PIRE-GEMADARC Internal Notes – Germanium Internal Amplification (GeIA): *

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To understand the solid-state physics emerging in the crystal for the germanium internal amplification at two conventional temperatures, which are liquid nitrogen temperature(77K) and liquid helium temperature(4K), some of the literature studies are completed with the content summarized in this note.

CONTENTS

I. INTRODUCTION

Since some of the experiments, such as the low-mass WIMP search with χN scattering, require the low-threshold detector for detecting the small amount of energy, the fundamental laws of internal amplification, which can be utilized for enlarging the signal directly, should be revealed for getting it to be manageable.

In 2000, two experts from Russian, who are the pioneers of our research, came up with the conceptual design about applying the high voltage on the Ge detector, along with the electron-hole pairs that can be enhanced within the avalanche region showing up in the crystal. Thereby, there are a bunch of experiments having an attempt to extend the idea and to see whether it can be worked out with the state-of-the-art technology in reality.

In our collaborations, two teams are realizing the notion under two conventional temperatures, which are 4K(USD) and 77K(THU). Under these two different temperatures, the phenomenon happening to the signal and noise in the crystal would be disparate. The studies are expected to carry out the difference between these two setups, and the advantage versus disadvantage in a variety of facets to them.

In the following sections, first, some of the basic knowledge related to the p-n junction would be conducted as the foundation of this research. Then, under these two temperatures mentioned previously, the internal amplification on the signal will be elaborated on. In parallel, as the signal is strengthened, the noise of the crystal could be unexpectedly magnified consequently. Dealing with the adversity of the high noise originating from three species of leakage currents in the crystal is the very next topic that should be addressed. After all, the signal-to-noise ratio is the ultimate criteria to compare between different setups.

At the end of the notes, in practical, because of the thorny problem on the dielectric breakdown, which is due to the tremendously high electric field and can sabotage the crystal intrinsically for both temperatures, the mechanism of that would be delivered to assess the crucial voltage on protecting the crystal from being destroyed.

II. BASIC P-N JUNCTION

Given the semiconductor containing the different types of impurity, two groups, including the n(electron-dominant) and p(hole-dominant) types, can be characterized. For any crystal containing both types of semiconductors, the properties of the p-n junction

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will occur. The phenomenon for it would be discussed as follows.

In Fig.1, the typical p-n junction is illustrated. On the p-n junction, the electron-hole diffusion, as well as the attraction, will start emerging in the crystal. After the "dynamic" get balance, the neutral region called "the depletion region", which the stable electric field flows in, will show up. In the reverse-bias case, the higher the voltage, the larger the region it will be. In the end, the voltage should be enhanced to the one which can deplete the whole crystal, implying all electrons and holes in the crystal get equilibrium. Afterward, the application of this "neutral" crystal can start off.

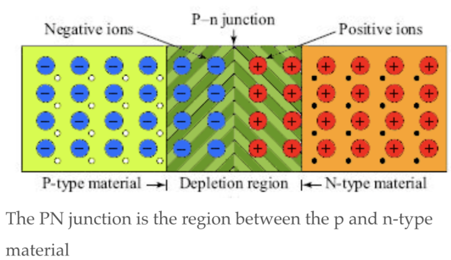

FIG. 1. The basic P-N Junction.

If the details of it about the fundamental physics in semiconductor is desired, chapter7 and chapter8 of the book[1] are recommended.

III. SIGNAL AMPLIFICATION

A. Necessary Parameters from "an electron":

At the start, let us visualize "an electron", which is ionized by a WIMP, flowing in the crystal. Many necessary parameters must be acquired in advance from this electron to unfold our studies. All of them will be depicted in the following subsections.

1. *Electrical Mobility(μ)*

From the definition of electrical mobility. which is as follows:

$$\mu = \frac{V_d}{E} \tag{1}$$

V_d is the velocity of the electron, and E is the electric field applied to the crystal.

The mobility is estimated by the formula above. Specially, since in our experiment, the ultra-high electric field is applied, the saturation phenomenon, referring to the situation that the velocity would be a constant when the electric field is beyond the critical one, can be obtained. In Fig.2[2], when the electric field is upon 10^4V/cm, which is also the critical electric field in calculating the ionization rate described in the latter section, the velocity of the electron is a constant for both temperatures.

