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Single photon emission from waveguide-integrated color centers in silicon

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Abstract: We demonstrate silicon color centers coupled to foundry-compatible silicon waveguides. We produced G-centers via carbon implantation in commercial silicon-on-insulator waveguides and measure through-waveguide single-photon emission in the telecommunications O-band.

1. Introduction

A central challenge for scalable quantum computing, sensing, and networking is the creation and distribution of entanglement among multiple individually-addressable qubits. Color centers in silicon emitting at telecommunications wavelengths have emerged as a promising candidate for optically-addressable qubits that are compatible with existing mature semiconductor and telecommunication industry platforms [1,2]. Recently, a number of color centers have been optically isolated in silicon-on-insulator and observed to emit in the telecom O-band [1,3,4]. Combined with silicon photonic integrated circuits, this platform has the potential to bring the scalability of microelectronics into quantum information processing [5]. However, to date there have been no demonstrations of single silicon silicon color centers coupled to photonic integrated circuits. Here, we demonstrate silicon color centers integrated in, and emitting single photons into, a foundry-written silicon-on-insulator photonic waveguide.

2. Sample fabrication and description

We generated silicon G-centers, consisting of interstitional-substitutional carbon pairs implanted within a silicon lattice, using a fabrication process that follows [1]. The samples started from a commercial silicon-on-insulator wafer (220 nm Si on 2000 nm SiO_2). The wafer was then cleaved into 1 cm^2 pieces, implanted with ^{12}C with a dose of 1×10^{13} ions/cm^{-2} and 36 keV energy, and then flash annealed for 20 s at 1000 °C. The sample was then electron-beam patterned and etched in a foundry (Applied Nano Tools), resulting in silicon waveguides with SiO_2 bottom cladding and air as top cladding. To enable fiber coupling, the sample was cleaved across the waveguides.

The device under study consists of a 400 nm wide waveguide (cross-sectional geometry shown in Fig. 1(c)) which starts and ends on the same chip facet and loops in a 63.5 μm radius 180° bend.

3. Measurement results

We optically characterized the color centers in our waveguide using above band-gap free-space excitation at 532 nm, imaged into a cryostat chamber that maintains a sample temperature of 6K. Excitation light was filtered with a bandpass filter centered on 532 nm. Emission from the color centers couples to the surrounding waveguide structure and was collected with an edge-coupled lensed fiber at the cleaved chip facet. The fiber-collected emission was band-pass filtered between 1250 nm and 1500 nm to isolate the zero-phonon line (ZPL) and phonon sideband (PSB) of the G-centers while removing residual pump light and waveguide background. The collected emission was then detected with either a cryogenic superconducting-nanowire single-photon detector (SNSPD) system (detection efficiency of 83%) or an infrared spectrometer.

We spatially locate our color centers using photoluminescence (PL) maps taken by scanning focused (NA = 0.55) continuous-wave excitation in the chip plane and detecting the filtered emission at each location with an electronically-gated SNSPD. We observed a PL signal in spatially isolated spots along the waveguide, as seen in Fig. 1(a,b). The PL spectrum from these spots indicates a ZPL wavelength of 1278.5 nm (Fig 1(d)), in agreement with prior results in bulk silicon-on-insulator [1,6]. Some of the PL hotspots along the waveguide appear to be brighter by roughly a factor of two and were observed to contain two ZPL peaks in the measured spectrum, suggesting that there are two color centers in close proximity.

We measured the excitation power dependence of the emission count rate, and observed a saturation power of 7.6 μW (Fig 1(f)). Background subtraction was performed by measuring the emission of a single color center and subtracting the PL signal from an area on the waveguide that does not show G-center emission.

