氏　　　　名	M. Jauhar Kholili
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学 位 論 文 題 目	Study on Diamond Detector to Develop Its Numerical Model and Charge Amplification Structure
論 文 審 査 委 員	主　査　　教授　三原　智 教授　佐波　俊哉 准教授　萩原　雅之 准教授　宮原　正也 教授　田中　真伸 グループリーダー　小泉　聡 国立研究開発法人 物質・材料研究機構　機能性材料研究拠点 電気・電子機能分野 ワイドギャップ半導体グループ

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Summary of Doctoral Thesis

Name in full M. Jauhar Kholili

Title: Study on Diamond Detector to Develop Its Numerical Model and Charge Amplification Structure

The plan to upgrade the luminosity of future high-luminosity (HL) and high-energy (HE) colliders will require an inner-tracking detector system that withstands flows of particles with fluence $\geq 10^{16}$ /cm2. Under the condition, the current silicon detectors technology cannot endure a long-term operation. In that heavily irradiated environment, silicon detector shows high leakage current, high full-depletion voltage, and poor charge collection efficiency. Compared to silicon, prior study indicates wide-gap semiconductor, especially diamond, give advantages of good radiation hardness and a low dark current under a high fluence condition at room temperature. Moreover, Silicon performance is sensitive to the temperature variation. In HL-HE condition, silicon detector system requires a thermal management system to maintain its temperature and perform optimally at low temperature. Some particles are created in in the innermost of detector system, but dedicated detectors for them is at outer layers of detector system. Hence, improvement of detection precision can be achieved by minimizing the total mass of inner tracking detector system to reduce multiple scattering. By introducing a better material that performs better at high temperature, the extra material for the cooling system can be reduced.

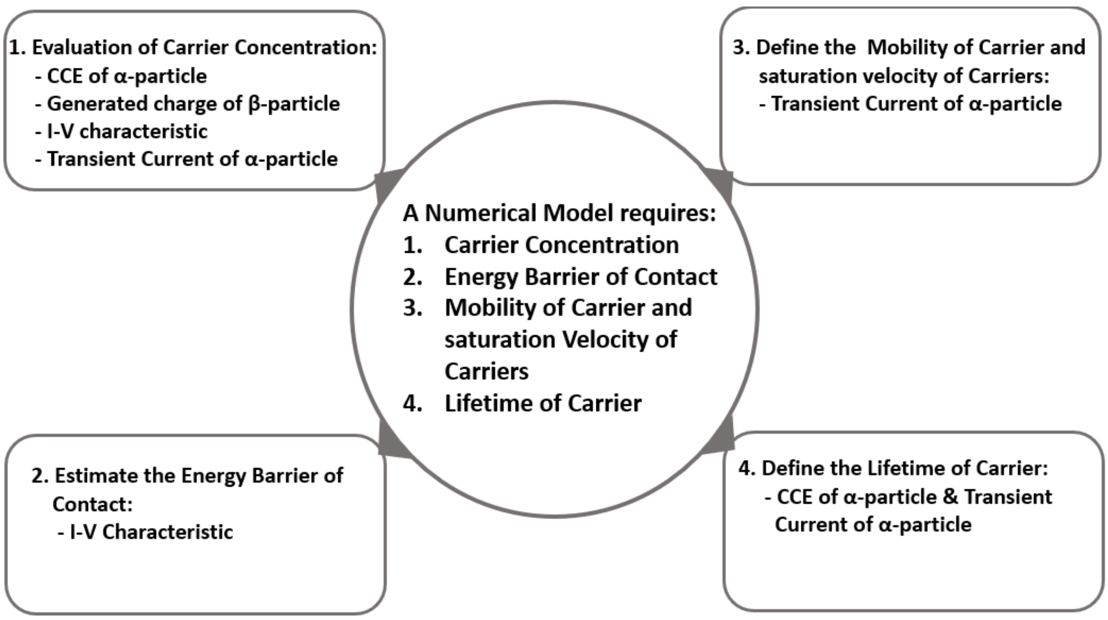


Figure 1. The important parameters to build a model for diamond detector and the related experiments.

Generally, diamond is excellent material to be detector in high-energy physics application. However, it has significant drawback of low signal generation compare to that of silicon. In order to resolve the problem, we need to understand the main properties of diamond to develop new type of diamond particle detector. Yet, there is no a comprehensive model that is capable to explain the complete experiment data related to charge-carrier transport mechanism with a set of parameters in a single model. Therefore, we evaluate the characteristic of high-quality diamond substrate and based on a set of parameters in a model by extracting the parameters from experimental data (Figure 1). With the knowledge of the parameters and exploiting the high field breakdown characteristic, we design a diamond detector that capable to generate Carrier Multiplication Effect (CME). The realization of diamond detector with CME can overcome the problem of diamond detector which is the low amplitude signal.

