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Superconducting Terahertz Mixer Using a Transition Edge Microbolometer

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Heterodyne receivers in the spectral range 100-2000 GHz are used in space-based, airborne, balloon-based, and earthbound observatories, as well as laboratory studies in diverse fields.[1] At frequencies up to about 600 GHz, SIS junctions have been employed in receivers with low noise temperatures.[1] Above 600 GHz, SIS devices suffer from increased noise due to intrinsic material properties, namely the energy gap. Cooled Schottky diodes are used above 600 GHz. Superconducting microbolometers operating well below T_c have been studied.[2] These had lengths > 1μm. They should achieve an intermediate frequency up to $\approx$ 160 MHz, since they use electron-phonon coupling as the cooling mechanism. In this paper, we propose the use of much shorter microbridges in which the dominant cooling is by out-diffusion of hot electrons into the leads.[3] The intermediate frequency -3 dB rolloff is predicted to be 4 GHz with good mixer conversion efficiency and low receiver noise temperature.

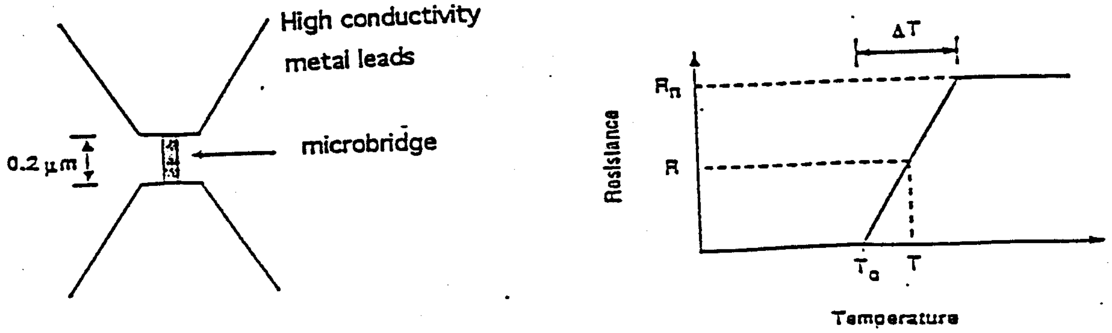

Figure 1: Microbridge geometry and resistive transition

The proposed device is a superconducting microbridge, with dimensions $L=0.2$ μm, $W=0.05$ μm, thickness=0.01 μm, and $R_n=80$ ohms, shown in Fig. 1a. The leads are thicker, non-superconducting films of high conductivity. The device is biased at a temperature T with resistance R near the midpoint of the resistive transition as shown in Figure 1b. When two radio frequency (rf) signals are applied to the bridge, the temperature will oscillate at the difference (intermediate) frequency. (For conventional microbolometers,[2] the cooling mechanism is electron-phonon coupling. For Nb, the electron-phonon inelastic scattering time, τ_{ep}, is ≈ 1 ns at 4.2 K.[2] This gives a -3 dB intermediate frequency response at 160 MHz.) An intermediate frequency of a few GHz is desired in most applications. If the microbridge is short enough, rapid outdiffusion of hot electrons into the leads can provide much faster cooling than electron-phonon cooling. The diffusion time, τ_{diff}, is given approximately by $(L/4)^2/D$, where D is the diffusion constant. For $L=0.2$ μm and $D=1 cm^2/s$,[3] we find $\tau_{diff}=25ps$, so that hot electrons diffuse out of the bridge before they emit phonons. In the thick contacts, the hot electrons cool by sharing their energy with large numbers of cool electrons. Later, phonons are emitted in the contacts.

The thermal time constant of the microbridge is given by C/G. The electronic heat capacity is given by $C=\gamma TV$, where[4] $\gamma=7\times10^{-4}$ J/K^2 cm^{-3}, and V is the volume in cm^3. The thermal conductance for small power dissipation is given by $G_o=LT/R_{eff}(W/K)$, where[5] $L=2.5\times10^{-8}$ $W\Omega/K^2$, and R_{eff} is the effective electrical resistance along the path through which heat flows out of the bridge, out the two ends: $R_{eff}=R_n/12$. G for finite dissipation is smaller than G_o due to self heating effects. If we take $I^2(dR/dT)/G=1/2$, then $G=1/2$ G_o. Thus, we find $\tau=0.04ns$.

The voltage responsivity, defined as the ratio of voltage across the bridge to the power dissipated in the bridge, is given by

$$S=I(dR/dT)/G(1+\omega_{if}^2\tau^2)^{1/2}=S_o/(1+\omega_{if}^2\tau^2)^{1/2}, \qquad (1)$$

where I is the bias current, R is the electrical resistance, G is the thermal conductance, ω_{if} is the intermediate frequency, and τ is the thermal response time, calculated above. For $\tau=0.04$ ns, we find a -3 dB response at 4 GHz, much higher than that allowed by a microbridge mixer which uses electron-phonon coupling.

