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THERMAL EFFECTS PRODUCED AT CRYOGENIC TEMPERATURES IN MATERIALS USED AS BOLOMETRIC DETECTORS FOR DARK MATTER*

I. LAZANU[1], S. LAZANU[2]

[1] University of Bucharest, Faculty of Physics, Bucharest-Magurele, POBox MG 11, Romania, E-mail: ionel.lazanu@g.unibuc.ro

[2] National Institute of Materials Physics, Magurele, Romania, E-mail: lazanu@infim.ro

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Abstract. In the modern cryogenic technique the heat deposited as phonons, the ionization and/or light from scintillation signals could be used for detection. Also, the formation of defects in the lattice structure of material is possible. In the case when the ionization signal is used for detection, a bias voltage must be applied and thus the generalised Luke-Neganov effect must be considered with contributions from the energy stored in the semiconductor lattice as stable defects in the form of Frenkel pairs. In the process of interaction between the projectile particle and the target, the transient phenomena by which the energy is transferred producing ionization, heat and defects was investigated in the frame of a thermal spike model. A detailed discussion of the associated difficulties of this analysis is done and the results put in evidence the interplay between the primary energies deposited in the electronic and lattice subsystems. This process affects the effective number of defects and the energy stored, which is taken into consideration in the balance of energy conservation in Luke Neganov effect.

Key words: cryogenic temperature, thermal spike model, semiconductors, dark matter.

1. INTRODUCTION

The historical idea to use the bolometric technique goes back to 1881 and its use for radioactive measurements was proposed by Simon [1] in 1935. Modern applications started with the searches for the properties of different kinds of neutrinos and massive components of the dark matter [2, 3, 4]. At the present time, this class of detectors is extended to various rare processes: searches for neutrinoless double beta decay and neutrino mass, for total energy measurements of free electron lasers, to measure the cosmological microwave background, etc.

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The bolometric technique is associated with a robust class of detectors, with benefits associated with a very large domain of application, with high energy resolution and scalability, and with the disadvantages of poor time resolution, cryogenic temperatures for operation and reproducibility [5].

The heat deposited in detectors as phonons, the ionization and/or light from scintillation signals could be used for detection. If the ionization signal is used for detection, a bias voltage must be applied. The Luke-Neganov effect consists mainly in the enhancement of heat deposited by an ionizing particle in a bolometer at low temperatures, when the induced charges are collected by an applied voltage [6], and thus it is possible to improve the signal-to-noise ratio of scintillation detectors [7].

For the case of semiconductor materials (silicon or germanium) used as bolometers, the authors of the present paper extended recently the Luke-Neganov effect, considering the contributions of the energy stored in the semiconductor lattice as stable defects in the form of Frenkel pairs following the interaction in the bulk of the detector [8]. In accordance with these results, in an applied bias voltage (V), the effect of the energy deposited in stable defects is enhanced by a factor $\left(E_d\right)\left(1+eV/\varepsilon\right)$, where ε is the energy of creation of an electron-hole pair.

In the process of interaction between the projectile particle and the target, the transient phenomena by which the energy is transferred producing ionization, heat and defects could be investigated in the frame of a thermal spike model (see, *e.g.* Ref [9] and references cited therein). During the temperature transient, in materials working at subKelvin temperatures, defect kinetics is poorly understood [10]. In this contribution a detailed discussion of the associated difficulties of this analysis is done. The differences between the temperatures of the nuclear and electronic subsystems during the transient time of the development of thermal spike generate interplay between them and thus affect the effective number of defects and the energy stored, which in taken into the balance of energy conservation in Luke Neganov effect used for identification of projectile parameters.

