

Measurement of Charge Transport Properties and Modelling of Charge Collection in Semiconductor Radiation Detectors

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A Thesis
in
The Department of
Electrical and Computer Engineering

**Presented in Partial Fulfillment of the Requirements for the Degree of Master
of Applied Science (M.A.Sc) at**

Concordia University
Montreal, Quebec, Canada

June, 2025

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CONCORDIA UNIVERSITY
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ABSTRACT

Measurement of Charge Transport Properties and Modelling of Charge Collection in Semiconductor Radiation Detectors

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In semiconductor X-ray photodetectors, efficient charge transport and collection are critical for their performance. This thesis presents an experimental and theoretical investigation into charge carrier mobility, trapping, and collection efficiency. Using time-of-flight (TOF) and interrupted-field time-of-flight (IFTOF) transient photoconductivity techniques, amorphous selenium (a-Se) photoconductive films of various thicknesses were characterized to measure carrier mobility and deep trapping lifetimes. A high-voltage transient photoconductivity setup was implemented to mitigate displacement current and switching transients, enabling precise capture of photocarrier transit dynamics. Measurements across different alloy-stabilized a-Se films revealed well-defined trap lifetimes and mobilities, shedding light on how alloy doping influences trap dynamics and charge transport in these X-ray photoconductors. Complementing the experiments, a semi-analytical carrier packet drift analysis (CPDA) and a numerical model were developed to examine charge collection efficiency of a radiation detector under non-uniform electric fields. These models account for space-charge effects from ionized dopants and trapped photogenerated carriers, allowing simulation of internal electric field profiles and CCE across a range of material parameters and operating conditions. The simulations show that field non-uniformity causes significant deviations from the idealized Hecht collection efficiency formula, and in most cases CCE deteriorates compared to the uniform-field scenario. However, for certain ratios of carrier lifetime to transit time, when X-ray absorption occurs near the incident electrode, non-uniform fields can even improve charge collection. The theoretical predictions were validated against published data from perovskite X-ray detectors, demonstrating good agreement for general radiographic applications. Together, the experimental and modelling results advance the understanding of charge transport and charge collection in photoconductors, guiding the design of high-performance X-ray radiation detectors.

Key words: Amorphous selenium, Time-of-Flight, Interrupted-Field Time-of-Flight, carrier mobility, lifetime, Charge collection efficiency, radiation detectors, space charge perturbed electric field and photocurrent, deep trapping in semiconductors, Hecht collection efficiency

To those
who were kind to me.

Acknowledgements

First and foremost, I would like to express my heartfelt gratitude to my supervisor, Professor M. Zahangir Kabir, for his constant support, guidance, and encouragement. His deep knowledge, patience, and thoughtful feedback played a crucial role in shaping this work. I am truly thankful for the opportunity to be a part of his research group and to learn under his mentorship. His unwavering support gave me the confidence and motivation to overcome the challenges that came with this research. Completing this thesis has been a deeply enriching experience, and I am sincerely grateful to all those who have supported me throughout this journey.

My research, focused on Measurement of Charge Transport Properties and Modelling of Charge Collection in Semiconductor Radiation Detectors, would not have been possible without the valuable data and experimental access provided by Analogic Canada. I am especially grateful to the team at Analogic for allowing me to work within their manufacturing facility and for offering technical support throughout the process.

I also wish to acknowledge the financial support I received from Mitacs and Analogic Canada, whose joint funding enabled my internship and facilitated the data collection process for this work.

I am deeply grateful to my family for their unwavering love and support. To my mother, Ayesha Akter, my father, Munshi Aminul, and my younger brother, Mohammed Mofiz Uddin, thank you for always believing in me and encouraging me to keep going, even when times were difficult. I would also like to remember my late brother, Mahtab Liaquat, whose memory has remained close to me throughout this journey.

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List of Abbreviations

a-Se	Amorphous Selenium
CCE	Charge Collection Efficiency
CMRR	Common-Mode Rejection Ratio
CZT	Cadmium Zinc Telluride
EHP	Electron Hole Pairs
FWHM	Full Width Half Maximum
HCE	Hecht Collection Efficiency
HV	High Voltage
IFTOF	Interrupted Field Time of Flight
MOSFET	Metal-Oxide-Semiconductor Field-Effect Transistor
OD	Optical Density
PC	Personal Computer
PCI	Peripheral Component Interconnect
PCB	Printed Circuit Board
RFI	Radio Frequency Interference
SPDT	Single-Pole Double-Throw
TOF	Time of Flight
TTL	Transistor-Transistor Logic
USB	Universal Serial Bus
UV	Ultra Violet

Chapter 1: Introduction

1.1 Background

Image creation by radiation waves such as X-rays through an object or body using differential attenuation of ionizing radiation is known as Radiography and this is recognized as a vital diagnostic instrument in hospitals and medical clinics. Wilhelm Roentgen discovered X-rays over a century ago, leading to the development of radiology and medical imaging. Radiographic techniques remain among the most effective tools for assisting physicians in patient diagnosis [1]. Despite being one of the most widely used diagnostic methods in medicine, radiography largely relies on traditional film-based, analog technology. In recent years, there has been growing interest in advancing solid-state, digital X-ray systems [2]. Advancements in digital imaging have the potential to greatly streamline the process of taking X-ray images [3]. An ideal digital radiography system would automatically evaluate image quality, adjust exposure settings accordingly, and display the image instantly on a monitor after the X-ray is taken. These types of 'real-time' detectors are particularly beneficial for procedures where continuous imaging is used to support internal treatments like angioplasty. Additionally, digital image quality can be improved using analytical software and facilitate the computer-aided-diagnosis of complex medical conditions [4]. Digital image files can be conveniently stored on central file servers and accessed across computer networks, allowing healthcare providers to deliver clinical care to patients in remote areas [5]. In addition to imaging and spectroscopic applications, radiation detectors are also used in experimental setups to quantitatively measure the amount of radiation emitted by a source. This capability is essential in laboratory environments, nuclear safety monitoring, and material characterization, where precise measurement of radiation intensity and dose is required.

Radiation detectors are essential tools in diverse fields such as medical imaging, security screening, crystallography, and materials analysis [6]. They convert incident radiation into measurable electrical signals. Among these, semiconductor-based radiation detectors offer superior spatial resolution and sensitivity, making them ideal for applications requiring precision, such as diagnostic radiography and radiation spectroscopy [6]. Figure 1.1 shows the diverse spectrum of X-rays and their applications.

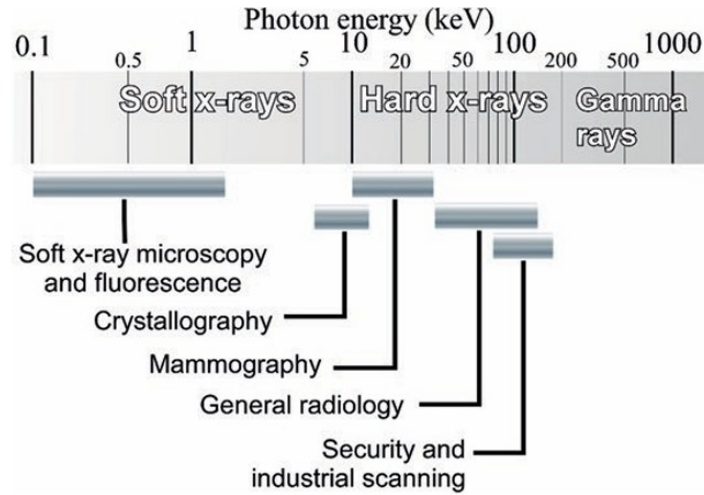


Figure 1.1 X-ray Spectrum and its applications [6].

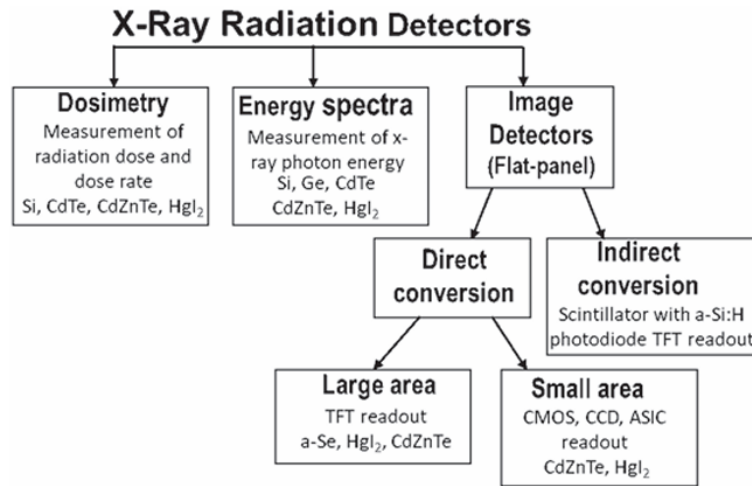


Figure 1.2 Basic categories of X-ray radiation detectors and their associated photoconductive materials. [6].

X-ray detectors can broadly be classified into scintillation-based detectors and semiconductor-based detectors [6]. In scintillators, X-rays are first converted into visible light, which is then detected by photodiodes [6]. In contrast, semiconductor detectors (also known as direct conversion detectors) generate electron-hole pairs (EHPs) directly within a photoconductive layer, which are subsequently collected on electrodes to produce an electric signal. Their solid-state nature and compatibility with thin-film technologies make semiconductor detectors highly suitable for integration into large-area imaging arrays [6]. Figure 1.2 shows the classification of different types of radiation detectors.

Common configurations include planar detectors (for simple photoconductive applications), co-planar detectors (for enhanced spectral resolution), and pixelated detectors (for imaging) as shown in Figure 1.3 [6]. These configurations enable different detector functionalities such as direct imaging,

energy resolution, and real-time monitoring [6]. Materials used for the photoconductor layer include amorphous selenium (a-Se), silicon, cadmium zinc telluride (CZT), and perovskites, among others. Each has distinct transport characteristics and application suitability.

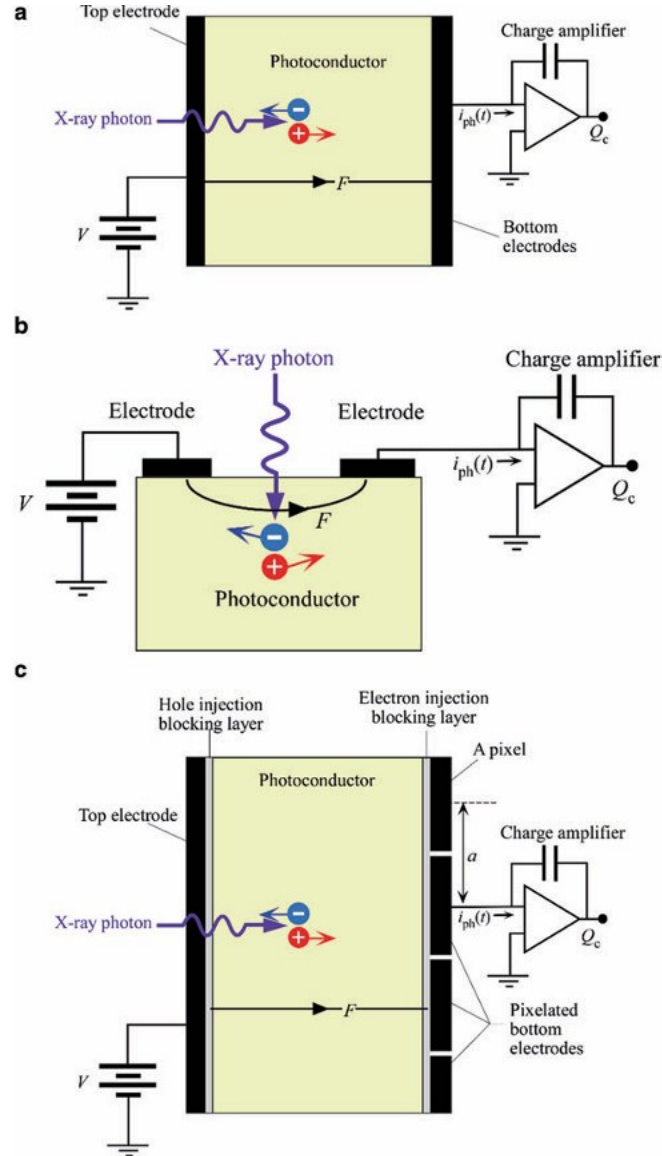


Figure 1.3 Basic cross-sectional layouts of three common X-ray detector types: (a) planar single-element detector, (b) co-planar detector, and (c) pixelated detector used for imaging. In each case, Q_c represents the collected charge and $i_{ph}(t)$ denotes the instantaneous photocurrent. [6].

Radiation detectors are also integral to spectroscopy, where they help measure the energy distribution of incident radiation [6]. In spectroscopic setups, the pulse height spectrum provides crucial information about the incident radiation by relating the collected charge to the photon energy [6]. These measurements are particularly important for applications in nuclear medicine, material analysis, and high-energy physics.

1.2 Literature Review

Charge collection efficiency (CCE) is a key parameter for evaluating the performance of radiation detectors, representing the fraction of the charge generated by incident radiation that is collected at the electrodes [8]. In many studies, CCE is analyzed using the classical Hecht collection efficiency (HCE) relation [9], which provides a means to estimate carrier transport properties such as drift mobility and lifetime [10]. The use of the Hecht model, however, rests on certain assumptions, including a uniform electric field across the detector and constant carrier mobility and lifetime within the photoconductive layer.

Kasap et al. [11] investigated how spatial variations in carrier mobility and lifetime influence charge collection efficiency (CCE). Meng et al. [12] developed a numerical model to study the impact of electric-field non-uniformity caused by ionized dopants, though their approach is mainly valid when photogeneration is confined near the detector surface and cannot fully describe bulk-irradiated systems such as X-ray detectors. Mahmood [13] introduced another numerical model that attributed non-uniform fields to trapped carriers, but this method relied on an empirical trap distribution and did not accurately account for photocurrent integration time, leading to an overestimation of the field effect. In contrast, our earlier work [14] established a physics-based analytical formulation for the trapped carrier profile, expressing it explicitly in terms of carrier lifetime. However, none of these works have shown the effect of non-uniform electric field on the CCE for distributed carrier generation across the photoconductor thickness.

Amorphous semiconductors are widely employed in large-area solid-state devices because they can be fabricated as uniform thin films at relatively low cost. Since charge transport strongly dictates device performance, its characterization is critical. However, theoretical modelling is complicated by the intrinsic structural disorder of these materials. As a result, experimental investigations remain the most reliable means of probing their electronic transport mechanisms. Among the techniques commonly used are the time-of-flight (TOF) and interrupted-field time-of-flight (IFTOF) methods, which are particularly effective for examining carrier mobility and deep trapping phenomena in low-mobility semiconductors.

Accurately determining charge-carrier mobility (μ) and deep-trap lifetime (τ) in photoconductors has relied on transient time-domain approaches (short-pulse photoconductivity), steady-state electrical techniques (current–voltage analyses), and optical/charge-decay methods that monitor relaxation after generation ceases. These types of methods have been widely applied to

amorphous selenium (a-Se) because transport is strongly trap-limited and difficult to capture with theory alone, making experimental characterization essential [57].

