Engineering of electron and phonon processes in HEB sensors

Andrei V. Sergeev[1,*] Sergey A. Vitkalov[2], and Boris S. Karasik[3]
[1]SUNY at Buffalo, Buffalo, NY 14260, USA
[2]City College of New York at CUNY, New York, NY 10031, USA
[3]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA
*Contact: asergeev@buffalo.edu, phone +1 (716) 645-1048

Abstract — **In this presentation, we discuss optimal parameters of superconducting materials for HEB mixer operation at elevated temperatures (> 10 K) (electron density, electron mean free path, and sound velocity) and characteristics of the film/substrate interface allowing for minimization of the energy loss to phonons. Our analysis of available experimental data shows a significant promise of ultrathin MgB_2 films and low-density MBE-grown quasi-2DEG LaCuO/LaSrCuO superconductors. We will also discuss the role of the inelastic electron-boundary scattering that bypasses the phonon subsystem for energy transfer from electrons to the substrate.**

I. Introduction

Superconducting hot-electron bolometers (HEB) are currently the most sensitive radiation mixers above 1 THz. The current HEB technology is based mainly on NbN superconducting ultra-thin films with operating temperature of ~ 10 K. The use of superconductors with higher critical temperature is attractive, as this would allow for operation of a heterodyne receiver with affordable mechanical cryocooling on suborbital platforms and in space. However, beside the availability of thin-film materials with high critical temperature, the substantial loss of conversion efficiency due to the strong interaction of excited electrons with phonons (heating of phonons) is an issue. The loss manifests itself via a distortion of the intermediate frequency (IF) spectrum where the conversion efficiency is small at the IF of several GHz. This loss mechanism is fundamental at elevated temperatures (10-100 K) and careful consideration of material parameters is required for achieving a useful HEB mixer in this temperature range. To avoid the phonon heating, two important conditions for phonons and electron relaxation times must be satisfied: (i) the electron-electron relaxation time, $\tau_{e\text{-}e}$, should be shorter than the electron cooling time, τ_ε, and (ii) the time of the phonon escape from the sensor to substrate, τ_{es}, should be shorter than the phonon-electron relaxation time, $\tau_{ph\text{-}e}$.

An YBCO HEB mixer with a critical temperature $T_C \approx 90$ K was pursued in late 90s but without much of success. A new interest have arisen recently to high-T_C HEB mixers in view of the availability of new thin-film materials (MgB_2 with $T_C \approx 40$ K [1, 2] and LaCuO/LaSrCuO with $T_C \approx 50$ K [3]). The hope is that the physical properties of these new materials can be tuned better, thus largely eliminating the role of the phonon "heat trap." The latter was the major hurdle in achieving an efficient YBCO HEB mixer.

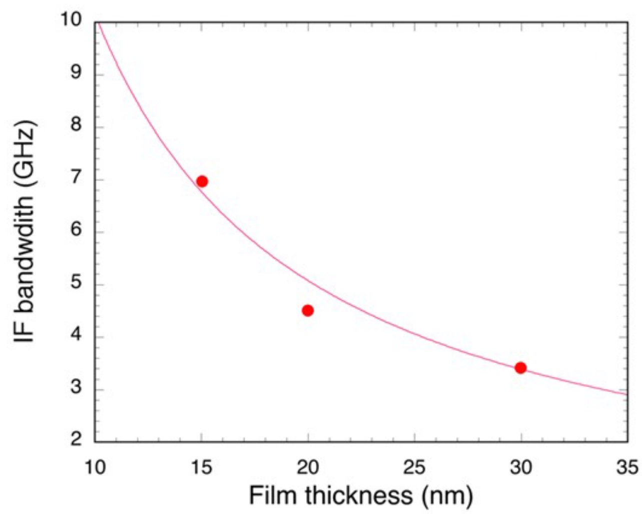

Fig. 1. An IF bandwidth in a MgB_2 mixer device on SiC substrate at 10 K.

