**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**

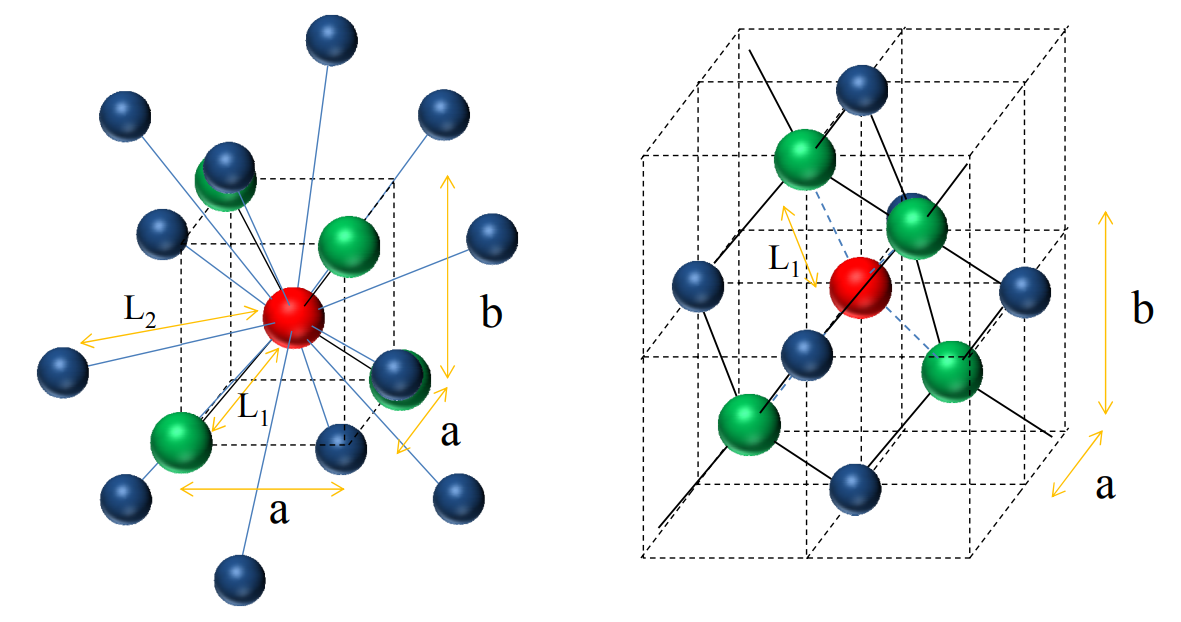
Erbium in silicon was explored extensively in the beginning of twentieth century, with the interest of building a silicon-based on-chip optical source. As a poor photonic material, silicon suffers from fast non-radiative decay dominating over slower radiative routes, and indirect bandgap (band edge luminescence 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. Therefore, various peaks in the crystal field split spectra can be undetected or unresolved.

**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 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.

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.

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.

References:

<https://uchicago.box.com/s/kmxa15p3v75gyemtdwthzj49pyue1m1p>

[1] A J Kenyon 2005 Semicond. Sci. Technol. 20 R65

[2] M. Hughes, M. Lourenço, J. Carey, B. Murdin, and K. Homewood, "Crystal field analysis of Dy and Tm implanted silicon for photonic and quantum technologies," Opt. Express 22, 29292-29303 (2014).

[3]

Link for this review:

<https://uchicago.box.com/s/a86qm7dh4pl9d7nl9i8uv1wxvj6cd9ft>

<https://docs.google.com/document/d/1EjAAh0tcFX6bs8du3sBQHlLPKCA9FJh_kPTTHQo79Hk/edit?usp=sharing>

Link for proposal:

<https://docs.google.com/document/d/1MWcsMxFnkexcZdgwJcvy8GtQEeyaecXYaoQZTtJtLzY/edit?usp=sharing>