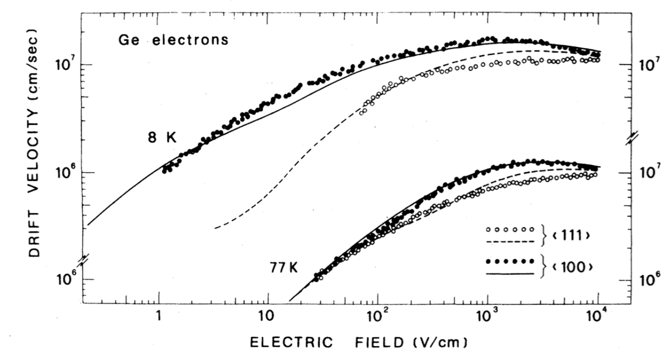

FIG. 2. The drift velocity as a function of electric field is shown for the different temperatures.

2. *Effective mass(m*)*

Under the different temperatures, the effective conductivity masses are various. In Fig.3[3], the hole has the higher effective mass when the temperature is low. BTW, since there is no such study for Ge, Si study is taken as our standard in this case to give us a sense of the tendency of it.

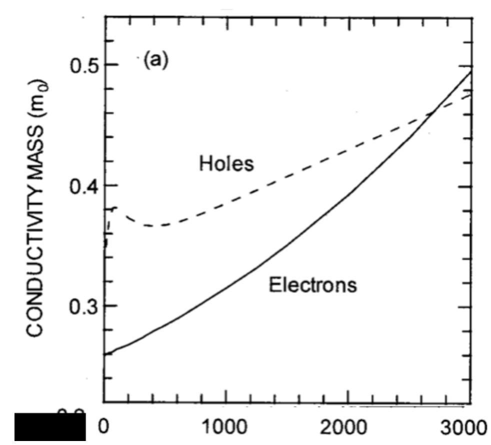

FIG. 3. The relation between the effective mass(m_0) and the temperature(T) is demonstrated for both electron/hole.

3. Relaxation Time(τ)

The period of time that the electron can survive without bumping into another atom:

$$\tau = \frac{\mu \times m*}{e} \tag{2}$$

e is the coulomb constant, μ is the mobility of the electron, and m* is the effective mass.

After acquainting the relaxation time, the next thing that should be figured out is the mean free path(L), which means how far the electron can go along without ramming with another atom in the crystal. The formula is as follows:

$$L = \tau \times V_d \tag{3}$$

V_d means the velocity of the electron, and τ is the relaxation time.

After all of the parameters are well-recognized in this section, those would be made use of in the next section for developing the theory of amplifying the signal.

B. Real beef: Ionization rate

The ionization rate, which is also referred to as "gain", is defined as the following description: How many electrons/holes can be ionized within 1cm?

After depleting the crystal, next the relation between the ionization rate and the E(V/cm) can be brought to light. Based on the formulae (4),(5) and (6) from paper[4], the ionization rate can be decided by exploiting the mean free path(L), electric field(E(x)) and ionization energy(U) of the material,

$$\alpha_s = \frac{a_s}{z} exp(-\frac{b_s}{E(x)}) \tag{4}$$

$$z(x) = 1 + \frac{b_n}{E(x)} exp(-\frac{b_n}{E(x)}) + \frac{b_p}{E(x)} exp(-\frac{b_p}{E(x)}) \tag{5}$$

$$a_s = \frac{1}{L_s}, b_s = \frac{U_s}{qL_s}, s = (p, n)type \tag{6}$$

α_s means the Ionization rate, E(x) is the electric field distributing in the crystal, L_s is the mean free path, and U_s means the Ionization energy.

The FIG.4 can be framed by employing the formulae introduced above. From this scheme, there are three important pieces of information that can be concluded:

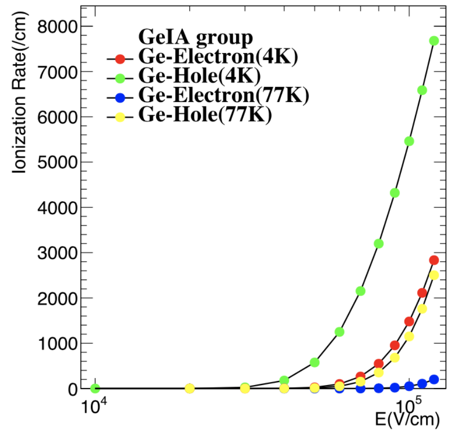

FIG. 4. The ionization rates for both electron and hole under both 4K and 77K.