Juska et al. introduced CELIV (Charge Extraction by Linearly Increasing Voltage), in which a linearly increasing voltage extracts photocarriers and the transient is analysed to estimate an effective mobility; however, CELIV typically cannot separate electron and hole contributions, and the extracted mobility can change based on the analysis model, the excitation profile, and the voltage-ramp conditions [58], [59]. Lampert and Mark established SCLC (Space-Charge-Limited Current) as a steady-state route to mobility and trap parameters from current density vs voltage curves. In practice, robust accuracy requires truly ohmic injection and a correct trap model, the inferred mobility can vary strongly with the assumed trap distribution, and lifetimes are not measured directly [60], [61]. Earlier a-Se studies by Blakney and Grunwald used photoconductive/xerographic decays and small-signal transients to infer trapping; although insightful, such decays in disordered solids are often non-exponential (dispersive), so a single lifetime is ambiguous and μ and τ are convolved rather than cleanly separated [35]. Furthermore, the Hall effect provides a direct mobility in high-mobility crystalline semiconductors, but in a-Se the very low drift mobility and hopping-assisted transport make Hall signals impractically small, so this method is rarely feasible for a-Se [62], [63].

By contrast, time-of-flight (TOF) directly times the drift of a short, optically injected carrier sheet to obtain μ with carrier selectivity (holes and electrons), while interrupted-field TOF (IFTOF) isolates deep-trap capture by switching the field off for a controlled interval and measuring the exponential loss of mobile carriers, yielding a capture-controlled lifetime; both have been implemented and validated for a-Se [7] and align with short N₂-laser excitation and fast, well-conditioned HV switching that suppress displacement-current artifacts. Together, TOF and IFTOF provide a more accurate and clear determination of μ and τ for stabilized a-Se than CELIV, SCLC, or decay-based methods, whose results can be mixture-weighted or heavily model dependent [57][64][7].

1.3 Motivation

In semiconductor radiation detectors, the charge collection efficiency (CCE) is a key performance metric. It defines the ratio of collected charge to the total photogenerated charge within the detector and is influenced by several factors, including carrier mobility, carrier lifetime, and the internal electric field distribution.

Under the assumption of a uniform electric field, models like the Hecht equation can be used to estimate the CCE. However, in real detectors, the electric field is often non-uniform due to effects such as space charge accumulation from ionized dopants or trapped carriers. These distortions lead to deviations from ideal behavior and complicate the accurate modeling of detector response.

Moreover, the spatial and temporal transport of carriers through the detector material plays a crucial role in determining its performance. Variations in material composition, fabrication inconsistencies, and exposure-induced defects can all result in non-uniform transport properties.

Accurate determination of carrier transport parameters (mobility and lifetime) is therefore critical. While techniques like Hall measurements exist, they are generally not well-suited for thin photoconductive layers used in detectors as the corresponding Hall Voltage would be of extremely low value and hence the mobility values cannot be determined in such cases. Instead, transient photoconductivity techniques such as Time-of-Flight (TOF) and Interrupted-Field Time-of-Flight (IFTOF) offer more practical and precise methods. These methods allow real-time observation of photocurrent transients, measurement of carrier lifetime, and assessment of material uniformity.

This thesis is motivated by the need to develop general models and accurate measurement systems that are applicable for the characterization of transport properties to a range of detector materials like amorphous selenium, perovskites and CdZnTe. This generalization allows our methods to apply to many different types of radiation detectors used across various applications.

1.4 Research Objectives

This research focuses on both theoretical and experimental aspects of charge transport in semiconductor radiation detectors. The specific objectives of the thesis are:

1. Comprehensive analysis of semi-analytical and numerical models for effects of non-uniform electric fields on CCE.
2. Comparing the results for CCE under non-uniform electric field with the Hecht Collection Efficiency for uniform electric field
3. Setting up TOF and IFTOF experiment techniques capable to measure μ and τ for various detector materials
4. To compare the transport properties (mobility and lifetime) of different amorphous selenium samples

Together, these efforts aim to deepen the understanding of carrier dynamics and improve the accuracy of CCE prediction for a wide range of radiation detectors.

1.5 Thesis Outline

This thesis is structured into five chapters. Chapter 1 presents the background and motivation for studying charge transport in semiconductor radiation detectors, along with a review of relevant literature and a statement of research objectives. Chapter 2 outlines the theoretical basis for charge collection, including the Hecht collection efficiency model and its limitations under non-uniform electric fields, as well as an overview of transient photoconductivity techniques used for transport measurements. Chapter 3 formulates and implements semi-analytical and numerical models for computing charge collection efficiency (CCE) in the presence of non-uniform electric fields caused by ionized dopants and trapped carriers. The impact of these non-uniformities on CCE is analyzed across a range of conditions, and the models are validated using published experimental data from perovskite-based detectors. Chapter 4 describes the experimental setup for high-voltage transient photoconductivity measurements, detailing the implementation of Time-of-Flight (TOF) and Interrupted-Field Time-of-Flight (IFTOF) methods, and presents the measured mobility and lifetime data for stabilized amorphous selenium films. Chapter 5 summarizes the key outcomes of the research and provides recommendations for future work, with emphasis on extending the modeling and measurement framework to other classes of photoconductive detector materials.

Chapter 2: Background Theory

2.1 Introduction

The collection of charges in the external circuitry occurs through specific mechanisms. This chapter introduces in brief the concepts for understanding charge collection mechanisms as well as the concepts involved in the Time-of-Flight and Interrupted Field Time-of-Flight transient measurement techniques for characterizing radiation detector materials that are used for purposes such as medical imaging X-rays.

2.2 Hecht Collection Efficiency and Irradiation of Photodetectors

When X-rays interact with detector materials, numerous electron-hole pairs are produced. In materials like semiconductors with doping, free charges readily drift towards existing mobile charges, thus significantly diminishing their fields against being detectable at large distances. Typically, neutrality is observed throughout the detector volume, and currents at the electrodes only develop as charge carriers physically reach them. Conversely, photoconductive materials lack a reservoir of free carriers around drifting charges, resulting in a persistent local charge neutrality disruption at timescales relevant to detector operation. The relaxation time in these materials is defined by $\tau_R = \varepsilon\rho$ where ρ denotes the resistivity, and $\varepsilon = \varepsilon_0\varepsilon_r$ represents the material's dielectric constant. For example, a-Se of resistivity around $10^{14} \Omega\cdot\text{cm}$ and a relative dielectric constant of about 6.7, possesses a relaxation time of approximately one minute, significantly longer than the usual carrier transit times. Thus, currents observed in photoconductors mainly originate from induction, driven by mobile carriers within the photoconductive layer.

When carrier trapping occurs, a part of it only out of the generated photocarriers reaches the external circuitry. Consider a scenario where an EHP is created at position x' , and both carriers move due to an electric field. The average photocurrents induced by electrons and holes are represented as $i_e(t) = (ev_e / L) \exp(-t / \tau_e)$ and $i_h(t) = (ev_h / L) \exp(-t / \tau_h)$, respectively, where $v_e = \mu_e F$, $v_h = \mu_h F$, e is the electronic charge, μ represents carrier mobility, and τ is the lifetime. The symbols e and h indicate electrons and holes, respectively. Both carrier types drift towards electrodes of opposite polarity. Hence, the net charge collected at the electrodes is the total of contributions from electrons and holes. The mean accumulated charge can thus be described as,

$$Q(x') = \int_0^{t_e} i_e(t') dt' + \int_0^{t_h} i_h(t') dt' \quad (2.1a)$$

Which further simplifies to:

$$Q(x') = \frac{e\mu_e\tau_e F}{L} \left[1 - e^{-\frac{(L-x')}{\mu_e\tau_e F}} \right] + \frac{e\mu_h\tau_h F}{L} \left[1 - e^{-\frac{x'}{\mu_h\tau_h F}} \right] \quad (2.1b)$$

Here, $t_e = (L - x') / \mu_e F$ and $t_h = x' / \mu_h F$ represent the transit times for electrons and holes, respectively. Equation (2.1) is widely recognized as the Hecht equation, which is commonly used to determine average charge collection in photoconductors under uniform electric field.

The schematic representation of the photoconductive detector circuit is shown in Figure 2.1. The detector consists of a photoconductive layer placed between two large-area parallel electrodes. The bottom electrode, serving as the pixel electrode, is connected to an integrating amplifier that measures the total charge collected by integrating the photocurrent generated by the incident X-ray. The top electrode, also called the radiation-receiving electrode, is biased with a voltage V to establish an electric field F across the photoconductor. This bias voltage may be either positive or negative. The electric field causes the X-ray-generated electrons and holes to drift in opposite directions. The collected charge is then measured at the pixel electrode after this drift.

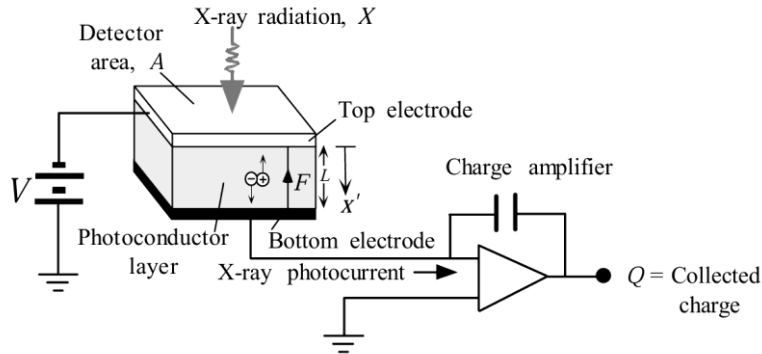


Figure 2.1 Schematic representation of the equivalent circuit of a photoconductive x-ray image detector. The detector is exposed to x-ray radiation over an area A , and an electric field F is established across the photoconductive layer by applying a bias voltage V . The resulting photocurrent is collected at the bottom electrode and amplified to measure the total charge Q . [1]

2.3 Charge Collection Efficiency under Non-uniform Electric Field

The charge collection efficiency (CCE) is one of the most important characteristics of radiation detectors, which is defined as the ratio of the collected charge to the generated charge in the

detector by the incident radiation [8]. Experimentalists mostly verify CCE of their radiation detectors by the well-known Hecht collection efficiency (HCE) formula [9] to find the carrier transport parameters (carrier drift mobility and lifetime) [10]. There are few assumptions on applying the Hecht collection efficiency formula such as the existence of uniform electric field, carrier drift mobility and lifetime throughout the photoconductor layer of the detector.

In conventional radiation detectors, a photoconductor layer is sandwiched between two parallel plate electrodes and the radiation is incident on the top electrode. The top electrode (i.e., the radiation receiving electrode) is biased with a voltage V to establish an electric field F in the photoconductor layer as shown in Figure 2.2. The electromagnetic radiation is attenuated exponentially

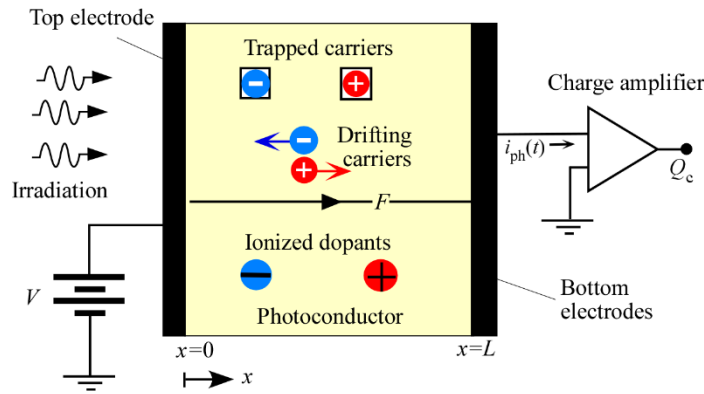


Figure 2.2 Incident radiation creates free electrons and holes, which are drifting under the influence of the electric field F . Some of the drifting carriers are trapped. The photoconductor layer may contain ionized dopants or impurity atoms.

as $\exp(-\alpha x)$ along the photoconductor thickness and generates an EHP concentration profile that follows the photon attenuation profile. Here x is the distance in the photoconductor from the radiation-receiving electrode.

The effects of non-uniform carrier drift mobility and lifetime on CCE were modeled by Kasap et al. [11]. Meng et al. [12] showed the effect of non-uniform electric field due to the ionized dopants on the CCE by a numerical model. Their model is applicable to the detectors when the photogeneration occurs near the surface of the detector. Therefore, the model is not appropriate for case of photogeneration throughout the detector such as X-ray detectors. Mahmood [13] proposed a numerical model to show the effect of non-uniform electric field due to trapped charge carriers on the CCE. However, this model failed to properly calculate photocurrent integration time, and, as a result,

it overestimates the effect of non-uniform electric field on the CCE. Moreover, it considered an empirical profile for the trapped carrier distribution. In a previous publication, we have derived an expression of trapped carrier profile across the photoconductor layer as a function of carrier lifetime based on a physics-based analytical model [14].

In this study, we have proposed both semi-analytical and numerical models for calculating the effect of non-uniform electric field on the CCE for distributed carrier generation across the photoconductor thickness. The theoretical results of these two models are compared. The results are identical, which validates both the models. Though the numerical model is straightforward, but it suffers from some truncation error and computation time. We have considered the space charge due to the ionized dopant and the charge carrier trapping of photogenerated carriers in the bulk photoconductor layer. We analyze the electric field distributions and CCE of the detector under various carrier transport parameters and detector operating conditions. The theoretical model has also been applied to the published experimental results on two perovskites X-ray detectors.

2.4 Transient Photoconductivity Methods to measure carrier mobility and lifetime

The transport properties of charge carriers in stabilized a-Se photoconductor films will be explored using Time-of-Flight (TOF) and Interrupted-Field Time-of-Flight (IFTOF) transient photoconductivity methods. The TOF technique is widely recognized for accurately determining drift mobility in low-mobility materials. In this experiment, a short pulse of strongly absorbed radiation, typically from a nitrogen laser, is injected into an electrode-coated sample. As the photocarriers traverse the film thickness under an applied electric field, they produce a transient photocurrent in the external circuit; measuring this signal yields the drift mobility of the photogenerated carriers. In IFTOF, the deep-trapping time is obtained by briefly removing the applied field to interrupt carrier drift and then examining how the recovered photocurrent changes with the interruption duration [7].

Several alternative approaches appear in the literature. Juska et al. introduced CELIV (Charge Extraction by Linearly Increasing Voltage), where a linear voltage ramp extracts photocarriers and the transient is analysed to estimate an effective mobility. However, CELIV typically cannot cleanly separate electron and hole contributions, and the extracted mobility can change based on the analysis model, the excitation profile, and the voltage-ramp conditions [58], [59]. Lampert and Mark established SCLC (Space-Charge-Limited Current) as a steady-state route to mobility and trap parameters from dark J–V curves. In practice, robust accuracy requires truly

ohmic injection and a correct trap model, the inferred mobility can vary strongly with the assumed trap distribution, and lifetimes are not measured directly [60], [61]. Blakney and Grunwald analyzed photoconductive/xerographic decays and small-signal transients in a-Se, while informative, such decays in disordered materials are often non-exponential (dispersive), making a single lifetime ambiguous and leaving μ and τ convolved rather than cleanly separated [35]. The Hall effect can provide a direct mobility in high-mobility crystalline semiconductors, but for a-Se the very low drift mobility and hopping-assisted transport make Hall signals impractically small, so this method is rarely feasible for a-Se [62], [63].

