

YBa₂Cu₃O_{7-δ} HOT-ELECTRON BOLOMETER WITH SUBMICRON DIMENSIONS

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Photoresponse of YBa₂Cu₃O_{7-δ} hot-electron bolometers to modulated near-infrared radiation was studied at a modulation frequency varying from 0.2 MHz to 2 GHz. Bolometers were fabricated from a 50 nm thick film and had in-plane areas of 10×10 μm², 2×0.2 μm², 1×0.2 μm², and 0.5×0.2 μm². We found that nonequilibrium phonons cool down more effectively for the bolometers with smaller area. For the smallest bolometer the bolometric component in the response is 10 dB less than for the largest one.

Recently there has been increasing progress [1-7] in the development of bolometric mixers which utilize electron heating in thin Nb and NbN superconducting films. Regimes of both phonon cooling [1-4] and diffusion cooling [5-7] of hot electrons have been studied. These results prove that hot-electron bolometric (HEB) devices can successfully be used in terahertz heterodyne receivers [4]. Implementation of high-T_c superconducting materials may allow one to operate the mixer at liquid nitrogen temperature and also to increase the intermediate frequency bandwidth up to at least 20 GHz [8] while the fundamental limitation suggests 140 GHz.

The major obstacle to the realization of superconducting electronics on the basis of nonequilibrium effects is the presence of the bolometric component in the resistive response of high-T_c films. For mixers this component significantly increases the conversion loss and noise temperature. Since the bolometric response relates to phonon heating in the film, it may be diminished by improving the heat exchange through the film/substrate interface. There are two approaches in doing that: decreasing acoustic mismatch between the film and the substrate or making use of thinner films. Another phenomenon which delays the phonon cooling is the heating of the substrate underneath the film. Such an effect substantially contributes to the total thermal resistance between phonons and substrate [9]. Minimization of the substrate heating can be achieved by making use of a smaller bolometer fabricated on a substrate with larger

heat conductivity. Finally, there is a possibility for phonons to be cooled down via their diffusion from the bolometer to contacts [10]. The contribution of this channel to the total cooling rate should also increase with a decrease of the bolometer dimensions.

In this work we studied how the cooling rate of phonons in a $\text{YBa}_2\text{Cu}_3\text{O}_{7.5}$ (YBCO) HEB evolved with a decrease of the bolometer size.

We manufactured bolometers with different in-plane area (see Table I), which were integrated into planar bow-tie antennas. YBCO films with a thickness of 50 nm were deposited onto LaAlO_3 substrates by pulsed laser deposition in an oxygen atmosphere. Details of the deposition technique are described elsewhere [11]. After deposition, the films had a superconducting transition temperature of ≈ 88 K. X-ray diffraction showed that the films were predominantly c-axis oriented. Bolometer and antenna structures were patterned using electron-beam lithography and argon ion milling. After processing, the devices had a transition temperature of ≈ 87 K. A scanning electron microscope (SEM) image of device #4 with the antenna is shown in Fig.1.

Table I. Length (l), width (w), critical temperature (T_c) and critical current density (j_c) at $T=77$ K for samples #1 through 4.

Sample number	l [μm]	w [μm]	T_c [K]	$j_c \times 10^6$ [A/cm ²]
1	10	10	87	5.2
2	0.2	2	87	6.7
3	0.2	1	87	4.8
4	0.2	0.5	87	2.0

The experimental setup is shown in Fig.2. A semiconductor laser (1.56 μm wavelength) coupled to a single-mode fiber was used as a radiation source. The radiation power in the fiber was 1.4 mW. An optical isolator added 3 dB loss. The intensity of the laser radiation was modulated by a high-frequency signal generator. The modulated part of the total radiation intensity was about 10%. The bolometer was

driven into resistive state by a dc bias current. The bolometer response was measured with a Tektronix 494AP spectrum analyzer for modulation frequency from 0.2 MHz to 2000 MHz. For frequencies higher than 300 MHz additional amplifiers with a total gain of 30 dB were used. The magnitude of the photoresponse and, thus, responsivity depended on the bias current (see Fig.3). Measurements were performed at 77 K using the bias current that corresponded to the largest responsivity.

The photoresponse of different bolometers versus modulation frequency is shown in Fig.4. The curves are made to cross each other at frequency 300 MHz for comparison.