1. Critical E=10^4 V/cm
2. The significant difference between e/h cases is the effective mass under such high electric field at the same T.
3. Hole can give us more signal under 4K.

C. Pioneer: Russian investigation[2000]

In light of the paper[5], the conceptual design on the coaxial detector HPGe, which is displayed in FIG.5, is provided. The selling point of this detector is as follows:

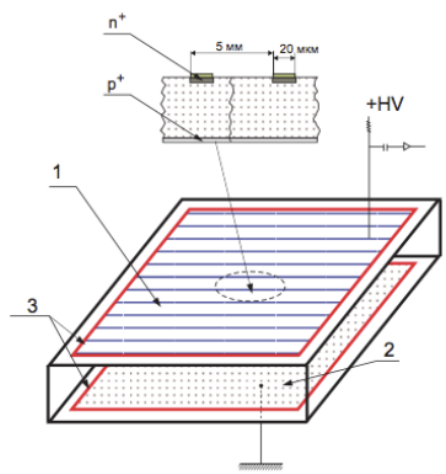

FIG. 5. Germanium detector with an internal amplification (schematic view): (1) anode strips, (2) cathode, and (3) guard electrodes. The scheme of n+ and p+ layers is shown in the upper part of the figure.

According to FIG.4, when the electric field is higher than 10^4(V/cm), the electron will be increased as the function of the electric field. As a result of that, two regions can be separated in FIG.6[5] with this critical electric field.

1. Avalanche region: When the electric field is above 10^4(V/cm), the avalanche effect will emerge, subsequently, the signal will be amplified.
2. Reach-through region: If the electric field is below the critical one, then the electron/hole will just go through normally without any effect.

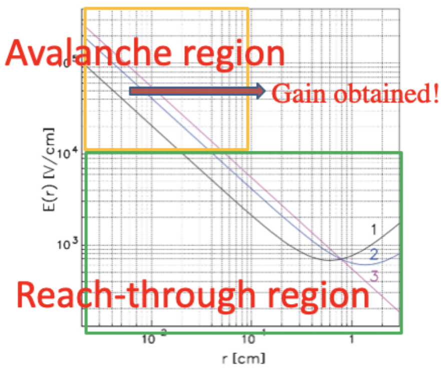

FIG. 6. The electric field as a function of the distance from the strip in FIG.5 with the different impurities. The number above the lines mean the different impurities: (1)$10^{10} cm^{-3}$, (2)4 $\times 10^9 cm^{-3}$ and (3) 0 cm^{-3}

These studies give out a clue that the detector can be devised to yield the amplification for the signal with the electric field above a certain level.

IV. NOISE IN THE CRYSTAL

Unfortunately, the noise in the crystal is inevitable. The genres of the noise in the crystal should be characterized as the criteria of the limitation of measuring the lowest mass for dark matter theoretically. There are three sorts of noise in the crystal, encompassing the bulk leakage current, the contact leakage current, and the surface leakage current. In the following paragraph, all of them are described individually.

A. Bulk leakage current

Because of the thermal fluctuation, the electrons from the bulk(purity, such as Ge) material will be ionized possibly. Fortunately, the level of this noise can be ignored below 77K. The associated information is well-written in the formula(10)[6]:

$$I = Ae^{\frac{-E_{\text{Ge Band}}}{2k_B T}} * q \tag{7}$$

A is the intrinsic concentration, $E_{\text{Ge Band}}$ is the band gap of Ge, q is the coulomb constant, and T is the temperature(K).

B. Contact leakage current

Because of

1. Barrier between the semi-metal connection
2. Thermal fluctuation

There is a possibility that the electron in the conductive band could leap into the metal, leading to the dark current which is unwanted.

In Fig.7[7], which is the measurement from USD, gives out the thread about the scale of the contact leakage current at 100K is around $5 \times 10^{-10} A/cm^2$. Compared with our result, the Fig.8[8], which is demonstrated by other group with the a-Ge detector, also has the similar results at 100K. Upon the usage of FIG.8, the contact leakage current under 77K, which is around $5 \times 10^{-16} A/cm^2$. can be extrapolated.

