Andrew Barabas

Surface acoustic wave resonators for hybrid quantum devices

Worster Fellowship project proposal for Andrew Barabas

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Acoustic waves in the quantum regime have been a topic of great research interest in recent years, particularly due to their potential use in hybrid quantum devices: they couple strongly to a wide variety of solid-state qubits, serving as interfaces between them and other quantum elements such as photons. Furthermore, they can store quantum information for relatively long periods of time, and can transmit quantum information over relatively long distances. A well-established means of driving acoustic waves is via interdigitated transducers (IDTs), which consist of planar, interdigitated electrodes on top of a piezoelectric substrate that convert an applied electrical signal into surface acoustic waves (SAWs). SAW devices are omnipresent in classical RF and microwave circuits, perhaps most notably as bandpass filters in communications applications, e.g. cellular phones. Very recently, SAWs have been shown to interact with superconducting and spin qubits, which has motivated their integration into complex quantum circuits that couple many different quantum elements.

Andrew Barabas's Worster project aims to design and test SAW devices for quantum information processing applications. This work will transition into an honors thesis in the Jayich lab focused on coupling diamond spins to GHz-scale diamond mechanical resonators. Importantly, the research will train Andrew with a broad experimental skillset in preparation for graduate school and a future career in science. This skillset includes microwave engineering, optical techniques, quantum control, and finite element modeling.

This project explores the feasibility of SAW resonators operating in the quantum regime. SAW resonators are devices that confine Rayleigh waves in a small area of a chip and can be used to enhance interactions between phonons and qubits. In the context of this project, the qubit of choice will be the Nitrogen-vacancy (NV) center in diamond, which can interact with mechanical motion via crystal strain. A major advantage of a SAW-based device is that the strain produced by SAW modes extends approximately a wavelength (~ 1 micron) into the bulk, enabling coupling to deep NV centers, which have been shown to have much better spin and orbital coherence than shallow NV centers due to isolation from surface noise. A successful SAW device will feature high mechanical quality factors ($> 10^5$) and high frequencies (1-10 GHz), which will enable experiments in the quantum regime, such as phonon-mediated coherent quantum information transfer between spatially separated NV centers. Week 1: Choose device parameters for IDT devices (first for AlN on silicon, then on AlN on diamond): number of fingers, spacing, thickness of the Al (AlN is fixed thickness), and free spectral range of SAW cavity with a ~ GHz target frequency. Use Comsol.

Week 2-4: Measure devices fabricated according to results of simulations. Measure S11 using network analyzer. Use LDV to image amplitude of motion. Use the results to estimate the electromechanical coupling strength and use those results to feedback to adjust design and fabrication. Jeff will be fabricating on diamond here too.Week 5: Characterize SAW cavities on diamonWeeks 6-8: measure SAW cavities at low temperature on diamond (Q). Measure and characterize coupling to NV centeWeeks 9-10: Drive Rabi oscillations of the NV center with S To achieve these goals, Andrew will simulate, design, and characterize SAW devices in both diamond and silicon. A thin layer of AlN between the diamond/silicon and the IDT electrodes will be used to provide the requisite piezoelectricity. Andrew will need to study the theory of IDTs and SAWs and write a program to analytically simulate different IDT device geometries. Andrew has already begun work on this aspect of the project during the school year, which should allow him to have mastered these useful tools before the summer and progress rapidly to the next phase of the proposed work during his fellowship period. I (Jeff) will then fabricate these devices in UCSB's nanofabrication facility and Andrew will characterize their electrical and mechanical properties. Andrew will characterize their electrical properties by measuring the S-parameters of an IDT with a network analyzer. This will require Andrew to learn RF circuit and measurement techniques, from practical matters such as wirebonding and handling RF cables and components to properly using and gathering data with a network analyzer. Mechanical characterization of these devices will be performed using a laser doppler vibrometer (LDV) in Prof. Kim Turner's lab. This tool will allow for the interferometric detection of the amplitude of SAWs generated by our IDTs. Andrew will also need to learn and perform X-ray diffraction (XRD) to measure the crystallinity of the AlN we deposit. After all these initial characterization steps, Andrew will proceed to measure the SAW devices at 4K and study the interactions between confined SAWs and NV centers using the Jayich lab's low-temperature confocal microscopy setup.

The end goal of this work, looking forward to Andrew's Senior year, is to demonstrate coupling between confined SAWs and NV centers. Furthermore, the different characterization measurements of the IDTs and SAWs he completes in the summer will be used to determine the electromechanical coupling factor of our AlN films, a figure of merit that measures how efficiently our film converts electrical to mechanical energy and vice versa, and which will be necessary to know as we continue to engineer and study devices that can operate in the quantum regime.

A preliminary outline for Andrew's Worster research is given below:

Week 1: Choose device parameters, such as the number of fingers in the IDT electrodes, spacing of the fingers, thickness of the Al electrodes), and free spectral range of the SAW cavity. This will require use of COMSOL and some analytical calculations.

Week 2-3: Jeff will fabricate devices on silicon according to the results of the prior week's simulations. Andrew will measure S_{11} and S_{21} of the SAW resonators using a network analyzer and use the Turner lab LDV to image amplitude of motion. Use the results to estimate the electromechanical coupling strength and use those results to feedback on device design and fabrication.

Week 4-5: Repeat weeks 2-3 with diamond devices instead of silicon.

Weeks 6-8: Measure SAW cavities in diamond at low temperature.

Weeks 9-10: Measure and characterize SAW coupling to NV center. Attempt to measure mechanical sidebands on the NV center's optical transitions due to interactions with SAWs.

To ensure that this project progresses successfully, I will meet with Andrew at least once per week to monitor progress and challenges, go over goals for the next week, and identify any roadblocks that I can assist Andrew with. At the outset of the project, including the work that Andrew is doing this quarter, I will work closely with Andrew in order to teach him the necessary skills for this project, but the intent is for Andrew to proceed with this work with a high degree of independence as the summer progresses and especially when he is working on his honors thesis during the next school year. This will allow Andrew to both contribute significantly to the overarching project and develop useful skills and knowledge that will aid him in his transition from undergraduate to graduate research.