Simulating the Phonon Collection Efficiency in KIPMDs

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Introduction to KIPMDs

• Kinetic inductance phonon-mediated detectors (KIPMDs) are superconducting microcalorimeters that use microwave kinetic inductance detectors (MKIDs) to read out phonon signals
• KIPMDs are attractive candidates for light DM searches because of their potential eV-scale sensitivity

Simulation Methods

• G4CMP is used to simulate solid-state processes in Geant4
• Generate and propagate electron-hole pairs in the Si substrate
• Produce acoustic phonons and model phonon dynamics
• Calculate phonon energy depositions in target volumes

Using Geant4/G4CMP simulations, we seek to reconstruct the single-point phonon collection efficiency and study the channels of phonon loss in the KIPMD currently deployed at the NEXUS underground facility.

Simulation Results

The experimentally determined $\eta_{\text{ph,point}}$ for the NEXUS KIPMD is $(0.89 \pm 0.11)\%$ [1]

• To simulate a pulse of 470 nm optical photons incident on the substrate, we generate

  1.00 electron-hole pairs each with 2.63 eV total energy (1.46 eV kinetic energy after

  overcoming the 1.17-eV Si band gap) in a disc with a 100-μm radius and a 100-μm

  length at the bottom of the substrate

  • We observe ~60% uncertainty in $\eta_{\text{ph,point}}$ for a 1 mm offset of the source spot
  • A factor of ~10 disagreement was observed between the current simulations and the
  experimentally-measured value. Some potential causes of this, which can be
  investigated in simulation, are

    • Potential location mismatch between simulated interaction region and photon
      source in experiment (see previous bullet point);

    • Electron/hole trapping in Si;

    • A higher Cooper pair binding energy for the Al thin film than used in this model

Channels of Phonon Loss

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References:


Table 1. *Calculated from equations in [3] by multiplying $P_{\text{trans}}$, the probability of transmission from substrate to metal, and $1-P_{\text{trans}}$ where $P_{\text{trans}}$ is the probability of a phonon with pair-breaking energy entering and escaping the metal film. Here $P_{\text{abs}}$ denotes phonon absorption probability across the interface between material X and Si, and $\eta_{\text{ph,point}}$ denotes the single-point phonon collection efficiency.

<table>
<thead>
<tr>
<th>Detector Element</th>
<th>$\eta_{\text{ph,point}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feedline</td>
<td>38.7%</td>
</tr>
<tr>
<td>Housing Mounts</td>
<td>26.4%</td>
</tr>
<tr>
<td>Nb Resonators</td>
<td>18.8%</td>
</tr>
<tr>
<td>Target Inductor</td>
<td>9.59%</td>
</tr>
<tr>
<td>Bilayer Capacitor</td>
<td>3.57%</td>
</tr>
<tr>
<td>Target Resonator Ground Plane</td>
<td>2.91%</td>
</tr>
</tbody>
</table>

Table 2. $\eta_{\text{ph,point}}$ for different detector elements as targets. Here we use the theoretically-motivated values in bold in the Table 1 or $P_{\text{trans}}$ calculated from [3] and generate the distribution of e-h pairs described above.

Fig. 1. Energy deposited in the Si detector substrate propagates in the form of phonons, which breaks Cooper pairs in the Al superconductor [2].

Fig. 2. (Left) The KIPMD at the Northwestern Experimental Underground Site (NEXUS) [1] in its housing. (Center) Geant4 geometry of the NEXUS KIPMD, which features an Al meandered inductor (the phonon-absorbing target) and a Nb-Al bilayer interdigitated capacitor.

Fig. 3. Portions of total phonon energy collected by various detector elements; colors of the slices correspond to the colors of the annotations in the G4CMP renderings.

Fig. 4. Energy deposited in the Si detector substrate propagates in the form of phonons, which breaks Cooper pairs in the Al superconductor [2].