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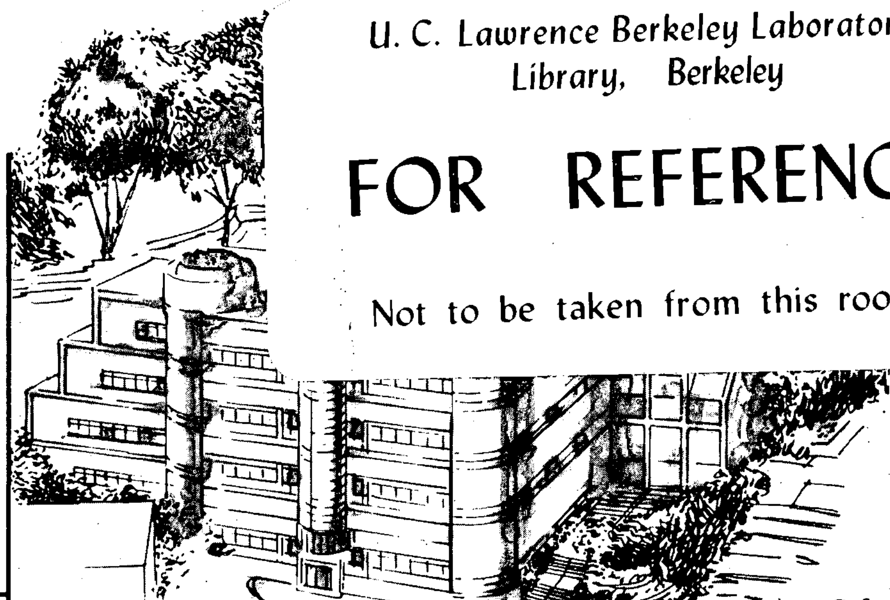

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SUPERCONDUCTING BOLOMETERS: HIGH-T_c AND LOW-T_c*

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ABSTRACT

A description is given of recent work at Berkeley on superconducting detectors and mixers for infrared and millimeter wavelengths. The first report is a review article which summarizes the status of development of superconducting components for infrared and millimeter wave receivers. Next, a report is given on measurements and theoretical modeling of the absorptivity (surface resistance) of high quality epitaxial films of the high-T_c superconductor YBCO from 750 GHz to 21 THz. The next report describes measurements of the thermal boundary resistance between YBCO films and various substrates. This resistance is much larger than expected from the acoustic impedance mismatch model and gives a thermal time constant in the nanosecond range for typical YBCO films. Then, there are reports on the design and experimental performance of two different types of high-T_c bolometric detectors. One is a conventional bolometer with a gold-black absorber. The other is an antenna coupled microbolometer. The properties of a low-T_c microbolometer are also described. The last reports describe accurate measurements and also theoretical modeling of an SIS quasiparticle waveguide mixer for W-band which uses very high quality Ta junctions. The best mixer noise is only 1.3 times the quantum limit. Both the mixer gain and the noise are in quantitative agreement with the quantum theory.

2. SUMMARIES

The superconducting components that have been developed for infrared and millimeter-wave receivers have been reviewed.[1] A brief description is given of the scientific principles on which each device is based, followed by a discussion of the performance that has been achieved in terms of the appropriate figures of merit. Finally, comments are made about the possibility that useful device performance can be achieved by using the new high-T_c oxide superconductors. This review emphasized photon-assisted quasiparticle tunneling and the SIS quasiparticle mixer, which is the only superconducting component to find substantial applications at infrared or millimeter wavelengths. Descriptions are given of the SIS quasiparticle direct detector, the Josephson effect oscillator, the Josephson effect parametric amplifier, and the various superconducting bolometers for which practical applications appear possible. The less promising Josephson effect detector and mixer and the various ideas for superconducting photon detectors were described because of the current interest in possible high-T_c versions of these devices.

Direct absorptivity measurements[2] have been made on thin films of $YBa_2Cu_3O_{7-\delta}$ and $ErBa_2Cu_3O_{7-\delta}$ from 25 to 700 cm^{-1} (750 GHz to 21 THz). The high quality c-axis oriented films are grown epitaxially on $SrTiO_3$, $LaAlO_3$ and MgO substrates by off-axis sputtering and laser ablation. In our measurements the film acts as the absorbing element in a composite bolometric detector operated at 2 K which is used to detect the signal from a Fourier transform infrared spectrometer. Despite the variety of sample deposition techniques and substrates, all the films exhibit similar absorptivities: In contrast to the interpretation of some reflectivity measurements, the absorptivity is non-vanishing down to the lowest frequencies in our measurements. Microwave loss measurements made on the same films allow the absorptivity to be deduced over nearly four orders of magnitude in frequency. These data fit both a homogeneous two-fluid model or a weakly coupled grain model with acceptable parameter values.

We have made direct measurements of the thermal boundary resistance, R_{bd}, between high quality epitaxial films of $YBa_2Cu_3O_{7-\delta}$ and a variety of substrates with and without buffer layers.[3] The boundary resistance was deduced from measurements of the electrical resistance changes in three parallel strips of $YBa_2Cu_3O_{7-\delta}$ when one was electrically heated. Results are available only for temperatures above the superconducting transition with this method. Our measurements indicate that R_{bd} is weakly dependent on temperature and, for all the measured samples, has a value of $0.9\text{-}1.4\times10^{-3}$ Kcm^2/W at 100K, which is a factor ~20 larger than the prediction of the acoustic mismatch model. The thermal response of these films to pulsed power is dominated by the heat capacity of the film and the boundary resistance. The resulting thermal response time of $\approx$1ns for typical $YBa_2Cu_3O_{7-\delta}$ films is observed in many experiments with pulsed laser sources.

