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Low noise and fast response of infrared sensing structures based on amorphous Y–Ba–Cu–O semiconducting thin films sputtered on silicon

Alain J. Kreisler *, Annick F. Dégardin, Xavier Galiano, David Alamarguy

[a] *CentraleSupélec/GeePs; CNRS UMR 8507; Univ Paris-Sud; Université Paris-Saclay; 11 rue Joliot-Curie, 91190, Gif sur Yvette, France*
[b] *Sorbonne Universités, UPMC Univ Paris 06; 4 Place Jussieu, 75005 Paris, France*

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ABSTRACT

$YBa_2Cu_3O_{6+x}$ (YBCO) cuprates are semiconducting when oxygen depleted ($x < 0.5$). We have deposited, by DC sputtering at 150 °C, amorphous YBCO (*a*-YBCO) semiconducting films to evaluate their potential as sensing layer for thermal detection of infrared (IR) radiation. Low temperature elaboration is a key advantage to integrate a radiation detector on a silicon chip bearing already processed readout electronics. We have studied an *a*-YBCO/metal planar structure test vehicle in the near-IR, concentrating on the high-pass pyroelectric response observed for the device. This response exhibited interesting features: i) because originating from a capacitance current signal, no DC bias was required, hence a low noise current level; ii) the high-pass pyroelectric cutoff was observed in the 20 to 40 kHz modulation frequency range; iii) the low-pass cutoff, of readout circuitry origin, was pushed towards the MHz range, with a time constant of ~2 µs. The use of an analytical model allowed to simulate correctly the device amplitude and phase of the response as a function of the modulation frequency. All the model parameters were introduced, without adjustment, according to the actual geometrical, physical and electrical characteristics of the device and its measurement setup. The low noise and fast response was characterized by a detectivity above $10^9\ \mathrm{cm \cdot Hz^{1/2} \cdot W^{-1}}$, in the 500 Hz to 100 kHz range; these features are very promising for fast imaging applications. Migration from near-IR towards mid- and far-IR is also considered.

1. Introduction

Today, two materials are commonly used in commercial infrared (IR) uncooled bolometer focal plane arrays (FPA): vanadium oxide VO_x and amorphous silicon *a*-Si. *a*-Si has been positioned as a lower cost alternative to VO_x because it can be processed with foundry machinery common to manufacture other electronic components, without many of the specialized processes of other detector technologies. *a*-Si detectors have, however, a slight disadvantage compared to VO_x in image quality. In research laboratories, other thermistor materials for bolometric applications have been or are being investigated: V-O-W [1], *a*-SiGe(O) [2], semiconducting phase of amorphous $Y_1Ba_2Cu_3O_{6+x}$ (*a*-YBCO with a low oxygen content $x < 0.5$) [3,4], $La_{0.7}Sr_{0.3}MnO_3$ (LSMO) manganite [5], $Mn_{1.56}Co_{0.96}Ni_{0.48}O_4$ (MCO) spinel [6].

Various works demonstrated the basic feasibility of *a*-YBCO FPAs in the near-IR (NIR). Indeed, *a*-YBCO exhibits a high thermal coefficient of resistance value (−3 to $-4\% \cdot K^{-1}$) at room temperature, a figure of merit that compares very favorably with VO_x ($-2\% \cdot K^{-1}$) [1] or hydrogenated *a*-SiH ($-2.5\% \cdot K^{-1}$) [7]. Indeed, Wada et al. [8] produced an IR FPA based on *a*-YBCO suspended bolometers and reported a low noise level, comparable to the VO_x bolometer noise in the 1-100 Hz frequency range. Kumar et al. [9] also used *a*-YBCO material to realize 2D arrays of suspended bolometers with good detectivity $D^* = 3.5 \times 10^7\ \mathrm{cm \cdot Hz^{1/2} \cdot W^{-1}}$ at 200 Hz but low response time (10 ms), which is in line with the low-pass bolometric behavior of the device. More recently, Kreisler et al. [10] exploited the pyroelectric behavior [11] of *a*-YBCO thin films sputtered at low temperature (150 °C) on silicon substrates. Promising performances were evidenced in the NIR range for unbiased planar devices that exhibited a low noise and fast high-pass pyroelectric response, with maximum detectivity $D^* = 2 \times 10^8\ \mathrm{cm \cdot Hz^{1/2} \cdot W^{-1}}$ at 60 kHz and time constants as low as 2 µs (against few ms for commercial IR pyroelectric detectors).