The primary aim of this part of research is the development of an experimental setup capable of executing both TOF and IFTOF measurements on stabilized a-Se photoconductors. Implementing IFTOF on materials with low carrier mobility such as a-Se poses a technical challenge because substantial bias is required during carrier drift; switching this high voltage can generate significant transients that obscure the desired photocurrent if not properly suppressed. To address this, an experimental system incorporating transient-suppression rectifiers and a bridge circuit will be employed to mitigate switching-related artifacts in IFTOF. The fundamental theories underlying the TOF and IFTOF measurements are detailed in later chapters

Chapter 3: Modeling CCE under Non-uniform Fields

3.1 Introduction

This chapter presents a comprehensive modeling framework for understanding charge collection efficiency (CCE) in radiation detectors operating under non-uniform electric fields. It introduces both semi-analytical and numerical approaches to account for field distortions caused by space charge from ionized dopants and trapped photogenerated carriers, giving insight into detector performance beyond the assumptions of the classical Hecht model.

3.2 Non-uniform electric field

The electric field profile across the detector is determined by the solution of the Poisson's equation, which is,

$$\frac{\partial^2 \phi}{\partial x^2} = -\frac{\partial F}{\partial x} = -\frac{\rho(x)}{\epsilon_s} \quad (3.1)$$

where ϕ is the electrostatic potential, ρ is the charge concentration, and ϵ_s is the permittivity of the photoconductor. For the positive applied bias, the boundary values for equation (3.1) are, $\phi(x=0) = V$ and $\phi(x=L) = 0$, where L is the photoconductor layer thickness.

The space charge in the detector volume can make the electric field non-uniform. The space charge can perturb the electric field profile if its amount is comparable to the initial charge at the electrode due to the applied field (the initial charge at the electrode is $\epsilon_s F_0$, where $F_0 = V/L$). The following are the main sources of space charges in the photoconductor layer: i) The space charge in the thin interface layer between the photoconductor layer and the electrode [18][19], (ii) the space charge due to the ionized dopant in the bulk photoconductor layer [12], and (iii) the trapped charge carriers in the bulk photoconductor layer [20][21]. While the electric field profile in the interface layers can vary widely due to interface charges, the electric field in the bulk remains very close to F_0 (provided there is no space charge in the bulk) because the voltage across these thin interfacial layers is very small. As such, the effect of the interface charge on the charge collection efficiency is negligible and not considered in this paper. Therefore, the change of the electric field profile due to ionized dopants and charge carrier trapping in the bulk are discussed in this paper.

3.3 Non-uniform electric field due to ionized dopants

The space charge concentration due to ionized dopants is $\rho(x) = eN_d$, where e is the elementary charge and N_d is the dopant concentration. For the p-type doping, the ionized dopant charge is negative. Depending on the doping concentration and the strength of the bias voltage, the photoconductor layer can be fully or partially depleted. For relatively higher bias voltage, the photoconductor layer is fully depleted. In this case, by solving equation (3.1), the electric field distribution is expressed as,

$$F(x) = \frac{V}{L} + \frac{eN_A}{2\epsilon_s}(L - 2x) \quad (3.2)$$

Note that one can expect a built-in voltage due to the work function mismatching of the two electrodes (top and bottom electrodes). However, this built-in voltage is usually much smaller than the nominal applied voltage of a radiation detector. Therefore, the built-in voltage is neglected as compared to the applied voltage in equation (3.2). The normalized electric field can be written as,

$$F_N(x) = \frac{F(x)}{F_0} = 1 + \frac{eN_AL}{2\epsilon_s F_0} \left(1 - \frac{2x}{L}\right) = 1 + r \left(1 - \frac{2x}{L}\right) \quad (3.3)$$

where, $r = eN_AL / 2\epsilon_s F_0$ is the ratio of the total space charge per unit area to the initial charge at the electrode due to the applied voltage. As evident from equation (3.3), the electric field collapses at $x = L$, when $r = 1$. That means, the partial depletion occurs when $r \geq 1$.

For partially depleted photoconductors, the electric field profile can be written as,

$$F(x) = \frac{V}{x_d} + \frac{eN_A}{2\epsilon_s}(x_d - 2x) \quad (3.4)$$

Where

$$x_d = \sqrt{\frac{2\epsilon_s V}{eN_A}} = \frac{L}{\sqrt{r}} \text{ for } r \geq 1 \quad (3.5)$$

Here x_d is the width of the depletion region. The normalized electric field can be written as,

$$F_N(x) = \sqrt{r} + r \left(\frac{1}{\sqrt{r}} - \frac{2x}{L} \right) \quad (3.6)$$

3.4 Nonuniform electric field due to the bulk trapped charges

The space charge profile due to trapping of photogenerated carriers in the bulk of the photoconductor layer is given by [14][21],

$$\rho(x) \approx \frac{Q_{eff}\alpha}{\eta} \left\{ \frac{(e^{-\alpha x} - e^{-x/Lx_b})}{(1 - x_b/\Delta)} - \frac{[e^{-\alpha x} - e^{-(L-x)/Lx_t} e^{-\alpha L}]}{(1 + x_t/\Delta)} \right\} \quad (3.7)$$

where $\Delta = 1/\alpha L$, $x_b = \mu_b \tau_b F_0/L$, $x_t = \mu_t \tau_t F_0/L$, α is the linear attenuation coefficient of the photoconductor, μ is the carrier drift mobility, τ is the carrier lifetime, $\eta = 1 - \exp(-\alpha L)$ is the quantum efficiency of the detector and Q_{eff} is the accumulated trapped charge carriers per unit area in the photoconductor due to X-ray, γ -ray or optical excitation. The subscripts t and b stand for the carrier types that drift towards the top and bottom electrodes, respectively. By solving equation (3.1), the electric field profile is expressed as,

$$F(x) = F_0 \left\{ 1 + \frac{r_{tr}}{\eta} \left[A_1 \left(\frac{x_b}{\Delta} e^{-x/Lx_b} - e^{-\alpha x} + \Delta\eta + \frac{x_b^2}{\Delta} (e^{-1/x_b} - 1) \right) + A_2 \left(\frac{A_3 x_t}{\Delta} e^{-x/Lx_b} + e^{-\alpha x} - \Delta\eta - \frac{A_3 x_t^2}{\Delta} (e^{-1/x_t} - 1) \right) \right] \right\} \quad (3.8)$$

where, $r_{tr} = \frac{Q_{eff}}{\epsilon_s F_0}$, $A_1 = \frac{1}{1 - \frac{x_b}{\Delta}}$, $A_2 = \frac{1}{1 + \frac{x_t}{\Delta}}$, and $A_3 = e^{-(1/\Delta + 1/x_t)}$

3.5 Charge collection efficiency

To find charge collection efficiency, we consider an infinitesimally short pulse of monoenergetic irradiation on the detector and follow the external photocurrent as a function of time. The X-ray absorption occurs exponentially across the photoconductor thickness and thus, the photogeneration follows the exponential profile. In this case, the photogenerated electron and hole profiles $n(x,t)$ and $p(x,t)$ at time $t = 0$, are $n(x,0) = p(x,0) = \alpha Q_0 \exp(-\alpha x)/e\eta$, where Q_0 is the total photogenerated charge per unit area within the detector volume. The photogenerated electrons and holes drift in the opposite directions by the electric field in the photoconductor layer and generate a photocurrent. The integration of the photocurrent over time gives the collected charge, Q_c . The charge collection efficiency, $\eta_{cc} = Q_c/Q_0$. In this work, we will describe two methods to calculate η_{cc} , namely (i) semi-analytical and (ii) Numerical. One relevant performance metric is X-ray sensitivity, which is defined as the collected charge per unit area per unit exposure of radiation. The X-ray sensitivity is an important selection criterion of a photoconductor for its use in X-ray detectors, which can be written as [22],

$$S = \frac{Q_c}{X} = \frac{Q_0}{X} \eta_{cc} \quad (\text{CR}^{-1} \text{cm}^{-2}) \quad (3.9)$$

where X is the exposure in Roentgen. The total photogenerated charge Q_0 depends on the amount of exposure. For an X-ray or γ -ray exposure [22],

$$Q_0 = \frac{8.72 \times 10^{-6}}{(\alpha_{\text{air}} / \rho_{\text{air}}) W_i} \left(\frac{\alpha_{\text{en}}}{\alpha} \right) X \eta \quad (\text{Ccm}^{-2}) \quad (3.10)$$

where α_{en} is the energy absorption coefficient of the photoconductor, W_i is the EHP creation energy, α_{air} and ρ_{air} are the energy absorption coefficient of air and its density, respectively ($\alpha_{\text{air}}/\rho_{\text{air}}$ is in cm^2/g and W_i is in eV). Note that the expression of Q_0 in equation (3.11) does not consider the secondary photon reabsorption. For a thin detector where the probability of secondary photon reabsorption is low, equation (3.11) is still good. However, in thick detectors where most of the secondary photons are reabsorbed in the detector volume, the expression of Q_0 becomes,

$$Q_0 = \frac{8.72 \times 10^{-6}}{(\alpha_{\text{air}} / \rho_{\text{air}}) W_i} X \eta \quad (\text{Ccm}^{-2}) \quad (3.11)$$

3.6 Semi-analytical model

In many detectors, the electric field, drift mobility and carrier lifetime can be non-uniform across the detector thickness [11][13][23]. In this case, one way of calculating the induced photocurrent is to track the charge packet propagation, calculate its corresponding induced photocurrent using Shockley–Ramo theorem and thereby find the total collected charge Q_c by integrating the photocurrent over time. The details of this charge packet drift analysis method are described elsewhere [11][24]. In this method, the charge collection efficiency for the positive bias at the radiation-receiving electrode can be written as [11][24]

$$\eta_{cc} = \frac{\alpha}{\eta L} \int_0^L \exp(-\alpha x) \left[\int_0^x \exp \left\{ - \int_{x'}^x \frac{dz}{\mu_t(z) \tau_t(z) F(z)} \right\} dx' + \int_x^L \exp \left\{ - \int_x^{x'} \frac{dx''}{\mu_b(x'') \tau_b(x'') F(x'')} \right\} dx' \right] dx \quad (3.12)$$

where, $z = (L - x)$. There is no closed form analytical solution of equation (3.12) and thus, one must seek a numerical solution. However, for the uniform electric field, drift mobility and carrier lifetime, equation (3.12) becomes,

$$\eta_{cc} = \frac{\alpha}{\eta L} \int_0^L \exp(-\alpha x) \left[\mu_t \tau_t F \left(1 - e^{-\frac{x}{\mu_t \tau_t F}} \right) + \mu_b \tau_b F \left(1 - e^{-\frac{(L-x)}{\mu_b \tau_b F}} \right) \right] dx, \\ \eta_{cc} = x_b \left[1 + \frac{(e^{-1/x_b} - e^{-1/\Delta})}{(\Delta / x_b - 1) \eta} \right] + x_t \left[1 - \frac{(1 - e^{-1/\Delta - 1/x_t})}{(\Delta / x_t + 1) \eta} \right] \quad (3.13)$$

Equation (3.13) is the well-accepted charge collection efficiency formula for the exponentially

distributed carrier generation profile [25], which can be named as modified HCE for exponentially carrier generation.

3.7 Numerical model

The continuity equations for photogenerated drifting holes and electrons (assuming thermal equilibrium carrier is negligible compared to the photogenerated carriers) under positive bias to the radiation-receiving electrode are,

$$\frac{\partial p(x,t)}{\partial t} = -\mu_h \frac{\partial [F(x)p(x,t)]}{\partial x} - \frac{p(x,t)}{\tau_h(x)} \quad (3.14a)$$

$$\frac{\partial n(x,t)}{\partial t} = \mu_e \frac{\partial [F(x)p(x,t)]}{\partial x} - \frac{p(x,t)}{\tau_e(x)} \quad (3.14b)$$

Here the subscripts h and e stand for holes and electrons respectively. The drift mobility and carrier lifetime are assumed to be uniform in the photoconductor layer. The carrier transit time for holes and electrons can be calculated as,

$$t_h = \int_0^L \frac{dx}{\mu_h F(x)} \quad (3.15a)$$

$$t_e = \int_0^L \frac{dx}{\mu_e F(x)} \quad (3.15b)$$

The collected charges due to hole and electron drifts are,

$$Q_h = \frac{e\mu_h}{L} \int_0^{t_h} \int_0^L F(x) p(x) dx dt \quad (3.16a)$$

$$Q_e = \frac{e\mu_e}{L} \int_0^{t_e} \int_0^L F(x) n(x) dx dt \quad (3.16b)$$

The charge collection efficiency is,

$$\eta_{cc} = (Q_h + Q_e) / Q_0 = Q_c / Q_0 \quad (3.17)$$

Equations (3.14a) and (3.14b) are numerically solved using Backward Euler method [21][26]. The detail of this method is described elsewhere [27]. The boundary conditions are, $p(0, t > 0) = n(L, t > 0) = 0$ for holes and electrons respectively.

3.8 Results and discussions

We have calculated the CCE of the detectors using both the semi-analytical and numerical methods and found almost identical results (one can find a traceable difference in some extreme cases.

One such example is shown in figure 3.6 below), which shows the accuracy of both models. Though the numerical model is straightforward, it has some inherent truncation or calculation error, which depends on step sizes.

The effect of ionized dopants on the electric field profile is shown in figure 3.1. It is assumed that the applied voltage is positive on the top electrode and the ionized dopants are negatively charged. If the ionized dopants are positively charged, the applied voltage should be negative for an efficient charge collection. In this case, figure 3.1 shows the strength of the electric field with a negative sign. The detector changes from fully depleted to partially depleted with the increase of r (i.e., with increasing doping concentration). The charge collection is significantly hampered in a partially depleted detector, which is discussed below.

