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Tech Notes

Superconducting Nanowire Photodetector Arrays

Overcoming basic physical limitations on individual detector speed enables broadband single-photon detection with high efficiency and low noise at record-high rates exceeding one billion photons per second.

Past successful NASA space exploration missions have relied on radio-communications links for interplanetary spacecraft as well as for Earth-orbiting satellites. However, this modality will not support future missions whose instruments demand much larger data rates. Optical networks represent the future of deep-space communications and will make it possible to collect ambitious data products from more distant destinations. Highly sensitive single-photon detectors are a key enabler for this next generation of optical communication technologies.

Advanced photon detectors are also enabling new optical quantum information applications, which may revolutionalize communication and computation. One such application is quantum key distribution (QKD), which takes advantage of the information properties of quantum systems to provide secure communication that cannot be intercepted without being corrupted.

These advancements in communication technologies would not be possible without significant improvements to the detection efficiency, signal-to-noise ratio, spectral range, and resolving power of single-photon detectors. Understanding the basic physical limitations on individual detector speed led to a collaboration between MIT Lincoln Laboratory and MIT Research Laboratory for Electronics to build a superconducting nanowire photodetector [SNPD, Figure 1(a)]. These detectors enable broadband single-photon detection with high efficiency and low noise at record-high rates exceeding one billion photons per second. An interleaved, four-element detector [Figure 1(b)] provides a new capability for ultrafast, ultrasensitive laser communications, as well as other applications and scientific measurements. The SNPD array utilizes a spatially interleaved array of up to eight serpentine detectors and occupies a region 7 to 20 micrometers in diameter.

An SNPD array can take advantage of a spatially multiplexed approach that allows detection of photons at a higher rate than a single SNPD would support without requiring complex optical coupling techniques typical of other photon-counting arrays. When illuminated by a single photon, only one of the SNPDs loses its superconductive properties. The remaining SNPDs remain available to detect the next photon, while the first SNPD recovers its superconductive properties.

Theory of Operation

Each SNPD consists of a superconducting film ~5 nanometers (nm) thick that has been lithographically patterned into a wire whose width is less than 100 nm.

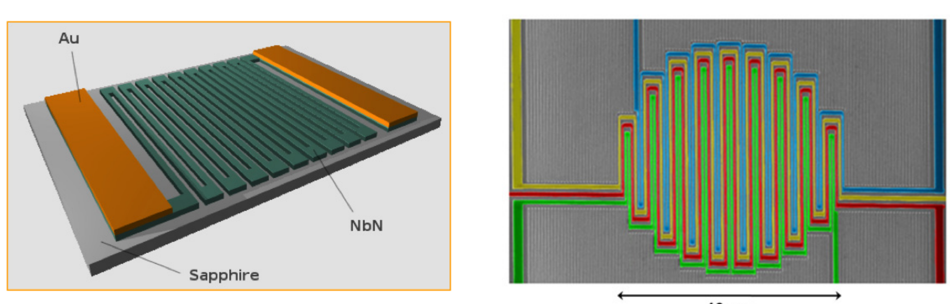

Figure 1. (a) A schematic of a single SNPD. The nanowire is typically 4 nm to 6 nm thick and 50 nm to 100 nm in width. (b) A false-color scanning electron micrograph of a four-element SNPD array.

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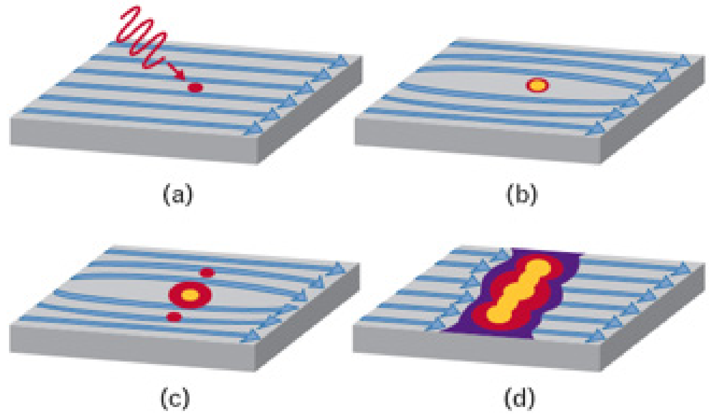

Figure 2. (a) An incident photon heats a nanowire, forming a localized hot spot (b) where the superconductivity is disrupted. The supercurrent diverts around this spot. (c) When the local current density on either side of the hot spot exceeds the critical current density, a resistive region spanning the entire cross section of the nanowire is formed (d).

The wire is cryogenically cooled below 4 K, which is cool enough to ensure superconducting properties. When a photon is absorbed by the wire [Figure 2(a)], a small, localized region known as a *hot spot* is created. Within such a hot spot, the temperature of the electrons is sufficiently elevated to disrupt the superconductivity and return the material to its normal, highly resistive state, causing the supercurrent to divert its path [Figure 2(b)]. Although this region is very small (e.g., on the order of 10 nm in diameter for a near-infrared photon [1]), its presence can be detected electrically if the wire is sufficiently narrow (e.g., less than 100 nm in diameter) and the initial DC current density J is close enough to the critical value J_C, above which a material's superconductivity breaks down. The occurrence of the initial hot spot can result in additional hot spots because the charge carriers moving around the spot are forced both to accelerate and to increase in density, leading to a J that exceeds J_C locally [Figure 2(c)]. The additional hot spots can disrupt superconductivity throughout an entire cross section of the wire [Figure 2(d)], producing an electrically detectable voltage across the wire. After a relaxation time, the hot spot subsides and the detector is ready to register another photon.

Unfortunately, the dimensions of the wire segment shown in Figure 2 are much smaller than the wavelength of light that must be detected, so even a diffraction-limited beam cannot be focused onto a very short wire. Instead, the nanowire is typically patterned to cover a larger area [Figure 1(b)] The density with which wires are packed in this structure affects the absorptance of the detector, with a more tightly packed structure increasing the absorptance. Consequently, a longer nanowire increases the probability of a detector absorbing photons, thus producing a higher-efficiency communication channel.

Although a tradeoff clearly exists in choosing nanowire length for a single detector (speed and yield improve for shorter nanowires while absorptance improves for longer nanowires), the SNPD array simultaneously achieves many of the advantages of short and long nanowires. One realization of this invention [Figure 1(b)] interleaves four independent nanowires to form a single optical active area. In this case, each nanowire is relatively short, compared to the four-times-longer wire that would be needed if only a single nanowire had been used. Therefore, each of the four shorter nanowires is faster and can be produced with high yield, while the combination of elements covers a large area with tightly packed wires. Although two- and four-element SNPD arrays have been investigated in the most detail, other arrangements can be highly customized for specific applications by implementing simple changes to the lithography pattern, without changing the fabrication processes themselves.

The Lincoln Laboratory SNPD array simultaneously achieves the speed and yield of shorter nanowires in addition to the improved absorptance of longer nanowires.

Example applications of the SNPD array include

- a Moon-to-Earth laser-communications link that will be part of NASA's Moon-orbiting Lunar Atmosphere and Dust Environment Explorer satellite, scheduled for launch in 2012 [2];
- a single-photon-counting detector for QKD systems operating at rates 100 times faster than current rates (for a fixed fiber optical cable length) [3]; and
- a high-resolution, noncontact probe to detect flaws in high-speed, very-large-scale integration complementary metal-oxide semiconductor circuitry [4]. ■

References

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