High-T_C THz HEB Mixers: Progress and Prospects

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***Abstract*—We analyze the pathways for achieving the THz hot-electron bolometer (HEB) mixers using high-T_C superconductors. Requirements to the material in order to obtain large (up to 10 GHz) intermediate frequency bandwidth as well as recent results on MgB_2 HEB mixer devices are discussed. Based on a thermal model of the energy relaxation in a thin film, we explain the difference between the mixing behaviors in previously studied HEB materials. We also introduce the concept of the HEB mixer based on the low electron density MBE-grown quasi-2DEG LaCuO/LaSrCuO superconductors with tunable critical temperature.**

I. INTRODUCTION

HOT-electron bolometer (HEB) mixers are the primary choice for astronomical THz heterodyne receivers. Thin NbN and NbTiN superconducting films have been used for making mixer devices employed in a number of instruments, most noticeably, the HIFI instrument on Herschel Space Observatory. An intermediate frequency (IF) bandwidth in HEB mixers is determined by the inverse energy relaxation time, τ_E. The need in a larger IF bandwidth (in NbN HEB, the bandwidth is limited to 3-4 GHz) for high-resolution spectroscopy of molecular lines across the galaxy (e.g., [OI] 4.7 THz line) motivates the search for suitable materials with higher critical temperatures where the electron thermal relaxation may go faster. Also, an HEB mixer with high operating temperature is sought in view of the reduced cryocooling requirement that is very important for applications in space.

II. ELECTRON AND PHONON DYNAMICS ABOVE 10 K

At low temperature (~ 1K and below), the energy relaxation in metal films is driven by the relatively slow electron-phonon interaction with a characteristic time τ_{ep}. Phonons leave the film fast and thermalize in the substrate thus not slowing down the overall relaxation. At higher temperatures, the phonon-electron interaction time, τ_{pe}, becomes so short that it compares to the phonon escape time, τ_{es}, even in the thinnest (3-5 nm) films of NbN (Fig. 1). At temperatures above 10 K, the phonon dynamics in a metal, beside the electron one, determines the mixer efficiency and relaxation rate. Interaction of acoustic phonons with electrons plays an increasing role as the operation temperature rises. As a result, a significant loss of the absorbed THz energy to phonons may occur and the overall relaxation may slow down. This loss mechanism is fundamental and careful consideration of material parameters is required in order to achieve a useful HEB mixer in the 10-100 K temperature range.

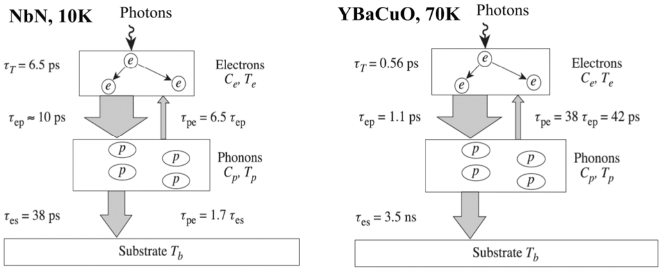

Fig. 1. Energy flow diagram in HEB sensors. τ_T is the electron thermalization time. Left: In NbN HEB, a significant portion of the electron energy is spent on the heating of phonons, which remain in the film. This reduces the quantum efficiency by a factor of ~ 2. Also, the IF bandwidth is set not by τ_{ep} alone but a combination of τ_{ep}, τ_{pe}, and τ_{es}. Right: In YBCO HEB, the situation is more drastic than in NbN. Most of the thermal energy is accumulated in phonons. The relaxation is slow and driven by τ_{es}.

The loss manifests itself via a distortion of the IF spectrum where the conversion efficiency is small within a useful range of several GHz. This is the case for YBCO HEB mixers (Fig. 1). The THz YBCO mixer has been a disappointment with the bandwidth of only ~ 100 MHz mostly limited by the slow phonon escape from the film. The poor acoustic transparency of the interfaces between YBCO and common substrates is the main reason. Also, it was hard to achieve YBCO films thinner than several 10s of nm.

