High-Speed and High-Efficiency Photon-Number-Resolving Detector at Telecommunication Wavelengths

Go Fujii (1,2), Daiji Fukuda (1), Takayuki Numata (1), Akio Yoshizawa (1), Hidemi Tsuchida (1), Hidetoshi Fujino (1) , Hiroyuki Ishii (1), Taro Itatani (1), Shuichiro Inoue (2) and Tatsuya Zama (1)
1: National Institute of Advanced Industrial Science and Technology, Tsukuba, 305-8563, Japan
go-fujii@aist.go.jp
2: Institute of Quantum Science, Nihon University

Abstract

A transition edge sensor (TES) can be used in many optical quantum measurements because of high detection efficiency, low dark counts and high resolving power of photon numbers in a weak light pulse from visible to near-infrared wavelengths. We developed an optical absorption structure of titanium-TES designed to maximize the quantum efficiency at 1550 nm wavelength. As a result, the devices showed the quantum efficiency of 64 % at 1550 nm, a fast decay time constant of 190 ns that enables the operation at the counting rate of a few MHz. The energy resolution was 0.49 eV (FWHM) at 1550 nm.

Introduction

Single photon detectors are indispensable requirements for many quantum information applications, such as quantum key distribution (QKD) [1], n-photon state quantum-optics experiment [2], photon-based quantum computing [3]. Superconducting transition egde sensor (TES) can determine the number of photons in the optical pulses in the wide wavelength from visible to near-infrared points. An operating principle of the TES is based on a calorimetric method. Photon energy of a light pulse is absorbed in the TES and the absorbed energy increases its temperature. The temperature rise is measured with a highly sensitive thermometer, which is the TES. Currently, a NIST group has developed tungsten-based transition edge sensors (W-TES), and has shown excellent performances such as 95 % quantum efficiency at 1556 nm, 800 ns response time, and 0.29 eV (FWHM) energy resolution [4]. However its slow response is insufficient for practical uses.

So far, we have developed new TES devices to improve the device performances, especially in terms of the response speed of the sensor. The response time of the devices greatly depends on the critical temperature T_c of the superconducting film. By using higher T_c superconducting materials, the response time would improve with T_c^3. From this point of view, we have developed high speed photon-number-resolving detectors with the titanium transition edge sensor (Ti-TES). The Ti-TES showed response time with the rise time of 60 ns and the fall time of 300 ns, however, quantum efficiency was limited to 9 %. In this paper, we report on improvement of the quantum efficiency using the optical cavity structure of Ti-TES designed to maximize photon absorption in the Ti layer.

Device fabrication

The quantum efficiency of a bare superconducting TES detector was decreased by reflection from the surface of the superconducting film and transmission of the light through the thin superconducting film. By embedding the superconducting film in an optical structure with optical dielectric layers, almost 100 % optical absorption at designed wavelength can be possible that leads to the high quantum efficiency. We developed the optical structure of Ti-TES designed to maximize photon absorption in the Ti layer. This structure consists of a backside reflecting mirror, plus a dielectric spacer of SiO_2, followed by the Ti layer. Finally, an antireflection coating is deposited on top of the Ti layer. The device size of the Ti-TES designed to maximize the quantum efficiency at 1550 nm wavelength is 10 µm x 10 µm square and the thickness is 22 nm. The Ti-TES showed the superconductivity at the temperature 290 mK.

Experiments

The device is optically and electrically configure as shown schematically in Figure 1. The light is irradiated to the Ti-TES device at sub-Kelvin through a single-mode optical fibre. The sub- Kelvin temperature for device is provided by an adiabatic demagnetization refrigerator. The temperature change due to energy deposition by a photon results in a change in the resistance, and the current change in the voltage-biased detector is measured with a 200- element series array of a dc-superconducting

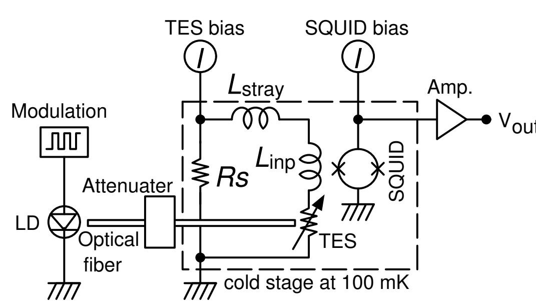

Figure 1: The experimental setup for photon number measurements

quantum interference device (SQUID) [6]. The change in the current is proportional to the photon energy, so the sensor can resolve the number of photons in a light pulse.

Results

Figure 2 shows signal responses of the Ti-TES with higher superconducting transition temperature (T_c ~ 440 mK). The signals have much faster rise and fall time of 40 ns and 190 ns, respectively. This indicates that the Ti-TES can be operated at a few MHz counting rate. The pulse heights are well proportional to the absorbed photon number.

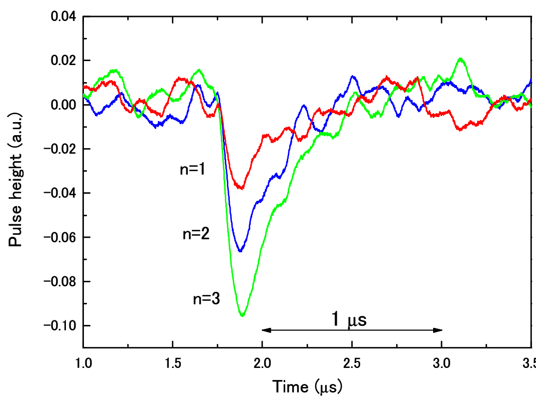

Figure 2: The examples of photon measurement signals with the Ti-TES.

Figure 3 shows the pulse height spectrum from the Ti-TES in response to 1550 nm (0.8 eV). We can discriminate each peak that corresponds to the number of absorbed photons in the TES. Since the incident laser pulses are highly attenuated, the photon number distribution obeys the Poisson statistics. By fitting the measured spectrum with the Poisson distribution, we obtained the energy resolution of 0.49 eV (FWHM) and quantum efficiency of 64 % at the 1550 nm wavelength.

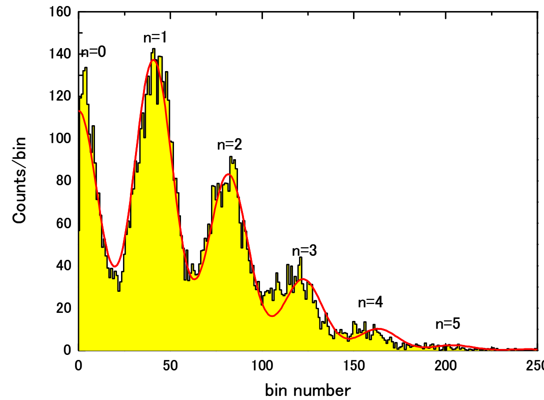

Figure 3: Pulse height spectrum from the Ti-TES in response to 1550 nm photon pulses.

Conclusions

We have fabricated the optical structure of the Ti-TES designed to maximize photon absorption. The Ti-TES successfully showed high performances such as 190 ns response time, 64 % quantum efficiency and 0.49 eV energy resolution at 1550 nm.

Acknowledgment

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