Phonon mechanisms for excess heat capacity in membrane isolated superconducting transition edge sensors

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Abstract:
The mechanics of phonon transport in membrane-isolated superconducting transition edge sensors is discussed. Surveys of the literature on this type of sensor reveal a number of designs with excess heat capacity and a smaller subset that exhibit decoupling of the superconducting film from the underlying dielectric. A simple model is addressed in which the membrane, despite its thermal isolation, fails to fully thermalize to the temperature of the metal film heating it. A population of phonons exists which is emitted by the metal film, partially thermalizes the dielectric and is then reabsorbed in the metal film without escaping from the device structure to the thermal bath. The size of this population and its contribution to the heat capacity are estimated for several device scenarios.
Phonon mechanisms for excess heat capacity in membrane-isolated superconducting transition edge sensors

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Choice in TES design: watch as phonons futilely attempt to thermalize a dielectric crystal at low temperature

The mechanics of phonon transport in membrane-isolated superconducting transition edge sensors is discussed. A survey of the literature on this type of sensor reveal a number of designs with excess heat capacity and a smaller subset that exhibit decoupling of the superconducting film from the underlying dielectric. A simple model is addressed in which the membrane, despite its thermal isolation, fails to fully thermalize to the temperature of the metal film heating it. A population of phonons exists which is emitted by the metal film and partially thermalizes the dielectric and is then reabsorbed in the metal film without escaping from the device structure to the thermal bath. The size of this population and its possible contribution to the heat capacity is estimated for a device scenario.

Series of Four Test Devices

Excess Heat Capacity Discussion – uniform application of a model to determine relative changes in device parameters

Large membrane silicon bolometers exhibiting excess heat capacity

A study undertaken by Zhao examined the role of an external load on the thermal conductance in TES bolometer structures exhibiting a large excess heat capacity. Noise and impedance in bolometers with cutouts near the TES were compared with identical structures with no cutouts.

Note: The suppression of the Kapitza conductance from bulk is not anticipated in these scenarios

Lit survey: Suspected causes of heat capacities

TABLE 1: Differences in heat capacity contributions.

Empirical models to large membrane-embedded bolometers have added heat capacities to fit data such as complex impedance. The Zhao study showed that a third heat capacity (in addition to, presumably, the TES metal and Si dielectric) was required to fit the data.

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A New Suspect: Trapped Population of Excess Ballistic Phonons in the Membrane Volume

Dielectric and Kapitza – Men? Or Myths?

Debye and Kapitza: Men? Or Myths?

Kapitza-superpowers of phonons from metal into dielectric has been modeled to include dynamic of the dielectric surface to modify the coefficients of transmission and reflection at the interface. The effects of non-atomic interference (of course, that’s the name) have been noted as increasing with increasing incident phonon energy. These models have not been fully developed, though. Not yet. But eventually they will be.

Debye theory is expected to be saturated for crystalline dielectrics such as SiN. The Debye temperature corresponds to a maximum energy of 100 mK. This results in a saturated phonon density that is limited by a material property.

Dielectric surface roughness effects – Since Si crystals have only the T^3 Debye component, surface roughness resulting in nano-scale roughness effects causes a third heat capacity. This roughness effect is not fully accounted for in the results of Zhao although with a more careful focus on where the heat capacity could be located.

A New Suspect: Trapped Population of Excess Ballistic Phonons in the Membrane Volume

Estimates of heat capacity for novel phonon confinement conditions:

Case I: phonons are completely non-interacting blocks of phonons peaked at (πc) filling the dielectric volume

Case II: phonons are completely non-interacting blocks of phonons peaked at (πc) filling the dielectric volume

Energy density in the Si membrane is lower than that of the leg (10%) in the same Si legs (~14% of the membrane)

Models fit to same impedance curves for T^4=320 mK; 50% Rn