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Publication date
2022

Document Version
Final published version

Published in
CLEO

Citation (APA)
Errando-Herranz, C., Gerlach, C., De Santis, L., Panuski, C., Prabhu, M., Raniwala, H., Christen, I., & Englund, D. (2022). Cavity-enhanced emission from an ensemble of color centers in silicon. In *CLEO: QELS_Fundamental Science, QELS 2022* Article FW5F.4 (Optics InfoBase Conference Papers). Optica Publishing Group (formerly OSA).

Cavity-enhanced emission from an ensemble of color centers in silicon

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Abstract: Optical quantum technologies require strong light-matter interaction. We couple silicon color center ensembles to high-Q/V cavities and show enhanced emission in the telecommunications O-band.

1. Introduction

The semiconductor revolution has already shown the vast scaling potential of solid-state systems. For this reason, a leading contender in the quantum information era is based on optical entanglement of quantum memories in the solid state. This will vastly benefit from enhanced interaction between light and matter in the form of cavity-coupled artificial atoms [1]. Traditional approaches based on diamond color centers face stringent limitations in fabrication and operation wavelengths, which has led to a bottleneck in the scaling of quantum technologies. Color centers in silicon have the potential to combine long coherence times with the scalability of silicon semiconductor technologies and the technological maturity of the optical telecommunication bands. Recently, single silicon color centers (G-centers) have been isolated in commercial silicon-on-insulator (SOI) samples, making them promising for quantum information processing [2]. However, no demonstration of cavity-coupled color centers in silicon has been reported to date.

Here, we demonstrate the generation of G-center ensembles in silicon-on-insulator samples and their coupling into high-Q-factor, small mode volume on-chip cavities.

2. Sample fabrication and description

The fabrication process follows [2], starting from a commercial SOI wafer with 220 nm silicon on 2 μm silicon dioxide. Cleaved chips from this wafer were implanted with ^{12}C with a dose of 2×10^{14} ions/cm^{-2} and 36 keV energy, and subsequently annealed at 1000 °C for 20 s in order to form the G-centers in the silicon layer. The sample was then processed by a foundry (Applied NanoTools) for electron beam patterning and etching, resulting in through-etched silicon cavities with SiO_2 bottom cladding and air as top cladding. As a final step, the sample was under-etched in a 49% solution of hydrofluoric acid for 2 min and dried using a critical point dryer.

We designed L3-type 2D photonic crystal cavities [3] with low mode volumes $\sim (\lambda/n)^3$ and high Q factors $\sim 10^4$, and optimized them for vertical coupling. The simulation result in Fig 1b shows the fundamental cavity mode for one of our cavities.

3. Measurement results

Our measurement setup consists of a cryogenic (46 K) confocal microscope (NA 0.9) equipped with infrared (O-band) and 532 nm excitation paths, and O-band collection. The collection path can be routed to a fiber-coupled superconducting nanowire single photon detector (SNSPD, system efficiency 83%) or to an infrared spectrometer.

Exciting with a continuous-wave 532 nm laser, we observe photoluminescence (PL) from the bulk SOI sections of our sample with a zero phonon line at 1278.8 nm, i.e. in the telecommunications O-band, characteristic of G-centers. By scanning our excitation and collecting the confocal emission from the sample, we obtained PL maps such as the one in Fig. 1a, which shows a 2x2 array of cavities with increased scattering of the PL emission in the cavity regions.

We measured the lifetime of our G-center ensemble in bulk SOI using a 532 nm pulsed laser with 50 μW power and a repetition rate of 78 MHz, yielding a single-exponential fit with a lifetime of $\tau = 5.39$ ns (Fig. 1c), in line with previous reports of G-center ensembles [4]. We measured power-dependent PL to determine the saturation

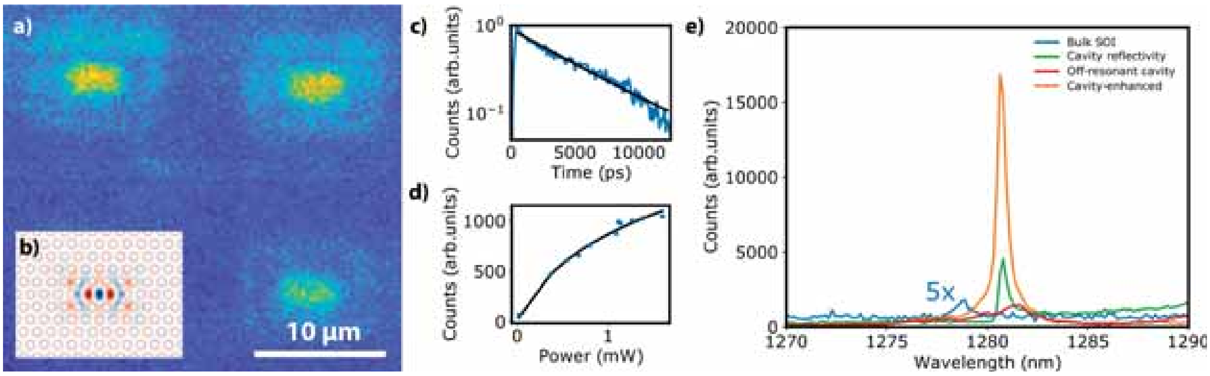

Fig. 1. a) Photoluminescence (PL) map showing the infrared scattering from silicon G-centers in an array of cavities. b) Simulation results showing the electric field distribution for the fundamental cavity mode. c) Lifetime measurement of our G-centers yield a lifetime of $\tau = 5.39$ ns. d) Power saturation measurement yielding Psat = 1.12 mW. e) PL spectra from a bulk SOI ensemble of G-centers (blue, magnified 5 times), infrared cavity reflectivity (green), PL from G-centers in a cavity off-resonant to the ensemble (red), and cavity-enhanced PL (orange).

characteristics of the ensemble, yielding a fit to an ensemble saturation curve [4] with a saturation power of 468 µW (Fig. 1d).

To characterize the cavity reflectivity we used a cross-polarization method, in which the excitation and collection polarizations are orthogonal to each other, and diagonal to the cavity mode [3]. This enables suppression of the direct reflection from the silicon and isolates the cavity signal. Using this measurement setup, we characterized a cavity centered at 1280.8 nm with a Q factor of ~ 2000, illustrated by the spectrum in Fig. 1e (green curve). This leads to a predicted Purcell enhancement of up to 160 for a spectrally-aligned color center.

The PL spectrum of the G-center ensemble in bulk SOI is shown in Fig. 1e (blue curve, magnified 5 times). To demonstrate that the increase in PL brightness is not solely due to increased scattering, we characterized the PL from another cavity that is off-resonant with respect to the G-center PL spectra (Fig. 1e, red curve). We observe a shift (~ 3 nm) and broadening of the inhomogeneous distribution of our ensemble between the off-resonant cavity and the bulk SOI measurements. We attribute this broadening, which we are currently investigating in depth, to increased environmental fluctuations from the nearby surfaces formed by the photonic crystal holes, and to differences in the strain environment from strain relaxation in suspended structures. The orange curve in Fig. 1e shows our cavity-enhanced G-center ensemble PL for a cavity aligned in resonance with the ensemble. In this device, we observe a clear enhancement of the PL intensity of $> 10\times$ with respect to the off-resonant cavity, and $> 45\times$ with respect to bulk SOI emission.

4. Conclusion

We demonstrated coupling between silicon color center ensembles and high Q/V on-chip cavities resulting in more than an order of magnitude enhancement in photoluminescence intensity. Our platform represents a crucial step towards large-scale quantum information processing based on strong light-matter interaction.

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