II. Electron and Phonon Heat Flows in Thin Films

A simple picture of the hot-electron effect assumes that electrons are heated by the THz radiation whereas phonons remain at the bath temperature. This is true only at low temperatures in thin films (e.g., for Nb, T < 4 K, film thickness, d < 10 nm [4]). Beside the small value of $\tau_{e\text{-}e}$ required for thermalization of the electron gas, a condition $\tau_{es} << \tau_{ph\text{-}e}$ must be fulfilled. Only in this case phonons will leave the film fast, without trapping the energy and reheating the electrons. $\tau_{es} \sim d/v_s$ (v_s is the sound velocity) and $\tau_{ph\text{-}e} = \tau_\varepsilon C_p/C_e$ (C_p and C_e are the phonon and electron heat capacities, correspondingly). Since $C_e \sim T$ and $C_p \sim T^3$, $C_e >> C_p$ at low temperature and thus the condition $\tau_{es} << \tau_{ph\text{-}e}$ can be met. At higher temperature (typically, above 10 K), this is not true anymore and the phonon heating become unavoidable. An analysis based on the two-temperature (2T) model [5] shows several different scenarios depending on the hierarchy of τ_{es}, $\tau_{ph\text{-}e}$, and τ_ε. The most radical case is that found in YBCO where $\tau_{es} >> \tau_{ph\text{-}e} >> \tau_\varepsilon$ [6]. Here the efficient mixing process could be expected only at the intermediate frequencies (IF) lower than τ_{es}^{-1} ~ 100 MHz. Even in thin (~4 nm) NbN films phonons trap some heat. As a result, the effective IF bandwidth depends on both temperature and film thickness thus bearing dependencies of τ_{es}, $\tau_{ph\text{-}e}$, and τ_{ε} mixed-in together according to equations of the 2T model [7]. In general, minimization of τ_{es} helps to mitigate the phonon heating issue. This has been demonstrated in two novel high-T_C materials: MgB_2 where v_s is very high (~ 8 km/s), and LaCuO/LaSrCuO which is only a few monoatomic layers thick.

III. MgB$_2$

The MgB_2 HEB mixer was proposed in [8]. The prediction of the 2T model was that a ~ 10 GHz IF bandwidth could be achieved in films with d < 10 nm. More recent measurements in high quality films with $T_C \approx 40$ K [9] showed that the IF bandwidth does depend on d as predicted by the model (see Fig. 1) but the absolute value is at least twice as high as in NbN. Even higher IF bandwidth has been measured at 20-25 K (Fig. 2). Given the progress in developing ultrathin films with d < 10 nm [10], achieving the 10 GHz IF bandwidth along with a good conversion efficiency is foreseen in the near future.

IV. LaCuO/LaSrCuO

Quasi-2D heterostructures that contain ultrathin $La_{2-x}Sr_xCuO_4$ (LSCO) layers are grown by atomic-layer-by-layer MBE (ALL-MBE) [11]. The transition temperature can be tuned from sub Kelvin temperatures to 50 K (see Fig. 3) using appropriate doping profiles. The interfaces between LSCO layers with different dopings are highly transparent for phonons, since the layers differ only slightly in their atomic composition providing an ultrafast phonon escape. Study of the thermal conductance in LSCO layers [3, 12] revealed that τ_{es} is the shortest time even at 50 K and that the relaxation rate is driven by the electron-phonon process, as in low-temperature materials.

V. Conclusions

Analysis of two promising high-T_C materials suggests that there are ways to reduce or even eliminate the effect of the phonon "heat trap" at temperature 10-50 K. This can open up a possibility to achieve efficient HEB sensors not requiring liquid He for operation.

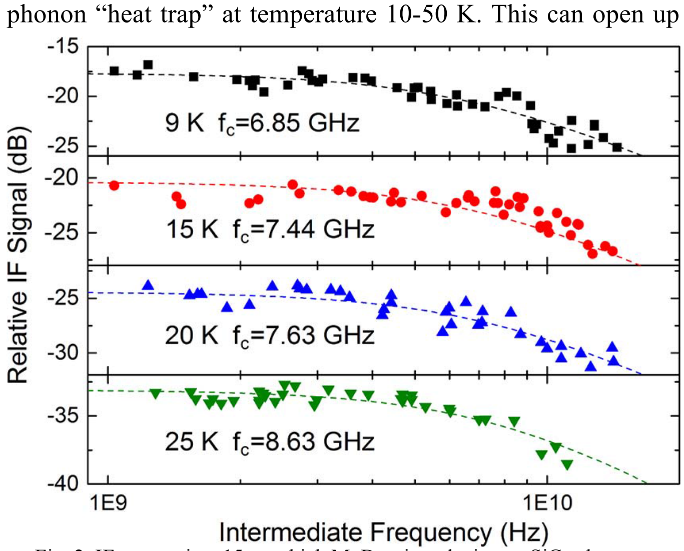

Fig. 2. IF spectra in a 15-nm thick MgB_2 mixer device on SiC substrate.

