Nuclear Instruments and Methods in Physics Research A 370 (1996) 183–186

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

ELSEVIER

The use of SiO_2 sublayers beneath titanium transition edge sensors for the purpose of phonon spectroscopy

T. Dumas[a,b], B. Neuhauser[a,b,*], B. Cabrera[c], R.M. Clarke[c], S.W. Nam[c], M.J. Penn[c]

[a] Thin Film Laboratory, San Francisco State University, Dept. of Physics and Astronomy, San Francisco, CA, USA
[b] NSF Center for Particle Astrophysics, University of California at Berkeley, Berkeley, CA, USA
[c] Department of Physics, Stanford University, Stanford, CA, USA

Abstract

We have investigated the effect of thin SiO_2 sublayers on the transmission of phonons into titanium transition edge sensors (TESs) fabricated on high-resistivity (100) float zone (FZ) silicon substrates. The response of a TES on native oxide is compared to that of an adjacent TES on a thermally grown SiO_2 sublayer. Latching current measurements indicate that thermal phonons are not attenuated by the film. However, pulse data from X-ray scattering experiments suggest that high frequency phonons are preferentially scattered.

1. Introduction

A new type of elementary particle detector intended for the direct detection of dark matter senses the phonons and electron–hole pairs created when an incident particle scatters elastically within a large (~200 g) ultrapure single crystal of silicon or germanium. A Weakly Interacting Massive Particle (WIMP) would scatter off a nucleus, while a background gamma or beta would scatter off an electron. The ratio of energy deposited as phonons to the energy dissipated in creating electron–hole pairs is nine-to-one for a ~10 keV nuclear recoil but less than three-to-one for an equal energy electron recoil. Thus measurement of the phonon-to-ionization ratio of a signal is a very effective method for distinguishing between a dark matter interaction and a background photon scattering event [1]. We will describe a technique for deducing this ratio by using only phonon sensors rather than by comparing the phonon signal with a separate charge collection measurement.

As phonons move through crystals, they scatter elastically off isotopes at a rate proportional to the fourth power of the phonon frequency. As a result, only very low frequency phonons are able to propagate ballistically through large crystals. Recent analysis of pulses produced by low-energy nuclear recoils in neutron scattering experiments and by low-energy electron recoils in X-ray scattering experiments indicates that the ballistic (i.e. low frequency) phonon content is at most 7% for nuclear recoils and only about 1% for electron recoils [2]. This is consistent with the model that phonons ultimately emerge from the region of a scattering event with a characteristic frequency of ~1 THz. Their "quasidiffuse" motion through the crystal is governed by isotope scattering and anharmonic decay.

When a scattering event occurs it is possible to generate a secondary population of phonons by drifting the electrons and holes through the crystal under the influence of a small electric field [3]. These would be distinct from the intrinsically-generated phonons because of their low frequency distribution [4], and they would be valuable for background rejection purposes because they are derived from the electron–hole pairs created during the scattering event. One scheme for identifying the two phonon populations would be to use a fast-responding detector to distinguish between the arrival times of the ballistic and quasidiffuse phonons. Another approach is to compare signals from a sensor fabricated directly on the surface of the substrate crystal with signals from an interleaved sensor fabricated over a sublayer that preferentially scatters high-frequency phonons. In this paper we report evidence that thin silicon dioxide films may be suitable for this purpose.

2. Device geometry and fabrication

Fig. 1 shows the geometry of the transition edge sensors (TESs) used for this experiment. The 1 cm^2 die has three TES patterns each covering an area of 2 mm × 4 mm. The central TES is on a thin "native" oxide layer, and the two

* Corresponding author. Tel. +1 415 338 1087, fax +1 415 338 2178, e-mail barbjn@stars.sfsu.edu.

