High-\(T_c\) Bolometers with Silicon-Nitride Spiderweb Suspension for Far-Infrared Detection

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Abstract—High-\(T_c\) \(\text{GdBa}_2\text{Cu}_3\text{O}_{7.5}\) (GBCO) superconducting transition edge bolometers with operating temperatures near 90 K have been made with both closed silicon-nitride membranes and patterned silicon-nitride (SiN) spiderweb-like suspension structures. As a substrate silicon-on-nitride (SON) wafers are used which are made by fusion bonding of a silicon wafer to a silicon nitride top layer. The resulting monocrystalline silicon top layer on the silicon-nitride membranes enables the epitaxial growth of GBCO. By patterning the silicon-nitride the thermal conductance \(G\) is reduced from about 20 to 3 \(\mu\)W/K. The noise of both types of bolometers is dominated by the intrinsic noise from phonon fluctuations in the thermal conductance \(G\). The optical efficiency in the far infrared is about 75\% due to a gold-black absorption layer. The noise equivalent power NEP for FIR detection is 1.8 \(\mu\)W/\(\sqrt{\text{Hz}}\), and the detectivity \(D^*\) is \(5.4 \times 10^{10}\) \(\text{cm} \cdot \text{dHz}/\text{W}\). Time constants are 0.1 and 0.6 s, for the closed membrane and the spiderweb like bolometers respectively. The effective time constant can be reduced with about a factor 3 by using voltage bias. Further reduction necessarily results in an increase of the NEP due to the \(1/f\) noise of the superconductor.

I. INTRODUCTION

Some ten years ago it was recognized that high-\(T_c\) superconducting (HTS) bolometers potentially have much better sensitivities at wavelengths > 20 \(\mu\)m than any radiation sensor operating at or above liquid nitrogen temperatures (77 K) [1]. HTS bolometers are thermal detectors in which a high-\(T_c\) superconducting film is used as an electrical resistance thermometer. The very sharp superconducting transition enables changes in temperature to be measured with high sensitivity. Since then a lot of effort has been put into the development and the optimization of these detectors. Nowadays state of the art high-\(T_c\) superconducting bolometers indeed offer the highest sensitivity for wavelengths > 20 \(\mu\)m at operating temperatures above 77 K [2-4].

Fig. 1. Schematic overview of the used production routes for the HTS bolometers: (a) resulting in bolometers with a foil of degraded GBCO with PtO between the SiN beams, and (b) without this foil.
In this paper the production processes for the HTS GBCO bolometers with SiN suspension beams are described. Their performance will be compared with the performance of the previously reported bolometers with closed SiN membranes. Furthermore the effect of using voltage bias instead of the regular current bias to improve the speed of the detector will be discussed.

II. PRODUCTION TECHNOLOGY

The production processes are illustrated by Fig. 1. The starting substrates for the production of the bolometers are silicon-on-nitride (SON) wafers. The SON wafers are made by bond-and-etch-back of two wafers: a commercially available silicon-on-insulator (SOI) wafer obtained from SOITEC and a silicon wafer on which a 1 µm silicon-rich silicon-nitride (SiN) layer is grown. Previous to the bonding the silicon nitride is chemically-mechanically-polished (CMP) using a procedure which is standard for IC planarisation. More details of this process were published elsewhere [6].

The SiN layer at the backside of the Si wafer is used as a mask for etching the membrane windows. The etching is stopped when the SiN membrane is still supported by about 25 µm of Si. The resulting membranes are strong enough for the following processes.

Next a 40 nm double buffer layer of yttrium stabilized zirconia (YSZ) and CeO₂ is epitaxially grown on the Si top layer using molecular beam epitaxy. The meander pattern for the high-\( T_C \) layer is etched in these buffer layers and the Si layer by argon sputter etching and reactive ion etching (RIE), respectively. This step will define the area of the GBCO layer that will be superconducting (inhibition patterning). A second resist mask is used to define the suspension beams in the SiN layer. Etching is done by RIE. It is stopped when about 250 nm of SiN is left between the suspension beams.

