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2	Investigation of Ti/Au Transition-Edge Sensors for
3	Single Photon Detection
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5	Xiaolong Xu 1 • Mauro Rajteri 2 • Jinjin Li 1 • Shuo Zhang 3 •
6	Carlo Pepe 2,4 • Jian Chen 1 • Huifang Gao 1 • Qi Li 1 • Wei Li 1 •
7	Xu Li 1 • Mingyu Zhang 1 • Yanyan Ouyang 1 • Xueshen Wang 1
8	
9	National Institute of Metrology (NIM), 100029 Beijing, China
10	Istituto Nazionale di Ricerca Metrologica (INRiM), 10135 Torino, Italy
11	ShanghaiTech University, 201210 Shanghai, China
12	Politecnico di Torino, 10129 Torino, Italy
13	
14 15	Abstract Transition edge sensors (TES) are remarkable superconducting
16	devices for a wide range of radiation detection with the ability of both
17	energy resolution and counting photons. For the detection of single photons
18	at telecom wavelength, optical Ti/Au bilayer TESs are fabricated and
19	characterized. The superconducting transition temperature ( $T_c$ ) of the Ti/Au
20	films are effectively tuned from 162 mK to 72 mK by increasing the relative
21	thickness ratio between the Au and Ti layer. The sensitive area is 20 $\mu m \times$
22	$20 \ \mu\text{m}$ , on which an SiO <sub>2</sub> /SiN <sub>x</sub> antireflection structure is coated by an ICP-
23	PECVD process. The TES device shows an energy resolution of 0.19 eV and
24 25	can discriminate up to 36 incident photons, with an effective time constant around $107 \text{ us at } 05 \text{ mK}$
23 26	around 107 µs at 95 lifk.
20	
21	<b>Keywords</b> Superconducting transition-edge sensors • 11/Au bilayer •
28	antireflection coating
29	
30	1 Introduction
31	
32	Superconducting transition-edge sensors (TESs) have been widely used for
33	single photon detection from near infrared, visible light, X-ray to even $\gamma$ -ray.
34	The most distinctive feature of TESs is the single photon energy resolution
33 26	and the photon-number resolving (PNR) capability (when the photon energy
30 27	is already known) [1], but they also snow high quantum efficiency [2],
31	[4] dork motter detection [5] X ray free electron locar [6] establish X ray
50	$T_{+1}$ , uark matter detection $T_{J}$ , A-ray free-electron laser $T_{J}$ , satellite A-ray

[4], dark matter detection [5], X-ray free-electron laser [6], satellite X-ray
observatory [7] and cosmic microwave background observatory [8]. In the

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field of optical metrology, TESs will realize the quantum revolution of
 photometry [9].

3 In this paper we report about the fabrication and preliminary 4 characterization of optical Ti/Au TESs for single photon detection at telecom 5 wavelength. The critical temperature  $T_c$  of Ti/Au superconducting films is 6 tuned by controlling the thickness ratio of the two layers. An antireflection 7 SiO<sub>2</sub>/SiN<sub>x</sub> coating is deposited on the Ti/Au bilayer film before the 8 alignment of an optical fiber, and the simulated reflectivity is shown. The 9 TES device shows a high energy resolution (0.19 eV) and PNR capability up 10 to 36 photons.

11

#### 12 **2 TESs Fabrication**

13

14 NIM fabricated TESs with two active areas ( $10 \mu m \times 10 \mu m$  and  $20 \mu m \times 20 \mu m$ ) on the wafer. Considering the reliability of the optical fiber alignment 16 and to avoid optical geometric loss. In this paper we present preliminary 17 results for the TES with  $20 \mu m \times 20 \mu m$  active area, which allows an easier 18 and better fiber optics alignment, but with a larger heat capacity that affects 19 the energy resolution. We have confirmed that the  $20 \mu m \times 20 \mu m$  Ti/Au 20 TES has sufficiently ability to resolve 1550 nm single photon detection.

