Erbium implanted silicon for solid-state quantum technologies

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Abstract

Quantum technology (QT) platforms with telecommunications and integrated circuit (IC) processing compatibility have important implications for the long-distance transfer of quantum information, and QT platforms based on ion implantation are inherently scalable. Here we establish the potential of Er implanted Si as a scalable QT platform with telecommunications and IC processing compatibility through coherence and superconducting resonator coupling measurements. The electron spin coherence time of Er implanted Si with an Er concentration of \(3 \times 10^{17} \text{ cm}^{-3}\) is \(\sim 10 \mu\text{s}\) at 5 K. The spin echo decay profile displays strong modulation due to super-hyperfine interaction with \(^{29}\text{Si}\) nuclei beyond the first coordination sphere; this interaction could be utilised for the telecommunications wavelength addressing of \(^{29}\text{Si}\) qubits. The collective coupling strength between a superconducting NbN lumped-element microresonator and Er implanted Si with an Er concentration of \(10^{17} \text{ cm}^{-3}\) at 20 mK was \(\sim 1\text{MHz}\).
Introduction

The field of QTs is receiving a surge in interest and has the potential to revolutionise computing, communication, metrology and our understanding of quantum physics. The optical fibre telecommunications network makes telecoms wavelength photons at 1.5 μm by far the best candidates for transferring quantum information over distance. However, there are currently no QT platforms with both long coherence times (T2) and telecommunications compatibility. Er transitions can be optically addressed at telecoms wavelengths which allows transfer of quantum information over distance. Rare earth (RE) ions are well suited to overcome a paradox of QT platform requirements: sufficient decoupling from the environment to avoid decoherence, but a strong enough interaction with the environment to allow addressing, readout and gating. This is because they possess a partially filled 4f shell which is shielded from the environment by the outer 5s and 5p shells, leading to extraordinary coherence times of 6 hours1 and 4.4 ms2 for optically detected nuclear spin and electron dipole transitions, respectively; however, even with their atomic scale shielding, long lived entanglement between RE dopants in a solid matrix has been observed,3, 4 and entanglement between internal degrees of freedom of single RE ions can still exist up to thousands of K, making this one of the most stable known entanglements.5

A practical quantum computing architecture developed in Si will move from a one-off device to production far quicker than for any other material, and features can be patterned in Si on the scale required for many quantum device architectures. Ion implantation of Si is a well understood technology in IC fabrication, and history has shown that commercial adoption of new technologies favours those based on established fabrication platforms and techniques. Recently, increases in coherence times by several orders of magnitude have been demonstrated in donor impurities in silicon by using isotopically pure 28Si.6 However, donor impurities do not interact with light at telecommunications wavelengths, which is critical for many quantum communication schemes. Given expected improvements in T2 by using 28Si, optimising processing for the appropriate Er-related centre7 and reducing Er concentration, Er implanted Si is potentially the only known QT platform with telecoms addressability, long T2 and IC tooling compatibility. The spin state of a single Er ion implanted into a silicon single electron transistor has been optically addressed and electrically
readout;\textsuperscript{8} whereas, the spin state of a single Er ion in Y\textsubscript{2}SiO\textsubscript{5}, coupled to a silicon nanophotonic cavity, can be readout optically with a single shot.\textsuperscript{9} This demonstrates that Er implantation is compatible with a potential quantum computing architecture and that Er could be integrated in to quantum communication and information processing schemes.

Nuclear spins in solid-state platforms are also useful systems on which to implement qubits because their isolation from the environment can lead to extremely long coherence times, usually significantly longer than electron spin coherence times.\textsuperscript{10} The \textsuperscript{29}Si isotope of Si has been proposed as the qubit of an all Si quantum computer,\textsuperscript{11} but this also lacks telecoms addressability.