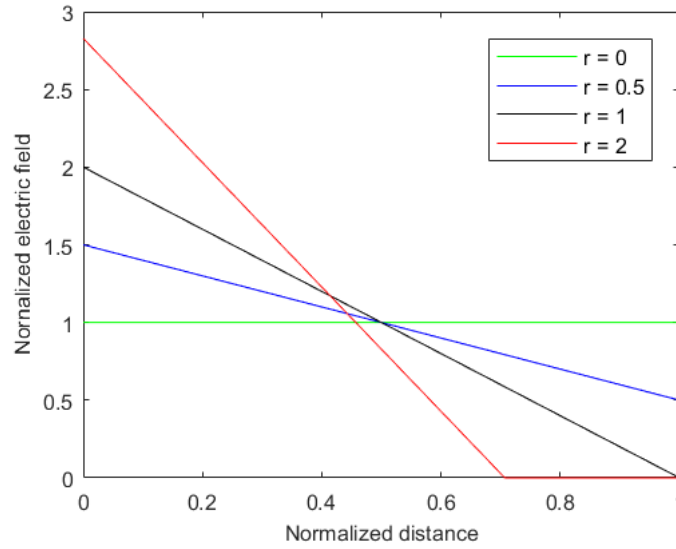
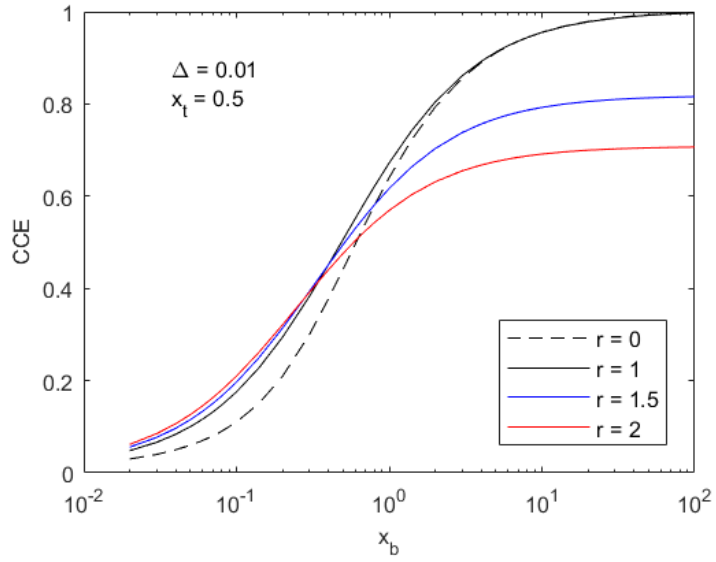


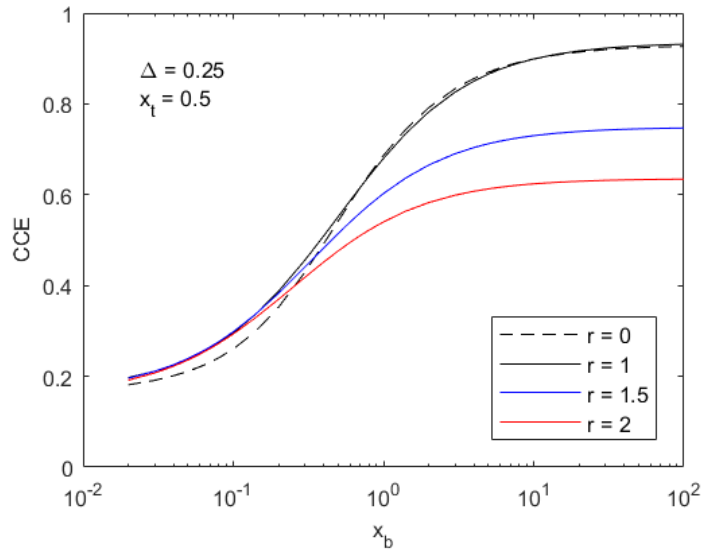
Figure 3.1 Electric field profiles across the photoconductor layer for various amounts of ionized dopants.

The CCE of a detector mostly depends on the carrier transport properties of the carrier type that drifts towards the bottom electrode. The effects of non-uniform electric field due to the ionized dopants on CCE as a function of x_b for three attenuation profiles $\Delta = 0.01, 0.25$ and 1.0 are shown in figures 3.2 (a), 3.2 (b) and 3.2 (c), respectively. A reasonable value for x_t is considered. The dashed line represents the CCE under uniform electric field ($r = 0$), which is determined by the modified HCE formula (equation (3.13)). The CCE improves (figures 3.2 (a) and 3.2 (b)) under non-uniform electric field provided that the irradiation (photons or particles) absorption occurs mostly near the top electrode and the detector is fully depleted ($r < 1$). This CCE improvement is more evident for lower values of x_b because the induced photocurrent occurs due to the carrier drift through the higher electric field region and these carriers mostly vanish before reaching the lower field region. However, this

improvement in CCE is absent under almost uniform carrier generation case ($\Delta = 1$, figure 3.2 (c)). As evident from figure 3.2, the CCE is reduced significantly under partially depleted detectors (i.e., $r > 1$).



(a)



(b)

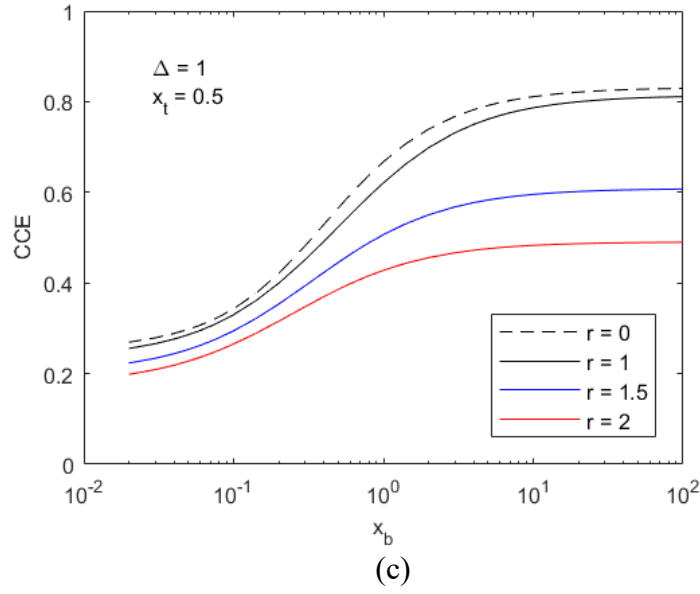
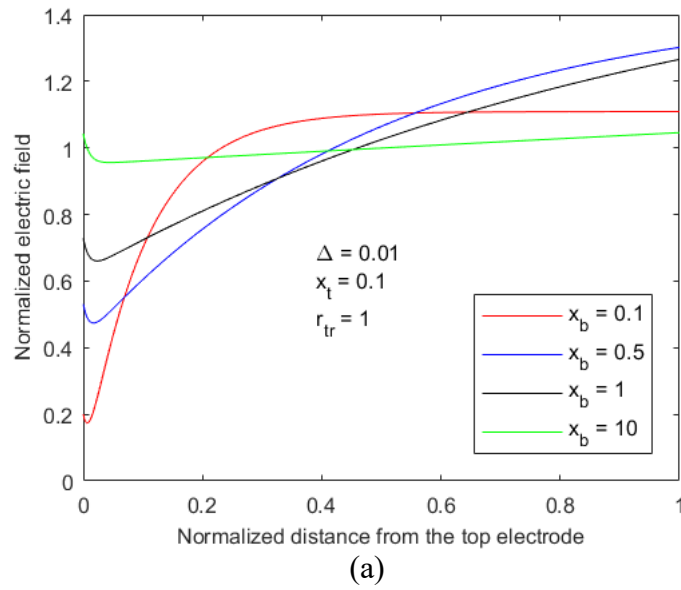
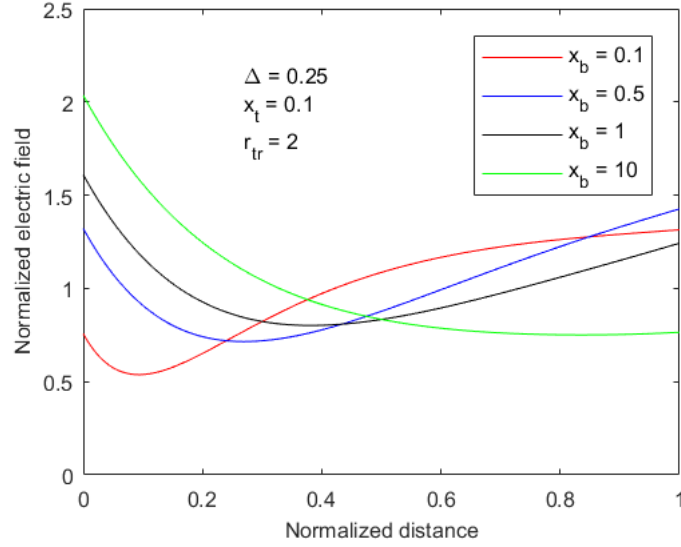


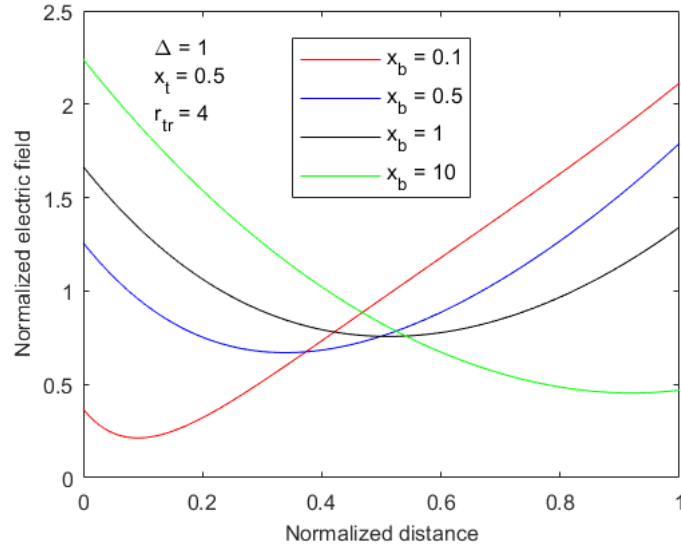
Figure 3.2 Charge collection efficiency as a function of normalized carrier lifetimes for different levels of ionized dopants. The normalized attenuation depth is different in three plots: (a) $\Delta = 0.01$, (b) $\Delta = 0.25$ and (c) $\Delta = 1$.

The effects of trapped charge carriers on the electric field distribution for various levels of trapping are shown in figure 3.3. For lower values of Δ , the electric field is almost entirely controlled by the trapping of carriers that move towards the bottom electrode. The minimum electric field point occurs in the middle part of the photoconductor layer.





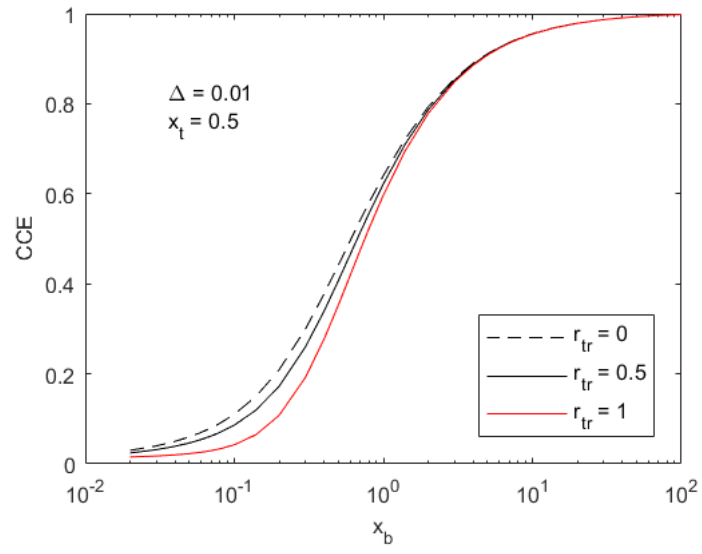
(b)



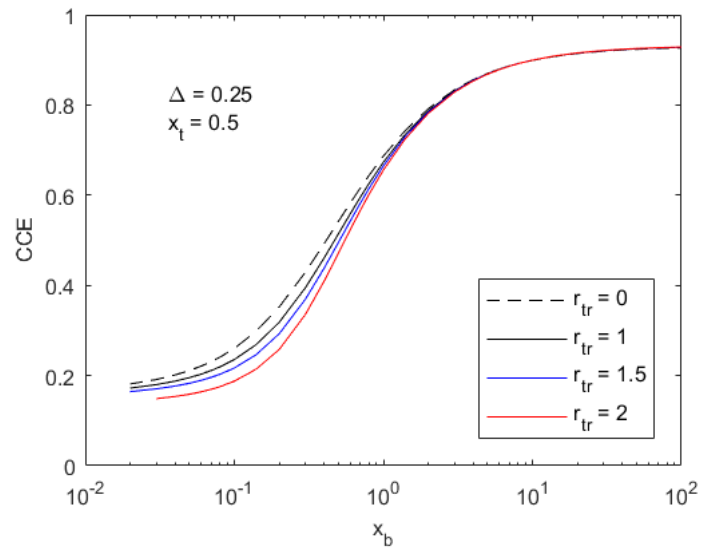
(c)

Figure 3.3 Electric field profiles across the photoconductor layer as a function of normalized carrier lifetime for three different values of Δ : (a) $\Delta = 0.01$, (b) $\Delta = 0.25$ and (c) $\Delta = 1$.

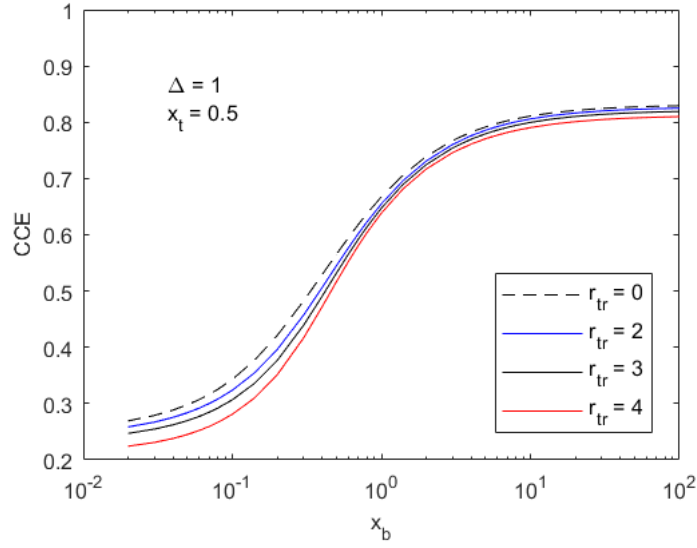
The effects of non-uniform electric field on CCE due to the trapped charge carriers in the bulk as a function of x_b for three attenuation profiles $\Delta = 0.01$, 0.25 and 1.0 are shown in figures 3.4 (a), 3.4 (b) and 3.4 (c), respectively. The dashed line ($r_{tr} = 0$) represents the CCE under uniform electric field (i.e., equation (3.13)). The CCE under non-uniform electric field degrades in all cases.



(a)



(b)



(c)

Figure 3.4 Charge collection efficiency as a function of normalized carrier lifetimes for various levels of trapped charge carriers. The normalized attenuation depth is different in three plots: (a) $\Delta = 0.01$, (b) $\Delta = 0.25$ and (c) $\Delta = 1$.

The theoretical model has been fitted with the published experimental data. Figure 3.5 shows the X-ray sensitivity of a 0.5 mm thick $\text{BA}_2\text{MA}_3\text{Pb}_4\text{I}_{13}$ (Butylamine Methylammonium Lead Iodide) perovskite detector as a function of applied voltage [55]. The symbols represent experimental data which were extracted from [55]. The experiment was carried out on a well-rested sample and thus the trapped carriers are assumed to be zero before experiment. The average photon energy is 31.7 keV and the quantum efficiency is 99 %. The fitted parameters are $N_a = 8 \times 10^{10} \text{ cm}^{-3}$, $\mu_h \tau_h = 1.25 \times 10^{-5} \text{ cm}^2/\text{Vs}$, and $\mu_e \tau_e = 1.5 \times 10^{-6} \text{ cm}^2/\text{Vs}$. This value of acceptor dopant concentration N_a is consistent with the previous findings [12]. The present model with non-uniform electric field agrees well with the experimental results. There is some improvement in CCE under the non-uniform electric field.

