Electrothermal modeling of Mo/Au Transition-Edge Sensors

M.Mas[1], C.Pobes[2], A.Camón[2], J.Bolea[3], P.Strichovanec[2], L.Fàbrega[1]

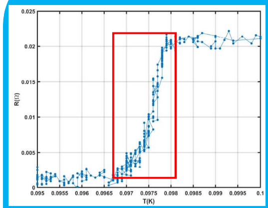
EXCELENCIA SEVERO OCHOA ICMAB [1]ICMAB-CSIC, Bellaterra (Spain) INMA [2]INMA, CSIC-Universidad de Zaragoza, Zaragoza (Spain) [3] Centro Universitario de la Defensa, Zaragoza (Spain)

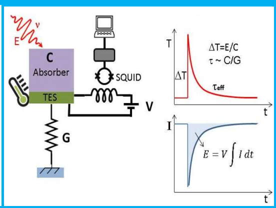
SUMMARY

Transition-Edge Sensors (TES) are radiation detectors working at cryogenic temperatures [1,2] (~ 100 mK) having capability for sensing very small amounts of energy coming from X-rays (~ few keV), for example, with superior sensitivity (~ 1 eV). TES can even detect single photons and measure their energy with high accuracy. TES are used in Astrophysics and Cosmology applications, as well as in Nanotechnology and Quantum Technologies. TES have already been implemented on telescopes and in a future (2032) the detector of the high spectral resolution instrument of the next telescope of X-rays from the European Spatial Agency (ESA), Athena, will be constituted by TES [3]. TES are microcalorimeters (electrothermal devices) made of a superconducting (SC) thin film (or bilayer). They take advantage of the steep resistive transition of the SC material between the normal and superconducting states (typically a few mK). This is what makes TES very sensitive to incoming radiation.

TES performances (their spectral energy resolution and response time) depend on TES parameters, which are extracted from fits to the measured complex impedance Z(ω); these fits require an electrothermal model of the TES, that is, knowing the number of relevant thermal blocks and their configuration. Therefore, in order to optimize TES performances and improve them, electrothermal modeling plays a key role. Usually, TES parameters are extracted by using the simplest electrothermal model, that is, considering the TES constituted by a single thermal block (1 TB). This is, though, an approximation even when no absorber is present. In this work we develop fits to Z(ω) of bare TES considering different configurations with 2 thermal blocks (2 TBs) and analyze when the second TB becomes relevant, and what is its impact on basic TES parameters. We report on the results obtained so far, including a critical analysis of fits reliability and the TES size effects on the TES thermal parameters, which in the end should help us to identify the present TBs.

TES PHYSICS and OPERATION

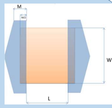




- TESs have an absorber to collect photons and convert the radiation energy into thermal energy (thermalization process) to be sensed by the superconducting part of TES (it heats).
- TES is in thermal contact with a bath, at a cryogenic temperature (T_{bath}) through a thermal link (a membrane for X-rays).
- TES resistance increases when a photon is absorbed, and since voltage is kept constant, that produces an inverse peak of current (this is what we measure).

Operation mode: negative electrothermal feedback [1]. TES is voltage-biased and thus self-heated above T_{bath}. Working at constant bias voltage enables the TES to return to its working point (after an excitation) and makes it stable thanks to the so-called Negative Electrothermal feedback: Joule power is inversely proportional to resistance ($P_J = V^2/R$) so, if T increases, so does R, and P_J is reduced. Thus, the TES cools down and returns to its equilibrium position.

Analyzed devices:



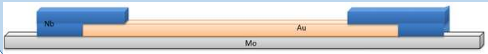
- Membrane (Si_3N_4) 0.5 µm, 250x250µm
- Mo/Au bilayers with Nb/Mo contacts
- R_n (normal resistance) = 24 mΩ;

Bilayer T_c (transition critical temperature): $T_{ci} \approx 92$ mK

5 devices with sizes (w (width) x L (length), µm²):
25x25, 25x50, 25x75, 25x100, 120x120

Dark characterization performed in Kelvinox dilution refrigerator. It included:

- I-V curves and Z(ω) measurements performed under DC bias at T_{bath} = 50 mK.



ELECTROTHERMAL MODELING, TES performances and TES parameters

TES performances: (1) Spectral energy resolution (δE) and (2) Response time (τ_{eff}) are determined by TES parameters*: (1) α and β: logarithmic derivatives of TES resistance to temperature and current and **(2) C and G (g's)**: heat capacity/ies and thermal conductance/s.

$$\delta E_{\mathrm{FWHM}} = 2\sqrt{2\ln 2}\sqrt{\frac{4k_{\mathrm{B}}T_0^2C}{\alpha}\sqrt{\frac{nF(T_0,T_{\mathrm{bath}})\xi(I_0)}{1-(T_{\mathrm{bath}}/T_0)^n}}}$$

*Obtained by fitting Z(ω): TES complex impedance data + data from I-V curves

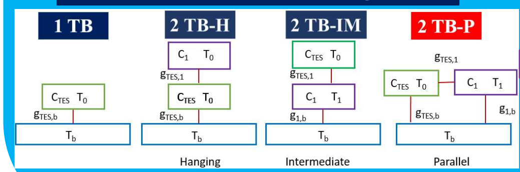
$$\tau_{\mathrm{eff}} = \frac{C}{G}\frac{1+\beta+R_L/R_0}{1+\beta+R_L/R_0+(1-R_L/R_0)\mathscr{L}_I} \quad \text{where } \mathscr{L}_I \equiv \frac{P_{J_0}\alpha}{GT_0}$$

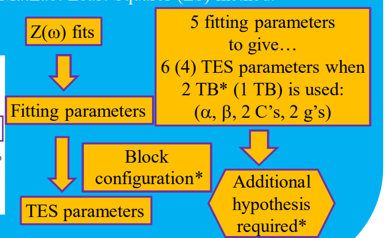
And $R_L = R_{SH} + R_{PAR}$**

***Shunt resistance (connected in parallel to TES to bias it at constant voltage) + parasitic resistance of the electrical circuit where TES is, respectively.*

Z(ω)'s fitting formulae and expressions from the electrothermal modeling provided by [4] according to a thermal block(s) model (1 TB, 2 TB). Z(ω) fits performed with MatLab: Least Squares (LS) method.

