**Literature review of Er:Si**

Outline:

Review of past research (PL, EPR, EXAFS)

Review of recent research (spectroscopy, optical lifetime, coherence measurements)

mention T center in Si, Er in molecules, CaWO4/GaN

Aspects: centers, symmetry, energy level structure, electronic states

Should add numbers of references later

Should add more details later

**Motivation**

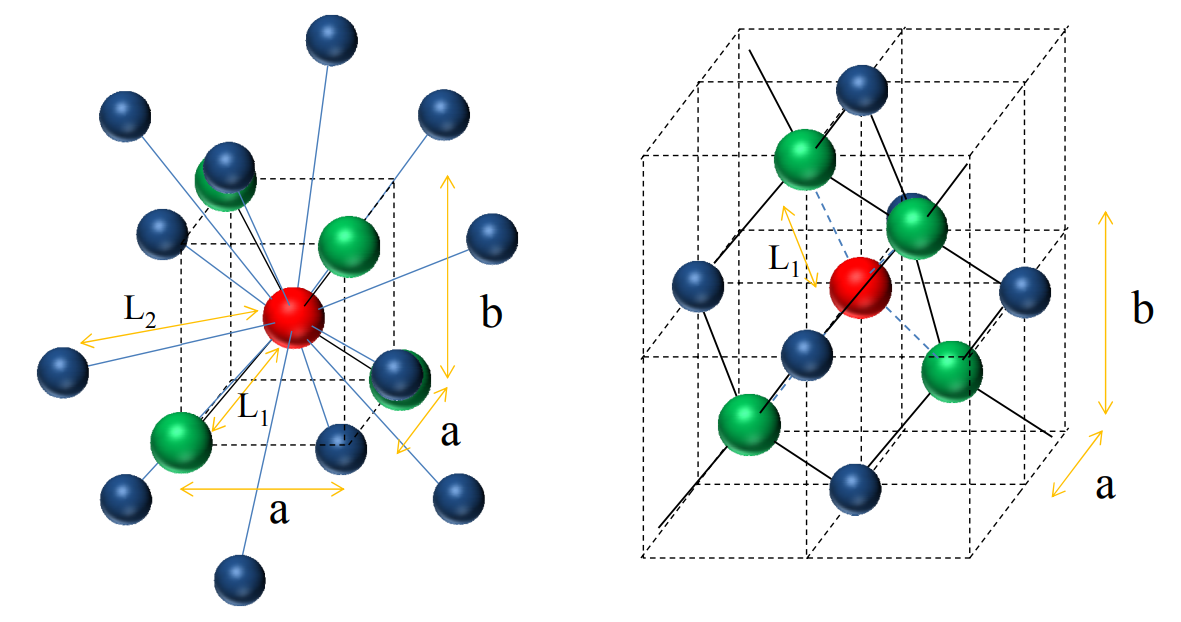
Erbium in silicon was explored extensively in the beginning of twentieth century, with the interest of building a silicon-based on-chip optical source. As a poor photonic material, silicon suffers from fast non-radiative decay dominating over slower radiative routes, and indirect bandgap (band edge luminescence at 1.1 μm). It was hoped that implanting optical active centers into this material will allow photoluminescence at specific wavelengths determined by the rare-earth optical transitions. Er3+ was chosen for its direct 4I13/2 → 4I15/2 transition at 1532 nm falling in the telecom band, which is convenient for optical fiber links in modern communication.

There have been considerable experimental researches towards this platform. To begin with, a major problem facing researchers was the relatively low solubility of erbium in crystalline silicon. This problem was solved by enhancing the equilibrium concentration by co-doping with impurities such as oxygen, carbon, nitrogen and fluorine. In experiments, co-implanting Er with O significantly increases the photoluminescence and leads to sharp lines in EPR spectroscopy. In later parts of this review, I will mainly discuss erbium and oxygen co-doped silicon.

**Electronic structure of Er and O co-doped silicon**

However, ion implantation also suffers from the disadvantage of introducing significant damage to the matrix. High temperature annealing can recover the majority of this damage and initiate the formation of Er–O clusters, but at the cost of producing aggregates of rare-earth ions or forming optically inactive silicides.

In practice, incorporating erbium into an interstitial site is more strongly preferred than a substitutional site, as the interstitial sites are predicted to be more stable from the estimations of the bonding mismatch between the rare earth ion and the covalent semiconductor.



substitutional site and interstitial site

There have been contradictory experimental findings on the local electronic structure of Er in Si, indicating that processing and annealing conditions have a strong influence in the local environment of Er implanted into Si.

Studies further demonstrate that neither of the simple erbium point defects, substitutional or interstitial, can be optically active, as both have electronic states too deep in the silicon band gap to produce 4f emission. The optically active center must be associated with erbium–impurity complexes like Er–O.

There are three generic models for the Er–O species: tetrahedral interstitial (Ti-O), tetrahedral substitutional (Ts-O), and hexagonal interstitial (Hi-O).