Thankfully, other electronic technology also starts to substitute the widely used silicon material to widegap material for some applications. The most common development is application of diamond for diode for high power switch. The development also helps to boost the improvement of fabrication process that eventually makes high quality substrates of diamond available. Furthermore, some authors report the availability of high-quality diamond substrate which can be used to detect particle with an excellent (≈100%) Charge Collection Efficiency (CCE).

1.1 Transient Current Technique

The results of TCT measurement can be seen in figure 2. The signal is the result of averaging of gali52+ amplifier signal for each bias voltage. The voltage signal is converted to current signal using equation 1.

$$i_{m_{e,h}}(t) = \frac{1}{R_{\text{in}} A}\left[R_{\text{in}} C_d \frac{dU(t)}{dt} + U(t)\right] \tag{1}$$

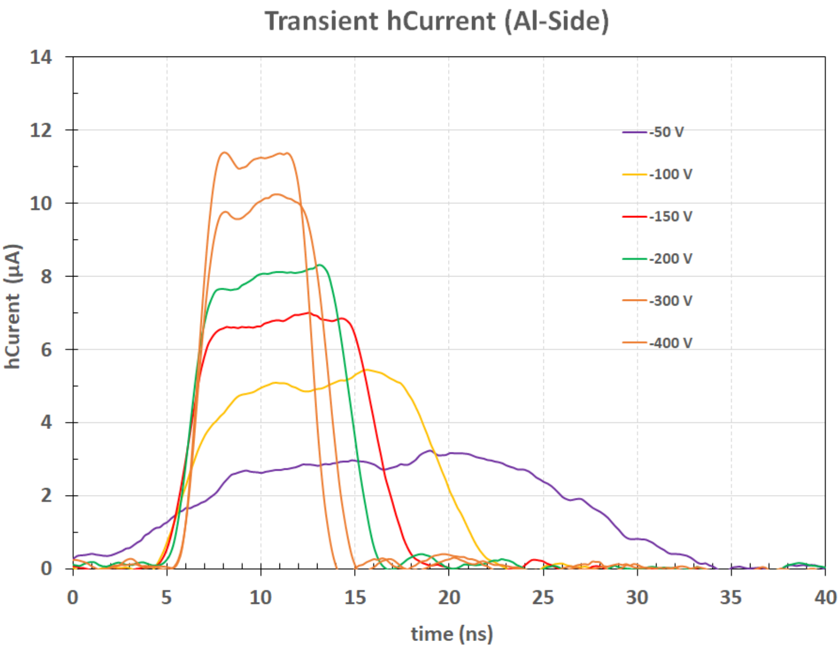
We consider the value of input resistance of amplifier R_{in} is 50 Ω. We measure the real gain of gali52+ amplifier A is ≈13. Due to the small value of detector capacitor (maximum 0.6 pF), the first term of equation 1 is negligible.

By fitting the leading edge and trailing edge of the signal, we can calculate the drift time of the carrier. The fitting is carried out using Error function in ROOT. With equation 2 the drift time of the carrier leads to the drift velocity of the carrier.

$$v_{\text{dr}}(E) = d/t_c. \tag{2}$$

E is electric field, v_{dr} is drift velocity of carrier, t_c is drift time of carrier and d is thickness of diamond substrate 500 µm.

(a)



(b)

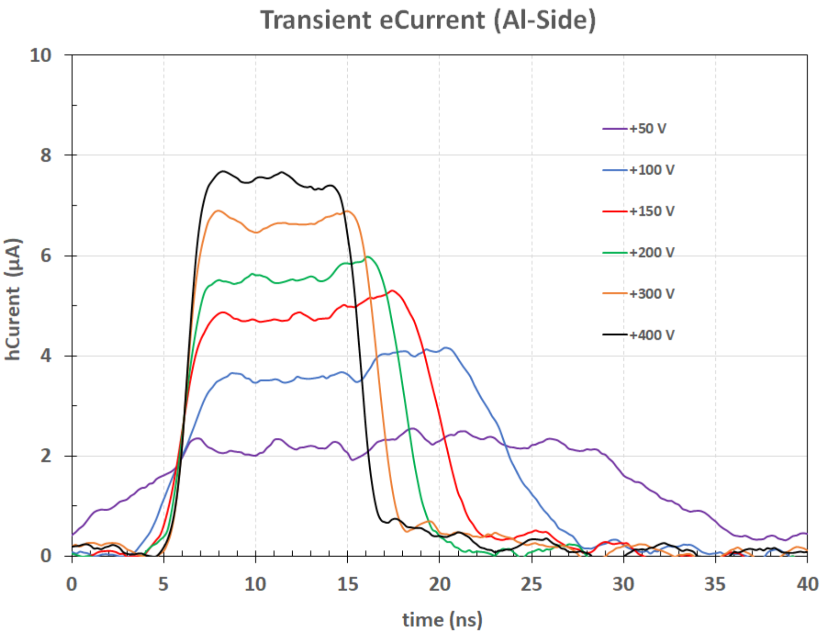


Figure 2. The transient signal as α-particle penetrates MIM device. (a) Holes current (b) Electron current.

