Production of Solid State Spin Qubits

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Introduction:

The focus of this project was to design and create an electron irradiation setup at The University of California, Santa Barbara (UCSB) to produce solid state spin quantum bits (qubits) in diamond and silicon carbide. Unlike the conventional bit, which is either 0 or 1, a qubit can be 0, 1, or any superposition of the two states. Quantum computing takes advantage of this property to perform some tasks, such as factoring and searching, much faster than conventional computers can. The setup designed during this project will allow efficient qubit engineering under precisely controlled conditions.

The Qubits:

Solid state spin qubits have several advantages over current qubit technologies: they have long coherence times (~ 2 ms) at room temperature, are optically readable, are scalable as a system, and certain polytypes of silicon carbide can be integrated easily into silicon devices.

A solid state spin qubit consists of a crystal vacancy complex containing a localized electron density. The spin state of this density can be manipulated with microwave frequency magnetic field and the state is read out optically. In diamond, the qubit structure consists of an atomic vacancy adjacent to a substitutional nitrogen atom. In silicon carbide there are six qubit structures. Four of them are known to be divacancies in varying orientations. Figure 1 shows each qubit structure.

The preferred method for creating these atomic vacancies is electron irradiation. Electron irradiation gives even distribution of qubits and a relatively low level of unwanted crystal damage, but creation is inefficient. Only 0.1% of the nitrogen atoms in diamond samples become part of viable qubits, and every extra nitrogen atom interferes with qubit coherence. Currently, samples must be sent to third parties for processing where we have minimal control over irradiation conditions. By creating a facility to manufacture qubits ourselves, we hope to improve creation efficiency and engineer samples with controlled qubit densities, and higher qubit densities than have been made before.

The Project:

To create these qubits, an irradiation setup was designed to interface with the UCSB free electron laser (FEL). The FEL's 5 MeV electron beam is diverted through the sample irradiation setup and into a beam dump. To protect the electron accelerator and eliminate scattering, the entire path of the beam must be under ultra-high vacuum conditions (UHV = 10^{-9} Torr). Because many materials outgas under

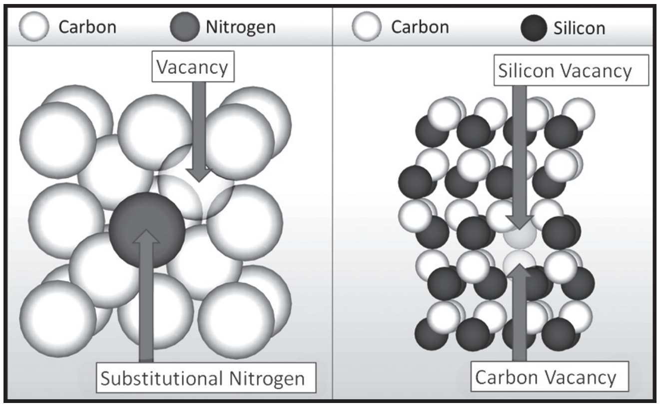

Figure 1: Nitrogen vacancy center in diamond (left) and silicon carbide divacancy (right).

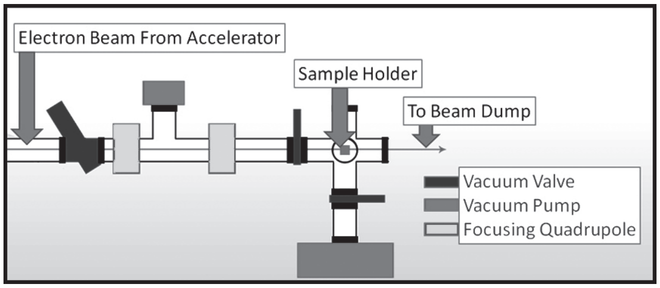

Figure 2: The irradiation addition layout.

UHV conditions, all parts in the vacuum, including sealing gaskets, must be metal. An estimated 9 W will be absorbed by the sample during irradiation so all parts of the system must withstand or dissipate this heat.

The Design:

The final design met all of the challenges of the high energy beam, UHV environment, and more. For the safety of the electron accelerator, the irradiation addition was automatically isolated from the rest of the beamline in the event of a leak, and could be manually isolated in multiple sections for access and pumping. For efficiency, the addition used standard vacuum parts with the exception of the sample holder, and a small volume to pump down. Figure 2 shows the irradiation addition to the FEL facility. The sample holder was a 20 × 16 × 75 mm block of copper with five insets for samples on the front face. The holder was threaded onto a high-power ¾″ copper feedthrough that was attached to a linear-shift bellows mechanism to offer a 50 mm movement range.

