Design of integrated nanocrystal light sources

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***Abstract*—We design and optimize different types of ultra-compact integrated light sources using colloidal nanocrystals as the gain medium. Transparency gain and spontaneous emission enhancement are compared.**

Keywords-colloidal nancrystals; integrated light sources; silicon photonics

I. INTRODUCTION

Over the last decade significant progress has been achieved in realizing silicon based photonic integrated circuits (PIC), fabricated using processes developed originally for the CMOS (complementary metal-oxide-semiconductor) industry. However, realizing an efficient integrated light source is still one of the major challenges for the future development and application of silicon PICs. Therefore we propose a novel solution using colloidal nanocrystals as the gain material. The advantages of colloidal NCs include their easy solution based synthesis, their wide and tunable range of light emission, and the room temperature deposition. Our proposal is based on earlier work by Caruge and coworkers [1], who demonstrated electrical injection for light sources based on colloidal nanocrystals using conductive oxide layers for the hole and electron transport layers. In this paper we propose and compare to integrate a similar structure with either silicon-on-insulator (SOI) based photonic circuits, as was proposed in [2] for realizing detectors or with a suitable metal layer stack for generating surface plasmon polaritons (SPP), as was reported in [3], using silicon nanocrystals. Both structures are investigated in detail and compared in terms of losses, confinement factor and transparency gain.

II. MODELING

The first issue in modeling the proposed integrated colloidal nanocrystal (NC) light sources is the model of the NCs themselves. Because of their extremely small size (<10 nm) and their large number in one device, it is unpractical to put the exact structure of every NC in the simulation model. The concept of local field factor provides a useful approximation for the NCs. The local field factor (f_{LF}) describes the ratio between the electric field inside (E_{in}) and outside (E_{out}) of a particle, when the distance between particles is much larger than the size of the particles [4]:

$$f_{LF} = E_{in}/E_{out} = 3\varepsilon_S/(\varepsilon_R + i\varepsilon_I + 2\varepsilon_S) \tag{1}$$

where ε_S is the dielectric constant of the particle material and ε_R and ε_I are the real and imaginary part of the dielectric constant of the surrounding material. The colloidal NCs in the designed structures have a dielectric constant of about 6.25. Since they are covered by organic ligands and sandwiched between oxide layers, the dielectric constant of the surrounding can be approximated to be 4. So the calculated f_{LF} is about 0.84. Fig.1 gives the schematic of the integrated NC light sources, and the modeling of NC layers using the local field factor.

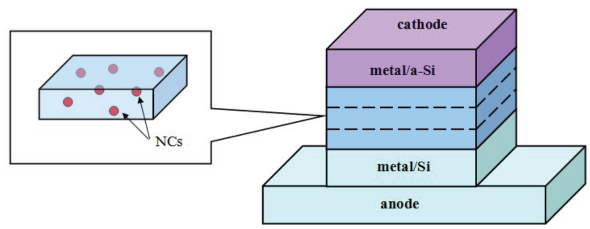


Figure 1. Schematics of the models for the light source and the NCs.

One important factor that can limit the performance of the integrated NC light sources is the optical loss. In this model, if metals are used as the electrodes, the optical absorption by metals has to be taken into account. Besides, the scattering loss caused by all the boundaries in Fig. 1 also needs to be considered. The total optical intensity loss in the designed device can be expressed as:

$$\alpha = \alpha_m + \alpha_s \tag{2}$$

where the absorption loss (α_m) can be extracted from the imaginary part of the effective index of the solved mode. The scattering loss (α_s) was estimated by calculating the normalized light intensity at the boundaries and then comparing with a reference SOI waveguide by assuming the same roughness [5].

From the loss coefficient, the propagation length can be calculated as:

$$L = 1/(\alpha_m + \alpha_s) \tag{3}$$

Next, it also need to be noted that only part of the mode in the structure in Fig. 1 will have interaction with the NCs. The confinement factor in the NCs can be defined as:

$$C = \frac{|f_{LF}|^2 \cdot n_A c\varepsilon_0 \iint_A |E|^2 dxdy}{\iint_\infty \mathrm{Re}\{E \times H^*\} \cdot \vec{e_z} dxdy} \tag{4}$$

where n_A is the refractive index of the NC region and $\vec{e_z}$ denotes the direction of light propagation.

