Study of TES detector transition curve to optimize the pixel design for Frequency Division Multiplexing read-out

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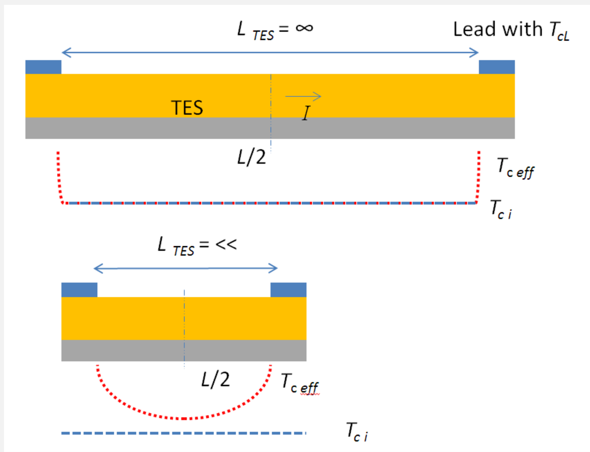
Outline

Superconducting transition-edge sensors (TESs) are highly sensitive detectors. Based on the outstanding performance on spectral resolution, the X-ray Integral Field Unit (X-IFU) instrument on-board Athena will be equipped with a large array of TES based microcalorimeters. SRON is developing a Frequency Domain Multiplexing (FDM) readout scheme for the X-IFU instrument. SRON will also develop and produce TiAu bilayer-based TES arrays for the X-IFU instrument as a backup option. For optimal performance in terms of the energy resolution it is essential to limit undesirable non-linearity effects in the TES detector. Weak link behavior is such a non-linearity effect and it has been observed when TES detectors are operated under ac bias in the MHz regime. Weak link behavior is induced by TES to lead contacts, and can cause kinks in the transition curve which drastically limit the access of optimal biasing points.
To determine the magnitude of the effect of the leads on the intrinsic transition curve of the TiAu bilayer, we designed smart test structures. With a basic experimental setup we measured and analyzed accurately the transition curves of the test structures. We found relations between long distance proximity effects as a function of TES length and different lead materials. The results can be explained if the TES is regarded as a weak link between superconducting leads.
Based on these results we can redesign and further optimize our TES based X-ray detectors.

Introduction

In the experimental work of Sadleir et al. [ref. 1 and 2] it was observed that when a TES is connected to superconducting leads with transition temperatures (T_{cL}) above the intrinsic transition temperature of the bilayers ($T_{c\,i}$), superconductivity is induced longitudinally into the bilayers. This Longitudinal Proximity Effect was observed over extraordinarily long distances, exceeding 100 µm, over 1000 times the mean free path. It was concluded that TESs behaves as a weak link induced by the superconducting lead contacts.
Here we recapitulate some experimental findings of the work:

- The effective transition temperature ($T_{c\,eff}$) of the TES scales approximately as $1/L^2$, were L is the lead separation.
- The width of the transition curve also scales as $1/L^2$.
- The proximity effect is increased near the leads and decays with distance away from the leads to a minimum at $L/2$.
- Leads with smaller difference between T_{cL} and T_{ci} tends to show less weak link behavior.



To determine the magnitude of the effect of the leads on the intrinsic transition curve of our TiAu bilayer, we have designed test structures with different TES lengths (L). We produced two sets of test structures, one set with Nb leads, one set with Ti leads.

