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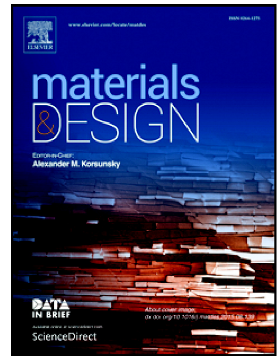

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Thin film analysis of transition edge sensors for use in next-generation superconducting radio frequency cavities

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Abstract

In order to increase the accelerating gradient, the next-generation of Superconducting Radio Frequency (SRF) cavities will be operated with superfluid helium cooling. This upgrade requires the development of a state-of-the-art cryogenic temperature mapping system, which can be used to identify quench initiation in new cavities, and thereby assess their suitability for installation. This paper presents a new mapping system based on an array of Transition Edge Sensors (TESs): electrical devices that exploit the superconducting transition of a thin film to identify temperature changes.

The TES array is manufactured using photolithography to deposit a thin film on a 100 mm diameter glass wafer. Two different designs of Au-Sn TES have been assessed; Design 1 was composed of a 10 nm Cr adhesive layer, followed by 20 nm of Au and 100 nm of Sn, and Design 2 was identical except that the Cr layer was not applied.

Design 1 showed excellent film adherence, however no superconducting transition was observed. In contrast, Design 2 showed poor film bonding but a superconducting transition. These insights are being used to design a new cryogenic temperature mapping device that combines Design 1 for robust electrical contacts and Design 2 for second sound detection.

Keywords

Transition edge sensor

Cryogenic temperature mapping

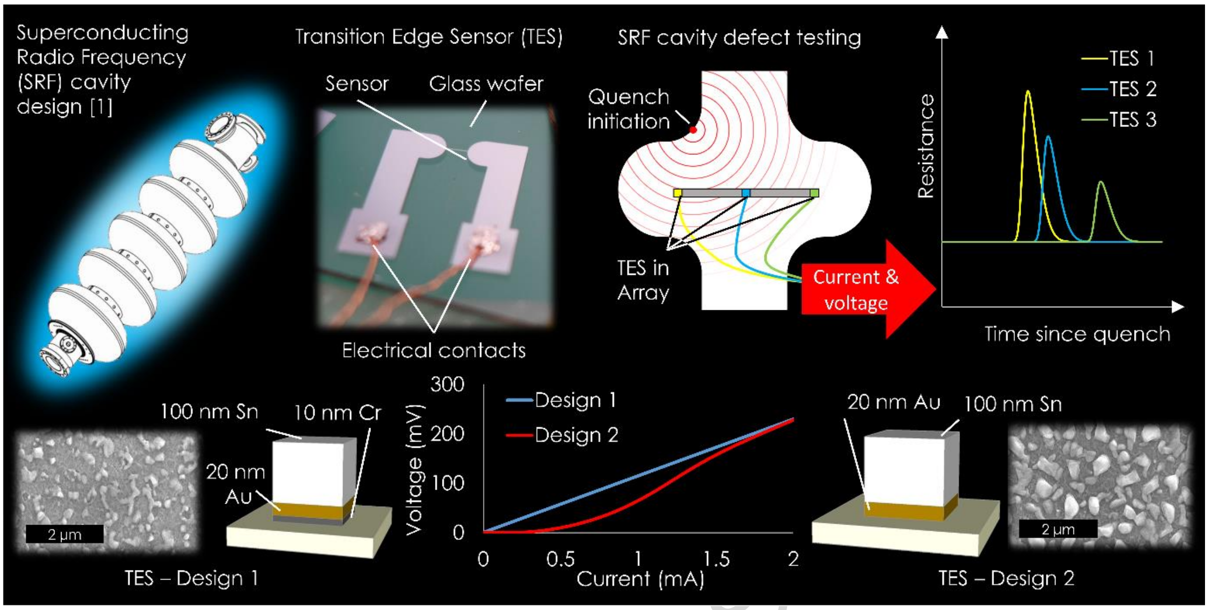
Thin films

Scanning electron microscopy

Superconducting radio frequency cavities

Large Hadron Collider

Figure/Graphical abstract



Article

Superconducting Radiofrequency (SRF) cavities are electromagnetic resonators which are used to generate carefully controlled oscillating electromagnetic fields in order to accelerate charged particles [1]. SRF cavities are operated under cryogenic conditions in order to maximise the operating current, amplitude of electromagnetic field generated and thereby the acceleration provided [2]. For example, the Large Hadron Collider (LHC) SRF cavities operate at ≈ 4.3 K [3]. To increase the achievable electromagnetic field intensity in the next-generation of SRF cavities the operating temperature will be reduced to below 2 K through the use of helium II (usually known as superfluid He).

