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Detectors of the Cryogenic Dark Matter Search: Charge Transport and Phonon Emission in Ge ⟨100⟩ Crystals at 40 mK

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Abstract The Cryogenic Dark Matter Search (CDMS) measures both the ionized charge and the energy in athermal phonons created by particle interactions in ultra-pure germanium and silicon crystals at a temperature of 40 mK. Charge collection potentials must remain at only a few volts, else emitted phonons from drifted carriers will dominate the phonons of the original interaction. At these drift fields, there are practically no thermal phonons and carrier transport is determined by phonon emission.

We present results for drift-limited carrier dynamics and rates of phonon emission in ⟨100⟩ germanium. As these transport conditions represent an extreme limit, a Monte Carlo technique was used to bypass analytical assumptions commonly used in solving the Boltzmann transport equation. This work will assist us in understanding phenomena found in our detectors.

Keywords Dark matter · Low temperature detectors · Germanium · Carrier transport

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1 Introduction

CDMS seeks to detect the scattering on germanium and silicon crystals of putative weakly-interacting massive particles (WIMPs) which could form the dark halo of our galaxy. Ionization and phonon signals are measured simultaneously, allowing us to distinguish between electron and nucleon recoils. This measurement technique provides discrimination between the expected signal of WIMPs and electromagnetic

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background. These detectors are cylindrical in geometry, 1 cm thick and 3.81 cm in radius. One cylindrical face is metalized into geometries forming electrodes. These electrodes are voltage-biased (-3 V Ge, -4 V Si) and collect ionization from recoil events. The opposite cylindrical face measures athermal phonon flux. It is divided into quadrants each of 1036 Al phonon collection fins coupled to W transition-edge sensors. This face serves also as a ground potential for ionization collection. Carrier-phonon interaction affects both our phonon and ionization measurements, so it is critical to understand the fundamental mechanisms of carrier-drift dynamics under our particular operating conditions.

This work examines carrier transport in our germanium detectors. Our germanium crystals are $\langle 100 \rangle$ with impurity concentrations of a few 10^{10} cm^{-3}. Drift fields of 3 V/cm at a temperature of 40 mK are conditions not standard in the literature.

We report on the results of a Monte Carlo simulation based on the wealth of literature on carrier transport in semiconductors [1–7]. We are able to predict the emission of phonons by carriers (the Luke-Neganov effect), as well as the carrier energy and spatial distribution functions. This allows us to compute properties such as mobility, diffusion, and carrier-trapping probabilities.

2 Background and Simulation Techniques

In our transport regime, the number of thermal phonons is negligible for the drift fields of interest. Carrier scattering is dominated by spontaneous phonon emission (or collision with zero-point fluctuations of the lattice), often called the "zero-point" regime. It is often considered in the literature [1–4] that germanium mobility data at $T = 8$ K is representative of zero-point behavior. Our operational temperature is two magnitudes lower than this value. With our small drift fields, it has been an open question how representative the 8 K data are of our conditions.

This Monte Carlo simulation follows closely that of [1, 5]. Scattering probability rates, derived from Fermi's Golden Rule, are numerically computed beforehand and are implemented as a function of energy. The simulation propagates a carrier in a uniform electric field. The step size is chosen such that the carrier has only a small probability to scatter, and is usually just accelerated by the field. A small proportion of the time, the carrier scatters via one of the allowed mechanisms. Once this occurs, the carrier momentum is reoriented with the random distribution appropriate for the given scattering mechanism. The momentum magnitude is also rescaled for appropriate energy and momentum conservation. The carrier is propagated through many such scatters, ensuring that it is well equilibrated to the applied conditions. The final position, momentum, and scattering history of the carrier are recorded. The simulation is repeated to produce an ensemble of many such carriers.

