Milano, January 8, 1986

CM-P00062952

HEAT CAPACITY OF A SILICON CALORIMETER
AT LOW TEMPERATURES MEASURED BY ALPHA PARTICLES

T.O.Niinikoski and A.Rijllart
C.E.R.N., Geneva, Switzerland.

A.Alessandrello, E.Fiorini, A.Giuliani,
Dipartimento di Fisica and I.N.F.N., Milano, Italy

ABSTRACT

A small implanted monolithic silicon calorimeter has been bombarded with alpha particles at low temperatures in order to determine its thermal properties. From the temperature dependence of the pulse height and the time structure we have obtained values for the lattice contribution to the heat capacity in excellent agreement with theory, while the contributions from the implanted zone are about an order of magnitude larger than expected from data on diffusion doped semiconductor. This and other thermal properties are discussed.

1. INTRODUCTION

The use of a crystal of a pure diamagnetic insulator as a low temperature calorimeter to detect single particles has been suggested recently⁽¹⁻³⁾. The main contribution to heat capacity comes in this case from lattice vibrations (phonons) and is proportional to $(T/\theta_d)^3$, where θ_d is the Debye temperature. At low temperatures it becomes very small and may allow the

detection and the energy analysis of single absorbed particles from the heat released in the crystal, by measuring the changes of the lattice temperature with a resistance thermometer. Pulses due to cosmic rays have been observed in resistance thermometer⁽⁴⁾ and this new technique has been successfully used to detect and analyze X-rays^(5,6) and alpha particles⁽⁷⁻⁹⁾ using monolithic totally or partially doped semiconductors, or simply a small thermistor glued in thermal contact with the actual calorimeter made of a diamond wafer⁽⁸⁾. This new method of detection looks very promising in astrophysics^(1-6,10,11) and in nuclear and subnuclear physics, in particular to detect rare ionizing or non ionizing events^(1,2,12) and also to measure the electron neutrino mass^(2,8,13-15).

The aim the present work has been to gain insight in the physics of thermal particle detection, in order to be able to optimize this technique. We use for the first time the known energy delivered by alpha particles to determine the specific heat of doped and pure silicon at low temperatures. We believe that the present attempt and hopefully further improvements of it will also allow new determinations of heat capacities at low and ultralow temperature with consequent better understanding of the electronic and lattice properties of various materials⁽¹⁶⁾.

This approach obviously implies that a large percentage of the energy deposited by the particle be dissipated in the calorimeter in the form of heat. For alpha particles the expected energy loss due to defect formation should be negligible⁽¹⁷⁾, at least in the limits of the present experiment (less than a few percents). Relevant energy losses due to excitation of nuclei, atoms and impurity levels⁽²⁾ with consequent slow de-excitation seems to be excluded by the fast decay with time of the pulses. The energy deposited in trapped electron maybe as large as 30% depending on the type of particles and on the material characteristics; this introduces a possible systematic error in the case of ionizing radiation.

2. EXPERIMENTAL DETAILS

The detector employed in the present experiment (Fig.1) was cut out of a Si:P resistance thermometer⁽¹⁸⁾ provided us by G. Frossati. It consists of a wafer of N-silicon of $1 \times .5 \text{ mm}^2$ surface and .3 mm thickness containing less than 10^{15} impurities per cm^3 . A resistive area of $0.3 \times 0.5 \text{ mm}^2$ has been obtained by implanting phosphorus ions up to a depth of $1000 \text{ \AA}$ with a concentration of $1.5 \times 10^{19} \text{ atoms/cm}^3$. The electric contacts have been obtained by two $2 \text{ }\mu\text{m}$ degenerate N^+ implants of $10^{21} \text{ atoms/cm}^3$ and by $1 \text{ }\mu\text{m}$ thicknesses of aluminium deposited on them. Electrical and thermal contact to the chip was obtained with two indium wires of about $100 \text{ }\mu\text{m}$ diameter and 3 mm length, which are cold welded at one end to the aluminium contacts and at the other to a copper frame in thermal contact with the mixing chamber of the dilution refrigerator.

