

Journal of Nanophotonics

SPIEDigitalLibrary.org/jnp

Whispering gallery modes at 800 nm and 1550 nm in concentric Si-nc/Er:SiO₂ microdisks

Elton Marchena
Brandon Redding
Tim Creazzo
Shouyuan Shi
Dennis W. Prather

Whispering gallery modes at 800 nm and 1550 nm in concentric Si-nc/Er:SiO₂ microdisks

Elton Marchena, Brandon Redding, Tim Creazzo, Shouyuan Shi, and
Dennis W. Prather

University of Delaware, Department of Electrical and Computer Engineering,
140 Evans Hall, Newark, Delaware 19716
marchena@ee.udel.edu

Abstract. We examined a concentric Si nanocrystal (Si-nc) and Er doped SiO₂ (Er:SiO₂) microdisk structure supporting high-Q whispering gallery modes (WGMs) at both visible and telecom wavelengths. This structure provides a means to utilize Si-nc luminescence as an optical pump for an Er:SiO₂ cavity without subjecting a telecom-wavelength, Er:SiO₂-based mode to loss mechanisms associated with the Si-nc material. After fabricating a concentric microdisk consisting of an inner Si-nc disk and an outer Er:SiO₂ ring, we characterize visible wavelength WGMs excited by the Si-nc photoluminescence and observed spectrometer limited quality factors as high as 10³. Telecom-wavelength photoluminescence from the Er:SiO₂ ring was measured to have a quality factor as high as 10⁴ in the erbium luminescence region using a passive pulled fiber setup.

Keyword: microresonator, nanocrystal, whispering gallery mode

1 INTRODUCTION

In recent years Si photonics has attracted considerable interest due to the possibility of expanding the functionalities of electronic circuits. Si photonics can provide low loss waveguides, high band width, and immunity to electromagnetic noise. Numerous Si components have been investigated including waveguides, modulators, detectors, and filters [1-3]. A missing component for the monolithic integration of Si photonics is a Si-based light emitter. Si is a good optical material but a poor light emitter due to its indirect band structure. The discovery of light emission from porous Si at room temperature [4] has boosted intense research in quantum confined Si structures such as quantum wells and quantum dots (called nanocrystals). Si nanocrystal (Si-nc) films are a promising candidate for Si-based light emission due to their high efficiency and tunability. Efficient photoluminescence (PL), electroluminescence (EL), and optical gain have been demonstrated in Si-nc films [5, 6]. Recently, Si-nc microdisks have been fabricated demonstrating enhanced spontaneous emission and WGMs with quality factors on the order of 10³ [7-9]. A major factor limiting the use of Si-nc as a lasing material is the presence of free carrier absorption under high pump powers.

While lasing from Si-nc films remains uncertain, the material may prove useful as a light-emitting-diode (LED) or as a pump for another lasing material [10]. As a recent example, a Si-nc based metal-oxide semiconductor LED with maximum EL output power of ~1 μW has been demonstrated [11]. This output power is comparable to the minimum pumping threshold of 4.5 μW reported for an erbium-doped SiO₂ (Er:SiO₂) toroidal laser [12]. In the concentric microdisk configuration investigated in this work, we seek to efficiently couple Si-nc luminescence to a spatially separated Er:SiO₂ region. The Si-nc emission could then act as an optical pump for an Er:SiO₂ lasing cavity without subjecting the lasing mode to Si-nc based free carrier absorption. In addition, by coupling the Si-nc emission to a high-Q WGM overlapping the Er:SiO₂ ring, we increase the interaction length of the pump signal, thus

mitigating limitations due to erbium's low absorption cross section, which is ~ 3 times smaller at 800 nm than 1480 nm (the pump wavelength typically used in Er:SiO₂ toroidal lasers) [13]. Indeed, the ability for PL from an inner Si-nc microdisk to excite WGMs extending into an outer SiO₂ ring was recently demonstrated [14]. In this work, we present a fully integrated concentric microdisk consisting of an inner Si-nc disk and an outer Er:SiO₂ ring. We demonstrate the co-existence of high-Q WGMs at visible wavelengths, as excited by the Si-nc PL, and at telecom wavelengths within the erbium emission spectrum.