3 Electrons

As we are using $\langle 100 \rangle$ germanium crystals, the influence of the eight L half-valleys of the Brillouin zone are assumed equal relative to the electric field. The elliptical nature of the L-valleys is therefore averaged out, and a spherical approximation was deemed adequate. Nonparabolicity was considered in the calculation of scattering rates, as well as in incrementing position and momentum. Emission and absorption rates for phonon scattering are calculated for acoustic, intervalley, and optical processes.

4 Holes

Holes spend only a few percent of the time occupying the light band before decaying to the lower-energy heavy band. Consequently, it is common to neglect all but the heavy band. In this simulation, both bands are considered in a parabolic way. In a manner similar to [7], this requires four independent scattering rates (intraband and interband) for each phonon scattering process.

Warped bands have been accounted for. A direction-dependent effective mass is used to increment position and velocity. Similar to [7], wavefunction overlap integrals are included in calculating scattering rates, and in selection of a final k-state. This makes final-state selection somewhat more complicated than the electron case. A random number search using a rejection technique is employed to select a suitable magnitude of phonon wavevector, q. Final values for electron wavevector and scattering angle are then constrained by energy and momentum conservation.

Some common assumptions and approximations have been re-examined in order to accommodate our extreme low-temperature, low-bias case. Unlike assumptions in previous work [1, 2, 4], there is no approximation of near-elastic energy conservation for phonon magnitudes. Available scattering angles are defined explicitly and series-expansions are not used to satisfy energy conservation.

5 Findings

Although we did not use this as input, simulated drift velocities for 40 mK, 0.5 V/cm are found to match well to those experimentally measured at $T = 20$ mK, $E = 0.5$ V/cm (holes: $v_d = 1.67 \times 10^6$ cm/s, electrons: $v_d = 2.37 \times 10^6$ cm/s) as reported by [8].

For electrons, simulated drift velocities at 8 K match well to data and to prior simulation as in [1–4]. See Fig. 1. As pointed out in [1], it is known that the data for Ge $\langle 111 \rangle$ electron velocities depict a negative differential resistance, in which velocities diverge from that of the $\langle 100 \rangle$ direction at about 2 V/cm. For $\langle 100 \rangle$, our simulated electron velocities match well to the existing theory. We have found that the zero-point approximation does not represent well the $T = 8$ K electron data for our bias levels. Instead, simulating $T = 40$ mK shows that electron drift velocities for fields of a few V/cm continue to increase by another factor of 2–3. At this lower temperature, both electron diffusion constants also increase.

Previous work [1–4] on hole simulation did not match well to data in the low-temperature/low-field range. With these results, we see that simulation matches well