We are considering here an improved *a*-YBCO planar detector, presenting in detail the main features of the optical response and suggesting a simple analytical model to interpret the fast response of the device. The specific character of the noise spectrum is also considered and discussed with respect to the *a*-YBCO dielectric properties and the non-linear character of the metal contacts. Finally, we are examining the migration from NIR towards mid-IR (MIR) and far-IR (FIR).

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* Corresponding author at: GeePs-CentraleSupélec, Plateau de Moulon, 11 rue Joliot-Curie, 91192 Gif sur Yvette Cedex, France.
E-mail address: Alain.Kreisler@centralesupelec.fr (A.J. Kreisler).

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2. Experimental details

a-YBCO films were deposited at ≈ 150 °C by off-axis DC cathode sputtering with a 50 mm diameter hollow target of the $YBa_2Cu_3O_{6.9}$ superconducting phase (Hitec Materials GmbH) [4]. The sputtering was performed under a 33 Pa pressure of oxygen/argon mixture in the 45%/55% flow ratio, on 380 μm thick *p*-doped Si substrates coated with a thermally grown 500 nm thick SiO_x layer on both sides (Silicon Materials). The device planar structure – 450 nm thick *a*-YBCO sensing element connected to two Au/Ti pads (see Fig. 1) – was patterned using standard lithography.

The device optical response was measured in the NIR at 850 nm wavelength for optimal absorption by *a*-YBCO [12]. A vertical cavity surface emitting laser (VCSEL) diode source (Honeywell model HFE4080-322/XBA) was used, which was amplitude modulated in the frequency range $f = 1$ Hz to 4 MHz. To avoid low frequency noise, the laboratory built modulator circuitry was designed with a second order high-pass filter ($f_{\mathrm{mod}} = 1.35$ Hz cutoff frequency). The detector response was readout with a low noise low input resistance current preamplifier (FEMTO® model DLPCA-200 between 1 Hz and 100 kHz, and model HCA-4M-500K between 25 kHz and $f_{\mathrm{PA}} = 4$ MHz cutoff frequency). The preamplifier output voltage was synchronously detected at frequency f with a lock-in amplifier (Stanford Research Systems, models SR830 up to 100 kHz and SR844 between 25 kHz and above). The preamplifiers and lock-in amplifiers frequency overlap was used to insure the amplitude/phase consistency on the whole measurement spectrum. The lock-in amplifiers were also used to measure the device noise current spectral density in a 1 Hz bandwidth. Besides, noise measurements above 50 kHz were also checked with a spectrum analyzer (Anritsu model MS2665C).

Ultraviolet photoelectron spectroscopy (UPS) measurements were undertaken at room temperature and under a vacuum of 7×10^{-7} Pa using a PHI 5000 *VersaProbe*™ spectrometer (UPS combined with X-ray photoelectron spectroscopy and Auger electron spectroscopy, from Physical Electronics) equipped with a helium discharge lamp (He I, incident energy = 21.2 eV) and with a hemisphere-type electron energy detector. Energy resolution was inferior to 0.12 eV. The position of the Fermi level was calibrated beforehand by measuring the Fermi edge of a gold leaf sample cleaned by Ar sputtering. A 900 nm thick *a*-YBCO film freshly prepared on a SiO_x/*p*-Si substrate was investigated. During measurements, a bias of −9 V was applied to the samples in order to shift the onset edge voltage down to a measurable range and therefore to collect low kinetic energy electrons into the analyzer. The sample work functions were determined by subtracting the binding energy of the secondary electron cutoff from the He I radiation energy.

