Characterisation of PbS/CdS Qdot absorption on SOI waveguides.

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We determine the losses induced by functionalizing 450 nm wide SOI waveguides planarized with an oxide layer with mono- and multilayers of colloidal PbS/CdS core shell quantum dots (Qdots). Close packed Qdot mono- and multilayers are locally deposited on the waveguides by combining Langmuir-Blodgett deposition with optical lithograpy. For a TE dominated mode-excitation, we find that this induces an additional waveguide loss of 3 dB/mm at a wavelength corresponding to the bandgap of the Qdots. Simulations where the Qdot layers are modeled as a Maxwell-Garnett effective medium yield values that are in line with the experimental losses.

Introduction

Over the years silicon photonics has matured from being a research area to a commercial reality. Due to the high index contrast between Si and air, it allows for extremely compact photonic circuits using CMOS-processing methods. This makes the fabrication of photonic ICs a cost-effective and high-yield process. However, major drawbacks of Si are its poor nonlinear figure of merit and indirect bandgap making it unsuitable for optical-signal processing and light emitting applications. Colloidal lead salt semiconductor nanoparticles or Qdots (PbX, X=S,Se) are an appealing class of materials, due to the combination of size-tunable optical properties in the NIR range, high photoluminescence quantum efficiency and high nonlinear figure of merit[1]. This makes them a solution for realizing light sources, lasers and all-optical signal processing. Opposite from vacuum deposition techniques, colloidal Qdots allow for suitable and cheap wet processing, favorising them for large-area processing. A problem facing the integrating of Qdots on SOI, is how to optimally coat the waveguides with Qdots and model the layer optical properties. A solution of the problem will allow to minimize the Qdot footprint and predict the losses, necessary requirements for optimal Qdot hybrid waveguide operation. In this paper we will show how to coat SOI waveguides, planarized with an oxide cladding, with mono- and multilayers of PbS/CdS Qdots. We will determine the optimal deposition parameters for achieving a close packed layer. Simulations predict loss values that are in line with the experimental results.

Syntheses of PbS/CdS quantum dots

We use PbS/CdS Qdots with a PbS core size of 5.3 nm, an overall diameter d of 7 nm and a size dispersion of 8%. This results in a band gap absorption that peaks at 1515 nm. The PbS core Qdots are prepared using a procedure as described in [2]. For the CdS shell

growth, a cationic exchange procedure was used, starting from a 5.7μM dispersion of PbS Qdots in toluene. The dispersion is heated to 125°C in a reaction flask placed under a nitrogen atmosphere. Cadmium oleate is added in a 20:1 Cd to Pb ratio. This starts a cationic exchange process in which the outer Pb^{2+} cations are replaced by Cd^{2+} cations, leading to a heterostructure with a PbS core and a CdS shell. The reaction is stopped by quenching it with a double amount of ethanol as compared to the reaction volume. After centrifugation and decantation, the PbS/CdS Qdots are suspended in toluene. A TEM image of the dots is given in Fig.1(b).

Close-packed multilayers of PbS/CdS Qdots on planarized waveguides.

For the integration on SOI oxide planarized waveguides (PWGs), a set of 4 identical waveguides is used with a width of 450 nm and a height of 220 nm. Qdot patterns are formed by combining Langmuir-Blodgett (LB) deposition and UV lithography using a previously described method[3]. In this way, we create Qdot strips on the waveguides with a width of 20μm and an interaction lengths of 200, 500, 1000 and 1500μm. In the LB technique, a known quantity of Qdots is dried and redispersed in 33 μL of toluene with a Qdot concentration of 9μM. Then, this Qdot solution is spread out on ultrapure water, and the solvent is allowed to evaporate. After evaporation of the toluene, the Qdot layer is compressed by closing the barriers at a rate of 10 cm^2 min^{-1}. During compression, the pressure is monitored with a Wilhelmy plate attached to a microbalance. At the target pressure, the compressed layer is transferred to the substrate of choice (*e.g.*, mica, glass or SOI waveguides) by vertically pulling it out of the water at a speed of 5 mm min^{-1}. To analyze the quality of the LB layers, we first deposit them on a mica substrate at two different LB target pressures (18 mN/m and 30 mN/m). Mica is chosen as a test substrate as it has a low surface roughness (1 nm) and it allows for an easy check of the layer uniformity using atomic force microscopy (AFM). Fig.1(c) shows the corresponding LB-isotherms and Figs.2(a,c) represent AFM images of the Qdot layer on mica, deposited at 18 and 30 mN/m, respectively. At a pressure of 18 mN/m, we observe a large hole, indicating the transfer of an incomplete monolayer. At a pressure of 30 mN/m, the surface is smooth, indicating a closed packed monolayer. This results provide us with the parameters we need to use for the deposition of PbS/CdS mono- and multilayers on the SOI chips with the oxide planarized waveguides(PWGs). In the next section, we will discuss the measured Qdot loss values on the PWGs. This will allow us to asses the Qdot medium optical constants, providing a check for the proposed modelling on PWGs.

