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Cavity-Enhanced Single-Photon Emission from Artificial Atoms in Silicon

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Abstract: We show enhanced single-photon emission from artificial atoms in silicon by coupling them to cavities with high quality factors and small mode volumes, thus enabling enhanced light-matter interactions which are crucial for quantum technologies. © 2023 The Author(s)

1. Introduction & Background

Although the realization of scalable quantum computation still poses significant challenges, advances in emerging quantum technologies are making this goal more and more feasible. In the context of photonic platforms, promising candidates are solid-state artificial atoms, which hold potential to ease scalable quantum information processing [1]. A key component in this scenario is enhanced light-matter interaction, which can be realized by coupling artificial atoms to optical cavities [2]. Such interactions have largely been explored using artificial atoms in diamond. However, diamond-based platforms face some limitations – e.g. in operation wavelength and fabrication – thus posing the need for a more convenient platform that would be better-suited for long-distance quantum information processing along with being easy to fabricate and integrate. Artificial atoms in silicon meet these requirements. Conveniently, they exhibit emission into the telecommunications O-band (thus obviating the need for frequency conversion) and may be readily integrated within existing commercial silicon platforms. In order to realize enhanced light-matter interaction, we therefore couple artificial atoms – such as the carbon-related G centers [3,4] – in silicon to photonic crystal cavities with high quality factor Q and small mode volume V and show enhancement of the zero-phonon emission from a single G center. The latter point is confirmed by a second-order autocorrelation measurement $g^{(2)}(0) < 0.5$, which confirms genuine single-photon emission.

2. Experimental Details

Our experimental setup consists of a confocal microscope (with NA of 0.65) to both excite and collect fluorescence from G centers in silicon. The setup is built such that the artificial atoms can be excited with either continuous-wave green light at 532 nm or with infrared light. The light collected from the emitters is in the telecom O-band and is detected with superconducting nanowire single-photon detectors (with an efficiency of $\sim 20\%$ in the O-band) for second-order autocorrelation measurements or sent to a spectrometer for obtaining the emitters' spectra. The G centers are fabricated starting from a commercial silicon on insulator (SOI) wafer consisting of 220 nm silicon on 2 μm silicon dioxide. The wafer was first cleaved and implanted with ^{12}C with a dose of 2 x 10^{14} ions/cm^2 at 36 keV energy, and then annealed at 1000 °C for 20 s. The sample was then electron-beam patterned and etched in a foundry (Applied NanoTools), thus realizing silicon cavities with SiO_2 bottom cladding and air as top cladding. Finally, the sample was under-etched for 2 minutes in a 49% solution of hydrofluoric acid and then dried with a critical point dryer. We designed and fabricated L3-, L5- and L7-type photonic crystal cavities with high Q and small V, in order to enable an enhancement in the spontaneous emission rate of the quantum emitter (the well-known Purcell enhancement [5]).

3. Measurements & Results

We analyze a single G center coupled to an L3-type cavity mode by exciting the emitter with light at 532 nm (at a power of 7 μW) and collecting its emission spectrum with a spectrometer (integration time of 60 s). At a temperature of 4 K, the zero-phonon line (ZPL) of the quantum emitter is shown in Fig.1a (blue curve). We observe a ZPL at 1279.85 nm, typical of G centers. To characterize the cavity, we measure its reflectivity (using

