Quasiparticle Diffusion and Energy Resolution in Superconducting Tunneling Junctions

Roland den Hartog¹, A. Kozorezov², J.K. Wigmore², P. Verhoeve¹, D. Martin¹, A. Peacock¹,

^aSpace Science Dept. of the European Space Agency, ESTEC, PO Box 299, 2200 AG, Noordwijk, Netherlands
^bDepartment of Physics, Lancaster University, Lancaster LA1 4 YB, U.K.

ESLAB 2001/061

To be published in the Proceedings of the 9th International Workshop on "Low Temperature Detectors"
23-27 July, Madison, WI, USA

CERN LIBRARIES, GENEVA

2298241

Quasiparticle Diffusion and Energy Resolution in Superconducting Tunneling Junctions

Roland den Hartog¹, A.G. Kozorezov², J.K. Wigmore², P. Verhoeve¹,
D. Martin¹, A. Peacock¹

¹) Space Science Department, ESA - ESTEC, P.O. Box 299, 2200 AG Noordwijk, The Netherlands

²) Department of Physics, Lancaster University, Lancaster LA1 4YB, U.K.

Abstract. One of the factors that limits the energy resolution of superconducting tunnel junctions (STJs) as photon detectors is the spatial dependence of the response on the photo-absorption site. To assess the role of spatial inhomogeneities we have analyzed quasiparticle (qp) diffusion processes in detail and developed a general analytical theory to describe the evolution of the qp density in an STJ. This theory accounts for (mild) non-linearity due to qp self-recombination, and includes the effects due to multiple qp tunneling, phonon coupling between the electrodes, diffusive losses into electrical connections and localized traps and losses at the edges. The theory does not require any assumptions about symmetry between base and counter electrode. We have derived an analytical model of the STJ response surface and the corresponding spectral lineshape, which allows the influence of the above features to be treated independently. We discuss two examples of the application of this model in practice and demonstrate how this model can be used to obtain a thorough understanding of the factors that limit the energy resolution in STJs as photon detectors.

A major source of excess broadening, at least in single STJs, is the spatial inhomogeneity of responsivity. This arises from quasiparticle (qp) diffusion to localized loss sites, such as electric leads, bridge connections, or local trapping sites but is also due to the dependence of the qp self-recombination rate on the absorption site position relative to the STJ edges and corners. Analysis of spatial inhomogeneity in the STJ response has previously received considerable interest both experimentally and theoretically. Using low-temperature scanning electron microscopy (LTSEM) [1, 2], or the recently developed technique of low-temperature scanning synchrotron microscopy (LTSSM) [3], it is possible to image the response surface of the STJ, i.e. its response as a function of position, and hence to assess the qp diffusion properties. The SRON group was among the first to attempt to model STJ's in this way. However, in the specific case they studied, qp backtunneling was suppressed, and uniform trapping of qps at the edge was the only loss mechanism [4]. Subsequently this model was expanded to include coupling between the electrodes via multiple qp tunneling [5]. However, there exists considerable experimental evidence that the actual loss sites that dominate the spatial response of the STJ are localized [6,7]. In particular the lead connections seem to have a large impact on the inhomogeneity of the response, see e.g. Fig. 1a. Furthermore, the electrodes are coupled through phonon transport across the barrier.

a. **b.**
FIGURE 1. (a) Illustration of an experimental response surface. This 5 keV LTSEM scan of the top electrode of one of our $50 \mu\text{m}^2$ STJs was obtained at Tübingen University. (b) The decomposition of a theoretical response surface into separate contributions.

FIGURE 2. Applications of the theory in practice. The white line on the LTSEM scan in Fig. 1a corresponds to the data in panel (b). The decomposition shown in Fig. 1b corresponds to the top film signal (left triangular peak) in panel (c) on the left. The fits in panels (a-f) were computed simultaneously using the same model parameters. (d-f) Fits to spectra taken simultaneously with larger STJs. (g-j) Computed response surfaces for the case of one to four identical, strong loss channels. (k-n) Corresponding spectral lineshapes. These panels demonstrate the link between surface topology and energy resolution: the higher the symmetry of the response surface, the better the energy resolution.

Here we present a comprehensive analytical model of the response surface, that takes into account these contributions [8], and which is able to describe convincingly many of the observed device characteristics [9]. The principle of this model is illustrated in Fig. 1b: the response surface (sum) is derived as a superposition of various contributions due to qp self-recombination (1st and 2nd iteration, see below), uniform losses at the edges and losses to localized sites, such as leads, bridges or traps (outflow), which are added to the ideal, flat response surface. These surfaces are solutions to Rothwarf-Taylor type balance equations [10, 11], with additional terms accounting for qp diffusion and the various loss mechanisms. They are obtained by an expansion of the solution in eigenfunctions of the Helmholtz equation, with boundary conditions appropriate for the geometry of the problem. Due to qp self-recombination these equations are inherently non-linear and defy a general analytical solution. However, under the assumption of weak non-linearity it is possible to expand the contributions of self-recombination into an infinite and alternating series of such surfaces, and to keep them separated from the other contributions. Our definition of weak non-linearity is therefore a practical one: $|S_{i+1}| \ll |S_i| \ll 1$, where $S_i(E, \mathbf{x})$ is the surface corresponding to the i th iteration in the series (with E the energy and $\mathbf{x}$ the absorption position of the incoming photon). This definition ensures a quick convergence of the series.