In order to successfully operate the cavities, testing is required prior to installation to identify surface defects which can induce quenching of the superconductor. This analysis is based on the generation of He-II second sound during a quench [4]. Mapping of a fast-travelling temperature wave within the cooling medium can be used to determine the initiation spot and associated defect, through a method comparable to the Global Positioning System (GPS); this is based on the time delay between wave detection at different locations, and the known propagation speed of the temperature wave [4, 5].

Second sound mapping has previously been performed using oscillating superleak transducers [6]. However, in order to improve the signal quality and increase the spatial resolution, a new generation of miniature, rapid and ultra-high sensitivity temperature sensors are required. This article outlines a new design methodology based on Transition Edge Sensors (TESs) which is needed to meet the production requirements associated with the next-generation of SRF cavities.

TESs are electrical devices which measure a temperature change by exploiting the superconducting transition of a thin film [7]. The combination of precise temperature quantification (to within $< 10^{-3}$ K), rapid transition speed (to within a few µs) and small sensing area ($< 1\ \mathrm{mm}^2$) of TESs ensures that an array can be used to precisely identify SRF cavity wall defects.

The SRF cavity TES array requires a cluster of sensors with a precisely determined spacing to be placed inside the He-II vessel. These devices therefore need to be robust to large temperature changes, and any surface contact which may occur during installation. One approach to improve film adhesion is to apply a thin Cr layer on the substrate as the first deposition step [5, 8].

In this study, photolithography was used to manufacture two different Au-Sn TESs samples through a photolithography, metal evaporation and lift off process. This procedure facilitates deposition on a $100\ \mathrm{mm}$ diameter borosilicate glass wafer which forms the basis of the detector array. Both designs were composed of $20\ \mathrm{nm}$ of Au followed by $100\ \mathrm{nm}$ Sn, however in the case of Design 1, $10\ \mathrm{nm}$ of Cr was applied prior to the Au deposition.

Experimental analysis of both TES designs showed satisfying thermal shock resistance to being rapidly ($< 1\ \mathrm{s}$) immersed in liquid nitrogen. The resulting thermomechanical shock is considered to be equivalent to 95% of the thermal shock from room temperature to liquid helium temperature. In order to assess film durability, 3M Scotch® Duct Tape was applied to the surfaces of the TESs. In the case of Design 1, full adhesion of the film was maintained, whereas near-complete peel-off was observed in Design 2. This result demonstrates that the large binding energy of the Cr-O bond (when compared to Au-O) can be exploited to provide an effective intermediary between the wafer and the Au-Sn layers.

A Zeiss XB40 Scanning Electron Microscope (SEM) was used to perform microscopy of the TESs using an imaging voltage of $20\ \mathrm{kV}$, accelerating current of $230\ \mathrm{pA}$ and an energy selective backscattered detector. Microscale elementally distinct regions rich in Au were observed on the surface of the TESs. Post-processing of the micrographs was performed using the software 'ImageJ' [9], to reveal that although these features were on average smaller in Design 1 ($0.06\ \mu\mathrm{m}^2$ vs $0.15\ \mu\mathrm{m}^2$), there were a larger number per unit area ($3.44\ \mu\mathrm{m}^{-2}$ vs $2.21\ \mu\mathrm{m}^{-2}$).

In order to assess the superconducting response of the TES, the samples were cooled to $1.5 - 2.1\ \mathrm{K}$ using liquid helium and a varying current from 0 to $2\ \mathrm{mA}$ was applied to the sensor (in steps of $5\ \mu\mathrm{A}$) while the voltage was recorded. Design 1 showed a constant resistance at all currents, however a superconducting transition was observed in Design 2 at currents less than $1.5\ \mathrm{mA}$.