The velocity of the carrier will not increase indefinitely if electric field inside the semiconductor bulk is increase. The empirical approach to explain this phenomenon is saturation velocity model that shown by equation 3.

$$v_{dr} = \frac{\mu_0 E}{1 + \frac{\mu_0 E}{v_s}}, \tag{3}$$

E is electric field, v_{dr} is drift velocity, μ_0 is low-field mobility, and v_s is saturation velocity.

By fitting the drift velocity to the electric field, we can get the value of mobility and saturation velocity of diamond detector (figure 3). The fitting results in the value of holes mobility is 2559 ± 33 cm^2/V.s and saturation velocity of holes is (1.35 ± 0.02) x 10^7 cm/s. On the other hand, the value of electrons mobility is 2204 ± 32 cm^2/V.s and saturation velocity of electrons is (0.76 ± 0.01) x 10^7 cm/s.

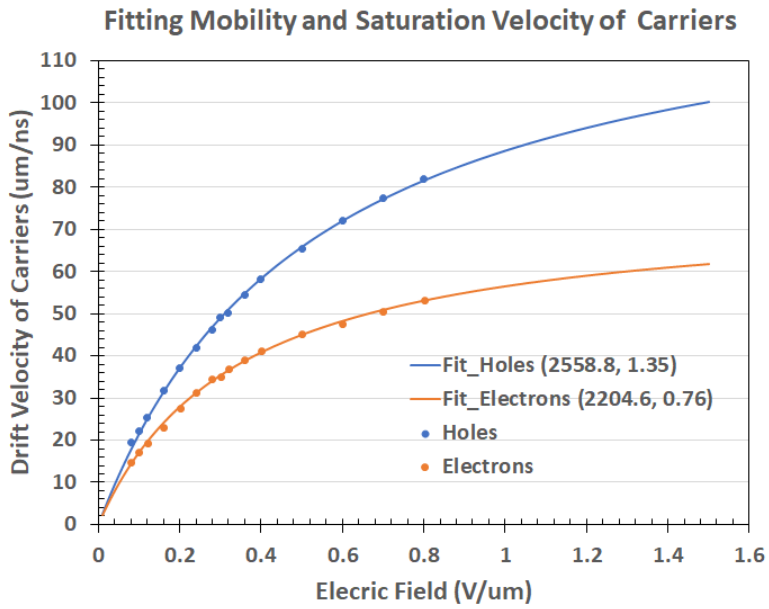


Figure 3. The fitting of mobility and saturation velocity of holes and electron in MIM Diamond detector.

For further characterization, we can also find the value of lifetime using the data of transient current. By using Hecht's equation (equation 4) we can fit the CCE as function drift time.

$$\frac{Q}{Q_0} = (\tau / t_{tr}) \cdot (1 - \exp^{-t_r/\tau}), \quad (4)$$

The variables in the equation consist of Q/Q_0 = CCE, t_{tr} for drift time of carrier, and τ for lifetime of carrier. The fitting of CCE versus drift time of carrier results in the lifetime of electron is 169 ns and the lifetime of the holes is 490 ns.

