Telecom spin-photon quantum interface based on silicon nanophotonics

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Abstract: We develop a telecom-band nanophotonic spin-photon interface with erbium dopants in silicon. We perform photoluminescence spectroscopy of Er^{3+} in silicon-on-insulator (SOI) wafers and measure Purcell enhancement, optical linewidths and transition dipoles in nanophotonic cavities. Comments and questions should be directed to Tian Zhong (tel: +1 773.834.4237, e-mail: tzh@uchicago.edu). © 2020 The Author(s)

Optically-interfaced spins in solids can enable a host of cutting-edge quantum technologies, such as quantum networks, quantum transducers, and quantum sensors [1]. The trivalent erbium ion (Er^{3+}) could serve as a coherent quantum light matter interface in the telecom band as it has demonstrated narrow optical transitions, as well as a 1.3s nuclear spin coherence time observed in $^{167}Er^{3+}:Y_2SiO_5$ [2]. Here we study Er^{3+}-dopants in silicon-on-insulator as a telecom-coupled spin qubit. Photoluminescence spectroscopy is performed on a ion-implanted Er^{3+}:SOI chip at dilution temperatures, revealing multiple peaks across the telecom band C with narrow inhomogeneous linewidths of Γ_{inh} ~2GHz. Silicon nanophotonic cavities are also created using standard CMOS fabrication techniques enabling Purcell enhancement of the ion's emission rate. Scalable fabrication of erbium-doped silicon make this platform promising for on-chip quantum technologies in the telecommunications band.

Silicon-on-insulator wafers were implanted at room temperature with 175keV naturally abundant Er^+ at a fluence of $2\text{x}10^{15}\text{cm}^{-2}$. The wafer was also co-implanted with 30keV $^{16}O^+$ at a fluence of $1.2\text{x}10^{15}\text{cm}^{-2}$ to optically activate the erbium. These conditions yield an estimated mean implantation depth of ~75nm from SRIM simulations. The samples were then annealed at 900C in a N_2 environment.

Photoluminescence spectroscopy was performed at ~100mK in a dilution refrigerator using a free-space double pass optical setup. The sample was illuminated with 1ms pulses and the photoluminescence signal was detected using superconducting nanowire single photon detectors. The photon counts were recorded as the laser wavelength was swept over 1530nm to 1542nm. Figure 1(a) shows multiple sharp photoluminescence peaks. High resolution scans for each peak reveal fine structure in the inhomogeneous line shapes and an inhomogeneous linewidths of Γ_{inh} ~ 2GHz (Fig 1(b)). The complex line shapes suggest the presence of a group of similar but distorted erbium sites. A least-squares exponential fit is also performed for the time-resolved photoluminescence signal, yielding consistent T_1 decay constants of ~2.3ms for all peaks as shown in Table 1 and Figure 1(c).

The long optical lifetime of erbium in silicon can slow readout and manipulation of erbium qubits. Therefore, the erbium ion's emission rate needs to be enhanced by coupling to an optical cavity via the Purcell effect. Enhancement of the erbium ion's optical decay rate has been achieved in ion-milled bulk crystal cavities and through evanescent coupling to bulk crystal substrates, however these cavities cannot be fabricated at scale [3,4]. On the other hand, high-throughput monolithic fabrication techniques can be directly applied to an erbium-implanted silicon wafer. We fabricated Si photonic crystal nanobeam cavities (SEM image of one device shown in

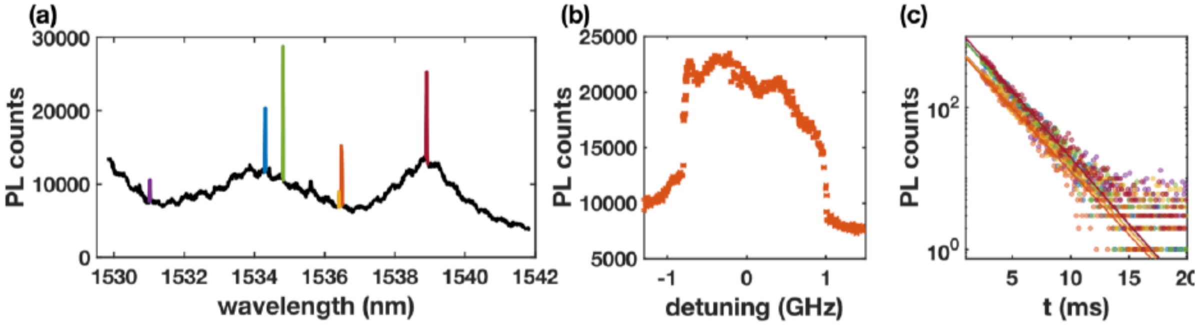

Figure 1 (a) Photoluminescence spectrum of Er:SOI. (b) Zoomed in scan shown for the peak at 1536.48nm. with Γ_{inh} ~2GHz (c) Time-resolved photoluminescence decay of ~2.3ms for all peaks shown in (a).