The results of this study demonstrate that while the addition of 10 nm of Cr coating increases the robustness of the TES, it suppresses the superconducting transition at the operating temperature. The addition of Cr changes both the composition and microstructure of the TES, nevertheless the antiferromagnetic nature of Cr and associated influence on the electron flow in the diamagnetic gold and paramagnetic tin is the most likely explanation for the suppression of superconducting response [10]. Despite this result, it should be noted that the superconducting transition in Design 1 may be present at temperatures below those achievable using the present test setup ($\approx 1.4\ \mathrm{K}$).

In conclusion, photolithography of Au-Sn TES can be used to manufacture precise sensor arrays for testing the next generation of SRF cavities or other similar cryogenic systems (such as superconducting solenoids or particle detectors). The addition of a $10\ \mathrm{nm}$ Cr bonding layer to Design 1 significantly increases the robustness of the thin film, however supresses the superconducting transition at the $1.5\ \mathrm{K}$ operating temperature. Based on this insight, a combination of Design 1 (for robust sensor leads) and Design 2 (for sensor strips), will be deposited in the final device using a modified photolithography procedure (in which Cr will only be applied to the sensor lead regions). In order to protect the sensor strips, plastic shielding will be applied close to these areas. Multiple (10's) of sensors will also be deposited on each wafer in order to build in redundancy in the case of sensor failure.

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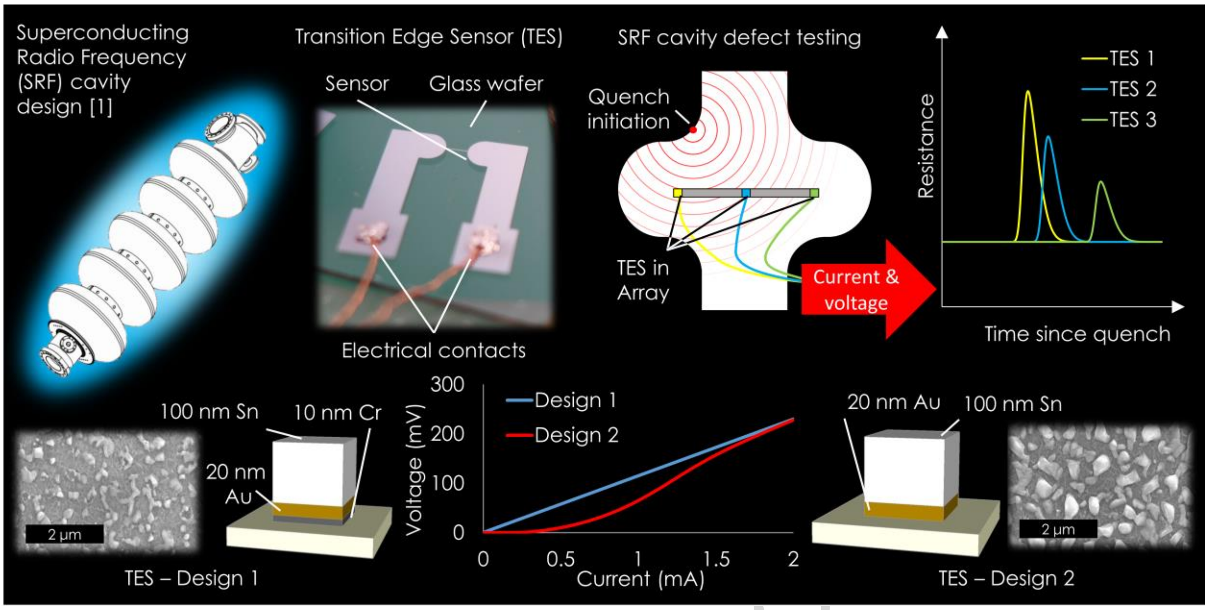

Superconducting Radio Frequency (SRF) cavity design [1]
Transition Edge Sensor (TES)
Sensor
Glass wafer
Electrical contacts
SRF cavity defect testing
Quench initiation
TES in Array
Current & voltage
Resistance
Time since quench
TES 1
TES 2
TES 3
100 nm Sn
10 nm Cr
20 nm Au
2 µm
TES – Design 1
Voltage (mV)
Current (mA)
Design 1
Design 2
300
200
100
0
0
0.5
1
1.5
2
20 nm Au
100 nm Sn
2 µm
TES – Design 2

Figure 1