Optical and near-infrared Photon detection with Superconducting Transition-Edge Sensors

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***Abstract*—There is increasing interest in using high-performance cryogenic optical photon detectors in a variety of applications in quantum information science and technology. These applications require detectors that have extremely low dark count rates, high photon count rates, high quantum efficiency, and moderate energy resolution or photon number resolution for near-infrared and optical photons. In this paper, we describe the operation, fabrication, and performance of superconducting transition-edge sensors designed for quantum optics and information applications.**

***Index Terms*—Single photon detector, superconductivity, quantum information**

I. Introduction

MANY quantum-information applications require high-efficiency, low-noise, single-photon detectors that operate at visible and near-infrared wavelengths. Tungsten-based superconducting transition-edge sensors (W-TESs) are ultra-sensitive microcalorimeters that meet these requirements. W-TESs have no dark counts and can resolve the number of photons in a pulse of monochromatic light with excellent accuracy. Furthermore, they can be designed to have high efficiency at any wavelength in the visible to near-infrared spectrum [1]. In the sections below, we discuss the operation and fabrication of these detectors as well as their performance.

II. Operation

Transition-edge sensors (TESs) are microcalorimeters that provide excellent energy resolution with very low noise. A microcalorimeter consists of a thermometer and an absorber that is weakly linked to a thermal bath. When a photon is absorbed, the temperature of the system increases and then recovers back to equilibrium as the heat flows to the thermal bath. TESs use the temperature dependence of the resistance in the superconducting transition as a very sensitive thermometer. The devices can be made sensitive to single photons from UV to near-infrared frequencies through the proper choice of materials and size[2].

The TESs that we have designed to detect near-infrared light are small (tens of micrometers on a side), thin (tens of nanometers) square of tungsten. The absorber for a W-TES is the electron system in the metal, and the weak link is provided by the anomalously low electron-phonon coupling within the tungsten at low temperatures. Heat is removed from the electrons in the tungsten through the phonons (lattice vibration of the tungsten atoms) which are well coupled to the phonons in the crystalline silicon substrate. The tungsten TES is cooled to well below the superconducting transition temperature and voltage biased. The Joule heating generated by the bias causes the temperature of the electrons to be higher than the thermal bath temperature. When the voltage is adjusted so that the tungsten is in the region of superconducting transition, the system experiences negative feedback and is stable to slight perturbations[3]. When a photon is absorbed by the detector, the electron system of the tungsten heats up, changing the resistance of the tungsten, and the resulting current change is read out by a SQUID array amplifier[4].

III. Fabrication

Fabrication of high quality tungsten with the appropriate superconducting transition temperature (T_c) is a challenging

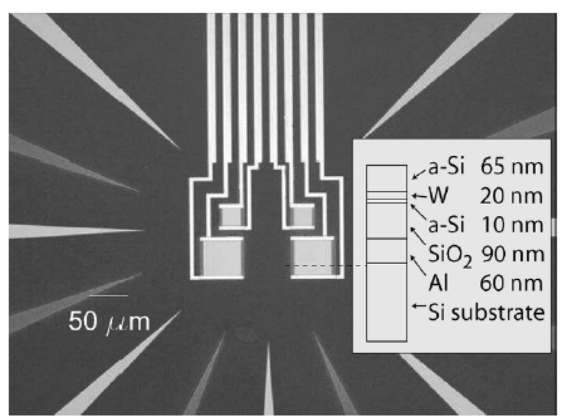

Fig. 1. Optical photograph of four completed W-TES detectors. The upper two squares are 25 micron x 25 micron devices. The lower, larger squares are 50 micron x 50 micron devices. The vertical bars are the aluminum wiring used to bias the device. The diagram on the right is a description of the layers in cross section of the device.