Before the deposition of GBCO the substrates are diced in pieces of 1 cm × 1 cm. The GBCO layer is deposited by hollow magnetron sputtering. On top of the GBCO a 200 nm thick passivation layer of platinum oxide (PtOₓ) is deposited by magnetron sputtering. Then, using a special chuck to seal-off the front side of the substrates, the remaining 25 µm of silicon is removed from the backside of the membranes by KOH etching. The 250 nm thick SiN layer between the beams of the web structure can be removed by RIE. Between the SiN beams a thin GBCO/PtOₓ layer remains (Fig. 1 a).

To get rid of the GBCO/PtOₓ between the SiN beams the second route was developed (Fig. 1 b). In this route the Si at the backside of the membrane and the 250 nm of SiN between the beams are removed before deposition of the GBCO.

Finally on top of the bolometers an absorption layer of gold-black is deposited through a shadow mask with a pinhole of 1.1 mm diameter. The thickness is between 25 and 50 µm, with a filling fraction of 0.003. The resulting absorption efficiency for radiation with wavelengths around 100 µm wavelength is approximately 90%.

Fig. 2 shows a photograph of the backside of a bolometer with 8 SiN suspension beams and 200 nm PtOₓ between the beams. The PtOₓ is buckling due to its compressive stress. In the center of the bolometer the superconducting meander can be seen through the SiN layer. In Fig. 3 a bolometer is shown with really freestanding SiN beams, prepared along the second route (Fig. 1 b).

III. BOLOMETER PERFORMANCE

The bolometers were characterized in a vacuum cryostat. They were operated with current biasing. To reduce the low frequency noise of the electronics, a square wave current modulation at 1 kHz was used together with phase sensitive amplification.
The thermal conductances $G$ were determined by measuring the superconducting transition at different current levels, and fitting the $R$-$T_m$ curves on top of each other. Here $T_m = T_s + (R+P)/G$ is the calculated temperature of the membrane, $T_s$ is the temperature of the substrate and $P$ is the radiation load on the bolometer. The results for the bolometer shown in Fig. 2 are given in Fig. 4. It was found that $G = 3.5$ pW/K. The normalized slope of the transition $\alpha = R dR/dT$ at the point where the slope is at maximum is 1.1 K$^{-1}$. For all bolometers typically values between 1 and 2.5 K$^{-1}$ were found.

An overview of the specifications of three typical bolometers with different geometries including the parameters $R_{\text{mid}}$, $T_{\text{mid}}$ and $\alpha_{\text{mid}}$ is given in Table I. The subscript mid indicates the midpoint in the transition where the slope is at maximum.

The bolometer of Fig. 3 was tested so far only in a cryostat with unknown radiation load. The $R$-$T$ measurements showed a sharp superconducting transition at 78 K, indicating the feasibility of this production route, but the data was insufficient to be incorporated in Table I.

The absolute optical responsivity of the bolometers has been determined with two radiation sources with different power levels. For these, two black bodies at 30 and 50 °C were used. Their radiation was filtered with a well-characterized filter at a temperature of 90 K and then collected on the bolometers with a compound parabolical concentrator (CPC or "Winston cone"). The resulting spectrum covers a band with wavelengths from about 70 to 200 μm with a maximum at 85 μm. The frequency roll off of the bolometer was determined by measuring the response to a modulated light emitting diode. Fig. 5 shows the resulting response spectra at indicated bias points of the three bolometers listed in Table I. By comparing the measured response with the electrically determined responsivity it was determined that the efficiency is about 0.7 to 0.8.

The noise equivalent power (NEP) of the bolometers was determined by dividing the noise spectra by the optical responsivity. The results for the three bolometers at the biaspoints indicated in Fig. 5 are shown in Fig. 6. In fact, the exact biasconditions are not very critical. For each bolometer there is a range of bias temperatures and bias currents for which the NEP spectra are similar and for which the NEP is minimal. Usually the current and the temperature can be chosen such that $R$ is around $R_{\text{mid}}$ and the bias parameter $L_{\phi} = F R_{\phi}/G$ is between 0.1 and 0.3.