In the following section we discuss the fabrication process for the Si-nc/Er:SiO₂ concentric microdisk structure. In Section 3 we present characterization of the visible wavelength WGMs in the Si-nc PL spectra and telecom wavelength WGMs, measured using a passive pulled fiber setup, in the erbium emission region. Finally, we discuss the implications of the presented device and its potential utility as a Si based light source for Si photonics.

2 FABRICATION

The concentric microdisk fabrication process begins by depositing a 110 nm thick Si-nc film on a Si substrate. The Si-nc film was deposited by plasma enhanced chemical vapor deposition (PECVD) as alternating a-Si and SiO₂ layers. After deposition, the sample was annealed at 1100 °C in an N₂ environment to precipitate nanocrystal formation in the a-Si layer, as confirmed by transmission electron micrograph (TEM), shown in Fig. 1(a). By controlling the a-Si layer thickness we limited the size of the nanocrystals, enabling us to tune the emission to 800 nm [14], near an erbium absorption line [13].

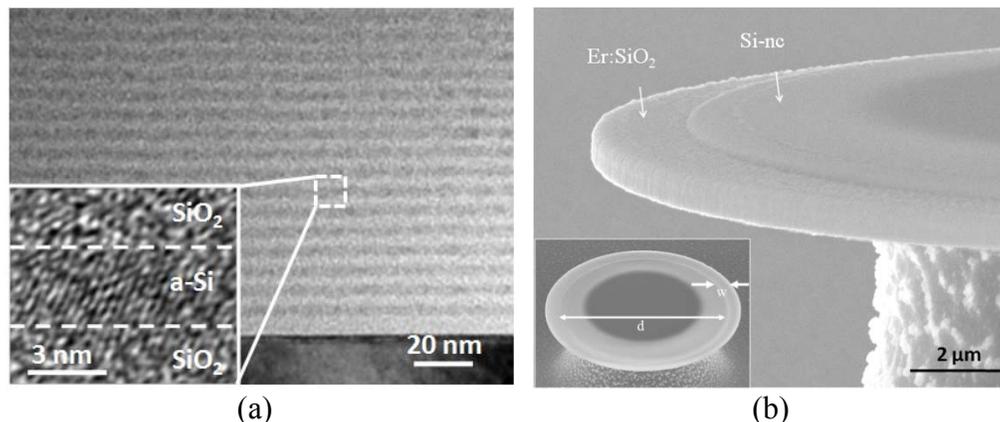


Fig. 1. (a) Transmission electron microscope image of the Si/SiO₂ superlattice. Inset shows Si-nc formations in the a-Si region after annealing. (b) SEM image of a concentric Si-nc/Er:SiO₂ microdisk structure. Inset shows the SEM image of an entire microdisk.

After deposition of the Si-nc film, we patterned the inner microdisk using conventional optical lithography. The inner microdisk pattern was transferred into the Si-nc film via inductively coupled plasma (ICP) etching in a C₄F₈, SF₆, and Ar environment. After this initial etch we deposited a 200 nm thick SiO₂ layer via PECVD. A slightly larger disk was carefully centered above the original Si-nc disk and transferred into the SiO₂ using the same lithography and etching processes. At this stage the device consisted of an inner Si-nc disk covered with a slightly larger SiO₂ disk on a Si substrate. We then applied a selective ICP etching process in an SF₆ environment to undercut the Si substrate such that the concentric disk structure was suspended on a Si pedestal at its center. Finally, we deposited a 300 nm thick Er:SiO₂ layer via radio frequency (RF) magnetron sputtering covering the entire

concentric microdisk and performed a 1 hour, 1100 °C anneal in an O₂ environment to activate the erbium ions. A scanning electron microscopy (SEM) image of the final structure is shown in Fig. 1(b). The inset of Fig. 1(b) shows an SEM image of an entire concentric microdisk structure and labels the Si-nc diameter, d , and Er:SiO₂ overhang width, w . In the following section we will present characterization of a concentric microdisk with diameter, $d = 40 \mu\text{m}$ and an Er:SiO₂ overhang width of $w = 1 \mu\text{m}$.

3 CHARACTERIZATION

The fabricated concentric structure was characterized in both the visible and telecom spectra. In the visible spectrum, the structure was optically excited by a focused 532 nm laser incident from above with a pump density of 3 kW/cm². Photoluminescence originating in the inner Si-nc disk excites WGMs extending into the outer Er:SiO₂ ring and radiating in the plane of the disk. To collect the radiation, we align our collection optics to the edge of the disk and focus the emission into a spectrometer.