So the transparency gain can be calculated as:

$$\gamma = (\alpha_m + \alpha_s)/C \tag{5}$$

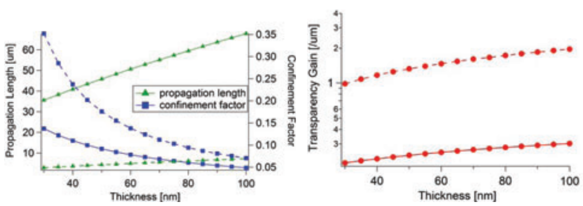
Last, as is shown in Fig. 1, the NCs are confined in an extremely small cavity (transversally). So the NC light sources can benefit from spontaneous emission enhancement to have more efficient light emission. In two dimensional (2D) waveguide structures, the enhancement factor (F) can be calculated as [6]:

$$F_{SP} = 3c\lambda_0^2 / \left(4\pi n^3 v_g A_{eff}\right) \quad (6)$$

where v_g is the group velocity of the mode in the waveguide and A_{eff} is the effective area defined as the integral of the light intensity over the 2D area divided by the light intensity at the light emitter's position. The transparency gain and the enhancement factor are two important criteria in comparing different NC light source designs.

III. Results

The first type of source we considered used a 220 nm thick silicon nanowire as the anode. We initially combined this structure with a silver cathode (Fig. 1). All simulations were carried out for a wavelength of 1.55 µm. The thickness of the NC region was kept at 20 nm, corresponding to 2 NC layers. It was found that both the propagation length (L) and the confinement factor (C) are much more dependent on the thickness of the carrier transport layers than on the width of these layers. The solved mode in this structure is quasi-TM, with the electric field mainly in the *y* direction and the magnetic field in the *x* direction. Fig. 2(a) shows the dependence of L (green triangle) and C (blue square) on the total thickness of the NC region and the carrier transport layers (solid lines), when the width is fixed to 300 nm to keep the structure single mode. The calculated transparency gain (γ) at different thicknesses is given Fig. 2(b) (solid line).



(a) (b)

Figure 2. Propagation length, confinement factor (a) and transparency gain (b) for different total thickness in the NC light sources on Si (solid lines) and in the NC light sources for SPPs (dashed lines).

From this figure, we can observe that L becomes longer but the value of C decreases, as the thickness increases. The calculated γ goes up with the thickness, indicating thinner carrier transport layers are more advantageous in order to achieve a smaller γ. The calculated enhancement factor FSP for the structure with total thickness of 60 nm was 8.84.

In the previous design, the absorption loss by silver is orders of magnitude larger than the scattering loss. In the second design we replaced the silver cathode by an amorphous Si (a-Si) layer. This lowers the absorption loss significantly and L can be much longer. This kind of NC light sources can be optimized by changing the thickness of the a-Si, while keeping the width and total thickness of the central layers at 300nm and 60 nm respectively. Fig. 3 presents the loss coefficients by material absorption, by scattering and the total loss coefficient. The calculated γ is also given. The inset shows the typical E_y distribution in this kind of structure. From the figure we see that the scattering loss is now much larger than the absorption loss, and γ is about two orders of magnitude smaller than in the previous structure, suggesting much better performance when replacing the silver cathode by an a-Si layer. The calculated F_{SP} in this structure is about 5.84.

In our last design, we used silver and gold as respectively the cathode and anode. Also in this case the total thickness of the layers had a stronger influence on L and C than the width of the layers. L and C as function of the total thickness are shown in Fig. 2(a) (dashed lines). The width was fixed to 200 nm to keep it single mode. Similar trends for L and C can be observed, though the value of L is about one order of magnitude smaller. For this kind of structure, γ is much larger than in previous designs (Fig. 2(b), dashed line). However, F_{SP} can be as high as 33.9 for this kind of structures.

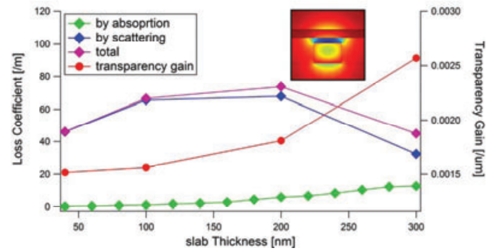


Figure 3. Confinement factor and transparency gain for different a-Si thickness.

Table I gives clear comparisons of the various parameters in these three kind of integrated NC light source designs with the same total thickness of 60 nm.

cathode	*silver*	*a-Si*	*silver*
anode	*Si*	*Si*	*gold*
L (µm)	50.6	2.17×10^4	4.94
C (%)	7.81	4.93	13.8
γ ($\times10^{-3}$/µm)	253	1.81	1470
F_{SP}	8.84	5.84	33.9

TABLE I. Key parameters in different integrated NC light sources.

IV. Conclusion

A model for different types of integrated colloidal nanocrystal based light sources was built using the local field factor. Different designs of integrated light sources were proposed either using silicon or metal as the anode. The former can have the lowest transparency gain by using amorphous Si as the cathode, while the latter has the highest spontaneous emission enhancement.

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