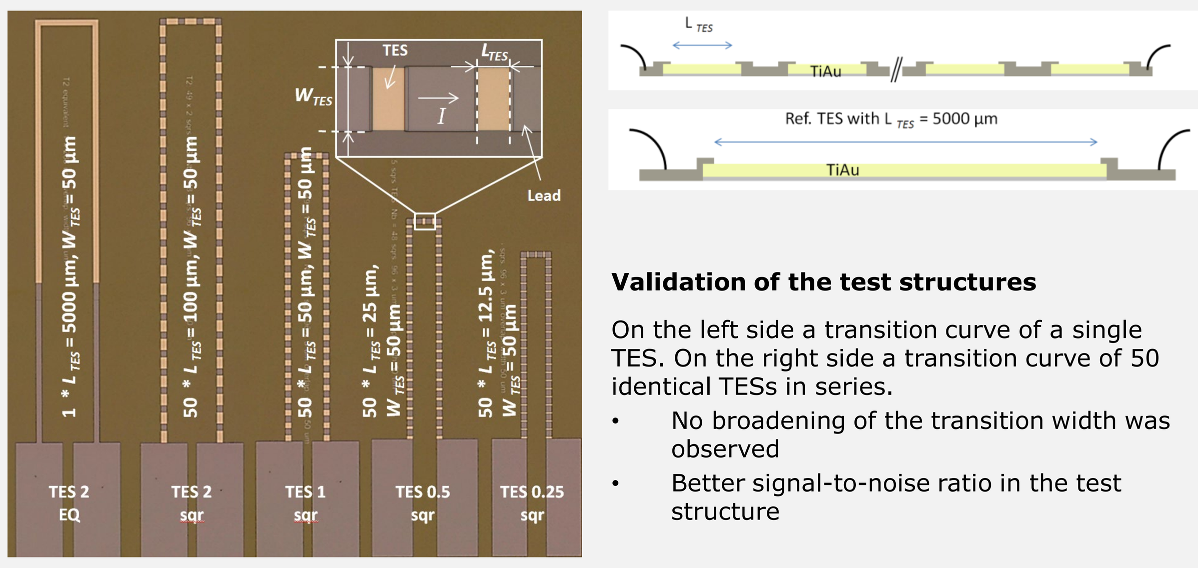
Design of the test structures and experimental setup

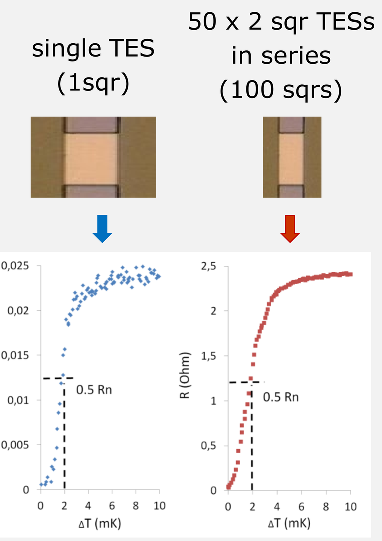
Materials

- The bilayer consists of 35/200 nm TiAu, with nominal T_{ci} of approximately 100 mK.
- For the leads we used Nb (T_{cL} ~ 9 K), and Ti (T_{cL} ~ 300 mK). The leads overlap the bilayer with 3 µm.

Measurements

- Transition curves were measured in an ADR cooler using a standard AVS-47 Resistance Bridge with a fixed current of 3 µA.
- The test structures consists of 50 identical TESs in series to increase measurement sensitivity. In this way we are able to measure low Ohmic TESs. See the photograph and the schematic cross sections for an overview of the test structures.
- To determine the intrinsic transition temperature T_{ci} and sheet resistance R_n of the TiAu bilayer, we designed extreme long TESs with L = 5000 µm, TES 2 Equivalent (EQ).



