Transition edge sensors for quench localization in SRF cavity tests

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Abstract. Transition Edge Sensors (TES) are bolometers based on the gradual superconducting transition of a thin film alloy. In the frame of improvement of non-contact thermal mapping for quench localisation in SRF cavity tests, TES have been developed in-house at CERN. Based on modern photolithography techniques, a fabrication method has been established and used to produce TES from Au-Sn alloys. The fabricated sensors superconducting transitions were characterised. The sensitive temperature range of the sensors spreads over 100 mK to 200 mK and its centre can be shifted by the bias current applied between 1.5 K and 2.1 K. Maximum sensitivity being in the range of 0.5 mV/mK, it is possible to detect fast temperature variations (in the 50 µs range) below 1 mK. All these characteristics are an asset for the detection of second sound. Second sound was produced by heaters and the TES were able to distinctively detect it. The value of the speed of second sound was determined and corresponds remarkably with literature values. Furthermore, there is a clear correlation between intensity of the signal and distance, opening possibilities for a more precise signal interpretation in quench localisation.

1. Introduction

The upcoming generation of accelerators demands for the design and installation of Superconducting Radiofrequency (SRF) cavities of different sizes and geometries. Many of these SRF cavities are based on bulk Nb in a He-II bath. The individual testing of these devices is necessary to assess the performance and exclude surface defects that could induce a quench during operation. A versatile and easily adaptable way of relating quench behavior to local defects is non-contact thermometry. Making use of the second sound propagation in He-II, a hot spot on the cavity can be localized by trilateration. Optical and metallurgic inspection can then be performed on the identified area to investigate the limited performance of the material.

So far, non-contact thermometry has been mainly based on Oscillating Superleak Transducers, oscillating membrane detectors sensitive to changes in the normal to superfluid component ratio in He-II. The sensors have been widely used in the field and have been characterized in previous works [1–3]. To improve the method, better space resolution and essentially thermometric information of the second sound wave could be beneficial. This is the reason why Transitions Edge Sensors (TES) are being developed at CERN.

TESs are based on the superconducting (SC) transition of a thin film in the He II temperature range. TESs sense the significant electrical resistivity change of the film as a function of temperature, for a given current density, in a very narrow temperature range. They are highly sensitive to temperature changes and the low thin film thermal inertia provides very fast response. Hence, the precise detection of second sound with TES is possible.
In this work, a TES fabrication method has been conceived using state-of-the-art photolithography techniques producing sensors of less than 1 mm² typical size. The fabricated sensors have been characterized in the SC transition, verifying the capability of these sensors to detect with good signal-to-noise ratio a second sound event.

In the near future, a robust camera-like device with a network of many sensors at different positions will be presented in order to provide a compact instrument that allows trilateration of quench hotspots.

2. The TES working principle

TES have been first presented in literature in the 1970’s for use as photon detectors. There are sensors of many different materials. Their main characteristics are the following:

- They are produced from a couple of metals, one SC and one normal.
- They are fabricated as thin films on a non-conducting substrate (glass).
- The sensing strip is narrow (~ 30 µm).
- They have current leads of larger width in order to be able to solder feeding cables.

When it comes to TES for second sound detection, the attention needs to be directed to the combination of Au (normal) and Sn (SC) as constituting elements [4], since in the right proportion they can have their transition edges in the range of 1.5 K to 2.1 K, where second sound exists and SRF cavities operate and are tested.

Au-Sn thin film alloys present complex microstructures which make the transition from SC to normal conducting gradual, i.e. the plot of resistance R as a function of temperature T for a given bias current I has an S-shape (sigmoidal). The centre of the S on the T scale shifts towards low T when I is increased. The width of the varying zone of the sigmoid can be in the order of 100 mK and is typically higher at higher T (low I). Figure 1 shows a schematic diagram of the behaviour of the sensors. Consequently, the sensor is highly sensitive only within the width of the S around its centre, which can be tuned by the bias current.