**Spectroscopic studies**

Because of the low number of optically active ions in implanted samples compared to bulk doped samples, measuring the crystal field splitting from absorption measurements in implanted samples is extremely difficult. PL spectra can often be detected, but are inherently weak because above band gap excitation is required, and this only penetrates the first few hundred nm from the sample’s surface. Above-bandgap excitation has the advantage of exciting many ions at the same time to provide a strong signal, it comes at the price of limiting the sensitivity to the small fraction of implanted dopants that is coupled to the conduction band. The spectrum includes decay from the lowest 4I13/2 to the multiple 4I15/2 levels following the excitation of the Si host, where the intensity depends on the excitation transfer efficiency from the Si. Therefore, various peaks in the crystal field split spectra can be undetected or unresolved.

OMMR [2]: Under 1.5-μm illumination an EPR resonance from a PL-active Er center with orthorhombic symmetry in Er-implanted Si can be observed, which has an intensity 3 orders of magnitude higher than that of unilluminated EPR resonances. This implies the presence of an Er-O defect state below 4I13/2 Er3+ excited state to enable spin selective non-radiative decay to the Zeeman ground state. This mechanism is analogous to the optical spin polarization mechanism of NV centers in diamond, and if correct could mean high temperature operation of Er qubits in Er implanted Si is possible.

Fitting the temperature quenching of PL indicated that the 4I15/2 Er3+ ground state was buried in the valence band, this was also indicated by OMMR measurements.

**Unsolved puzzles**

**Recent Quantum researches**

Quantum coherence is of key importance in the context of modern researches. The coherence time of individual dopants is paramount, specifically, the forbidden 4f-4f intra-shell transitions of erbium become weakly allowed in the presence of crystal field, which result in sharp optical transitions with high quantum efficiency falling in telecom C-band. This provides great convenience for optical fiber links between distant quantum nodes, since telecom photons travel in fibers without significant loss of their coherence.

Additionally, the confinement of the inner 4f electrons near the erbium nucleus and the shielding of the crystal field by the outer 5s and 5p electrons protects the electronic state from decoherence via phonons, and also hinders phonon-sideband emission that reduces the radiative efficiency of other defects. Silicon is a predominantly spin-free material. Combining the shielding of RE f-electrons with the low nuclear spin and processing pedigree of silicon offers a novel system in which to implement quantum technologies. Further isotopic purification eliminates the coupling of dopants to nuclear spins and facilitates ultra-narrow optical linewidths and significantly improved coherence time.

**Recent spectroscopic studies**

A novel in-situ PLE method [3]: The crystal field levels in the excited 4I15/2 state are inaccessible in PL, but obtainable in PLE when using a narrow band laser to resonantly excite the population into multiple 4I13/2 levels and collect the photoluminescence. Less free carriers are generated that can affect the spectrum and lifetime. Achieved a highly efficient detection of 70 excitation frequencies, of which 63 resonances have not been observed in literature. Observed inhomogeneous broadening of less than 400 MHz and an upper bound on the homogeneous linewidth of 1.4 MHz and 0.75 MHz for two separate resonances, which is a reduction of more than an order of magnitude observed to date. These narrow optical transition properties show that Er in Si is an excellent candidate for future quantum information and communication applications.

A hybrid electro-optical detection method [4]: The first measurements of individual interacting Er ion pairs. Two examples of Er3+ pairs were identified in the optical spectrum by their characteristic energy level splitting patterns, and linear Zeeman spectra were used to characterize the sites. The identical pair displayed Ising-like g-tensors and a very strong, 200 GHz, Ising spin interaction in addition to a 1.5 GHz optical interaction between the ions of the pair.

Integrating erbium dopants into nanophotonic wire waveguides [5]: Perform pulsed resonant fluorescence spectroscopy in weakly doped samples. resonant fluorescence technique, sensitive to all dopants that decay radiatively. observe erbium incorporation at well-defined lattice sites with a thousandfold reduced inhomogeneous broadening of about 1 GHz and a spectral diffusion linewidth down to 45 MHz.

Spin echo from erbium implanted silicon [6]: Origin of the echo is an Er center surrounded by six O atoms with monoclinic C1h site symmetry. T2 and T1 were measured to be 7.5 us and 1 ms respectively at 5 K. The spin echo decay profile had superimposed modulations due to strong superhyperfine coupling with a spin bath of 29Si nuclei.

Coupling erbium dopants to superconducting resonators [7]: Address the difficulty in characterizing, identifying, and controlling the large number of generated EPR- and PL-active centers by coupling the Er spin ensemble to a superconducting resonator, which provides sensitivity enhancements over traditional EPR techniques. Low doped sample (1017 cm−3). Observe coupling between a SC resonator and Er implanted Si with gcol = 1 MHz and gi > 6 Hz. Of six known Er-related EPR centers, only one trigonal center couples to the SC resonator at 20 mK.

**Other platforms**

Radiation damage centers in Si [8]: Assess the centers for its potential as a silicon telecom photon-spin interface. Most radiation damage centers have ZPL transitions that are unsplit by magnetic fields, with no unpaired electron spins in their unexcited states, limiting their usefulness as photon-spin interfaces.

