High-Efficiency Photon-Number-Resolving Detectors based on Hafnium Transition-Edge Sensors

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Abstract. Generation of nonclassical states of light is at the foundation of numerous quantum optics experiments and optical quantum information processing implementations. One such non-Gaussian optical quantum state can be obtained by photon subtraction from a squeezed optical state. Photon-number-resolving detectors with high efficiency and low dark counts are needed for heralding the subtraction of one, two or more photons. Transition-edge sensors (TES) optimized for high detection efficiency at 850 nm, seem to be ideal heralding detectors for such quantum optics experiments. In this work, we describe the fabrication and characterization of hafnium TESs embedded in an optical structure for optimal absorption at 850 nm. Accurate measurements of optical constants for all materials and fine control of layer thicknesses in the optical cavity should increase the detector efficiency to values higher than 95 %.

Keywords: Optical superconducting transition edge sensor, Photon number resolving detector, Quantum optics
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INTRODUCTION

Single-photon detectors with wavelength-tunable high detection efficiency (η), photon-number-resolving capabilities and very low dark-count rate are required to enable a number of applications in the field of Quantum Information [1] such as Quantum Optics, and Quantum Information Processing (e.g., Linear Optics Quantum Computing, Quantum Key Distribution). Generation of nonclassical states of light is at the foundation of numerous quantum optics experiments and optical quantum information processing implementations. One such non-Gaussian optical quantum state can be obtained by photon subtraction from a squeezed optical state [2]. The size and fidelity of the obtained nonclassical state increases with the number of photons subtracted. In this case, detectors are required that have high detection efficiency and have the ability to unambiguously resolve photon number. Superconducting transition-edge sensors (TESs) optimized for high efficiency at 850 nm have been implemented as the heralding detectors for such an experiment [2]. In this paper we describe the fabrication and device performance of bare hafnium TESs and hafnium devices optimized for high detection efficiency at 850 nm.

HAFNIUM TRANSITION-EDGE SENSOR

Superconducting transition-edge sensors can be optimized to count the number of visible/infrared photons in a pulse of light with negligible dark count rates. For this type of microcalorimeters, we use the superconducting transition as the thermometer to measure the temperature increase resulting from the absorption of energy, the superconducting material as the absorber of the photons, and the weak thermal link between the electrons and phonons in the superconductor to reset the electrons in the device to their steady-state operating temperature [3].

Hafnium has been previously studied as a promising material for superconducting devices such as superconducting tunnel junctions [4]. Our sputtered hafnium (Hf) thin films have a superconducting transition temperature around 200 mK. It has a hexagonal close-packed crystallographic structure that may not be as susceptible to thermal stresses as the β-tungsten's (W) A15-crystallographic structure [5]. The Hf TESs described in this paper measure 25×25 μm^2 and are approximately 30 nm thick. The optical absorption of a 30 nm bare Hf film (with no optical cavity structure) was measured to be ~ 40 % at 850 nm wavelength. The superconducting transition

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temperature (T_c) of an uncoated device is 195 mK with a width of ~ 3 mK, and is comparable to the T_c measured for an unpatterned film. Figure 1 shows the power and current as a function of voltage bias for the Hf TES. The power in the self-biased region (where the power is constant with the applied voltage) can be used to estimate the electron-phonon coupling constant, κ [3]. Hafnium, as with tungsten, displays a low thermal coupling constant between the electrons and phonons (κ(W)= 0.3 nW/(μm^3·K^5); κ(Hf)= 0.46 nW/(μm^3·K^5)) that provides a weak thermal link from the electron system to the phonon system at base temperature.

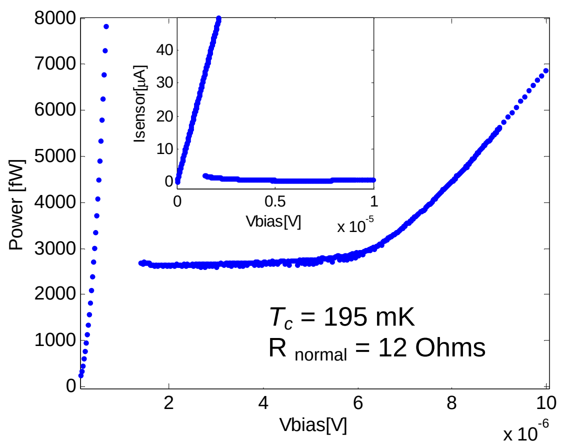

FIGURE 1. Power and current (inset) as a function of voltage bias for 25 μm×25 μm Hf TES. Below 5 μV the sensor is self-biased.

The TES is operated as a photon detector in the self-biased region. Any heat from absorbing photons increases the temperature of the electrons in the hafnium and raises the resistance of the device.

