INVITED PAPER *Special Section on Superconducting Electronics for Quantum Information Technologies*

Single-Photon Measurement Techniques with a Superconducting Transition Edge Sensor

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SUMMARY The optical-transition edge sensors are single-photon detectors that can determine photon energies at visible to telecommunication wavelengths. They offer a high detection efficiency and negligible dark count, which are very attractive qualities for applications in quantum optics or bioimaging. This study reviews the operating principles of such detectors and the current status of their development.

key words: *detection efficiency, dark count rate, time jitter, low temperature device, superconductor, single photon*

1. Introduction

Single-photon measurement plays an important role in observing neutrinos in nuclear physics, detecting photons from green fluorescent protein (GFP), and in the development of super-resolution microscopes for bioimaging. Additionally, new studies that intend to introduce next-generation industrial reforms are being conducted by extracting the quantum of light to the utmost; some of the examples are quantum cryptography communication (quantum key distribution) that can obtain almost perfect confidentiality in communications and quantum information communication that enables high speed and large capacity optical communication.

To detect extremely low optical power, in the order of just a few photons, a single-photon detector is required. Conventionally, photomultiplier tubes and semiconductor photodiodes based on avalanche amplification have been applied for single-photon detection. Recently, however, a new single photon detection technology based on superconducting materials has been developed. Such detectors exploit the superconducting phase transition to detect photons and to offer novel advances in detection efficiency, a low dark count rate, and rapid response. Currently, several superconducting single photon detectors have been commercialized and are promising to be used in the weak-light measurement and industrial fields.

At present, two types of superconducting single photon detectors are available, including a nanowire-type single photon detector [1] and a superconducting transition-edge sensor (TES) [2]. The latter sensor exhibits a unique characteristic of being able to detect the incidence of a single photon while measuring the energy of that particular photon. Because energy is related to the wavelength of the photon or the number of photons, TES can spectrally decompose the photon energy or discriminate the number of photons, which also enables single photon spectroscopic imaging for photon-starved science. In this report, we will introduce the TES superconducting photon detector and discuss the precise measurement technology that is used with it.

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2. TES for Single Photon Detection

Figure 1 depicts the operating principle that is used by a superconducting transition edge sensor (TES) for photon detection. In a TES, the energy values of the photons are measured through the changes in the resistance of the TES films. When a photon with energy, E, is incident on the TES in its equilibrium state (in Fig. 1 (i)) within the temperature-transition region, the TES temperature is slightly increased by the absorbed photon energy so that the superconducting state of TES is interrupted (Fig. 1 (ii)). Thus, some resistance is observed in the TES due to the breakdown of this superconducting state. Because this change in resistance is proportional to the absorbed photon energy, E can be determined by the change in resistance. The absorbed energy, E, further dissipates out of the TES films with a certain time constant, and the TES temperature returns to the original equilibrium state.

The size of the TES typically ranges from several microns to several tens of microns square, and the heat capacity, C, is in the order of 10^{-16} J/K. Because the energy of one photon of 1.5 μm in the communication wavelength band is

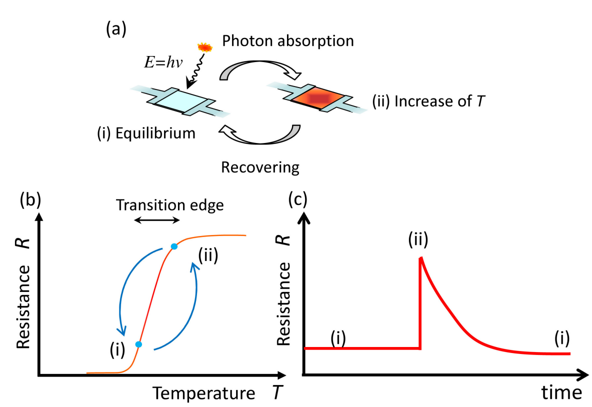

Fig. 1 (a) Phase diagram of the TES superconducting state. (b) TES resistance depending on the temperature. (c) Change in resistance with time in case of the absorption of photons.

