Heat Capacity and Thermal Conductance Measurements of a Superconducting/Normal Mixed State by Detection of Single 3 eV Photons in a Magnetic Penetration Thermometer

T.R. Stevenson1, M.A. Balvin2, S.R. Bandler3, K.L. Denis1, S.-J. Lee2, P.C. Nagler1,1, S.J. Smith4,2
1 Detector Systems Branch, NASA Goddard Space Flight Center, Greenbelt, MD, USA
2 X-ray Astrophysics Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD, USA
3 Department of Physics, Brown University, Providence, RI, USA
4 University of Maryland Baltimore County, Baltimore, MD, USA

MPT operation

Cartoon of self-inductance MPT

MPT circuit diagram

- A persistent current is trapped in the bias circuit above the Tc of aluminum wirebonds that connect each sensor to its associated SQUID.
- As we cool or warm through the MoAu sensor’s superconducting transition, the inductance of the meander changes as the MoAu film expels or allows entry of flux, and we measure a current proportional to the sensor’s magnetic response.
- MPTs give us a unique avenue to probe superconducting effects in MoAu films.

C and G Measurements

1. Using 3-eV photons from a Blu-ray diode

- An example data set at 1001 uA and 109 mK (photon number resolved)

- 405 nm (3.8 eV) photons from a Blu-ray diode outside the crystal
- Photon pulse width: 0.7 us, repetition rate: 70 Hz
- 10,000 triggered records at each T

- Measured C and G using 3-eV photon data only (left) and together with noise spectrum data (right)

- The two methods share the same d/dT and τ values

2. Noise spectra measurement

- At 100 Hz & Blu-ray

3. Measured C and G

- Measured C and G

Theory

1. Free-energy difference between superconducting and normal states of MPT

- f = fraction of meander length for which MoAu enters a partly-normal intermediate state
- g = fractional width of normal stripes in intermediate state region
- C = superconducting energy gap reduction in Ginzburg-Landau equation

Solve to find state with minimum free energy of MPT relative to fully normal state. Free energy contains inductive and condensation terms:

\[ G_{\text{free}} = \frac{1}{2} \int \left( \frac{dI}{dt} \right)^2 dV + \frac{1}{2} \int \left( \frac{d^2V}{dt^2} \right)^2 dV + \frac{1}{2} \int \left( \frac{d^4V}{dt^4} \right)^2 dV \]

\[ C = \frac{1}{2} \int \left( \frac{dI}{dt} \right)^2 dV + \frac{1}{2} \int \left( \frac{d^2V}{dt^2} \right)^2 dV + \frac{1}{2} \int \left( \frac{d^4V}{dt^4} \right)^2 dV \]

2. Heat capacity from second derivative of free energy

3. Thermal conductance: quasiparticle recombination & electron-phonon cooling

- In superconducting regions, recombination of quasiparticles into Cooper pairs should be dominant cooling mechanism.
- In normal regions, quasiparticles cool by only phonon emission.
- We estimated Kaplan’s τ and Wellstood’s Z2 from the electronic and mechanical parameters for Mo and Au. A priori values fit dI/dT data within one order of magnitude.
- Fit results: τ = 56 µs, Z = 1.1x1010 W/mK²

Conclusions

- We measured the variation in heat capacity and thermal conductance of a molybdenum-gold Magnetic Penetration Thermometer (MPT) near its field dependent Meissner transition temperature.
- We did this by two methods: detection of pulses in response to absorption of one or more 3 eV photons, and equilibrium noise measurements.
- Observed C & G show peaks in approximate agreement with a Ginzburg-Landau model of the superconducting intermediate state of an MPT.

References