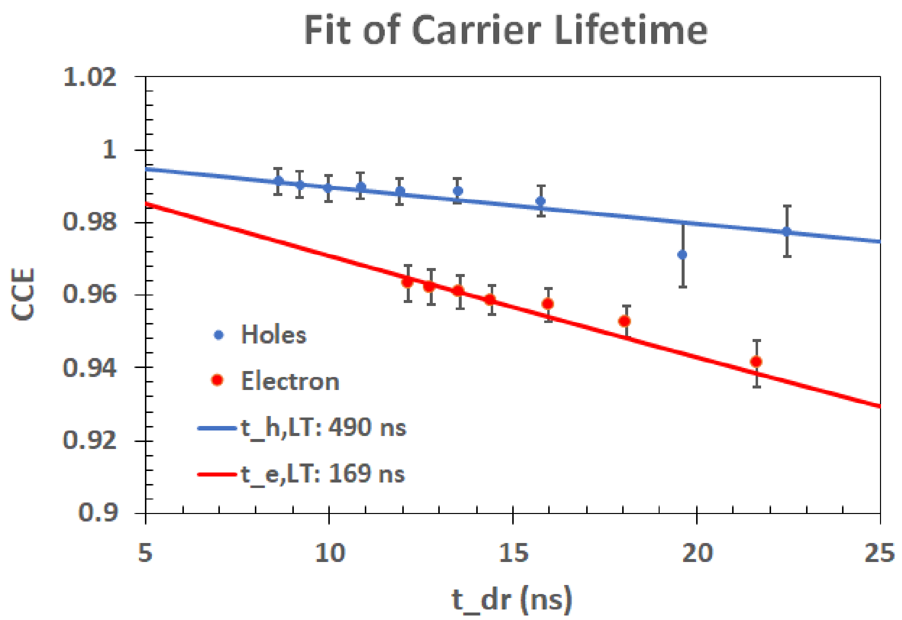


Figure 4. The fitting of carrier life time using Hecht's equation. The error-bars represent the Gaussian distribution of Alpha particle peak histogram

To construct a reliable model using TCAD simulation program, we need to get all of the important parameter of the diamond substrate. However, one more crucial parameter is needed, the carrier density inside the diamond bulk. The value of carrier density can be clarified by fitting of electric distribution inside diamond substrate. To find the distribution of electric field, we need an equation that shows the relation between transient current with drift velocity of carrier as shown by equation 5. Furthermore, we should also get relation between the

$$I = \frac{Qv}{d}, \tag{5}$$

I is transient current, Q is total generated charges, v is drift velocity and d is the thickness of the substrate. By substituting the drift velocity in equation 5 to equation 6, we got new equation that give us information about the relation of electric field (E) and specific position inside the diamond bulk (x) as shown in equation 6.

$$x = \int_0^t v \, \mathrm{d}t = \frac{d}{Q} \int_0^t I \, \mathrm{d}t. \tag{6}$$

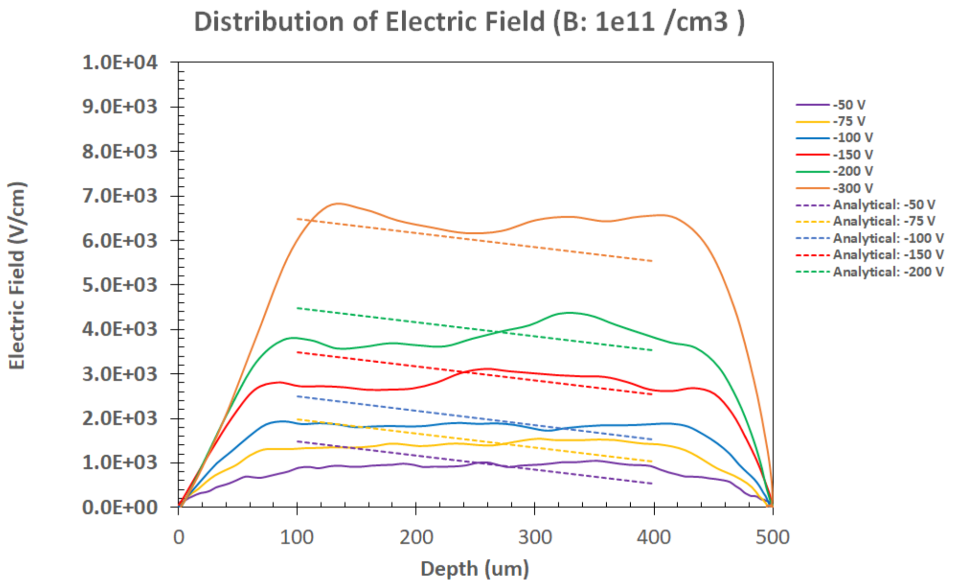
In the previous discussion the value of mobility (μ) and saturation ($vsat$) are already acquired. The parameter Q is total of generated charge. The value of this parameter can be gotten from integration of transient current. The average value of the integration is 67 fC. By solving these analytical equations, we can get the distribution of the function of carrier concentration. Using the equation, the current signal can be converted to graph of electric field distribution inside the diamond bulk. By comparing the analytical distribution of the electric field with the graph derived from transient current (figure 5), we can conclude the analytical distribution of electric field that has carrier concentration of 1 x 10^{10} /cm^3 represent the experimental data better.

1.2 Depth of Depletion Layer

Energetic beta particle can penetrate the thick substrate of diamond. From calculation by using Bethe's equation, beta particle with energy > 0.5 MeV penetrate 500 um thick diamond bulk. In this experiment ^{90}Sr emits beta particle with energy 0.4-2.2 MeV. The peak of spectra is around 1 MeV. Therefore, the beta particle can penetrate our MIM diamond detector.