$E = 0.8$ eV, the temperature of the TES will be increased by $\Delta T = 0.3$ mK when it absorbs one photon. C is also related to the minimum detectable energy. Assuming that the operating temperature of TES is $T \sim 0.1$ K, the number of phonons, N, associated with the lattice vibration of TES is $N \sim CT/k_BT \sim 10^7$ because the energy of a phonon is $\sim k_BT$. Therefore, the thermodynamic limit of the detected energy is approximately $\Delta U \sim \sqrt{N} \times k_BT \sim 0.02$ eV because of the thermal fluctuation of TES. This corresponds to the wavelength resolutions of 5 nm and 40 nm for photons with wavelengths of 550 nm and 1550 nm, respectively.

Because TES is basically a metal, Fresnel reflection occurs on the surface when light is incident on the TES. For example, the complex refractive index, m, of titanium, which is typically used in TESs, is $m = 4.47 - 3.91i$, which yields 34% in reflectance and 17% in transmittance for a thin film with a thickness of 20 nm. Therefore, the light absorption efficiency of a TES is observed to be only approximately 50%. This absorption efficiency is significantly related to the detection efficiency of single photons and places an important limitation on the device performance, especially in case of quantum-communication applications. To maximize the detection efficiency, the light absorption must be increased. For this purpose, various structural modifications, such as embedding a TES into a light absorption cavity with dielectric multilayer film [3], coupling with optical waveguide [4], or using a plasmon light absorption antenna [5], have been applied for improving the absorption efficiency.

An optical fiber is frequently used to deliver photons to the TES, which must be kept in a refrigerator to maintain the superconducting state. Several types of optical fibers, such as single mode fibers and multimode fibers, with various core diameters and numerical apertures (NA) are available, and these parameters are observed to affect the total system detection efficiency. In case of the optics of such a system, a target photon to be measured using the TES will be accumulated by a lens and focused onto the end face of the optical fiber. The TES is directly connected to the other end face of the fiber. Generally, a multimode fiber is used when the focal size is large and a high coupling efficiency is required such as in case of astronomical observations [6]. A single-mode fiber [7] is used when the focal size is small such as the size that is observed while using an optical microscope. The optical transmittance of the optical fiber is high in the visible region and the near infrared region; however, the loss becomes large when the wavelength is below 300 nm or more than 2 μm. Additionally, note that the blackbody radiation is transmitted through the fiber to the TES at low temperatures, which will lead to photon counts from the background radiation [8], because the end of the fiber at the focal plane is maintained at room temperature. The intensity of blackbody radiation is maximum at a wavelength of 10 μm and a temperature of 300 K even though this intensity attenuates at longer wavelengths (> 2 μm) due to low transmittance. Therefore, blackbody radiation appears as a single peak with a maximum intensity of approximately 1.8 μm wavelength in the photon spectrum. The total count

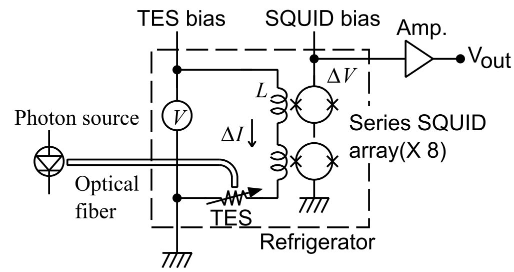

Fig. 2 Readout circuit for an optical TES with a current amplifier of an 8-series SQUID array.

rate of the background photon peak is typically in the order of hundreds of counts per second.

