absorbed by the silicon generate electron–hole pairs that can then be separated by the electric field associated with the Schottky junction at the material interface. Increasing the work function of the graphene increases the voltage drop at the interface, which leads to more efficient separation of electron–hole pairs into useful current. The hydrophobic dopant also acts to protect the device, endowing it with superior environmental stability as compared with pristine graphene solar cells, which degrade over time.

The factor of 4.5 increase in efficiency achieved though TFSA doping represents a significant improvement in performance, which could lead to these cells acting as viable alternatives to expensive silicon diode cells and less stable organic cells. Alternatively, the doped graphene layer could itself be applied to a range of other substrates including flexible polymer semiconductors.

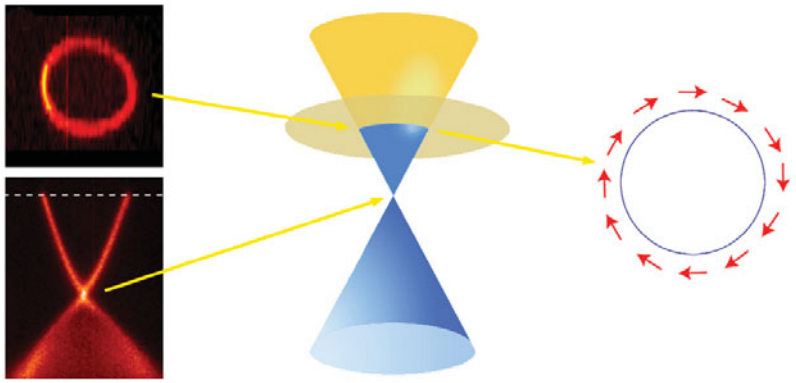
Tobias Lockwood

Nano Focus

Topological insulator Bi_2Se_3 opens path to room-temperature spintronics

In the search for new materials with improved electrical conductivity, a team of researchers led by Tonica Valla of Brookhaven National Laboratory has found a potential candidate in the topological insulator Bi_2Se_3. Electrons on the metal surface of a topological insulator can flow with little resistance. Using angle-resolved photoemission spectroscopy (ARPES) at Brookhaven's National Synchrotron Light Source and at the Advanced Light Source at Lawrence Berkeley National Laboratory (LBNL), the researchers discovered that the surface electrons of Bi_2Se_3 can flow at room temperature, making it an attractive candidate for practical applications like spintronics devices, plus farther-out ones like quantum computers.

As reported in the May 4 issue of *Physical Review Letters* (10.1103/PhysRevLett.108.187001), Valla, Alexei Fedorov of LBNL, Young Lee of the Massachusetts Institute of Technology, and their colleagues generated a direct graphic visualization of the sample's electronic structure. The band structure of the surface states of a topological insulator like Bi_2Se_3 appear as two cones that meet at a point, called the Dirac point. There is no gap between the valence and conduction bands, only a smooth transition with increasing energy. This is similar to the band structure of graphene in which ARPES diagrams look like slices through the cones, an X centered on the Dirac point.



ARPES maps the electronic properties, including the band structure and Fermi surface, of the topological insulator bismuth selenide (left). Like graphene, the lower energy valence band of a topological insulator meets the higher energy conduction band at a point, the Dirac point, with no gap between the bands (center). Unlike graphene, however, the Fermi surface of a topological insulator does not usually pass through the Dirac point. For surface electrons, distinct spin states (red arrows) are associated with each different orientation in momentum space (right).

Although graphene and topological insulators have similar band structures, their other electronic characteristics are very different. The combinations of different speeds and orientations equivalent to a material's highest particle energies (at zero degrees) make up its momentum space, mapped by the Fermi surface. While the Fermi surface of graphene lies between the conical bands at the Dirac point, this is not true of topological insulators. The Fermi surface of Bi_2Se_3 cuts high across the conical conduction band, mapping a perfect circle. It is as if the circular Fermi surface were drawn right on the surface of the topological insulator, showing how spin-locked surface electrons must change their spin orientation as they follow this continually curving path.

"One way that electrons lose mobility is by scattering on phonons," said Fedorov. Phonons are the quantized vibrational energy of crystalline materials, treated mathematically as particles. "Our recent work on a particularly promising topological insulator [TI] shows that its surface electrons hardly couple with phonons at all. So there's no impediment to developing this TI for spintronics and other applications."

Values including electron–phonon coupling can be calculated from the diagrams that ARPES builds up. ARPES measures of Bi_2Se_3 show that electron–phonon coupling remains among the weakest known to have been reported for any material, even as the temperature approaches room temperature.

Fedorov said, "Although there's still a long way to go, the experimental confirmation that electron–phonon coupling is very small underlines Bi_2Se_3's practical potential." With continued progress, the spin-locked electronic states of room-temperature topological insulators could open a gateway for spintronic devices

and even quantum computing.

For example, by layering a superconducting material onto the surface of a topological insulator, it may be possible to create a theoretical but yet unseen particle that is its own antiparticle, one that could persist in the material undisturbed for long periods. Discovery of these so-called Majorana fermions would be an achievement in itself, and could also provide a way of overcoming the main obstacle to realizing a working quantum computer, a method of indefinitely storing data as "qubits."