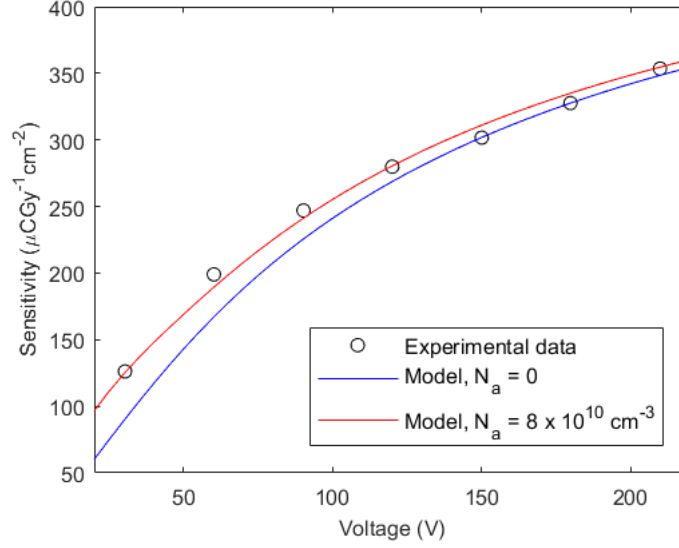


Figure 3.5 X-ray sensitivity of a 0.5 mm thick $\text{BA}_2\text{MA}_3\text{Pb}_4\text{I}_{13}$ perovskite detector as a function of applied voltage. The experimental data were extracted from [55].

Figure 3.6 shows the collected charge of a 1.0 mm thick MAPbI_3 detector as a function of dose [56]. The average photon energy is 41.3 keV and the quantum efficiency is 99 %. The applied electric field is 0.2 V/ μm . The symbols represent experimental data which were extracted from [56]. The collected charge is supposed to be proportional to the dose if the electric field is uniform (dashed line in Figure 3.6). The experimental result indicates that the collected charge versus dose is not linear. The trapped charge concentrations in the photoconductor layer increases with increasing dose. However, it is not a linear function of dose. A portion of the trapped carriers can be detrapped or recombined with oppositely charged carriers before the next exposure. The accumulated trapped carrier may follow a first order rate equation, so that $Q_{\text{eff}} = Q_s(1 - \exp(-\beta D))$, where Q_s is the saturation value of the trapped carriers, β is an irradiation energy dependent constant and D is the total dose. As a result, the deviation of the electric field profile from uniformity increases with increasing dose. The fitted values of parameters are $Q_s = 5.33 \times 10^{-8} \text{ C}$, $\beta = 0.4 \text{ mGy}^{-1}$, and $\mu_h \tau_h = \mu_e \tau_e = 1.5 \times 10^{-4} \text{ cm}^2/\text{Vs}$. The theoretical model with non-uniform electric field agrees well with the experimental results. The slight difference between the semi-analytical and numerical models is probably due to the inherent truncation or calculation error of the numerical model.

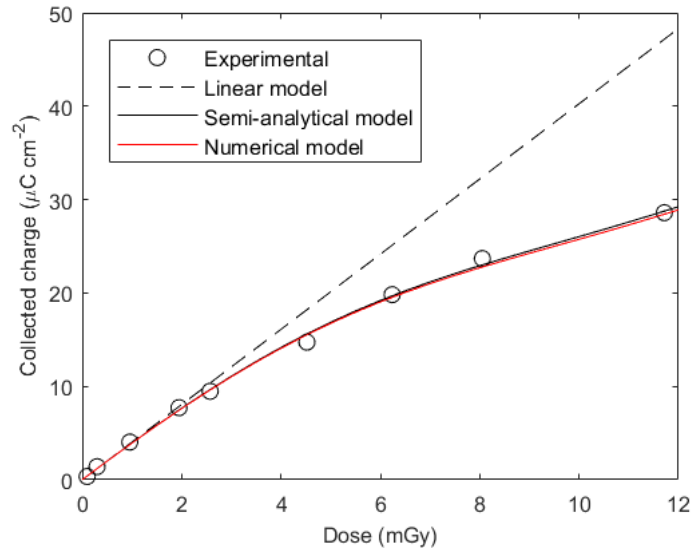


Figure 3.6 The collected charge of a 1.0 mm thick MAPbI₃ detector as a function of dose. The experimental data were extracted from [56].

The electric field profile as a function of dose for the detector of figure 3.6 is shown in figure 3.7. The effective carrier transit time in non-uniform electric field case is higher than that of uniform electric field case (the transit time under uniform electric field is $L/\mu F_0$). For example, the carrier transit time for the red curve in Figure 3.7 is almost 4.5 times higher than $L/\mu F_0$.

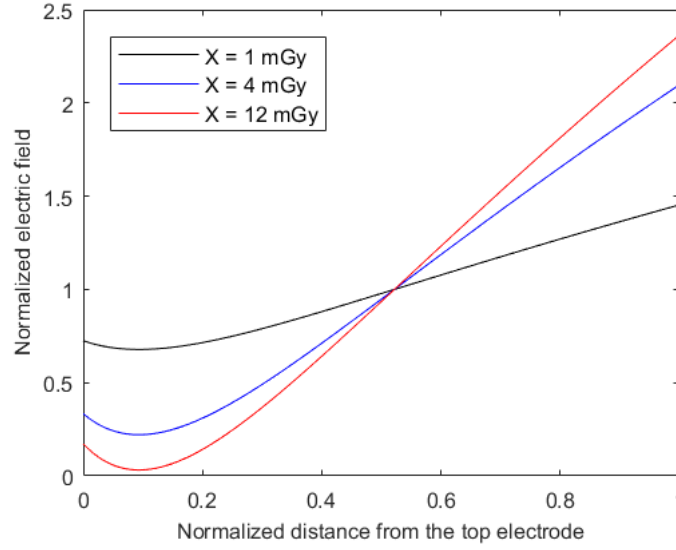


Figure 3.7 The electric field profile as a function of dose for the detector of figure 3.6.

3.9 Conclusions

In summary, the CCE in radiation detectors under non-uniform electric field deviates significantly from the well-known HCE in equation (3.12). The deviation has been quantified in terms of trapped charge ratio (r or r_{tr}), normalized attenuation depth and carrier lifetimes. We have used the carrier packet drift analysis and a numerical solution of the continuity and Poisson equations to calculate CCE. Both models have provided identical results. The space charge due to ionized dopants and the trapped charges due to the photogenerated carriers in the bulk photoconductor layer are considered. In most cases, the CCE under non-uniform electric field deteriorates from HCE. The CCE under non-uniform electric field can be improved for some normalized carrier lifetimes provided that the irradiation (photons or particles) absorption occurs mostly near the top electrode. The theoretical model has been applied to the published experimental results in perovskites X-ray detectors and few important material properties are estimated. The analysis of these results can be a guideline to enhance the CCE under non-uniform electric field in the photoconductor layer of a radiation detector.

Chapter 4: Time-of-Flight and Interrupted Field Time-Of-Flight Techniques to Measure Transport Properties

4.1 Introduction

Amorphous semiconductors are widely used in large-area solid-state devices, mainly as they can be cost-effectively produced as large, uniform films. The charge transport behaviour of these materials is crucial, as it significantly influences device performance. Understanding these transport properties requires direct experimental methods, since theoretical modelling is challenging due to the inherent disorder in amorphous materials. In fact, experimental results provide key insights into the mechanisms of electronic transport in these systems.

Two key techniques used for this purpose are time-of-flight and interrupted-field time-of-flight transient photoconductivity measurements. These methods are especially useful for studying charge mobility and deep trapping effects in materials with low mobility.

In these experiments, researchers analyse the voltage response generated by the injection and subsequent drift of free charge carriers. This chapter explains the working principles of TOF and IFTOF techniques, along with the theories used to interpret the resulting photocurrent signals for various transport and trapping behaviours.

4.2 The Time-of-Flight Technique

The TOF transient photoconductivity method is used to measure the time-dependent electrical response resulting from the movement of charge carriers injected into a highly resistive material. This method captures the behaviour of carriers as they drift through the sample under an applied electric field [7]. Figure 4.1 provides a schematic explanation of this technique. In this setup, a solid material with thickness L , assumed to be free of traps, is placed between two non-injecting metallic electrodes labelled A and B.

Electrode A is connected to a voltage source to apply an external field, while electrode B is connected to ground through a resistor. Because the resistance R is significantly

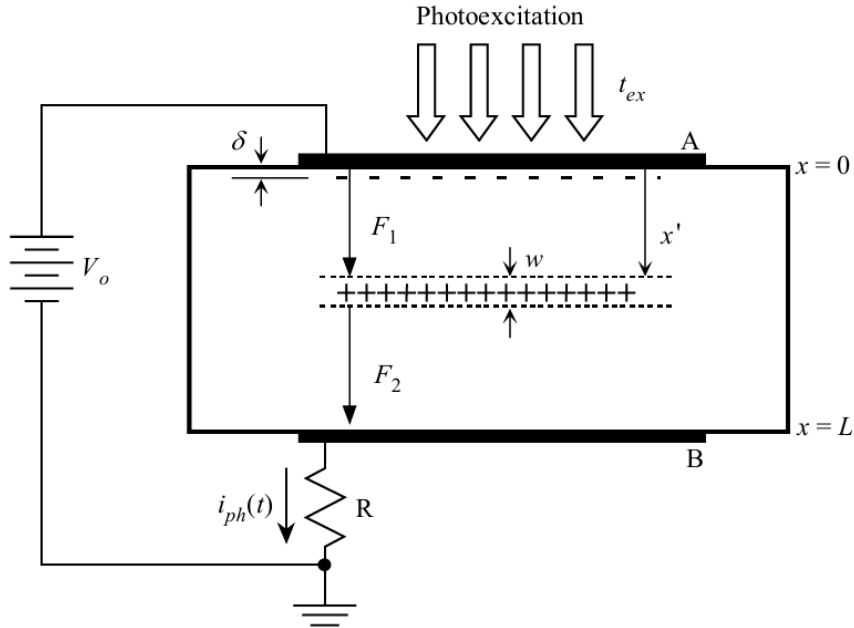


Figure 4.1. Schematic diagram of TOF technique [28].

lower than the resistance of the sample itself, nearly the entire voltage drop appears across the sample thickness.

A short pulse of excitation light is used to generate electron-hole pairs directly beneath the top electrode. This excitation pulse can be optical, provided that the top electrode is either transparent or semi-transparent. If the radiation wavelength is chosen so that the absorption depth δ is much smaller than the sample thickness L , then electrons will be rapidly collected at electrode A. Under the influence of the applied electric field, the holes will drift toward electrode B, producing a transient photocurrent $i_{ph}(t)$ that flows through the external resistor R . To measure the drift of electrons instead, the polarity of the applied voltage can simply be reversed. To make the transient photocurrent signal easier to analyse, the excitation source must be carefully selected. First, the radiation wavelength should be such that the absorption depth δ is much smaller than the sample thickness. This ensures that only one type of charge carrier moves across the full length of the sample. However, the absorption depth should not be too small, as this may cause the carriers to be generated near the surface and get trapped by surface states, thus not contributing to the photocurrent. Second, the duration of the excitation pulse must be significantly shorter than the time it takes for the carriers to drift through the material. This ensures that the carriers travel as a narrow charge packet with a width w much smaller than the total thickness of the sample. Lastly, the intensity of the excitation radiation

should be kept low to avoid distorting the internal field with space charge effects. These experimental conditions are optimal when testing is conducted under small-signal assumptions, as discussed in more detail in the following sections.

The origin of the photocurrent observed in the external circuit can be explained by examining how the injected holes influence the electric field inside the sample. Since the excitation pulse is much shorter than the transit time of the carriers, the injected holes move across the sample length as a compact group or "sheet" of positive charge with width $w \ll L$, where L is the thickness of the sample. This charge packet drifts toward the bottom electrode at a velocity v_d . At a specific position x' within the solid, as illustrated in Figure 4.1, the electric fields on either side of the charge sheet, F_1 and F_2 , remain constant in the absence of space charge and vary based on the sheet's location. These fields are given by:

$$F_1 = F_0 + \frac{ep_0w}{\varepsilon} \left(\frac{x'}{L} - 1 \right) \quad (4.1)$$

$$F_2 = F_0 + \frac{ep_0w}{\varepsilon} \left(\frac{x'}{L} \right) \quad (4.2)$$

where p_0 is the hole concentration in the sheet, and ε is the dielectric constant of the material [7]. The formulas show that the moving charge disturbs the applied electric field $F_0 = V_0 / L$, where V_0 is the applied voltage. As a result, the electric field F_1 behind the charge sheet becomes weaker, while F_2 , the field in front of the sheet, becomes stronger. This shift in the electric field distribution causes the net force that drives the photocurrent through the external circuit.

To accurately extract drift mobility from the TOF photocurrent signal, it is essential that the perturbation terms in Equations 4.1 and 4.2 remain significantly smaller than the applied electric field. This condition is satisfied when the value ep_0w / ε is much less than V_0 / L , indicating minimal influence from the injected charge on the electric field.

Such a scenario arises when the total injected charge Q_0 is much smaller than the charge on the electrodes, which is defined by $C_s V_0$, where C_s is the sample capacitance. This is known as the small-signal condition, implying that the internal field can be assumed uniform and that the charge sheet moves at a constant drift velocity [30]. However, if the charge sheet disturbance becomes comparable to the applied field, space charge effects must be considered, making the system significantly more complex [31].

The transient current caused by the movement of the charge sheet in the sample can be

described by Ramo's theorem [32]. Suppose a positive charge q is introduced at position l in a highly resistive medium with an electric field $F_0 = V_0 / L$, as in Figure 4.2. This charge travels leftward with constant drift velocity $v_d = \mu F$, where μ is the charge mobility in the material. The transit time t_T , or the time it takes the charge to travel from its point of origin to the collecting electrode, is given by $t_T = l / v_d$. As the charge moves through the material, it generates a current in the external circuit depicted in Figure 4.2. This induced current continues for the entire transit time. Once the charge reaches the collecting electrode, it is absorbed, and the resulting photocurrent drops to zero.

The strength of the current that appears in the external circuit can be explained through basic physical principles. First, consider that a charge q experiences a force qF_0 as it moves through the sample. The work done in moving the charge a small distance dx is $qF_0 dx$, and this energy must come from the external power supply. Thus, the power delivered over a time dt to move the charge is given by $F_0 q dx = V_0 i_{ph}(t) dt$. Using the relationship $F_0 = V_0 / L$ and $v_d = dx / dt$, the magnitude of the photocurrent generated by the drifting charge can be written as:

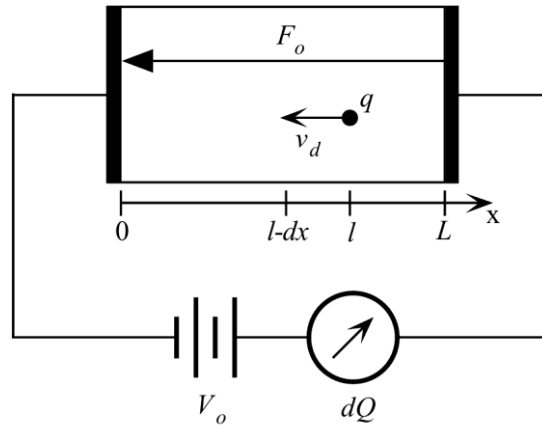


Figure 4.2 An illustration showing how the displacement of a charge q over a distance dx within a material results in an induced current dQ in the external circuit. [7]

$$i_{ph}(t) = \begin{cases} \frac{qv_d(t)}{L} & , 0 < t < t_T \\ 0 & , t > t_T \end{cases} \quad (4.3)$$

This equation holds true under the small-signal condition described earlier and applies to the TOF setup shown in Figure 4.1 [7]. Under these assumptions, the total number of holes injected into the sample is given by:

$$Q_0 = ep_0 wA \quad (4.4)$$

where p_0 is the hole concentration, w is the thickness of the charge layer determined by the absorption depth of the light, and A is the area of the illuminated region .

