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Simultaneous High Resolution Measurement of Phonons and Ionization Created by Particle Interactions in a 60 g Germanium Crystal at 25 mK

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We demonstrate simultaneous high energy resolution (rms $\approx$ 800 eV) measurements of ionization and phonons created by particle interactions in a semiconductor crystal of macroscopic size (60 g germanium) at 25 mK. We present first studies of charge collection at biases below 1 V/cm, and find that, contrary to commonly held opinion, the full recoil energy of particle interactions is recovered as phonons when charge trapping is negligible. We also report an unanticipated correlation between charge collection and phonon energy at very low bias, and discuss this effect in terms of charge trapping.

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A wide range of particle detection experiments, so far unachievable by other means, may become feasible with the use of devices based on the measurement of small quantum energy excitations such as phonons or quasiparticles at temperatures well below 1 K [1]. Besides having extremely good energy sensitivity, such detectors can potentially yield additional information about the initial particle interaction. One important example is the simultaneous measurement of the energy in phonons and the number of electron-hole pairs created in a semiconductor crystal by an event. Recoils of nuclei (from, for example, scattering of weakly interacting massive particle dark matter) produce less ionization than do recoils of electrons (produced by photons or charged particles) of the same recoil energy [2]. Thus, this simultaneous measurement could recognize and reject a background of photons in a search for dark matter.

Although this joint measurement technique has been demonstrated in small devices by our group and others [3], much of the underlying physics of these devices is as yet poorly understood. In particular, the charge collection properties of silicon and germanium have not been adequately studied at low temperatures and low charge collection fields. The magnitude of the field is critical because energy is acquired from the field by the drifting charges and emitted as phonons [4]. In order for this drift energy not to overwhelm the phonon energy from the initial interaction, the bias must be limited to a few volts. Further, since this energy depends on the drift *voltage*, while the ionization collection efficiency depends only on the drift *field*, the ability to collect charge with small fields becomes more important as the detector size is increased.

We report measurements made with a 58.4 g germanium device operated at ≈ 25 mK. Using 59.5-keV γ rays as a probe, we demonstrate for the first time that it is possible to simultaneously measure both phonons and ionization with sub-keV resolution in a detector of macroscopic size. We find that charge collection is good for drift fields ≥ 200 mV/cm. At lower biases we discover an interesting correlation between charge collection and phonon energy (besides the expected charge drift heat). We interpret this effect as being due to charge trapping, and deduce that the *full initial recoil energy* from particle interactions is recovered as phonons. This conclusion is verified by an independent calibration of the phonon measurement via two different techniques. Our analysis suggests further that simultaneous ionization and phonon measurement may be a powerful tool for studying impurity levels in semiconductors at low temperatures. The nuclear and electronic recoil discrimination capability of this detector is discussed elsewhere [5].

Our device consists of a disk of single-crystal germanium, 3.8 cm in diameter and 0.96 cm thick, onto which several $1.3\times1.3\times0.33$ mm^3 neutron-transmutation-doped (NTD) germanium thermistor phonon sensors have been bonded [see Fig. 1(a)]. It is mounted in a dilution refrigerator and typically operated at ≈ 25 mK. Two of the sensors are bonded with a simple film of silver-filled epoxy and four others with a germanium-gold eutectic [6] in order to test the phonon transmission properties of these interfaces. We used only one of the eutectically bonded thermistors in the work described here, however, and defer a discussion of the interfaces and phonon ener-

