Characterization and fabrication of Ti/Pd bilayers for transition-edge sensors

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Abstract. Transition-edge sensor (TES) microcalorimeters are extensively used as single photon detectors from infrared to x-ray. Their good energy resolution and photon number resolving capability at visible and near-infrared wavelengths make them powerful tools for quantum information and quantum computation. In this work we report details on the fabrication of Ti/Pd TESs deposited by e-beam evaporation on silicon nitride substrates. By the proximity effect between Ti and Pd, the Ti critical temperature was tuned down to 100 mK, usual working temperature for these devices. Sharp transition of two-three mK and reproducible Tc were obtained. The Pd material can be a valid alternative to widely used Au proximity material thanks to its stronger influence on the Ti layer, that allows to obtain the same temperature reduction with thinner layers. Thermal and electrical characteristics of Ti/Au and Ti/Pd bilayers are compared in view of single photon detection.

Introduction
TES microcalorimeters have become fundamental in a wide range of applications like high-energy astrophysics, nuclear science and biophysics, astronomy and quantum information [1, 2] thanks to their photon number resolution. TESs can be made sensitive to single photon from visible to near-infrared wavelengths through the proper choice of material and size [3]. The working temperature of a TES usually ranges from about tens of mK to hundreds of mK depending on speed, noise, resolution that are requested for the specific application. Few elements have a superconducting transition in this range of temperatures, thus bilayers and multilayers of normal metal alternate to superconducting films are often used as thermometers [4]. In these structures $T_c$ can be tuned by varying the film thicknesses as a consequence of the proximity effect. The majority of TESs are a combination of Ti or Mo and noble metal (Cu, Au, Ag) with high thermal conductance to improve the temperature uniformity on the TES. The critical temperature of a superconducting-normal structure depend on interface transparency and coherence length of the Cooper pair in the normal layer $\xi_N$, besides on the film thicknesses [5]. The interface transparency is fabrication process dependent while $\xi_N$ is related to the material of the normal layer. Among non-magnetic metals, Pd is that one that causes the stronger $T_c$ reduction in a normal-superconducting structure and it has a $\xi_N$ half of that of metals with high electrical conductance as Au [6].

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In this work, we report the fabrication and characterization of Pd/Ti bilayers in view of application to TESs for photon counting. The electrical and thermal properties of Pd/Ti TES are compared to that of Au/Ti TES.

**Experimental**

TES were fabricated on double side polished Si wafers covered on both sides by 500 nm thick SiN layer grown by LPCVD. The pressure in the evaporation chamber was lower than 2x10^{-7} mbar before deposition. The substrate temperature $T_s$ was settled at 100 °C. Ti films have been prepared by starting from a 99.99+% bulk Ti. The distance between crucible and substrate was 10 cm and the deposition rate was about 1.5 nm/sec for Ti, Au and Pd. The fabrication process consisted of three steps. First, 10-15 nm of Ti was deposited on SiN substrate in order to improve the adhesion of the Pd or Au layer (second step). The last step was the deposition of the superconducting Ti film. Previous work [7] shows that inverting the traditional order superconductor-normal metal undesirable effects on the reproducibility of the $T_c$ can be avoided.

The devices were fabricated by standard photolithographic process. For Ti/Au TES the unwanted material was usually removed using chemical wet etching. Ti/Pd TESs and few samples of Ti/Au were etched by RIE (Ti) and ion-milling (Au, Pd). The superconducting wiring of Al, with thickness between 100 and 150 nm, was defined by lift-off technique combined with rf-sputtering of the superconducting films.

The sensor resistance was measured using four wire readout and a lock-in amplifier with typical sinusoidal excitation current of 0.2-1µA and a frequency of 37 Hz.

**Results and discussion**

In figure 1 the resistance $R$ vs temperature $T$ curve of a Pd/Ti TES, at a bias current $I_b=0.2$ µA, is shown.

![Figure 1](image_url)

**Figure 1.** The resistance $R$ vs temperature $T$ curve of a Pd/Ti TES at a bias current $I_b=0.2$ µA and the logarithmic derivative $\alpha=T/R(dR/dT)$.

The film thicknesses of Pd and Ti are 16 nm and 65 nm respectively. The area of the TES is 20 µm x 20 µm. The logarithmic derivative of $R-T$ curve, $\alpha = T/R(dR/dT)$, has a peak value of 1180. The transition is rather narrow (~ 0.5 mK), a sign of the good quality of the TES edges. In fact imperfections along the outer edges can reduce the proximity between normal metal and superconductor and as result the superconducting transition of a TES is relatively wide with undesirable features [8].
Figure 2. (a) The transition temperature of the Pd/Ti film ($T_c$) on Ti film transition temperature ($T_{c0}$) is plotted against Pd thickness ($d_n$) on Ti thickness ($d_s$). The solid curves are evaluated by equation (1) with different transmission coefficient $t$. (b) Normalised transition temperature of Au/Ti vs Au thickness ($d_n$) on Ti thickness ($d_s$) for our data (full circles) and data from [7] (open circles).

