Fast Pyroelectric Response of Semiconducting YBaCuO Detectors with High IR Sensitivity; Development of THz Imaging Arrays

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***Abstract*—$YBa_2Cu_3O_{6+x}$ oxides are semiconducting for $x < 0.5$ and are amorphous (*a*-YBCO) at low deposition temperature (100 °C, typically). *a*-YBCO also exhibits pyroelectric properties. Metal/*a*-YBCO planar micro-structures were processed to fabricate IR sensors. When unbiased, the device exhibited a pyroelectric near-infrared response as f^{+1} up to about 35 kHz, followed by a slow thermally diffusive decrease as $f^{-1/2}$ up to about 3 MHz. NEP was measured below 15 pW/Hz^{½}, with detectivity D^* above 10^9 cm·Hz$^{1/2}$·W^{-1} in the 500 Hz to 100 kHz range. 32×32 arrays of THz log-periodic planar antennas to be coupled with *a*-YBCO patches were also designed.**

I. INTRODUCTION

THE semiconducting phase of $YBa_2Cu_3O_{6+x}$ (YBCO) with a low oxygen content ($x < 0.5$) offers key advantages for developing uncooled thermal sensors: bolometers [1] or pyroelectric detectors [2]. Moreover, YBCO can be deposited in an amorphous form (*a*-YBCO) under low-temperature processing conditions (150 °C, typically), which are compatible with CMOS readout circuitry integration. Recently, very promising performances in terms of detectivity and fast pyroelectric response at infrared wavelengths have been reported with *a*-YBCO film detectors [3].

II. IR RESPONSE RESULTS

In order to confirm the *a*-YBCO potential for room temperature imaging, planar structures - 450 nm thick *a*-YBCO film connected to two metal pads (see Fig. 1) - were patterned on SiO_x (500 nm) / *p*-Si (380 µm) substrates. The device was illuminated with an 850 nm VCSEL diode source modulated in the frequency range f = 1 Hz to 4 MHz. The detector response was readout with a low noise current preamplifier and synchronously detected at f. The lock-in amplifier was also used to measure the device noise current spectral density in a 1 Hz bandwidth. Besides, noise measurements above 50 kHz were checked with a spectrum analyzer.

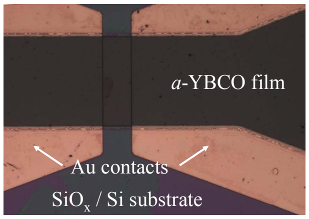

Fig. 1. Top view of the as-processed planar device. The *a*-YBCO film is 450 nm thick and the sensing micro-bridge dimensions are 30 µm × 100 µm.

The (unbiased) device current response is shown in Fig. 2. Unbiasing allows eliminating the resistive / bolometric low pass response, and the associated Johnson noise as well. The resulting high pass behavior is typical of a pyroelectric response, i.e., sensitive to the capacitance current (thermally modulated electrical polarization). Such a capacitance current could be collected because of the *p*-doped Si substrate acting as a floating counter-electrode [3]. For this high-pass f^{+1} pyroelectric behavior, the frequency cut-off at ~35 kHz can be related with dielectric relaxation in the *a*-YBCO material [3], [4]. The higher frequency low-pass response – close to $f^{-1/2}$ behavior typical of thermal diffusion across the substrate – is limited by the current preamplifier at ~3 MHz.

The device current noise (i_N) spectrum, as shown in Fig. 2, exhibits a rather unusual "blue noise" behavior, which can be thought as reflecting *a*-YBCO AC conductivity (σ_{AC}) dependence with frequency. As a consequence of the fluctuation-dissipation theorem, one can expect that the noise power density $<i_N^2>(f) \propto \sigma_{AC}(f)$. The main features observed are: $i_N \propto f^{0.3}$ below a few kHz (rough trend), then a significant rise $i_N \propto f^{0.7}$ between a few kHz and 100 kHz (the dielectric relaxation region), and $i_N \propto f^{0.3}$ above 100 kHz.

From the correlated barrier hopping (CBH) model, it follows that $\sigma_{AC}(f) \propto f^n$ with $n = 1 - 6k_BT/E_b$, where E_b is the energy barrier for the hopping process that can be deduced from optical measurements [5]. We thus measured E_b = 0.46 eV, leading to n = 0.67 at room temperature, whereas we directly measured $\sigma_{AC} \propto f^{0.71}$ for 10 kHz < f < 100 kHz as explained in [4]. We should therefore expect $i_N \propto f^{0.35}$ (i.e., $\sim f^{0.71/2}$) in this latter frequency range from noise measurements. The remaining 0.3 to 0.35 exponent as exhibited in Fig.2 in the whole frequency range (assuming additivity of noise power), may be attributed to a hopping mechanism across a contact barrier, with hopping energy around 0.4 to 0.5 eV.

