DDF annual report

Title of Investigation:

The ZeptoBolometer: Towards Far-Infrared Photon Counting

Principal Investigator:

Dominic Benford (Code 665)

Other In-house Members of Team:

James Chervenak (Code 553), Thomas Stevenson (Code 553), Harvey Moseley (Code 685), and Stephen Rinehart (Code 685)

Other External Collaborators:

None

Initiation Year:

FY 2005

Aggregate Amount of Funding Authorized in FY 2004 and Earlier Years:

$0

Funding Authorized for FY 2005:

$68,000

Actual or Expected Expenditure of FY 2005 Funding:

In-house: $40,000 for materials and instrumentation; Contracts: $27,000 to Swales and SSAI

Status of Investigation at End of FY 2005:

Transitioning to RTOP

Expected Completion Date:

December 31, 2006

Purpose of Investigation:

The goal of this work is to push the frontiers of detector physics by attempting to produce a far-infrared detector that is an order-of-magnitude more sensitive than any ever produced. NASA needs such an invention to achieve its goals of building and flying very sensitive observatories, including the Single Aperture Far-Infrared Observatory (SAFIR) and the Sub-millimeter Probe of the Evolution of Cosmic Structure (SPECS). This work will position Goddard as a key player in the instrumentation for these missions. Several aspects of this effort are challenging. The physics of the two approaches we are considering—phonon-mode-suppression and electron-phonon decoupling—are poorly understood. The methods of getting light into such devices through a method called "antenna coupling" are at the limits of technical capability. Testing these detectors will require a very capable and low-noise test-bed facility.

Accomplishments to Date:

The zeptobolometer is a very sensitive far-infrared detector. It is made by using a superconducting Transition Edge Sensor (TES) fed by an appropriate antenna, It is read out by a Superconducting QUantum Interference Device (SQUID) amplifier. The TES is used to detect the energy in the far-infrared wavelength bands. We have implemented TES as superconductor/normal metal bilayer (Figure 1) that allows us to tune the resistance and transition temperature by adjusting the fabrication process (Figure 2). We have modeled combinations of Mo or Ti combined with Cu or Au, and derived the required transition temperature, material choice, and bilayer thickness consistent with the desired detector noise (Figure 3).

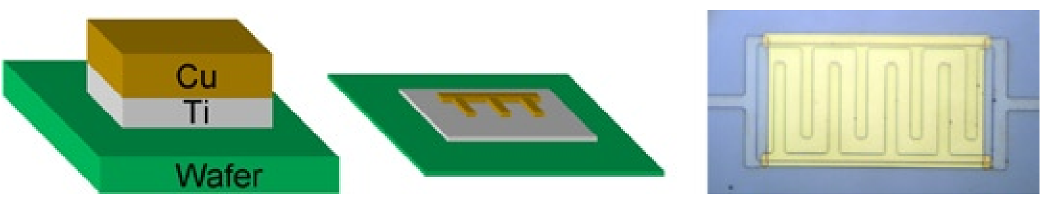


Figure 1. Diagram of a bilayer transition-edge sensor (TES); photo of an Au/Mo bilayer

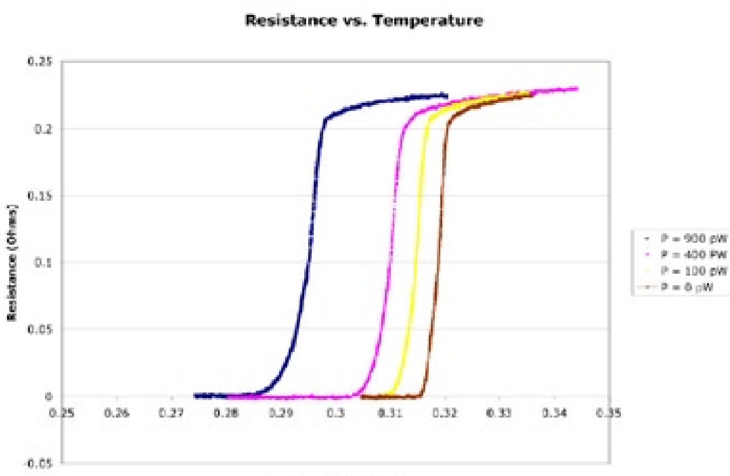


Figure 2. (Left). Resistance vs. temperature for different amounts of power dissipated in the absorber. From these measurements, we can scale to ultra-low temperatures and small volumes to obtain the desired zeptobolometer noise performance.

