The superconducting transition in TES: possible role of vortex pair unbinding

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Abstract

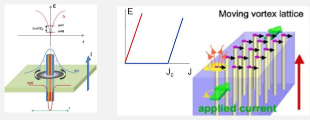
The R(T,I,H) shape of the superconducting transition of Transition Edge Sensors (TESs) is crucial for their operation and performances. Its sharpness as a function of temperature and current influences the devices noise. Also, the behaviour of the resistance as a function of these three parameters can provide understanding of the physical phenomena governing the transition, which in turn can be essential to define optimization routes.

Estimates of fundamental lengths of TESs suggest that they behave as dirty type II superconductors, likely two-dimensional (2D). The onset of dissipation in 2D superconductors at H=0 is most often related to the so-called Berezinskii-Kosterlitz-Thouless transition, that is, the thermal unbinding of vortex-antivortex pairs: this may cause the motion of free vortices through the film under any applied electrical current, which would result in a voltage drop, and thus the appearance of a finite resistance at a temperature below the superconducting mean field critical temperature (that is, without Cooper pair breaking). This flux motion is considered a possible source of excess noise in TESs.

We have performed a study of the resistive transition of Mo/Au-based TESs with diverse sizes and critical temperatures, under different applied electrical currents and magnetic fields. We have found a distinct analytic expression for R(T,I) at zero magnetic field, which holds for all the devices analysed at low biases, from the appearance of resistance up to quite high R/R_n values in some cases. We argue that this expression might be indicative of a current assisted vortex pair unbinding mechanism, and discuss the possible impact of such an effect on TES parameters and performances.

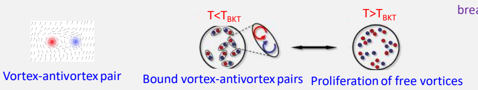
Background

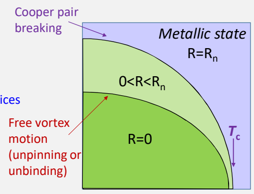
- The appearance of finite resistance in a superconductor can be due basically to two mechanisms:
  - Cooper pair breaking ($T \approx T_c$): current is carried by Cooper pairs plus free charge carriers (two fluid model). Resistance is due to the latter.
  - Existence of magnetic vortices ($T<T_c$): their motion when applying a current generates a voltage and thus a resistance, <u>without Cooper pair breaking</u>.



In fact, *usually the critical current defined as the onset of dissipation is much lower than the depairing current*: $J_c(T) << J_d(T)$. This denotes the relevance of vortex motion: $J_c(T)$ is the current producing a Lorentz force able to move vortices

- Vortices in a type II superconductor can be basically due to:
  - The existence of a nonzero magnetic field (applied, remanent, self-field)
  - The Berezinskii-Kosterlitz-Thouless transition (in 2D superconductors): vortex-antivortex pairs are present in the superconductor at any T; above $T_{BKT}<T_c$, thermal energy breaks the pairs.

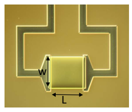




Strictly speaking, a 2D superconductor never displays R=0, since any applied current can tear apart the vortex pairs. However, this effect is vanishingly small for $T<T_{BKT}$ and $J \to 0$

Experimental

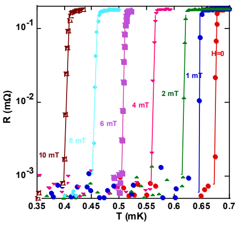
The R(T,I,H) transition was measured in a PPMS system with a ^{3}He insert for several TES with different designs and T_c's.
Temperature scans carried out in ZFC conditions with constant H and I.



- Bare TES (no abs)
- No banks
- No metallic features

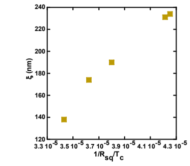
TESs analysed in this work

T_c (mK)	Pads and wiring	d_{Mo}/d_{Au} (nm)	Design	Size (wxL) (μm^2)	R_n (mΩ)	Maximum R/R_n for fits to eq. (4)
642	Nb	100/115	0Z, Membrane	200x200	70	30%
612	Nb	100/110	1Z, Bulk	200x200	70	35%
584	Mo/Nb	100/110	1Z, Bulk	120x120	57	79%
473	Mo/Nb	100/220	1Z, Bulk	120x120	26	70%
467	Mo/Nb	100/220	1Z, Bulk	50x50	26	70%
552	Mo/Nb	70/115	2Z, Bulk	25x25	64	50%
547	Mo/Nb	70/115	2Z, Bulk	25x50	120	60%
552	Mo/Nb	70/115	2Z, Bulk	25x100	253	30%

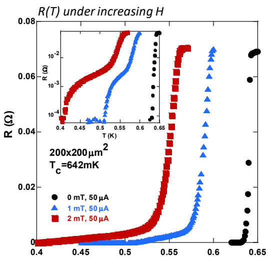


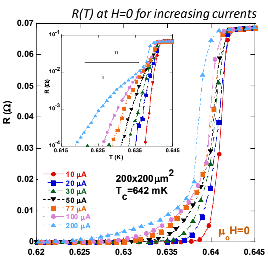
Are TES 2D superconductors?