The resistance of the TES increases with a change in temperature, ΔT, caused by the photon energy imparted to the TES, and the change in resistance, ΔR, is detected by a superconducting quantum interference device (SQUID) as the change in current, ΔI, because the circuit is biased at a constant voltage. The typical readout circuit used for the TES signals is depicted in Fig. 2. The SQUID has an input coil with inductance, L, and the magnetic flux created by the inductance interferes with the superconducting loop that includes a Josephson junction so that the output signal is the voltage difference, ΔV, which is caused due to the Josephson effect. In case of optical TES, the arrival time of photons must be precisely measured, especially for applications such as autocorrelation measurements of a light source, measurements of the fluorescence lifetime of phosphors, or identification of single events for a pulsed laser with repetition frequency, $f_{\rm rep}$. A fluctuation in the measured photon arrival time is referred to as the sensor's temporal resolution or time jitter, which must be minimized. This temporal resolution Δt_σ is described as $\Delta t_\sigma \approx \frac{\sigma}{A_{\rm max}}\tau_{\rm rise}$ [9], where $A_{\rm max}$ represents the maximum amplitude of the signal, σ is the standard deviation of the signal voltage, and $\tau_{\rm rise}$ is the rise-time. Δt_σ is mainly limited by the readout circuit, including the SQUID in the optical TES. To improve the temporal resolution, the input inductance L of the SQUID should be optimized because the signal bandwidth should be widened for fast $\tau_{\rm rise}$ by using smaller L or the current-voltage conversion gain of the SQUID should be improved for small σ and large $A_{\rm max}$ by using larger L. By applying this optimization, a time jitter of 4 ns was reported in [9], which was shorter than the time window of the mode-synchronization frequency ($\sim$ 80 MHz) of the Ti:Sapphire lasers that are typically used for quantum communications.

3. Development of Optical TES at AIST

Our research group is developing an optical TES device that features superconducting double layers of titanium (Ti) and gold (Au) [3]. Figure 3 (top) depicts a photomicrograph of a prototype fabricated at AIST. The dimensions of the TES is 5 μm × 5 μm or 10 μm × 10 μm, and the thicknesses of the layers are 20 nm for Ti and 10 nm for Au. By varying the thickness ratios of Ti and Au, the superconducting critical temperature, T_c, can be tuned to be approximately in the range of 150 mK to 410 mK. Because T_c affects the response speed and energy resolution of the TES, this parameter must be tuned according to the measurement target or the application. Additionally, to achieve a high detection efficiency, we have constructed a high-absorption structure in which the TES layers are embedded in an optical cavity that is formed by dielectric multilayer films. Figure 3 (bottom) depicts the cross-sectional view of the optical cavity, which is obtained by focused ion beam (FIB) imaging. The layer marked with arrows is a Ti/Au TES, and the inside of the rectangle is an optical cavity. The optical cavity can be fabricated using alternating layers of silicon dioxide and tantalum oxide. The thickness of each layer is set to approximately a quarter of the target photon wavelength. Figure 4 depicts the photon absorptance measurements for an optical cavity constructed at a target wavelength of 1550 nm. The solid line denotes the design value, whereas the dotted line denotes the measured value. This cavity structure improves the absorptance from 35% to almost 100% efficiency. At the upper side of the optical cavity, the optical fiber is coupled coaxially, aligned with very precise positioning stages. The optical fiber is fixed to this junction with ultraviolet curable resin. We are also working to establish a self-aligning optical fiber coupling method [10] to improve the reliability of this device.

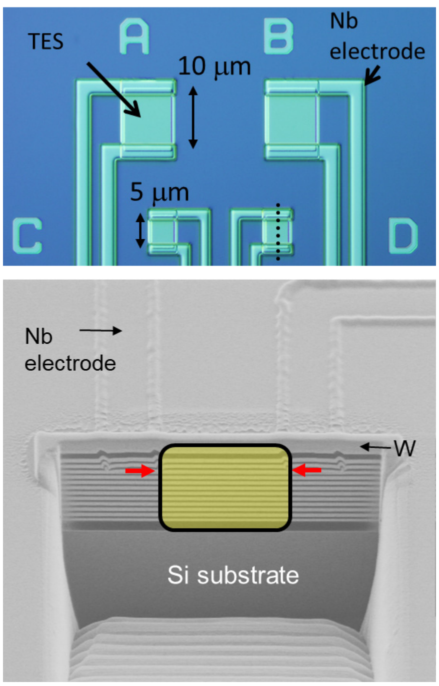

Fig. 3 (upper) Microscopic view of the optical TES developed at AIST. (below) Cross sectional view of the TES along the dotted line in the upper figure, which is obtained by focused ion beam (FIB) imaging. The TES layer is marked by the two arrows, and the square indicates the optical cavity. "W" represents the tungsten protection layer for Argon milling in FIB.