2. ANALYSIS OF THE TRANSIENT PHENOMENA IN SEMICONDUCTORS AT CRYOGENIC TEMPERATURES

2.1. MODEL

It is known that heat propagates in solids by means of thermal vibrations (phonons) and by free electrons. The first mechanism is dominant in insulators and semiconductors, and the second in metals. The time and space evolution of the temperatures of the electronic and atomic systems is the solution of the system of coupled differential equations developed in previous works [8, 9, 11, 12, 13]. The thermal spike model is based on the hypothesis that the energy transferred from the

projectile to the target is partitioned between electronic and nuclear subsystems in accordance with Lindhard prescriptions [14, 15, 16, 17], that the energy lost by ionization and in nuclear collisions is used to increase the temperatures of electrons (T_e) and of the lattice (T_a) respectively in the transient regime. The temperatures evolve *via* heat diffusion. The energy is exchanged between systems at a rate proportional to the difference of power p of the temperatures, multiplied by the electron phonon coupling constant (g).

2.2. CONSIDERATIONS ABOUT THE TEMPERATURE DEPENDENCE OF MATERIAL THERMAL PARAMETERS

The time and space evolution of the temperatures of the electronic and atomic systems is the solution of the system of coupled differential eqs 3.1 from Ref. [13]. The temperatures of the two subsystems satisfy the non-homogeneous heat equations, the space and time integral of the sources are the linear energy losses (electronic and nuclear), and a coupled through the electron-phonon interaction. Following the ionization energy loss, the electrons transfer energy to the lattice by emission and absorption of phonons, resulting a net flow of energy from the carriers to the lattice. This transfer takes place at a time characteristic to the electronic subsystem, which is the time when the majority of the electrons deposit their energy [18]. Both for Ge and Si this time is in the order of 10^{-15} s. In its turn, the lattice transfers energy to electrons at a time characteristic to the lattice, which is in the order of 10^{-13} s.

The solution of the system depends strongly on the material parameters (heat capacities and thermal conductivities) of the two systems, and also on their coupling constant. Due to the fact that there are not experimental data for all these five physical quantities in the whole range of temperatures of interest, in some situations estimations from the theory are used.

The quantization of lattice vibrations in the frame of the Debye model [19] describes accurately the behaviour of the lattice heat capacity both at low and at high temperatures. In the low temperature limit ($T<<T_D$, T_D standing for Debye temperature), the model predicts a T^3 dependence of the specific heat, while in the high temperature limit, the Dulong-Petit law is derived, *i.e.* C_a is temperature independent.

In contrast to heat capacity, thermal conductivity cannot be described without the consideration of phonon interactions: Debye pointed out that if the atomic vibrations are described by their normal modes, then phonons will always be in nonequilibrium distribution upon the application of a temperature gradient across the sample, and the result is an infinite thermal conductivity. Thermal conductivity is determined by the phonon scattering mechanisms, and consequently is more a sample than a material characteristic. Some general trends of the temperature dependence of K_a derived from theory [20] are: a power law increase at low

temperatures (a T^3 dependence), followed by a maximum, and at high temperatures a $1/T$ dependence. The value of the maximum depends on the purity of the sample.

The electronic system is usually studied on metals. In the free electron gas model [19], the low temperature limit of the heat capacity is:

$$C_e = \frac{\pi^2 k_B n_e}{2T_F} T_e , \tag{1}$$

where k_B is Boltzmann's constant and T_F is the temperature corresponding to the Fermi energy, defined as $T_F = \frac{\hbar^2}{2m_e k_B}\left(3\pi^2 n_e\right)^{2/3}$, with $\hbar$ the reduced Planck constant, m_e and n_e are electron mass and number density. The high temperature limit, which is valid for $T_e > 3T_F / \pi^2$, is:

$$C_e = \frac{3}{2} k_B n_e . \tag{2}$$

Thermal conductivity of electrons increases linearly with increasing temperature in the very low temperature limit, passes a maximum and eventually attains a constant value at high temperatures [20].

For semiconductors and insulators, the free electron gas model is valid only when the temperature exceeds the band gap energy ($E_g = k_B T_g \sim 1$ eV, corresponding to $T_g \sim 10^4$ K).

