and LC thermometers. 1962: the first switchable orientation of LC molecules was utilized in laser devices. 1963: The first prototype LCD was developed by George H. Heilmeyer before finding limited applications. 1969-1971: The first twisted nematic cell displays were developed from the initial work of Martin Schadt and incorporated in devices. 1980-1990s: LCDs found widespread application in small mobile devices as the display of choice. From the 1990s onwards, much larger LCDs have appeared while advances in the technology have allowed the production of high-resolution small scale displays. Beginning in the new millennium, LCs have emerged as desirable optoelectronic materials. They have as such been studied from natural sources such as can be found in beetles, as well as in polarised light-selective waveguiding and in holography. The discovery of graphene in 2004 opened up new avenues for LC science and, since 2010, the emergence of LCs combined with 2D materials has opened applications in developing 2D material fibers (reproduced with permission from Xu & Gao, Nature Communications, 2011© (©2011 Nature Publishing Group)), reflective displays (reproduced from He et al, Nanoscale, 2014© with permission from The Royal Society of Chemistry ©2014), deposition of uniform layered structures (reproduced with permission from Jall et al, ACS Nano, 2013© (©2013 American Chemical Society)) and as a platform for novel optofluidic devices (reproduced with permission from Hogan et al, Sci. Rep., 2017© (©2017 Nature Publishing Group)). The future of the field promises to revolutionise fields from CMOS photonics, to metastructures and metadevices and wearable technologies. All images utilised under a free-to-use creative-commons license except where otherwise credited.

Figure 2: Liquid phase exfoliation of 2D materials. (a) Starting material (e.g., graphite), (b) chemical wet dispersion, (c) ultrasonication and (d) final dispersion after the ultracentrifugation process. Reproduced with permission from Bonaccorso & Sun, Opt. Mater. Exp., 2014© (©2014, The Optical Society).

Figure 3: (a) Polarized light microscopic images between crossed polarizers of GO aqueous dispersions in planar cells with increasing maximum mass fractions from 1 to 6. Green arrows indicate disclinations of the liquid crystal phase, and the scale bars represent distances of 200 μm. (b) Microscopic images between crossed polarizers of GO aqueous dispersions in test tubes with increasing maximum mass fractions from 1 to 7. Reproduced with permission from Xu & Gao, ACS Nano, 2011© (©2011, American Chemical Society).

Figure 4: Phase diagram of graphene oxide aqueous dispersions in terms of osmotic pressure, volume fraction of GO and salt concentration in the solution. Reproduced with permission from Konkena & Vasudevan, J. Phys. Chem. C, 2014© (©2014, American Chemical Society).
Figure 5: Schlieren textures observed in dispersions of graphene oxide in a range of organic solvents under microscopy using crossed polarisers. Reproduced with permission from Jalili et al., ACS Nano, 2013. ©2013 American Chemical Society.

Figure 6: (a) Photograph of a flexible free-standing paper of LC GO made by a cast drying method. (b) SEM image of the cross section of as-cast dried LC GO paper. (c) SEM image of the surface of the layer-by-layer composite, marked as region (i) in (b). (d–f) Cross section of composite paper at different. Reproduced with permission from Jalili et al., ACS Nano, 2013. ©2013 American Chemical Society.

Figure 7: (a) Four-metre-long wound GO fibre. SEM images of the fibre (b), and a typical tighten knot (c). (d) The morphology of the GO fibre after tensile tests. All scale bars 50 μm. Reproduced with permission from Xu & Gao, Nature Communications, 2011. ©2011 Nature Publishing Group.
Figure 8: (a) Control of liquid crystal dispersed 2D material particle using laser light. (b–c) SEM images of GO flakes integrated in microfluidic channels with a nematic liquid crystal host. (d) SEM image of GO flakes integrated into a microfluidic waveguide after removal of host fluid. (e) A CMOS photonic circuit coupled to a microfluidic layer integrating dynamically reconfigurable 2D material metastructures by exploiting liquid crystal technology. Adapted with permission from Hogan et al., Sci. Rep., 2017©2017 Nature Publishing Group.

Figure 9: Images of a defined structure in a liquid crystalline e-ink of graphene oxide dispersed in water in (a,d) reflection with unpolarised light, (b,e) transmission with unpolarised light and (c,f) transmission between crossed polarisers. Reproduced from He et al., Nanoscale, 2014©2014 with permission from The Royal Society of Chemistry ©2014.