DEVELOPMENT OF TI BASED TRANSITION EDGE SENSORS FOR CRYOGENIC DETECTORS

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Ti based TES (Transition Edge Sensor) both of the single layer type and bilayers have been produced with critical temperatures ranging between 140 and 390 mK. Gain $\alpha = \frac{T}{R} \cdot \frac{dR}{dT}$ up to 400 have been obtained. A possible application of TES as temperature reference point is examined.

1 Transition Edge Sensors

In the last decade transition Edge Sensors (TES) have found application both in calorimeters for particle detection and for high-resolution light detectors from X rays to the infrared waves. TES consists of a superconducting phase transition thermometer evaporated onto a substrate. The detector works within the superconducting-to-normal transition , where the strong temperature dependence of the electrical resistance makes the film a very sensitive thermometer. Among the superconducting materials,Ti films [1] and Ti based bilayers [2,3,4] have been investigated by several authors. Ti based TES operating around 300 mK have been used for X-ray detectors and for millimeter waves, both with a single layer [5,6,7] and with bilayers [8,9,10,11]. At lower temperatures, TES have applications as sensors to detect dark matter in calorimetric experiments [12,13,14,15,16,17] and as photon counters in the UV-NIR region [5]. In the case of a single layer, T_c depends mainly on the residual resistivity[18]. In the case of bilayers, because of the proximity effect, it is possible to tune the transition temperature T_c according to the experimental requirements, by varying the relative thicknesses.

2 A brief history of Ti superconducting transition

Several authors have investigated the superconducting transition of titanium and the influence of various factors on it since the first observations done by Meissner[19], who assigned its temperature the value 1.13 K for a single crystal of a claimed purity of 0.9975. Temperature values greater than 1 K were assigned to this transition [20] until 1940, when Shoenberg [21], using an inductive method for observing the transition, found no transition occurring down to 1 K on a sample of nominal purity 0.999. Measurements of better quality were carried out in 1949 by Daunt and Heer [22]: the temperature value obtained via paramagnetic thermometry on titanium of nominal purity 0.9995 was (527 ± 6) mK. The influence of the magnetic induction $(dT/dB)_{T_c}$ was found to be 21.3 K/T. These results were basically confirmed in 1952 by measurements of Smith and Daunt [23] on the same sample, but after having annealed it, the values changing to $T_c = 558$ mK and to $(dT/dB)_{T_c} = 22.2$ K/T. However, substantially different values were observed the same year by Smith et al. [24] on a different sample with nominal purity 0.9999 and annealed: $T_c = 387$ mK and $(dT/dB)_{T_c} = 112$ K/T.

The effect of impurities started to be investigated in 1953 by Steele and Hein [25]. A single crystal 0.9999 pure (with 50 10^{-6} oxygen as the main impurity) gave $T_c = (490 \pm 10)$ mK, $(dT/dB)_{T_c} = 25$ K/T. A policrystal wire 0.9998 pure (with 100 10^{-6} oxygen and chromium as the main impurities) gave $T_c = 370 \pm 10$ mK, $(dT/dB)_{T_c} = 25$ K/T.

Among magnetic impurities, which were learned to have a strong influence on T_c of superconductors, manganese was found to have the strongest influence due to its localized magnetic moment. Matthias et al. [26] in 1959, found T_c to increase with manganese content and, extrapolating from Mn impurities in the range 0.015 – 0.025, predicted a T_c value for manganese-free titanium of about 400 mK. However, in subsequent measurements, Falge [27] for alloys with very low Mn contents obtained fully different results: Tc decreasing from 420 mK with 5 10^{-6} Mn, to 170 mK with 30 10^{-6} Mn, to less than 60 mK (which was the minimum measured temperature) for 100 10^{-6} Mn. The 1978 NIST Report on superconducting transitions [28] apparently preferred Falge's work, by indicating $T_c = (400 \pm 40)$ mK. Ti superconducting transition has been proposed as reference point[29] and it has been recently used[30].

Thin films of titanium has been deposited to produce superconducting bolometers for infrared and mm-wave astronomy. Transitions at 370 mK(Si substrate) and 300 mK (Si_3N_4 substrate) were measured[31].

Bilayers made of Ti and Au were also produced for X-ray astronomy detectors [32,33].

3 Single layer Ti films

We have deposited single layer Ti films by e-gun at the base pressure of 2–3x10^{-5} Pa on SiN substrates. The temperature of the substrates, monitored by a thermocouple, was varied between 25 °C and 500 °C by a small molybdenum heater with small gas release. The distance between crucible and