0168-9002/96/$015.00
SSDI 0168-9002(95)01082-3

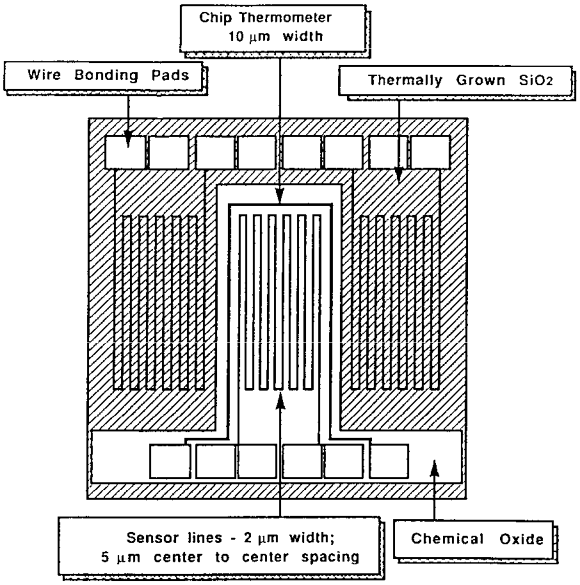

Fig. 1. Schematic of the TES device layout. Sensor lines, thermometer pattern, and bonding pads are all 400 Å thick titanium.

outer patterns are on a thermally grown SiO_2 sublayer. Each sensor consists of a 400 Å thick titanium film in a meander pattern with 2 μm wide lines on a 5 μm pitch. These sensors were fabricated in the Thin Film Laboratory at San Francisco State University. The three-inch silicon wafers were cleaned in an oxidizing bath of heated 9:1 H_2SO_4:H_2O_2, rinsed in deionized (DI) water, dipped in 50:1 DI:HF to strip the oxidized surface layer, rinsed in DI, cleaned in a heated 1:1:5 HCl:H_2O_2:DI, and rinsed a final time in DI. Thin SiO_2 layers then were grown by inserting the wafers into a quartz-lined oxidation furnace tube at a temperature of 800°C in a dry oxygen flow of 2.5 standard liters per minute. Oxidation times ranged from about 60 minutes for a 50 Å film up to 22 hours for a 300 Å film. An ellipsometer was used to make precise measurements of the oxide layer thickness. Photolithographic procedures were used to pattern the oxide layer, which was then etched in 10:1 buffered oxide etch. Complete removal of the SiO_2 in the central channel region was confirmed by the usual water bead test based upon the fact that bare silicon is hydrophobic. A thin oxide was regrown by immersing the wafer in a heated HCl:H_2O_2:DI bath. The thickness of this "native" oxide was measured by ellipsometry to be on the order of 15 to 20 Å. Previous experience had shown that when this thin oxide film was not regrown prior to deposition of titanium, the superconducting transition was too broad to be useful. Finally a 400 Å titanium film was deposited in a UHV electron-beam evaporator, then patterned and etched in 1:1:5 NH_4OH:H_2O_2:DI to form the TES channels.

3. Device testing

The TES chips were tested at Stanford in a self-contained cryopumped helium-3 cryostat. Fig. 2a shows a typical superconducting transition with $T_c = 413$ mK and width ≈7 mK. Devices were irradiated with 60 keV gammas from an ^{241}Am source located in a hole in the Pb shielding surrounding the cryostat. Voltage pulses from the FET preamplifiers could be sent either to a Tracor-Northern MCA to produce a pulse height spectrum or to a VXI data bus system coupled to an Apple 8100 PowerMac for storage of digitized pulses.