The CCE of beta particle is acquired by comparing the peak position of deposition energy by beta particle and peak position of deposition energy of alpha particle in diamond substrate (figure 7). The measurement is conducted under high bias voltage to ensure the maximum charge is generated by both particles. This comparison concludes maximum energy deposited by beta particle in MIM diamond detector is 2.8 fC. The maximum generated charge is used for the reference for maximum CCE of beta particle. Based on Ramo's theorem, energetic particle only generates signal if it creates e-h pairs in region that is covered by electric field. Therefore, we can use beta particle to study the depth of depletion layer by evaluating CCE of beta particle in the thick MIM diamond substrate. By converting the deposited energy function of bias voltage to the depth depletion layer by using Bethe's equation (equation 9), the information about the depth of depletion layer can be acquired. Furthermore, we can compare the data with analytical calculation of depth of depletion layer using derivation of Gauss' equation (equation 10). By applying carrier concentration of 1 x 10^{11} /cm^3, the experiment data can be reproduced quite well (figure 7). However, if CCE is taken into account, the slope of in the low bias condition should be less steep. Therefore, the carrier concentration should be less than 1 x 10^{11} /cm^3.

(a)



(b)

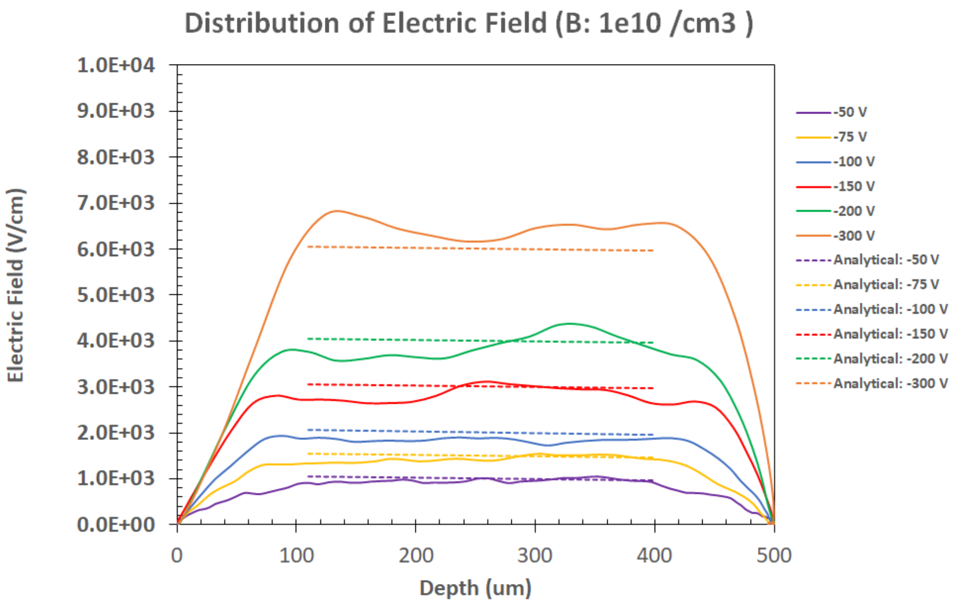


Figure 5. Fitting of the distribution of electric field as function of position inside diamond MIM substrate. Solid line is distribution electric field derived from experiment data. Dashed lines are analytical distribution of electric field for (a) carrier concentration N_A: 1 x 10^{11} /cm^3 and (b) N_A: 1 x 10^{10} /cm^3.

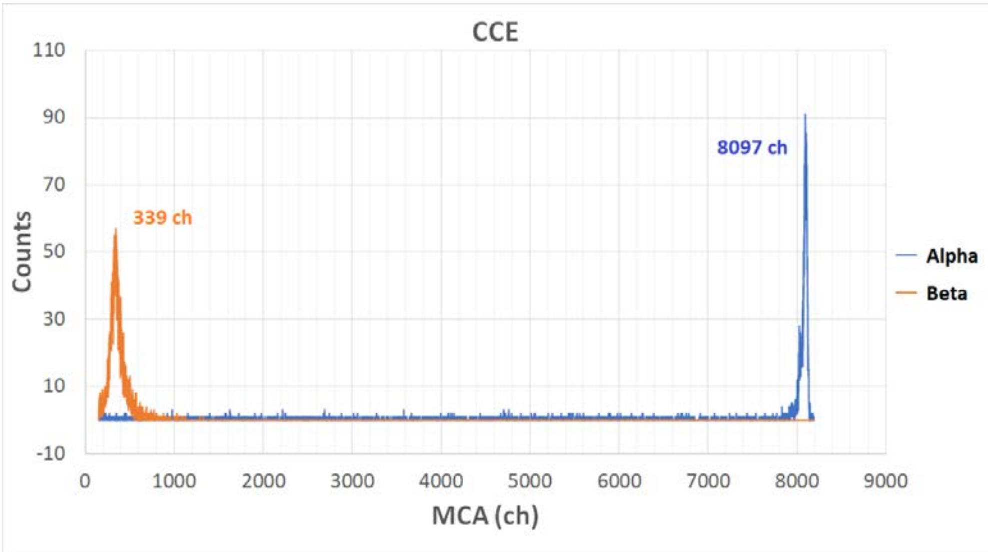


Figure 6. Comparison of the peak position of deposition energy by beta particle and peak position of deposition energy of alpha particle in diamond substrate.