For sample #1 in the frequency range from 1 MHz to 10 MHz there is a gradual decrease of the response according to $f^{-0.3}$, where f is the modulation frequency. At frequencies larger than 40 MHz this dependence changes to f^{-1} , which characterizes a roll-off process with a single relaxation time. Such an evolution of the response agrees well with the observation made earlier [12] for bolometers of the same size. Samples #1 and #2 demonstrate practically the same dependence of the response on the modulation frequency. The response of the sample #3 shows a 5 dB smaller decrease in the low frequency bolometric range. For this sample the response remains constant for $f < 1$ MHz, decreases according to $f^{-0.3}$ at larger frequencies, and follows a f^{-1} law at $f > 40$ MHz. For sample #4 that has the smallest bolometer area the magnitude of the response remains constant until 60 MHz (within 3 dB) and then rolls off according to f^{-1} .

Several studies of hot-electron detectors from thin YBCO films have been made in the optical and millimeter wavelength ranges [11-16]. Both bolometric and nonbolometric components have been identified in the resistive response. The nonbolometric component controls the early stage of relaxation after pulse excitation or, in the case of modulated continuous wave excitation, the frequency dependence of the response at high modulation frequency (above 2 GHz) [11, 17]. The nonbolometric component corresponds to the heating up and cooling down of quasiparticles. The quasiparticle cooling rate is controlled by the reciprocal electron-phonon interaction time $(\tau_{e-ph})^{-1}$ in the resistive state of the superconductor. Recent direct measurements have shown that in thin YBCO films at 80 K this time equals 1.1 ps [17], i.e. the electron temperature can be modulated with a frequency as large as 140 GHz.

The bolometric component of the response is related to the heating of both the phonons and electrons in the film. If the film thickness d is smaller than $l_{ph,f}/\alpha_{f,s} \approx 500$ nm [9], where $l_{ph,f}$ is the phonon mean free path in the YBCO film and $\alpha_{f,s}$ is the transparency of the film/substrate interface for thermal phonons, thermal diffusion in the film towards the substrate can be neglected. Hence, the rate of phonon cooling is determined by the heat exchange rate through the film/substrate interface. It has been shown [9] that the total heat exchange rate depends not only on the rate of phonon escape $(\tau_{esc})^{-1}$ from the film into the substrate but also on the rate of reverse flow $(\tau_R)^{-1}$ of phonons back from the substrate to the film. Depending on the substrate material, for a 50 nm thick film the phonon escape time varies from 2 ns to 5 ns [9, 11], which corresponds to roll-off frequencies from 80 MHz to 30 MHz. The reverse phonon flow slows down the cooling of phonons in the film and results in the gradual decrease of the bolometric component of the response at small modulation frequencies according to f^{-m} , where m is between 1/2 and 1/3. The characteristic time of the phonon return to the film can be estimated as $\tau_R \approx \tau_{ph,s}/(\alpha_{s,f})^2$ where $\tau_{ph,s}$ is the phonon scattering time in the substrate and $\alpha_{s,f}$ is the transparency of the interface for phonons in the direction from the substrate to the film. Corresponding characteristic length is $l_R = (D_s \tau_R)^{1/2} = l_{ph,s}/\alpha_{s,f}$ where D_s is the phonon diffusivity in the substrate and $l_{ph,s}$ is the phonon mean free path in the substrate. The length l_R is the mean distance over which a phonon travels in the substrate until it returns to the film. The reverse flow of phonons can be minimized making use of substrates with larger heat conductivity, i.e. larger $\tau_{ph,s}$ and $l_{ph,s}$, and also by decreasing the in-plane sizes of the bolometer down to a magnitude less than l_R . Using $\tau_{ph,s} \approx 42$ ps and $\alpha_{s,f} \approx 0.059$ [9] we estimate $l_R \approx 0.4$ μ m for our samples. Our estimate corresponds well to the area (0.5×0.2 μ m²) of the bolometer #4 that demonstrates a flat response in the frequency range from 2 to 60 MHz.

In the absence of the reverse flow of phonons from the substrate to the film, the response of HEB follows predictions of the two-temperature model [18] even at lowest modulation frequencies used in our experiment (see the solid line in Fig.4). The frequency dependence of the conversion loss in the heterodyne regime is controlled

by the frequency dependence of the responsivity [19]. Therefore the conversion loss in the hot-electron mode scales with the magnitude of the bolometric component. This suggests that at frequencies larger than 30 MHz and, consequently, in the hot-electron mode the conversion loss for a submicron YBCO HEB mixer should be ≈ 5 dB and ≈ 10 dB less, than for a 1 μm and 2 μm wide HEB mixer, respectively.