As the injected charge packet is much thinner than the length of the sample, it effectively travels across the full thickness L of the material. Under small signal conditions, the drift velocity $v_d = \mu V_0 / L$ remains constant, so the transit time t_T of the charge sheet is given by:

$$t_T = \frac{L}{v_d} = \frac{L^2}{\mu V_0} \quad (4.5)$$

where μ is the mobility of the holes within the material [7]. From this expression it is possible to calculate the carrier mobility while performing the TOF method. The resulting current in the external circuit, generated by the drift of the injected charge sheet, can then be expressed as:

$$i_{ph}(t) = \begin{cases} \frac{ep_0 wA v_d}{L} = \frac{ep_0 wA}{t_T}, & 0 < t < t_T \\ 0, & t > t_T \end{cases} \quad (4.6)$$

The voltage signal produced by this current depends on the external circuitry shown in Figure 4.1. The equivalent small signal circuit is depicted in Figure 4.3, where C_s includes both the sample's capacitance and any stray capacitance from cables or measurement equipment. This current generates a voltage across the parallel combination of the resistor R and the capacitance C_s . If $V(s)$ and $I_{ph}(s)$ represent the Laplace transforms of the voltage and current signals, then their relationship is given by:

$$V(s) = \frac{R}{sRC_s + 1} I_{ph}(s) \quad (4.7)$$

To retrieve the voltage signal in the time domain, one can take the inverse Laplace transform of the above equation. If the duration of the photocurrent is significantly longer than the characteristic time constant RC_s , then the circuit behaves like a simple low-pass filter with smoothing determined by the values of R and C_s .

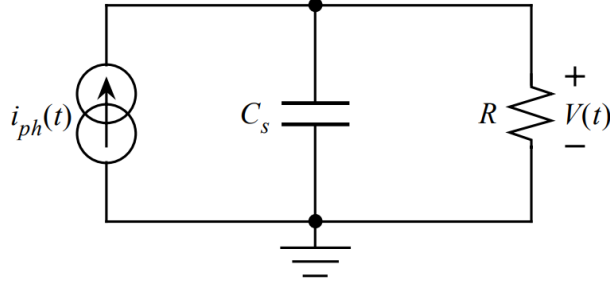


Figure 4.3 A basic AC equivalent circuit model used in the TOF experiment setup. Here, C_s accounts for both the intrinsic capacitance of the sample and any stray capacitances from external circuitry [28].

When the product RC_s is much smaller than the transit time t_T , the inverse Laplace transform of Equation 4.7 gives the following time-domain expression [7]:

$$v(t) \approx \begin{cases} Ri_{ph}(t), & 0 < t < t_T \\ 0, & t > t_T \end{cases}; RC_s \ll t_T \quad (4.8)$$

This form of the signal is referred to as the I-mode signal because its magnitude is directly proportional to the photocurrent $i_{ph}(t)$. In an ideal scenario, the I-mode response increases immediately after charge carrier generation and remains constant until the carriers reach the collecting electrode. At that moment, the signal drops sharply to zero. The I-mode is particularly useful for measuring charge carrier mobility, since the precise moment when the signal falls corresponds to the time when carriers exit the sample.

Previously it was assumed that the number of mobile carriers in the charge packet does not change over time, implying that there are no trapping effects in the material. However, this assumption generally is not valid for amorphous semiconductors, where structural disorder creates numerous localized trap states in the mobility gap. As the charge sheet travels through the material, some carriers become trapped in these localized states and are no longer part of the transport band.

Consequently, the number of mobile carriers within the packet decreases over time, leading to a gradual drop in the photocurrent signal, which is directly linked to the number of drifting carriers [7].

Suppose a group of hole traps is located at a fixed energy level deep within the semiconductor's mobility gap, characterized by an average trapping time τ_c . It is assumed that these trapped carriers are not released back into the transport band during the course of the experiment because τ_c is much longer than the charge packet's transit time. As a result, the number of free carriers decreases as the packet moves through the material, causing the photocurrent to decay exponentially.

4.3 The Interrupted-Field Time-of-Flight Technique

The interrupted-field time-of-flight transient photoconductivity method is highly effective for measuring the deep trapping lifetimes of carriers in high-resistivity materials like amorphous selenium. This technique is based on similar principles as the standard TOF method discussed earlier.

In this approach, a brief laser pulse injects a narrow distribution of free charge carriers into a sample of thickness L , which is subjected to an external voltage V [7]. As the charge packet drifts through the material, it generates a transient photocurrent signal across the external resistor R . Provided that the small-signal condition holds, the drift velocity $v_d = \mu V / L$ remains constant because the electric field is uniform and the carrier mobility μ is a fixed material parameter. If the applied voltage is chosen such that the transit time t_r is much longer than the trapping time τ_c , then the photocurrent magnitude is given by [7]:

$$i = e\mu PV / L \quad (4.9)$$

Here, P represents the number of mobile carriers in the charge packet. Equation 4.19 demonstrates that, under appropriate experimental conditions, the observed photocurrent is directly proportional to the number of carriers in the drift packet.

The IFTOF method determines the trapping lifetime of drifting charge carriers by briefly turning off the electric field at a time t_1 , before the charge sheet reaches the collecting electrode, i.e., when $0 < t_1 < t_r$. Once the field is removed, the motion of the charge sheet stops, and the photocurrent in the external circuit drops to zero. Under zero-field conditions, the charge carriers remain stationary at a location approximately equal to $l \approx t_1 L / t_r$ until the electric field is reapplied at time t_2 . The

carriers then continue drifting through the sample and generate a post-interruption photocurrent until they are collected at the electrode.

During the interruption period $t_i = t_2 - t_1$, some of the mobile carriers may get trapped in localized gap states located at position l and so the hole dynamics are governed by the hole continuity equation,

$$\frac{\partial p}{\partial t} = G - R - \frac{1}{e} \nabla \cdot \overline{J_p} \quad (4.10)$$

where G is the volumetric generation rate of free holes due to illumination, R is the volumetric loss rate of free holes by capture/recombination, and J_p is the hole drift–diffusion current density. When the electric-field bias of the photodetector is removed for the short interruption t_i , the drift part of J_p vanishes because $F = 0$. Over this interruption time, with blocking (no-injection) contacts and a nearly uniform device, there is no appreciable net flux through the contacts and minimal spatial redistribution, so the divergence of the residual diffusion current is negligible on this timescale. In the standard timing, the photodetector is irradiated with a single short laser pulse before the field is turned off, therefore, during the dwell no new carriers are generated and $G = 0$. Under these conditions the continuity equation (4.10) reduces to,

$$\frac{dp}{dt} = -R \quad (4.11)$$

Modelling the carrier recombination during the interruption as first-order trapping with a trapping time τ_c gives,

$$\frac{dp}{dt} = -\frac{p}{\tau_c} \quad (4.12)$$

Rearranging and integrating from t_1 to t_2 gives,

$$\begin{aligned} \frac{1}{p} dp &= -\frac{1}{\tau_c} dt \\ \int_{p(t_1)}^{p(t_2)} \frac{1}{p} dp &= -\int_{t_1}^{t_2} \frac{1}{\tau_c} dt \end{aligned}$$

$$\begin{aligned}
\left[\ln p \right]_{p(t_1)}^{p(t_2)} &= -\frac{t_2 - t_1}{\tau_c} \\
\ln \frac{p(t_2)}{p(t_1)} &= -\frac{t_i}{\tau_c} \\
\frac{p(t_2)}{p(t_1)} &= \exp\left(-\frac{t_i}{\tau_c}\right)
\end{aligned} \tag{4.13}$$

Since the induced photocurrent right after the field is restored is directly proportional to the instantaneous concentration of mobile carriers remaining after the interruption, the same exponential decay carries to the current. Thus, the ratio of the post-interruption current (immediately after bias is reapplied at t_2) to the pre-interruption current (just before bias is removed at t_1) is,

$$\frac{i(t_2)}{i(t_1)} = \exp\left(-\frac{t_i}{\tau_c}\right) \tag{4.14}$$

In the experimental setup, that transport current flows through the variable resistors of the grounded-bridge network and the oscilloscope displays the corresponding voltage drop, which is linearly proportional to the current after being amplified in the IFTOF amplifier stage. Therefore, the same exponential relation holds for the measured voltage:

$$\frac{v(t_2)}{v(t_1)} = \exp\left(-\frac{t_i}{\tau_c}\right) \tag{4.15}$$

4.4 Amorphous Selenium Sample

Amorphous selenium (a-Se) samples are typically fabricated using standard vacuum deposition methods. Since pure a-Se films lack long-term thermal stability and tend to crystallize over time, they are generally alloyed with small quantities of As to enhance their stability. An arsenic, As, content of around 0.2% is often used for this purpose. Additionally, a trace amount of halogen, such as Cl, is usually introduced (e.g., approximately 10 ppm) to help offset the reduced hole lifetime associated with arsenic doping. This combination of As and Cl results in a more thermally stable composition commonly referred to as stabilized a-Se. For instance, a composition like a-Se:As_{0.5%} + 10 ppm Cl is typical, and in general practice, this stabilized form is simply labelled as a-Se in discussions [7].

Oxidized aluminium substrates are typically employed as bottom electrodes and to offer a suitable surface for a-Se film deposition. In transient photocurrent measurements like TOF, it's generally necessary that the electrical contacts be blocking to suppress undesired charge injection. This approach ensures that the photocurrent signal dominates over any background conduction current when a voltage bias is applied across the sample. The naturally formed oxide layer on the Al substrate surface acts as an insulating barrier between the metal and the a-Se film, effectively minimizing injection and creating a stable amorphous base for film growth [37].

In the present investigation, the a-Se samples used were specifically prepared with a composition of 0.3% As and 4 ppm Cl. These values were selected to achieve thermal stability while maintaining favourable transport properties. The selenium source material for this experiment was obtained from Analogic, located in Montreal, QC.

4.5 Charge Transport Measurements

The charge transport characteristics of three a-Se photoconductor samples were analyzed using conventional Time-of-Flight and Interrupted-Field-Time-of-Flight transient photoconductivity measurements. These techniques assess the transient response resulting from the movement of charge carriers through the high-field region of a semiconductor. The I-mode signal is a measurement approach that directly represents the amount of photocurrent produced within the material. Under ideal conditions, the I-mode signal follows a distinct pattern: it rises abruptly when charge carriers are generated, remains steady while they traverse the material, and then rapidly drops to zero upon their collection. The duration of this "on" period corresponds to the transit time of the charge carriers.

The TOF technique is widely recognized as a reliable method for measuring the drift mobilities of charge carriers, such as electrons or holes, across a broad spectrum of materials including amorphous semiconductors, liquid systems, and semiconductors that exhibit negative differential mobility. Originally developed in the 1950s and 60s by researchers such as Spear [29], Kepler [38], Leblanc [39], and Brown [40], the method has since undergone numerous modifications.

Literature reports various implementations of the technique, such as the use of pulsed or continuous-wave excitation, differing electrical biasing methods, and advanced or delayed photoexcitation protocols designed to probe bulk space charge buildup [41] and carrier recombination phenomena [42]. Typically, charge carriers are injected using a brief pulse of high-intensity light, with the wavelength of the excitation source carefully chosen to match the material's band gap and

minimize unwanted photogeneration. Examples of optical excitation sources found in past TOF mobility experiments include argon-ion lasers modulated via acousto-optic devices, xenon flash lamps, Kerr cells, nitrogen (N₂) flash lamps, condenser-based spark gaps, nitrogen-pumped dye lasers, and Q-switched ruby lasers [34][35][43][44][45][46]

In the case of TOF, a high-voltage power supply, applies a voltage bias V to the sample. After a brief stabilization period to allow high-voltage switching transients to subside, a short-duration pulse of light injects a narrow sheet of charge carriers into the sample. As the charge sheet drifts across the sample, it induces a transient photocurrent $i(t)$ through the sampling resistor R . The resistor converts this current signal into a voltage signal, $v(t) = Ri(t)$, which is then amplified and recorded by an oscilloscope.

The recorded signal is directly proportional to the value of the sampling resistor. Increasing R enhances the signal magnitude but also increases the RC time constant of the circuit, where C represents the combined capacitance of the sample and any stray capacitances from cables and signal-conditioning electronics. If the RC constant is too large, the sampling circuit's bandwidth will be restricted, distorting the captured signal. For accurate I-mode TOF detection, R must be chosen such that $RC \ll t_f$, where t_f represents the minimum expected TOF pulse width.

The TOF technique provides a direct method for determining the drift mobility of either holes or electrons across various materials, including liquids, amorphous semiconductors, and materials exhibiting negative differential mobility. In a-Se, the TOF photocurrent pulse typically features a broadened falling edge, as shown near time t_f in Figure 4.4(a). This extended photocurrent tail is indicative of carrier dispersion during transit, which can be credited to effects such as carrier diffusion, mutual Coulombic repulsion, and multiple trapping in shallow states. The carrier transit time is conventionally measured at the half-magnitude point of the photocurrent tail, as illustrated in Figure 4.7(a). This point roughly corresponds to the moment when half of the injected carriers have been collected and represents the mean transit time of the charge packet. Alternatively, the mean transit time can be determined by identifying the "knee" in the photocurrent curve or locating the

inflection point on the photocurrent tail.

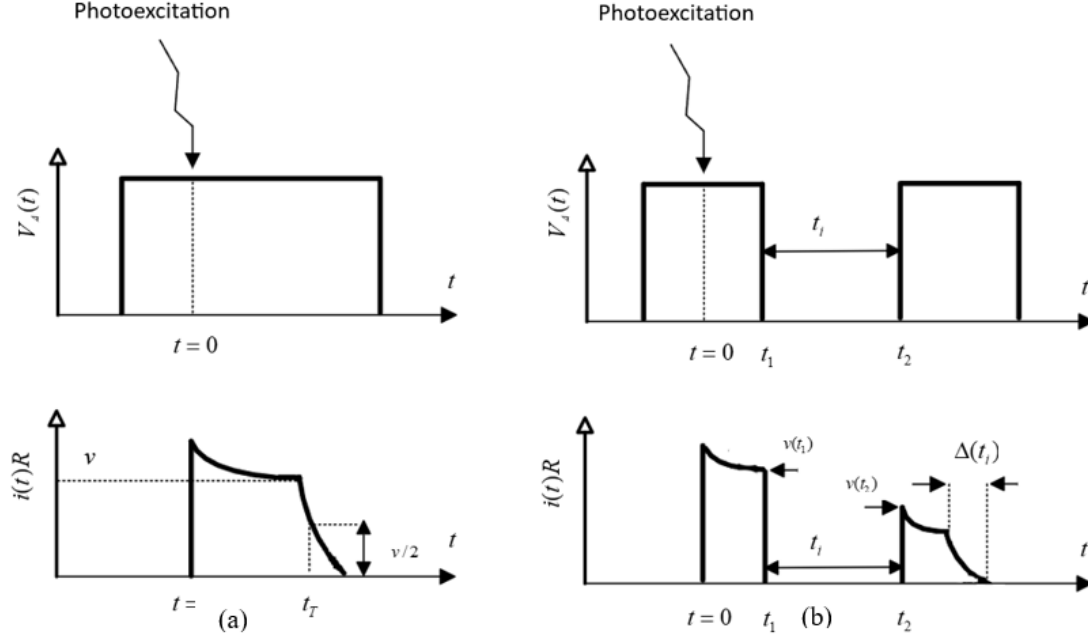


Figure 4.4 Transient voltage response illustrating hole drift in (a) TOF and (b) IFTOF experiments. The hole mobility is determined from the transit time of the TOF pulse, while the hole lifetime is measured by temporarily interrupting the applied field in the IFTOF experiment.