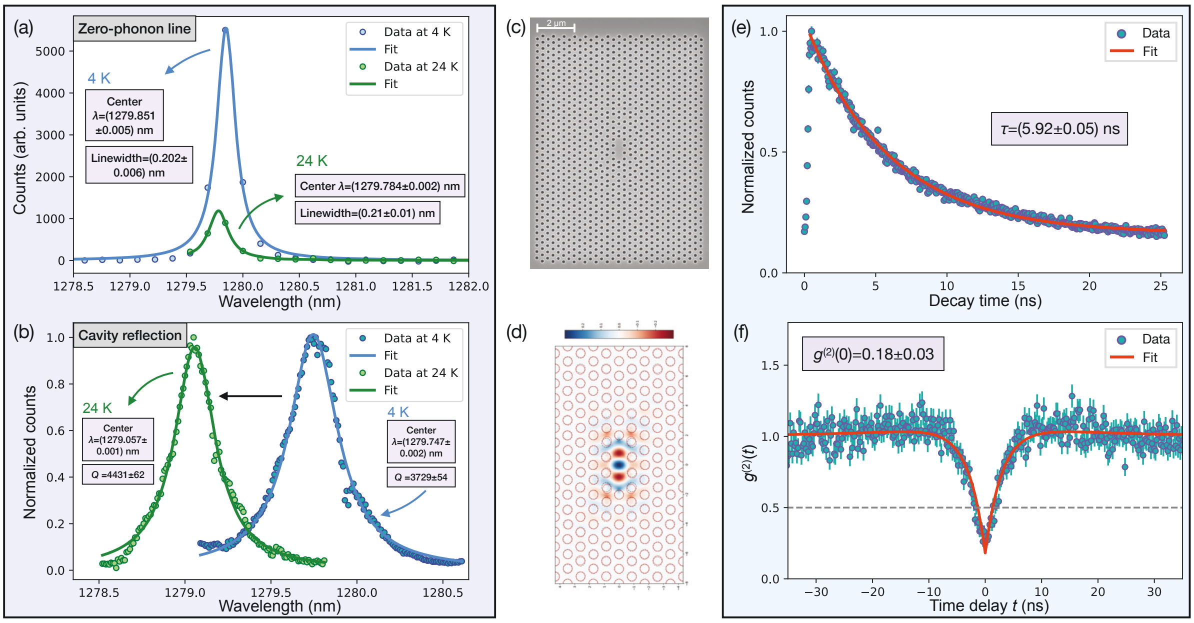

Fig. 1. (a) ZPL measured at a temperature of 4 K (blue curve) and 24 K (green curve). (b) Cavity reflectivity measurement at 4 K (blue curve) and 24 K (green curve). (c) SEM image of an L3-type photonic crystal cavity. (d) Simulation showing the electric field distribution for the fundamental cavity mode. (e) Lifetime measurement. (f) Second-order autocorrelation measurement $g^{(2)}(t)$.

a tunable infrared laser) in cross-polarization, meaning that the excitation and the collection paths are orthogonal to each other. The cavity reflectivity measurement is reported in Fig.1b (blue curve) and shows a Q of 3729 ± 54 and a resonance center wavelength of (1279.747 ± 0.002) nm, very similar to the ZPL wavelength of the emitter which is therefore resonant to the cavity mode. A way to detune the cavity from the emitter such that the resonance condition would be lost is to change the cryostat chamber's temperature. We therefore warmed up to 24 K and re-measured the emitter's ZPL and cavity reflectivity (see green curves in Fig.1a and b, respectively). We observe a shift of the cavity resonant mode – now at (1279.057 ± 0.001) nm – and therefore a detuning of the emitter from the cavity. By integrating the intensity of the ZPL curves for the on- and off-resonance cases and taking the ratio of the integrals, we observe a spectrally-resolved enhancement of $\sim$5 when the emitter matches the resonant cavity mode, compared to the off-resonance case. This is to be attributed to the Purcell enhancement of the zero-phonon spontaneous emission into the resonant mode. Fig.1c and d show a SEM image of an L3-type cavity and the simulated electric field distribution for the fundamental cavity mode, respectively. Moreover, at the temperature of 4 K, we performed a lifetime measurement (Fig.1e, from which an excited state lifetime of (5.92 ± 0.05) ns is extracted from the fit) and a second-order autocorrelation measurement, which led to a fitted value of $g^{(2)}(0) = 0.18 \pm 0.03$ (see Fig.1f). The fact that $g^{(2)}(0) < 0.5$ is a signature of single-photon emission.

4. Conclusion

We have shown enhancement of the zero-phonon emission from a single G center in silicon by coupling the emitter to a cavity with a high Q/V. This may represent a crucial step towards the development of integrated single-photon sources as well as of scalable quantum computation based on enhanced light-matter interaction.

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