The physics of nanowire superconducting single-photon detectors

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Chapter 8

Conclusion and Future Work

8.1 Summary

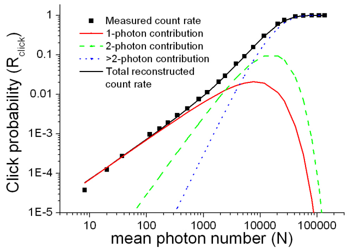
The main result of this thesis is strong experimental evidence for a diffusion-based vortex crossing detection mechanism in superconducting single-photon detectors. The physical picture which arises from our experiments is as follows: when a photon is absorbed, a cloud of quasiparticles is created. That cloud spreads, forming an obstacle which diverts some of the bias current towards the edges of the wire. This removes the energy barrier that otherwise prevents vortices from entering the film, causing a vortex to enter. This vortex then causes a transition to the normal state by the friction experienced as it is pulled across the wire by the Lorentz force.

We have provided the following experimental evidence for this picture (see Figure 8.1):

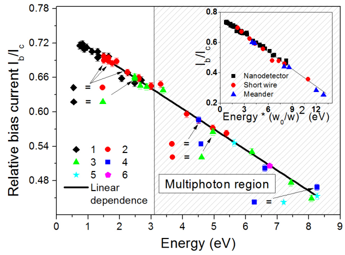
- We have demonstrated that the number of photons that excite the detector does not influence the detection response directly. Rather, only the overall energy of the excitation, combined with the applied bias current, sets the detection probability. This is evidence that it is the total amount of quasiparticles at the band-edge in some relevant volume that sets the detection probability.

- We find that the energy-current relation is linear in applied bias current and photon energy (see Figure 8.1b). This is strong evidence for the role of diffusion: in a model where there is no point in the wire that is in the normal state, the effect of the impinging photon on the superconductivity is only through the reduction of the Cooper pair density.

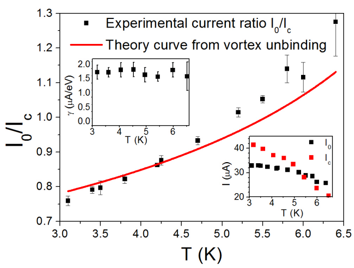
- We find that the temperature dependence of the device follows the temperature dependence of the energy scale for vortex entry into the



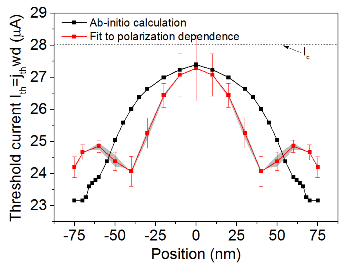
(a) From Chapter 2: Quantum detector tomography on an SSPD - the workhorse experiment of this thesis



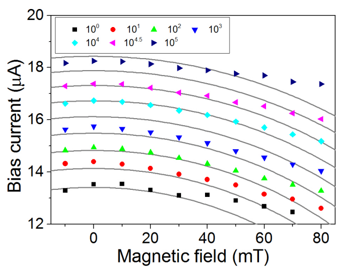
(b) From Chapter 4: The linear energy-current relation in SSPDs.



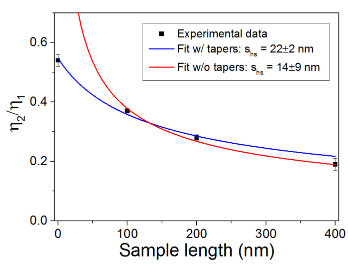
(c) From Chapter 4: Temperature dependence of the internal detection mechanism of an SSPD, which follows that of the energy scale for vortex entry (red line).



(d) From Chapter 5: The experimentally derived position-dependent internal detection efficiency, as well as a theory curve computed for the diffusion-based vortex model.



(e) From Chapter 6: The quadratic dependence of bias current on applied magnetic field, for constant detection probability.



(f) From Chapter 7: Measurement of the size of a hotspot in an SSPD.

Figure 8.1: The main results of this thesis. Full descriptions of each figure can be found in the respective chapters.

film (see Figure 8.1c). This is evidence for the role of vortices in the detection mechanism.

- We find that the detector is polarization-sensitive in its internal detection probability, which is evidence of a position-dependent internal detection efficiency (IDE) (See Figure 8.1d). We have reconstructed this position-dependent IDE with a resolution of approximately 10 nm. We find that the edges of the wire have a lower threshold current for photodetection than the center of the wire, leading to a regime where the wire is more efficiently photodetecting at the edges than in the center. The explanation for this is that the vortex barrier is lowered by the presence of quasiparticles, so if the quasiparticle cloud is in contact with the edge of the wire, the current required for vortex entry is reduced. This is further evidence for the role of vortices in the detection mechanism.

- We have measured the size of the excitation in the detector, which we found to be 22 nm (see Figure 8.1f). Our preliminary result is that this value is independent of wavelength, which fits with our physical picture. Moreover, this length scale is in reasonable agreement with the distance at which we observe strongly reduced threshold currents in our position-dependent IDE.