Further decrease of the conversion loss can be achieved due to additional improvement of the heat removal from the bolometer. One possibility is to decrease the film thickness and, consequently, shorten the phonon escape time. Another direction is to utilize the diffusion of nonequilibrium phonons from the bolometer to contacts. This mechanism of phonon cooling has been discussed in [10]. Authors theoretically estimated out-diffusion time τ_{diff} for a 0.2 μm long bolometer. They found $\tau_{\text{diff}}=260$ ps that is an order of magnitude less than τ_{esc} for a 50 nm thick film. The effective cooling time due to both cooling mechanisms can be estimated as $(\tau_{\text{esc}}^{-1}+\tau_{\text{diff}}^{-1})^{-1}$ which results in a 240 ps overall cooling time and a corresponding roll-off frequency of 650 MHz. In comparing modulation frequency dependence of the response we did not find a noticeable difference between roll-off frequencies of bolometers with the length 10 μm and 0.2 μm (devices #1 and #3). The absence of the diffusion contribution to the phonon cooling rate in our samples can be attributed to defects and impurities that are not considered in [10] but may decrease the diffusivity of phonons.

In conclusion, we studied the response of YBCO hot-electron bolometers of different sizes to modulated laser radiation. We found that the decrease of the in-plane size of the bolometer below 1 μm resulted in the disappearance of the $f^{-0.3}$ dependence of the bolometric component in the response. It means that for a bolometer with such a small area the bolometric response is flat at frequencies smaller than the roll-off frequency corresponding to the phonon escape time, and above this frequency drops according to the two-temperature model. The obtained results suggest that the use of the submicron bolometer as mixer in the hot-electron mode should result in an increase of the conversion efficiency of the order 10 dB compared to larger bolometers.

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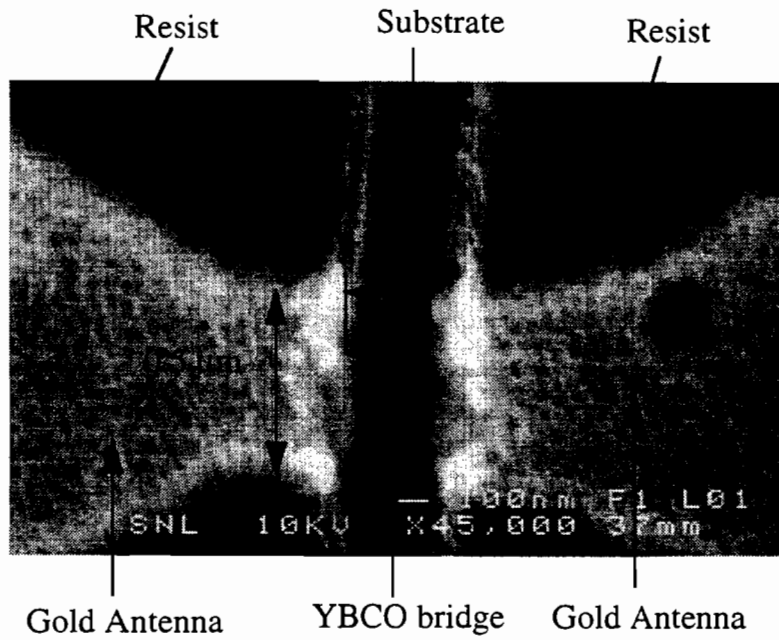


Fig.1. Scanning electron microscope image of sample #4.

