Size Effects and Excess Noise in Superconducting Nanowire Single-Photon Detectors

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Superconducting Nanowire Single-Photon Detectors (SNSPDs) offer unique performance such as extended spectral sensitivity (from visible to near-infrared range), low dark count rate (1 dark count per hour), and high timing resolution (a few picoseconds) making them highly desirable for applications in quantum computing, quantum communication, and quantum/classical light detection. However, new sophisticated applications such as deep-space communication or direct detection of dark matter particles require even more stringent performance criteria from the SNSPD technology. Among others, they require extremely low, if any, dark count levels and broad spectral sensitivity up to the middle infrared range. We identify new strategies for improving the overall performance of these devices from a material science perspective by investigating size effects and excess noise in superconducting nanowires.

The photon detection mechanism in a current-carrying superconducting nanowire is relatively simple. An absorbed photon with energy largely exceeding the superconducting gap locally breaks superconductivity that eventually drives the nanowire into the resistive state which is experimentally registered as a photon count. The dynamics of this process is governed by phonons and electron systems and thermal coupling to the substrate. The miniaturization of device sizes in superconducting nanoelectronics, and particularly in SNSPDs, which are conventionally made of 5 nm-thick and 100 nm-wide superconducting nanowires, leads to modification of their thermal properties at low temperatures. The reciprocal film thickness limits the phonon wave vectors perpendicular to the film plane, significantly altering the phonon spectrum and the heat capacitance of phonons. Our extensive studies of superconducting NbTiN films [1, 2] with polycrystalline granular morphology revealed the impact of mean grain size on the phonon heat capacitance. Such size effect can be used to tune the cut-off in the spectral sensitivity of SNSPDs via engineering the phonon properties.

In SNSPDs, besides stochastic dark counts caused by thermal fluctuations [3], there are conditional dark counts, or afterpulsing [4], as a kind of excess noise that presents a significant challenge in improving device performance. We observed that the probability of an afterpulse in an SNSPD made of amorphous MoSi depends on the mean number of photons per light pulse, including values much less than one. Our proposed phenomenological model explains our findings by introducing slowly relaxing afterpulsing centers, which we believe may be two-level systems in amorphous materials. While two-level systems are well-known sources of decoherence and losses in superconducting qubits and resonators, their impact on SNSPD performance is yet to be explored. Therefore, understanding the microscopic details and material science aspects may play a dominant role in further improving the performance of superconducting devices.

Keywords:

superconducting nanowire detectors, granular films, afterpulsing

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