High-Resistivity Sub-kelvin Tc Superconductors for Quantum Sensors

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Introduction

- Superconducting pair-breaking sensors detect a signal by its dissipation into quasiparticle excitations of a superconductor.
- Small gap of a superconductor (e.g., 0.0002 eV for aluminum) compared to conventional semiconducting detectors enables much smaller signals to be detected.
- Science applications: high energy particle detectors, calorimetry, low background searches for dark matter, axions and low energy neutrinos, cosmological surveys, and more were discussed at RDC7 and 8 workshops.
- Sensors come in many flavors, such as the transition-edge sensor (TES), kinetic inductance detector (KID), superconducting nanowire single photon detector (SNSPD), quantum capacitance detector (QCD), ... with different operating principles, energy resolutions, speed, multiplexability, ...

Film properties and sensor performance

- Low gap, which implies a low Tc, reduces energy threshold and sensitivity.
    - Minimum Tc set to slightly above the bath temperature to ~10x the bath temperature, depending on sensor type, principle of operation of the particular sensor, and gap-Tc relation.
    - Tunability of Tc is very useful.
- A low effective loss tangent or high quality factor for resonator based detectors.
    - Absence of subgap states, low stress, low density of two level systems and other loss mechanisms.
- High or low resistivity, depending on the type of sensor.
    - High resistivity = high kinetic inductance. Desirable for resonator-type sensors.
- Long or short quasiparticle lifetime, depending on the type of sensor.
- Uniformity, stability and repeatability of fabrication.
- Insensitive to subsequently processing steps in fabrication.

Proposal

- Expand our work developing low-Tc high resistivity superconductors for pair-breaking sensors.
  - Optimize popular quantum sensor superconductors for lower-Tc operation.
  - Test materials that have shown good results for one type of sensor in other types of sensors.
- Study Tc, resistivity, quasiparticle lifetime, quality factor in materials and their dependence on deposition conditions in test structures.
- After developing good films, study their performance in functional sensors.
- Look at several classes of materials
  - Elemental superconductors (e.g. Hf, Ir), transition metal silicides (e.g. WSi), transition metal nitrides and oxides (e.g. VN), binary alloys (e.g. NbMo).
  - Crystalline and amorphous deposition conditions.
- Look at different mechanisms for Tc tuning
  - Composition,doping, stress, annealing

Hafnium

- Transition temperature 130-400 mK depending on deposition conditions.
- Many promising results in superconducting tunnel junctions, transition edge sensors and kinetic inductance detectors.
- Can good quality factors observed in resonators with 400 mK Tc films be extended to lower Tc?
- Relatively long quasiparticle lifetimes have been observed (400 us), but can it be increased to match the milliseconds achieved in aluminum?

Amorphous tungsten silicide

- Tc tunable over a wide range up to 5 K and at least down to 0.5 K by varying elemental composition.
- Very short quasiparticle lifetime ideal for fast SNSPDs and sensitive TKIDs.
- Good quality factors in resonators not reported below 1 K Tc.
- Low Tc at high silicon content may suffer from sub-gap states that poison resonator quality factor. Can other methods of Tc tuning do better? E.g. manganese doping, or substitution of tungsten with other transition metals.

The team and responsibilities

- Bryan Steinbach, staff at Caltech.
    - Expertise: 15 years in designing and developing superconducting sensors (TES, TKID).
    - Will design test structures and survey literature for materials and interpretation.
- Roger O'Brient, staff at JPL.
    - Expertise: 20 years in superconducting device fabrication and characterization (TES, MKID, TKID, SNSPD)
    - Will lead sample preparation team at JPL fab, room temperature characterization (stress, SEM) and cryogenic testing in 80 mK cryostat at JPL.
- Aritoki Suzuki, staff at LBNL.
    - Expertise: 15 years in superconducting device fabrication and characterization (TES, MKID).
    - Will manage preparation of samples through external vendor and cryogenic characterization down to 20 mK with a postdoc at LBNL.

Overlap with RDCs

- Collaboration built through RDC8, quantum and superconducting sensors.
- Significant overlap with RDC7, low-background detectors, where superconductors would be used.

Timeline - 2025

- We will fabricate films at JPL in an existing sputter system that the team own. These studies will vary deposition conditions and stoichiometry.
- We will cryogenically characterize these samples in existing testbeds at JPL and LBL. This sample prep and testing will happen in first 6 months of FY25.
- We will fabricate resonators from promising recipes in JPL's microdevices laboratory cleanroom.
- We will test the resonators in existing cryostats at JPL and LBL using pre-established RF test installation. Tests will scrutinize resonator Q and quasiparticle lifetimes. Fab and testing will happen in last 6 months of 2025.

Timeline - 2026

- Continue activities from 2025 as needed
- Design and fabricate superconducting sensors to demonstrate linkage between material property vs sensor performance. These will use common films between different detectors as a means of controlling material properties between different technologies.

Timeline - 2027

- Continue acrtivires from 2026 as needed
- As motivated by progress in 2025-26, we will explore more exotic superconductors like vanadium oxides and nitrides, and niobium molybdenum. We will also explore doping with manganese to further refine the transition temperatures.
- We will publish reports on material properties as a function of stoichiometric composition and deposition parameters.