Arguably the most sophisticated quantum computers to-date use superconducting (SC) circuits, with 72 qubit machines demonstrated to-date,\textsuperscript{12} but they are limited by short coherence times compared to dopant-ion based qubits. SC circuits can be readily coupled to spin ensembles with longer coherence times which can then act as a quantum memory.\textsuperscript{13} Using Er spin ensembles can also provide a telecommunications interface for SC resonator qubits,\textsuperscript{14} and a single ensemble could be used to store many qubits by using holographic encoding.\textsuperscript{15}

Here we report the first coherence measurements of Er implanted Si, or, in fact, any implanted Er, in the form of spin echo measurements. We also report the strong superhyperfine interaction between Er and \textsuperscript{29}Si, which could give telecoms addressability to a \textsuperscript{29}Si based quantum device. In addition, we demonstrate the first of coupling between Er implanted in Si and a superconducting resonator. This represents the first integration of REs in a scalable QT platform and demonstrates the potential of Er implanted Si as a platform for future QTs.

Results

1. Spin Echo Measurements

We used three different annealing recipes- \(a\), \(b\) and \(c\) (see Methods for details) and isotopically selective implantation of \textsuperscript{166}Er to fabricate samples with Er concentrations between \(10^{17}\) and \(10^{19}\) cm\textsuperscript{-3} for electron spin resonance (ESR), spin echo and SC resonator coupling measurements. When implanted into Si, Er exists in its usual 3+ oxidation state.\textsuperscript{16} Oxygen was co-implanted to a
concentration of $10^{20}$ cm$^{-3}$ for all samples and is required to generate narrow Er-related ESR$^{17}$ and photoluminescence (PL)$^{18}$ lines. Previous measurements of the angular dependence of the Er-related ESR lines in Er implanted Si have identified a number of different centres: three monoclinic centres labelled OEr-1, OEr-1’ and OEr-3, and three trigonal centres labelled OEr-2, OEr-2’ and OEr-4$^{17,19,20,21}$. The $g$ tensors of these centres are given in supplementary Table S1. By comparison to these angular dependencies we can attribute the CW ESR line at 963 G from $10^{19}$ cm$^{-3}$ Er and $10^{20}$ cm$^{-3}$ O with annealing recipe $a$ (sample 1), shown in Figure 1a, to the OEr-1’ monoclinic centre illustrated in the inset. These Er-related ESR lines have been attributed to an Er centre based on similar $g$ tensors to Er doped Y$_2$O$_3$, which has the same crystal structure as Er$_2$O$_3$, and EXAFS measurements of Er and O implanted Si which found a similar Er-O bond length to that in Er$_2$O$_3$.$^{17,21}$ We recently reported$^{22}$ using a tuneable 1.5 μm laser to modulate an ESR resonance of the OEr-1’ monoclinic centre from sample 1. The optical spectrum of this modulation agreed with the characteristic Er PL measurements of Er implanted Si, showing beyond any reasonable doubt that the ESR resonance from the OEr-1’ monoclinic centre originates from an Er centre.$^{22}$ Figure 1a also shows that the spin echo peaks at the same magnetic field ($B_0$) as the Er-related ESR resonance at 963 G, which has a full width at half maximum (FWHM) of 8 G. However, the majority of the spin echo signal was also present off-resonance, we refer to the extra echo signal present at resonance as the intrinsic on-resonance and is calculated by treating the off-resonance echo as a background and subtracting it. Figure 1b shows the spin echo intensity as a function of $B_0$ for a delay time, between the $\pi/2$ and $\pi$ pulses ($t_{12}$), of between 130 and 270 ns for a sample with $10^{19}$ cm$^{-3}$ Er. The intrinsic on-resonance echo intensity was ~30% of the off-resonance echo at the shortest delay time. Figure 1c shows the integrated intensity of the intrinsic on-resonance echo peak, and the off-resonance echo as a function of $t_{12}$. The echo decays were analysed using the empirical Mims equation,$^{23}$

$$I = I_0 e^{-(\frac{2t_{12}}{T_2})^x},$$

(1)

where $T_2$ is the coherence time, and $x$ is an exponential stretch factor which is determined by spin dynamics, and was found to be 1 in the decay profiles in Figure 2 a, c and e. Fits to Eq. 1, with $x = 1,$
give an estimated $T_2$ of $180 \pm 80$ and $800 \pm 40$ ns for on- and off-resonance echoes, respectively, for sample 1.

