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Semiconducting YBaCuO films grown on silicon substrates: IR room temperature sensing and fast pyroelectric response

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Abstract. $YBa_2Cu_3O_{6+x}$ (YBCO) oxides, well known as superconductors for $x > 0.5$, are semiconductors (SC) for lower oxygen content. SC films DC sputtered at 150 °C in amorphous form (a-YBCO) exhibited a temperature coefficient of resistance competitive with other bolometric sensing materials. Such deposition conditions are highly beneficial to integrate a radiation detector on a silicon chip bearing already processed readout electronics. IR detector structures have been processed: simple planar or more advanced metal/a-YBCO/metal trilayers. IR response was investigated at 850 nm as a function of the modulation frequency. The planar structure exhibited a regular bolometric response below 100 Hz, then a pyroelectric high-pass response up to 100 kHz. The trilayer device only exhibited the pyroelectric behavior up to 100 kHz. In the pyroelectric regime, detectivity values peaked above 2×10^8 cm Hz^{½}/W with time constants in the µs range, under both DC biased and unbiased conditions.

1. Introduction

There has been a constant interest, during the last decade, in room temperature (RT) semiconducting IR bolometric detectors. Being sensitive to power, they are in principle wavelength independent, an advantage for wide spectral operation, whereas photon detectors only operate beyond the absorption cutoff. Among the popular semiconductors, we find amorphous silicon a-Si [1] and vanadium oxide families [2]. In practice, co-integration of the sensing device (or device array) with silicon readout electronics is also a key feature that would *a priori* give advantage to a-Si (or a-SiGe [3]) sensors because of the low deposition temperature of the amorphous material, compatible with already processed readout circuitry. Y-Ba-Cu-O oxide (in its oxygen depleted, non superconducting form i.e. $YBa_2Cu_3O_{6+x}$ with x below 0.3) has also raised interest: it offers competitive sensitivity and noise level and can be easily elaborated in amorphous form (a-YBCO) at 100-200 °C on silicon based substrates [4,5]. Moreover, a-YBCO exhibits pyroelectric properties [4], which paves the way to an alternate thermal sensing detector type, with advantages we wish to stress in the present paper.

2. a-YBCO film preparation and material properties

a-YBCO films were DC sputtered using a hollow Y-Ba-Cu-O stoichiometric cathode under a Ar + O_2 atmosphere (total pressure: 33 to 67 Pa, Ar:O_2 flow ratio 55%:45%). The growth rate increased from

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60 nm/h at 67 Pa to 160 nm/h at 33 Pa, with no noticeable change in the film quality [6]. Insofar as the bolometric device application is concerned, the temperature coefficient of resistance *TCR* = $(1/R)(dR/dT)$ is a key parameter to monitor the quality of the films. *TCR* as a function of deposition temperature is shown in figure 1. Substrates were either MgO (001) single crystal or p-doped silicon (1-10 Ω·cm resistivity) bearing a thermal SiO_x (500 nm) layer.

It appears that deposition temperatures in the 100-200 °C lead to amorphous films of low roughness (3 to 5 nm rms) exhibiting 20 nm grains immersed in a seemingly homogenous matrix [7].

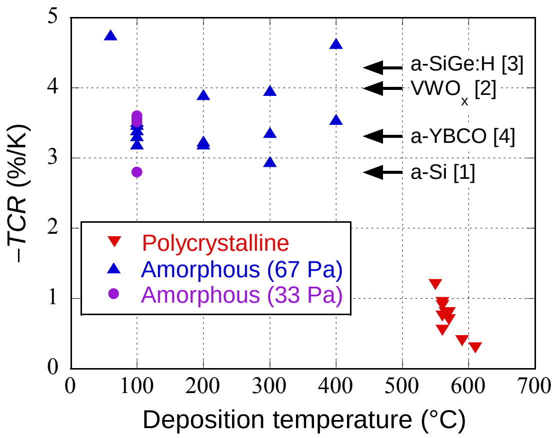

Figure 1. For DC sputtered Y-Ba-Cu-O films, temperature coefficient of resistance (*TCR*) as a function of deposition temperature T_d. For T_d above 550 °C, the films were polycrystalline and exhibited a low *TCR*. Whereas for $T_d < 500$ °C, the films were amorphous with good *TCR* values. For $100 < T_d < 200$ °C, no noticeable effect of substrate nature or film thickness was observed. The arrows indicate other published data. After [6].

