Measuring the local response of a superconducting single-photon detector

Main author:

WANG Qiang

Co-authors:

de Dood Michiel, Leiden University

Engel Andreas, University of Zurich

Fiore Andrea, Eindhoven University of Technology

Gaudio Rosalinda, Eindhoven University of Technology

Renema Jelmer, Leiden University

van Exter Martin, Leiden University

Wang Qiang, Leiden University

Superconducting single photon detectors (SSPDs) are a crucial technology in experimental physics and applications. When the detector is biased close to its critical current, absorption of a single photon is sufficient to induce a transition from the superconducting to the normal state to create a voltage pulse. Both the initial photon absorption [1-2] and the creation of voltage pulse [3] are well understood. Recently, we have made several important steps in the understanding of the intermediate microscopic detection mechanism in these detectors by a combination of quantum detector tomography, the use of short nanowire test samples and multiphoton excitations [4-6]. These experiments have conclusively demonstrated that the detection mechanism in NbN SSPDs involves both magnetic vortices, and a diffuse cloud of quasiparticles.

In this talk I will focus on two aspects: the measurement of the current-energy relation in an NbN SSPD nanodetector [4] and the position-dependence of the detection efficiency [5-6]. Both of these are crucial probes into the properties of the detection mechanism.

Different models of the detection mechanism predict different functional dependencies between the bias current and photon energy required to produce a given detection probability. Measurement of this relation therefore constitutes a decisive probe of the detection mechanism.

We measure the current-energy relation with high accuracy for an energy range of 0.75 to 10.5 eV (1650 nm to 118 nm effective wavelength) using multiphoton excitations and quantum detector tomography. We find that equal bias currents are required to detect equal energy packets composed of different numbers of photons, validating our method and demonstrating that the detector is sensitive to overall energy. The linear dependence throughout our measurement range is indicative of the role of a diffused cloud of quasiparticles in the detection event.

The temperature dependence of our observed energy-current relation is evidence for the role of vortices in the detection process. Vortices are expected to lead to a position dependence of the detection efficiency along the cross-section of the wire, because the vortex is formed on the edge of the nanowire. Numerical simulations of the detection process predict much higher detection efficiency at the edges. We observe the signature of this effect in experiments with polarized light because the two polarizations are absorbed at different locations in the cross section of the wire.

We apply quantum detector tomography to separate the linear absorption efficiency from the internal detection efficiency and conclude that there is a polarization-dependent internal detection efficiency. In our analysis, we use the known wavelength dependence of the optical expulsion length to probe the position-dependent detection efficiency on a $\sim$ 10 nm length scale. Based on these results, we obtain the first ab-initio predictions of the SSPD response and find good agreement with experimental results.

Our experimental results of current-energy relation and position-dependent detection efficiency comprise a complete picture of the microscopic photon-detection process in the NbN SSPDs based on the photon-assisted vortex entry model: The initial excitation diffuses in the superconductor without breaking superconductivity and lowers the edge barrier for vortex entry. If this barrier is lowered enough, a magnetic vortex transits the wire cross section and dissipates additional energy that triggers the detector. The absorption at the edge of the wire reduces the density of superconducting electrons, which slightly increases the barrier potential. However, this is more than compensated by the reduction of the vortex self-energy, which is proportional to the density of the superconducting electrons. The overall effect is that the total barrier for vortex entry is lowered.

[1] E.F.C. Driessen, et al., Eur. Phys. J. Appl. Phys., 47, 10701, (2009)
[2] V.Anant et al., Opt. Express, 16, 10750, (2008)
[3] A. J. Kerman et al. Appl. Phys. Lett., 88, 111116, (2006)
[4] J.J. Renema et al., Phys. Rev. Lett., 112, 117604, (2014)
[5] J.J. Renema et al., arXiv:1504.05003
[6] A. Engel et al., IEEE Trans. Appl. Supercon., 25, 2200407, (2015)