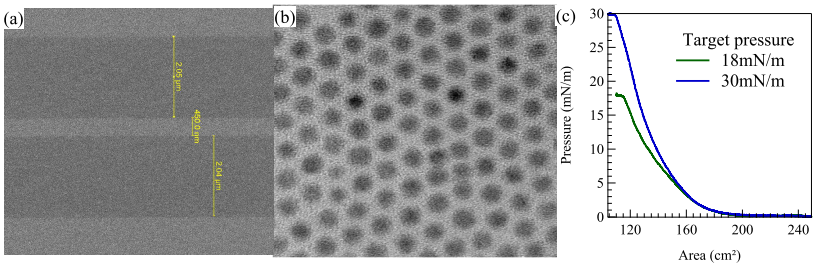

Figure 1: (a) Top view of the oxide planarized SOI waveguides.(b) TEM picture of PbS/CdS Qdots. (c) LB-isotherms for target pressures of 18 and 30mN/m.

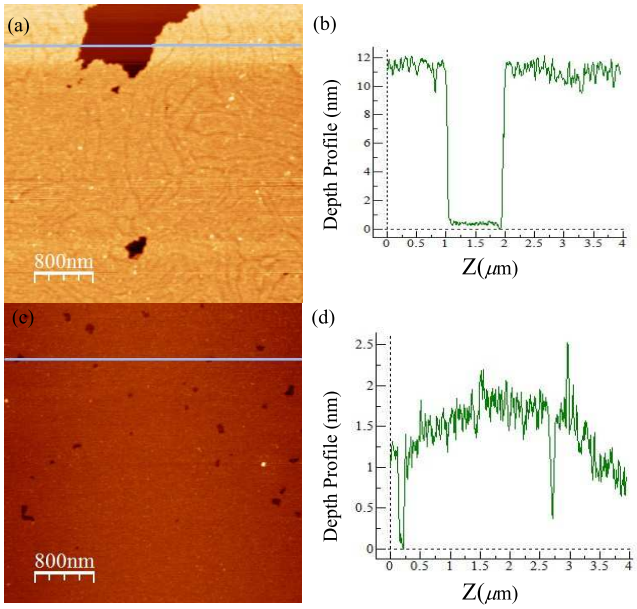

Figure 2: (a) AFM profile of the LB deposition at 18mN/m showing a sub-monolayer on the mica surface. (b) Depth profile corresponding at drawn line in Fig.1(a) showing a depth of 10nm in agreement with the Qdot sizes. (c) AFM profile of the LB deposition at 30mN/m showing a close packed a monolayer on the mica surface. (d) Corresponding depth profile shows a variation of 1nm in agreement with the surface roughness of mica.

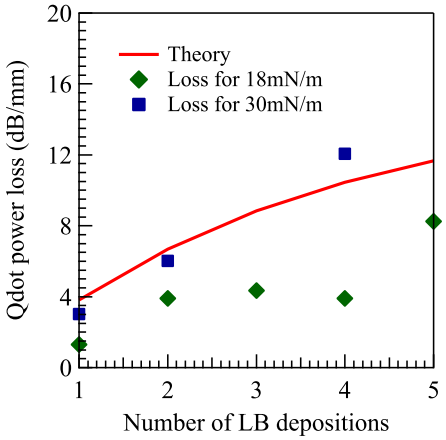

Figure 3: PbS/CdS Qdot losses at 1.55μm showing good agreement with simulations for a deposition at 30mN/m confirming the creation of a close packed layer on PWGs.

Qdot loss measurements and simulations

In Fig.3, we show the measured absorption losses at 1.55 μm of the quasi-TE mode of the PbS/CdS coated PWGs. The coating is done by successive LB depositions, at fixed target pressure, to create Qdot multilayers. The losses are determined by subtracting the transmission values of the PWGs at different interaction lenghts from a reference length of 200μm. The LB at 18mN/m yields no difference in absorption between second, third and fourth deposition. Indeed, as seen on the coated mica subtrate Fig.2(a), addition of an extra layer will mainly fill up gaps of the previous layers, which will not result in an increase in absorption losses as expected from mode simulations. The simulations are performed by assuming the Qdot layer as a homogeneous close packed layer. Once the intrinsic PbS/CdS Qdot refractive index is determined we estimate the layer refractive index *n* by considering the layer as a mix of Qdot spheres surrounded by a host environment (air/ligand molecules). Maxwell-Garnett theory yields then a complex value *n* of 1.3+0.005i for the layer. Simulations yield the red in curve in Fig.3(b), showing a good agreement with the LB deposition at 30 mN/m. This is in line with the results on mica and infers that the PWGs are coated with a close packed monolayer of PbS/CdS Qdots, yielding a minimal coating footprint on the PWGs. The absorption losses of Qdots increase by number of added Qdot layers with a typical loss value of 3dB/mm for each monolayer.

Conclusion

We determined the absorption coefficient of PbS/CdS core shell colloidal quantum dots (Qdots) deposited on 450 nm wide SOI waveguides planarized with an oxide layer. We optimized the deposition parameters on SOI waveguides to obtain a closed packed monolayer of Qdots using the Langmuir Blodgett technique. We show that the typical induced waveguide losses for a PbS/CdS Qdot monolayer excited with the quasi-TE mode at 1.55μm around the bandgap transition of the Qdots is 3dB/mm. Simulations assuming the Qdot layer as a homogeneous layer predict values that are in line with the experimental losses. Efficient modeling of the Qdot layers on PWGs enables to reduce the Qdot footprint and predict the losses, which is necessary for making hybrid Qdot devices.

Acknowledgements

We acknowledge the Institute for the Promotion of Innovation through Science and Technology in Flanders (IWT- Vlaanderen) for a scholarship (A.O.). This project was also supported by the Belgian Science Policy Office (IAP P7/35). We acknowledge Stijn Flamée and Liesbet Van Landschoot for respectively the TEM and SEM picture.

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