Figure 1d shows the CW ESR and field dependent echo for $3 \times 10^{17}$ cm$^{-3}$ Er and $10^{20}$ cm$^{-3}$ O with annealing recipe $b$ (sample 2). There are two main resonances (peaks 1 and 2) at 867 and 934 G, respectively; similarly to sample 1, these resonances are attributed to the OEr-1’ centre, with the shift and splitting of the resonance attributed to a small angular deviation compared to sample 1. There are also satellite resonances at 892 and 964 G, which are attributed to a small vertical misalignment of the sample in the magnetic field. All of these resonances are visible in the echo spectrum. Like sample 1, the majority of the spin echo signal was also present off-resonance, with the on-resonance echo intensity being ~20% of the off-resonance echo signal at the shortest delay time. Figure 1e shows the echo intensity as a function of $B_0$ for various $t_{12}$ between 0.14 and 2.24 μs for sample 2.

The on-resonance echo signal disappears below the detection limit then reappears with increasing $t_{12}$, indicating the presence of very strong electron spin echo envelope modulation (ESEEM). Figure 1f shows the integrated intensity of the intrinsic on-resonance echo from peaks 1 and 2, and the off-resonance echo, as a function of increasing delay time. Fits to Eq. 1 give estimated $T_2$ values of $11 \pm 5$, $7 \pm 4$ and $3.5 \pm 1$ μs for intrinsic on-resonance peaks 1 and 2, and off-resonance echoes, respectively. In contrast to the $10^{19}$ cm$^{-3}$ Er sample, the intrinsic on-resonance $T_2$ is now longer than the off-resonance $T_2$. 
Figure 1 Field dependant spin echo. a, CW ESR and echo signals with various $t_{12}$ for $10^{19}$ cm$^{-3}$ Er and $10^{20}$ cm$^{-3}$ O with annealing recipe $a$ (sample 1); limitations of the measurement system meant that delays shorter than 130 ns could not be used. The inset, after ref 21, illustrates the monoclinic ESR centre. b, Contour plot showing the echo intensity as a function of magnetic field at various $t_{12}$ for sample 1. c, Integrated intensity of the intrinsic on- and off-resonance echo signals as a function of delay time for sample 1. The on-resonance echo contains both off-resonance and an intrinsic on-resonance echo. The intrinsic on-resonance echo was separated from the off-resonance echo by interpolating a baseline for the on-resonance echo from the off-resonance echo. d, CW ESR and echo signals with various $t_{12}$ for $3\times10^{17}$ cm$^{-3}$ Er and $10^{20}$ cm$^{-3}$ O with annealing recipe $b$ (sample 2). e, Contour plot showing the echo intensity as a function of magnetic field at various $t_{12}$ for sample 2. f, Integrated intensity of the intrinsic on- and off-resonance echo signals as a function of delay time for sample 2. All CW ESR measurements were made at 10 K, all echo measurements at 5 K, and the microwave frequency was 9.61 GHz.
The $B_0$ dependent measurements in Figure 1a,b,d and e allowed us to separate the on and off resonance components of the echo, but with limited temporal resolution. In Figure 2 we show the echo decay profiles, at fixed $B_0$, which give much better resolution of temporal features. The echo decays, shown in Figure 2a,c and e, display strong superimposed oscillations from the ESEEM effect\cite{24} caused by superhyperfine coupling with neighbouring nuclear spins; similar oscillations were observed in Er:CaWO$_4$, but were significantly weaker.\cite{25} Since the 4f wavefunction is highly localised, the superhyperfine coupling between a RE and a neighbouring nuclear spin is usually regarded as magnetic dipole-dipole only.\cite{26,27} The echo decay of an isolated Er$^{3+}$ ion (effective electron spin $S = \frac{1}{2}$) in proximity to a $^{29}\text{Si}$ nuclei (nuclear spin $I = \frac{1}{2}$) can be described as follows,\cite{24}

$$I(t_{12}) = I_0 e^{-\left(\frac{2\pi t_{12}}{\tau_2}\right)^2} \left[1 - 2k\sin^2\left(\frac{2\pi v_\alpha t_{12}}{2}\right)\sin^2\left(\frac{2\pi v_\beta t_{12}}{2}\right)\right].$$

The first term is Eq. 1, which describes the echo decay in the absence of nuclear coupling. $k$ is the modulation index, $v_\alpha$ and $v_\beta$ are the $^{29}\text{Si}$ nuclear resonance frequencies for the two possible Er$^{3+}$ electron spin orientations ($S = \pm\frac{1}{2}$).