The drift mobility is derived from the measured transit time. Since the generated holes originate near the sample surface, the charge sheet is assumed to travel the entire sample thickness L . Consequently, the average drift velocity of the charge sheet is given by $v_d = L/t_T$. Assuming a uniform internal electric field $F = V/L$, the drift velocity remains constant and relates to the effective hole drift mobility u_h through the equation:

$$v_d = u_h F \quad (4.16)$$

From this relationship, it follows that:

$$u_h = \frac{L^2}{V t_T} \quad (4.17)$$

where V is the magnitude of the applied bias and t_T is the transit time obtained using the Full Width Half Maximum method. The same arguments can be made to calculate the effective electron drift mobility u_e from the electron TOF waveform.

In the case of IFTOF, at $t = 0$, a short-duration laser pulse injects a narrow sheet of charge into the biased sample, causing the drift of the charge sheet to induce a photocurrent signal in the

external circuit. At $t = t_1$, the applied bias is removed, halting the drift of the charge sheet and causing the transient signal to drop to zero. The charge sheet remains in its position until the bias is reapplied at a later time $t = t_2$, at which point its drift resumes, producing a post-interruption photocurrent signal in the external circuit.

During the bias interruption period $t_i = t_2 - t_1$, some holes become trapped in localized states deep within the material's mobility gap and are effectively lost from the charge sheet for the remainder of the experiment. Then, at time t_2 , the voltage bias is reapplied and the carrier loss can be observed. This carrier loss is observed in the difference between the magnitudes of the transient voltage signals recorded before and after the bias interruption. For a discrete set of hole traps with a well-defined capture time τ_h , it can be demonstrated that the fractional recovered photocurrent signal $v(t_2)/v(t_1)$ is mathematically related to t_i as shown in equation (4.15).

The IFTOF technique is done multiple times at the same intervention point to measure $v(t_2)/v(t_1)$ for different values of t_i typically ranging from 5-20 μ s for holes and 20-200 μ s for electrons in the case of a-Se. The slope of a semi-logarithmic plot of $v(t_2)/v(t_1)$ versus t_i gives the value of the lifetime. The IFTOF technique is ideal for materials with long carrier lifetimes, as the interruption time can be changed over an interval that is much longer than the carrier transit time. The timing sequence of the IFTOF experiment and an example of a typical IFTOF hole transient signal are depicted in Figure 4.4(b). By reversing the polarity of the applied voltage, an electron IFTOF signal can be generated, and the following discussion can similarly be applied to analyze electron trapping dynamics.

4.6 System Overview

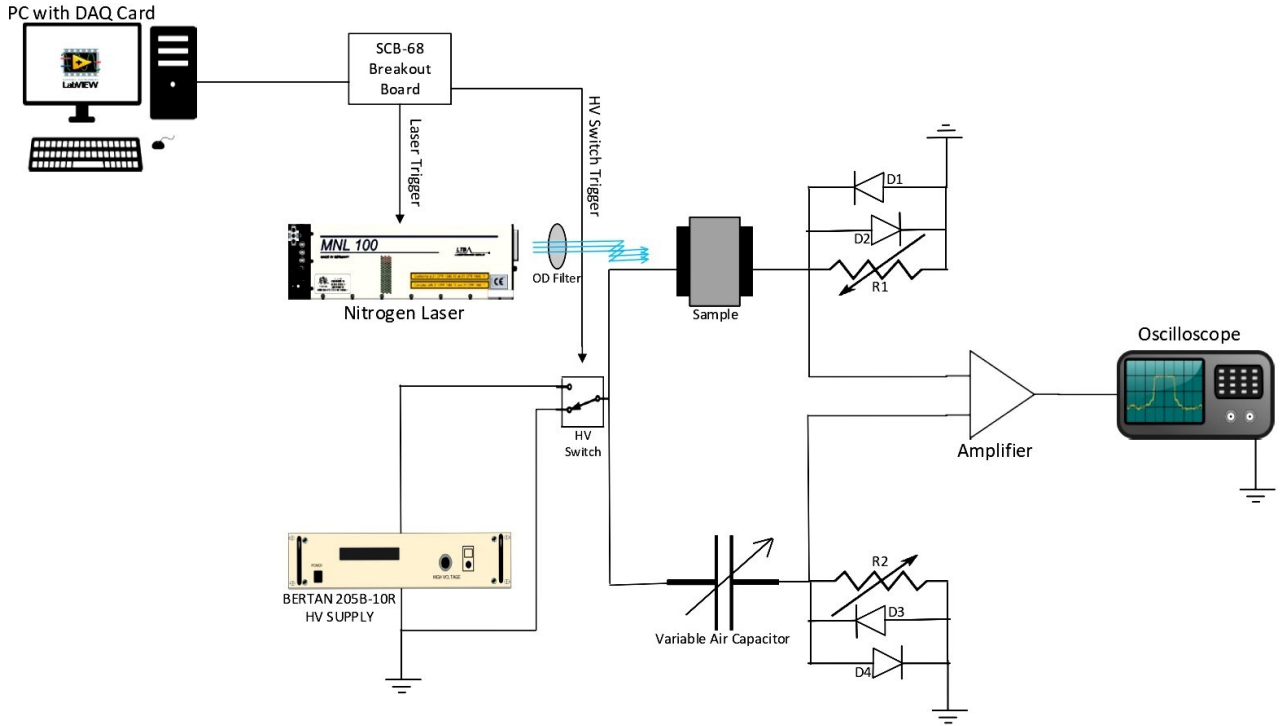


Figure 4.5 The schematic of the TOF/IFTOF system for up to 1kV displacement current-free measurements utilizes a grounded bridge network. The timing for the trigger signals is provided by the PCIE-6361 DAQ board, which is connected to the PC's PCI bus. The SCB-68 allows the user to access the outputs from the DAQ in the form of terminal blocks and the trigger signals are transmitted via BNC cables to the laser and the HV switch. The photocurrent is monitored using a digital oscilloscope, and the collected data is retrieved through the oscilloscope's USB port.

This section explains in detail on how to set up and operate the experimental setup that was used for the TOF and IFTOF experiments to measure sample carrier mobility and lifetime. Figure 4.5 presents the entire system designed to perform both TOF and IFTOF measurements, utilizing a grounded bridge network to suppress displacement current signals in IFTOF experiments. To balance the bridge, a variable open-air capacitor C_N with a high breakdown voltage was incorporated. We reduced large unwanted electrical noise (common-mode switching transients) by adding two very fast diodes (MUR120) to each resistor in the bridge circuit. A special amplifier (differential amplifier) is used to cancel out any remaining common signals and only amplify the useful signal (the transient photocurrent).

Various methods have been proposed to suppress displacement currents in transient photoconductivity measurements. For instance, Kasap and colleagues employed a complementary bias-switching scheme to cancel displacement currents up to 200 V; however, mismatches between

switch outputs made it impractical at higher voltages [36]. Helfrich and Mark addressed the problem by using a resistance-ratio bridge network in space-charge-limited current studies on anthracene crystals, which floated both the power supply and bridge so that only half of the applied voltage appeared across the sample [47].

Moreover, Polishchuk and Kasap implemented a floating Schering bridge to achieve displacement-current-free IFTOF measurements at bias levels up to 1 kV [48]. Although effective at reducing leakage, the floating supply introduced substantial stray capacitance, complicating bridge balancing and limiting the method's practicality [7].

In the current study, a grounded bridge network was utilized to suppress displacement current signals during measurements. A key benefit of this method is its compatibility with grounded voltage supplies, which offers improved RFI shielding. The schematic layout of the bridge circuit is presented in Figure 4.6. When a high voltage is applied and then removed, it generates a displacement current in both arms of the bridge. If the variable capacitor C_N is accurately tuned to match the sample capacitance C_S , the resulting displacement currents across the two bridge resistors will be equal and cancel out in differential measurements. The photocurrent, being present only in one arm of the bridge, is selectively detected by the differential amplifier.

Although the approach is conceptually simple, implementing a pure differential detection method comes with significant challenges. Differential amplifiers used in this context must exhibit very high common-mode rejection ratios (CMRR), typically around 100 dB, across a wide frequency range. Additionally, these amplifiers must be able to tolerate large common-mode input signals without entering saturation, a requirement that places demanding constraints on component performance.

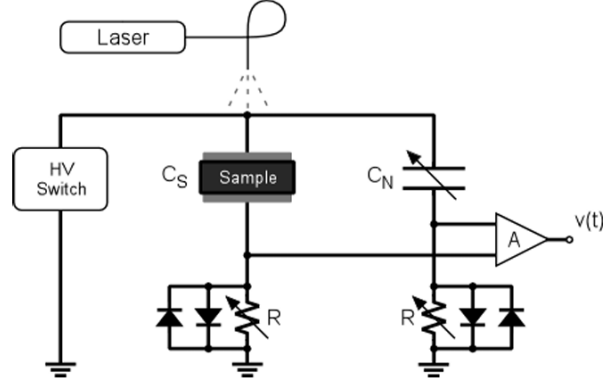


Figure 4.6 Schematic of a grounded bridge circuit designed to suppress displacement current components during IFTOF transient photoconductivity experiments [7].

To address the amplifier saturation issue, a practical solution involved placing back-to-back high-speed rectifiers across each bridge resistor. This configuration effectively limits the displacement current signal to a peak value of approximately 0.7 V, which corresponds to the forward voltage drop across a typical diode. As depicted in Figure 4.6, this method prevents the differential amplifier from being overwhelmed by large signals [7]. In this way, any residual common-mode signal can be efficiently rejected by a differential amplifier, assuming that the bridge resistors are closely matched and the CMRR is about 60 dB.

The voltage bias was supplied by a BERTAN 205B-10R high-voltage power supply and applied to the sample through HV switch. The trigger signals required for the switches, laser, and oscilloscope were generated by a PCIe-6361 counter board installed in the PCI slot of a Windows 10 PC. The experiment was controlled through a custom graphical user interface developed in LabVIEW, running on the same PC. A Tektronix MDO4104-3 Mixed Domain Oscilloscope was used to digitize and capture the photocurrent signal, with the recorded data stored on a USB drive via the oscilloscope's USB port. Figure 4.5 illustrates the complete system, including the computer, trigger mechanism, oscilloscope, high-voltage power supply, HV switch, laser, sample, variable capacitor, bridge network, and amplifier.

By carefully tuning the variable air capacitor within the bridge, most of the displacement current signal could be minimized. However, the dark current in a-Se samples is not entirely negligible and increases significantly with the applied electric field F . Additionally, this dark current tends to decrease over time.

It is important to understand how the large displacement currents are taken care of using this system. First, when the HV switch is turned ON, a large displacement current signal is produced by

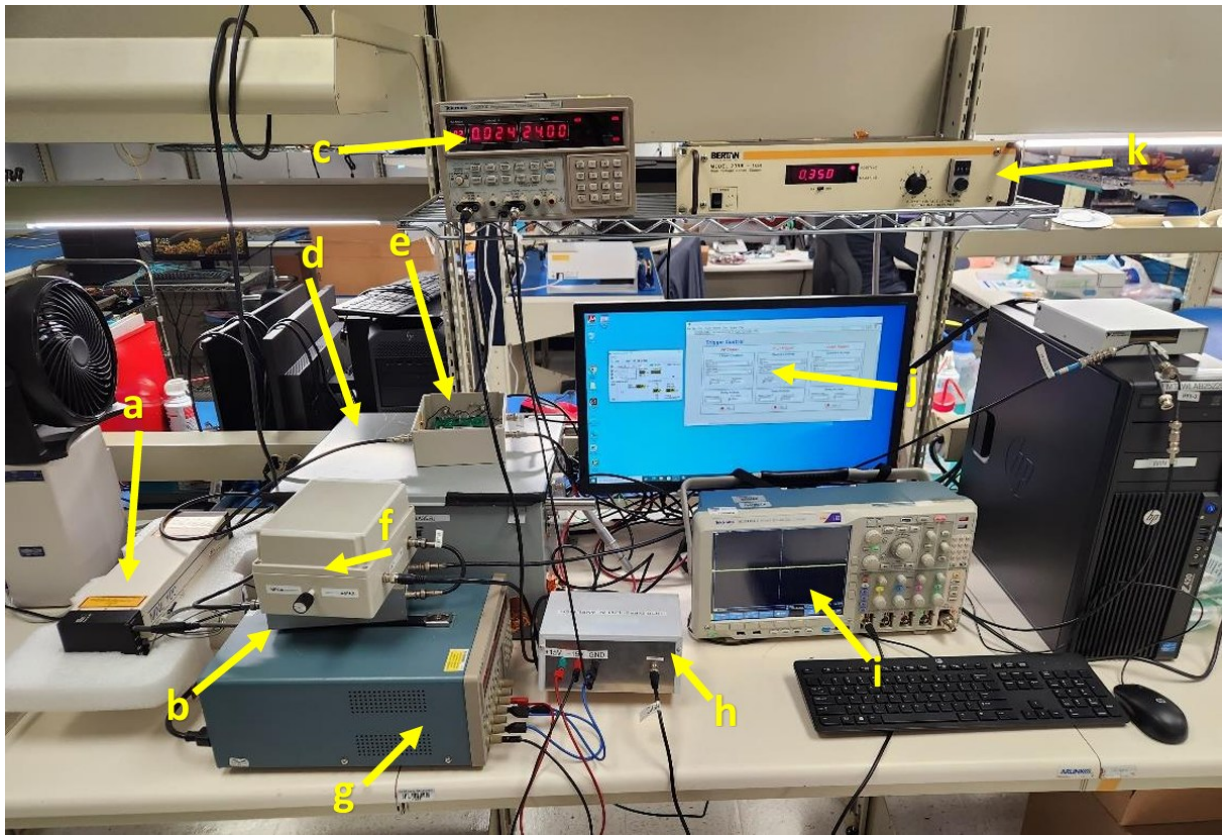


Figure 4.7 The entire experimental setup view. All the Equipment used are shown here. (a) Nitrogen Laser. (b) HV Splitter box with one HV input and two HV outputs, one going to the HV switch and the other going to the Air Capacitor. (c) DC Power supply for the HV switch with Channel 1 being 24V and Channel 2 is 18V. (d) Sample box enclosure. (e) HV switch. (f) Air Capacitor enclosed. (g) DC power supply for powering up the amplifier. (h) the 16 dB differential Amplifier. Note that the grounds are made common from CH2 of (c), both channels of (g) and the GND terminal of the amplifier in (h). (i) Digital Oscilloscope. (j) PC with the LabView GUI and the Interphase for controlling the Laser. (k) BERTAN HV power supply.

the sample as well as the variable air capacitor. Then, these go through the resistors R1 and R2, but since these variable resistors R1 and R2 have the diodes D1, D2 and D3, D4 connected across them as shown in Figure 4.5, they clip off a large part of the displacement current signal and bring it down to about 600mV. However, for IFTOF, even this is too much and so it needs to be brought even further down. Once the fine tuning of the resistors can no longer reduce those displacement current signals, that is when we have to use Digital Subtraction, by taking one reading by applying the laser and another without laser and then subtract the two. That will give the remaining pure IFTOF result. Figure 4.7 shows all the equipment that were used during this experiment. Figure 4.8 is an image of

the sample box in which the a-Se sample was placed and the laser being irradiated on it, making sure no external light interfered with the experiment.