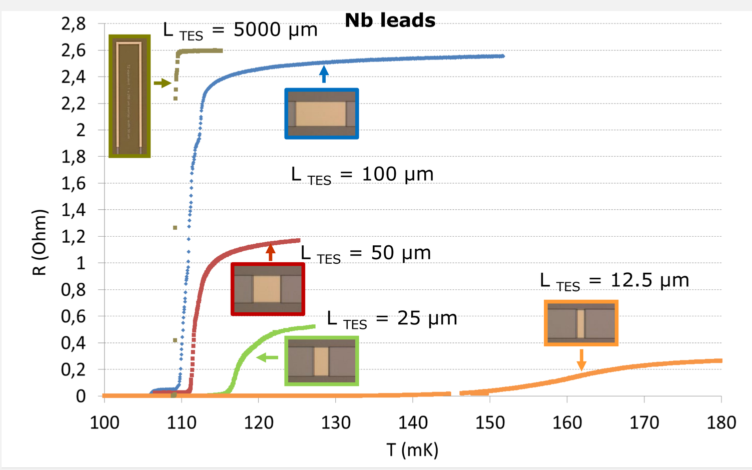


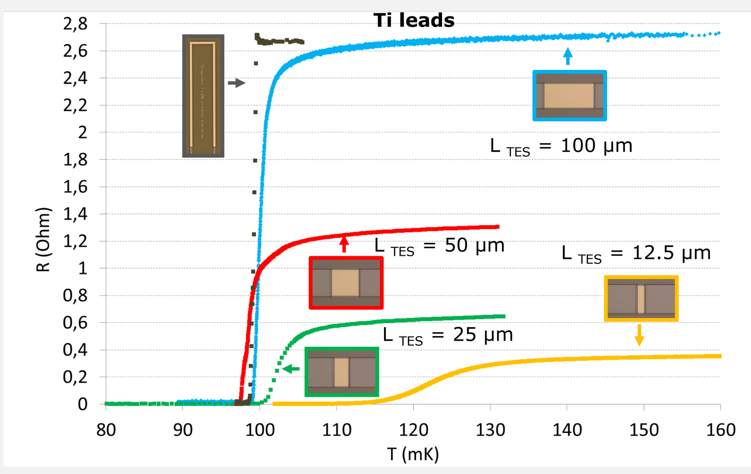
Validation of the test structures

On the left side a transition curve of a single TES. On the right side a transition curve of 50 identical TESs in series.

- No broadening of the transition width was observed
- Better signal-to-noise ratio in the test structure

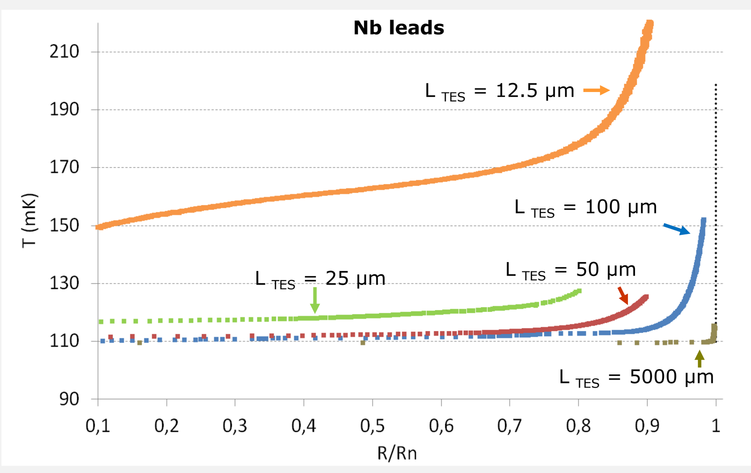
Measured R(T) curves

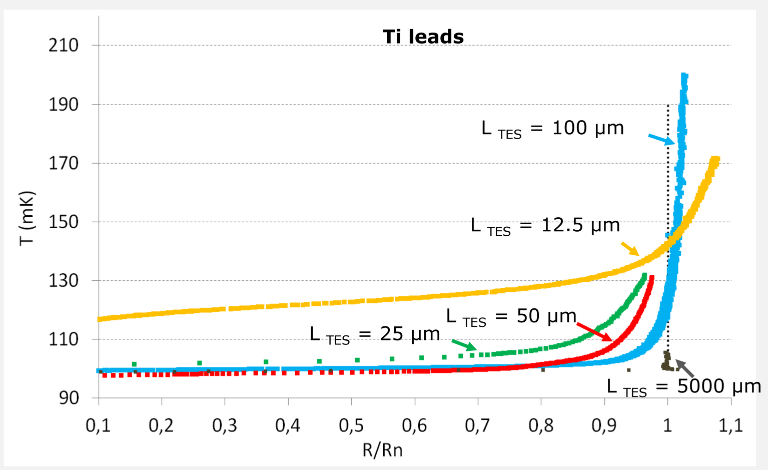




R (T) curves of test structures with 35/200 nm TiAu bilayer TESs. On the left side plot TESs were connected with Nb leads, on the right side Ti leads.