Figure 2a shows the off-resonance echo decay fitted to Eq. 2 at a $B_0$ of 850 G. The fitting indicates $v_\alpha$ and $v_\beta$ of 0.63 and 0.58 MHz, respectively, the $\tau_2$ of 4 $\mu$s from the fit is consistent with Figure 1f. Figure 2b shows the fast Fourier transform (FFT) of both the measured and fitted off-resonance decay. The measured decay has a single resolvable frequency peak at 0.69 MHz, which is close to the Larmor frequency ($v_L$) of 0.72 MHz for $^{29}\text{Si}$ at this magnetic field, and which we assign to the superposition of $v_\alpha$ and $v_\beta$. The similar frequencies for $v_\alpha$, $v_\beta$ and $v_L$ indicate weak coupling to $^{29}\text{Si}$ nuclear spins. Eq. 2 contains weaker sum ($v_+ = v_\alpha + v_\beta$) and difference ($v_ - v_\beta$) frequency components; the FFT of the fitted decay show the $v_+$ component, which cannot be resolved on the FFT of the measured decay because of insufficient signal-to-noise.

Figure 2c shows the on-resonance echo decay, which has significantly stronger ESEEM modulation than the off-resonance decay. Fitting to the data required the sum of two sets of Eq. 2 because this decay profile contains the decay profile of both the off-resonance and the intrinsic on-
resonance decays, with the two sets of adjustable parameters given the subscripts $a$ and $b$ respectively, as shown in Eq. 3.

$$I(t_{12}) = I_{0a} e^{-\frac{2\pi t \nu_{\alpha} t_{12}}{T_2^a}} \left[ 1 - 2k_a \sin^2 \left( \frac{2\pi \nu_{\alpha} t_{12}}{2} \right) \sin^2 \left( \frac{2\pi \nu_{\beta} t_{12}}{2} \right) \right]$$

$$+ I_{0b} e^{-\frac{2\pi t \nu_{\beta} t_{12}}{T_2^b}} \left[ 1 - 2k_b \sin^2 \left( \frac{2\pi \nu_{\alpha} t_{12}}{2} \right) \sin^2 \left( \frac{2\pi \nu_{\beta} t_{12}}{2} \right) \right]$$

Fitting indicates one of the components had stronger modulation ($k_a=0.43$) than the other ($k_b=0.2$). Figure 2d shows the FFT of the measured on-resonance decay in which two peaks at 0.73 and 1.64 MHz can be resolved and are assigned to $\nu_{\alpha}$ and $\nu_{\beta}$, respectively; these peak positions and their intensities correspond well to those from the FFT of the fit. The intrinsic on-resonance decay, obtained by taking the difference between on- and off-resonance decay profiles, is shown in Figure 2e; the fitting to Eq. 2 yields $\nu_{\alpha}$ and $\nu_{\beta}$ of 0.70 and 1.63 MHz, respectively, these frequencies and $\nu_+$ can be clearly seen in the FFT in Figure 2f. The deviation of $\nu_{\beta}$ from $\nu_L$ indicates stronger superhyperfine coupling between Er electron spins and $^{29}$Si nuclear spins. The modulation of the intrinsic on-resonance decay is very strong with fitting yielding $k = 0.45$. The fit also yielded a $T_2$ of $9 \pm 3 \mu s$ which is consistent with Figure 1f. Our $T_2$ of $\sim 10 \mu s$ at 5 K compares to $\sim 5 \mu s$ at 5 K ($\sim 50 \mu s$ at 2.5 K) for $\sim 10^{16}$ cm$^{-3}$ Er doped CaWO$_4$. It is notable that Er implanted Si has double the $T_2$ of an Er doped crystal with 30x lower Er concentration. It is also notable that the Er was implanted, whereas the Er in the CaWO$_4$ crystal was introduced during crystal growth, since recrystallization after implantation can often leave lattice defects that lead to decoherence. Further optimisation of the recrystallization process, reductions in Er concentration and isotopic purification of the Si may lead to coherence times applicable to quantum communication and computation.