III. MgB_2 HEB MIXER

The complex dynamics illustrated in Fig. 1 was described satisfactory in simple terms of the so-called two-temperature (2T) model (see e.g., [1] for NbN HEB and [2] for YBCO HEB). The corresponding mixer operation was also analyzed for both materials [3, 4]. The critical condition needed for improvement of both the IF bandwidth and the mixer quantum efficiency is: $\tau_{es} << \tau_{pe}$. Since $\tau_{es} = 4d/\alpha v_s$ (d is the film thickness, α is the acoustic transparency of the film-substrate boundary, v_s is the sound velocity in the sensor's metal), the use of a substrate which is better matched acoustically to the film can improve the mixer operation at elevated temperatures. This, indeed, has been observed in NbN HEBs on MgO substrates, as well as on MgO buffer on Si [5, 6, 7], where the IF bandwidth exceeded 4 GHz.

More drastic approach is the use of a different superconductor. MgB_2 was proposed as a promising HEB material where τ_{es} can be substantially shortened due to the very high sound velocity $v_s \approx 8$ km/s, which is a factor of 2.5 greater than that in NbN [8]. Another factor is the high acoustic transparency of the film-substrate interface. More recently, an MgB_2 mixer fabricated using the Hybrid Physical-Chemical Vapor Deposition (HPCVD) process has demonstrated a large IF bandwidth of 8-9 GHz in a 15 nm thick film with T_C = 36-38 K (Fig. 2) [9], that is a factor of 2-3 greater than the IF bandwidth in the state-of-the-art NbN HEB mixers. Even a larger IF bandwidth is expected in the recently

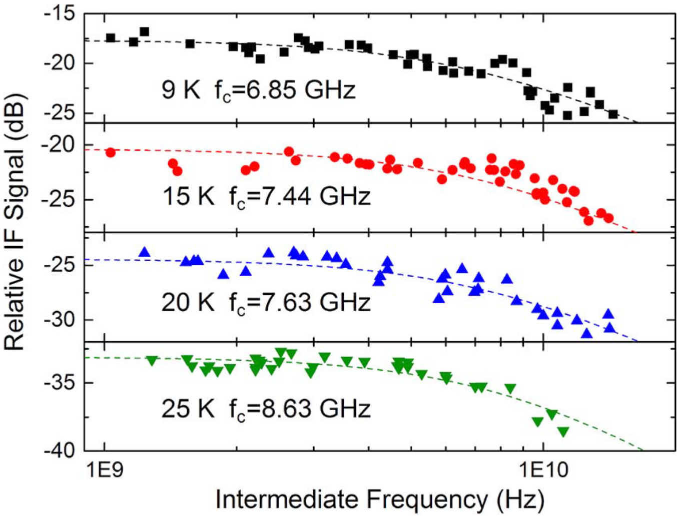

Fig. 2. IF spectra in a 15-nm thick MgB_2 mixer device on SiC substrate coupled to a broadband planar microantenna. The results obtained using two monochromatic 600 GHz sources. f_c denotes the -3 dB cut-off frequency.

achieved 3-7 nm thick MgB_2 films [10] since the bandwidth scales inversely proportional to the film thickness in this electron temperature range (that is, $T_e \approx T_C \sim 40$ K) (Fig. 3). The currently achieved 8-GHz bandwidth at 20 K (Fig. 2) can be expanded to 15-20 GHz by using 5-10 nm thick films.

IV. LSCO HEB

The MgB_2 HEB is expected to operate at around 20 K, which is a substation relaxation of the cryocooling requirement compared to the NbN HEB. Even higher operation temperature may be achieved using novel quasi-2D superconducting heterostructures that contain ultrathin $La_{2-x}Sr_xCuO_4$ (LSCO) layers grown by atomic-layer-by-layer MBE (ALL-MBE) [11]. The transition temperature can be tuned from sub Kelvin temperatures to 50 K using appropriate doping profiles. The interfaces between LSCO layers with different doping 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 [12, 13] 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. At 50 K, τ_{ep} is expected to be or the order of 100 ps however a much shorter τ_E can be engineered using the electron diffusion which will be the dominating energy relaxation channel in submicron long LSCO HEB devices.

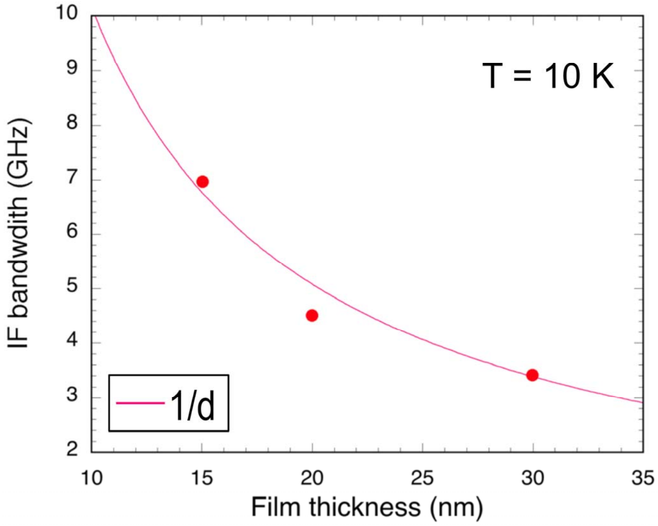

Fig. 3. Film thickness dependence of the IF bandwidth in an MgB_2 HEB.