![Figure 1. Schematic working principle of a Transition Edge Sensor. Left: SC transitions at different bias current. Right: Sensitivity temperature range tuning by bias current.](image)

3. Fabrication of the TES

TES have a fast thermometric response thanks to the low mass of the thin film structure. The sensing strip need to be narrow enough to have sufficiently low feeding currents, thereby reducing self-heating. Microtechnology methods are therefore required for TES fabrication. Previously produced TES were made by processes involving masked evaporation deposition and chemical etching of thin films [4, 5]. In order to simplify and accelerate the R&D process, a new method based on more up-to-date techniques was designed and implemented. This method is based on photolithography and thin film evaporation without mask. All the production steps were carried out at the CMi of EPFL (Centre de Microtechnologie of École Polytechnique Fédérale de Lausanne, Switzerland).

3.1. Photolithography
The process starts with a clean borofloat33 glass wafer of 10 cm diameter. This wafer is spin-coated with a double layer of lift-off resin (LOR) and photoresist AZ1512. The automatic coating machine dehydrates the surface before start and bakes the resins after each layer application; thus, the wafer is ready to be exposed immediately. The geometric pattern of the TES on the wafer is drawn by CAD. Figure 2 shows one of the CAD patterns that was eventually fabricated. The exposition of the photoresist is done with an automatic laser machine which reads the pattern file and writes on the wafer with a UV laser. The precision of the pattern is in the 1 µm range. Subsequently, the pattern is developed by the application of a solvent in an automatic apparatus. As a result, the wafer is covered by a polymer layer which has gaps with the shape of the desired pattern. Figure 3.a shows an image of the obtained sensor pattern after development.

**Figure 2.** CAD Design of a wafer and of a single TES.

**Figure 3.** Fabricated TES sensing strips. a) After development. B) After lift-off. The width of the strips is 30 µm and the overall sensing area is in the range of 1 mm².

### 3.2. Evaporation

The next step is the evaporation of the thin film. This step is the most critical as it is here that the sensors are produced. The thin film is produced by depositing successively Au and Sn in 20 nm and 100 nm of thickness, respectively. The wafers are placed in a vacuum chamber outfitted with evaporation crucibles charged with small grains of the two metals. The deposited thickness is inferred from an oscillating crystal thickness monitor. The deposition rate is 0.3 nm/s. Residual pressure in the evaporator, measured by a Penning gauge, is $2 \cdot 10^{-6}$ mbar.
3.3. *Lift-off*

The last step of the process is lift-off. Wafers are placed in a remover bath which will attack the LOR and will thus detach all the region which had not been exposed to the laser. After 48 hours, the wafers can be cleaned and only the thin films with the shape of the pattern remain. Figure 3.b shows the obtained thin film sensor strip after lift-off.

It is worth to point out that special care was taken to avoid any process that involved heating above room temperature after the thin film had been deposited. Even a moderate temperature annealing has been reported to have a great impact on the thin film SC transition behavior [4].

4. **Cryogenic testing of TES**

The cryogenic test of the TES had two distinct stages:

- Characterizing the SC transitions of the sensors;
- Assessing the second sound detection capabilities of the sensor.

This section will describe the set-up which allowed performing this two studies, while the next two sections present the results.

![Figure 3](image1.png)

**Figure 3.** Lift-off. The liftoff is performed by placing the wafers in a remover bath, which will attack the LOR and detach the non-exposed regions. After cleaning, only the thin films with the pattern remain.

4.1. **The cryostat**

The experiments were carried out in a vertical cryostat of 1 m depth and 0.2 m diameter. This cryostat is connected to a manifold to pump on it and reduce internal pressure. In order to obtain saturated superfluid helium at a precise temperature, pressure is controlled by an MKS pressure transducer and valve actuator control system. This system can lower the temperature of the bath down to 1.5 K. Pressure can be controlled with 5 Pa precision in all the superfluidity range. Figure 4, right, shows a schematic drawing of the cryostat PID and control. The temperature of the bath is determined from the p-T saturation curve of helium, which is the definition of temperature in ITS-90 in liquid helium range. The resulting precision of the measured bath temperature is between 0.4 mK at $T_\lambda$ and 2 mK at 1.5 K.
4.2. The TES setup