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material science task. We have found that depositing the tungsten *in situ* with an underlayer of amorphous silicon and a coating of amorphous silicon (a-Si) stabilizes the T_c of DC-magnetron sputtered films. Tuning the T_c of the tungsten (~100mK) with this trilayer is accomplished by adjusting the sputtering conditions such as the Argon pressure and sputtering power[5]. Fig. 1 shows four detectors and a schematic of the cross section, neglecting the aluminum wiring layer used bias the detectors, for detectors embedded in a stack of optical elements designed to maximize the absorption of 1550 nm photons. A 60 nm-thick aluminum layer is deposited on a double-sided polished silicon substrate using electron-beam evaporation. A photoresist lift-off process is used to leave squares of aluminum that will form a mirror underneath the tungsten detector. SiO_2 is deposited using plasma-enhanced chemical vapor deposition and is followed by the DC-sputtered a-Si/W/a-Si trilayer. To pattern the trilayer films into sensors, a photoresist mask is used to expose squares of the trilayer. The top layer of a-Si is ion milled to expose the tungsten, which is then etched with a commercial tungsten etch. The wafer is again coated with photoresist and patterned, exposing the edges of the trilayer squares for the wiring layer. The a-Si is ion-milled to expose the tungsten, and approximately 60 nm of aluminum for the wiring layer is e-beam evaporated directly onto the tungsten. The excess aluminum is removed via a lift-off technique. The final step is the deposition of ~50nm of a-Si as an anti-reflection layer.

IV. Performance

Fig. 2 shows examples of the pulses from the TES detector system. The pulses are the response of the TES detector to a pulsed, attenuated, gain-switched 1550nm laser diode. The different pulse heights correspond to a different number (1, 2 or 3) photons absorbed by the detector. Two noise triggers are also included to indicate the signal to noise ratio. The rise time of these pulses is ~1μs and is limited by the inductance of the SQUID array amplifier and the bias resistance of the sensor. The thermal recovery time of the device is approximately 4μs.

The quantum efficiency (QE) of a bare tungsten TESs, defined as the ratio of the number of electrical pulses out to the number of photons incident on the detector, is typically around 15–20% broadband from the near-IR to the visible wavelengths. It is limited by light being reflected from the front surface of the detector or transmitted through the tungsten. We have increased the QE by embedding the TES in an optical structure that maximizes the absorption in the tungsten[6]. To date, we have been able to demonstrate a fiber-coupled TES detection system with a system detection efficiency (DE) that is >88%[1]. The system DE is limited by losses in the aluminum mirror and bending losses in the fiber between the room temperature fiber port and the fiber coupling at the detector.

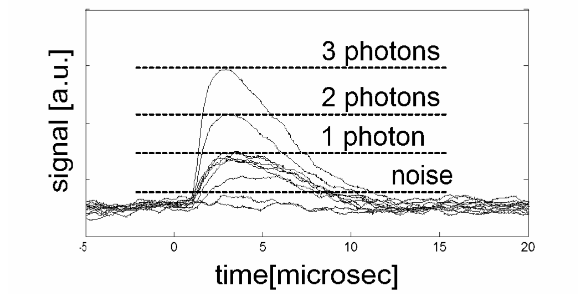

Fig. 2. These are examples of electrical pulses from the TES detector when illuminated with a heavily attenuated pulsed 1550nm laser. The different pulse heights (3 different heights) correspond to a different number of photons absorbed by the detector. Two noise triggers are also shown.

V. Conclusions

With their low noise and photon-counting ability, transition-edge sensors are an enabling technology for a number of quantum-information experiments[7], [8]. Increasing the detection efficiency beyond 88% at 1550 nm is in principle simple and involves fabricating an optical structure with more layers and finer control over layer thickness. Simulations indicate the possibility of increasing the efficiency well above 99% at any given wavelength in this spectrum. With better thermal engineering and material science advances in superconducting T_c control in W, we expect to decrease the thermal recovery time to less than 1μs. The combination of improved detection efficiency and faster speeds should make these detectors an extremely valuable tool for quantum optics and quantum-information processing.

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