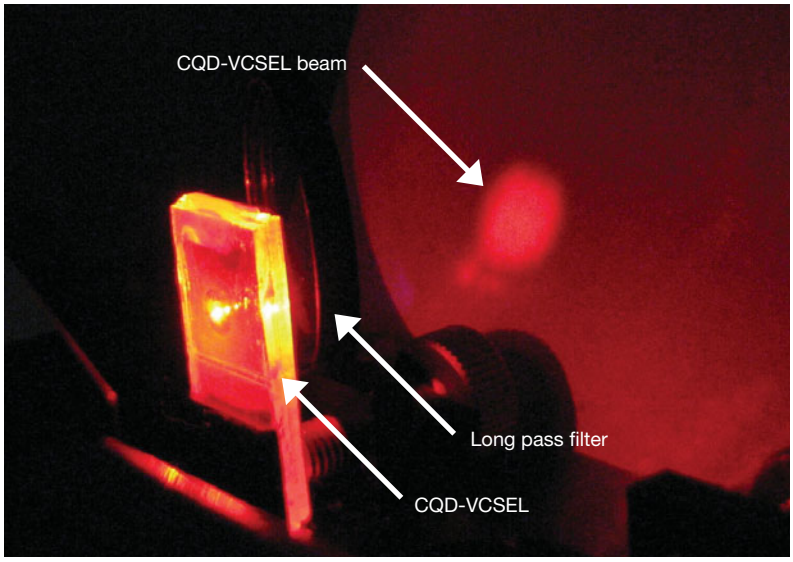
Nano Focus

Colloidal quantum dot films show RGB lasing

Colloidal semiconductor quantum dots exhibit efficient luminescence and bandgap controllability due to quantum confinement effects. However, to obtain laser emission from these materials, it is necessary to achieve a high colloidal-quantum-dot (CQD) packing density, and to reduce losses arising from nonradiative, multi-excitonic (Auger) recombination. In a joint collaboration, C. Dang of Brown University, C. Breen of QD Vision, Inc., Massachusetts, and their colleagues have demonstrated how these requirements can be met to achieve red-green-blue (RGB) lasing.

As published in the May issue of *Nature Nanotechnology* (DOI: 10.1038/nnano.2012.61; p. 335), the researchers report lasing emission from CdSe/ZnCdS core/shell CQD with aromatic ligands. These form densely packed films that exhibit optical gain across the visible spectrum with an average of less than one exciton per CQD. This single-exciton gain allows the films to reach the threshold of amplified spontaneous emission at very low optical pump energy densities of 90 μJ cm^{-2}. This is more than one order of magnitude better than previously reported values. The gain of these nanocomposite films was used to produce the first colloidal quantum dot, vertical-cavity surface-emitting laser (CQD-VCSEL).

In this work, the researchers prepared type I CdSe/$Zn_{0.5}Cd_{0.5}S$ core/shell CQDs by high-temperature organometallic synthesis with nominal CdSe core diameters of 4.2 nm, 3.2 nm, and 2.5 nm. The thin (1 nm) ternary shell reduces strain and creates a moderate core/shell bandgap difference. Transmission electron microscopy images showed well-defined crystallinity and "pyramid-like" morphologies. Together, these properties modify the electronic states from those of ideal spherical CQDs, where the anisotropic shape of the CQDs is a key feature that enables lasing with one single exciton.



Photographic image of a red colloidal quantum dot, vertical-cavity surface-emitting laser (CQD-VCSEL) showing a spatially well-defined output beam, which is collinear with the pump beam. Reproduced with permission from *Nat. Nanotechnol.* **7** (2012) DOI: 10.1038/nnano.2012.61; p. 335. © 2012 Macmillan Publishers Ltd.

In ideal spherical CQDs, the Auger process is typically two orders of magnitude faster than photoluminescence decay, which severely hinders the dynamic buildup of population inversion. In this work, the dynamics of optical gain in CQD films were studied in pulsed stripe, photoexcitation experiments. Emission from the film edge with increasing pump power exhibits a clear transition from photoluminescence to stimulated emission (here observed as amplified spontaneous emission, ASE) through an abrupt increase in output intensity and spectral narrowing.

In contrast, in the densely packed CQD films, the ASE process is so fast that it can readily overcome this Auger loss. Indeed, very low thresholds of ASE across the RGB spectrum were obtained and the first CQD-VCSELs by single-exciton gain in type I CQD films were reported. Single-exciton gain was confirmed in this work by four independent

Correction

The affiliations for the authors of the article, "Survey reveals interdisciplinarity of MSE faculty," published in *MRS Bulletin* **37** (June 2012) p. 541, are Parag Banerjee, Department of Mechanical Engineering and Materials Science, Washington University, St. Louis, MO (parag.banerjee@wustl.edu) and Robert M. Briber, Department of Materials Science and Engineering, University of Maryland, College Park, MD (rbriber@umd.edu).