As the TES are grown on circular glass wafers, it was necessary to produce supports to mount the wafers in the cryostat. These were made out of glass fiber epoxy. The fixation of the wafer on the support is achieved by three spring loaded clamps on screws to avoid high forces resulting from thermal contraction. A plate containing nine heaters on a row was placed in front of the wafer. Heaters are SMD thick film resistors of 47 Ohm of 3.2 x 6.4 mm² size, and are intended to produce controlled second sound. The heater plate is fastened to the wafer support, fixing the distance between wafer and heaters to 47±1 mm. This assembly is then placed on the insert supported by the cryostat flange. In figure 4, a photograph on the left bottom shows the support with the heaters and the TES wafer.

4.3. Signal reading

To avoid heating the thin film with soldering, current and signal reading wires were attached to the thin film leads by cold In-soldering technique. This consists in applying a sub-mm indium grain on the surface, smearing it and gluing it on the surface with a flat tool, pushing the tip of a very fine cable inside, and finally covering it with another smeared indium grain. The result on a TES can be observed in figure 4, left top. Although the technique is cumbersome, time consuming, and requires some level of manual skill, the junction presents non-appreciable electric resistance at low temperature and is strong enough to lift the whole wafer from one single wire.

The 4-wire connections were used to feed the sensors with constant current while reading voltage. The signals from many sensors were read simultaneously using four NI9251 acquisition cards with a sampling rate of 200 Hz for the characterization and up to 50 kHz for second sound detection. Pulses on heaters were produced by an independent power source and an NI9472 module acting as a controllable trigger. All the system is mounted on a single chassis, USB-connected to a PC and controlled by a LabVIEW interface.

5. TES characteristics

5.1. Experimental procedure and data treatment

The TES SC transition characterization consisted in finding the dependence of the sensor voltage on temperature and applied current, i.e. V(T,I). To obtain the experimental data of this function, we proceeded as follows:

- The temperature of the bath was fixed at a given value with the pressure control system.
- A current sweep from 0 to 3-5 mA with steps of 20-50 µA was performed.
- The voltage of the TES was measured with 200 Hz - 400 Hz sampling rate.
- The procedure is repeated for temperature values, from 1.5 K to 2.1 K, in 0.025 K steps.

At each temperature, the data was treated to have one point of voltage per current step. This gave a table of V and R (V/I) with two entries, T and I. Then, the derivative dV/dT at constant I, i.e. the sensitivity in fixed-current operation mode, was determined by finite difference formula.

5.2. Results

Figure 5.a shows the measured V-I curves at different temperature set points. From these curves, the resistance of the sensor is calculated and plotted in Fig. 5.b, highlighting the transition. The values of dV/dT as a function of current are plotted in figure 5.c for different bath temperatures. The sensitivity presents a peak at a given current value, which represents the optimal operation current at that bath temperature. The maximum achievable sensitivity of the sensor has been plotted as a function of bath temperature in figure 5.d. It can be seen that this parameter decreases as T increases. The latter curve is an intrinsic property of each TES, its characteristic, resulting from its length and composition. Increasing length will result in a multiplication constant on every sensitivity value. Increasing Sn content would presumably shift the curve to the right, due to the increase in absolute critical temperature [4].
6. Second sound detection

6.1. Experimental procedure

The TES were biased with the optimal current for the temperature bath (e.g. 0.9 mA at 1.6 K). In order to produce second sound pulses, the LabVIEW interface counted with a trigger button to produce a pulse on demand on selected heaters. The pulse intensity was regulated by changing the voltage of the power source. The trigger also launches the writing of a file of the voltage drop on the heater and on the sensors. As the relative position of the heaters is known with respect to the sensors, it is possible to determine the correlation between distance and intensity or time of detection of second sound.