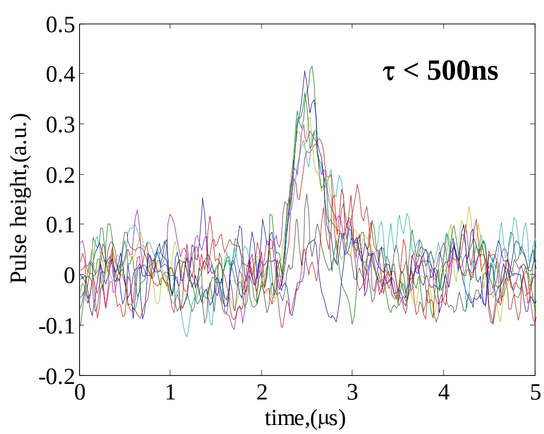

FIGURE 2. Hafnium (bare) device response to 850 nm (1.46 eV) photons. The measured (1/e) decay time is ~ 500 ns.

The change in resistance causes a measurable drop in the current flowing through the device.

We use a standard single-mode telecommunication fiber with a 9 μm core to couple light into the device. The response of the device to single photons at 850 nm is shown in Figure 2. The measurements of bare Hf devices indicate that Hf is a good candidate for superconducting single-photon detectors and to embed in an optical stack in order to obtain a device of high detection efficiency at 850 nm.

TRANSITION-EDGE SENSOR OPTIMIZED FOR 850 nm

TES devices can be optimized for high quantum efficiency at particular wavelengths from the near-ultraviolet to the near-infrared by designing multilayer device structures that include integrated thin-film layers that enhance the absorption of light into the active device material [6,7,8]. By embedding tungsten TES in an optical structure that enhances absorption, we have previously fabricated devices that can be used in systems with 95 % ± 2 % detection efficiency at 1550 nm [6]. Using the same principle, we can optimize the TES for absorption at 850 nm. However, a tungsten TES embedded in an optical structure requires being sandwiched between two thin layers of amorphous silicon to stabilize the superconducting transition temperature against thermal-stress-induced-suppression [5]. Optically, amorphous silicon begins to absorb light at wavelengths shorter than 1000 nm. In order to achieve close to 100 % detection efficiency at 850 nm we need to eliminate amorphous silicon from our optical designs and hence, switch from tungsten to hafnium as the TES material.

Similar to previous work on tungsten and titanium TESs [6,7,8], we designed two optical structures that were calculated to increase the absorption in hafnium to higher than 99 % without the use of amorphous silicon. The optical structure consists of a mirror of silver or gold metal layer, a dielectric spacer, the Hf TES, and an antireflective (AR) coating designed for 850 nm. In one structure, we used HfO_2 as the AR coating; in the other, we used Si_3N_4.

When embedding Hf in an optical structure, we found out that there are a number of processing steps that are important for successful TES fabrication. Growth of Si_3N_4 on top of either Au or Ag (metallic mirrors for 850 nm) requires a thin (~ 1nm) flashing layer of Ti in order to improve adhesion and preserve the optical properties of the Si_3N_4. Also, Hf grows a hard native oxide that has to be carefully removed in order to be able to make electrical contacts for the TES.

HfO_2 is a conventional optical coating material and has a room-temperature coefficient of thermal expansion very close to that of Hf. We deposit HfO_2 on Hf using electron-beam deposition in an oxygen atmosphere. Devices made with HfO_2 as AR coating result in an increase by a factor of 10 in the normal-state resistance of the Hf device (compared to that of the bare Hf device), making it unusable. It is possible that during HfO_2 deposition, oxygen diffuses through the HfO_2 and reacts with the thin Hf layer, resulting in a much thinner Hf film.

Si_3N_4 is also a commonly used optical coating material. In order to prevent a high normal resistance as a result of possibly intermixing between Si_3N_4 and Hf, we use an ammonium hydroxide cleaning step prior to Si_3N_4 deposition on the Hf film.

For the Si_3N_4 coated device, the optimized optical structure (Figure 3) consists of a back-side reflecting mirror (electron-beam-evaporated Au film ~60 nm thick), a dielectric spacer (physical-vapor-deposition (PVD) grown layer of Si_3N_4 ~290 nm thick), and the Hf detector layer (DC-sputtered high-purity Hf, 29 nm thick). Finally, an antireflecting (AR) coating is deposited on top of the Hf detection layer (PVD-grown layer of Si_3N_4 ~ 103 nm thick). Figure 3 indicates a good agreement between the predicted reflectance of the optical stack (simulation curve) and the measured reflectance of the stack (measurement curve). Measurements of the structure reflectivity indicate that the expected device efficiency, neglecting system losses, is greater than 99 % at 850 nm wavelength (Figure 3).