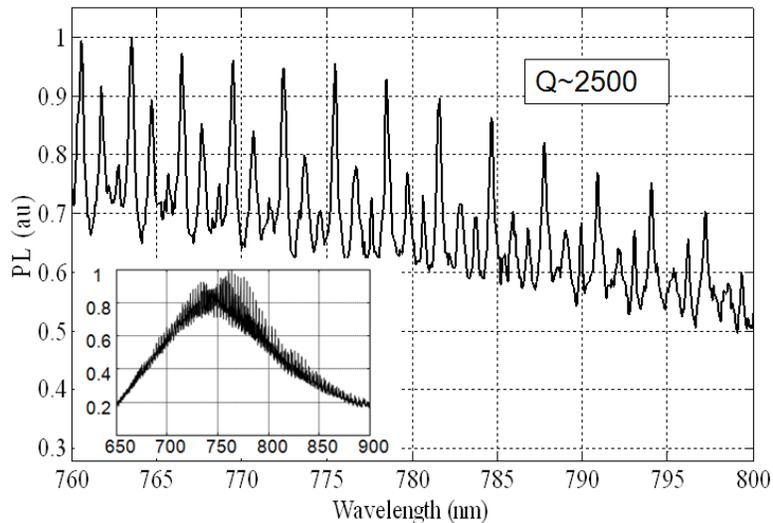


Fig. 2. Photoluminescence spectrum from a 40 μm diameter Si-nc disk with a 1 μm Er:SiO₂ outer ring. The observed quality factor is limited by our spectrometer resolution. Inset shows the broad PL spectrum.

The collected PL spectrum shows high-Q WGMs as can be seen from Fig. 2. The PL spectrum reveals multi-mode behavior, as expected for a concentric disk in which various higher order radial modes are excited [15]. The quality factors observed are as high as 2500, limited by the spectral resolution of our spectrometer. The background bias present in this measurement corresponds to the typical Si-nc PL emitted from the center of the disk which does not contribute to the WGMs. The inset of Fig. 2 shows the broad PL spectra from the concentric microdisk. Based on the free spectral range (FSR) observed for concentric disks with varying Er:SiO₂ widths, we confirm that the Si-nc based WGMs are confined at the outer edge of the Er:SiO₂ ring. Despite the interfaces involved, the quality factors for these WGMs are similar to those for typical Si-nc microdisks [8, 9].

The concentric disk structure was also characterized passively in the telecom spectrum using a pulled fiber setup. The disk was placed in close proximity to a 1 μm diameter fiber.

The fiber was made using conventional fiber pulling techniques [16]. A tunable laser was fed into one end of the fiber and collected with a detector at the other end. The transmission through the fiber was measured as a function of input wavelength and quality factors were determined by the drops in the transmission spectrum. This method allows us to resolve higher quality factors than is possible by analyzing the active PL spectrum with our spectrometer. Figure 3(a) shows the overall transmission spectrum for the same concentric disk analyzed above. Quality factors as high as 2×10^4 were measured and can be seen in Fig. 3(b). These quality factors are limited by sidewall roughness from our fabrication processes. These high quality factors imply that the fabrication process produces smooth side walls as confirmed by the SEM image. The inset of Fig. 3(a) shows the Er:SiO₂ PL spectrum for the concentric structure when optically excited by a 532 nm laser. Note that no active modes are observed since the modes within the Er emission spectrum are too close to each other for our spectrometer to resolve.