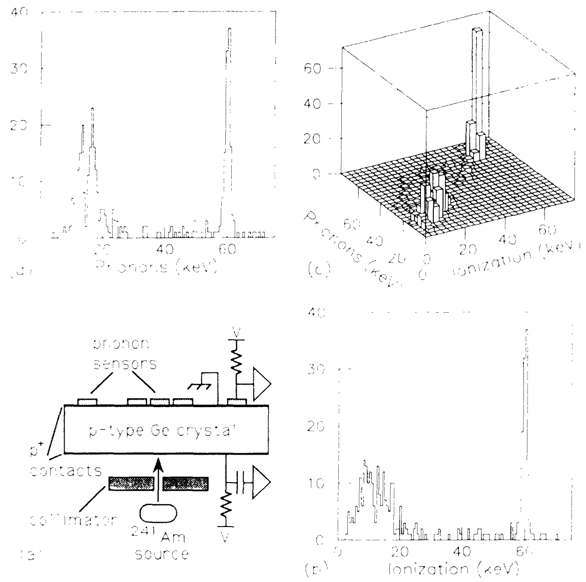

FIG. 1. Simultaneous measurement of ionization and phonons with a ^{241}Am source. (a) Schematic of the device, radioactive source arrangement, and phonon and charge measurement circuits. (b) Projection of the simultaneous measurement onto the ionization energy axis. The rms resolution of the 60-keV peak is 730 eV. (c) Two-dimensional distribution of energy in ionization and in phonons. (d) Projection onto the phonon-energy axis. The rms resolution of the 60-keV peak is 800 eV.

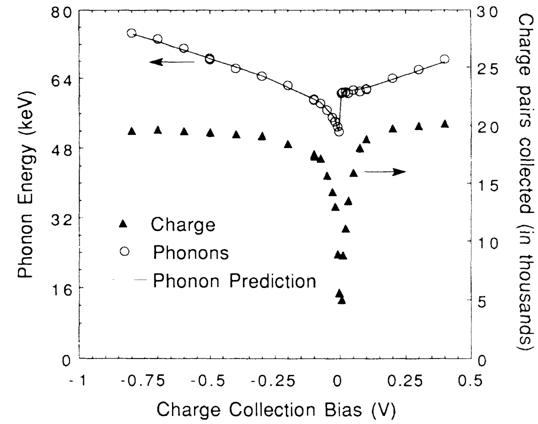

FIG. 2. The number of electron-hole pairs and total phonon absolute energy for 59.5-keV photons as a function of the charge collection bias. The lowest bias data points are at ± 5 mV. Each point represents the mean from a measurement of several hundred events, with statistical errors less than 0.5%. Systematic errors are discussed in the text. The curve is a prediction of the phonon energy based on the charge measurement. For this fit we deduce that the fraction of trapped holes that fall into shallow sites is 0.20 ± 0.1, while for electrons this fraction is 0.45 ± 0.1.

gy spectra to a future publication.

The bulk germanium disk is configured as a p^+-p-p^+ resistive device that collects charge between the two faces of the disk. The ultrapure p-type germanium has a net dopant concentration $(N_A - N_D)$ that varies across the device from 0.5×10^{11} to 2×10^{11} cm^{-3}. Degenerately doped p^+ contacts that do not freeze out at sub-kelvin temperatures were made on each face of the disk by a (4000 Å deep, 3×10^{14} cm^{-2}) boron implant followed by annealing. At these temperatures, all of the net acceptor charges in the bulk are frozen out—hence there is no free charge to "deplete." If there is no net space charge, an applied voltage produces a constant electric field throughout the device, and charge collection can be accomplished with a very low bias.

The electronics for both the charge and phonon measurements utilize front-end junction field-effect transistors mounted in the cryostat about 40 cm from the device and operated at $\sim$130 K [7]. Our thermistor signal is very slow, with $\sim$1 msec rise and $\sim$40 msec fall. We avoid the severe $1/f$ noise and 60 Hz pickup on these time scales by using a 1 kHz ac bias technique, and minimize microphonic noise pickup with a carefully designed gate-wire system [8]. Pulses are digitized and fitted to templates constructed from the average of many carefully selected clean events.

In the work presented here, we irradiated a small spot on one face of the device with 13.9- and 17.6-keV x rays and 59.5-keV γ rays from a 2 μCi ^{241}Am source. The distribution of the energies simultaneously observed in the ionization and phonon channels is shown in Fig. 1(c) and their projections in Figs. 1(b) and 1(d), respectively. In order to facilitate comparison, the two signals have been scaled so that the 59.5-keV peak appears in both channels at this value. The rms resolution for the 59.5-keV photons is 820 ± 50 eV in phonons and 730 ± 50 eV ($230e^-$) in ionization. The baseline noise, obtained by fitting our signal template to randomly "triggered" samples of the amplifier output with no event present, is 600 eV in phonons and 500 eV in ionization. To our knowledge, this phonon measurement represents the best resolution per unit detector mass reported for a cryogenic detector. Note that the x rays, which travel only a few tens of microns into germanium, are not well resolved in the ionization measurement, indicating that charge collection is poor in the transition region between the p^+ implanted layer and the bulk material.