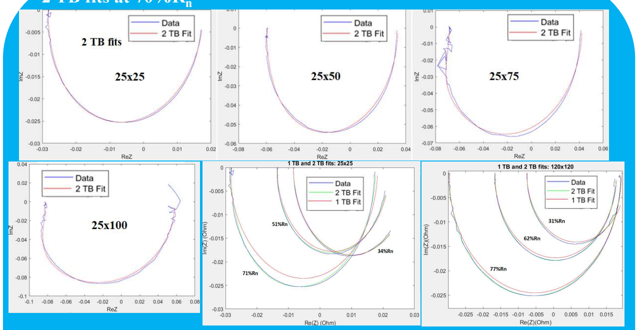
Thermal block models and configurations





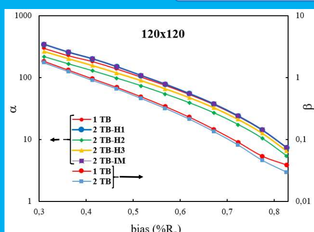
FITS OF Z(ω): 1 TB and 2 TB

2 TB fits at 70%R_n



- Even for these bare TES Z(ω) clearly deviates from the expected semicircular shape of 1 TB. 2 TB fits better describe the data.
- 2 TB features more evident at high bias (%R_n) and high Aspect Ratio (AR).

RESULTS: α, β, C's and g's

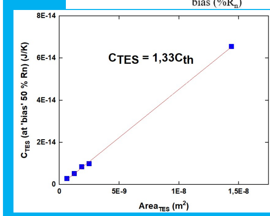


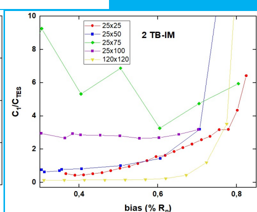
(1) β is independent of the 2 TB specific configuration. Its values using 1 TB and 2 TB differ slightly (few %).

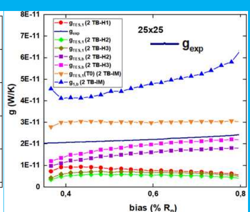
(2) α depends on the 2 TB configuration, although it coincides for 2 TB-IM and 2 TB-H1 (algebraic result)

(H1: hypothesis $g_{TES,b} = g_{exp}$ (from IV's data))

α values change in some cases significantly. Bias dependence not strongly affected.



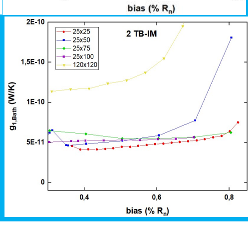




(1) C_{TES} (from one block):

- changes significantly (increases) when we use 2TB instead of 1TB.
- scales (increases proportionally) with TES size (area), with a scaling factor ~ 1,33C_{th} (C_{th} *is the calculated normal state heat capacity for the Mo/Au bilayer)*

(2) The extra heat capacity C_1 in general can never be neglected ($C_1/C_{TES} \gtrsim 1$).



(1) All g's in all configurations display the same order of magnitude, thus emphasizing the need of considering 2TBs.

(2) The g's do not scale with TES perimeter; rather, there could be a g independent of TES size.

CONCLUSIONS

- The fitting procedures for Z(ω) using two thermal blocks have been developed.
- The impact of:
  - (1) several fitting algorithms
  - (2) initial values of fitting parameters

  on the fits quality and fitting parameters reliability have been evaluated.
- The relevance of the 2nd TB has been analyzed as a function of bias and TES size. It turns out that it is increasingly important as bias and TES aspect ratio increase.
- Two block configurations (hanging and intermediate) have been analyzed. The effects on TES parameters of these configurations and of their required hypotheses have been studied.
- The impact of the 2nd block on the logarithmic sensitivities α and β has been analyzed.
- TES thermal parameters (C's and g's) have been analyzed for the different configurations as a function of TES size; some preliminary conclusions have been drawn but more work is required to ascertain the suitable block configuration and identify the blocks.

REFERENCES

[1] K.D.Irwin and C.C. Hilton , "Transition-Edge Sensors in cryogenic particle detection". Topics in Applied Physics ed C Enss vol 99 (Berlin: Springer) (2005)

[2] J.N. Ullom, D.A. Bennett, "Review of superconducting transition-edge sensors for x-ray and gamma-ray spectroscopy", Supercond. Sci. Technol. 28, 084003 (2015)

[3] L. Fàbrega et al., "Towards Mo/Au based TES detectors for Athena/X-IFU", SPIE Proceed.Series 9144, 91445P (2014)

[4] I.J. Maasilta, "Complex impedance, responsivity and noise of transition-edge sensors: Analytical solutions for two- and three-block thermal models", AIP Adv. 2, 042110 (2012)

ACKNOWLEDGEMENTS

Financial support from the Spanish Ministerio de Ciencia e Innovación MICINN, through project RTI2018-096686-B-C22 and FPI contract (MM), is acknowledged. LF and MM acknowledge also MICINN for support through the Severo Ochoa Programme for Centres of Excellence (project FUNFUTURE, CEX2019-000917-S).