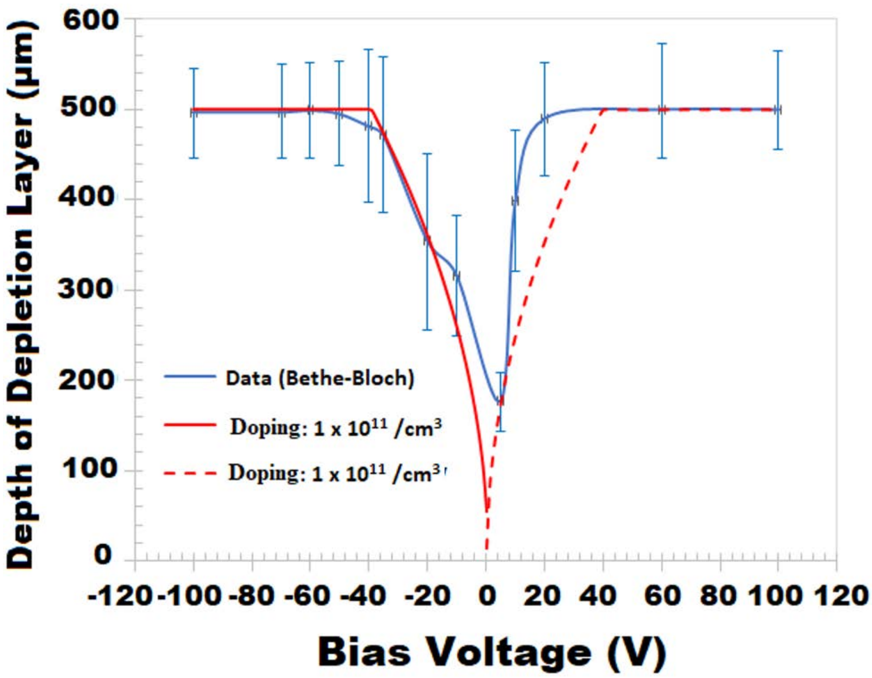


Figure 7. Depth of depletion layer inside diamond substrate. The blue line is converted from CCE of beta particle in diamond substrate. Red line is depth of depletion layer based on analytical calculation (equation 10) with the carrier concentration of 1 x 10^{11} /cm^3.

$$-\left(\frac{dE}{dx}\right)_{\leq E_{\max}} = 4\pi N_A r_e^2 m_e c^2 z^2 \frac{Z}{A}\frac{1}{\beta^2}\left[\ln\left(\frac{\sqrt{2m_e c^2\gamma^2\beta^2 E_{\max}}}{I}\right) - \frac{\beta^2}{2} - \frac{\delta(\gamma)}{2}\right] \quad (9)$$

$$W_A = \sqrt{\frac{2\varepsilon_s}{qN_A}\left(\psi_{bi} - V - \frac{kT}{q}\right)} \tag{10}$$

1.3 Application of the Model

The model can reasonably reproduce CCE of diamond substrate at high bias voltage, but the lifetime should be decrease to < 30 ns for both carriers to reproduce the data (figure 8). However, the implementation of the model to TCAD simulation also succeed to reproduce the transient signal of hole and electron quite well in the range of bias voltage from ±50 V to ±400 V (figure 9). Thus, this model performs are utilized to be a reference for development of a new diamond detector.