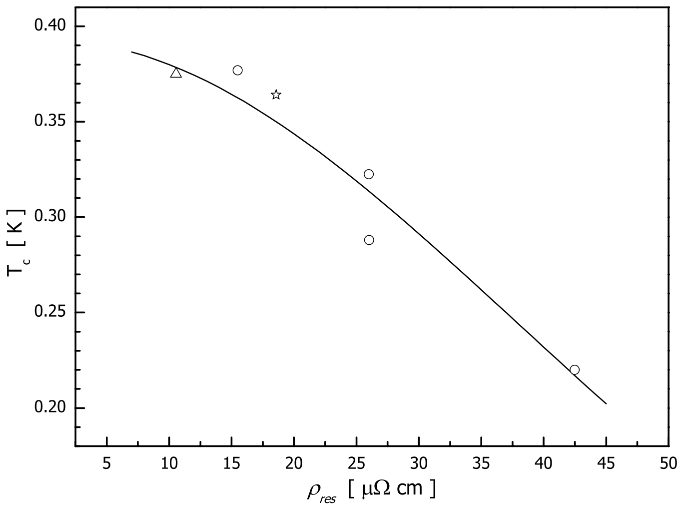

Figure 1. Transition temperature T_c as a function of residual resistivity ρ_{res}.The solid line is computed using Testardi Mattheis model.

substrate was 10 cm and the deposition rate, monitored by a quartz microbalance, ranged between 3 and 8 nm/s. In spite of the strong gettering effect of Ti, the pressure during deposition increased of about one order of magnitude with respect to the base pressure because of high degassing level. Films were patterned for resistance measurements by standard photolitographic process and chemical etching. All samples had a length of 3.5 mm and a width of 50 μm. Film thickness was measured by a Tencor profilometer. The uniformity on the strip of the film thickness was in 5%.

The measurement of resistivity as a function of temperature was performed with a cryogenic insert dipped in liquid nitrogen or liquid helium vapor. The critical temperature was measured in an Air Liquide dilution refrigerator by means of a Linear Research LR700 and an ORPX Barras-Provence AC bridges. Transition temperatures of six Ti films vs residual resistivity are shown in fig. 1.

In fig 2 the transitions (first and third point of fig.1) of two films both of nominal 310 nm depth are shown.

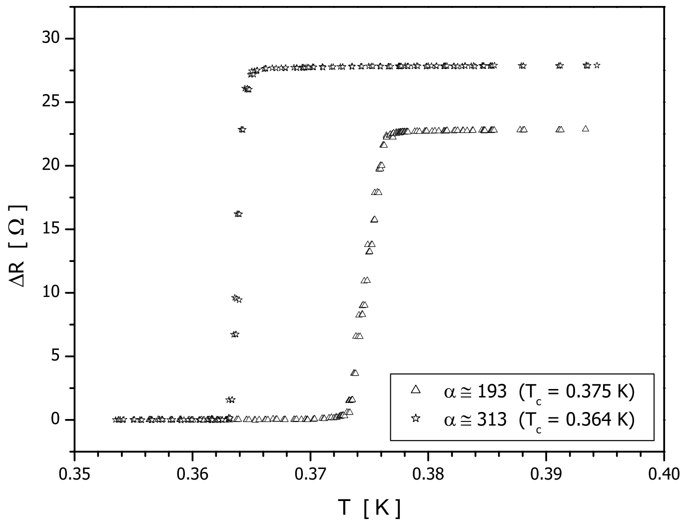

Figure 2. Transition of two single layer Ti films of 310 nm thickness.

4 Au/Ti bilayers

The Au/Ti films were produced by means of a four-crucible electron beam evaporator at a base pressure of 2-3 10^{-5} Pa, in one vacuum cycle. The target was a sapphire disk, placed at 40 cm from the evaporator. The temperature of the substrates was varied between 25 °C and 300 °C. A water-cooled quartz crystal, placed 3 cm away from the target, was used to monitor the thickness of the deposited layer during the evaporation. The deposition rate was around 2 nm/sec. The pattern of the bilayers was 0.2x4 mm^2. At the ends of the pattern, electrical wires were soldered onto two evaporated, 0.2 μm thick, Au pads. The resistance–temperature curves of Au/Ti TES were measured by two ac bridges (LR700 and Barras Provance). Measurements were made in an Air Liquide dilution refrigerator. By varying the thickness of the deposited layers, T_c between 140 and 300 mK were measured.

In Fig. 3, a transition for a Ti/Au (Ti 24 nm, Au 25 nm) bilayer is shown: the maximum value of $\alpha = \frac{T}{R} \cdot \frac{dR}{dT}$ is about 80. Although larger values of α are reported in the literature [19,20], the transition temperatures for our Ti/Au

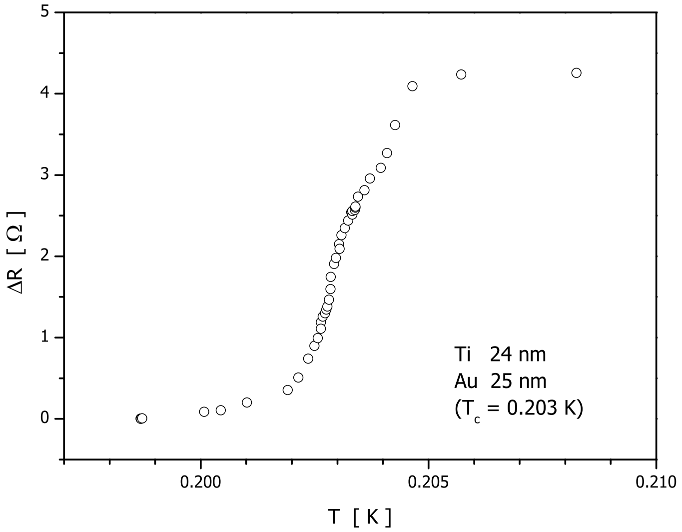

Figure 3. Transition of Au/Ti bilayer film.

bilayers are among the lowest ones ever reported [21,22].

