Letter to the Editor

Operation of a high-purity silicon diode alpha particle detector at 1.4 K

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Detection of alpha particles at temperatures as low as 1.4 K was demonstrated using a specially fabricated Si diode. The diode was 475 mm² by 0.280 mm thick, fabricated from high-purity silicon with degenerately doped contacts. This is an important step toward development of dual-mode (ionization plus phonon) silicon detectors for low energy radiation.

There is now great interest in direct detection of Dark Matter, which may exist in the form of weakly interacting particles interacting gravitationally with the ordinary matter distribution [1]. Current limits on direct detection of such interactions [2], as well as the interaction rates calculated for a variety of particle candidates [3], correspond to interaction rates of a few counts per kg day. Backgrounds at this level exist due to low-LET radiation from cosmogenic [4] and primordial radioisotopes in the detectors and support structures.

The most popular particle physics candidates for Dark Matter have masses above 10 GeV/c² and low interaction cross sections, as suggested by theory and permitted by available accelerator data [5]. A detector for such particles must have the lowest possible radioactivity and must be capable of discriminating the high-LET recoils produced by elastic scattering of Dark Matter from the residual radioactive backgrounds.

A promising candidate technique is a dual-mode silicon radiation detector, in which one detects both the ionization produced, and the substantial fraction of deposited energy which appears as phonons [6]. In the energy range of interest, the phonon-to-ionization ratio differs by a factor of 4 between Dark Matter interactions and beta decays or photon interactions depositing the same energy [7]. This potentially provides a powerful discriminant against radioactive backgrounds.

However, a clear phonon signal can only be obtained from detector crystals at temperatures below ∼ 4 K. This is due to phonon-phonon interactions with the thermal background present at higher temperatures, and to the characteristics of available phonon transducers [6].

Up to now, operation of silicon diode detectors below about 40 K has not been successful. Previous workers have reported gross pulse lengthening, loss of resolution and loss of pulse height, culminating in insensitivity of the detectors to radiation at liquid-helium temperature [8]. The poor low-temperature performance is believed to be due to two related factors: charge trapping and freezeout of the contacts to the crystal. Impurities and defects may form very shallow trapping levels, which at low enough temperature become effective in capturing drifting charge from radiation interactions. This slows the detector response and reduces the signal size. In addition, the impurity levels in lightly doped pn junction detector contacts may not ionize at low temperature, so charge transfer leading to formation of a depletion region and drift field cannot occur efficiently or uniformly. Low-field regions with poor charge collection result.

As a first step in our group’s development of dual-mode silicon Dark Matter detectors, we have successfully designed and operated a special silicon diode as an ionization detector at temperatures below that of liquid helium. The detector was a 1 in. diameter, 280 µm thick, fully depleted, diffused junction type. It was fabricated from uncompensated high-resistivity silicon (> 1
kΩ cm). The high-purity material was selected to reduce the density of shallow traps. The n^+ (boron) and p^+ (phosphorus) diffusions were carried out under conditions resulting in degenerate doping levels in the contacts (> 10^{19} cm^{-3}). Band tailing in these heavily doped regions will insure availability of charge carriers even below 4 K [9,10]. The doped regions and conventional thin film metal contacts were kept as thin as possible (total 1 μm front (n^+), 4 μm back (p^+)), with a view toward eventual fabrication of dual-mode detectors. In such designs it is important to minimize phonon scattering and absorption in the highly doped contact regions.

The detector was mounted in vacuum inside a helium cryostat and irradiated from the n-type, biased side. The detector temperature was measured with a Lakeshore calibrated Ge thermistor attached to the

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Fig. 1. Single preamplifier pulses from Si detector exposed to ^{241}Am alpha particles at room temperature (a) and 1.4 K (b) respectively. Scale is 100 ns/div horizontal, 5–10 mV (variable) vertical.
copper sample holder, as well as a calibrated Allen Bradley carbon resistor attached to the fiberglass-epoxy detector mounting ring.

The radioactive source was $4 \times 10^4$ Bq of $^{241}$Am at a distance of 5.0 mm, behind a slit ~ 0.25 mm in diameter. The source was rather thick, producing a 5% spread of alpha particle energies. The counting rate was about $3 \text{s}^{-1}$, with practically all the energy deposition resulting from the alpha activity. Alphas from $^{241}$Am stop in the first 20 $\mu$m of silicon encountered. Only observations of alpha particle pulses are reported here.

The preamplifier used was an Ortec Model 142B with Siliconix U308 input FET. The signals were amplified using an Ortec model 450 amplifier with shaping time constants of 1 $\mu$s, and then pulse height analyzed.

Preamplifier pulses were observed on the oscilloscope and the rise time measured at room temperature, 77 K, 4.19 K and 1.4 K. Typical pulses at room temperature and 1.4 K are shown in fig. 1. The rise time is seen to be slightly faster at low temperature.

No sign of detector polarization (buildup of immobile trapped ionization charge, modifying the depletion region and leading to resolution broadening and lower pulse height) was observed in 24 h operation at 4 K and below, with the pulse height remaining stable during this period.

Pulse height spectra taken at room temperature and 1.4 K with identical electronic settings are shown in fig. 2. No large variation of pulse height or resolution with temperature was found. Slight intermittent broadening of the spectrum at low temperature was due to electronic pickup from pumps and other building equipment not under our control.

This work demonstrates that a properly constructed Si diode can be successfully operated as a radiation detector below liquid-helium temperature.

References


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