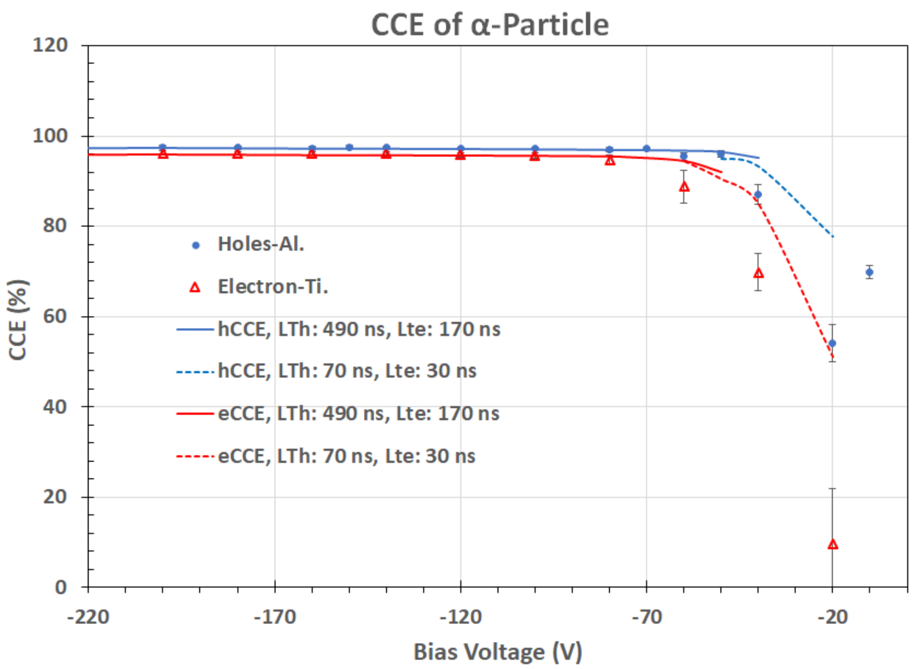
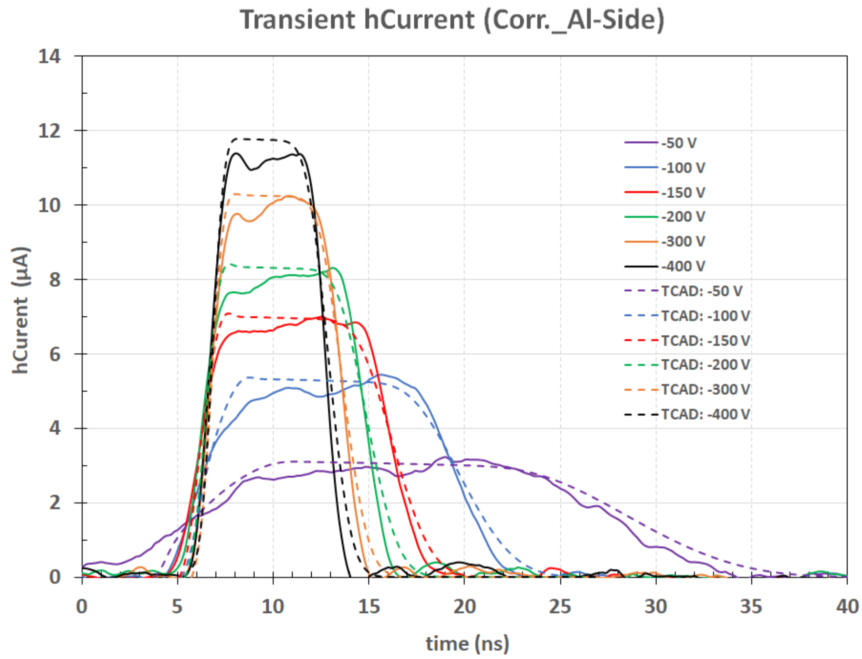


Figure 8. The model can reproduce the CCE value quite well at high bas voltage but it failed to reproduce the value of CCE for bias voltage < 60 V. By lowering the life time for holes and electrons to 70 ns and 30 ns (dashed-line), respectively, the model fits the data better for bias voltage < 60 V. The error-bars represent the FWHM of MCA histogram.

(a)



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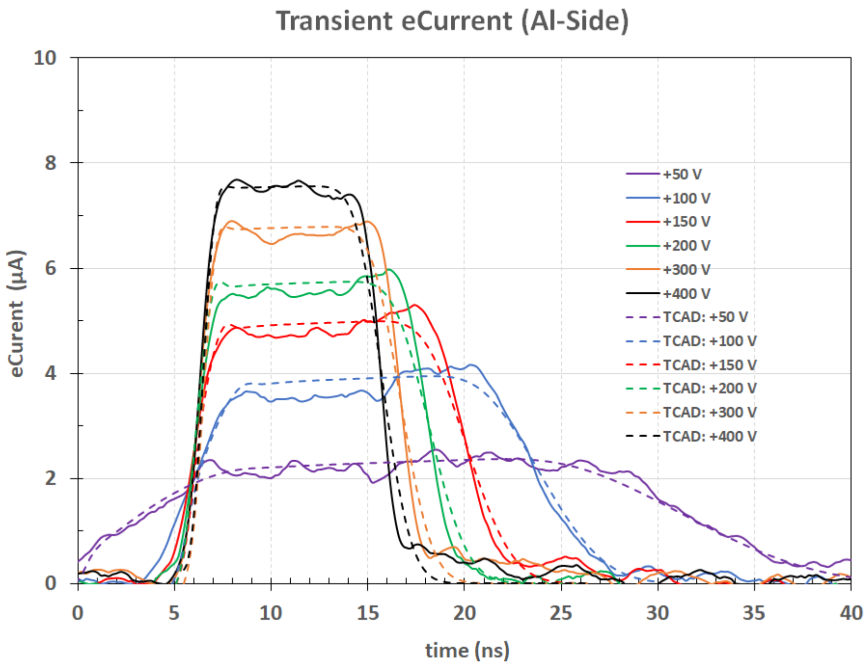