We also measured the spin relaxation time, $T_1$, at 5 K, see supplementary Figure S1, to be $\sim 0.5$ ms off-resonance and $\sim 1$ ms on-resonance. This further illustrates the different nature of the on- and off-resonance centres. Given that $T_1 >> T_2$ at both on- and off-resonance, $T_2$ is limited by local field fluctuations in both cases. For both donors in silicon and RE doped transparent crystals, the ESEEM effect is thought to be caused largely by nuclear spins in very close vicinity to the echo.
producing centre. For example in both $^{28,29}$P and $^{30}$Bi doped Si, the ESEEM effect is attributed to the four nearest Si lattice positions, in $^{3+}$Ce doped CaWO$_4$, the ESEEM of Ce$^{3+}$ can be accurately modelled using the closest ten lattice positions of surrounding W atoms. $^{24}$ Spectral diffusion can be caused by various electron$^{31}$ and nuclear$^{32}$ spin flip-flop process; in Er implanted Si, nuclear induced spectral diffusion is most likely since $^{29}$Si nuclear spins are present and electron spin $T_1 >> T_2$. The nuclear spins involved in ESEEM, which experience large hyperfine fields, cannot flip flop their spins and contribute to spectral diffusion due to conservation of energy, whereas the nuclear spins involved in spectral diffusion must experience very weak hyperfine fields to allow flip-flops, and therefore consist of a separate, larger, group of nuclei that are further from the echo producing centre. $^{28}$ The observation that $x \sim 1$ in Figure 2 a, c and e for the on and off-resonance decay profiles is somewhat unexpected and indicates no significant spectral diffusion occurs. $^2$ Due to our isotope specific implantation, the only nuclear spins in our sample are from $^{29}$Si. The OEr-1’ centre responsible for the intrinsic on-resonance echo is attributed to an O coordinated Er centre, so coupled $^{29}$Si nuclei must lie outside at least the first coordination sphere. The observation of strong ESEEM indicates that the OEr-1’ centre can couple to nuclear spins significantly further away than previously investigated Er centres; the lack of spectral diffusion is consistent with this hypothesis since a hyperfine field extending further from the Er centre would push the nuclear spins capable of inducing flip-flops, and therefore spectral diffusion, further from the Er centre.

Although the intrinsic on-resonance echo signal can be confidently assigned to the OEr-1’ monoclinic Er-related centre, the origin of the off-resonance echo signal is less clear, but relative similarities in $T_1$, $T_2$ and ESEEM to the intrinsic on-resonance echo signal, and that its $T_2$ increases with decreasing Er concentration, suggest another, as yet unidentified, Er-related centre.
Figure 2 Spin echo decay profiles for $3\times10^{17}$ cm$^{-3}$ Er and $10^{20}$ cm$^{-3}$ O. a, Off-resonance echo decay profile at a $B_0$ of 850 G fitted to Eq. 2. b, FFT of measured and fitted off-resonance decay profile. c On-resonance echo decay profile at a $B_0$ of 867 G fitted to Eq. 3. d, FFT of measured and fitted on-resonance decay profile. e, Intrinsic on-resonance decay profile, extracted by taking the difference between on- and off-resonance decay profiles, fitted to Eq. 2. f, FFT of measured and fitted the intrinsic on-resonance decay profile. All measurements were on sample 2 ($3\times10^{17}$ cm$^{-3}$ Er and $10^{20}$ cm$^{-3}$ O, with annealing recipe $b$) at 5 K, and the microwave frequency was 9.61 GHz. The on-resonance decay corresponds to peak 1.
2. Superconducting resonator coupling