3. Device geometries and electrical characteristics

In order to test a-YBCO IR sensing performance, two device geometries were considered; both were elaborated on p-Si/SiO_x substrates, as depicted in figures 2 and 3.

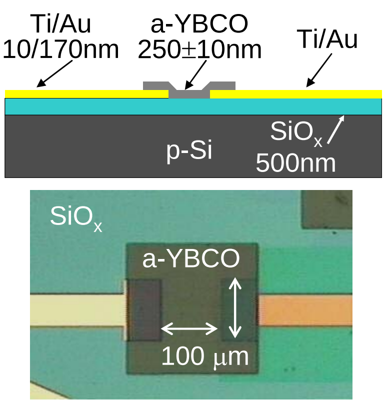

Figure 2. Cut-view (top) and photograph (bottom) of the planar device (DevP).

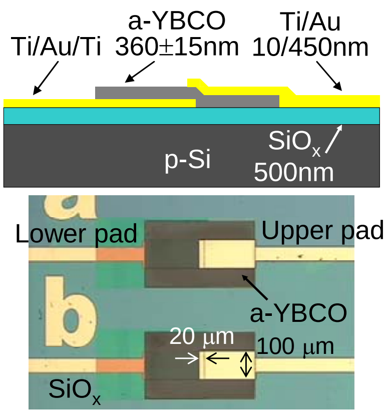

Figure 3. Cut-view (top) and photograph (bottom) of the trilayer device (DevT).

In the planar configuration (DevP), a-YBCO was in-plane connected to two gold pads (figure 2). The DC $I(V)$ characteristic exhibited a close to symmetric linear variation for $|V| > 2$ V, with a resistance slope of 12-13 MΩ and a resulting resistivity $\rho_{DC} \cong 300$ Ω·cm. The low voltage non-linearity was fitted with a $I \propto V^{1.75}$ power law due to a bulk effect (not to a contact effect, see below) related to a-YBCO structural disorder, the film behaving as an assembly of resistive elements, randomly connected e.g. at grain boundaries. Such a model provides 1 to 2 exponent values [8].

A trilayer configuration (DevT) was designed to decrease the device access resistance (figure 3). a-YBCO was sandwiched between gold contacts with an extra titanium layer. The DC $I(V)$ characteristic was highly non-linear, we ascribed to the Schottky nature of the contacts. At low level, a very good fit $I \propto \exp(V^{1/4})$ was obtained for both polarities, which well models a reverse biased Schottky diode with image force barrier lowering [9]. The device actually presents a reverse biased junction for both polarities (back to back connected Schottky diodes). Assuming the p-type nature of a-YBCO, as the work function for Ti (4.3 eV) is lower than for Au (5.1 eV), the metal/a-YBCO junction would be Schottky for Ti (DevT) but ohmic for Au (DevP).

From $\rho_{DC}(T)$ variations (T = 100-300 K) in the (quasi-)linear regime (V_{DC} = 8 V for DevP and 3.7 V for DevT), an Arrhenius behavior was observed as $\rho_{DC} \propto \exp(E_A/k_BT)$. From the activation energy we deduced $TCR = -E_A/(k_BT^2)$ = –2.8 %/K at 300 K for DevP and –2.0 %/K for DevT. The degradation with respect to bare films is significant for DevT, due to the more critical processing sequence.

4. Near-IR characterization results and discussion

The optical response was measured at 850 nm, with modulated power at frequency f. The device was voltage biased at V_{DC} and the delivered current i_S was readout with a transconductance preamplifier, which output was detected at reference frequency f with a lock-in amplifier (also used to measure the device 1 Hz bandwidth noise current density i_N). Other details can be found elsewhere [5,10].

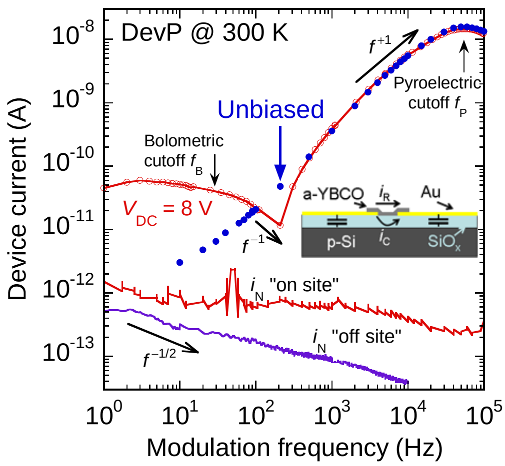

Figure 4. NIR response of DevP (biased and unbiased) as a function of modulation frequency. "Off site" refers to measurement in an electromagnetically quiet location. Inset: the substrate behaves as a counter-electrode for the capacitance current path.

