Recent Advances in Solid-State Single Photon Detectors*

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Abstract: This paper reviews recent advances in the detection of single photons at visible and near-infrared wavelengths, focusing on detectors based on superconducting and semiconducting technologies.

OCIS codes: (230.5160) Photodetectors; (270.5570) Quantum detectors

1. Introduction

Detectors that are sensitive to single photons have applications in a wide variety of fields, such as biomedical imaging, astronomy, quantum cryptography, and quantum computing. Here we review various superconducting and semiconducting technologies for the detection of single photons, including avalanche photodiodes, visible light photon counters, quantum-dot-gated field-effect transistors, superconducting single photon detectors, and superconducting transition-edge sensors. Although all of the detectors discussed here are single-photon sensitive, some have the additional ability to resolve the number of photons in a pulse of light.

Different applications have varying detector requirements. Quantum key distribution (QKD), for example, generally requires detectors with high efficiency and low dark count rate. If the QKD system is fiber-based, the detectors must operate at the telecommunication wavelengths, 1310 nm and 1550 nm. Energy-resolving detectors can also be used to verify that the source used creates the expected distribution of photon-number, an important determination because the ultimate security of many QKD systems rests on the transmission of single photons. Linear-optics quantum computing requires very high detection efficiency, low dark count rate, and photon-number-resolving detectors.

2. Semiconducting technologies

Single Photon Avalanche Diodes (SPADs) are p-n junction devices sensitive to single photons. In linear mode, standard avalanche photodiodes are biased just below the breakdown voltage. In contrast, SPADs are operated in “Geiger mode”, biased *above* the breakdown voltage at the expected time of arrival of the photon. The field is very high in the depletion region, and when a photon is absorbed in this region, it creates a primary electron-hole pair that is then accelerated by the high field, generating new secondary electron-hole pairs and creating an avalanche process that results in large current flow. An external circuit quenches the avalanche by lowering the bias voltage and then resets the voltage to the original value above the breakdown threshold. The time between the initiation of the avalanche and the reset is called the “dead time” because the sensor is unable to detect photons during this time. It is sometimes necessary to increase the dead time to avoid the likelihood of afterpulsing, the re-triggering of the avalanche by temporarily trapped carriers.

Silicon SPADs, which operate from 300-1100 nm, can have detection efficiency as high as 75 % and typical dark count rates of approximately 100 Hz or lower. InGaAs SPADs, which cover the telecom wavelengths of 1310 nm and 1550 nm, have poorer performance, with typical detection efficiencies of approximately 20 % and dark count rates of tens of thousands of counts per second. Minimization of afterpulse effects requires hold-off times of order 10 μs for InGaAs SPADs, severely limiting their performance. If the expected photon arrival rate is known, the dark count rate of a SPAD can be reduced by gating the detector, giving an effective dark count rate which depends on the width of the gate (usually ~1 ns) and the rate of the system. SPADs are relatively easy to use, widely available, require cooling only to 200 K, and have typical timing resolutions less than 100 ps, facilitating their use in high-speed systems.

SPADs are the most commonly used semiconducting single-photon detectors, but other notable single photon detectors based on semiconductor technologies include the visible light photon counter (VLPC) and the quantum-dot-gated field-effect transistor (QDOGFET). VLPCs are large-area detectors that rely on multiplication of carriers in shallow impurity levels in silicon. They operate at ~6 K and have high detection efficiency of 85% at 540 nm and 20 kHz dark-count rate [1]. Unlike SPADs, VLPCs can determine the number of photons in a pulse of light as long as the likelihood of more than one photon hitting the detector within a diameter of a few microns is small. QDOGFETs contain a layer of quantum dots between a semi-transparent gate and the conducting channel of a GaAs/AlGaAs FET. Photo-excited holes are trapped by the quantum dots and modulate the channel current by an amount proportional to the number of trapped carriers. Although initial results have demonstrated efficiency <1 % for devices cooled to 4.2 K [2], new heterostructure designs with increased absorption in the active area are expected to lead to higher detection efficiency.

3. Superconducting technologies

Superconducting single photon detectors (SSPDs) are meanders of NbN with typical superconducting critical temperatures T_cs of around 10 K. The meander is cooled below T_c and biased close to the superconductor critical current I_c. Absorption of a photon along the meander creates a local “hot spot”. Current flows around the hot spot, and when the current density becomes larger than I_c, a measurable voltage develops across the device. These devices can be sensitive over the entire ultraviolet to near-infrared spectrum, have fast recovery times on order 10 ns, and timing resolution less than 100 ps. Reported system detection efficiencies are less than 1%, but the intrinsic detector efficiency is higher, around 20% at visible wavelengths and 10% at telecom wavelengths. Dark count rates are highly dependent on biasing conditions, and typical rates are 1-10 kHz for biasing conditions giving the highest detection efficiency at 4.2 K [3].

Transition-edge sensors (TESs) measure the temperature change of a small mass of superconducting sample upon absorption of energy deposited by a photon. The sensor is voltage-biased on the edge of the superconductor-to-normal transition where the dependence of resistance on temperature is very steep, creating an extremely sensitive thermometer. In order to detect single photons with energy of order 1 eV, the heat capacity of the detector must be small, necessitating operation at temperatures around 100 mK. The intrinsic dark count rate of TESs is negligible, and their extremely low noise has allowed observation of room-temperature blackbody radiation propagating through single-mode optical fiber at the single photon level [4]. TESs can detect single photons over a wide wavelength range, from ultraviolet to near-infrared, and they can reliably determine photon number for monochromatic light. In contrast to other detectors, every photon that is absorbed in the sensor leads to a measurable effect, so improving the detection efficiency is possible by increasing the probability that the photon is absorbed in the detector. By embedding tungsten TESs in an optical structure designed to enhance absorption in the tungsten, system detection efficiencies of 88% at 1550 nm have recently been demonstrated [5]. The timing resolution of these devices is 80 ns FWHM and the recovery time is approximately 5 μs. Further increases in detection efficiency are achievable by improving the optical coupling to the device and the optical structure for maximizing absorption at the target wavelength.

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