The total heat capacity and thermal conductivity of a semiconductor is usually the sum of lattice and electronic components. With the exception of temperatures in the mK range, and depending also on the concentration of charged carriers, the electronic contribution is much less than the atomic one, and consequently is impossible to be evaluated experimentally.

Measurements of the heat capacity in the mK range, both in Si [21, 22, 23, 24] and in Ge [21, 25, 26, 27], evidenced a temperature dependence of the type:

$$C(T) = \gamma T + \alpha T^3 . \tag{3}$$

The two terms are interpreted as the electronic and atomic heat capacities respectively. Values in the range $6.8\times10^{-7} - 1.5\times10^{-4}$ J/cm^3/K^2 are reported for γ in Si, and $1.21\times10^{-8} - 1.5\times10^{-6}$ J/cm^3/K^2 in Ge respectively. For α, the values found for Si are between $(1 - 6.6)\times10^{-7}$ J/cm^3/K^4, and for Ge there is a relatively narrower interval, around 3×10^{-7} J/cm^3/K^4.

At higher temperatures, experimental measurements are directly correlated with the atomic heat capacity, as the electronic contribution becomes negligible. The data for Si are from Refs. [28, 29, 30], and for Ge from Refs. [29, 30].

For the lattice thermal conductivity, the experimental data used are from Refs. [30, 31] for silicon, and from Refs. [31] and [32] for Ge. In the calculations, a function of the form [33]:

$$K_a = AT_a^3\left(B\exp\left(-CT_a\right)+\exp\left(-DT_a\right)\right) \tag{4}$$

fits well the experimental data for both semiconductors.

In previous calculations [11, 12, 13] we used fits on experimental data for C_a, and a constant value for C_e, in agreement with the values used in the literature [34]. In new calculations in the frame of the thermal spike model [35, 36], a linear dependence of the electronic heat capacity on the electronic temperature is considered up to T_F, followed by a constant value. If formulae (1) and (2) are used, the problem is the estimation of the electron density n_e.

In what concerns the electronic thermal conductivity, in old calculations in the frame of the thermal spike [11, 13, 34], it is taken constant. The theory predicts a linear increase of K_e with T_e at very low temperatures, and then K_e passes a maximum, decreases and eventually attains a plateau at high temperatures [20]. There exist experimental determinations for K_e in Si [37] in the range of mK temperatures, which confirm the linear dependence on temperature, and also the relatively more important contribution of the electronic system up to around 300 mK.

In literature there exists the idea to consider a temperature dependence of the electronic thermal conductivity [36], and this idea was used only for metals and insulators (Au and SiO_2). An extension from metals to which the electron gas model is applicable to insulators is made. The electronic diffusivity D_e is the ratio between thermal conductivity and heat capacity, being defined through the relation:

$$K_e = C_e D_e. \tag{5}$$

In the present calculations we will consider that the electronic diffusivity is constant and that both the electronic heat capacity and thermal conductivity are linear increasing functions on the electron temperature, because at the temperatures attained in the transient processes accompanying the loss of energy by the selfrecoil following a primary interaction are sufficiently low.

There are evaluation for the electron – phonon coupling constant g, both in the very low temperature limit, where the mechanism of heat exchange is with T^6, *i.e.* the corresponding term in the differential equations is $g_{lowT}\left(T_e^6 - T_a^6\right)$, and around room temperature (RT), where the mechanism of electron-phonon coupling satisfies Fourier law: $g_{RT}\left(T_e - T_a\right)$: see the discussion in Ref. [13] and references cited therein.

The coupling constant at very low temperatures, is temperature independent, and is 500 W/cm^3/K^6 in Si [38], and around 50 W/cm^3/K^6 in Ge [27]. At room temperature, the coupling constant [39] is approximately 2×10^{12} W/cm^3/K in Si [40], and 2×10^{13} W/cm^3/K in Ge [41].

