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DATA ACQUISITION AND ANALYSIS OF CALORIMETRIC SIGNALS

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ABSTRACT

Calorimetric signals have been obtained by irradiating implanted Si and melt-doped Ge detectors of about one cubic millimetre size with an alpha source. A room temperature preamplifier and a CAMAC-based data-acquisition system have been used to resolve the time structure of the signals and to filter them for spectrum analysis. The thermal response is analysed in terms of a model with two heat reservoirs.

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1. INTRODUCTION

In order to understand the limiting factors in the decrease of the heat capacity with decreasing temperature of low-temperature calorimeters, a detailed study of their thermal response to 6 MeV alpha particles was done. The main contribution to the heat capacity of pure crystalline Si and Ge at low temperatures comes from phonons and is proportional to $(T/\theta_D)^3$, where θ_D is the Debye temperature. At very low temperatures the heat capacity may become dominated by impurities, or by contacts and leads which are necessary to measure the temperature of the device.

A description will be given of the detector biasing, signal amplification, and data acquisition and analysis techniques, used to determine the various heat capacities and conductivities of the detector assembly. Some conclusions are drawn from our new and earlier published data [1] regarding the excess specific heat and the non-thermal behaviour of the heat transport.

2. DETECTOR BIASING AND SIGNAL AMPLIFICATION

The temperature of the detector was determined by measuring the resistance of a thermistor which had been created by the introduction of suitable impurities, either in a local area or throughout the whole detector. The resistance was measured by applying a voltage on a bias resistor in series with the detector, and measuring the voltage across the detector (see Fig. 1).

To amplify the signal from the detector a JFET input operational amplifier was used with a noise voltage of 1.5 nV/ $\sqrt{\text{Hz}}$ and a gain of 20 dB operating at room temperature. Further amplification increased the total gain to 73 dB and was also used to create a balanced signal, suitable for transmission across a twisted-pair cable of 5 m length to a receiver amplifier (see Fig. 2). The bandwidth of the amplifier chain was chosen to be 0.5 MHz, to correspond to the fastest expected rise-times of the signals, limited by the parasitic capacitance of the input lines.

3. DATA ACQUISITION AND PROCESSING

The data acquisition was done using easily available CAMAC equipment for which on-line and off-line software was written. An 8-bit digitizer with a minimum sampling time of 50 ns and a memory depth of 1 kbyte was used to digitize the detector signals generated by the 6 MeV alpha source. The digitized signal was then transferred to a 16-bit Stand-Alone CAMAC processor (MC68000 STAC) [2], which performed on-line analysis, reducing the data typically by a factor of 100. A Super-Caviar microcomputer was used for CAMAC control, histogram storage and display, and off-line analysis. A block diagram of the data-acquisition system is shown in Fig. 3.

The on-line data processing consisted of three different algorithms to calculate the pulse height from the digitized signal. The first two algorithms searched for a maximum, one without filtering, the other using low-pass digital filtering. The third, a matched filter algorithm, calculated the maximum using a reference signal, which was created from an averaged signal. This produced three different multi-channel histograms, which provided important information about resolution limiting noise background. The reference signal was also used to perform an r.m.s. error calculation, to be able to reject unwanted signals, such as false triggers and double pulses (two pulses very close in time). All accepted signals were averaged to obtain a very high resolution and noise-free signal for off-line time structure analysis at the end of each measurement.

The off-line data analysis included the calculation of rise- and decay-time constants from averaged signals, and the Fourier analysis of the signals and of the background noise for the purpose of finding the performance and limits of the measurement system.

The measured noise levels, obtained using a random trigger, are compatible with the noise figure of the preamplifier.

4. TIME-STRUCTURE ANALYSIS OF CALORIMETRIC SIGNALS

The decay parts of the pulses obtained by irradiating the detectors with 6 MeV alpha particles show two different time constants in all cases, which can easily be seen in a semi-logarithmic plot of a typical averaged signal, shown in Fig. 4. The vertical axis has an arbitrary logarithmic scale. This behaviour can be described using a model with two heat reservoirs, shown in Fig. 5, where two heat capacities C_1 and C_2 are in series, interconnected with heat conductance G_1 , and with G_2 connecting C_2 to the copper heat sink. In this model, C_1 represents the heat capacity of the Si or Ge calorimeter with the integrated thermometer, and C_2 the heat capacity of the metallic lead system. G_1 represents the surface heat conductance at the interface between the calorimeter and the leads, and G_2 the heat conductance of the leads.