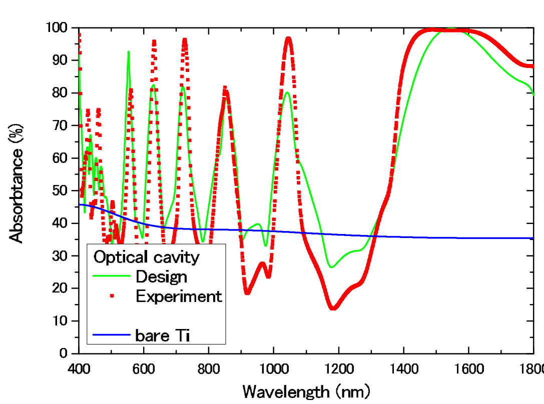

Fig. 4 Optical absorptance of the optical cavity. The solid line denotes the design calculation, and the dotted line denotes the experimental result.

4. Experimental Tests of Photon Counting

An optical TES is generally operated in photon-counting mode. A response signal is observed for the absorption of each photon into the TES, and the amplitude of the signal is observed to be proportional to the incident energy of a photon or photons. To evaluate the TES performance, we have used optical pulse trains with an average photon number of several photons per pulse. The pulse trains are supplied by a heavily attenuated pulsed laser source. The typical response signals are depicted in Fig. 5. The photons are injected into the TES at $t = 0$, and a sharp increase in voltage can be immediately observed. Subsequently, the signal waveform recovers to its original equilibrium state with a certain time constant of $\tau_{\mathrm{fall}} \sim 100$ ns. In this experiment, the peak of the response-signal waveform is proportional to the number of photons, n, because the wavelength of the input photons is unique. Figure 6 depicts the pulse-height distribution of the observed signal waveforms. Because the photon energy is discretized, the pulse height distribution exhibits some peaks. Each peak corresponds to an event of photon absorption with the photon number, n. The photon numbers in this experiment should follow a Poisson distribution, which verifies that the number of photons injected from a heavily attenuated pulsed laser should obey the Bernoulli process. From Fig. 6, we can derive the average photon number, u

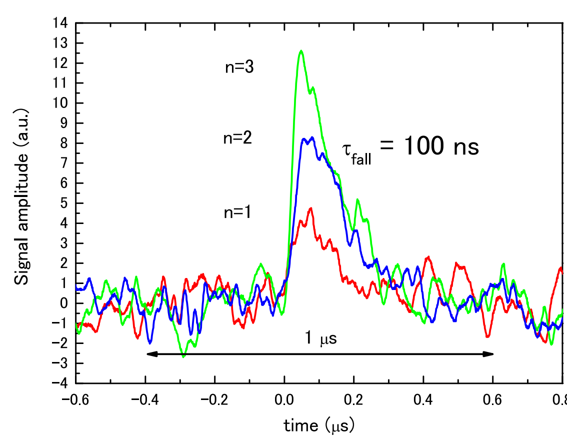

Fig. 5 Example of observed signals from an optical TES.

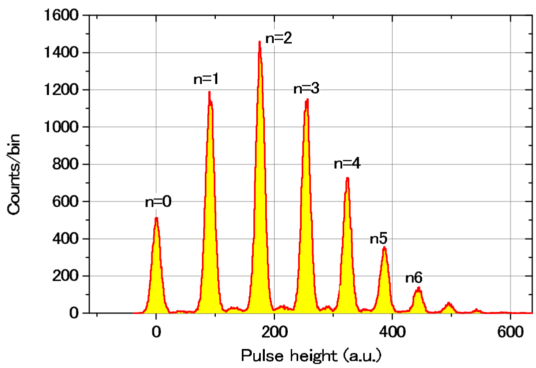

Fig. 6 Pulse-height distribution for a weakly coherent pulsed laser.

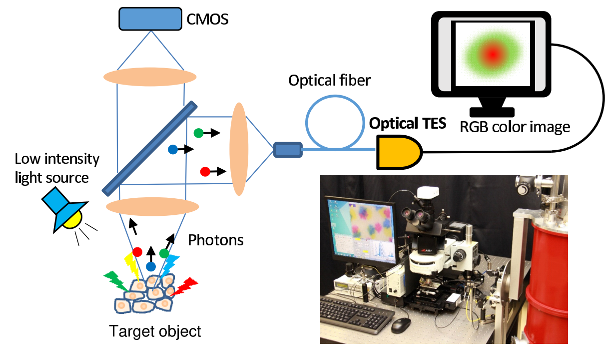

Fig. 7 Schematic of single-photon spectral imaging.