6.2. Data analysis and results

Figure 6 shows the response of three different sensors to an identical pulse on different heaters (the sensors are identified on the wafer in figure 1). The heaters (H#) are placed on a line whose projection on the wafer passes through the center of the wafer, horizontally. H4 is exactly in front of the center, H1 is 30 mm to the left and H8 is 40 mm to the right. The pulse intensity is \((1.40 \pm 0.07) \times 10^5 \text{ W/m}^2\) and its duration is \((1.5 \pm 0.1) \text{ ms}\).

It is seen that after the pulse on the heater and for a period of time superior to 2 ms the signal of the sensor does not show any significant alteration with respect to its state prior to the pulse (in the case of sensor 1, the very narrow peaks at 0 ms and around 1.5 ms are simultaneous to the power steps and are due to electric cross talk). However, at a given point in time, an ascending peak is observed and after this peak the signal becomes very noisy with regular frequency peaks whose intensity decays in time. The ascending slope is due to second sound.

If we try to correlate the time elapsed since the power on the heater rises up to the occurrence of the first peak, with the distance between sensor and heater, we obtain the plot in figure 7.a. The second sound arrival time was defined as the time when the ascending flank exceeds average noise level before...
the pulse. A linear fit of the data for sensor 3, which is the one that has the higher extent over distance, especially at low values, reveals that the velocity of the travelling wave is 20.57 m/s, to 1% precision with the literature value of 20.36 m/s for linear second sound at 1.6 K, the temperature of the test [6]. The uncertainty on the measured value can be estimated to be less than 4%, taking into account an uncertainty of less than 2 mm in the distances and of 0.05 ms in the determination of the arrival time. The independent term of the fit is smaller than uncertainty in spatial measurement and can therefore be neglected.

The correlation between the intensity of the signal and the distance to the heater was also analyzed, as show in figure 7.b. The maximum amplitude of the first second sound peak was converted to temperature variation by means of the obtained sensitivity values. It is remarkable that the power-law fits for the results of the three sensors are in excellent accordance. The three sensors are measuring equivalent average intensity response at equal distance. The dispersion in intensity is quite high compared to that of arrival time. The reason for this could be that the reading of the real maximum of the signal is skipped due to discrete sampling. The intensity of a spherical wave of second sound is expected to decay as $\Delta T_{\text{max}} \propto r^{-1}$ [7]. However, from our data it was found that $\Delta T_{\text{max}} \propto r^{-\alpha}$ with $\alpha = 1.53 \pm 0.07$. This increased dependence of intensity with distance can be explained by geometric
factors. The TES are disposed on a plane parallel to the heaters plane; thus, there is a direct relation between distance and angle formed by the normal to the heater (or to the sensors) and the line of sight formed by heater and TES. When distance increases, the angle increases too. Recent studies [8] show that in 3D propagation of second sound produced by a finite planar heater, there is no spherical symmetry and the intensity of the wave is more pronounced in the normal direction. Furthermore, when the wave arrives on the wafer, it is reflected. The constructive interference between incident and reflected wave can be affected by the angle. These two factors reduce the intensity of the wave with increasing angle, and thus can make the dependence on distance steeper.

7. Conclusions
Transition Edge Sensors have been produced by means of photolithography and Joule heating evaporation of Au-Sn thin films. The TES were characterized, showing satisfying values of sensitivity. Furthermore, their confrontation to controlled second sound pulses in He II validated them as second sound detectors and showed that they can be used to assess very precisely (to 1 mm precision) the position of the source. These results are promising for the SRF cavity testing, where TES could be used as a thermal mapping system for quench localization.

The flexibility in the fabrication process with laser photolithography opens the door to endless possibilities regarding the geometry and spatial disposition of these sensors on a wafer. The size of a single wafer would allow to place sensors at distances of cm from one another, which could be enough for thermal mapping in some cases (small cavities). This could mean that a single wafer device (or only few of them) could be enough for the task of localizing a quench hot spot.

Besides the production of a good array of sensors, other issues deserve attention. Reproducibility of the properties of the thin film TES produced by the process described here is in question. It is necessary to lead a study of all the parameters that can influence the process and manage to control them. Furthermore, a more extensive understanding of second sound propagation is mandatory for the correct interpretation of the signals.

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