This model (in its linearized form) leads to the decay of the temperature pulse with two time constants τ_0 and τ_∞ , describing the asymptotic limits of the effective time constant at $t = 0$ and $t = \infty$, and with two amplitudes V and V' , describing the pulse heights at $t = 0$. These amplitudes are obtained by the extrapolation of the initial and final exponential decay curves, as shown in Fig. 4. By denoting

$$U = V'/V \quad \text{and} \quad T = \tau_\infty/\tau_0,$$

we can relate the time constants and amplitudes to the parameters of our model:

$$\begin{aligned} C_1 &= \Delta E/\Delta T \propto 1/V \\ G_1 &= C_1/\tau_0 \\ C_2 &= C_1 T^2 (1-U)/U(T-1)^2 \\ G_2 &= G_1(T-U)/U(T-1)^2. \end{aligned}$$

When assuming $\tau_\infty \gg \tau_0$, which is often the case above 0.3 K, the last two formulae simplify to

$$\begin{aligned} C_2 &\cong C_1(1-U)/U \\ G_2 &\cong G_1/UT. \end{aligned}$$

The results for a Si:P calorimeter [1] are shown in Figs. 6 and 7. In Fig. 6 we note that C_1 follows closely the C_{Si} , which is the theoretical heat capacity of the detector chip using the Debye specific heat of Si, with a deviation growing at lower temperatures. This deviation is expected from the implanted zones for the thermistor (P impurity) and the ohmic contacts (degenerate zones created by diffusion of P). The size of this deviation is about one order of magnitude larger than what one would expect from the data on bulk P-doped Si [3]. This could reflect the influence of the radiation damage due to the implantation which is not entirely annealed away, but could also be due to the much heavier P doping in the ohmic contacts.

The temperature dependence of C_2 agrees with that of the phonon heat capacity of the superconducting In leads and solder pads on the aluminium contacts. The magnitude of C_2 , however, is only about 20% of the heat capacity of the total amount of indium in the leads and the contacts. The line C_{In} in Fig. 6 corresponds to this 20% of the heat capacity of the total amount of indium.

The above results could be regarded in very good agreement with our thermal model, but unfortunately the dynamic heat conductances are in disagreement with the theoretical G_K and G_{ph} and, in particular, with the measured static heat conductance G_{DC} . These are plotted in Fig. 7: G_K is the theoretical surface boundary conductance between the Al contact and the Si calorimeter and is obtained from the experimental conductances between metals and dielectric materials; G_{ph} is the phonon heat conductance in the In leads and is obtained by using the phonon mean free path of 100 μm , which is the thickness of the leads.

5. DISCUSSION

5.1 Heat capacities

We believe that our present results agree with the heat capacities derived from the specific heats of the various constructional materials. Our analysis of the lowest temperature data (not shown here), however, suggests that there are new and so far unknown contributions to the heat capacity. As a possible explanation we would like to point out that the dominant phonon wavelength in Si is $\lambda = 0.3 \text{ mm}$ at 10 mK; this is the thickness of our calorimeter. We could therefore expect that both the phonon specific heat and heat conduction would be dependent on standing-wave modes and their couplings among themselves and other heat reservoirs.

Another heat reservoir, which may be significant in small calorimeters, is that of the surface impurities. Oxide layers with H_2O absorbed or adsorbed can present rotational, vibrational, and librational degrees of freedom, leading to large heat capacities. Even the clean surface has Rayleigh surface excitations and associated heat capacity; this may also play a role in the heat transmission through interfaces.

Finally, the ^4He heat exchange gas usually leaves several monolayers on the calorimeter and may be observable at a suitable temperature range in a small calorimeter.

5.2 Heat conduction

The remarkable discrepancy between measured steady-state heat conductance G_{DC} and the dynamic heat conductances G_1 and G_2 could be explained in at least two ways.

Firstly, our thermal model may require a correction due to a possible thermal resistance between the thermistor electrons and the bulk phonon system. The electron-phonon heat resistance is size dependent and can be very large in small thermistors. It is then, however, difficult to understand the agreement in the heat-capacity measurements, which suggests that the electron-phonon resistance in Si:P is small above 0.3 K at least.

Secondly, the electron-transport mechanism by hopping and tunnelling under the barrier is dependent on the applied electric field. In restricted geometries this effect may become large at low temperatures, because the resistance and voltage drop may concentrate on small critical domains owing to the microscopic inhomogeneities in the doping. The result would be an erroneous reading of the calorimeter temperature from calibrations performed using low electric fields.

Other non-thermal phenomena may include ballistic phonons and excitations such as hot electrons or excitons, and slowly relaxing heat from magnetic impurities or vibrational states related to lattice faults and impurities. The superconducting contacts and leads may also trap normal electrons (quasiparticles) which are heated above the phonon temperature; this could offer an explanation of the difference between conductances in steady state and in short transients involving non-thermal excitations.

We conclude that, although the physics of the thermal detection of ionizing particles seems to be understood with regard to the orders of magnitude of the parameters involved in the temperature range above 0.3 K, there are many phenomena which may merit detailed study already for the sake of their own fundamental interest.

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Fig. 1 Detector biasing circuit.

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Fig. 2 Amplifier circuit.

Fig. 3 The CAMAC data-acquisition system.

Fig. 4 Semi-logarithmic plot of a typical averaged signal.

Fig. 5 Detector model with two heat reservoirs.

Fig. 6 Heat capacities plotted against temperature.

Fig. 7 Heat conductances plotted against temperature.