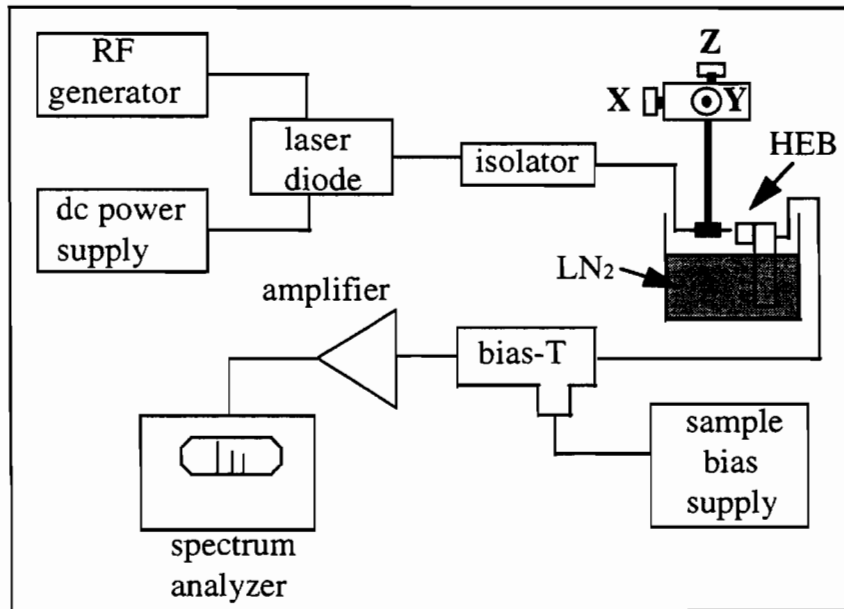


Fig 2. Experimental set-up.

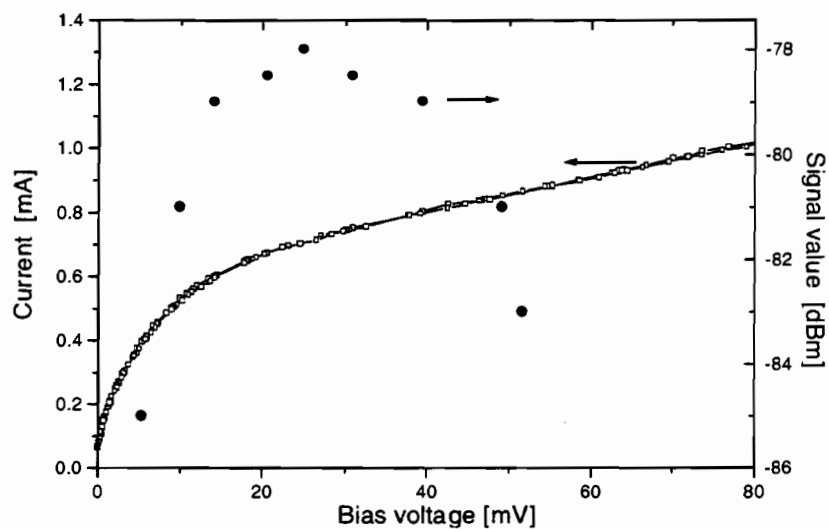


Fig.3. Current-voltage and detected signal vs. bias voltage characteristics of sample #4 ($0.5 \times 0.2 \mu\text{m}^2$).

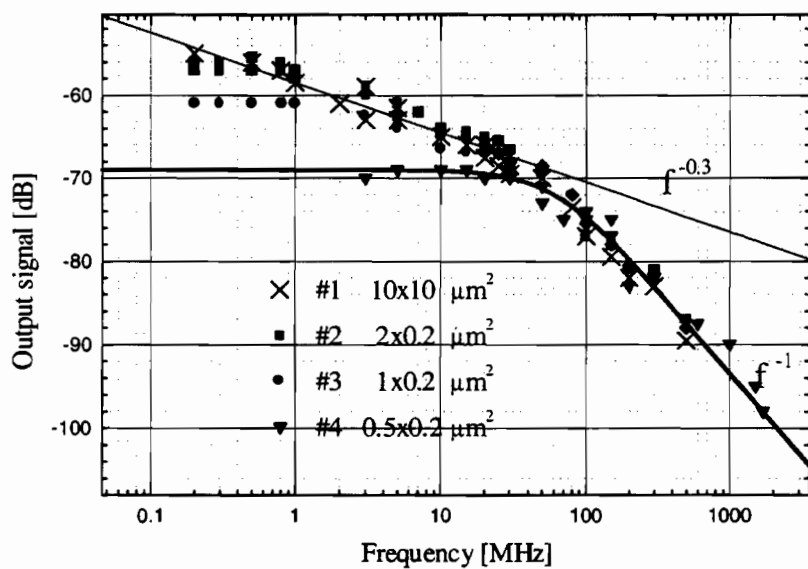


Fig.4. The photoresponse of samples #1 through 4 vs. modulation frequency. The solid line corresponds to the two-temperature model calculation.