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Spectrally Programmable Individual Color Centers in Silicon Waveguides

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Color centers are leading qubit candidates for quantum information processing but are limited by their weak light-matter interactions and their operation wavelengths. Recently isolated color centers in silicon may, however, enable strong light-matter interactions at telecom wavelengths. We report on the integration of individual color centers in silicon photonic waveguides and their spectral programmability using optical tuning.
Keywords: *quantum photonics, color centers, single-photon emitters, silicon photonics*

INTRODUCTION

Color centers are leading candidates for quantum information processing due to their long spin coherence times and high-quality single-photon emission and spin-photon interfaces [1], [2]. Traditionally studied color centers are hosted in diamond and silicon carbide. However, these platforms face critical scaling challenges such as their lack of monolithic manufacturability and their visible or near-infrared operation wavelengths [3].

Recently, several color centers have been isolated in silicon [4]–[6], including the carbon-based G-center [7], [8]. Such color centers have shown single photon emission at telecom wavelengths, making them particularly attractive for quantum networking applications. A spin-photon interface based on silicon color centers could thus be seamlessly integrated into the world's most advanced microelectronic and photonic platforms.

We recently demonstrated the monolithic integration of single G-centers in silicon photonics and showed single photon emission in the telecommunications O-band with a narrow inhomogeneous linewidth into silicon waveguides [9]. However, their spectral programmability, key for achieving indistinguishable photons and required for all quantum communication and computing protocols, remains a challenge.

Here, we report on the first demonstration of spectral programmability of silicon color centers. We show optically-induced non-volatile spectral tuning up to 300 pm (55 GHz) in-situ in silicon photonic waveguides. The spectral shifts are comparable to the inhomogeneous distribution of 1.1 nm (200 GHz) and large enough to tune G-centers into standard 25-GHz telecom bands.

RESULTS

Our fabrication process proceeds as follows. To generate the G-centers, we start from a silicon-on-insulator (SOI) commercial wafer and implant it with carbon atoms, followed by a rapid thermal annealing process to heal the lattice. The cleaved chips were then patterned and etched down to the underlying silicon dioxide to make waveguides with single-mode operation in the O-band. The device under study consists of a looped-back waveguide (63.5 µm radius bend) and was cleaved on the edges for edge coupling to a fiber (Fig. 1a). A more detailed description of our sample and fabrication process can be found in Ref. [9].

Our measurement setup consists of a home-built confocal microscope designed for optical excitation of the device located inside a 6K cryogenic chamber. The collection consists of a lensed fiber (2.5 µm mode diameter) actively aligned to the waveguide facet. The collected color center emission is filtered via a free-space optical bandpass filter (1250 - 1550 nm) and detected via superconducting single-photon emitters or a spectrometer. More details on the measurement setup can be found in Ref. [9].

In our previous measurements with this sample, reported in Ref. [9], we observed diffraction-limited emission spots with a photoluminescence (PL) zero phonon line (ZPL) centered in 1278.7 ± 1.1 nm and two-level system saturation characteristics: lifetimes of 8.33 ± 0.68 ns fitting to a two-level system, and single-photon emission demonstrated via a through-waveguide second-order autocorrelation measurement $g^{(2)}(0) < 0.5$.