To probe the physics of this simultaneous measurement technique, we repeated the measurement shown in Fig. 1, but varied the charge collection bias between 5 and 800 mV while holding all parameters of the phonon measurement fixed. In Fig. 2 we show the *absolute total* phonon energy (determined by a calibration described below) and the number of charge pairs collected for the 59.5-keV γ-ray peak as a function of charge bias. The charge measurement was calibrated by using the detector disk itself as a capacitor to pulse the charge measurement circuit. We have used a dielectric constant of 16.0, and the overall calibration uncertainty is a few percent. For high, positive bias, the collected charge is essentially the full 19850 charge pairs expected from the interaction at this temperature [9]. The maximum bias was limited by breakdown, presumably due to current flow around the edges of the detector. It did not occur at the same point for both polarities of bias, and showed hysteresis and erratic time evolution.

It is clear from the figure that a bias field of about 200 mV/cm is necessary to achieve good charge collection in our crystal. At lower biases the collection efficiency decreases dramatically, an effect we attribute to trapping of the drifting charge. The rise time of the ionization pulses remains faster than ~ 2 μsec at the lowest biases, indicating that the mobilities are greater than 5×10^7 $cm^2V^{-1}sec^{-1}$. Recombination in the interaction region seems unlikely with mobilities this large. An additional important point in this regard is that charge collection is very poor at all voltages immediately after initial cooldown of the device. The collection efficiency improves dramatically, however, if the bias is held at ground and the device is exposed to an intense radioactive source (which produces a few 10^{10} charges/h) for several hours. We attribute this improvement to a neutralization of the compensated impurities, greatly reducing their trapping cross sections. Note that these impurities would otherwise remain charged, even if there is no net space charge.

The phonon behavior in Fig. 2 seems to be divided into a high-bias regime (above ~ 100 mV) of nearly complete charge collection, where charge drift energy can be easily seen, and a low-bias regime of incomplete charge collection, where the phonon behavior is more complicated. The pulse shapes were independent of electric field, indicating that the phonons generated by the drifting charges produce the same response in the thermistor as those from the initial interaction. The drift heat in the high-bias region thus yields an absolute calibration of the measurement. The drift energy for N charges and bias voltage V is simply eNV, where e is the magnitude of the electron's charge, so that $dE/dV=eN$. Equating the slope of the uncalibrated signals in the high-bias regime to eN indicates that the extrapolated energy at zero bias is 58 ± 5 keV. It had often been assumed that the phonon energy would be $E=E_R-NE_{\rm gap}+eNV$, where E_R is the electron recoil energy and $NE_{\rm gap}$ is the band-gap energy stored by the electron-hole pairs. For $V=0$, this would give $E=45$ keV. Our estimate of the slope suggests, to the contrary, that the full recoil energy is measured. After the fact, this is easily explained if the charge carriers fall to the Fermi level via phonon emission when they reach the p^+ contacts, so that the measured energy is $E=E_R+eNV$. This is illustrated schematically in Fig. 3. Our calibration assumes this later picture (and takes into account the effect of incomplete charge collection as described below).

As an independent test of this calibration, we passed brief (5–10 μsec) current pulses through sections of the slightly resistive ($R\sim100$ Ω) implanted contact between the bottom contacts of several different sets of thermistors which are several mm away from the measurement thermistor. The resulting phonon pulses were nearly identical to those from the 59.5-keV photons, but represented $\sim5\%$ less than the input electrical energy. The pulses also had slight (a few percent) size and leading-edge shape variations for the different pulsing paths, indicating a loss of energy in the thermistors, gold pads, and silver-epoxy patches immediately above the pulsing paths. These results indicate, if anything, a higher overall phonon calibration, strongly supporting the conclusion that the full recoil energy from particle interactions is recovered as phonons.