A design analysis[4] has been given for a bolometric infrared detector that uses the resistive transition of a high-temperature superconductor as the temperature sensing element, and liquid nitrogen as the coolant. It was shown that for highly oriented c-axis films, the measured low-frequency noise causes little or no degradation of the performance. With the incoming radiation chopped at 10 Hz, noise equivalent powers (NEP) in the range $(1\text{-}20)\times10^{-12}$ W $Hz^{-1/2}$ should be achievable. These values compare favorably with the NEP of other detectors operating at or above liquid nitrogen temperatures for wavelengths greater than 20 μm.

A sensitive high-T_c superconducting bolometer has been fabricated on a 20 μm thick sapphire substrate with a YBCO thin film transition edge thermometer.[5,6] Optical measurements with a He-Ne laser gave a noise equivalent power of 2.4×10^{-11} $W/Hz^{1/2}$ at 10 Hz and a responsivity of 17 V/W, in good agreement with electrical bolometer measurements. Gold black smoke was then deposited on the back side of the assembled bolometer as an absorber. Spectral measurements on a Fourier transform spectrometer showed that the bolometer has useful sensitivity from visible wavelengths to beyond -100 μm. This performance is clearly superior to that of a commercial room temperature pyroelectric detector. Some improvement appears possible.

We propose an antenna-coupled microbolometer based on the resistive transition of a high-T_c superconducting film as a detector for far infrared and millimeter waves.[7] Such microbolometers can be mechanically stronger, more easily fabricated, and much faster than conventional bolometric infrared detectors. A design analysis shows that a noise equivalent power of 2.5×10^{-12} W $Hz^{-1/2}$ is achievable for modulation frequencies up to 10 kHz. The superconducting film must be of high quality with narrow resistive transition and low $1/f$ noise.

We have fabricated and measured the performance of antenna-coupled microbolometers[8] based on the resistive transition of a high-T_c superconducting film for use as detectors of far-infrared and millimeter waves. A planar lithographed antenna (log-periodic or log-spiral) is used to couple the radiation to a thin

YBCO film with dimensions $\approx 6\times13\ \mu m^2$, which are much smaller than the wavelength to be measured. This film acts both as the resistor to thermalize the RF currents and as a transition edge thermometer to measure the resulting temperature rise. Because of its small size, both the thermal conductance from the film into the bulk of the substrate and the heat capacity of the thermally active region are small. Consequently, the microbolometer has low noise, fast response and a high voltage responsivity. We have measured a phonon noise-limited electrical NEP of 4.5×10^{-12}WHz$^{-1/2}$ at 10 kHz modulation frequency and a responsivity of 478 V/W at a bias of 550 μA. Measurements of the optical efficiency are in progress.

We propose a novel antenna-coupled low-T_c superconducting bolometer which makes use of the thermal boundary resistance available at low temperatures.[9] The radiation is collected by a planar self-complementary antenna and thermalized in a small thin film resistor. The resulting temperature rise is detected by a transition edge thermometer which can be (but need not be) a separate film. All components are deposited directly on a substrate so that arrays can be conveniently produced by conventional lithographic techniques. The active area of the bolometer is thermally decoupled by its small size and by the thermal resistance of the boundaries with the substrate and the antenna terminals. Design calculations based on a 2×2 μm square film of a superconductor with $T_c \approx 0.1$ K give an NEP = 10^{-18} WHz$^{-1/2}$, a time constant of 10^{-6} s and responsivities up to 10^9 V/W. These specifications meet the requirements for NASA's Space Infrared Telescope Facility and Sub-Millimeter Moderate Mission. Useful applications also exist at ^{3}He and ^{4}He temperatures. The calculated NEP scales as $T^{5/2}$. Materials, architectures, and readout schemes are discussed.

We have made accurate measurements of the noise and gain of heterodyne mixers employing small area (1μm^2) $Ta/Ta_2O_5/Pb_{0.9}Bi_{0.1}$ superconductor-insulator-superconductor (SIS) tunnel junctions.[10,11] These junctions have very low sub-gap leakage current and an extremely sharp current rise at the sum-gap. We have measured an added mixer noise of 0.61±0.31 quanta at 95.0 GHz, which is within 25 percent of the quantum limit of 0.5 quanta for a single-sideband mixer. Values of the imbedding admittances were deduced from the shapes of I-V curves pumped at the upper and lower sideband frequencies. Using these admittances, the mixer performance calculated from the quantum theory is in good agreement with the experiment.

We have made the first direct measurement of the quantum susceptance which arises from the non-dissipative part of quasiparticle tunneling in a superconductor-insulator-superconductor tunnel junction.[12,13] The junction was coupled to an antenna and a superconducting microstrip stub to form a resonator; the resonant frequency was determined from the response of the junction to broadband radiation from a Fourier transform spectrometer. A 19% shift of the resonant frequency, from 73 GHz to 87 GHz was observed which arises from the change of the quantum susceptance of the junction with dc bias voltage. This shift is in excellent agreement with calculations based on the Werthamer-Tucker theory, which includes the quantum susceptance. We also demonstrate that it is essential to include the quantum susceptance in our theoretical computation to explain the photon-assisted-tunneling steps which have negative dynamic conductance. Such steps are observed when the junction is pumped at slightly below the resonant frequency of the capacitor and the stub. The quantum susceptance should exist in all tunnel devices whose nonlinear I-V characteristics are due to elastic tunneling.

A detailed analysis of the effects of the quantum susceptance on the performance of superconductor-insulator-superconductor (SIS) mixers has been presented.[14] We find that the principal effects of the quantum susceptance is to change the dc bias at which optimum coupling of the signal to the mixer occurs, and to change the output admittance at the IF frequency, thus changing the available gain.

3. ACKNOWLEDGMENTS

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