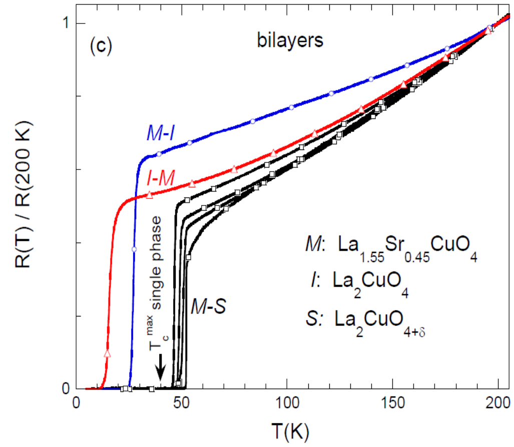

Fig. 3. Superconducting transition in bilayer system La_2CuO_4 /$La_{1.55}Sr_{0.45}CuO_4$.

Acknowledgment

This research was carried out in part at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. The research of AVS was supported by was supported by NSF (ECCS 1128459).

References

[1] D. P. Cunnane, J. H. Kawamura, M. A. Wolak, N. Acharya, T. Tan, X. X. Xi, and B. S. Karasik, "Characterization of MgB_2 Superconducting Hot Electron Bolometers," *IEEE Trans. Appl. Supercond.,* vol. 25, pp. 2300206 (2015).

[2] S. Bevilacqua, S. Cherednichenko, V. Drakinskiy, H. Shibata, Y. Tokura, and J. Stake, "Study of IF Bandwidth of MgB2 Phonon-Cooled Hot-eElectron Bolometer Mixer," *IEEE Trans. THz Sci. & Technol.,* vol. 3, pp. 409-415 (2013).

[3] B. Wen, R. Yakobov, S. A. Vitkalov, and A. Sergeev, "Superconducting cuprate heterostructures for hot electron bolometers," *Appl. Phys. Lett.*, vol. 103, pp. 222601 (2013).

[4] E. M. Gershenzon, M. E. Gershenzon, G. N. Gol'tsman, A. M. Lyul'kin, A. D. Semenov, and A. V. Sergeev, "Electron-phonon interaction in ultrathin Nb films," *J. Exp. Theor. Phys.,* vol. 70, pp. 505-511 (1990).

[5] N. Perrin and C. Vanneste, "Response of superconductive films to a periodic optical radiation," *Phys. Rev. B,* vol. 28, pp. 5150-5159 (1983).

[6] B. S. Karasik, M. C. Gaidis, W. R. McGrath, B. Bumble, and H. G. LeDuc, "Low noise in a diffusion-cooled hot-electron mixer at 2.5 THz," *Appl. Phys. Lett.,* vol. 71, pp. 1567-1569 (1997).

[7] S. Cherednichenko, P. Yagoubov, K. Il'in, G. Gol'tsman, and E. Gershenzon, "Large bandwidth of NbN phonon-cooled hot-electron bolometer mixers on sapphire substrates," in *8th Int. Symp. Spc. THz Technol.*, Cambridge, MA, USA, 1997, pp. 245-257.

[8] S. Cherednichenko, V. Drakinskiy, K. Ueda, and M. Naito, "Terahertz mixing in MgB2 microbolometers," *Appl. Phys. Lett.,* vol. 90, pp. 023507 (2007).

[9] D. Cunnane, J. Kawamura, B. S. Karasik, M. A. Wolak, and X. X. Xi, "Development of the hot-electron THz bolometric mixer using MgB2 thin film," *Proc. SPIE,* vol. 9153, pp. 91531Q (2014).

[10] M. Wolak, N. Acharya, T. Tan, D. Cunnane, B. Karasik, and X. Xi, "Fabrication and characterization of ultrathin MgB2 films for hot electron bolometer applications," *IEEE Trans. Appl. Supercond.* (2015), in press.

[11] A. Gozar, G. Logvenov, L. F. Kourkoutis, A. T. Bollinger, L. A. Giannuzzi, et al., "High-temperature interface superconductivity between metallic and insulating copper oxides," *Nat.,* vol. 455, pp. 782-785 (2008).

[12] A. Sergeev and S. Vitkalov, "Next Generation Superconducting Hot Electron Bolometers for THz Sensing," in *RJUS TeraTech-2014*, Buffalo, NY, 2014 (in press).