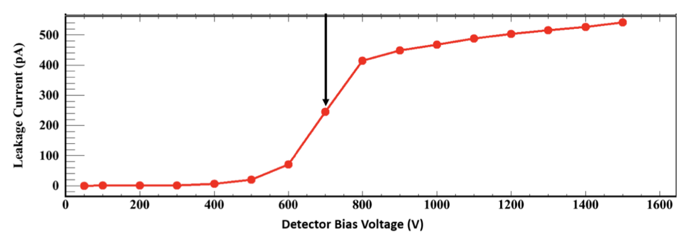

FIG. 7. The determination of full depletion voltage for detector USD-L01 using I-V measurements at 100 K.

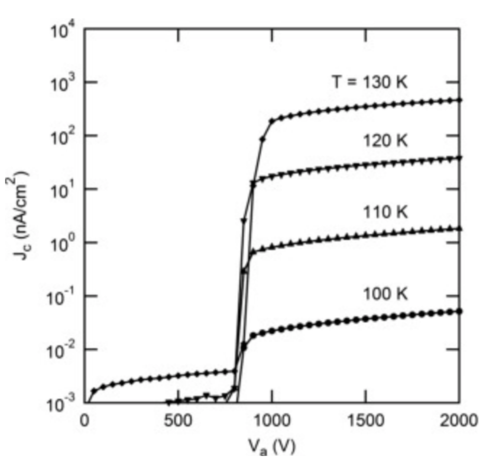

FIG. 8. Measured center contact leakage current density plotted as a function of bias voltage at various temperatures for an a-Ge/HPGe/a-Ge detector

The fundamental physics is "Schottky effect", which is a kind of the thermal emission. The simplified formula can be expressed with the "Richardson's law" as follows:

$$I \propto T^2 e^{\frac{W}{k_B T}} \tag{8}$$

$E_{\text{Ge Band}}$ is the band gap of Ge, q is the coulomb constant, T is the temperature(K), W is the work function of the material, and A is the measured constant.

The detail of this mechanism is compiled in the book[9]. This leakage current will be the dominant one under 77K.

Basically, it is a Metal-Semiconductor junction problem, which is a very big topic authentically and the chapter 10, 11 of book[9](Strongly recommended!) and chapter 6 and 7 of book[10] are recommended to acquire more detail on the related topic.

C. Surface leakage current

It depends on the quality of the crystal. By and large, lowering the temperature can help get rid of the noise.

There are two papers depicting the measurement of the surface leakage current for Ge. Please look at Fig.9[11], which shows the surface leakage current from InAs Avalanche Photodiodes. Although this is not for Ge, it gives us a hint on the scale of the semiconductors. The points(■) can be expanded in the figure to predict the surface leakage current under more lower temperatures. The extremely low surface leakage current can be inferred in this paradigm under the low temepratura.

Currently, the new results of a-Ge for the surface leakage current from USD are published. Amazingly, In FIG.10[12], the leakage current is projected down to the temperature at 4K, and the considerably low leakage current is illustrated at the very low temperature, leading to the feasibility of detecting the low-mass dark matter.

D. Summary for three currents

In FIG.11, the chart for summarizing these three currents under the saturation circumstance are displayed. Overall, the surface leakage current is the severe

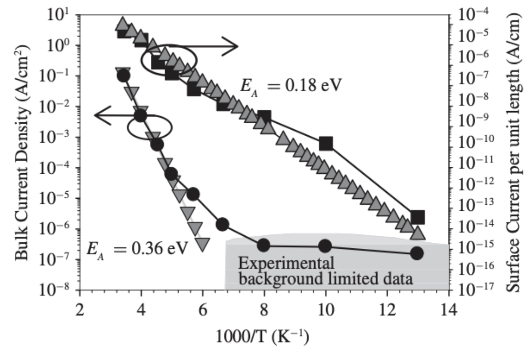

FIG. 9. The surface leakage current, which is remarked by (■), is measured with the InAs Avalanche Photodiodes.

