Broadband Millimeter-Wave Bolometric Mixers Based on Ballistic Cooling in a Two-Dimensional Electron Gas

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The intermediate frequency (IF) bandwidth of "hot" electron bolometric mixers is determined by the energy relaxation time for the electron system to dissipate energy absorbed from the electromagnetic fields into a heat sink. For devices of small enough length scale L, the energy relaxation time is set by the transit time τ_{tr} for hot electrons to cross a channel and deposit excess energy into the leads, which act as the thermal reservoir. This transit-time limited cooling principal has been implemented successfully to construct low-power, wideband bolometric mixers using thin superconducting metal films.[1,2] In these mixers hot electrons diffuse elastically across the channel, so that momentum but not energy is relaxed in the channel. The constraint on IF bandwidth in metal films is the small diffusion constant $D \sim 1$ to $10\ cm^2s^{-1}$, which necessitates fabricating devices with $L \sim 0.1\ \mu m$ in order to obtain several GHz of IF bandwidth. It has been suggested[3] and shown[4] that this same diffusion-cooling principal applies to a high mobility two-dimensional electron gas (2DEG) of the type formed at the interface of a GaAs-AlGaAs semiconductor heterostructure. Because the 2DEG can have D be two orders of magnitude larger than in metal films, IF bandwidths exceeding 10 GHz can be obtained in a 2DEG at much larger channel lengths $L \sim 5\ \mu m$ at 77 K.

We have examined the fundamental physical speed limits on bolometric mixing bandwidth using the transit-time cooling principal. When the transit mechanism is elastic diffusion, τ_{tr} is the elastic diffusion time $\tau_D = L^2/\pi^2 D$, so that the –3 dB IF bandwidth $f_{3dB} \propto L^{-2}$. This bandwidth-length scaling is the signature of the diffusion-cooling process. However, it is clear that this diffusive scaling cannot persist to arbitrarily small L because it makes no physical sense for τ_D to be smaller than L/v_F, which is the time it takes electrons near the Fermi velocity v_F to cross a channel in the absence of any elastic scattering. More specifically, the diffusion-cooling mechanism should fail when $L < \ell_{el}$, the elastic mean free path, since there is then on average no momentum nor energy relaxation in the channel. The hot electron outflow is then expected to be

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[1] A. Skalare, *et al.*, Appl. Phys. Lett. **68**, 1558 (1996)
[2] I. Siddiqi, *et al.*, IEEE Trans. Appl. Supercond. **11**, 958 (2001)
[3] K. S. Yngvesson, Appl. Phys. Lett. **76**, 777 (2000)
[4] M. Lee, *et al.*, Appl. Phys. Lett. **78**, 2888 (2001)

ballistic rather than diffusive, changing the bandwidth-length scaling to $f_{3dB} \propto L^{-1}$. Ballistic-cooling establishes the fundamental speed limit on IF bandwidth for a given bolometric mixer size and bias condition.

While the condition $L < \ell_{el}$ is unreachable in metal films, in sufficiently high quality 2DEGs ℓ_{el} can exceed 3 µm at 77 K and 50 µm near 1 K. To test whether a ballistic-cooling mechanism is observable, we performed millimeter-wave mixing experiments using a GaAs-AlGaAs 2DEG with mobility $\mu = 3.1 \times 10^5$ cm^{2}V^{-1}s^{-1} at 77 K and 7.5×10^6 cm^{2}V^{-1}s^{-1} at 1.5 K. The mixers had channel lengths L ranging from 1.3 µm to 10 µm. Heterodyne mixing was done using a fixed 105 GHz source as the *rf* signal and a tunable 105 to 145 GHz source as the local oscillator (LO). The IF bandwidth of the system was 40 GHz, limited by the IF low-noise amplifier.

At 77 K, a clear crossover in the bandwidth-length scaling from $f_{3dB} \propto L^{-2}$ for $L > 4$ µm to $f_{3dB} \propto L^{-1}$ for $L < 3$ µm was observed. For the smallest device, $L = 1.3$ µm, an IF bandwidth $f_{3dB} = 38$ GHz was measured. At 1.5 K $f_{3dB} \propto L^{-1}$ across the entire range of L, consistent with a complete transition to ballistic rather than diffusive cooling. Further evidence for ballistic dynamics comes from measurements of the average transit velocity $v_{av} = 2\pi f_{3dB} L$ as a function of DC bias voltage V. Data for all channel lengths can be collapsed onto one common curve described completely by semiclassical Bloch acceleration. There is also a signature of kinetic inductance in the mixer load impedance when in the ballistic-cooling regime.

The change in LO power requirement and noise temperature of these mixers will be compared between diffusion-cooled and ballistic-cooled states. We find preliminary evidence that the both the optimal LO power and the noise temperature decrease by about an order-of-magnitude upon crossing into the ballistic-cooling regime.