21

22 2.1 Ti/Au bilayer films

23

24 The Ti/Au bilayer films are deposited on double-polished 3-inch 500 µm 25 silicon substrates with 500 nm SiN<sub>x</sub> layers on both sides using a magnetron 26 sputtering process. The base pressure is  $\sim 10^{-6}$  Pa, and the sputtering pressure is 0.1 Pa. Firstly, a 5 nm Ti film is sputtered as the adhesion layer. Then an 27 Au layer is deposited as the normal metal layer with a thickness  $d_{Au}$  of 60 28 29 nm. A variable thickness  $d_{Ti}$  of Ti layer (40 to 70 nm) is deposited on Au 30 layer. T-L 1 TL 

31

<b>Tab. 1</b> The $\rho_{\rm eff}$ and $R_{\rm q}$ of Ti/Au films					
Sampla	Thickness/nm		- /= 0 -==	D /nm	
Sample	Ti	Au	$\rho_{\rm eff}/m^2 \cdot m$	$\Lambda_q/mm$	
NIM-21	70	60	76	1.11	
NIM-22	60	60	65	1.02	
NIM-23	50	60	57	1.04	
NIM-24	40	60	53	1.01	

32

The effective resistivity  $\rho_{\text{eff}}$  root mean square roughness  $R_q$ , and  $T_c$  of the Ti/Au bilayer are measured for different  $d_{\text{Ti}}/d_{\text{Au}}$  ratios. The  $\rho_{\text{eff}}$  is defined as  $R_{\Box} \times (d_{\text{Au}} + d_{\text{Ti}})$ , where  $R_{\Box}$  is the sheet resistance. The  $\rho_{\text{eff}}$  is proportional to

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1 the ratio  $d_{\text{Ti}}/d_{\text{Au}}$  as shown in Tab.1. NIM-21 shows the highest  $\rho_{\text{eff}} = 76$ 2  $n\Omega \cdot m$ , and NIM-24 shows the lowest  $\rho_{\text{eff}}$  as 53  $n\Omega \cdot m$ , which trends to the 3 bulk Au resistivity ~ 22  $n\Omega \cdot m$  [10]. The  $\rho_{\text{eff}}$  will be helpful for the resistance 4 design of the TESs. The  $R_q$  are similar ~ 1 nm, indicating a good interface 5 morphology between the Ti and Au layers. The smooth interface will make 6 weak proximity effect [11,12].

7 The  $T_c$  are measured in an adiabatic demagnetization refrigerator (ADR) 8 system with a base temperature ~ 30 mK and are shown in Fig.1. The weak 9 proximity effect occurs for the largest  $d_{Ti}/d_{Au}$  ratio, and the  $T_c$  of NIM-21 is 10 162 mK. Inversely, NIM-24 shows a stronger proximity effect which 11 suppresses the  $T_c$  to 72 mK.



13 14 **Fig. 1** The  $T_c$  of the Ti/Au bilayers with different  $d_{Ti}/d_{Au}$  ratios. (Color figure 15 online)

15 16

2.2 Ti/Au TESs

17 18

19 The optical image TES device is shown in Fig. 2. The  $20 \ \mu m \times 20 \ \mu m$  active 20 Ti/Au film area is defined by UV lithography followed by a lift-off process. 21 The Nb superconducting leads for electrical wiring are also fabricated via a 22 lift-off process. The thickness of the Nb layer should be thick enough to

23 maintain its superconductivity after the following fabrication steps.

24



- **Fig. 2** Images of an optical Ti/Au TES with a 20  $\mu$ m × 20  $\mu$ m sensitive area with Nb leads: (a) a whole view of the TES device; (b) the enlarged view of
- the device achieved during the optical fiber alignment process. A light spot can be observed at the center of TES to locate the position of optical fiber.
- 29 can be observed at the center of TES to locate the positi 20 (Color figure online)
- 30 (Color figure online)

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1 2 2.3 Antireflection structure 3 4 An antireflection structure composed of  $SiO_2$  and  $SiN_x$  dielectric layers is 5 deposited on the TES devices to reduce the device reflectivity. The vertical 6 stack structure is shown in Fig. 3(a). The  $SiO_2$  and  $SiN_x$  layers are fabricated 7 using an inductively coupled plasma assisted plasma-enhanced chemical 8 vapor deposition (ICP-PECVD) method. The refractive index and extinction 9 coefficient (n, k) are (1.47, 0), (1.92, 0), (4.03, 3.81), (0.56, 9.91) for SiO<sub>2</sub>, 10 SiN<sub>x</sub>, Ti and Au at 1550 nm, respectively. These optical parameters were 11 measured using a Horiba UVISEL2 spectroscopic ellipsometers. The refractive index of the UV-resin for the fiber alignment process (n = 1.56) is 12 13 similar to that of the fiber core (n = 1.47) [2]. With the above parameters, 14 the reflectivity at 1550 nm is simulated and shown in Fig. 3(b). The lowest 15 reflectivity is near 23%. The simulated transmittance is 10<sup>-3</sup>. To control the thickness accurately by the end point detection module of ICP-PECVD, 270 16 17 nm SiO<sub>2</sub> and 350 nm SiN<sub>x</sub> are deposited on the TES device. 18



