Colloidal Quantum Dot Silicon Nitride Platform

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The tunability of semiconductor quantum dots offers many opportunities for development of on-chip integrated light sources. Therefore we want to develop a high index contrast waveguide platform compatible with colloidal quantum dots (CQDs) integration. Silicon nitride (Si_3N_4) is promising because of its high index contrast with air and compatibility with the emitting wavelengths of CQDs. We have developed recipes for low temperature Si_3N_4 deposition (helps us to retain the quantum yield of CQDs) and etching. With these optimized recipes, we demonstrated waveguide loss at 900 nm of 0.95dB/cm @ 2um width (without CQDs and 4dB/cm @ 2um width (with CdSe/CdS CQDs having a band gap transition at 610 nm embedded), while the CQDs keep quite good quantum efficiency and couple efficiently into the waveguide.

Introduction

A full integrated photonics platform requires an efficient light emitter. On the silicon integrated photonics platform, researchers have managed to use bonding techniques to combine III-V materials (which exhibit excellent light properties as light emitters) with the silicon photonics platform. Using these bonding techniques efficient on chip integrated light sources were demonstrated. However, it is difficult to scale up this technology to full wafer scale and alternatives are still being searched for.

Colloidal quantum dots (CQDs) are nanometer-sized semiconductor particles synthesized and suspended in the solution phase using chemical methods. In the past several decades, they have attracted considerable attention as an important new class of materials because their high quantum yield and wide-ranging spectral tunability afforded by the quantum size effect make them perfect candidates for realizing an on chip light source. Since CQDs are synthesized using wet chemistry, they are mostly investigated while still in solution or as stand alone films. For further intergration, there is a need of developing methods to embed CQDs in a solid matrix, guaranteeing both stability and functionality. [1]

A high index contrast waveguide platform is particular interesting for integrated photonics as it allows small bending radii and hence compact devices. The traditional silica waveguide platform provides a very large transparent window, ranging from the visible to the infrared. However, its low index contrast results in large devices. The silicon waveguide platform provides a very high index contrast but it can not support shorter wavelengths. Si_3N_4, which is also widely used in the CMOS industry as a dielectric, has proven to be a very good optical waveguide material and has a transparent window covering both the visible and the infrared wavelength ranges. Moreover, its relatively high index (~2) offers a small bending radius and a high mode confinement. All these features make this material very suitable for integration with CQDs.

In this work, we developed a Si_3N_4 waveguide platform for integration of CQDs. First, we demonstrated low loss Si_3N_4 waveguides consisting of just a single layer of Si_3N_4

and double layers of different types of Si_3N_4 films. Next we demonstrated low loss Si_3N_4 waveguides with a monolayer of CdSe/CdS CQDs in the middle. We pumped this waveguide and observed the luminescence from the CQDs. However, due to the thin layer of CQDs and re-absorption from the layer, the output power is not yet very high. [2]

Si_3N_4 Waveguide Platform

Our aim is to develop a Si_3N_4 platform with integrated CQDs, maintaining CQDs luminescence while having a low waveguide loss at the same time. We would like to position the CQDs layer in the area where they have high overlap with the electromagnetic field inside the waveguide. Previous experiments show that a high temperature PECVD environment damages the CQDs and lower their photoluminescence. So we proposed a sandwich waveguide structure as shown in Figure 1, consisting of a standard Si_3N_4 layer (deposited using PECVD at 270℃), the CQD layer and then a second Si_3N_4 layer deposited at low temperature (120℃). The CQD layer can be deposited using the Langmuir-Blodgett (L-B) method or using spin coating. Reducing the temperature of the second Si_3N_4 to 120℃ reduces its optical quality somewhat but helps preserving the luminescence of the CQD-layer. [3] [4] A single etch step then determines the waveguide structure.

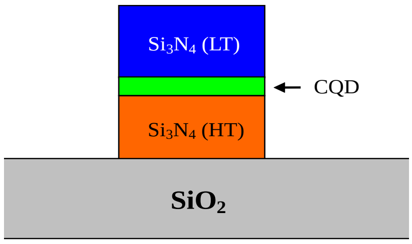


Figure 1. CQD integrated sandwich waveguide structure

We have fabricated spiral waveguides with different length and widths and measured the waveguide transmission for different wavelengths. From these we determined the waveguide loss at 900, 1310 and 1550 nm. The spiral waveguide lengths are 1, 2, 4 and 8 cm, and the spiral waveguide widths are 0.8, 0.9, 1, 1.1, 1.2, 1.5, and 2 µm, respectively. Figure 2 shows the waveguide loss at 900 nm with just one layer of 200 nm high temperature Si_3N_4. As we can see the waveguide loss goes down as the waveguide width is increased. This indicates that for the narrow waveguide, the loss mainly comes from the sidewall roughness. As the waveguide becomes wider, overlap of the sidewall with the modal field decreases, thereby resulting in a reduced scattering loss. Also from Figure 2 we notice a dramatic increase of loss for waveguides narrower than 1µm. This indicates our lithography system cannot guarantee a good pattern transfer when the feature size gets below 1µm and the defects introduced result in additional loss.