The sample holder and beam were aligned using a 6 mm diameter calibration hole at the bottom of the holder while maximizing the current at the beam dump. When the system was aligned, the 7 mm spacing between samples allowed us to move between all five samples without breaking the vacuum. The calibration process also provided an electron flux measurement that could be used to calculate irradiation dose when the sample was in the beam. For heat conduction out of both faces of the samples, each was secured in its inset by a 4 mm thick copper faceplate and two bolts. Heat was drawn from the sample holder via the feedthrough which was water cooled outside the chamber for vacuum safety.

To reduce unnecessary heating there was a free path for the beam through the center of each faceplate and through the holder behind each inset. The first sample holder accommodated two 2.3 × 2.3 mm samples and three 3 × 3 mm samples, but the threaded attachment made installing other sample holders for future experiments simple.

Figure 3 shows the elements of the irradiation assembly and Figure 4 shows the finished sample holder.

Conclusion and Future Work:

At this point the irradiation addition to the FEL is under construction. Several components required for the protection of the accelerator are being ordered. When completed, the setup will be used to study how different irradiation conditions affect resulting qubit quality.

Acknowledgements:

This project would not have been possible without input and support from many individuals. The Awschalom Group provided tremendous feedback and assistance throughout the project. Engineer David Enyeart and Research Scientist Gerald Ramian, of the UCSB FEL staff, provided regular consultation on construction, acquiring parts, and interfacing to the beam. Professor Christopher Palmstrom provided input on the construction of UHV systems and considerations for the optimal design. And the NSF, NNIN REU Program, UCSB, DARPA, and the Air Force provided funding and facilities.

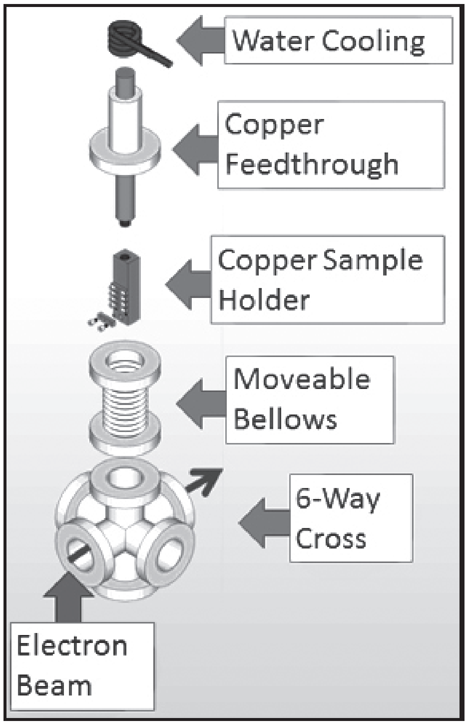

Figure 3: The irradiation assembly.

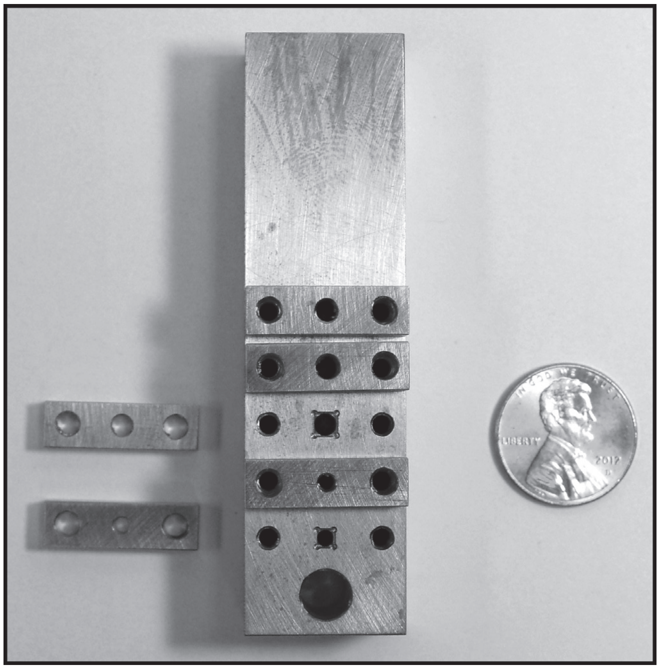

Figure 4: The completed sample holder.