Figure 9. The model can reproduce the transient current for bot (a) holes carrier (b) electron current quite well.

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Results of the doctoral thesis screening

博士論文審査結果

Name in Full
氏　名　　M. Jauhar Kholili

Title
論文題目　Study on Diamond Detector to Develop Its Numerical Model and Charge Amplification Structure

本論文において、出願者は、これまで部分的にしか得られてなかったダイヤモンド検出器の信号出力特性を決める物性値を実験的に決定し、これを用いてダイヤモンド検出器の動作を定量的かつ系統的に表す数値モデルを確立することに成功した。この数値モデルに基づき、増幅機構を内蔵する新しい検出器の構造を提案した。更にダイヤモンド検出器を測定装置として高エネルギー加速器実験に使用することを目的に、低消費電力・低雑音信号処理を可能とする集積回路の開発を行い、ダイヤモンド検出器と接続して、十分な信号読み出し動作性能が得られることを確認した。これらの研究成果は、今後のダイヤモンドを使用した新しい検出器構造の検討や開発プロセスの研究において重要な指針となる。

ダイヤモンド検出器は耐放射線性能、冷却性能、低雑音性能にすぐれていることから、近年、世界中の加速器・放射線施設での使用例が報告されてきている。ここで使用されているダイヤモンド検出器は、ほとんどがダイヤモンドを金属電極で挟んだ構造を有しており、その信号出力特性を表す、リーク電流と検出器バイアス電圧（I-V）特性、電荷収集効率や、検出器からの電流信号のバイアス電圧依存性、などを定量的にかつ系統的に再現できるモデルは、現在までに得られていない。このために、ダイヤモンド検出器の動作の定量的な評価ができておらず、検出器の開発指針は経験則に頼っていた。

出願者は、結晶製造と電極形成の手法が既知のダイヤモンド検出器について、その特性を実験データから詳細に評価し、モデルパラメータを抽出した。このモデルパラメータを用いて、I-V 特性、検出器の電荷収集効率のバイアス電圧特性など、ダイヤモンド検出器の重要な特性を再現可能なモデルを構築した。この過程で、これまで曖昧であったダイヤモンド検出器の電極付近の電気的構造を明確にし、先行研究の誤りを指摘し、より的確なデータ解釈の道を示した。更にこのモデルを使用し、市販されているダイヤモンド検出器の特性の再現および使用しているダイヤモンドの持つ電気的特性パラメータの抽出ができること、動作不良を起こした検出器の原因を示すこと、に成功しモデルの有効性を示した。

このモデルを利用し、出願者は、ダイヤモンド検出器の欠点である、出力信号の小ささを補うための増幅機構を内蔵する検出器の提案を行った。この提案においては、製作可能な素子構造に対して、構造に関係するパラメータと増幅度の関係を定量的に示すことに成功した。増幅機構の内蔵については、基礎となるダイヤモンドの物性値の研究が発展途上であることから、一部の物性値に関し議論の余地はあるが、一連の評価手法としては確立しており、その実現に関する今後の研究に対して十分な可能性があることを示している。

更に出願者は、ダイヤモンド検出器を測定装置として動作させるための信号処理回路を開発した。この回路は高エネルギー加速器実験での使用を視野に、低消費電力・低雑音信

号処理を達成すること目的として開発した。開発した回路を実際にダイヤモンド検出器と接続して、従来の回路と比較して、消費電力が百分の一でありながら、ほぼ同等ノイズ性能と 2 GHz を超える帯域を持つことを確認した。これによって将来のダイヤモンドピクセル検出器を使用した超高速･高位置分解能な測定装置の開発に有用な要素技術を確立した。

以上の成果は、物理学会や国際会議において発表されている。9 月の国際会議においては本成果の主要部分についての演題が採択済みである。また、本成果をまとめた投稿論文について投稿準備を進めている。出願者の博士論文本文は英語で書かれており、国際会議での英語での発表も行っていることから、英語による十分な研究遂行能力を持っていることが確認された。

以上の理由により、審査委員会は、本論文が学位の授与に値すると全員一致で判断した。