We also fabricated double layer stack Si_3N_4 waveguides, initially without CQDs layer. As shown in Figure 1, these waveguides have one layer of high temperature Si_3N_4on the bottom and one layer of low temperature Si_3N_4 on the top, both layers' thickness is 200nm. Figure 3 shows the result of the waveguide loss measurement. Compared to the waveguide loss of just one layer of high temperature nitride, the loss of the double layer waveguide

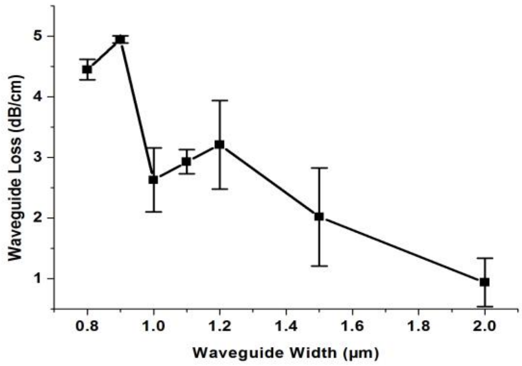


Figure 2. Si_3N_4 waveguide loss at 900nm. Waveguide has one 200nm layer of high temperature Si_3N_4.

increases considerably. The extra loss mainly comes from the additional sidewall scattering. Because here two different layers are used, the etching process reduces in quality and additional sidewall roughness is introduced. There is also some loss caused by the low quality of low temperature Si_3N_4 and the defects from the interface. However, as above, the waveguide loss decreases for wider waveguides. The waveguide loss measured at 1550 nm is very large and originates from the OH^- absorption peak around 1520 nm. This loss can be reduced by high temperature annealing, but this will damage the CQDs if we want to have CQDs embedded in the waveguide.

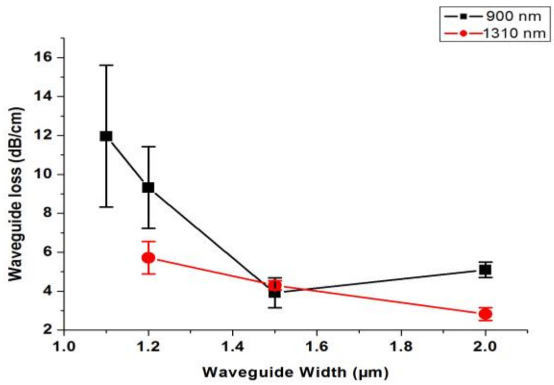
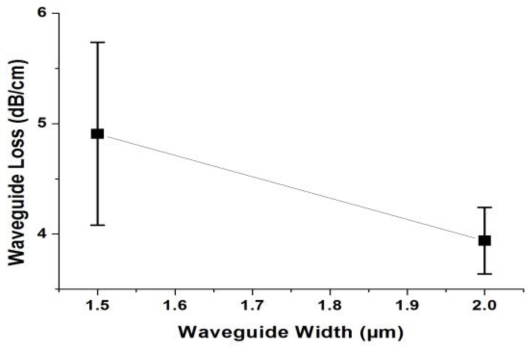


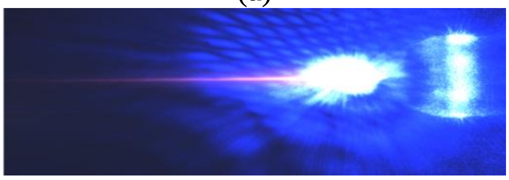
Figure 3. Si_3N_4 waveguide loss at 900nm and 1310nm. The waveguide consists of a 200nm layer of high temperature Si_3N_4 and a 200nm layer of low temperature Si_3N_4.

We also fabricated CQDs embedded Si_3N_4 waveguides and measured the waveguide transmission. The embedded CQDs have an emission peak at 610 nm when they are in the solution phase. The peak will slightly shift when embedded in the solid matrix. [3] The embedded CQDs layer is deposited using the Langmuir-Blodgett method, guaranteeing a perfect monolayer of CQDs.

From Figure 4(a), we can see that with one monolayer of CQDs embedded in the waveguide, the waveguide loss did not dramatically increase. With transmitted 900 nm light having a lower photon energy than the CdSe/CdS CQDs' bandgap, the CQDs layer shows very low absorption and scaterring.



(a)



(b)

Figure 4 (a) Si_3N_4 waveguide loss at 900nm with monolayer of CQDs inside
(b) Camera picture of Si_3N_4 waveguide with monolayer of CQDs inside pumped with side coupled blue light

transmitted 900nm light. We also tried to pump the waveguide with a 445 nm laser, as shown in Figure 4(b). We can clearly see the luminescent red light being scattered along the waveguide and decaying as the light propagates along the waveguide. Thus far we have not yet successfully collected the luminescence because the signal is very weak when reaching the end of the waveguide. We assume this is because of CQDs' re-absorption, which we will verify by further experiments.

Conclusion

We have experimentally demonstrated a colloidal quantum dot silicon nitride platform. By improving the deposition and etching processes, we have developed the technique to retain the photoluminescence from CQDs and obtain low waveguide loss at the same time. We demonstrated the emission from CQDs couples very well into the waveguide .

References

[1] Jin Young Kim, Oleksandr Voznyy, David Zhitomirsky, and Edward H. Sargent, "25^{th} Anniversary Article: Colloidal Quantum Dot Materials and Devices: A Quarter-Century of Advances," Advanced Materials, vol. 25, issue 36, 4986-5010, Sep. 25, 2013.

[2] A. Omari, P. Geiregat, D. Van Thourhout, Z. Hens, "Light absorption in hybrid silicon-on-insulator/quantum dot waveguides," Optics Express, vol. 21, issue 20, p.23272-23285, Sep. 2013.

[3] B. De Geyter, K. Komorowska, E. Brainis, P. Emplit, P. Geiregat, A. Hassinen, Z. Hens, D. Van Thourhout, "From fabrication to mode mapping in silicon nitride microdisk with embedded colloidal quantum dots,"Applied Physics Letters, vol.101, issue 16 p.161101~4, Oct. 2012.

[4] Lambert, K.; Capek, R. K.; Bodnarchuk, M. I.; Kovalenko, M. V.; Van Thourhout, D.; Heiss, W.; Hens, Z., Langmuirâˆ’Schaefer Deposition of Quantum Dot Multilayers. *Langmuir*, vol 26, p. 7732-7736, 2010.