5 A proposed metrological application

The American National Bureau of Standard (NBS, now National Institute of Standard and Technology, NIST) produced two devices (SRM 767a and 768) containing 6 and 5 superconducting samples respectively with transitions between 15 mK and 9.3 K [30,31,32]. These devices were based on ITS 90 [34] and on the so called NBS-CTS [35] but now they are no longer produced. A great effort has been done to replace the two devices after the agreement on the extension of the ITS 90 down to 0.9 mK. A new reference device (SRD1000), for example, has been developed by a Dutch consortium [36].

Fig. 2 shows a transition of Ti at 300 mK with a transition width of 0.3 mK The closest transition temperatures both in NBS devices and SRD1000 are 205 and 520 mK,with widths of 0.4 and 1.7 mK respectively. This means that in principle a TES would be a good reference point . Repeatability and magnetic field influence shall be measured.

References

1. A.T. LEE, B.Cabrera and B.Ayoung, IEEE Trans.Magn. 27, 2753 (1991).
2. A.Luukanen et al., J.Physica B 284, 2133, (2000).
3. H.F.C. Hoevers et al., Nucl.Instrum.&Method A444, 192, (2000).
4. R.Fujimotoet al., Nucl.Instrum.& Method A444, 180, (2000).
5. A.J.Miller et al., Nucl. Inst. and Meth. in Phys. Res A444, 445, (1999).
6. D.Fukuda, H.Takahashi, M.Ohno and M.Nakazawa, Nucl. Inst. and Meth. in Phys. Res A444, 241, (1999).
7. A.J. Miller et al., IEEE Trans Appl. Supercond. 9, 4205, (1999).
8. C.K.Stahle et al., Nucl. Inst. and Meth. in Phys. Res A444, 224, (1999).
9. J.Olsen et al., Nucl. Inst. and Meth. in Phys. Res A444, 253, (1999).
10. K.D.Irwin et al., Nucl. Inst. and Meth. in Phys. Res A444, 184, (1999).
11. A.D. Holland et al., Nucl. Instr. and Meth. A 436, 226, (1999).
12. U.Nagel et al., J. Low Temp. Phys. 93, 543, (1993).
13. P.Colling et al., J. Low Temp. Phys. 93, 549, (1993).
14. P.Ferger et al., Phys. Lett. B 323, 95, (1994).
15. M.Buehler et al., Nucl. Instr. and Meth. A 370, 237, (1996).
16. S.W.Nam et al., Proc. LTD 7, 217, (1997).
17. M.Sisti et al, Proc. LTD 7, 232, (1997).
18. L.R.Testardi and Mattheiss, Phys. Rev. Lett. 41, 1612, (1978)
19. Meissner W., Zeits. f. Physik, 60, 181-183, (1930); Meissner W., Franz, Westerhoff , Ann. d. Physik 13, 555, (1932).
20. De Haas W.J., van Alphen P.M., Proc. Amst. Roy. Akad. Sci., 34, 70, (1931).
21. Shoenberg D., Proc. Camb. Phil. Soc., 36, 84, (1940).
22. Daunt J.G., Heer C.V., Phys. Rev., 76 (6), 715-717, (1949).
23. Smith T.S., Daunt J.G., Phys. Rev., 88 (5), 1172-1176, (1952).
24. Smith T.S., Gager W.B., Daunt J.G., Phys. Rev., 89 (3), 654, (1953)
25. Steele M.C., Hein R.A., Phys. Rev., 92 (2), 243-247, (1953).
26. Matthias B.T., Compton V.B., Suhl H., Corenzwit E., Phys. Rev. 115, 1597-1598, (1959)
27. Falge R.L. Jr, Phys. Rev. Lett., 11 (6), 248-250, (1963).
28. Roberts B.W., Properties of Selected Superconductive Materials, NBS Technical Note 983, (1978).
29. A.Peruzzi et al., Metrologia 37, 2, E1143 (2000).
30. E.Gazo, L'.Lokner, R.Scheibel, P.Skyba, N.Smolka, Cryogenics 40, 441, (2000).

31. A.T.Lee et al., Proc. of LTD-7 pag 123.
32. M.Ukibe, K.Tanaka, M.Koyanagi, T.Morooka, H.Pressler, M.Ohkubo, N.Kobayashi, Nucl. Inst. and Meth. in Phys. Res, A444, 257, (1999).
33. R.Fujimoto et al., Nucl. Inst. and Meth. in Phys. Res, A444, 180, (1999).
34. Preston, Thomas, Metrologia, 27, 3, (1990).
35. R.J.Soulen jr, H.Marshak, Cryogenics, 20, 408, (1980).
36. W.A.Bosch et al., "Status report on the development of a superconductive reference device for precision Thermometry below 1K", Tempmeco Proceedings.