3. Results and discussion

3.1. NIR response: experimental results

The room temperature optical response of the unbiased device, in terms of both amplitude and phase of the short circuit current, is shown in Fig. 2. The f^{+1} behavior between ~100 Hz and ~10 kHz is typical of a pyroelectric response originating from a capacitance current. Such a current can be observed with this planar structure because, as previously discussed [10], the conducting *p*-type Si substrate acts as a floating counter-electrode, whereas no resistive current (related to a bolometric response) can be in principle collected due to the unbiased situation. The cutoff at $f_{\mathrm{rel2}} \approx 20$ kHz of this high-pass response can be related to the dipolar relaxation as previously reported [13]. The high frequency low-pass response, close to $f^{-1/2}$, is typical of a thermal diffusion effect as discussed below in Section 3.2; it is limited by the current preamplifier at ~3 MHz. The f^{+2} behavior below ~100 Hz can be related to another reported dipolar relaxation at $f_{\mathrm{rel1}} \approx 200$ Hz [13], as also considered in Section 3.2. The lower f_{mod} and higher f_{PA} limiting frequencies are also indicated (see Section 2). The −3 dB bandwidth, in the ~12 to 85 kHz range, lies 2 to 3 orders of magnitude higher than the usual pyroelectric detectors do; a tentative explanation is given in the following.

3.2. Amplitude and phase response: analytical model

3.2.1. Modeling of regular pyroelectric response

The pyroelectric short circuit current delivered by the device and measured by the transconductance preamplifier + lock-in amplifier chain results from the temperature variations sensed by the *a*-YBCO active volume. The resulting detected signal is then driven by three contributions:

i) the intrinsic sensitivity of the pyroelectric material that relates the dielectric polarization variation to the temperature variation;

ii) the thermal budget parameters that relate the material temperature variation to the input irradiating power variation;

iii) the electric response of the amplifying chain.

All three contributions are *a priori* dependent on the modulation frequency $f = \omega/2\pi$ of the input power, hence a global complex transfer function that will include all the available dielectric, thermal and

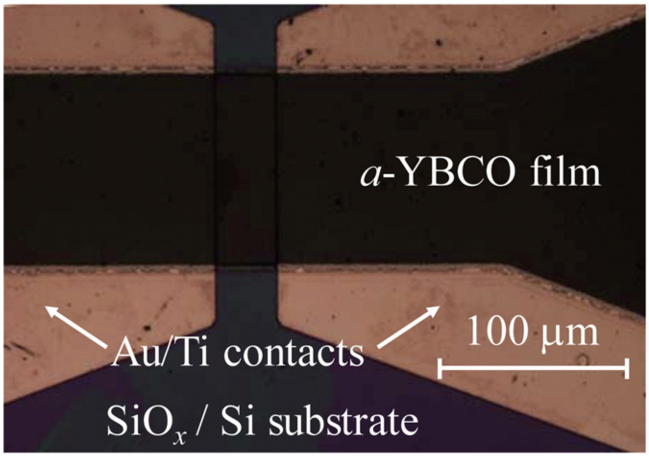

Fig. 1. Top view of the as-processed planar device. The *a*-YBCO film is 450 nm thick and the sensing micro-bridge dimensions are 30 μm × 100 μm.

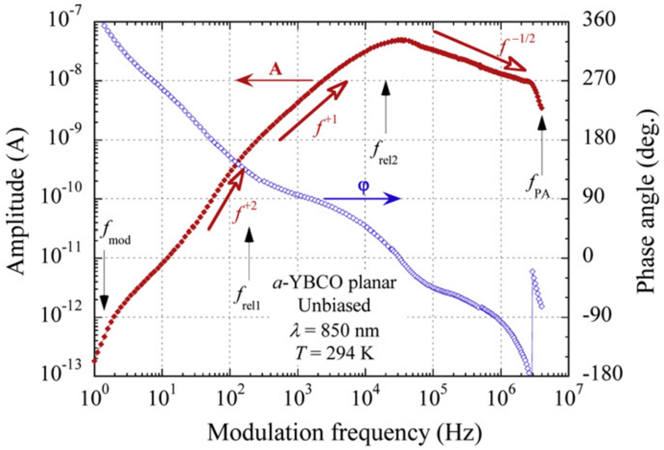

Fig. 2. For the *a*-YBCO planar structure of Fig. 1, amplitude and phase of the device current response as a function of the modulation frequency of the laser source intensity. The main features are discussed in Section 3.1.

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