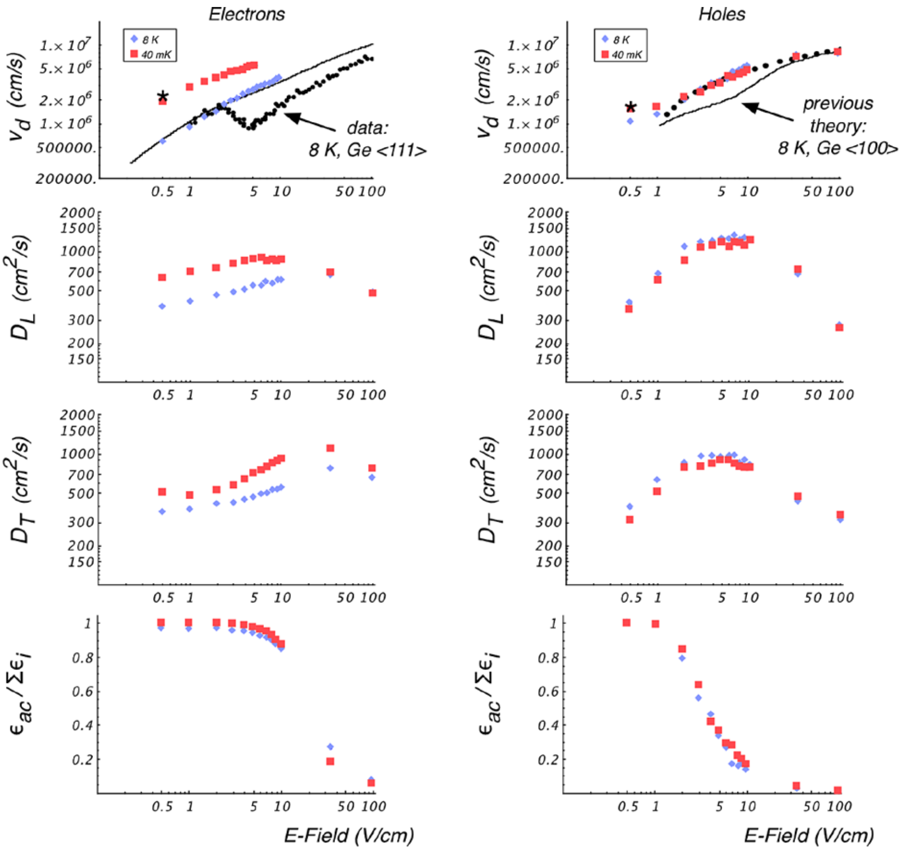

Fig. 1 (Color online) A comparison of electrons and holes, 8 K (*diamonds*) and 40 mK (*squares*). *Top* graphs show drift velocity compared to pre-existing 8 K theory (*continuous lines*) and experiment (*points*) [1–4]. *Asterisks* (*) denote data from [8]. The next *two rows* of graphs show simulated diffusion, longitudinal and transverse. The *bottom row* shows the ratio of energy dissipated by acoustic phonon emission to that of all phonon emission processes

to data, and that there is generally little difference upon comparing 8 K to 40 mK. Although heavy, holes have high carrier energies relative to electrons due to lower scattering rates. Substantial emission of optical phonons by holes at fields only of the order V/cm was not anticipated. Consequently, the pronounced maxima in the diffusion of holes seen in Fig. 1 may not have been previously investigated. At fields of a couple V/cm, holes gain kinetic energy and become more diffusive. At field-strengths higher than about 10 V/cm, hole mobility begins to decrease due to the onset of substantial optical phonon emission.

Emission of optical phonons is of course highly inelastic. High-energy carriers able to produce optical phonons will loose substantial energy upon emission. Therefore, as seen in Fig. 2, the common analytical assumption of a displaced Maxwellian distribution quickly breaks down for holes even at these low bias values.

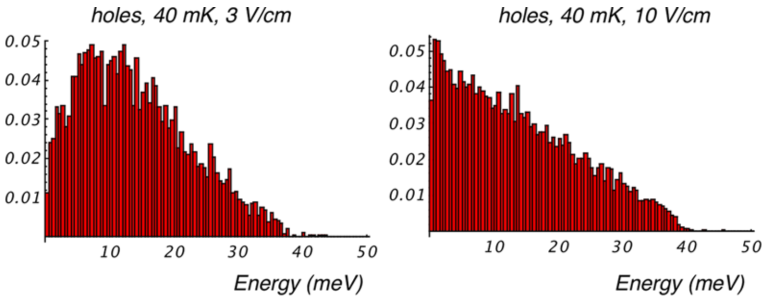

Fig. 2 (Color online) Drift-limited energy distributions at 40 mK. Due to optical phonon emission, carrier energies are not represented well by those of a displaced Maxwellian distribution

6 Conclusions

We have been able to reproduce the theoretical and experimental results obtained for electrons at low temperature and low field, and to fix the problems existing in the literature with holes. While electron transport is dominated by the emission of acoustic phonons, holes appear to emit a substantial amount of optical phonons. This model has to be validated further with the measurements of drift velocities at low field at 40 mK that we are currently performing.

This Monte Carlo simulation will be a valuable tool to understand better the behavior of detectors, in particular carrier trapping on neutral and ionized impurities, and the energy and angular distribution of the Luke-Neganov phonons emitted by the carriers. Such phonons modify the rise time of our phonon pulses, which is a principal discrimination tool against surface electrons.

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