Clearly the minimum NEP decreases with decreasing thermal conductance $G$ (cf. Table I). In the frequency range where the NEP is approximately constant and at a minimum it is dominated by the phonon noise in the thermal conductance $G$. The observed levels are in agreement with the theoretical level for the phonon noise given by $\text{NEP}_{\text{phonon}} = (4kT^2G)^{1/2}/I$. In Fig. 6 the straight line indicates the relation
NEP of all HTS GBCO bolometers. By substituting $G=C/\tau=2\pi f C$ in the formula for $\text{NEP}_{\text{phonon}}$ it can be seen that it is in fact determined by the heat capacity $C$ of the bolometers. For all three bolometers $C$ is roughly 2 $\mu$J/K. Improvement of the NEP beyond this limit can be achieved by reducing the heat capacity, for instance by decreasing the SiN thickness or by getting rid of the PtO$_x$ foil between the SiN beams as in Fig. 3.

By using voltage bias with strong electrothermal feedback the effective timeconstant of a superconducting bolometer can be decreased [7]. Consequently, voltage bias offers the possibility to reduce the NEP by reducing the thermal conductance of the bolometers while keeping $C$ and the effective speed of the bolometer the same. This strategy works well for low-$T_c$ superconducting bolometers. For HTS bolometers however, it is not very useful due to the relatively high level of $1/f$ noise of the superconductor. This can be seen as follows.

The NEP due to the Johnson and the $1/f$ noise of the superconductor are -independently of the biasing scheme- given by [4]

$$\text{NEP}_J = \frac{4kT}{\eta L_0 \alpha} \left[1 + \omega \alpha \right] = \frac{\omega C}{\eta L_0 \alpha G}$$

for $\omega \gg 1/\tau$. \hspace{1cm} (1)

and

$$\text{NEP}_{1/f} = \frac{C}{\omega \alpha} \sqrt{\frac{G}{\eta \alpha \omega}} \approx \frac{C}{\eta \alpha \omega}$$

for $\omega \gg 1/\tau$. \hspace{1cm} (2)

Here $c$ is a constant depending on the superconducting material and its volume. Clearly, only the Johnson noise is suppressed by using voltage bias with a large loopgain value $L_0$. Substituting typical values for our bolometers, i.e. $C=2 \mu$J/K, $\alpha=2$, $K$, $\eta=0.75$ and $c=1.2 \times 10^{-12}$ [4], yields $\text{NEP}_{1/f} = 1.2 \times 10^{-12}$ W/Hz $x f^{1/2}$. The optimal NEP is obtained for the situation where the phonon noise and $1/f$ noise are equal, which gives $\text{NEP}_{\text{opt}} = 1.7 \times 10^{-12}$ W/Hz $x f^{1/2}$. So compared to the present situation, a factor of 3 gain in speed is feasible by using voltage bias while keeping the same NEP. Larger gains will result in a higher $1/f$-dominated NEP.

### IV. CONCLUSIONS

By using a new technique to decrease the thermal conductance, i.e. by structuring the supporting SiN membrane, HTS bolometers have been made with an optical NEP of $1.8 \times 10^{-12}$ W/Hz $x f^{1/2}$ at an operating temperature of 90 K. A limit given by $\text{NEP}_{\text{lim}} = 3 \times 10^{-12}$ W/Hz $x f^{1/2}$ is observed for the NEP of the bolometers. In terms of detectivity $D^* = (\text{Area})^{1/2} \text{NEP}$ it can be expressed as $D^* = 8 \times 10^{-10}$ cm Hz/W $x f^{1/2}$. This is a factor 5 higher than the empirical Havens limit for room temperature thermal detectors [8].

The present bolometers have reached the limit set by the heat capacity and the operating temperature. A further improvement of the NEP without sacrifices in speed is -apart from a small improvement by using voltage bias- only possible by decreasing the heatcapacity and/or the operating temperature. A way to reduce heatcapacity is by removing the PtO$_x$ between the SiN beams. These bolometers with really freestanding SiN beams have been fabricated, but no conclusive data can be presented yet.

### REFERENCES