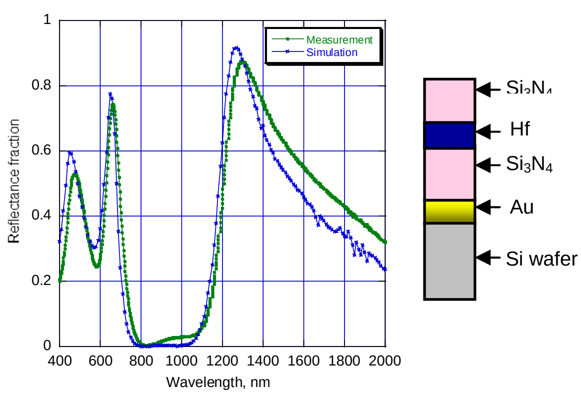

FIGURE 3. Optical structure for Hf optimized TES devices at 850 nm. The plot shows good agreement between predicted reflectance of the stack (simulation) and reflectance measurement of the stack (measurement).

Hafnium TESs embedded in the above optical structure displayed a broad superconducting transition temperature range 140 mK-190 mK. This broad transition compared to the sharp transition (195 mK) for Hf only devices, may indicate stress-induced transition broadening as the structure is cooled down to millikelvin temperatures [5]. The coefficients of thermal expansion for Hf and Si_3N_4 are dissimilar at room temperature.

Our system detection efficiency with these devices was measured to be ~ 85 % at 850 nm. Figure 4 illustrates the pulse-height distribution from our TES photon counter in response to a 850 nm (1.46 eV) pulsed laser, attenuated to give an average of ~ 1.06 photons per pulse. As Figure 4 shows, the TES displays good discrimination between multiphoton events.

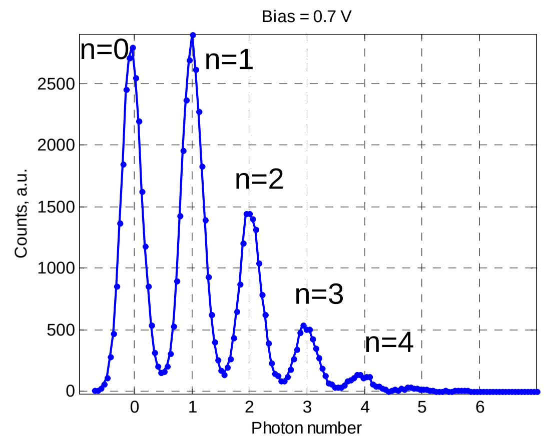

FIGURE 4. Pulse-height distribution of a pulsed laser source measured with the Hf TES embedded in the optical cavity. The source was 10 ns wide pulses of 850 nm laser light at a repetition rate of 10 kHz and containing an average photon number of μ ~ 1.06.

Figure 5 shows the TES response from absorption of different photon numbers.

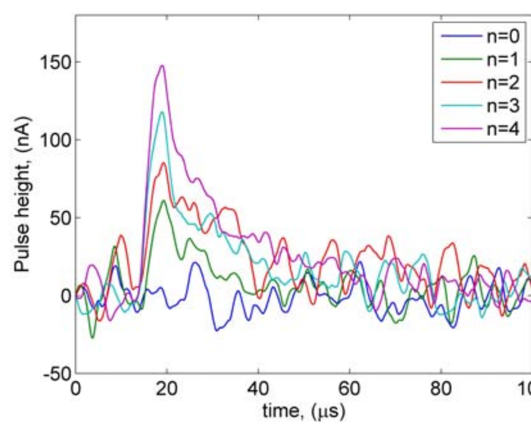

FIGURE 5. Detector response to 850 nm (1.46 eV) photons. The pulses correspond to zero-, one-, two-, three-, and four-photon events. The measured (1/e) decay time is ~ 20 μs.

A significant increase in recovery time was observed compared to the bare hafnium devices (Figure 2). The recovery time (1/*e*) for these pulses is 20 μs, and the rise time is 600 ns. These slow recovery times are likely to be a result of the broad transition displayed by the Hf TES once embedded in the optical structure.

Although the estimated absorption in Hf TES embedded in optical structure was higher than 99 %, we measured ~ 85 % system detection efficiency. Possible sources of this unexpected additional loss are being investigated.

CONCLUSIONS

Hafnium is a promising material for optical TESs, however, when embedded in an optical stack, materials properties such as reactivity and compatibility need to be addressed. The Hf TES embedded in an optical structure displayed superconducting transition broadening that is likely to be related to materials compatibilities in the optical structure. Our first generation Hf TESs embedded in an optical stack measured ~ 85 % system detection efficiency at 850 nm. In the future, different buffer layers and/or AR coatings will be explored in Hf TES optical structures.

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