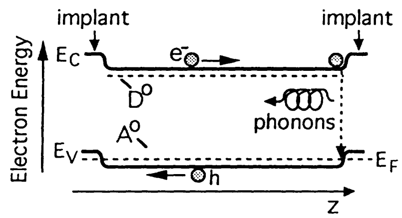

FIG. 3. Schematic diagram of the energy bands in the device (z is the direction perpendicular to the faces of the disk) showing relaxation of electrons in the p^+ implanted regions.

We can make use of this concept of electron relaxation at the p^+ contact to offer a tentative explanation for the asymmetry of the data in the low-bias, incomplete charge collection regime. The detector itself is symmetrically designed for charge collection, with identical p^+ contacts on the faces of the p-type disk. The 59.5-keV photons, however, strike the face on which the bias is applied [Fig. 1(a)] and have an attenuation length of only 0.86 mm in the 9.6-mm-thick crystal. Thus for positive (negative) bias holes (electrons) drift most of the distance across the detector while electrons (holes) drift a short distance. Since our germanium is p type, the Fermi level is very close to the valance band. If electrons are trapped into shallow levels (i.e., $D^0+e\rightarrow D^-$) before reaching the p^+ contact, they release the small trap binding energy, but the energy they could have released at the contact is not released. Since holes release very little energy at the p^+ contact, essentially no energy is "lost" if they are trapped into shallow levels. Thus we expect the phonon energy measured to be reduced when electrons are trapped in significant numbers (negative bias case), and not significantly affected if holes are trapped in large numbers (positive bias case).

The curve in Fig. 2 is the prediction from a simple extension of the above idea where the number of charges trapped is calculated from the charge collection data, assuming that incomplete charge collection is due only to trapping. The derived trapping cross sections are a few $\times10^{11}$ cm^2 at the lowest biases. We allow trapping of both holes and electrons into shallow states (i.e., $D^0+e\rightarrow D^-$) and nearly across-the-band states (i.e.,

$A^0+e\rightarrow A^-$), and treat the fraction of each process that occurs as a fit parameter. Although the agreement is good, this model ignores a number of effects such as the buildup of space charge due to charge trapping, and must be further refined and tested. We conclude by noting, however, that if our interpretation is correct, detectors with p^+-i-n^+ charge collection structures will also have to be understood in terms of the behavior of collected charges in the contact regions. Additionally, this simultaneous ionization and phonon measurement could prove to be very useful for the study of impurity levels in semiconductors at low temperatures, especially if combined with spectroscopic methods.

We wish to thank P. Luke for many insightful discussions about charge collection at low temperature. This work was supported by the Center for Particle Astrophysics, a National Science Foundation Science and Technology Center operated by the University of California, Berkeley, under Cooperative Agreement No. ADT-88909616, and by the Department of Energy under Contract No. DE-AC03-76SF00098. B.A.Y. is a Presidential Fellow of the University of California.

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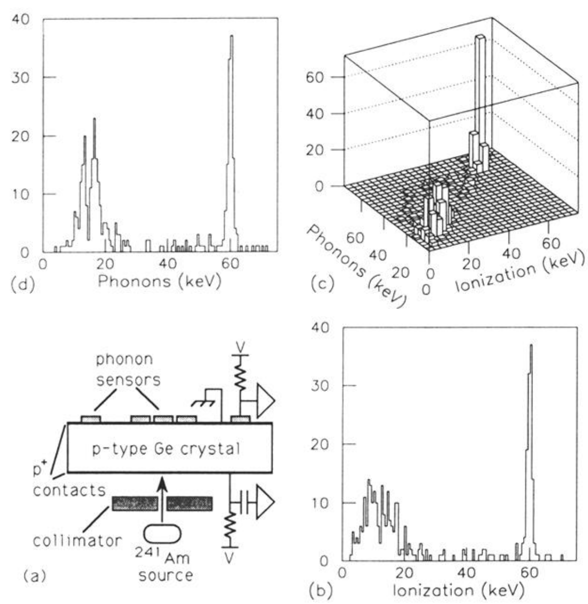

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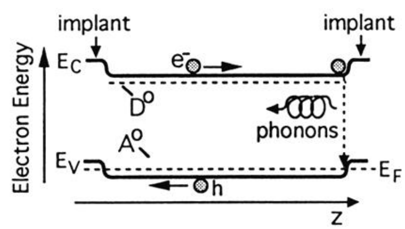

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