- Preliminary evaluation of the coherence length using the slopes of the upper critical field indicate that:
  - ξ~230 nm for T_c~550 mK
  - ξ increases with decreasing R_{sq} and T_c, as expected
- Therefore:
  - **The bilayers and TES analysed in this work are 2D**
  - For lower T_c's, ξ is expected to increase (ξ~µm for T_c~100mK). Thus they are most likely 2D too.



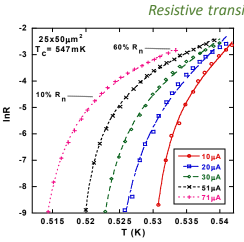
Broadening of the R(T,I,H) transition

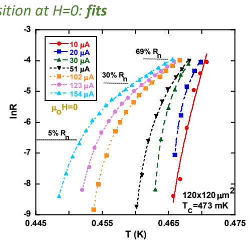




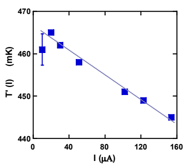
- The R(T) broaden significantly for increasing currents. Their behaviour is <u>much different</u> from that observed under an applied H.
- Different regimes as bias increases

Resistive transition at H=0: fits



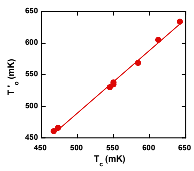


$$ln\left[\frac{R(T)}{R_n}\right] \sim -b'\left[\frac{T_c-T}{T-T'(I)}\right]^{1/2}$$



$$T'(I) = T'_o\,(1 - I/I_o)$$

$$T'_o \approx 0.98\,T_c$$



- Fits of the lower part of the R(T) at H=0 follow the law expected for the BKT transition, but with a current-dependent characteristic temperature.
- This law does not describe the R(T) with an applied H
- No other R(T,J) dependences fit the data
- **All** the studied devices display the same behaviour: the extracted characteristic temperatures at I=0 scale with T_c
  - T_o' could be identified with T_{BKT}
  - T'(I) can be interpreted as an effective reduction of T_{BKT} for high enough currents, which favour vortex unbinding

Implications for TES analyses and performances

- The transition width may increase significantly in biased TESs: problems with the definition of T_c and with the extraction of thermal parameters.
- On basis of the R(T,I) law, analytical expressions can be obtained for α and β.
- An expression for the excess noise associated to vortex motion can be obtained from ref.[2]

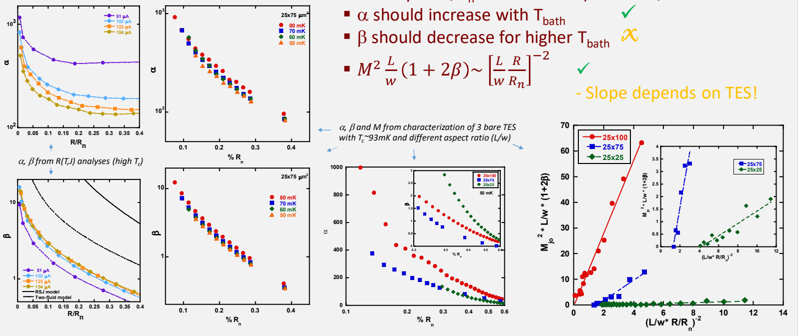
$$\alpha = -\frac{T}{2}\,\frac{T_{co}-T'(I)}{T_{co}-T}\,Ln(R/R_n)$$

$$\beta = -\frac{I}{2\,I_o}\,\frac{T'_o}{T-T'(I)}\,Ln(R/R_n)$$

$$M^2 = const.\frac{1}{T^2}\,\frac{1}{A\,(1+2\beta)\,R_0^2}$$

- ✓ Functional dependences of α and β vs bias compatible with model
- ✓ Order of magnitude of M as predicted by model

- *For identical T_c's:*
  - α and β vs R/R_n should not depend on L/w ✗
  - α should increase with T_{bath} ✓
  - β should decrease for higher T_{bath} ✗
  - $M^2\,\frac{L}{w}\,(1+2\beta) \sim \left[\frac{L}{w}\,\frac{R}{R_n}\right]^{-2}$ ✓
  - - Slope depends on TES!



Conclusions

- Huge broadening of the lower part of the R(T) transition (up to quite high biases, and full in the operational range of TESs) at H=0 for increasing currents.
- Plausible interpretation in terms of current enhanced vortex pair unbinding, which allows motion of free vortices.
- Predictions for α, β and M are made on basis of this mechanism. Preliminary analyses of TES data show that they might be compatible with this scenario but are not conclusive yet.

References

1. Fabrega L Camón A Pobes C Strichovanec P González-Arrabal R 2019 Supercond. Sci. Technol. 32 015006
2. Fraser GW 2004 Nucl. Instr. Meth. A 523 234
3. Berezinskii V L 1972 Zh. Eksp. Teor. Fiz. 61 1144 [1972 Sov. Phys. JETP 34 610]
4. Kosterlitz J M and Thouless D 1973 J.Phys. C6 1181; Kosterlitz J M 1974 J.Phys. C7, 1046
5. Beasley M R Mooij J E and Orlando T P 1979, Phys. Rev. Lett. 42 1165
6. Halperin B I and Nelson D R 1979 J. Low Temp. Phys. 36 599
7. Ezaki S Maehata K Iyomoto N Asano T and Shinozaki B 2018 J. Appl. Phys. 123 084504

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