In the figure 2 (a) the critical temperature ($T_c$) of Pd/Ti bilayers on critical temperature of Ti film ($T_{c0}$) is plotted vs $d_n/d_s$ where $d_n$ is the normal film thickness and $d_s$ the superconducting film thickness. The fitting curves in figure 2 (a) are calculated by the equations of Usadel’s model [9]:

$$T_c = T_{c0} \left[ 1.13 \left( 1 + \frac{1}{\alpha} \right) \left( \frac{1}{t} + \frac{2d_n e^2}{3h\sigma_n \left( \frac{\lambda_f}{2} \right)} \right) \right]^a$$

$$d_0 = 1.57k_BT_{c0}\lambda_f^2N_s$$

$$\alpha = d_s^{-1}N_s^{-1}(d_sN_n)^{-1}$$

where $T_{c0}$ is the critical temperature of the superconducting film, $t$, ranging between 0 and 1, is the transmission coefficient at the interface between the superconductor and normal metal, $\lambda_f$ is the Fermi wavelength, $N_s$ and $N_n$ are the densities of electronic states for the superconducting and normal films respectively and $\sigma_n$ the electrical conductance of normal layer. As $T_{c0}$ we take the transition temperature $T_c = 380$ mK of a Ti film with a thickness of 65 nm. $\lambda_f = 1.12$ nm obtained by the best fit of experimental data with (1) is in the range of $\lambda_f$ reported in literature (0.45 nm and 3.6 nm) [10]. For Ti and Pd, from the literature, we have $N_s = 1.81x10^{17}$ 1/Jm$^3$ [11] and $N_n = 6.41x10^{17}$ 1/Jm$^3$ [10] respectively. The electrical conductivity of Pd, $\sigma_n = 2x10^5$ $\Omega^{-1}$cm$^{-1}$, has been obtained as difference between the electrical conductance of the Pd/Ti bilayer and that one of the Ti layer. In ref. [12] the authors estimate for sputtered Pd in Pd/Nb multilayer a similar value of $\sigma_n$. The data in figure 2 (a) are fitted by (1) with different transmission coefficient indicating a different transparency of the Pd/Ti interface. Furthermore, this spread in the experimental data could be due to differences in the vacuum pressure before the deposition of Ti that causing a different contamination level in the first atomic layer of Ti gives up an lower interface transparency.

Figure 2 (b) shows the normalised critical temperature of Au/Ti against $d_n/d_s$, for our data (full circles) and data from [13] (open circles) together with the linear fit $T_c/T_{c0} = 1-0.54$ $d_n/d_s$. By
comparison between figure 2 (a) and figure 2 (b) it is clearly visible that the $T_c$ diminution of Pd/Ti bilayer is stronger than that of Au/Ti bilayer and a film of Au four time thicker than a Pd film is required to reduce the transition temperature of the same extent at $T_c/T_{c0} = 0.26$.

![Figure 3](image)

(a) ETF-TES bias circuit with SQUID read out. (b) TES current vs. bias current of a Pd/Ti TES and Au/Ti TES for a bath temperature close to 50 mK.

Figure 3. (a) ETF-TES bias circuit with SQUID read out. (b) TES current vs. bias current of a Pd/Ti TES and Au/Ti TES for a bath temperature close to 50 mK.

The thermal properties of a TES can be extracted from curve of TES current $I_{TES}$ vs. bias current $I_{bias}$. In figure 3(a) is shown the bias circuit of a TES where $R_{bias}$ is the shunt resistor of 9.5 mΩ used to apply the voltage biasing to the TES. The trend of the $I_{TES}$ vs. $I_{bias}$ at a bath temperature close to $T_B = 50$ mK is shown in figure 3(b) for a Pd/Ti TES and Au/Ti TES. We can distinguish at low $I_{bias}$ values the superconducting vertical region, except for a parasitic resistance of some mΩ, for $I_{bias} > 65 \mu$A (100 µA for Au/Ti TES) a normal region, corresponding to the 1.6Ω (0.225 Ω for Au/Ti) straight line, is observed. The intermediate region corresponds to the superconducting to normal transition.

![Figure 4](image)

Figure 4. The decay time of pulse, from 690 nm single photon, is $\tau_{ETF} = 20 \mu$s for Pd/Ti and $\tau_{ETF} = 5 \mu$s for Au/Ti.