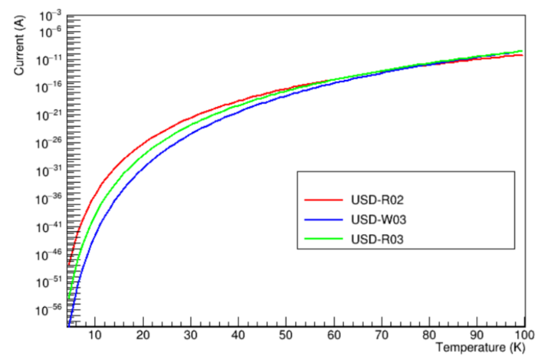

FIG. 10. Projected variation of the surface leakage current with temperature for a PPC detector using the parameters obtained for the a-Ge used in detectors USD-R03, USD-R02 and USD-WO3. .

conundrum for any temperature. At 77K, the contact leakage current is competitive with the surface leakage current, as their numbers are very close to each other. At 4K, surprisingly, the surface leakage current surpasses all others overwhelmingly.

V. ELECTRICAL BREAKDOWN

The electrical breakdown can not only alter the electrical properties of the Ge atoms permanently, but also give rise to the grave damage to the crystal, resulting in our effort to grow the available crystal is wrecked. Therefore, the theoretical forecast on the breakdown voltage should be explored ahead of time for preserving our detector from being broken.

Since the bandgap between the conductive band and the valance band is around 0.68eV, the energy stockpiled in the capacitance(detector) should be around this number for letting the electrons in the valance band have the sufficient energy to hop to the conductive band,

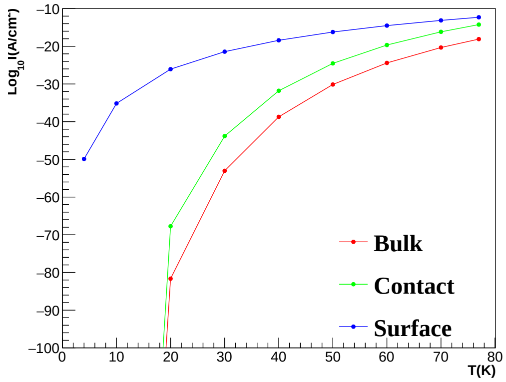

FIG. 11. The leakage current as a function of the temperature for three types of leakage currents.

bringing about the breakdown occurring in the crystal.

The simple estimation can be compiled with the calculation demonstrated as follows:

$$u = \frac{1}{2} \times \epsilon_r \epsilon_0 \times E^2 \tag{9}$$

u is the energy stored in the capacitance, and ϵ_r is the relative permittivity, differing between the different material. ϵ_r is the vacuum permittivity, and E is the electric field distributing in the crystal.

After the substitutions for those parameters with the authentic numbers from our experiment, the calculations can be generated as follows:

$$\frac{1}{2} \times 16 \times (8.8 \times 10^{-12}) \times E^2 = 0.68eV \tag{10}$$

In the end, the final result for the scale of E is around E(MV/cm) for the electrical breakdown. To compare between the experimental values on the scale of electrical breakdown at varying temperatures, E_{ds}, which is employed to delineate the electric field strength at which the breakdown occurs, would be investigated.

E_{ds} obeys the following formula[13]:

$$E_{ds} = C \times T^{\frac{1}{3}} \tag{11}$$

C is a constant determined by the experiment, and T is the temperature.

With respect to the difference for E_{ds} under two different temperatures, the ratio calculation can be made as follows:

$$\frac{77^{\frac{1}{3}}}{4^{\frac{1}{3}}} \approx 2.68 \tag{12}$$

Basically, the breakdown electric field for the crystal under 77K is three times higher than the case under 4K.

VI. CONCLUSION AND DILEMMA

1. Evidently, if the temperature is lessened to 4K, the leakage current will be absolutely small.
2. Under the high temperature, such as 77K, the crystal could easily break down because of the high leakage current, now the experiment under 4K is anticipated to produce a first version stable amplification.

VII. ACKNOWLEDGEMENT

Thanks to Prof. Henry Wong at IoPAS on guiding me through the whole studies and providing me a lot of extraordinary advice for the direction of many issues. And thanks to Prof. Dongming on answering me most of the problems originating from the published paper and assisting me see whether the physical concepts I summarize are right.

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