2.3. RESULTS AND DISCUSSION

The Cryogenic Dark Matter Search (CDMS) collaboration identifies nuclear recoils (including those that would occur in WIMP interactions) using semiconductor detectors (silicon) operated at 40 mK.

These detectors use simultaneous measurements of ionization and non-equilibrium phonons to identify such events among the far more numerous backgrounds of electron recoils. Three WIMP-candidate events were observed, with recoil energies of 8.2, 9.5, and 12.3 keV [42].

Starting from these results, in the present paper an analysis of the behaviour of silicon and germanium is performed, considering the thermal spike induced by a selfrecoil produced in the primary interaction of a WIMP, at temperatures in the order of tens of mK. This domain of investigation is also in accordance with the total exposure of 113 kg·d obtained by the EDELWEISS Collaboration, during 14 months in 2009−2010 by an array of ten ID germanium detectors from which the constraints for WIMP masses are in the range 7−30 GeV [43].

The influence of the parameters of the electronic system (heat capacity and thermal conductivity) is studied by considering successively a linear dependence of the electronic temperature, in accordance with the theory and the measurements reported in the mK range, and constant values, as used traditionally in thermal spike analyses.

The effect of a WIMP of 10 GeV/c^2, which moves with a velocity of 260 km/s in respect of a terrestrial detector, and which produces a selfrecoil of 13 keV in Si is represented in Figs. 1 and 2 respectively. The linear electronic and nuclear energy losses for a Si ion in Si, at this kinetic energy, are 121.5 and 395.5 KeV/μm respectively. Here, the space and time development of the electronic and lattice temperatures is represented, calculated in the frame of the cylindrical thermal spike [11]. The parameters of the atomic subsystem are the same in both cases: $C_a = 6.5\times10^{-7}\ T_a^3$ [J/cm^3/K] up to 2 K, than interpolation of experimental data, $K_a = 0.08\times T_a^3$ up to 1 K, than interpolation of experimental data, $g = 500$ J/cm/K^6, energy transfer between electron and phonon systems corresponding to $p = 6$.

In Fig. 1, the calculations are performed considering that $C_e = 1\times10^{-4}\ T_e$ [J/cm^3/K]; $K_e = 5\times C_e$ [W/cm^3]. Initial temperature of system is 25 mK.

The same calculations were performed, using temperature independent values for C_e and K_e, and the results are presented in Fig. 2.

In this case, the electronic and nuclear energy losses are comparable, but the heat capacities and thermal diffusivities of the electronic and atomic subsystems are completely different. An examination of Figs. 1 and 2 reveals that in the distribution of the electronic temperature there exists only one peak, situated at $t \sim 5\times10^{-15}$ s, while in the atomic temperature there are two peaks: the first is due to the transfer from the electronic subsystem, and is the most pronounced in both situations, while the second is due to the nuclear energy loss itself, and is more important in the case of low values of C_e and K_e due to the fact that less energy is transferred to the electronic subsystem in this situation.

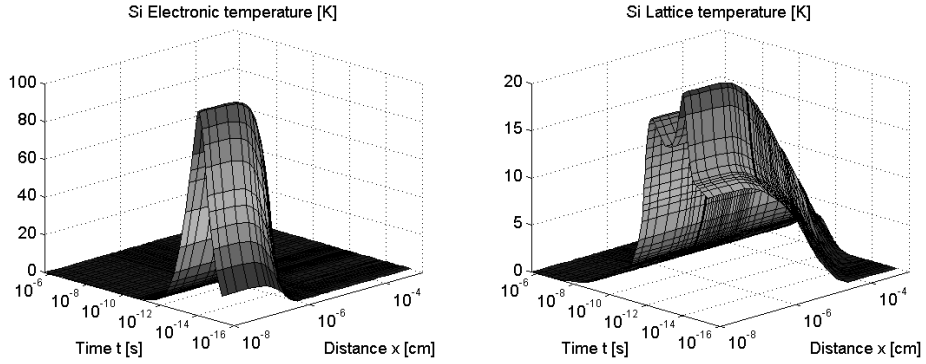

Fig. 1 – Electronic (left) and atomic (right) temperature rise, in space and time, produced by a selfrecoil of 13 keV in Si, following the interaction with a WIMP, for linear dependence of C_e and K_e on electronic temperature.