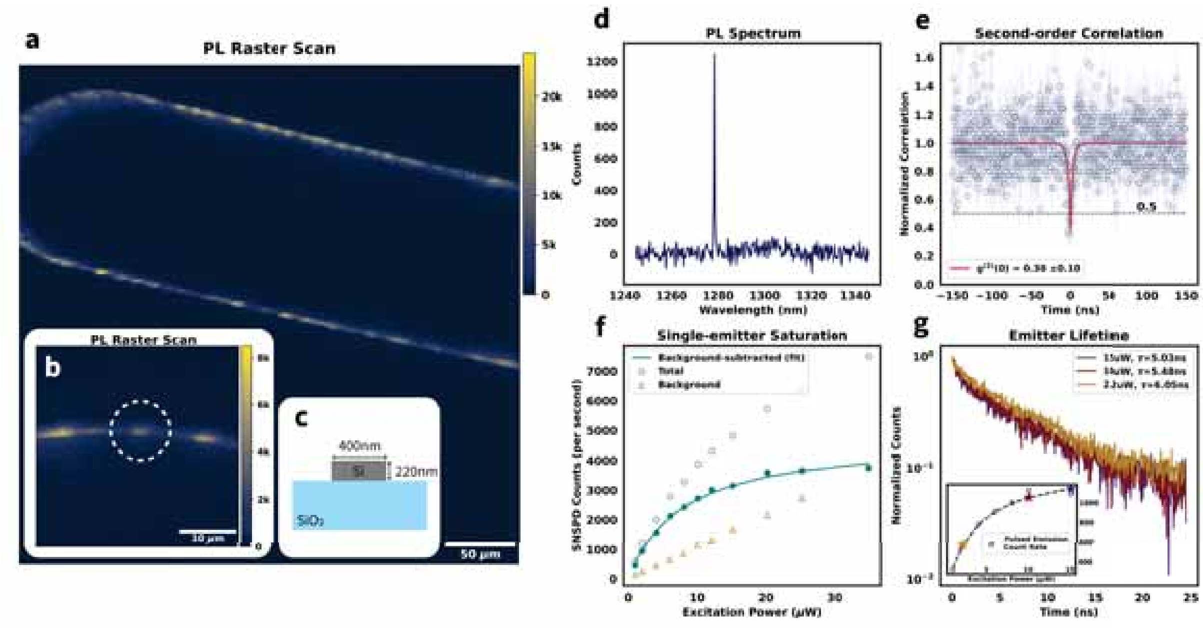

Fig. 1. a) Photoluminescence (PL) intensity map of silicon color center emission into the waveguide. b) Zoom-in showing the color center chosen for this study. Color bar axes for both PL scans are listed in counts per second. c) Cross-section of the waveguide. d) The PL emission spectrum from the selected emitter. e) Through-waveguide second order correlation below 0.5. f) Saturation curve under 532 nm continuous-wave excitation. g) Lifetime measurements (inset: saturation curve under pulsed 532 nm excitation).

To confirm the presence of a single color center in an excitation spot, we performed second-order correlation measurements using Hanbury-Brown-Twiss interferometry with an excitation power of 10 μW. Fiber-collected emission from our sample is split with a 50:50 O-band fiber beamsplitter and detected by two time-tagged SNSPDs. The correlation data is fitted to the autocorrelation of a two-level system emitter, displaying a characteristic single-photon antibunching dip of $g^{(2)} = 0.38 \pm 0.10$ (Fig 1(e)).

We also performed pulsed lifetime measurements of the single emitter with a range of excitation powers along the pulsed-excitation saturation curve (Fig 1(g) inset). Resulting decay curves fit well to an exponential function. The emitter exhibits a lifetime of 6.05 ns for sub-saturation excitation power and slightly decreased lifetimes for high excitation powers above saturation (Fig 1(g)).

4. Conclusion

We generate color centers in silicon photonic waveguides and demonstrate waveguide-coupled single-photon emission. Our work paves the way towards integrated spin qubits and single-photon emitters in foundry-compatible silicon photonic devices for large-scale quantum information technologies.

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