V. SUMMARY

The state-of-the-art NbN HEBs demonstrate excellent performance throughout the THz range but an increase of both the IF bandwidth and operating temperature are highly desired for the next generation of heterodyne instruments. New high-T_C materials (MgB_2 and LSCO) are very promising for achieving this goal. While operation of the mixer at 20 K is already a great improvement for an astrophysical receiver, the 50 K operation would make it possible to use the high-T_C mixer in space on planetary missions.

VI. ACKNOWLEDGMENT

This work 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 NSF (ECCS 1128459).

REFERENCES

[1]. K. S. Il'in, M. Lindgren, M. Currie, et al., "Picosecond hot-electron energy relaxation in NbN superconducting photodetectors," *Appl. Phys. Lett.*, vol. 76, pp. 2752-2754, 2000.

[2]. M. Lindgren, M. Currie, C. Williams, et al., "Intrinsic picosecond response times of Y–Ba–Cu–O superconducting photodetectors," *Appl. Phys. Lett.*, vol. 74, pp. 853-855, 1999.

[3]. R.S. Nebosis, A.D. Semenov, Y. P. Gousev, et al. "Rigorous Analysis of a Superconducting Hot-Electron Bolometer Mixer: Theory and Comparison with Experiment," *Proc. 7th Int. Symp. Spc. THz. Technol.*, Charlottesville, VA, March 12-14, 1996, pp. 601-613.

[4]. B. S. Karasik, W. R. McGrath, and M. C. Gaidis, "Analysis of a high-T_C hot-electron superconducting mixer for terahertz applications," *J. Appl. Phys.*, vol. 81, pp. 1581-1589, 1997.

[5]. S. Cherednichenko, M. Kroug, P. Yagoubov, et al., "IF Bandwidth of Phonon Cooled HEB Mixers Made from NbN Films on MgO Substrates," *Proc. 11th Int. Symp. Spc. THz. Technol.*, Ann Arbor, MI, May 1-3, 2000, pp. 219-227.

[6]. Y. B. Vachtomin, M. I. Finkel, S. V. Antipov, et al., "Gain Bandwidth of Photon-Cooled HEB Mixer made of NbN Thin Film with MgO Buffer Layer on Si," *Proc. 13th Int. Symp. Spc. THz. Technol.*, Cambridge, MA, March 26-28, 2002, pp. 259-270.

[7]. A.D. Semenov, H.-W. Hübers, H. Richter, et al., "Superconducting Hot-Electron Bolometer Mixer for Terahertz Heterodyne Receivers," *IEEE Trans. Appl. Supercond.,* vol. 13, pp. 168-171, June 2003.

[8]. S. Cherednichenko, V. Drakinskiy, K. Ueda, et al., "Terahertz Mixing in MgB_2 Microbolometers," *App. Phys. Lett.*, vol. 90, pp. 023507, 2007.

[9]. D. P. Cunnane, J. H. Kawamura, M. A. Wolak, et al., "Characterization of MgB_2 superconducting hot electron bolometers," *IEEE Trans. Appl. Supercond.*, vol. 25, pp. 2300206, 2015.

[10]. M. A. Wolak, N. Acharya, T. Tan, et al., "Fabrication and characterization of ultrathin MgB_2 films for hot electron bolometer applications," *IEEE Trans. Appl. Supercond.*, vol. 25, pp. 7500905, 2015.

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

[12]. B. Wen, R. Yakobov, S. A. Vitkalov, et al., "Superconducting cuprate heterostructures for hot electron bolometers," *Appl. Phys. Lett.*, vol. 103, pp. 222601, 2013.

[13]. A. Sergeev and S. Vitkalov, "Next Generation Superconducting Hot Electron Bolometers for THz Sensing," *Proc. RJUS TeraTech-2014*, Buffalo, NY, June 17-21, 2014 (in press).