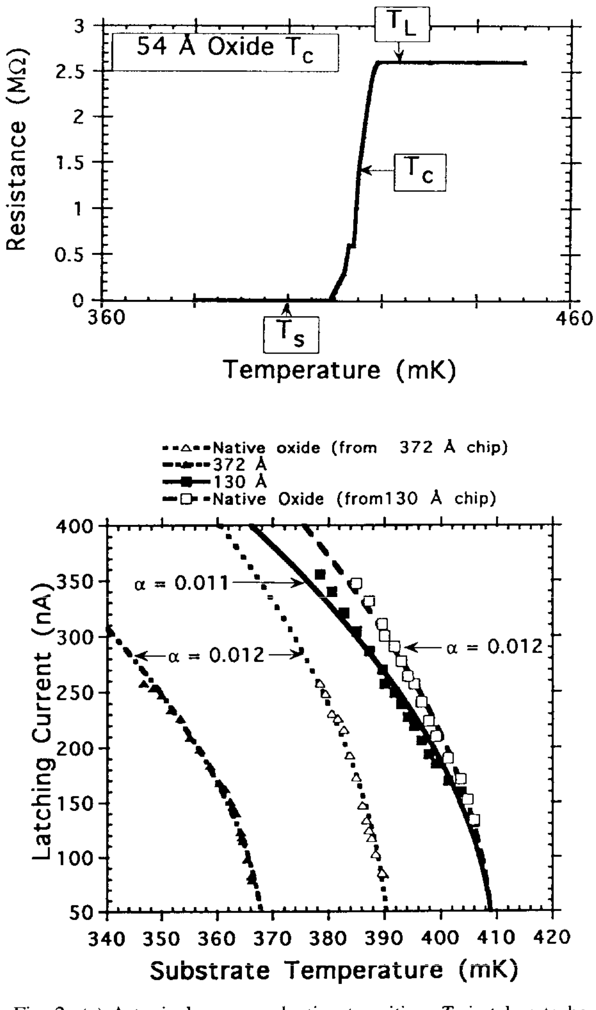

Fig. 2. (a) A typical superconducting transition. T_c is taken to be midway through the transition, T_L is the temperature at which local latching occurs, and T_s is a typical substrate operating temperature (~0.96T_c). (b) Latching current measurements for SiO_2 sublayer thicknesses ranging from a native oxide to 372 Å. Note that the fitted values of α, the thermal coupling coefficient, agree quite well with each other. Error bars are on the order of the point size.

Evidence that a thermal oxide sublayer does not attenuate low frequency phonons can be derived from measurements of the latching current, which is the lowest bias current at a specific substate temperature T_S for which pulses do not recover. Latching occurs when the part of the TES film which was driven normal by a phonon pulse locally self-heats by an amount δT which is about as far above T_c as T_c is above T_s. An expression for latching current as a function of T_s can be derived by equating Joule heating in the sensor to thermal phonon radiation into the substrate: $I(T_s) = (\alpha/R)^{1/2}[(T_c + \delta T)^4 - T_s^4]^{1/2} = (\alpha/R)^{1/2}[(2T_c - T_s)^4 - T_s^4]^{1/2}$ where the parameter α characterizes the propagation of phonons between the TES and the substrate. Fig. 2b shows that fits of this expression to experimental data can be made with nearly the same value of α for sensors on native oxide, on 130 Å SiO_2, and on 372 Å SiO_2. This is consistent with the fact that the average wavelength of 400 mK phonons (1200 Å) in SiO_2 is so much greater than the range of thermal oxide thicknesses that scattering does not occur.

For fixed energy deposition within the substrate, the pulse height observed in a TES varies with the depth of the scattering event. Theoretical considerations confirmed by experimental measurements show that the maximum pulse height is nearly proportional to the total deposited energy [5]. Thus direct comparisons of the energy transmitted into a TES on native oxide and a TES on thermal oxide can be made if maximum pulse heights are compared and if the sensors are operated at the same energy sensitivity, which is defined to be the threshold energy required to drive the superconducting film normal across the full width of a square section of the TES line. (For a BCS superconductor at a temperature very near to T_c the energy sensitivity is proportional to $T_c(T_c - T)$). It has been observed that the maximum 60 keV pulse amplitude in a TES over a thermal oxide sublayer is less than the maximum 60 keV pulse amplitude in an identical TES over native oxide when the sensors are operated at the same energy sensitivity. Since we have shown that low frequency phonons are not affected by the sublayer, it is likely that the energy deficit is due to scattering of high frequency phonons.