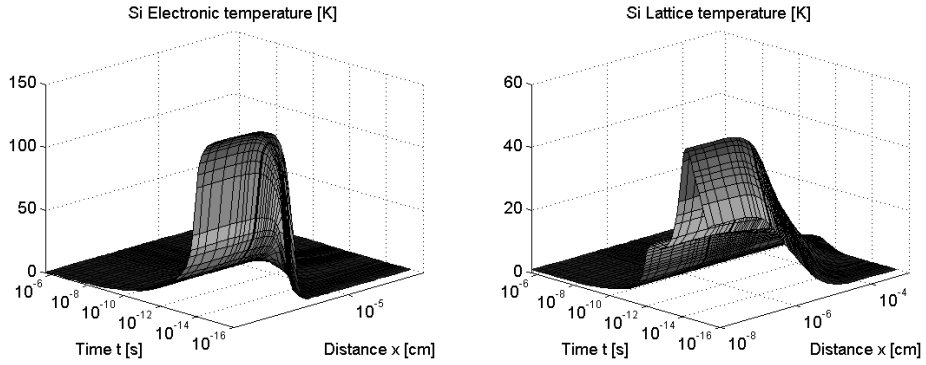

Fig. 2 – Electronic (left) and atomic (right) temperature rise, in space and time, produced by a selfrecoil of 13 keV in Si, following the interaction with a WIMP, for temperature independent C_e and K_e .

If the same WIMP would interact in Ge, it would produce a Ge selfrecoil of 15 keV, for which the linear electronic and atomic energy losses are 51.67 and 1066 keV/μm respectively.

We used the following lattice parameters for Ge: $C_a = 3\times10^{-6}\ T_a^3$ [J/cm^3/K] up to 5 K, than interpolation of experimental data, $K_a = 0.146\times T_a^3\times(0.017\times \exp(-0.772T_a)+\exp(-0.252T_a))$ up to 2 K, than interpolation of experimental data. The electron-phonon coupling constant, corresponding to $p = 6$, is $g = 50$ J/cm/K^6.

In Figs. 3 and 4 we present the space and time distribution of the electronic and atomic temperatures for linear dependence on electronic temperature, and for temperature independent C_e and K_e respectively.

The results reported in Fig. 3 were obtained using $C_e = 1.5\times10^{-6}\ T_e$ [J/cm^3/K]; $K_e = 80\times C_e$ [W/cm^3], and those from Fig. 4 with $C_e = 0.165$ J/cm^3/K; $K_e = 80\times C_e$ [W/cm^3].

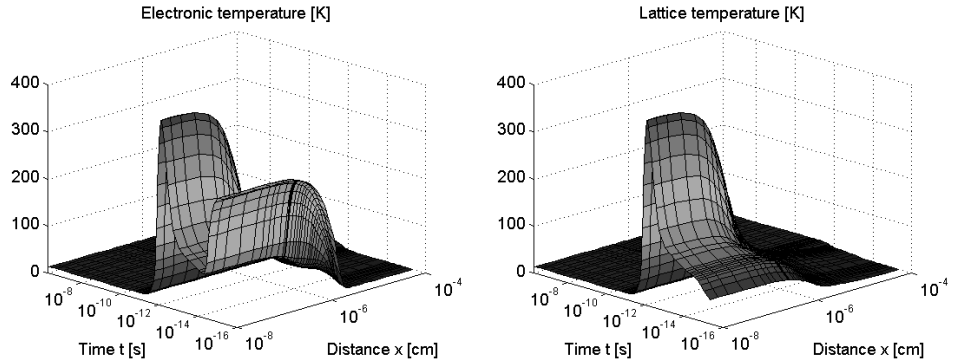

Fig. 3 – Electronic (left) and atomic (right) temperature rise, in space and time, produced by a selfrecoil of 15 keV in Ge, following the interaction with a WIMP, for linear dependence of C_e and K_e on electronic temperature.