Figures 2a-f illustrate the application of our model in a practical situation, with mixed types of data: spectra for Nb/Al STJs with different sizes, LTSEM scans, and, not shown here, pulse decay time information. The computation of a full solution like this is very efficient, as long as second and higher iteration steps are omitted. This opens up the possibility of fitting model parameters to the data, as is shown in Fig. 2. Inclusion of the second iteration step takes considerably longer, and the time for subsequent steps of order i progresses as N^{2i} , with N the number of spatial harmonics taken into account (in this case 50). In the spectra of Fig. 2, the qp self-recombination is mainly of influence on the relative location of the base film K_α and K_β (two peaks on the right of each spectrum), which is in full agreement except for the smallest STJ. In this particular example, shown in Fig. 1b, we see that $|S_2| \sim |S_1| < 1$. This means that in our smallest STJ the convergence condition breaks down. However, as the series is alternating, subsequent terms tend to partially cancel, and the total sum turns out to be close to zero. So, by ignoring all S_i we obtained the fit in Fig. 2c. For the remaining fits, Figs. 2d-f, the first and second iteration step were included. Interestingly, these fits provide fairly strong constraints on the diffusion constants in top and base film, for which the best fitting values were found to be $D_{\text{base}} = 50 \text{ cm}^2 \text{ s}^{-1}$ and $D_{\text{top}} = 1 \text{ cm}^2 \text{ s}^{-1}$.

The application of our theory goes beyond providing fits to model parameters, as is illustrated in Figs. 2g-n and 3. In the right-hand panels of Fig. 2 we demonstrate an important principle governing the link between the topology of the response surface and the resulting energy resolution (defined as usual, as the full width at half maximum of the histogram of the surface): the higher the degree of symmetry of the distortion of the response surface, the better the energy resolution. In order to significantly improve the energy resolution all localized contributions that break the symmetry of the response surface (such as localized traps, leads, bridges) must be eliminated together. For the energy resolution it is better to have four loss channels on an electrode, than two or three, because with four channels, the response surface is

FIGURE 3. Illustration of how an edge with many localized traps of random strength on it (a), converges to the situation discussed in Refs. 6 and 7 (c). (b,d) Corresponding spectra.

more symmetrically disturbed than in the case of one, two or three channels. So, removing one source of qp losses, e.g. a trap at an edge, caused by a flaw in the fabrication process, will not necessarily improve the energy resolution, and could actually have an adverse effect, depending on the topology of the response surface. This might explain why improving the energy resolution of STJ's to the statistical limit has proven to be such a persistent problem over the past decades.

Finally, in Fig. 3 we illustrate the link between previous work and ours. Previously, qp losses were assumed to result from a uniform non-ideal reflectivity of the edges. This can be considered as an ideal limit of a more realistic situation, in which the edge is populated by many, small traps. In Fig. 3a and b the response surface and corresponding spectrum is shown for the situation in which 50 small traps with randomly distributed positions and strengths are located on the edges. There is a clear similarity with the surface for the case of a uniform, non-ideal edge, as shown in Figs. 3c. The spectral line, however, is more topped off in Fig. 3d than the one shown in Fig. 3b, reflecting the difference in curvature in the center of the surfaces.

In conclusion, we have demonstrated that the concept of a superposition of separate contributions to the topology of the response surface is valuable for the characterization and understanding of detectors in which diffusion of the charge carriers plays a dominant role. In particular, in combination with analysis techniques such as LTSEM or the newly developed LTSSM, which directly probe the STJ response surface, our model provides a powerful tool in the analysis and solution of problems associated with the energy resolution in STJ's. But we are confident that the techniques developed in this work are useful in a much wider range of applications.

REFERENCES

1. R. Gross and D. Koelle, *Rep. Prog. Phys.* **57**, 651 (1994)
2. S.P. Lemke, *Ph.D. thesis*, Tübingen University (1995)
3. H. Pressler, M. Ohkubo, M. Koike, T. Zama, T. Nakamura et al., *Appl. Phys. Lett.* **77**, 4055 (2000)
4. M.L. van den Berg, M.P. Bruijn, J. Gomez et al., *IEEE Trans. Appl. Supercond.* **7**, 3363 (1997)
5. L. Parlato, G. Ammendola, R. Christiano, E. Esposito et al., *Nucl. Instr. Meth.* **A440**, 15 (2000)
6. J. Martin, S. Lemke, R. Gross, R.P. Huebener et al., *Nucl. Instrum. Meth.* **A370**, 88 (1996)
7. R.H. den Hartog, D. Martin, A. Kozorezov, P. Verhoeve et al., *Proc. SPIE* **4012**, 237 (2001)
8. A. Kozorezov, K. Wigmore, R. den Hartog, D. Martin, P. Verhoeve et al., *Phys. Rev. B* (submitted)
9. R. den Hartog, A. Kozorezov, K. Wigmore, D. Martin, P. Verhoeve et al., *Phys. Rev. B* (submitted)
10. A. Rothwarf and B.N. Taylor, *Phys. Rev. Lett.* **19**, 27 (1967)
11. P. Verhoeve, N. Rando, J. Verveer, A. Peacock et al., *Phys. Rev. B* **53**, 809 (1996)