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Colloidal Quantum Dot Photodetectors

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Low cost CMOS compatible materials are widely investigated in the framework of silicon photonic structures. In particular, materials that absorb light beyond the silicon bandgap are desired for photodetection. Here we review operating modes of photodetectors and recent advances made with colloidal quantum dots.

Colloidal quantum dots are nanometer sized particles in which the bandgap can be tuned through the quantum size effect. Through the choice of material composition as well as the size, any bandgap from the blue to the infrared can be realized. These materials are readily synthesized and processed from solution and thus form an ideal building stone for CMOS photonic circuits. The surface of the dots is capped with ligands, which are necessary to keep the dots suspended in a solution, prevent particles from aggregating and passivate surface states. The engineering of the surface trap states through the choice of ligands is an integral part to realize high performance photodetectors.

Colloidal quantum dot photodetectors can be divided into two classes which operated either in high gain mode or high speed mode (Fig. 1). The former is based on the photoconductive gain mechanism, while the latter is realized through the photodiode architecture. In photodiodes photogenerated electrons and holes are transported to opposite electrodes, which limit the quantum efficiency of these devices to unity. However, the response times of these photodiodes can be shorter than the electron-hole lifetimes which are in the nanosecond to microsecond range. On the other hand, photoconductive photodetectors are capable to generate high gains but operate at lower speeds. Photoconductive gain occurs when one carrier type is trapped while the opposite carrier can circulate through the circuit before combining with the trapped carrier.

Carrier mobilities in colloidal quantum dot films are several orders of magnitude smaller compared to crystalline semiconductors: 10^{-5} – 10^{-3} cm^2/Vs compared to 10^2 cm^2/Vs leading to extended carrier extraction times. However, due to the unusually long exciton lifetimes of microseconds, carriers have been efficiently extracted leading to reported external quantum efficiencies of more than 50% at exciton absorption peak [1-3]. These devices had megahertz response frequencies, demonstrating that fast colloidal quantum dot photodiodes operate with response times comparable to the exciton lifetime and do not suffer from long-lived midgap traps. Doping levels obtained in colloidal quantum dot films has led to depletion region widths of several 100 nm [4]. In order to fully absorb all incident photons, films are required to be much thicker than these depletion widths. Diffusion in such a case has to ensure carriers can be moved to the edge of the depletion region to allow for electron-hole separation and extraction. Improved mobilities have now been reported surpassing the 1 cm^2/Vs range [5]; together with good midgap passivation schemes this would allow for sufficient carrier diffusion lengths to realize unity external quantum efficiency obtained with film thicknesses for which all photons are absorbed.

Photoconductive photodetectors are unipolar devices in which a single carrier type is conducted. Upon optical excitation an electron-hole pair is generated after which a single carrier is trapped in a long-lived midgap state. The trapped carrier allows for the opposite carrier to recirculate through the circuit until it recombines with the trapped carrier. The photoconductive gain is thus given as the ratio of the lifetime of the trapped carrier and the transit time of the free carrier. Due to the abundance of interfaces within a colloidal quantum dot film, excess noise could accumulate originating from the trapping and de-trapping effects of excited carriers. To accommodate such noise in comparing different photodetector architectures, normalized detectivity D^* can be used in which both the noise characteristics and the responsivity of the photodetector are considered. In the best solution-processed detector [6] a D^* of $5x10^{13}$ was measured, which is comparable to the best values obtained in crystalline photodiodes. This remarkable result was realized through careful optimization of the conductive paths together with surface state passivation. Here trap-free colloidal quantum dots were first electrically connected and subsequently gain providing sites were established, suppressing the transport noise through absence of fluctuating barriers along the transport path. This methodology was applicable to quantum dots operating in both the infrared [6] and visible [7].

An additional path towards improved sensitivity of colloidal quantum dot photodetectors is multiple exciton generation (MEG). Here, instead that a high energy exciton thermalizes to the ground state, it releases its energy through the generation of additional ground state excitons. Auger recombination, which is the inverse of MEG, is efficient in colloidal quantum dots and therefore has the large potential to reduce a multiple exciton population with no net win as result. Thus MEG has the potential to generate more than one carrier for each high energy absorbed photon, if carrier extraction is faster than Auger recombination. Recently, electrical devices based on colloidal quantum dots have demonstrated that MEG can occur [8, 9] and therefore could lead the path towards fast AND sensitive photodetectors

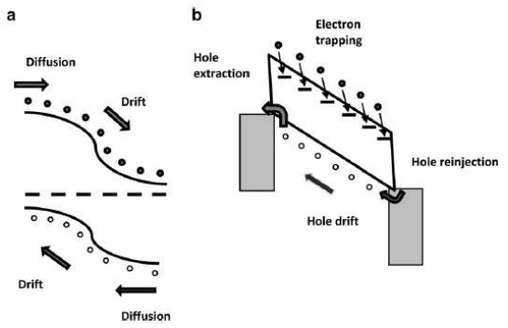

Fig. 1: Operating mechanisms of a) photodiodes and b) photoconductive photodetectors. Reproduced from [10]. Copyright 2011 Elsevier.

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