In order to determine the suitability of Er implanted Si for hybrid solid-state qubits, we placed the implanted face of sample 3 ($10^{17}$ Er cm$^{-3}$ and $10^{20}$ O cm$^{-3}$, annealing recipe c) in contact with the superconducting NbN lumped-element microresonator on R-cut Al$_2$O$_3$ shown in Figure 3a, which had a centre frequency $\omega_r/2\pi = 3.04$ GHz, see Methods. Figure 3b shows the loss tangents due to coupling to Er ions ($\tan \delta_{\text{ions}}$) as function of $B_0$ and orientation. There is a single narrow resonance, with a FWHM of 50±10 G, that varies smoothly between 740 and 870 G depending on the $B_0$ orientation. By fitting this angular dependence for a trigonal centre we obtain $g_{\|} = 1.02$ and $g_{\perp} = 2.95$. There is also a very broad resonance centred at 500 G and at $B_0 \parallel [001]$ (0° orientation) which shifts to 600 G at 50° $B_0$ orientation; we simulated the angular dependence of the six ESR centres (three trigonal, three monoclinic) previously identified Er and O implanted Si system$^{17}$, see supplementary Table S1, but found no correspondence with this broad resonance. The narrow resonance had a remarkable correspondence with the trigonal OEr-2' centre identified in ref. $^{17}$ with $g_{\|} = 0.69$ and $g_{\perp} = 3.24$, which is shown in the simulation in Figure 3c. The two other resonances are also visible in this $B_0$ range but are significantly weaker, which explains why only one resonance is observed in the microresonator measurement. A higher $B_0$ range shows the positions of all three expected ESR resonances with trigonal symmetry in the simulation in Figure 3d. Only one previously identified Er centre is evident in the hybrid measurements. This could be due to preferential coupling of the trigonal centre, or the trigonal centre has a shorter $T_1$ than the other centres at 20 mK, which prevented saturation.

The Q factor of a resonator coupled to an ensemble of spins can be modelled as a single mode harmonic oscillator according to

$$Q_{\text{tot}} = \frac{\Delta^2 + \gamma^2}{2g_{\text{col}}^2\gamma + \kappa(\Delta^2 + \gamma^2)\omega_r}, \tag{4}$$

where $\Delta$ is the detuning from the spin resonance peak, $\gamma$ is the spin linewidth, $\kappa$ is the cavity linewidth $= 2\pi\omega_r/Q_{\text{tot}} = 0.56$ MHz for the 0° orientation and was independently measured away from the resonance for each $B_0$ orientation, $Q_{\text{tot}}$ is the total measured cavity Q, and $g_{\text{col}}$ is the collective coupling strength. Supplementary Figure S2 shows the fitting of Eq. 4 to the $Q_{\text{tot}}$ for the 0° orientation which gave $g_{\text{col}}/2\pi = 1$ MHz and $\gamma/2\pi = 80$ MHz. The average for all $B_0$ orientations was $g_{\text{col}}/2\pi = 1.1 \pm 0.3$.
MHz and $\gamma/2\pi = 85 \pm 25$ MHz. The coupling strength of an individual spin to the SC resonator is $g_i = g_{\text{col}}/\sqrt{N}$, where $N$ is the number of spins coupled to the resonator; using the number of Er ions above the microresonator ($\sim 3.7 \times 10^{10}$) gives $g_i \sim 6$ Hz. This compares to $g_i \sim 2$ Hz for Gd implanted Al$_2$O$_3$ \cite{33} and $\sim 70$ Hz for Er implanted Y$_2$SiO$_5$ crystal.\cite{14} We observed no change in $\omega_r$ as $B_0$ was swept through the Er spin resonance, indicating the system is operating in the weak coupling regime. The number of Er ions observed in our measurement was certainly less than $N$, since we only observed the trigonal centre with $g_{||} = 1.02$ and $g_{\perp} = 2.95$, which is one of six ESR and three PL centres in the Er and O coimplanted Si system.\cite{22}

Our micro-resonator measurement represents the first reported coupling of a SC resonator to a RE ensemble implanted in Si. The strong coupling regime could be attained by optimization of the annealing recipe to produce only one ESR centre and by operating at higher centre frequencies.
**Figure 3** Superconducting resonator coupling. **a,** Image of the superconducting micro-resonator that was coupled to sample 3 (10$^{17}$ Er cm$^{-3}$ and 10$^{20}$ O cm$^{-3}$, annealing recipe $c$). **b,** Angular dependent micro-resonator ESR measurement of sample 3 at 20 mK. **c,** simulated angular dependent ESR spectrum using EASYSPIN numerical modelling for the trigonal OEr-2' centre identified by Carey et al. with $g_// = 0.69$ and $g_\perp = 3.24$. **d,** Simulated angular dependent ESR extended to higher $B_0$ to show the positions of the three expected ESR resonances with trigonal symmetry. The microwave frequency was 3.04 GHz for all micro-resonator measurements and simulations.