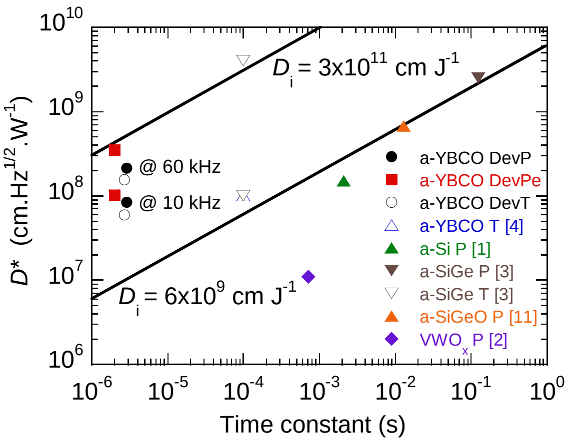

Figure 5. For the various devices listed (P: planar, T: trilayer), detectivity as a function of time constant. The first three symbols refer to the present study (enhanced conditions – DevPe – are detailed in [10]). D_i represents the impulse detectivity, as commented in the text.

Results for DevP are shown in figure 4. For V_{DC} = 8 V bias, the regular bolometric response (thermal variation of resistance) exhibits the expected low-pass behavior (cutoff $f_B \cong$ 30 Hz). As DevP is not a suspended structure, the bolometric response is low. A sharp rise of the response is observed above 300 Hz, with a high-pass behavior (cutoff $f_P \cong$ 55 kHz) in line with a-YBCO pyroelectricity [4]. The thermal variation of the electric polarization could be detected because a capacitance current i_C is collected due to the Si-substrate acting as a (floating) counter-electrode (figure 4, inset). In fact, with an insulating MgO substrate, only the bolometric response was observed [5]. Moreover, from unbiasing the device (V_{DC} = 0) resulted a pure pyroelectric response without signal degradation.

For DevT, only the pyroelectric response was observed due to the intrinsic capacitor structure of this device (figure 3), the resistive (regular bolometric) current becoming negligible ($i_R << i_C$).

The device detectivity was obtained from the current responsivity i_S/P_I (P_I is the effective incident IR power) and i_N (on-site, figure 4) as $D^* = A_D^{1/2} i_S/(i_N P_I)$ (A_D is the effective device area). Our pyroelectric response data are collected in figure 5 with other published results [1-4,11]. Plotting D^* vs. detector time constant τ allows to illustrate the impulse detectivity parameter $D_i = D^* \tau^{-1/2}$ (in cm·J^{-1}) that is an invariant for a given class of detectors (same working principle, same background noise temperature [12]). $D_i = 6\times10^9$ cm·J^{-1} represents an average for a majority of published results that mainly concern suspended devices optimized for low frequency operation [1,3,4,11]. Our data are gathered around more than one order of magnitude higher, due to the fast pyroelectric response.

Among other points that would deserve addressing in detail, let us cite: i) the origin of the short response time (fast heat removal might be related to i_C flowing in the Si substrate and/or to the metal contacts); ii) the relationship between the pyroelectric cutoff frequency and the upper dielectric relaxation frequency observed at a few 10 kHz [13]; iii) the correlation between the dipole charges (origin of pyroelecticity) and the charge carriers photo-induced above the optical gaps observed in [7].

5. Conclusion

Semiconducting a-YBCO is an attractive sensing material for IR thermal detection. a-YBCO thin films can be deposited on silicon substrates and thus allow integration with CMOS readout electronics. Planar and tri-layer structures have been processed and tested in the near IR. Only the planar structure exhibited a regular bolometric response at low frequency. However, both structures exhibited a high-pass pyroelectric behavior, with detectivity values above 2×10^8 cm·√Hz/W and 2-3 µs time constants – whether DC biasing the device or not. Besides, many issues concerning the detecting principles (with respect to a-YBCO material properties and device geometry) still remain open.

The pyroelectric high frequency sensitivity offers a promising solution for fast imaging applications, especially in the far IR / THz range. Improvements are under consideration: for front-end radiation coupling with THz micro-antennas [14], the advantage of the trilayer resides in its lower access impedance. For back-end electric coupling, they deal with high impedance/low noise readout circuitry and correction of the lower frequency response distortion as well.

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