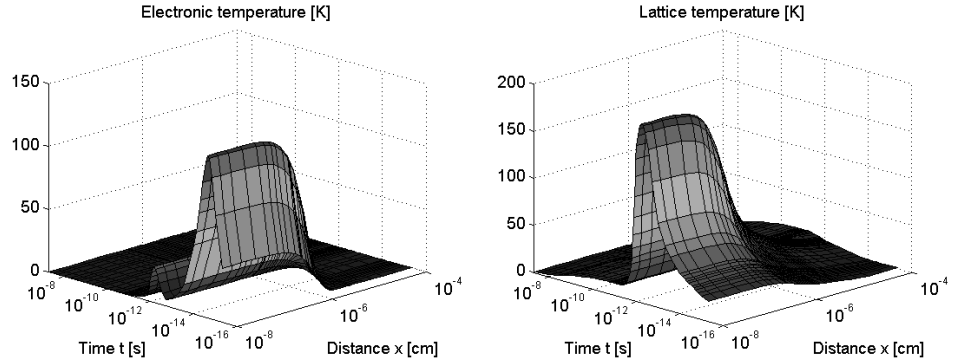

Fig. 4 – Electronic (left) and atomic (right) temperature rise, in space and time, produced by a selfrecoil of 15 keV in Ge, following the interaction with a WIMP, for temperature independent C_e and K_e.

Lower specific heat and thermal conductivity, and which has a linear temperature dependence, has as main effect a higher increase of the temperature in both electronic and atomic subsystems, and also a longer time extension of the pulses. From the comparison of Figs. 3 and 4, it could be seen that, although the coupling between the subsystems is the same, the relative peak size of the two maxima in the electronic temperature, situated at 5×10^{-15} and 5×10^{-13}s is reversed. For low C_e, the temperature in the electronic system has a higher increase, and for low K_e the heated region extends farther. While the first peak in T_e has approximately the same amplitude in both situations, the second one is different. The low values of C_e and K_e are also reflected in the lattice temperature, through the subsystems coupling: in the first case, the temperature pulse lasts longer. As a consequence, the initial energy deposited into the lattice is modified by the energy exchanged with the electronic system and this quantity contributes to defect formation.

3. CONCLUSIONS

In the processes of interaction between the incoming particle and the target, the transient phenomena by which the energy is transferred producing ionization, heat and defects was investigated in the frame of a thermal spike model. The solution of the system depends strongly on the material parameters (heat capacities and thermal conductivities) of the two systems, and also on their coupling constant. Due to the fact that there are not experimental data for all these five physical quantities in the whole range of temperatures of interest, in some situations estimations from the theory were considered. A detailed discussion on the associated difficulties was presented.

An analysis of the behaviour of silicon and germanium is performed, considering the thermal spike produced by a selfrecoil resulting in the primary interaction of a WIMP with a mass close to ten GeV, at temperatures in the order of tens of mK. These values are in accordance with the events observed in the current experiments, candidates to WIMPs. The influence of the parameters of the electronic system (heat capacity and thermal conductivity) is studied by considering successively a linear dependence on the electronic temperature and constant values. In all cases studied, the two subsystems exchange energy.

In the estimation of the number of defects produced in the lattice, the interplay between the primary energies deposited in the electronic and lattice subsystems modify the primary number of stable defects.

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