19 20

Fig. 3 (a) the cross section of the layer structure of the TES including the
 coupled optical fiber; (b) Simulation results of the reflectivity of the optical
 structure. (Color figure online)

23

24 2.4 Optical fiber alignment25

26 The optical fiber alignment process is operated with an inverted optical 27 microscope with a near-infrared CCD. The TES device is fixed on the 28 sample holder, and the optical fiber is aligned perpendicular to the device by 29 a six-dimension adjustment frame. Fig.2b shows the backside image 30 captured from the CCD. As the pig-tail optical fiber is connected to a 1550 31 nm light source, the fiber core emits a light spot. When the light spot locates 32 at the center of the TES, the resin is cured with UV light to fix the fiber to 33 the device.

34

# 35 **3 TES characterization**

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1 The NIM-23 device shows a  $T_c$  of 95.2 mK in the voltage-biased circuit with 2 a DC-SQUID (Fig.4(a)). The TES's  $T_c$  in constant voltage mode shows 3 around 30 mK shift compared with the film shown in Fig.1. The device 4 shows a sharp superconducting transition with a width  $\Delta T = 4.3$  mK. The 5 TES working point is around 6% of  $R_n$ .

6 Fig. 4(b) shows the current flowing through TES  $I_{\text{TES}}$  as a function of 7  $I_{\text{Bias}}$  for the bath temperature  $T_{\text{b}}$  from 40 mK to 88 mK. The 20 mΩ shunt 8 resistance  $R_{\text{s}}$  on the SQUID chip is selected. From the  $I_{\text{TES}}$ - $I_{\text{Bias}}$  curves, the 9 parasitic resistance  $R_{\text{p}} = 10 \text{ m}\Omega$ , the normal resistance of TES  $R_{\text{n}} = 475 \text{ m}\Omega$ 10 and the working point resistance of TES  $R_{\text{o}} = 28 \text{ m}\Omega$  at 6% of  $R_{\text{n}}$  can be 11 obtained. The heat capacity *C* of the Ti/Au bilayer is calculated as 2.2 fJ/K 12 [13].

13



14 Temperature (mK)  $I_{Bias}(\mu A)$ 15 **Fig. 4** (a) The  $T_c$  of the TES device *vs.* temperature measured with a DC-16 SQUID (b)  $I_{TES}$  *vs.*  $I_{Bias}$  at different base temperatures. (Color figure online) 17

18 The photon detection properties are characterized with a pulsed laser at 19 1550 nm. With the statistics data of the pulse signals of photons detected by 20 the TES device, the histograms of photo states are shown in Fig. 5(a) and 21 Fig. 5(b). The energy resolution  $\Delta E$  is defined as the full width at half 22 maximum (FWHM) of the first photon state peak. Fig. 5(a) shows the count 23 histogram for the pulses filtered with a Wiener filter [14]. The fit of the 24 histogram with Gaussians convoluted with a Poissonian statistics (typical of 25 lasers) gives a detected mean photon number  $\mu = 0.6$  photons per pulse and 26 an energy resolution  $\Delta E = 0.19$  eV. In the same experimental conditions, we 27 have also continuously reduced the attenuation of the laser during the 28 acquisition, obtaining the histogram of Fig.5(b). In this case our TES can 29 clearly distinguish up to 36 photons before reaching the saturation region. 30 The typical averaged pulse response is shown in Fig. 5(c), which is fitted by 31 a double exponential equation. The electrical time constant ( $\tau_{\text{eletrical}}$ ) is 32 about 360 ns. And the response time constant ( $\tau_{eff}$ ) is about 107 µs.



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2 3 Fig. 5 Histograms of pulse height and photon states. The measurement 4 conditions are reported in the insets. (a) The histogram is obtained from 5 waveforms filtered with Wiener filter. The red curve is a fit with Gaussians 6 convoluted with a Poissonian statistic; (b) The histogram is obtained directly 7 with the signal acquired with a digital oscilloscope while the attenuation of 8 the laser is reduced to show the whole photon states detectable with the TES; 9 (c) Single photon pulse response. (Color figure online)

1

# **4** Conclusions

12 13 The optical Ti/Au bilayer TES device shows an energy resolution of 0.19 eV 14 with a 20  $\times$  20  $\mu$ m<sup>2</sup> active area. The devices can discriminate up to 36 photon states. The results have shown that TESs are promising detectors for 15 counting single photon and promote the application of TES on the optical 16 17 quantum metrology. In the future, the quantum efficiency will be evaluated 18 and improved by optimal optical cavity.

19

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