- The intrinsic transition temperature T_{ci} of the TiAu bilayer was found to be 110 mK (for the test structures with Nb leads) and ~100 mK (Ti leads). Note: The test structures were processed in separate batches.
- R_n = 26 mΩ/sqr, we could accurately determined this value by using the R(T) curves of the long TES's
- Reduction of the TES length L clearly leads to increase of the $T_{c\,ff}$. This effect is stronger for the TESs connected with Nb leads.

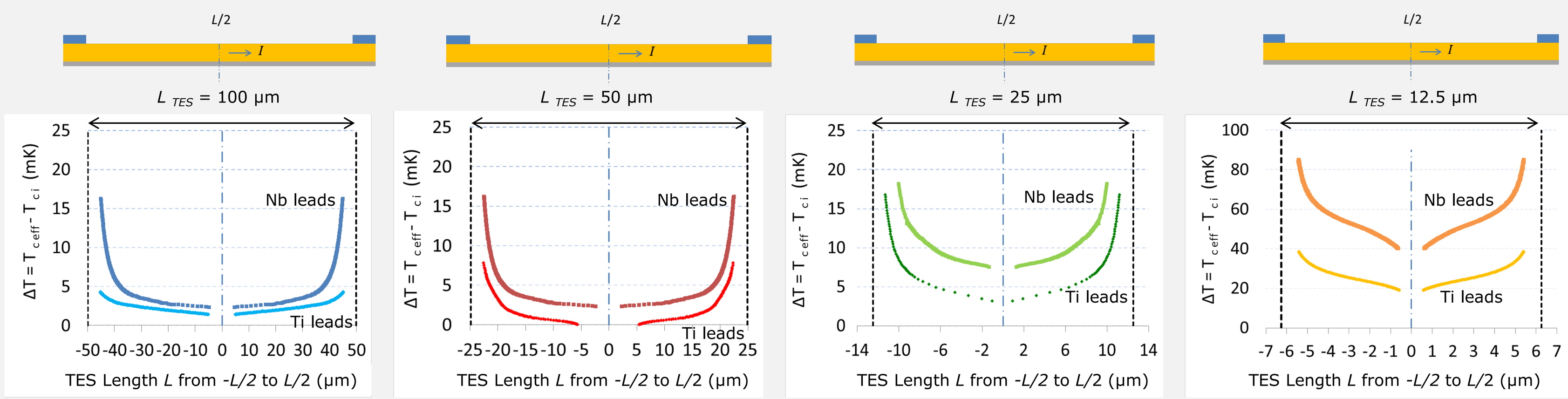




$T_{c\,i}$ and $T_{c\,eff}$ *plotted as a function of R/Rn. The long 5000 µm length TES defines the R/Rn = 1 limit (dashed line) based on the value of the measured sheet resistance Rn.*

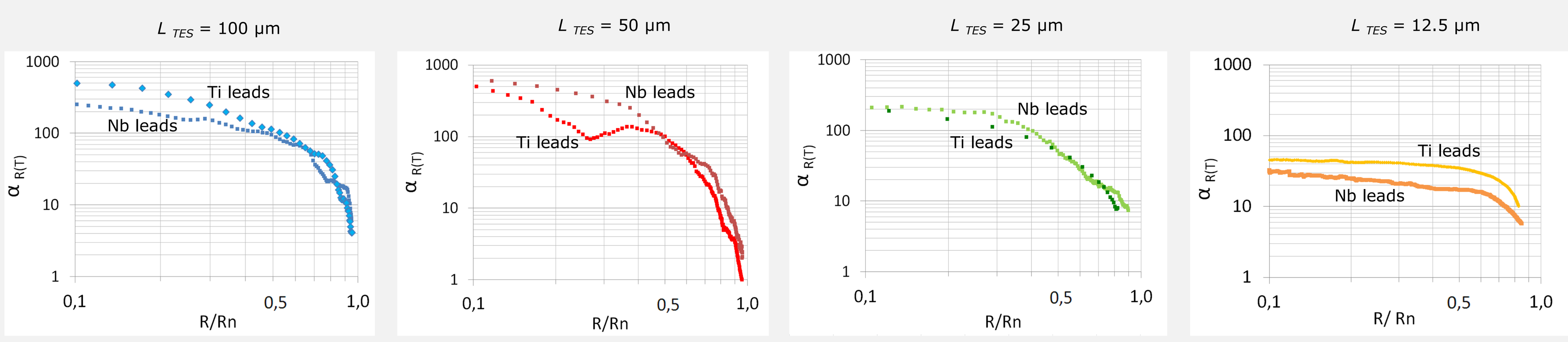
- $T_{c\,eff}$ is the highest for the TESs with the Nb lead-to-lead separation (TES length) of 12.5 µm. Note that for the samples with the Ti leads the R/Rn exceeds the value 1. This indicates that a small fraction of the bilayer below the 3 µm overlap of the remains in the normal state.