The steady resistance R_L of the calorimeter was measured with an A.C. Kelvin bridge. The pulses produced in it by absorption of the incoming alpha particles were detected using the bias circuit shown in the inset of Fig. 2. The voltage from R_L is first amplified by an AH0013 OEI integrated circuit with $1.5 \text{ nV/Hz}^{1/2}$ voltage and $10 \text{ fA/Hz}^{1/2}$ current noise, respectively, with feedback to give 30 dB gain and 0-500 kHz bandwidth. Pulses are then digitized, filtered and stored by means of a Camac digitizer with read-out to an 8 bit microcomputer. The noise amplitude, in the absence of pulses from the calorimeter, is compatible with the noise figure of the amplifier.

Pulses from the detector have been obtained by placing inside the cryostat and in immediate vicinity of it an implanted ^{228}Ra alpha source which produces a counting rate of about 4 Hz. Measurements have been carried out at various temperatures from 30 to 960 mK, but in the lower range of this interval the relative increases in temperature become so large that the response of the system is not linear. The present analysis has therefore been limited to measurements carried out at

temperatures above 300 mK.

We would like to note that thermal links have been studied in view of high rate experiments, requiring pulses (Fig.2) faster than those obtained in other searches. The preamplifier bias circuits has been chosen accordingly.

3. RESULTS AND THEIR ANALYSIS

The pulse risetime ranges from 1 to 3 μ sec, in agreement with the input circuit time constants above 600 mK, and slightly larger below. These risetimes are almost an order of magnitude larger than the expected thermalization times of the detector^(1,2). Most of the information on thermal properties of the calorimeter comes therefore from the pulse height and decay properties as a function of temperature, as in all "classical" methods to measure specific heat at low temperatures⁽¹⁶⁾. The decay pattern is compatible with the sum of two exponentials^(5,6,19) as expected from the thermal model of Fig.3, where C_1 is the heat capacity of the silicon wafer, G_1 the heat boundary conductance between implanted silicon and the aluminium-indium system, C_2 is the heat capacity of the aluminium layer and, mainly, of the indium contact, and G_2 the heat conductance of the indium wires to the copper frame, which act as an heat sink. Since the energy is delivered to the bolometer in a time negligible with respect to the decay time, the decay behaviour of the temperature increase can be written as:

$$\Delta T(t) = \Delta T_{\max} \left[k e^{-t/\tau_1} + (1-k) e^{-t/\tau_2} \right] \quad (1)$$

where $\Delta T_{\max}$ is the value of ΔT extrapolated to $t=0$, and the parameters k , τ_1 , and τ_2 , which are functions of C_1 , G_1 , C_2 , and G_2 , can be extracted from the fit to the experimental time behaviour of the pulses at the different temperatures. We have first determined C_1 from the integration

$$E = \int_{T_0}^{T_{\max}} C_1 \cdot dT \quad (2)$$

where E is the average energy delivered by the alpha particle. In order to perform this integration we have assumed that the heat capacity of the monolithic silicon wafer be dominated by a term due to lattice contribution, which is proportional to T^3 ⁽²⁾, and by a term weakly dependent on the temperature as expected for the implanted part of the chip ⁽²⁰⁾. We have obtained good fits to experimental data with the following functions:

$$C_1 = AT^3 + BT \quad (3)$$

$$C_1 = A'T^3 + B' \quad (4)$$

The corresponding values of C_1 are reported in Table I. The fit to equation (3) give values: $A=(9.2 \pm 1.2) \times 10^{-11} \text{ J/K}^4$ and $B=(1.5 \pm .4) \times 10^{-11} \text{ J/K}^2$ with a value of 1.1 for chi-square per degree of freedom, while fit to (4) gives $A'=(10.3 \pm .9) \times 10^{-11} \text{ J/K}^4$ and $B'=(0.6 \pm .1) \times 10^{-11} \text{ J/K}$ with a value of .73 for chi-square per degree of freedom. Calculations based on the lattice vibration term ⁽²⁾ predict a value of $A \sim A' = 9 \times 10^{-11} \text{ J/K}^4$ in excellent agreement with our experiment results. The situation is more complicated for the term weakly dependent on temperature. The measurements carried out by J.R. Marko and J.P. Harrison ⁽²⁰⁾ on Si:P with densities from 3.5×10^{17} to $1.05 \times 10^{20} \text{ atoms/cm}^3$ show a dependence on the temperature for the specific heat due to implanted regions intermediate between those predicted in (3) and (4). The predictions from these measurements for the contribution to heat capacity by the implanted regions in our calorimeter are however an order of magnitude lower than the experimentally determined parameters B and B' in (3) and (4).

This disagreement could be accounted for by the fact that the measurements by Marko and Harrison were carried out on diffusion doped samples, while in our case doping has been obtained by implantation and only partially activated by annealing at 600 K⁽¹⁸⁾. A similar increase by an order of magnitude with respect to predictions has in fact found recently for the heat capacity of an implanted monolithic silicon bolometer by P.M.Downey et al⁽¹⁰⁾. Obviously other contributions to heat capacity slowly decreasing, or even increasing with decreasing temperature cannot be excluded⁽²⁾.

Once C_1 is determined, the fit to the decay with time of the pulses allows us to obtain the other three parameters which are reported as a function of temperature in Table I. The values of C_2 are in good agreement with the behaviour $A \times T^3$ expected from lattice contribution only, and with an experimental value of A $(3.6 \pm .7) \times 10^{-9} \text{ J/K}^4$ in excellent agreement with the value evaluated theoretically for the superconductive Indium contacts $(3.5 \times 10^{-9} \text{ J/K}^4)$.

CONCLUSIONS

The present experiment on the thermal properties of a monolithic implanted silicon calorimeter bombarded with alpha particles at low temperature indicates a contribution to heat capacity due to lattice vibration in excellent agreement with theory both for the detector itself and for the indium contacts. The contribution from the implanted zones is found to be weakly dependent on temperature as expected, but considerably larger than predicted by measurements in bulk doped silicon. We tentatively attribute this discrepancy to incomplete activation of the implanted zone.

We are in the process to improve this new method to determine specific heat at low temperatures with specially built detectors and better thermometry.

We would like to thank G. Frossati for providing us with one of his Si:P thermometers used in this work and to acknowledge very useful discussions with G.Benedek, G.Cerofolini, and H.Ravn, who also provided us with the implanted source of alpha particles.

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FIGURE CAPTIONS

Fig.1. The implanted Silicon bolometer.

Fig.2. A typical pulse (at 500 mK). In the inset, the input circuit.

Fig.3. Thermal model for the calorimeter.

TABLE I

Temperature (mK)	$C_1 = AT^3 + BT$				$C_1 = A'T^3 + B'$			
	C_1 (10^{-11} J/K)	C_2 J/K	G_1 (10^{-7} W/K)	G_2 W/K	C_1 (10^{-11} J/K)	C_2 J/K	G_1 (10^{-7} W/K)	G_2 W/K
363	1.0± .15	17± 4	7.6±1.4	12± 2	1.1± .4	19± 4	8.4±1.4	13.6±2.2
422	1.3± .2	36± 8	14± 2	26± 5	1.4±.15	38± 8	14± 2	27± 4
485	1.8± .2	25± 5	25± 4	55± 9	1.8±.17	25± 5	25± 3	55± 8
531	2.2± .3	38± 8	41± 7	81± 13	2.2± .2	37± 7	41± 5	80± 11
644	3.4± .4	68±14	74± 11	165± 25	3.4± .3	67±13	72± 9	162± 21
730	4.7± .5	122±25	119± 18	233± 36	4.6± .4	121±23	118± 15	230± 29
958	9.6±1.1	443±92	269± 41	735±113	9.7± .8	450±86	274± 35	748± 96

Fig. 1