(photon / pulse), of the pulse train detected by an optical TES by fitting the data to $P(n|u) = u^n \exp(-u)/n!$. This gives $u = 2.424 \pm 0.004$, indicating that the photon number distribution observed by the TES is consistent with the Poisson distribution, with only a small error.

5. Applications Made Possible by Precise Photon Measurements

Due to the ability of optical TES for photon-number discrimination and spectroscopy, the optical TES will allow highly precise photon measurements that will completely utilize the quantum nature of photons. For example, we first observed a non-Gaussian state of photons at the telecommunication wavelengths using an optical TES [11]. This physical state is essential for quantum computers to realize universal quantum optical gates. We also used an optimum quantum receiver to achieve minimum bit error rate below the standard quantum limit (SQL) in binary-phase coherent communication [12], in collaboration with the National Institute of Information and Communications Technology, Nihon University, and the National Institute for Materials Science. Quantum cryptographic communication and a quantum key distribution (QKD), which allow extremely secure telecommunications, are being developed for use in the management and transmission of medical records [13]. Ultra-long-distance secure communications have also been tested using small satellites [14]. Evaluating the performances of single photon detectors, including optical TESs, is crucial for the success of these applications. The detection efficiency of photon detectors is a crucial parameter to guarantee the security of quantum-cryptographic communications. AIST is also participating in verifying the consistency detection-efficiency tests of single photon detectors in international collaborations [15].

In this section, we introduce a novel approach for using the TES for single-photon spectroscopic imaging [7]. In bioimaging, an optical microscope or a confocal microscope is used to observe a biological sample or a sample labeled with fluorescent dyes. However, a very weak illumination must be used to avoid damage to delicate targets such as living cells. If the illumination source is weak enough, a clear and high-contrast image cannot be obtained using conventional means. To address this restriction on bioimaging, the optical TES can be integrated with an optical microscope to obtain clear color images even with extremely low-level photons. Figure 7 schematically depicts the single photon spectroscopic imaging apparatus. Weak reflections from the observed specimen is condensed by the objective lens that is coupled to an optical fiber. This fiber guides the photons to the TES, which further identifies each photon wavelength so that a color image can be constructed. Figure 8 depicts an example taken from the surface of a printed circuit board (PCB) with only approximately 1 to 20 photons recorded per pixel. The copper (orange), resist (green), and silk pattern (white) can be clearly distinguished even with such a low number of photons. The image is obtained by scanning a field of view of dimensions 400 μm × 400 μm with an exposure time per point of 50 ms and a scanning width of 0.5 μm. The pixel values at each measurement point comprise the spectra of wavelengths from 400 nm to 1.8 μm, and these spectra reflect the optical properties of the substance at that observation point. We believe that this single-photon spectrum can serve as a useful fingerprint for identifying specific substances and molecules in delicate samples.

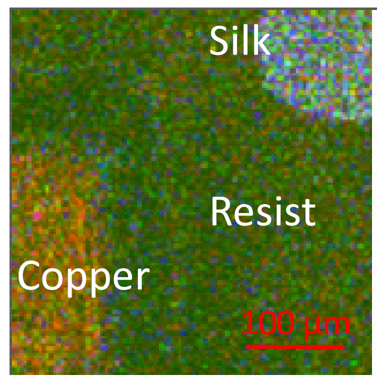

Fig. 8 Example of single-photon spectral imaging using an optical TES. The target sample is the surface of a printed circuit board (PCB). Copper (orange), resist (green), and silk patterns (white) can be discriminated at an extremely low intensity of tens of photons per pixel.

6. Conclusion and Future Work

We have developed an energy-dispersive single-photon detector that uses a superconducting TES. This prototype offers considerable potential for use in applications in quantum computing and bioimaging. A TES is the only photodetector capable of both photon-number discrimination and single-photon spectral measurements. In future studies, we plan to develop a new optical TES with a broadband optical cavity that can be used with wavelengths ranging from visible to infrared. We also plan to use an arrayed TES and a multiplexed readout system to allow real-time 2D-imaging and high-throughput single-photon spectroscopy.

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