We have attempted to derive a scattering length parameter from our data. Our very simple one-dimensional model of this process assumes that the high frequency phonons scatter elastically with the same scattering length λ_s and that they are as likely to scatter forward as to scatter backward. If in addition it is assumed that the oxide thickness d is an integral multiple of λ_S, then it can be proved by induction that the ratio of the number of phonons entering the SiO_2 film to the number transmitted into the TES is simply d/λ_s. (This model is useful only as an asymptotic form which is valid when $d > \lambda_s$. Clearly, as $d \to 0$ the amplitude ratio should approach 1.) Fig. 3 is a plot of the ratio of the maximum signal in the native oxide TES to the maximum signal in the thermal oxide TES for four sensors having oxide thicknesses of 54, 87, 177, and 315 Å. We fitted a straight line to these points subject to the consistency criterion that the reciprocal slope, which should equal the scattering length λ_s, must exceed the value of oxide thickness d for each point used in the fit. The result was an excellent linear fit to the three points corresponding to the thicker oxides. The derived value $\lambda_s \approx 66$ Å is consistent with the ~60 Å wavelength of 1 THz phonons in SiO_2, and it is large enough to justify our implicit assumption that negligible phonon scattering occurs in the native oxide. It also is in reasonable agreement with the value of 125 Å calculated for 1 THz phonons in SiO_2 using the equation $\lambda_s = (10)^5$ Å $(100\,\mathrm{GHz}/f)^{2.9}$ found empirically for elastic scattering of phonons in thick layers (~1 μm) of electron-beam evaporated SiO_2 [6]. Possible systematic effects arising from charge trapped into the Si–SiO_2 interface have not been fully analyzed and are not included in the error bars.

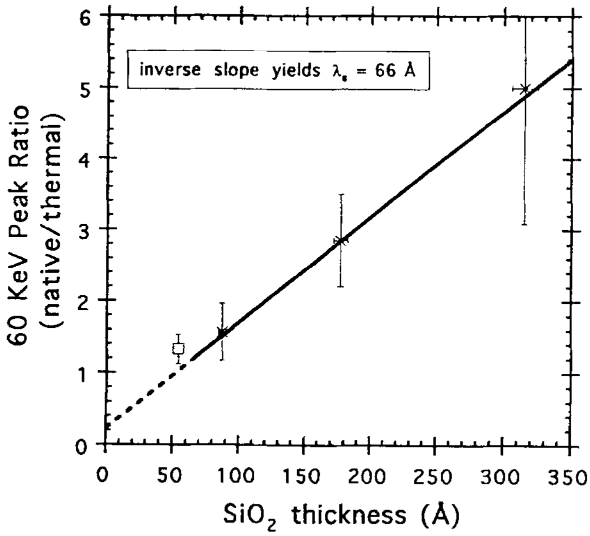

Fig. 3. Ratio of the maximum 60 keV signal in the native oxide channel to the maximum 60 keV signal in the thermal oxide channel for sensors having SiO_2 sublayers ranging from 54 to 315 Å. The reciprocal of the slope of the linear fit gives an estimate of the scattering length λ_s.

We conclude that thin thermal SiO_2 sublayers can be used as low-pass filters for implementing the background rejection scheme presented in the introduction.

Acknowledgements

We would like to thank S. Chamberlain and L. Nuyens for participating in the early stages of this experiment. Research at SFSU was funded by the following NSF grants: PHY 90-58517, PHY 94-07930, and PHY 94-14675; and by the NSF Center for Particle Astrophysics subcontract AST-912005. Research at Stanford was supported by U.S. Department of Energy Grant DE-FG03-90ER40569.

References

[1] T.A. Shutt, Ph.D. Thesis, University of California at Berkeley (1993).

[2] B. Cabrera, P.L. Brink, B. Chugg, B.L. Dougherty, K.D. Irwin, M.J. Penn, S.W. Nam, A.T. Lee, J.G. Pronko, S. Tamura and B.A. Young, Proc. 4th Int. Conf. on Phonon Physics (1995) to be published in Physica B.

[3] P.N. Luke, J. Appl. Phys. 64 (1988) 6858.

[4] B. Cabrera, B.L. Dougherty, A.T. Lee, M.J. Penn, J.G. Pronko and B.A. Young, Proc. 5th Int. Conf. on Low Temp. Detectors (1993) J. Low Temp. Phys. 3/4 (1993) 365.

[5] A.T. Lee, Ph.D. Thesis, Stanford University (1992).

[6] W. Dietsche and H. Kinder, Phys. Rev. Lett. 43 (1979) 1413.