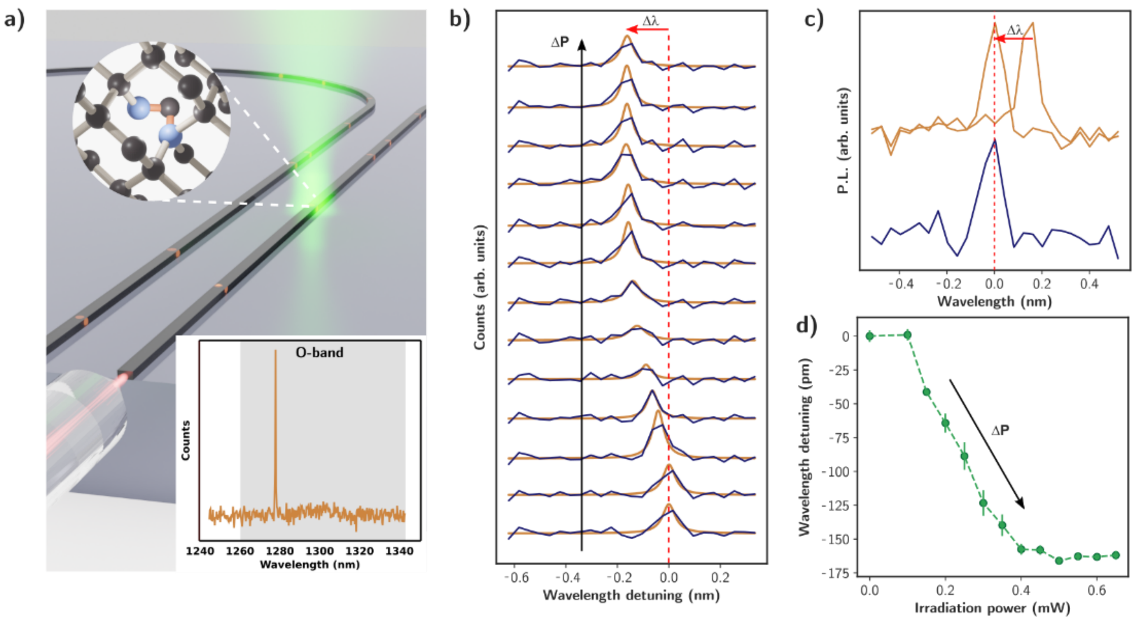

Fig. 1. a) Schematic of the device, showing the waveguide-coupled G-centers (zoom in showing the atomic configuration, with black = silicon and blue = carbon atoms), and a representative PL spectrum for a single emitter. b) By illuminating with increasing optical power, we observe non-volatile spectral detuning of the ZPL of a color center. c) This technique allows for spectral alignment of separate color centers in silicon. d) Fitted ZPL central wavelength versus increased optical tuning power for the device in b), showing controllable spectral shifts.

We demonstrate spectral programming and deactivation of single silicon color centers in this sample. To achieve these effects, we locally irradiate our G-centers with a 532 nm CW laser in-situ inside our 6 K cryostat.

We achieve spectral programming for the emitters under irradiation by illuminating with powers above 0.1 mW (estimated power density of 54.4 kWcm^{-2}) for 15 seconds, followed by probing PL measurements with excitation near the emitter saturation power. Under optical irradiation with powers above 0.1 mW, we consistently observe non-volatile ZPL spectral shifts for all but one of our 12 probed emitters. Example spectra of an emitter under increasing irradiation powers are shown in Fig. 1b. The average ZPL detuning for all sampled emitters is observed to be 150pm (27.5 GHz, see Fig. 1d), with a maximum detuning of 300pm (55GHz). The observed tuning range is large enough to match the 25 GHz telecommunication bands and to enable spectral alignment of separate emitters in the same waveguide (Fig. 1c).

For irradiation powers in the order of 1 mW (estimated power density of 544.3 kWcm^{-2}), we observe broadening and deactivation of the emitters. An example of this process can be found in Fig. 2. We observe that this effect is highly localized and leaves the waveguide and adjacent emitters unaffected (Fig. 2c).

In our experiments, the programming and deactivation effects are non-reversible.

Our thermal simulations rule out local annealing as the cause for the observed trimming and deactivation effects. Our hypothesis is that these effects are due to optically-induced variation of surface charge density leading to Stark tuning of the emitters, followed by ionization into a dark state for high irradiation powers.

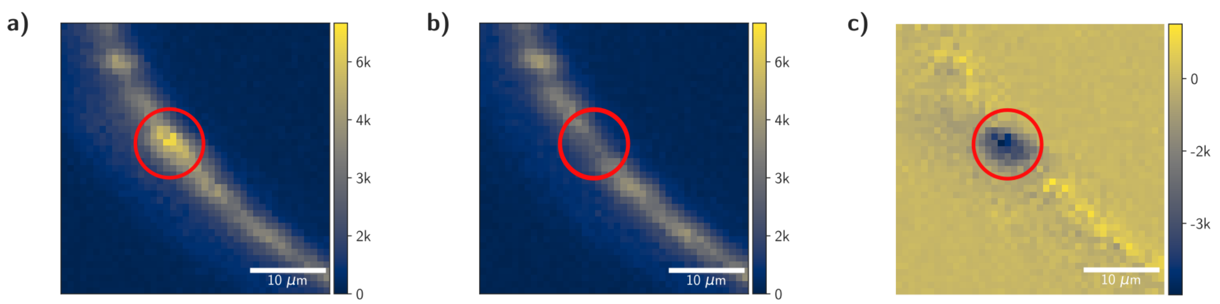

Fig. 2. a) Before and b) after PL maps of a section of a waveguide containing G-centers, showing the local deactivation of single color centers via high-power irradiation. Units are in counts per second. c) A subtracted image from a) and b), which highlights the locality of the effect. The red circle marks the irradiation location.

DISCUSSION

The demonstrated spectral programming provides a path towards in-situ fine-tuning of color center emission wavelength. The presented effect already enables the alignment of color center spectral lines into standard 25 GHz telecommunications bands, into cavities for enhanced light-matter interaction, or to other emitters and achieve quantum interference or cooperative emission. Moreover, the localized color center deactivation can be applied to trimming waveguides and cavities of interfering emitters. To reveal the physics explored in this work, further investigations are required. Examples may involve higher resolution spectroscopy, changing the geometry or crystal purity of samples, or experimenting with different optical tuning parameters.

In conclusion, we demonstrated for the first time the spectral programming and local deactivation of silicon color centers. We demonstrated significant non-volatile spectral tuning comparable to their inhomogeneous linewidth and showed spectral alignment between two separate color centers. Our results pave the way towards a silicon photonic color center platform for large-scale quantum information technologies.

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