Moreover, we have studied the magnetic field dependence of the detection mechanism (see Figure 8.1e). While our explanation for that field dependence is conceptually separate from the model described above, it is entirely compatible with it. The reason for this is that our description, which is based on the Usadel equation, is concerned with the initial properties of the film, whereas the model described above is concerned with the dynamics of the detection event itself. We do observe that the permanent presence of a vortex in the material is strongly detrimental to the detection mechanism.

8.2 Detection Models

We discuss the implications of our results for the four models: the normal-core hotspot model, the diffusion-based hotspot model, the normal-state vortex model and the diffusion-based vortex model (see Section 1.2).

Allthough the normal-core model appears not to be applicable to NbN, recent simulations show [32] that in WSi the normal state might play a role in detection events. Moreover, recent experiments similar to Chapter 7 of this thesis show that in WSi the hotspot is well approximated as an object of constant size, indicating that there is no role for diffusion [123]. These results can be interpreted as evidence for the normal-core model in WSi, although the definitive experiment on this topic has not yet been performed. Moreover, it is known that for keV excitations, the normal-core model is valid [75, 85].

The diffusion-based hotspot model has the strong advantage that it generates the correct energy-current relation. It is, however, not able to capture all the physics of the detection event, such as the temperature dependence and the position dependence of the internal detection efficiency. However, this model has an important role as a toy model and a guide for experiments, since it is the most correct model for which an analytical expression is available. Moreover, more advanced models have not yet been able to reproduce the width dependence which is implied by this model [16].

Lastly, we turn to the two vortex-based models. Both models predict a position-dependent detection efficiency [32, 34], and both models have a role for vortices. Moreover, with the most recent refinements, the normal-state vortex model also has an energy-current relation which is able to account for the experimental results. Since it is clear that the models are quite evenly matched, it is best to set out some of the conceptual differences. In the normal-state vortex model, vortices arise naturally, whereas additional assumptions are needed to relate the size of the hotspot to the incoming photon energy. In the diffusion-based vortex model, on the other hand, the entry of vortices has to be computed separately from the rest of the model, while the hotspot is included naturally. This is due to the fact that the normal-state model was computed in the Ginzburg-Landau formalism, whereas the diffusion-based model was computed in the London formalism.

Apart from conceptual differences, the two models currently have one big experimental difference: in the diffusion-based vortex model, vortices always enter from the side of the wire, whereas in the normal-state based model, vortices can also form around the hotspot. This difference is amenable to further experiments.

8.3 Future Work

Based the discussion above, we envisage two lines of experiments. First, a series of measurements of the energy-current relation on detectors of different materials would answer the question whether the mechanisms which we have studied for NbN SSPDs are generic for all SSPDs, or whether there is a crossover to normal-state behaviour. This could be done by investigating WSi or one of the other amorphous materials, but another interesting candidate would be MgB_2, out of which SSPDs were fabricated only recently [101]. MgB_2 has a higher T_c than NbN and therefore represents a data point 'in the other direction' compared to WSi.

A second line of inquiry should look into the differences between the normal-state vortex model and diffusion-based vortex model. The difference in the vortex entry locations is most easily accessed via the magnetic field. Since the current density in the middle of the wire is not disturbed by the presence of a magnetic field, detection events which occur there should experience only a weak influence on an applied magnetic field. In the diffusion-based model, in contrast, all detection events should be strongly influenced by the field since the effect of the applied magnetic field is strongest at the edges [35]. This experiment has been done in Chapter 7 of this thesis. We showed that the predictions of the version of the diffusion-based vortex model presented in [24, 25] are contradicted by experiments. However, there are at present no predictions from the more advanced versions of this model. Therefore what is needed to resolve this question is futher refinement of the theoretical models.

There are still some open problems within the topic of SSPD detector physics. First, as mentioned previously, there is no good theoretical account of the width dependence yet. Second, while we have demonstrated a current scale which follows the temperature dependence of vortex entry, in principle in the diffusion-based vortex models, this current scale should be the critical current. There is no theoretical explanation for the experimentally observed regime in which the detector doesn't respond to single photons while operating close to the critical current.

Connected to this last problem is the issue of dark counts. We have seen repeatedly throughout this thesis that dark counts behave qualitatively different than photon counts. In particular, dark counts do not behave as $E = 0$ excitations. While part of this issue, presented in Chapters 3 and 4, is resolved by the position-dependent detection efficiency presented in Chapter 5, this is not a complete solution. Moreover, dark counts and photon counts also differ in their response to a magnetic field. This is still an open problem, for which measurements of very low-energy excitations would be useful [16].

8.4 Conclusion

In summary: we have studied the detection mechanism in superconducting single-photon detectors through quantum detector tomography. We have studied single and multiphoton excitations on a nanodetector and a series of bridge samples of varying lengths. We have demonstrated strong evidence for the role of vortices in the detection mechanism. We have investigated the temperature and position dependence of the detection mechanism. These results pave the way to a complete, quantitative understanding of superconducting single-photon detectors.