Comparison Nb and Ti leads



By assuming the proximity effect is increased near the leads and decays with distance away from the leads to a minimum at L/2, we converted the R/Rn value to distance units. The plots above show the difference between $T_{c\,eff}$ *and* T_{ci} *as a function of TES length displayed from −L/2 to L/2.*

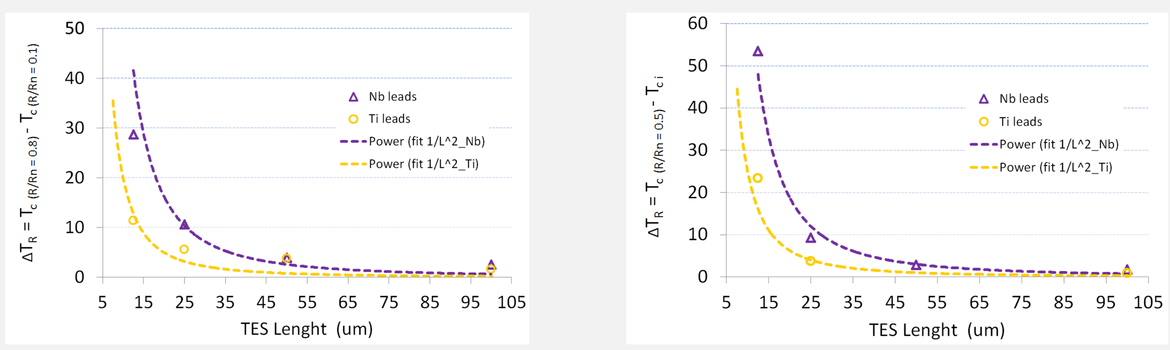
- $T_{c\,eff}$ is elevated above T_{ci} for all the TES lengths. Nb leads stronger proximitizes the TESs than the Ti leads.



Plots of α versus R/R$_n$ for all the TES lengths to compare Nb with Ti leads. Transition parameter α = (T/R)(dR/dT)

- The different lead materials do not result in large effects on the α, except for the TES with length of 12.5 µm

Weak link behavior



The width of the measured transition curves defined as $T_{c\,(R/Rn\,=\,0.8)}$ - $T_{c\,(R/Rn\,=\,0.1)}$ scales as $1/L^2$(plot left side). Also the $T_{c\,eff}$ at 0.5 R$_n$ showed the $1/L^2$ scaling (plot right side). The $1/L^2$ scaling clearly indicates weak link behavior.

Conclusions

- By using a basic measurement setup we were able to measure longitudinally proximity effects in our TiAu bilayers induced by the leads. This result can aid in the explanation of weak link behavior in a TES sensor.
- We found relations between the long distance proximity effect as a function of TES length.
- We found that Nb leads has a stronger proximity effect on the TES than Ti leads.
- Based on these results we can redesign and further optimize our TES based X-ray detectors

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Reference

Ref 1. J. E. Sadleir, S. J. Smith, S. R. Bandler, J. A. Chervenak, and J. R. Clem, *Phys. Rev. Lett.* **104**, 047003 (2010).

Ref 2. Sadleir J E, Smith S J, Robinson I K, Finkbeiner F M, Chervenak J A, Bandler S R, Eckart M E and Kilbourne C A 2011 Proximity effects and nonequilibrium superconductivity in transition-edge sensors, *Phys. Rev.* B **84** 184502 (2011).