**Discussion**

A promising scheme to develop a hybrid quantum computer is to link the long coherence time of silicon-based qubits with the ability to entangle superconducting qubits, which tend to have shorter coherence times. This requires the coupling of silicon and superconducting qubits which can be achieved by the exchange of a microwave photon. These hybrid quantum circuits would exhibit long coherence times while allowing quantum state manipulation, and a quantum transducer could be developed using the ability of REs coupled to superconducting resonators to coherently convert optical photons to microwave photons using RE microwave Zeeman transitions as intermediaries.
This would have applications in networking quantum signal processors, quantum key distribution and quantum metrology.

We envisage a quantum network consisting of nodes of superconducting qubits, for quantum information processing, which are coupled to Er implanted Si for quantum information storage and transfer over the fibre optic network. Such a scheme would have major advantages over similar schemes using Er doped Y$_2$SiO$_5$ in that it could utilise IC tooling for fabrication.

For qubits based on donor impurities in Si, the coupling of donors to $^{29}$Si nuclei, as observed in the ESEEM effect, would be deleterious to qubit operations; however, the engineering challenges for donor and RE qubits are rather different. The wavefunction of the excited Rydberg states of the P impurity in Si can extend several nm beyond the atomic radius, making the control of the quantum state of other atoms a possibility. However, in REs the wavefunction of the f-orbital is strongly confined, giving an intrinsic barrier to decoherence, but making control of the states of surrounding atoms significantly more difficult. The superhyperfine interaction is an efficient method of accessing nuclear spins; in Er$^{3+}$:Y$_2$SiO$_5$ the superhyperfine interaction between Er$^{3+}$ and an $^{89}$Y ion in its first coordination sphere was used to optically address the $^{89}$Y nuclear spin. The strong superhyperfine interaction between the OEr-1’ centre and $^{29}$Si which extends at least beyond the first coordination sphere could be used for the optical addressing of $^{29}$Si nuclear spins through the Er telecommunications transition.

Conclusions

Er implanted Si is shown to be promising platform for the development of QTs and is potentially highly scalable since it can utilise the silicon and ion implantation technology used in the IC industry. Er implanted Si can also exploit the atomic scale barrier to decoherence that is intrinsic to REs, and the recently developed ultra-low spin environment of isopically purified $^{28}$Si. Whereas the Er component itself is compatible with telecommunications wavelength photons and could be utilised for quantum communications schemes. We report the first coherence measurement of implanted Er in the form of a spin coherence time of $\sim 10$ μs at 5 K for $3\times10^{17}$ cm$^{-3}$ Er, which is similar to $\sim 10^{16}$ cm$^{-3}$ Er doped CaWO$_4$ at 5 K, but with 30× higher Er concentration. The origin of this echo is an Er centre
surrounded by six O atoms with monoclinic site symmetry. The spin echo decay profile had superimposed modulations due strong superhyperfine coupling with $^{29}$Si nuclei extending at least beyond the first coordination sphere. This coupling could be exploited for the telecommunication wavelength addressing of $^{29}$Si nuclear spins.

We observed the first coupling between a superconducting resonator and Er implanted Si with $g_{\text{col}} \sim 1\text{MHz}$ and $g_i \sim 6\text{ Hz}$, which provides a basis for future networks of hybrid quantum processors that exchange quantum information over the telecommunication network. Out of six known Er-related ESR centres, only one trigonal centre coupled to the SC resonator at 20 mK.