Fig. 2(a)) with measured quality factors up to 500,000, and a mode volume of 0.14 um^3. The distribution of impanted Er dopants with respect to the cavity mode is shown in Fig. 2(b). The Purcell factor is calculated as:

$$F = F_{cav}\left(\frac{\vec{E}(\vec{r})\cdot\vec{\mu}}{|\vec{E}_{max}||\vec{\mu}|}\right)\frac{1}{1+4Q^2\left(\frac{\lambda}{\lambda_{cav}}-1\right)^2} \qquad (1)$$

where Q is the quality factor, $\vec{E}(\vec{r})$ is the electric field, $\lambda(\lambda_{cav})$ is the (cavity) wavelength, and $F_{cav}=3/(4\pi^2)(\lambda_{cav}/n)^3(Q/V_{mode})$, n the index of refraction, and V_{mode} the mode volume [5]. Using the devices in Fig. 2(c), we obtain F_{cav}~*900* and *F~40 after ensemble averaging*. We estimate an emission rate enhancement from 70Hz to ~650Hz using the branching ratio of Er's Y_1-Z_1 crystal field transition, which is β=0.21 in oxide hosts [4].

Table 1. T_1 decay constants, and R^2 fit coefficients for transitions measured in Figure 1(a).

λ (nm)	T_1 (ms)	R^2
1531.025	2.332	0.986
1533.310	2.256	0.994
1534.808	2.329	0.991
1536.413	2.288	0.987
1536.471	2.435	0.991
1538.906	2.243	0.993

Furthermore, we will use these cavities to measure the optical homogeneous linewidth and optical dipole moment of the erbium ions. We will perform two-pulse photon echo experiments to obtain optical T_2. The optical dipole will be measured from the cavity reflection. The dipole moment can be computed from the single ion-cavity coupling rate $g=\mu/\hbar(\hbar\omega/2\varepsilon V)^{1/2}$, which is determined by the cavity reflection $R=((C/N)/(1+C/N))$ on resonance, through the cooperativity $C=Ng^2/\kappa\Gamma_{inh}$, where N is the number of ions, and κ is the cavity decay rate.

In summary, we report dilution temperature photoluminescence spectroscopy of Er^{3+}:SOI and Purcell enhancement of erbium ions in silicon nanophotonic cavities. These cavities are fabricated at scale using monolithic fabrication techniques to yield a maximum F_{cav}~*900*. These cavities are used to characterize the optical dipole moment for Er^{3+}:SOI and its optical linewidths. This study demonstrates Er^{3+}:SOI as a promising platform for optically interfaced spin qubits in the telecom band.

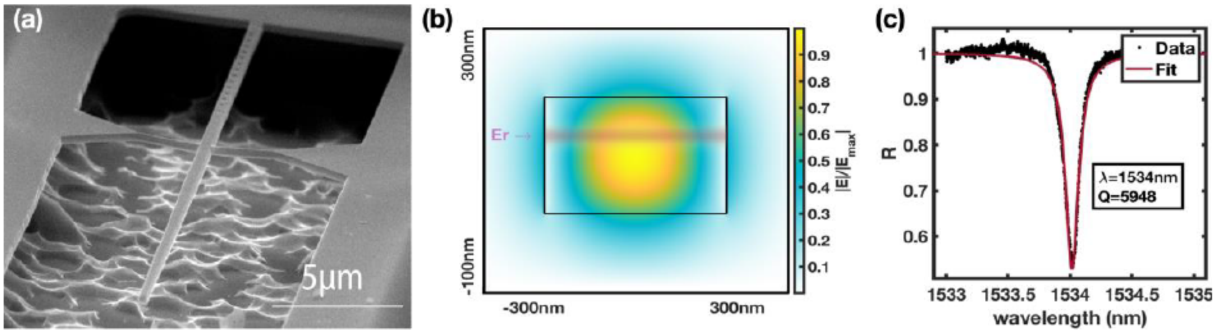

Figure 2 (a) SEM showing suspended Er:SOI nanophotonic cavity. (b) FEM simulation of TE mode of waveguide overlapped with implanted erbium distribution (c) Reflection spectrum of nanophotonic cavity with Q~5948 at 1534nm.

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References

[1] H. J. Kimble, "The quantum internet," Nature, vol. 453, pp. 1023–1030, June 2008.
[2] M. Rančić, M. P. Hedges, R. L. Ahlefeldt, M. J. Sellars, Nature Physics, vol. 14, pp. 50-54, September 2017.
[3] T. Zhong, et al., "Optically Addressing Single Rare-earth Ions in a Nanophotonic Cavity," Physical Review Letters vol. 121, pp. 183603, October 2018.
[4] A. M. Dibos, M. Raha, C. M. Phenicie, and J. D. Thompson, "Atomic Source of Single Photons in the Telecom Band," Physical Review Letters, vol. 120, pp. 243601, June 2018.
[5] T. Zhong, et al., "Nanophotonic coherent light-matter interfaces based on rare-earth doped crystals," Nature Communications 6, pp. 8206, September 2015.