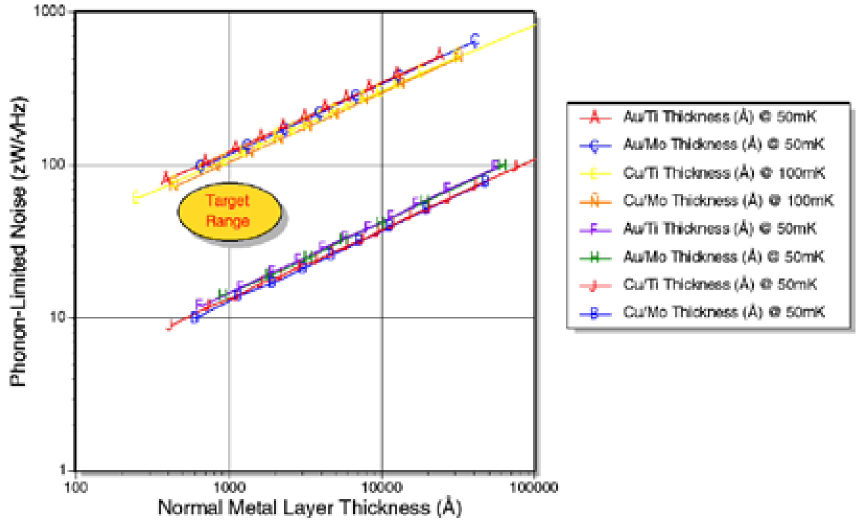


Figure 3. Calculations of the phonon-limited noise of a 10 μm X 10μmTES, using two different normal metal layers, two different superconducting layers, and two different designed transition temperatures. Given our desired target range of metal layer thickness and phonon noise, we can see that the Zeptobolometer can be achieved with any combination of the metals operating at a temperature of ~80 mK.

We have conducted a limited TES bilayer investigation (including characterization of superconductors and development work for process integration) to determine the proper fabrication approach and material choices for the target design. Based on this, Ti/Cu appears to have transition temperatures and resistances in the desired range. We have developed a testing facility able to reach this temperature (~80 mK) and measure these bilayers (Figure 4).

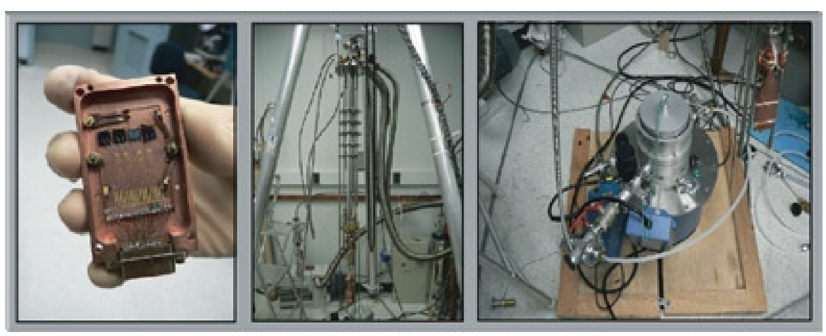
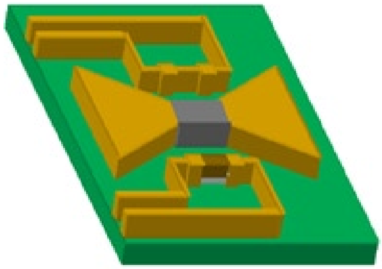


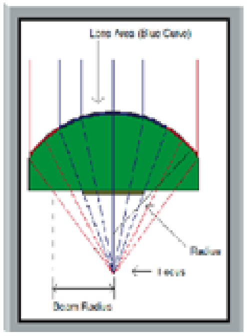
Figure 4. Zeptobolometer bilayer characterization occurring in a low-temperature test facility. At left is a package containing TES devices under test; at right is the dilution refrigerator capable of cooling to 50 mK.

In addition to the TES bilayer effort, we also simultaneously designed the method for matching the TES to an antenna and matching the antenna to free space: Our design dictates a certain size for the TES, which in turn determines its heat capacity, effective time constant, noise, etc. The design choice has driven us to higher resistance systems using Ti/Cu bilayers made out of ultrapure materials. For a range of useful frequencies, we have designed the antenna, termination resistor, and TES bilayer size (Figure 5). For good optical efficiency, we also have had to design a hyper-hemispherical lens to couple far-infrared light into the antenna (Figure 6). We also have been testing high-impedance termination resistor materials and calculating the antenna efficiency (Figures 7 and 8). Overall, we have demonstrated that all aspects of these detectors are feasible with our techniques.