**Methods**

**Sample preparation**

Sample 1, with $10^{19}$ cm$^{-3}$ Er and $10^{20}$ cm$^{-3}$ O, was prepared by implanting Er with a total areal dose of $2.6 \times 10^{15}$ cm$^{-2}$ and O with a total areal dose of $1.3 \times 10^{16}$ cm$^{-2}$ at 77 K into one face of $<100>$ 5000-9999 Ωcm 500 µm thick Si wafer supplied by Topsil, then annealing with recipe $a$, which consisted of a 450°C for 30 min anneal to smooth the crystalline-amorphous interface, a 620°C for 180 min anneal to recrystallize the amorphised region and a 850°C for 30 s anneal was to activate the Er. It was found that annealing at 850°C significantly increased the ESR signal strength.$^{22}$ Sample 2, with $3 \times 10^{17}$ cm$^{-3}$ Er and $10^{20}$ cm$^{-3}$ O, and sample 3, with $10^{17}$ cm$^{-3}$ Er and $10^{20}$ cm$^{-3}$ O, were prepared by implanting at room temperature into both faces of $<100>$ 5000-9999 Ωcm 50 µm thick Si wafer supplied by Si-Mat. Samples 2 and 3 were annealed with recipe $b$ (750°C for 2 min) and recipe $c$ (600°C for 167 min, then 850°C for 30 s), respectively. For all samples, O and Er were implanted at a range of energies to give a flat concentration profile down to a depth of around 1.5 µm, see supplementary Figure S3. Isotope specific implantation was used so that only the zero nuclear spin $^{166}$Er was implanted.

**ESR and spin echo measurements**

CW and pulsed ESR measurements were performed in a Brucker E580 ESR spectrometer. All ESR measurements were recorded with the magnetic field, $B_0$, parallel to the [001] direction of the Er
implanted Si sample with an uncertainty of ±5°. When using Er concentrations ≤ 10^{18} \text{ cm}^{-3} and recipe \textit{a}, no spin echo could be observed. We then tried two different recrystallization strategies: shorter time, higher temperature and longer time, lower temperature. These were 750°C for 2 min (recipe \textit{b}) and 550°C for 335 min (recipe \textit{d}), with no activation anneal; recipe \textit{d} resulted in no measurable ESR resonances. However, recipe \textit{b} resulted in strong, narrow ESR resonance lines, and a measurable echo signal. With samples 1 and 2, the Q factor of the ESR resonator was ~600 and ~9000, respectively, due to metallic doping at the high Er concentrations in sample 1. For pulsed measurements the Q factor was detuned to ~100 for both samples.

**Superconducting resonator coupling**

Superconducting resonator coupling measurements were performed in a dilution refrigerator, fitted with a vector magnet, at 20 mK. A superconducting lumped element micro-resonator was fabricated by sputtering 200 nm of NbN, patterned by standard e-beam lithography, onto an R-cut sapphire substrate. Sample 3 was placed face down on the microresonator. The microresonator was placed in a magnetic field that was stepped from zero to 93 mT. At each magnetic field the microwave transmission coefficient, S_{21}, was measured using a vector network analyser (VNA). This was repeated for magnetic field orientations between 0° and 160° in steps of 5°, with 0° corresponding to $B_0$ parallel to the face of the resonator and sample. The magnetic field was rotated around the [110] crystal axis of the sample. Numerical fitting of the S_{21} response of the microresonator was used to extract the total measured loss tangent $\tan\delta_{\text{tot}} = 1/Q_{\text{tot}}$, where $Q_{\text{tot}}$ is the total measured Q factor. $\tan\delta_{\text{tot}}$ = $\tan\delta_c + \tan\delta_{\text{d}} + \tan\delta_B + \tan\delta_{\text{ions}}$, which are the loss tangents due to coupling to the transmission line, dielectric losses, the external magnetic field and the Er ions, respectively. Numerical fitting was then used to extract $\tan\delta_{\text{ions}}$. 
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Author Contributions

The concept was developed by MAH. Experimental work was performed by M.A.H., N. A. P., M. U. and I. W. with input from J. D. C. and T. L. The manuscript was written by M.A.H. with editorial input from J. D.C, K. P. H. and B. M. All authors contributed to analyzing the results and commented on the paper.

Data availability

The datasets generated during the current study are available in the Mendely Data repository http://dx.doi.org/10.17632/s73x8nb8dn.1

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