The mixer conversion efficiency, η_m, is defined as the ratio of the [if output power into a matched load] to the [rf input power]. The voltage across the mixer may be written as $V(t) = V_{lo}\cos(\omega_{lo}t) + V_s\cos(\omega_s t)$. The instantaneous power dissipated in the bridge is given by $V(t)^2/R_n$, but the mixer will average out the signals at $2\omega_{lo}$ and $2\omega_s$, so that the resultant power dissipated in the bridge is given by

$$P(t) = P_{lo} + P_s + 2(P_{lo}P_s)^{1/2}\cos(\omega_{if}t), \qquad (2)$$

where $P_{lo}=V_{lo}^2/2R_n$, $P_s=V_s^2/2R_n$, and $\omega_{if}=\omega_{lo}-\omega_s$. The intermediate frequency voltage is given by $V_{if}(t)=S_oP_{if}(t)=S_o2(P_{lo}P_s)^{1/2}\cos(\omega_{if}t)$ for $\omega_{if}\tau<<1$ and no load. For a matched load, the intermediate frequency voltage is one half of this value. The dc power coupled into the matched load is given by $<V_{if}^2/R>$, so that

$$<P_{if}> = S_o^2P_{lo}P_s/(2R). \qquad (3)$$

If we take $dR/dT=2R/\Delta T$, i.e., the bias resistance as half the normal resistance, and $\delta T_{dc}=I^2R/G=\Delta T/4$ and $\delta T_{lo}=P_{lo}/G=\Delta T/4$, and use Equation 1, then

$$\langle P_{if}\rangle = 2(\delta T_{dc}/\Delta T)(\delta T_{lo}/\Delta T)P_s = (1/8)P_s \equiv \eta_m P_s, \qquad (4)$$

so that $\eta_m=1/8$.

A heterodyne receiver will have noise contributions output from both the mixer element and the intermediate frequency amplifier, as well as from "shot noise" due to the discreteness of the electromagnetic field. The mixer itself has two sources of noise: (1) Johnson noise at the intermediate frequency, given by $P=BkT$ where B is the bandwidth, and (2) intrinsic temperature fluctuations, given by $\delta T_n^2 \approx B4kT^2/G$, for frequencies below $(2\pi\tau)^{-1}$. The intrinsic temperature fluctuations give rise to a mean square voltage in a matched load of $[I(dR/dT)/2]^2\delta T_n^2$. If we again take $I^2(dR/dT)/G=1/2$, and $dR/dT=2R/\Delta T$, then the mean square voltage across the matched resistor due to the temperature fluctuations in the mixer is given by $RkT^2B/\Delta T$. Neglecting the photon shot noise for the moment, the noise power is given as

$$P_{n,if} = kB[T(T/\Delta T) + T + T_{if}], \qquad (5)$$

where we have written the if amplifier noise as $kT_{if}B$. The receiver double-sideband noise temperature, T_R(DSB), is defined as the temperature of an rf source which will produce additional noise power $2kT_R\eta B$ at the if equal to the noise power given in Equation 5, where η is the overall conversion efficiency, $\eta=\eta_{rf}\eta_m\eta_{if}$. (For waveguide coupling, $\eta \approx 0.1$, while for antenna coupling $\eta \approx 0.05$.[6]) For $\eta=0.1$, valid for waveguide coupling, we find

$$T_R = (2\eta)^{-1}[T(T/\Delta T) + T + T_{if}] \qquad (6)$$

$$\approx 5T\,[T/\Delta T + 2], \qquad (7)$$

where we have assumed $T \approx 4.2$ K and $T_{if} \approx 4$ K. For $T=4.2$ K and $\Delta T=0.1$ T, T_R(DSB) = 260 K; for $\Delta T=0.5$ T, T_R(DSB)=90 K. An additional source of noise in any receiver is photon shot noise, with a quantum noise temperature of $h\nu/2k$, which is 12 K (DSB) at 500 GHz.

The predicted noise temperature of this device is very competitive with existing waveguide coupled SIS receivers below 500 GHz, and up to an order of magnitude better than cooled Schottky diodes well above 500 GHz. In addition, the device has essentially no inductance or capacitance, so that complicated tuning circuits are not required as in the case of SIS devices. Finally, the optimum local oscillator power is on the order of a few nW, which is much less than the mW local oscillator power required by cooled Schottky diodes.

Test devices of Nb with Au leads have been fabricated at the Space Center for Microelectronics Technology at the Jet Propulsion Laboratory. Some initial dc tests have been performed, and more are currently in progress. The initial devices were of varying lengths, and had normal resistances of 20-40 Ω/square. The transition temperatures were between 4 K and 7 K, and $\Delta T/T$ was between 0.05 and 0.4. Devices for use in rf receivers are currently being designed and fabricated.

In conclusion, we have proposed an idea for a superconducting transition edge microbolometer with low noise temperature and small required lo power. The device should have lower noise than existing devices at frequencies above ≈ 600 GHz.

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[6] See Ref. 2 and references therein.