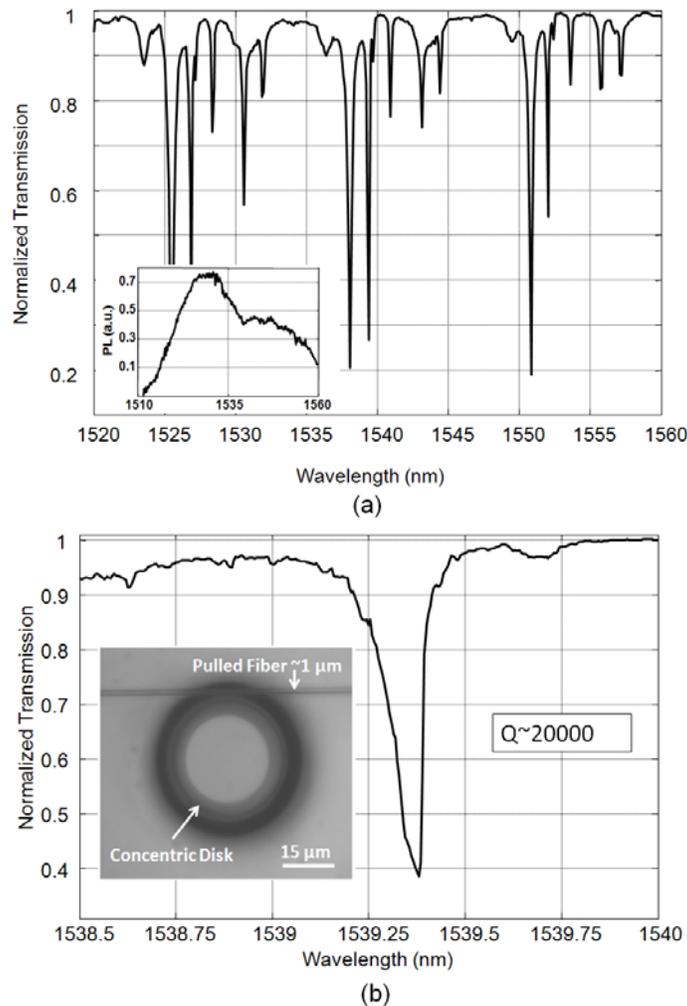


Fig. 3. (a) Passive telecom spectrum showing WGMs in a concentric structure measured with a pulled fiber. Quality factor indicated smooth sidewall roughness after fabrication. Inset shows the PL spectrum from the Er:SiO₂ outer ring when pumped with a 532 nm laser. (b) Close-up of a high-Q mode at 1539.35 nm. Inset shows a top view image of a concentric microdisk in close proximity to a 1 μm diameter pulled fiber.

As discussed above, the concentric microdisk structure presented in this work provides a means to utilize the efficient luminescence of Si-nc films as an optical pump for an Er:SiO₂ based lasing cavity. This approach, based on the spatial separation of the Si-nc and Er:SiO₂ film, provides a number of advantages compared to a plain Er:SiO₂ cavity or a more directly integrated erbium doped Si-nc film. The concentric approach may be extended to allow for electrical excitation by using Si-nc electroluminescence as the pump signal, whereas Er:SiO₂ is highly insulating. The spatial separation realized in the concentric disk design circumvents potential limitations due to Si-nc based loss mechanisms which may prohibit net gain in directly integrated erbium doped Si-nc materials. Thus, the presented structure, leveraging the separate advantages of Er:SiO₂ and Si-nc materials, could be extended to realize an electrically pumped, CMOS compatible light source operating in the telecom regime.

4 CONCLUSION

We presented an integrated Si-nc/Er:SiO₂ microdisk in which Si-nc based luminescence may act as an optical pump for Er:SiO₂ without subjecting Er:SiO₂ based modes to Si-nc related loss mechanisms such as free carrier absorption. The integrated device could leverage the efficient electroluminescence of Si-ncs and the demonstrated lasing capabilities of erbium doped glass resonators. In this work we presented fabrication of a concentric microdisk structure for optical characterization. We observed excitation of WGMs in the PL spectrum of the Si-ncs, confined at the edge of the outer Er:SiO₂ ring. Si-nc based modes exhibited spectrometer limited quality factors as high as 2500. We employed a passive pulled fiber technique to measure quality factors on the same disk in the erbium emission region, near 1530 nm, and observed quality factors as high as 2×10^4 . In the future we hope to refine our fabrication processes to minimize sidewall roughness and achieve higher quality factors needed for gain in erbium.

Acknowledgments

This work was supported in part by the U.S. Air Force Office of Scientific Research (AFOSR) under Grand FA9550-06-1-0470.