Design Frequency	Opening Angle (°)	Length (mm)	Impedance (Ω)	Max. Resistor Overlap (µm)
45 GHz	85.01	5.291	69.584	133.333
95 GHz	84.99	2.506	69.5951	63.158
1 THz	84.98	0.238	69.6	6.0
3 THz	84.53	0.079	69.851	2.0

Figure 5. Designed antennas and termination resistors for representative far-infrared to millimeter-wave frequencies



Design Frequency	Radius (cm)	Angle (°)	Area of Lens (cm^2)	Focus (cm)	Beam Radius (cm)
45 GHz	6.9	1.7345	2.97	2.85	3.57
95 GHz	3.29	4.154	3.25	1.399	2.357
1 THz	3.129	4.422	3.28	1.292	2.29
3 THz	1.04	29.4	4.88	0.4296	1.038

Figure 6. Designed lenses to couple to the antennas

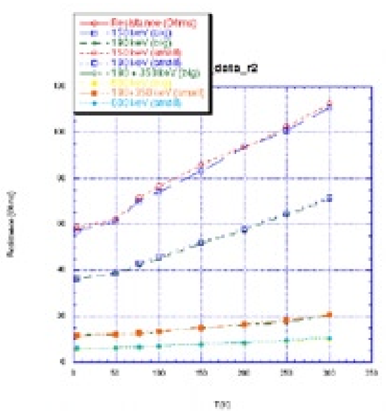


Figure 7. R-per-square versus temperature for a series of n-type implanted Si resistors

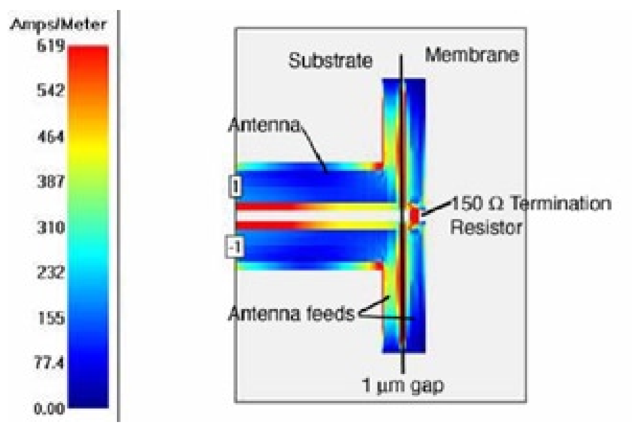


Figure 8. Simulated current flows on termination folded coplanar strip transmission line structure

Planned Future Work:

Our highest priority for future investigations is to further characterize antenna-coupling termination materials. We need a combination of sensitivity at 1–3 THz and suitable electron-phonon decoupling to avoid degrading the noise in the signal between the antenna and the zeptobolometer. Preliminary measurements indicate that implanted silicon below 100 Ohm/sq should have suitable properties at optical frequencies, but may require a sintering step to make Ohmic contact to the TES. Currently, our preferred system is single-crystal Bi, with semi-metal properties. This may remain a more difficult fabrication task.

Key Points Summary:

Project's innovative features: The innovative element of this work is to push the frontiers of detector physics by attempting to produce a far-infrared detector that is an order-of-magnitude more sensitive than any yet produced. However, the physics of the two approaches we have considered—phonon-mode-suppression and electron-phonon decoupling—are poorly understood. We have conducted theoretical and experimental investigations into the sensor for both these approaches. We also have worked out many of the details to fabricate the antenna to couple radiation into a device using either approach.

Potential payoff to Goddard/NASA: Recent mission studies for far-infrared space telescopes, including SPIRIT (Space Infrared Interferometric Telescope), SAFIR, and SPECS, have each identified a key enabling technology: large arrays of direct detectors with sensitivities of NEP $<10^{-19}$ W/√Hz, which is the sensitivity to detect the power of one visible photon every two seconds. Currently, the Jet Propulsion Laboratory (JPL) leads in this technology, but we have pushed Goddard's capabilities to become more competitive. Future technology-development funding is, therefore, much more likely to be within Goddard's reach.

The criteria for success: The ultimate success of this investigation is to measure the detection of light with a sensitivity of $<10^{-19}$ W/√Hz. While we have not yet achieved that, a similar effort underway at JPL also has not reached this goal. Our effort has made significant progress along this path, and we are at a point where we can transition to future funding through the ROSES RTOP mechanism.

Technical risk factors: Research in the two mechanisms we have selected is promising, but very preliminary and is essentially empirical rather than analytical. Therefore, new and unanticipated phenomena are to be expected. In our case, we had to spend considerable time designing and modeling these just to select the proper combination of materials, device dimensions, and antenna/lens parameters. We have completed all of these designs, with the requirement that they be constructed using the techniques we have available. However, the scope of this effort did not permit us to complete the device.