The power flow from TES at temperature $T$ to thermal bath at temperature $T_B$ is given by $P = \Sigma V (T^n-T_B^n)$ from which it derives the dynamic thermal conductance $G = dP/dT = n \Sigma V T^{n-1}$ where $n = 4+5$, $V$ is the TES volume and $\Sigma$ is the material dependent constant. $G$ can be written in term of average thermal conductance $G_{av} = P/(T-T_B)$ as $G = G_{av} n^{n-1} (T-T_B)/(T^n-T_B^n) = n P T^{n-1} (T^n-T_B^n)^{-1}$. For Au/Ti TES we find $G = 1.5x10^{-10}$ W/K for $n = 4$ ($G = 1.8x10^{-10}$ W/K for $n = 5$) where $T = T_c = 103$ mK, $T_B = 51$ mK, and $P = 3.6x10^{-12}$ W is the power dissipated in TES at the bias point $I_{bias} = 48 \mu$A, $I_{TES} = 10 \mu$A. For Pd/Ti TES the dynamic thermal conductance is $G = 5.24x10^{-12}$ W/K for $n = 4$ ($G =$
6.45x10^{-12} \text{ W/K for } n = 5), \text{ where } T_c = 110 \text{ mK}, T_b = 55 \text{ mK and } P = 1.4x10^{-13} \text{ W at } I_{bias} = 15 \mu\text{A and } I_{TES} = 1.1 \mu\text{A}. \text{ The heat capacity } C \text{ of Au (72 nm)/Ti (55 nm) TES is calculated as the sum of every layer capacity. In this way we have [4] } C = 0.93 \text{ (Ti)} + 0.19 \text{ (Au)} = 1.07 \text{ fJ/K at the transition temperature of } T_c = 103 \text{ mK. Total heat capacity has to be enhanced by a factor of 2.43 because the Ti layer is supposed to be superconducting at that temperature [4], so the final heat capacity become } C = 2.43 \text{ fJ/K. In a similar manner we find for Pd (16 nm)/Ti (65 nm) TES } C = 3.33 \text{ fJ/K where the Pd specific heat is taken from [13]. By knowing } C, G, \alpha \text{ and } n \text{ the effective time constant } \tau_{\text{ETF}} = \frac{\tau_{\text{th}}}{1 + \alpha I/n} \text{ where } \tau_{\text{th}} = \frac{C}{G}, \text{ responsivity } S = \frac{I_{TES} a G T_c}{I}, \text{ and energy resolution } E = 2.35(4k_B T_c^2 C/\alpha (n/2)^{1/2})^{1/2} \text{ can be evaluated. } a_0, \text{ the derivative } \frac{\text{dln} R}{\text{dln} T} \text{ at } I_{TES}, \text{ can be estimated by } \alpha_I = n(\tau_{\text{ETF}}/\tau_{\text{th}} + 1)^1 \text{ where } \tau_{\text{ETF}} \text{ is the decay time of a TES pulse. From best fit of pulse for Pd/Ti TES (figure 4) we have } \tau_{\text{ETF}} = 20 \mu\text{s, that substituted in the above equation with } \tau_{\text{th}} = 500 \mu\text{s gives } \alpha_I = 125. \text{ In the same way, for Au/Ti TES, it is obtained } \tau_{\text{ETF}} = 5 \mu\text{s, and } \alpha_I = 8.2 \text{ with } \tau_{\text{th}} = 13 \mu\text{s. Finally, responsivity and energy resolution can be calculated as } S = 1.9x10^8 \text{ V/W and } E = 0.078 \text{ eV for Pd/Ti TES and } S = 4.4x10^6 \text{ V/W and } E = 0.242 \text{ eV. With } n = 4 \text{ responsivity and energy resolution don’t change significantly.}

Both type of TES have a energy resolution sufficient for single photon detection in the visible range but if TES with Au as normal layer is faster, TES with Pd has an higher responsivity as result of a lower thermal conductance. Faster Pd/Ti TES could be realised by reduction of Ti films that gives the higher contribution to the thermal capacitance.

References

[1] Ali Z A, Drury O B, Cunningham M F, Chesser J M, Barbee T W, and Friedrich S, 2005 IEEE Trans. Appl. Supercond. 15, 526
[2] Nam S, Miller A J, and Rosenberg D, 2004 Nucl. Instr. and Meth A 520 523
[3] Miller A J, Cabrera B, Clarke R M, Figueroa-Feliciano E, Nam S, and Romani R W, 1999 IEEE Trans. Appl. Supercond. 9 4205
[4] Irwin K D, Hilton G C, 2005 Topics Appl. Phys. 99 63
[5] Broussard P R, 1991 Phys. Rev. B 43 2783
[6] Tesauro A, Aurigemma A, Cirillo C, Priscea S L, Salvato M and Attanasio C 2005 Supercond. Sci. Technol. 18 1
[7] Luukainen A, 2003 Ph.D. Thesis, University of Jyväskylä, Finland.
[8] Hilton G C et al., 2001 IEEE Trans. Appl. Supercond. 11 739
[9] Martinis J M, Hilton G C, Irwin K D and Wollman D A, 2000 Nucl. Instrum. Methods A 444 23
[10] Sarborn, B A, Allen, P B, and Papaconstantopoulos, D A, 1989 Phys. Rev. B. 40 6037
[11] Boucher R, T May, Wagner Th, Zakosarenko V, Anders S and Mayer H G, 2006 Supercond. Sci. Technol. 19 138
[12] Cirillo C, Prischea S L, Romano A, Salvato M, Attanasio C, 2004 Physica C 404 95
[13] Chen Y Y, et al. 1989 Phys. Rev. B. 52 9364