References

- [1] K. K. Lee, D. R. Lim, H. Luan, A. Agarwal, J. Foresi, and L. C. Kimerling, "Effect of size and roughness on light transmission in a Si/SiO₂ waveguide: experiments and model," *Appl. Phys. Lett.* **77**, 1617-1619 (2000) [doi:10.1063/1.1308532].
- [2] C. E. Png, G. T. Reed, R. M. H. Atta, G. Ensell, and A. G. R. Evans, "Development of small silicon modulators in Silicon-On-Insulator (SOI)," *Proc. SPIE* **4997**, 190-197 (2003) [doi:10.1117/12.476666].
- [3] A. W. Poon, L. Zhou, C. Li, N. K. Hon, and H. Chen, "Microring and microdisk resonator integrated circuits on a silicon chip," *Proc. SPIE* **6476**, 647607 (2007) [doi:10.1117/12.707849].
- [4] L. T. Canham, "Silicon quantum wire array fabrication by electrochemical and chemical dissolution of wafers," *Appl. Phys. Lett.* **57**, 1046-1048 (1990) [doi:10.1063/1.103561].

- [5] G. Franzo, A. Irrera, E. C. Moreira, M. Miritello, F. Iacona, D. Sanfilippo, G. Di Stefano, P. G. Fallica, and F. Priolo, "Electroluminescence of silicon nanocrystals in MOS structures," *Appl. Phys. A* **74**, 1-5 (2002) [doi:10.1007/s003390101019].
- [6] L. Pavesi, L. Dal Negro, C. Mazzoleni, G. Franzo, and F. Priolo, "Optical gain in silicon nanocrystals," *Nature* **408**, 440-444 (2000) [doi:10.1038/35044012].
- [7] R. Zhang, S. Seo, A. P. Milenin, M. Zacharias, and U. Gosele, "Visible range whispering-gallery mode in microdisk array based on size-controlled Si nanocrystals," *Appl. Phys. Lett.* **88**, 153120 (2006) [doi:10.1063/1.2195712].
- [8] R. D. Kekatpure and M. L. Brongersma, "Fundamental photophysics and optical loss processes in Si-nanocrystal-doped microdisk resonators," *Phys. Rev. A* **78**, 023829 (2008) [doi:10.1103/PhysRevA.78.023829].
- [9] M. Ghulinyan, D. Navarro-Urrios, A. Pitanti, A. Lui, G. Pucke, and L. Pavesi, "Whispering-gallery modes and light emission from a Si-nanocrystal-based single microdisk resonator," *Opt. Exp.* **16**, 13218-13224 (2008) [doi:10.1364/OE.16.013218].
- [10] D. W. Prather, B. Redding, T. Creazzo, E. Marchena, and S. Shi, "Integration of Silicon Nanocrystals and Erbium Ring Cavities for a Silicon Pumped Er:SiO₂ Laser," *J. Nanosci. Nanotechnol.* **10**, 1-7 (2010) [doi:10.1166/jnn.2010.2038].
- [11] G. Lin, Y. Pai, and C. Lin, "Microwatt MOSLED using SiO_x with buried Si nanocrystals on Si nano-pillar array," *J. Lightwave Technol.* **26**, 1486-1491 (2008) [doi:10.1109/JLT.2008.922177].
- [12] J. Kalkman, A. Tchebotareva, A. Polman, T. J. Kippenberg, B. Min, and K. J. Vahala, "Fabrication and characterization of erbium-doped toroidal microcavity lasers," *J. Appl. Phys.* **99**, 083103 (2006) [doi:10.1063/1.2188050].
- [13] W. J. Miniscalco, "Erbium-doped glasses for fiber amplifiers at 1500 nm," *J. Lightwave Technol.* **9**, 234-250 (1991) [doi:10.1109/50.65882].
- [14] T. Creazzo, B. Redding, E. Marchena, J. Murakowski, and D. W. Prather, "Tunable photoluminescence and electroluminescence of size-controlled silicon nanocrystals in nanocrystalline-Si/SiO₂ superlattices," *J. Lumin. (at press)*, [doi:10.1016/j.jlumin.2009.11.007].
- [15] B. Redding, T. Creazzo, E. Marchena, S. Shi, and D. W. Prather, "Coupling Si nanocrystal microdisk emission to whispering-gallery modes in a concentric SiO₂ ring," *Opt. Lett.* **34**, 1384-1386 (2009) [doi:10.1364/OL.34.001384].
- [16] J. C. Knight, G. Cheung, F. Jacques, and T. A. Birks, "Phase-matched excitation of whispering-gallery-mode resonances by a fiber taper," *Opt. Lett.* **22**, 1129-1131 (1997) [doi:10.146-9592/97/151129].