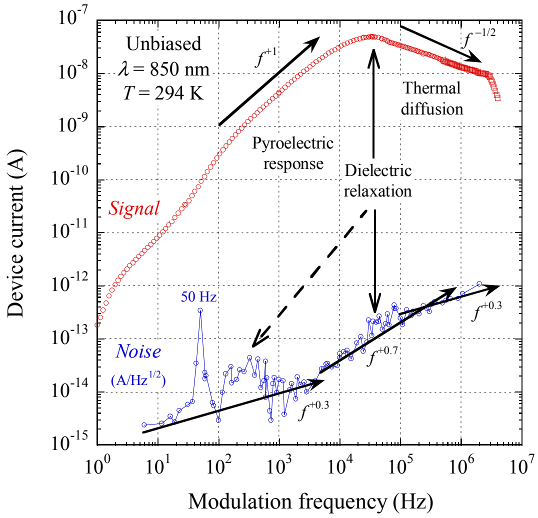

Fig. 2. Typical room temperature NIR response (top) and noise spectrum (bottom) of the unbiased *a*-YBCO planar device shown in Fig. 1.

Two extra features can be noticed in the noise spectrum, in the form of "bumps" arising at a few hundred Hz and at a few tens of kHz. These bumps can be related to fluctuations in the dielectric response, which includes a low frequency relaxation and a high frequency relaxation, as previously reported [6].

Noise measurements allowed to extract the NEP and detectivity D^* of the device. As shown in Fig. 3, NEP remains below 15 pW/Hz^{½}, and D^* above 10^9 cm·Hz$^{1/2}$·W^{-1}, in the 500 Hz to 100 kHz range. With minimum NEP ≈ 2 pW/Hz^{½}, and maximum $D^* \approx 7\times10^9$ cm·Hz$^{1/2}$·W^{-1} (theoretical room temperature limit ~ 2×10^{10} cm·Hz$^{1/2}$·W^{-1}), this pyroelectric detector is quite competitive compared to other reported NIR thermal detectors (see Table 1). The very short response time $\tau \approx 2$ µs should also be noticed.

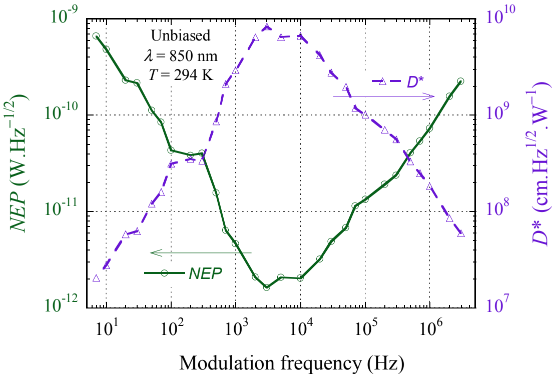

Fig. 3. For the unbiased *a*-YBCO planar device, NIR noise equivalent power and detectivity as a function of modulation frequency.

Table 1. For planar structures based on amorphous and/or oxide materials, room temperature performance for NIR thermal detection.

Material ref.	f (Hz)	NEP (W/Hz$^{1/2}$)	D^* (cm·Hz$^{1/2}$/W)	τ (s)
a-YBCO this work	200 1×10^4 1×10^5	3.8×10^{-11} 2×10^{-12} 1.3×10^{-11}	3.5×10^8 6.6×10^9 1.0×10^9	1.9×10^{-6}
a-YBCO [7]	30	4.1×10^{-11}	1.2×10^8	5.7×10^{-3}
a-Si [8]	200	8×10^{-12}	1.3×10^8	2.1×10^{-3}
a-SiGe [9]	n.a.	n.a.	2.5×10^9	125×10^{-3}
a-SiGeO [10]	250	n.a.	6.7×10^8	13×10^{-3}
VWO*x* [11]	15	5.4×10^{-10}	1.1×10^7	7.2×10^{-4}
MCO [12]	30	3.7×10^{-10}	6×10^7	19×10^{-3}

III. THz DEVELOPMENT

Due to *a*-YBCO reflectivity in the THz [13], coupling of the radiation to the sensing area is being performed using a planar antenna. We have considered the design of antenna arrays; an example of 32×32 array is shown in Fig. 4. A major outcome is the overall array size, according to the criteria of both THz bandwidth and inter-pixel cross talk. Another aim is to test the antenna impedance matching with the *a*-YBCO patch using FTIR spectroscopy measurements on such dense arrays of adequately loaded micro-antennas.

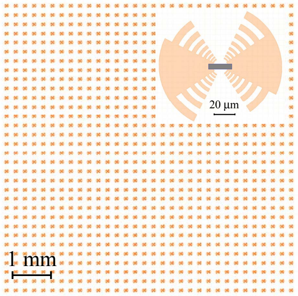

Fig. 4. THz pixel array design. Inset: detail of a loaded log-periodic antenna.

IV. SUMMARY

Simple planar detectors structures based on *a*-YBCO films have been designed and tested. The optical response of the device can be interpreted in terms of a pyroelectric capacitive current. Competitive NEP and detectivity are exhibited in the near-infrared, together with fast response in the microsecond range. THz imaging arrays using these detectors are further considered.

V. ACKNOWLEDGMENTS

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