Towards CMOS-Compatible, Solution-Processed Quantum Dot Nanocrystal Optical Sources, Modulators, Detectors, and Optical Signal Processing Elements across the Extended Communications Band 1200-1700 nm

Edward H. Sargent
Dept. of Electrical & Computer Engineering, University of Toronto, Toronto M5S 3G4, Canada.
ted.sargent@utoronto.ca

The terabit-per-second fibre-optic networks of today are enabled by a combination of high-speed electronic devices such as transistors with high-performance photonic devices such as lasers, modulators, and detectors. Electronics and optics are often joined together in an awkward fashion: the processes used to make these chips are incompatible, and as a result, post-fabrication assembly, with painstaking alignment and manual assembly, is required. This is in striking contrast with integrated electronic circuits in which millions of transistors are conveniently integrated on a single chip.

Solution-synthesized quantum dots, which can be spin- or spray-coated onto any smooth substrate, could enable monolithic integration uniting photonics and electronics. Solution-processible PbS, PbSe, or InAs quantum dots could form the active optical material within the photonic component of a combined optical-electronic chip: following CMOS fabrication, the electronics surface would be planarized, solution-processible active photonic materials spun on, and further dielectrics or metals deposited as needed. All of the post-CMOS processes could be carried out at or near room temperature.

To create the quantum dots and make them available in a convenient organic solvent for spin-casting such as toluene, chloroform, or THF, PbS quantum dot nanocrystals are synthesized in solution within a single flask [1]. A lead oleate precursor is prepared by heating PbO in oleic acid under argon at 150^{o}C for 1 hour. Bis(trimethylsilyl)sulfide in octadecene is then injected into the vigorously-stirring lead oleate solution. Nanoparticle diameter may be varied from 2-10 nm. The standard deviation in nanocrystal diameters may be as little as 1 monolayer. The nanoparticles may be isolated from the growth mixture by precipitation with methanol and then redispersed in an organic solvent such as toluene.

Nanocomposites consisting of PbS nanocrystals in a conjugated polymer matrix have been demonstrated [2] to show photo- and electroluminescence across the spectral range 1000 to 1600 nm with tunability via the quantum-size effect. Electroluminescent devices combining two families of PbS colloidal quantum dots to achieve spectrally tailored two-color emission were demonstrated [3]. Electroluminescence internal quantum efficiencies as high as 3.1% were obtained.

We have recently demonstrated [4] electric field-induced modulation of absorption in PbS nanocrystal quantum dots across the spectral region 600 – 2000 nm. The maxima in the electroabsorption spectra correspond with the positions of the first excitonic peak, confirming the predominance of excitonic broadening as the basis for the observed effect.

We have reported photoconductivity for light between 975 and 1300 nm from a polymer/nanocrystal quantum dot composite [5]. Biased films of the conjugated polymer MEH-PPV sensitized with PbS nanocrystals (~5 nm diameter) demonstrate photocurrent at wavelengths beyond the response of the polymer and corresponding to the absorption of the nanocrystals. The photocurrent is attributed to absorption in the nanocrystals with subsequent hole transfer to the polymer.

We have recently made progress towards lasing of such materials at communications wavelengths on a substrate such as silica or silicon. We have reported [6] room-temperature amplified spontaneous emission and spectral narrowing at infrared wavelengths in solution-processed films made up of PbS quantum dot nanocrystals. The results are relevant to optical amplification and lasing integrated on a variety of substrates. The active optical medium operates at room temperature without any additional matrix material, providing an optical gain of 260 cm^{-1} and pump threshold of 1 mJ/cm^{-2}. Nanocrystals synthesized in aqueous solution and stabilized using short ligands result in a high quantum dot volume fraction in solid films and a three-dimensional superlattice effect which red-shifts emission relative to absorption.

[1] M. A. Hines, G. D. Scholes, “Colloidal PbS Nanocrystals with Size-Tunable Near-Infrared Emission: Observation of Post-Synthesis Self-Narrowing of the Particle Size Distribution,” Advanced Materials, vol. 15, no. 21, pp. 1844-1849, 2004.

[2] L. Bakueva, S. Musikhin, M. A. Hines, T.-W. Chang, M. Tzolov, G. D. Scholes, and E. H. Sargent, “Size-tunable infrared (1000-1600) electroluminescence from PbS quantum dot nanocrystals in a semiconducting polymer,” Applied Physics Letters, vol. 82, no. 17, pp. 2895-2897, 2003.

[3] L. Bakueva, G. Konstantatos, L. Levina, S. Musikhin, and E. H. Sargent, “Luminescence from processible quantum dot-polymr light emitters 1100-1600 nm: tailoring spectral width and shape,” Applied Physics Letters, vol. 84, no. 18, pp. 3459-3461, 2004.

[4] E. J. D. Klem, L. Levina, and E. H. Sargent, “CMOS-Compatible PbS quantum dot electroabsorption modulation across the extended communications band 1200-1700nm,” 2004, submitted.

[5] S. A. McDonald, P. W. Cyr, L. Levina, and E. H. Sargent, “Photoconductivity from PbS-Nanocrystal / MEH-PPV Composites for Solution-Processible, Quantum-Size Tunable Infrared Photodetectors,” 2004, submitted.

[6] V. Sukhovatkin, S. Musikhin, I. Gorelikov, S. Cauchi, L. Bakueva, E. Kumacheva, E. H. Sargent, “Room-Temperature Amplified Spontaneous Emission at 1300 nm in Solution-Processed PbS Quantum Dot Films,” 2004, submitted.