These individual emitters provide a wide diversity of bright, linearly polarized single-photon emissions in the near-infrared range. Some single defects exhibit additional appealing properties, such as a small spread of the ZPL energies or a strong PL intensity well above the liquid nitrogen temperature.

Er: CaWO4 [9]: Erbium ions doped into crystals have unique properties for quantum information processing, because of their optical transition at 1.5 um and of the large magnetic moment of their effective spin-1/2 electronic ground state. By selecting a host matrix with a low nuclear-spin density (CaWO4) and by quenching the spectral diffusion due to residual paramagnetic impurities at millikelvin temperatures, we obtain an Er3+ electron spin coherence time of 23 ms, without having to resort to ZEFOZ transitions nor isotopic purification.

Er3+ electron spin transition can exhibit first order magnetic sensitivity greater than 200 GHz/T and has thus demonstrated electron spin coherence no greater than 10 us in Y based materials.

Er in molecules, GaN

**Proposals for Er:Si**

Long coherence times combined with a rich selection of spin levels (both electronic and nuclear) and optical addressability make REI attractive candidates for qubits as a building block in quantum information science. Quantum memories operate by reversibly mapping the quantum state of light onto the quantum transitions of a material system.

Compatibility with the telecom bands is offered by Kramers ions, with an odd number of electrons (like Er). However, it is much more difficult to make quantum memories with Kramers ions, and not a single Kramers system has demonstrated an on-demand quantum memory. The root of the difficulty is that, unlike for non-Kramers ions, the electronic magnetic moment of Kramers ions cannot be quenched by a crystal field as they possess a half-integer spin. For these ions there is a rapid electronic spin relaxation which shortens the hyperfine state lifetimes. This is similar to the electron spin lifetime and only an order of magnitude longer than the optical excited state lifetime, making efficient optical spin pumping very difficult. Once the electron spin is frozen in the lower ground state, the hyperfine levels associated with this state can have extremely long lifetimes and coherence times.

Implanted Er3+ in Si has shown comparable spin coherence times in low magnetic fields to Er substitutional dopants, but it can occupy a large variety of possible sites in silicon, and the properties of these sites, even for ensembles, are not well known. Sites have been studied with photoluminescence, photoluminescence excitation and electron paramagnetic resonance. However, only a small number of sites have been positively identified.

Knowledge of rare-earth ion symmetry is important in maximizing the number of optically active centers and for quantum technology applications where local symmetry can be used to control decoherence.

The use of rare earths as a spin ensemble is beneficial because they generally possess large g factors, as the orbital angular momentum is not quenched, which is advantageous for strong coupling.

Can be used for spatially multiplexed, on-chip quantum memories. will require a higher optical depth

The light-matter interaction can be strongly enhanced via collective effects in nanophotonic waveguides, and via optical resonators. Using ultra-high Q photonic crystal cavities, as demonstrated recently, a Purcell-enhancement by six orders of magnitude is expected. This would not only bring the system into the strong-coupling regime of cavity QED, but also shorten the radiative decay to the nanosecond range, such that the lifetime-limited linewidth is of the same order as the spectral diffusion linewidth. Thus, we expect that erbium-doped silicon can be used as an optical interface of single spin qubits, operating in the telecom C-band. This offers unique promise for cavity-based quantum networks and distributed quantum information processors based on a scalable platform.

Long-distance entanglement distribution is a vital capability for quantum technologies. An outstanding practical milestone towards this aim is the identification of a suitable matter-photon interface that possesses, simultaneously, long coherence lifetimes and efficient telecommunication-band optical access.

Silicon is a convenient and attractive host for a photon-spin interface as it underpins both the most established integrated electronics and integrated photonics platforms. Silicon, and in particular isotopically purified 28Si, is a host to many atomically reproducible defects with exceptional spin and/or optical properties.

In order to isolate matter qubits that feature an optical interface enabling the long-distance exchange of quantum information while benefiting from well-advanced silicon integrated photonics, one strategy is to investigate defects in silicon that are optically active in the near-infrared telecom bands.

Combining optical and microwave magnetic excitations could enable the investigation of the spin properties attached to these unidentified single-photon emitters in view of isolating individual spin-photon interfaces in silicon operating at telecom wavelengths.

Dilute paramagnetic impurities in a crystal lose phase coherence by interacting with the surrounding fluctuating magnetic moments of other paramagnetic species and nuclear spins of the host matrix. To obtain long coherence times, it is thus beneficial to use crystals that have minimal concentrations of paramagnetic impurities and a low nuclear-spin density.

However, host matrices for REIs are often based on yttrium, such as Y2SiO5 and YVO4, and tend to have high residual REI paramagnetic impurities due to the chemical similarity amongst rare-earth elements. Moreover, Y has only one natural isotope with nuclear-spin I = 1/2 in 100% abundance, so it cannot be isotopically enriched to suppress nuclear magnetic noise. Therefore, it has been difficult to achieve long coherence times with magnetically-sensitive electron-spin transitions in these materials.

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