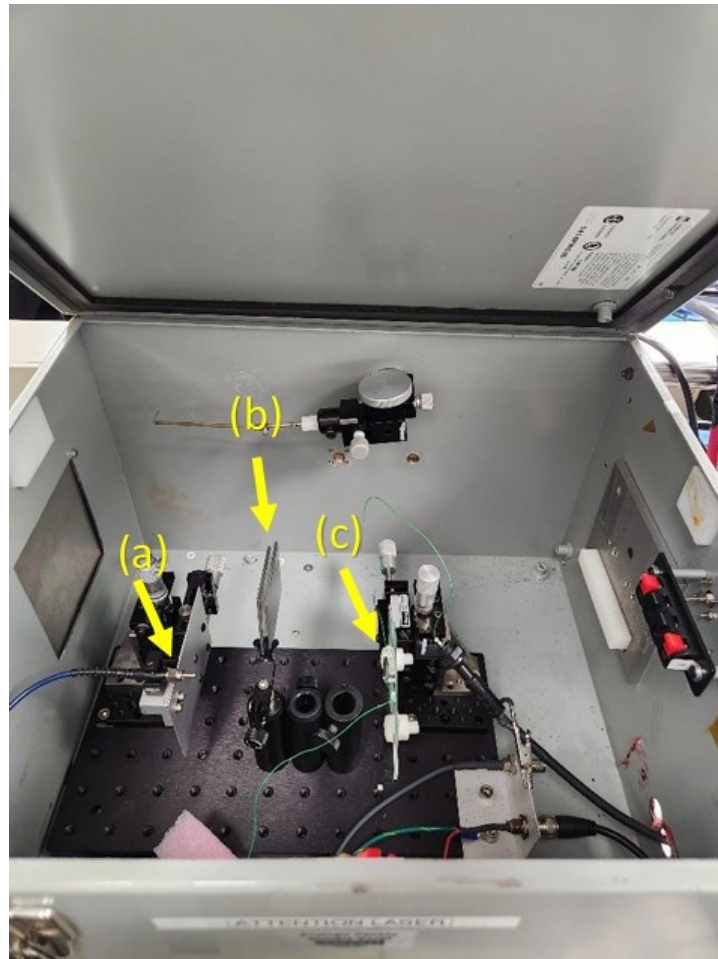


Figure 4.8 Sample box enclosure. This box is made sure to prevent external light from interfering with the experiment. (a) The Nitrogen Laser head is at the left most of the image. (b) is the OD filters which are used to reduce the intensity of laser light falling on to the Sample and there are two of them in this image. (c) is the sample held tightly with the sample holder and screwed in place. Two thin green wires can be seen coming out of the sample. One of these is for the HV bias (from the HV OUT knob of the HV switch) and the other is for the charge collection (which comes out and is connected to the INPUT 1 of the amplifier).

4.7 High Voltage Switch

The first of the main components in the switch includes the 24V DC-DC converter. In this experiment, every single equipment, electronic component and device has to be grounded to a common point except this DC-DC converter. Figure 4.9 shows the schematic for the HV switch that was designed and built for the experiment. It must be made sure that this converter, is completely isolated from the rest the of the setup. It acquires +24V and -24V from the positive and negative terminals of a DC power supply, say for example, CH 1 of the DC supply. However, since the Opto-Coupler (HCPL-31200-300E) requires 18V, an 18V regulator is connected at the output of the 24V DC DC converter to bring down the voltage to 18V and then we supply it to the top HCPL-3120. The 0.22 μF and 0.1 μF capacitors are connected according to the datasheet of each component. Next are the two Opto-Couplers, one on top and the other at the bottom. The bottom one is grounded to the common ground of the entire system, while the top one is not. The top Opto-Coupler should never

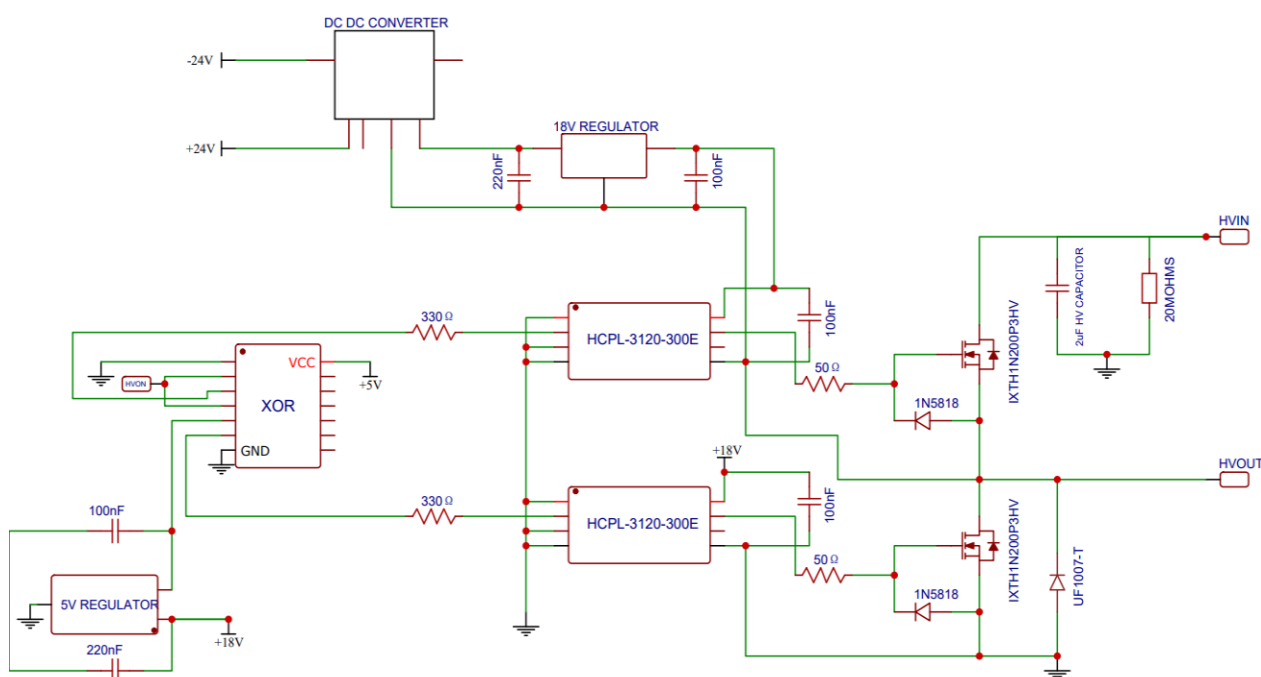


Figure 4.9 Schematic of the ultra-fast 1000V HV switch with a switch speed of faster than 300ns built for the TOF/IFTOT experimental setup.

touch the ground otherwise the switch cannot give any voltage as output and a large amount of current could flow leading to failure of the MOSFETS or even burning them. The switching of these HCPL-3120 is controlled by the logic XOR gate to the left of the schematic in figure 4.9. At the extreme bottom left is just a 5V voltage regulator, since the XOR device needs to be powered up by 5V. The

2M Ω resistor and the 2 μ F HV capacitor (rated 1000V) act as filters for the voltage input. Finally, the main workers of the switch are the MOSFETs, top and bottom configured in a totem-pole arrangement. The 1N5818 diodes are just for protecting the MOSFETs to make sure in case of any sudden voltage surges of more than the breakdown voltage of those diodes (typically around 30V) the diodes will burn out and protect the MOSFETs. The MOSFET used in this setting can handle voltages up to 2KV, but it will not work because the Opto-Couplers, HCPL-3120 cannot handle voltages that high. The HCPL-3120 can handle continuous voltage supply of 630V, but 1181V is possible if the ON time of the switch is less than 1 second. Therefore, it is recommended not to keep this HV switch ON for more than one second if the applied voltage is more than 630V and to not exceed 1181V when using this switch.

The HV switch is designed to apply only positive bias to the sample. When a positive bias is applied to the top electrode, holes drift toward the lower electrode, generating a hole transient photocurrent signal. For electron measurements, the sample connections are simply reversed while all other experimental procedures remain unchanged. It is important to make sure Safe High Voltage (SHV) cable connectors are used at the input and output side of the switch. The switch must be properly sealed in an enclosure with the ground connections properly made. Otherwise, the obtained signal will not be clear and have interferences with the signal output. Figure 4.10 shows an image of the PCB of the HV switch.

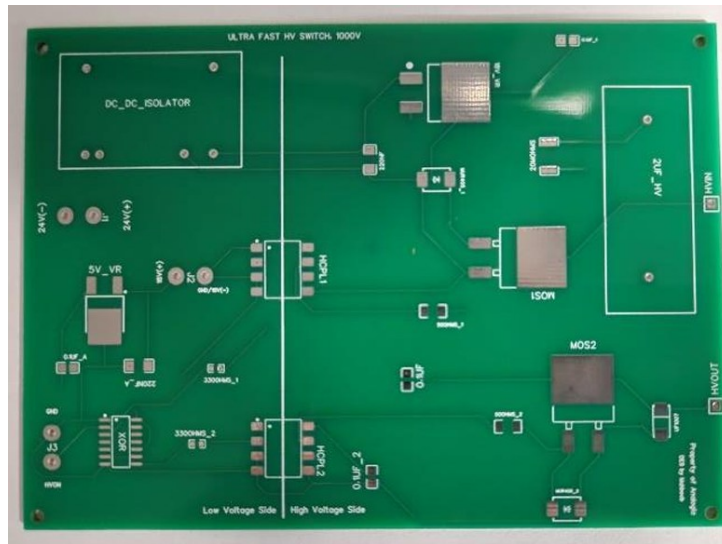


Figure 4.10 HV Switch bare PCB without any of the components soldered. Each component footprint is specified which needs to be placed and soldered onto the PCB. The major components are (from the Top Left) DC-DC isolator, 5V regulator, XOR Logic gate, HCPL1 and HCPL2 Opto-Couplers, 18V regulator, MOS1 and MOS2 HV (MOSFETs) and the 2M Ω HV Capacitor. The rest of the footprints include capacitors, input/output pins, diodes and power supply pins.

The bias voltage is supplied by a BERTAN 205B-10R high-voltage power supply, which is connected to the HV switch input (HVIN). To apply a positive bias for transient photoconductivity measurements, the HV switch output (HVOUT) is connected to the sample's top electrode. Functioning as a single-pole double-throw (SPDT) switch, the HV switch normally grounds its output through the lower MOSFET. A +5V pulse at the trigger input (HVON) activates the upper MOSFET, connecting the high-voltage supply to the sample for the duration of the trigger pulse. This switch has a switching speed of less than 300ns.

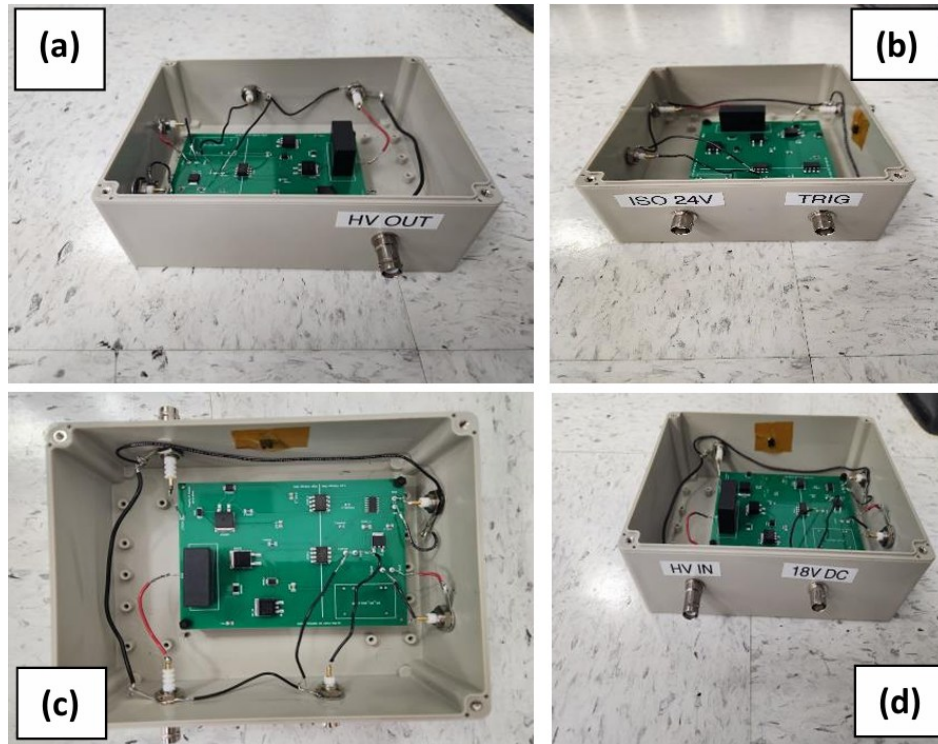


Figure 4.11 This image shows the HV switch after soldering all the components and placing it inside the enclosure. (a) is the Right View where the HV cable is to be connected as the output voltage to reach the sample which is inside the sample enclosure box. (b) shows the Rear View containing the connection from the 24V isolated power supply and next to it is the trigger signal connector. (c) This is the Top View showing the internal connections. (d) The Left view has a knob which is the HV input which is the connecting cable coming from the HV power supply and the 18V DC supply connector.

4.8 Amplifier

A wide-bandwidth, two-stage differencing amplifier was designed to amplify the differential photocurrent signal while rejecting the common-mode displacement current. The schematic of this amplifier is shown in Figure 4.12. The AD830ARZ is the differential amplifier and the AD827 is the operational amplifier. Both of them were supplied with +15V and -15V supply in order to function.

Suppose there is a DC power supply with 2 channels, CH1 and CH2, then in order to obtain negative voltage, -15V, short the positive terminal of CH1 of the DC power supply with the negative terminal of CH2 of the same DC power supply. This shorted path is now the common ground that can be connected with the ground for the entire experimental setup. After shorting these two, the CH2 positive terminal will supply +15V and the CH1 negative terminal will supply -15V. It is important to measure using a DMM each time before conducting experiments. This way one can easily supply +15V and -15V to the amplifiers. In this setup the voltage chosen was 15V, but one can supply higher or lower, given that it does not go beyond the functional range of the amplifiers according to their datasheets. The 0.1 μ F capacitors are just decoupling capacitors that help filter any noisy signals so that it doesn't interfere with the amplification process.

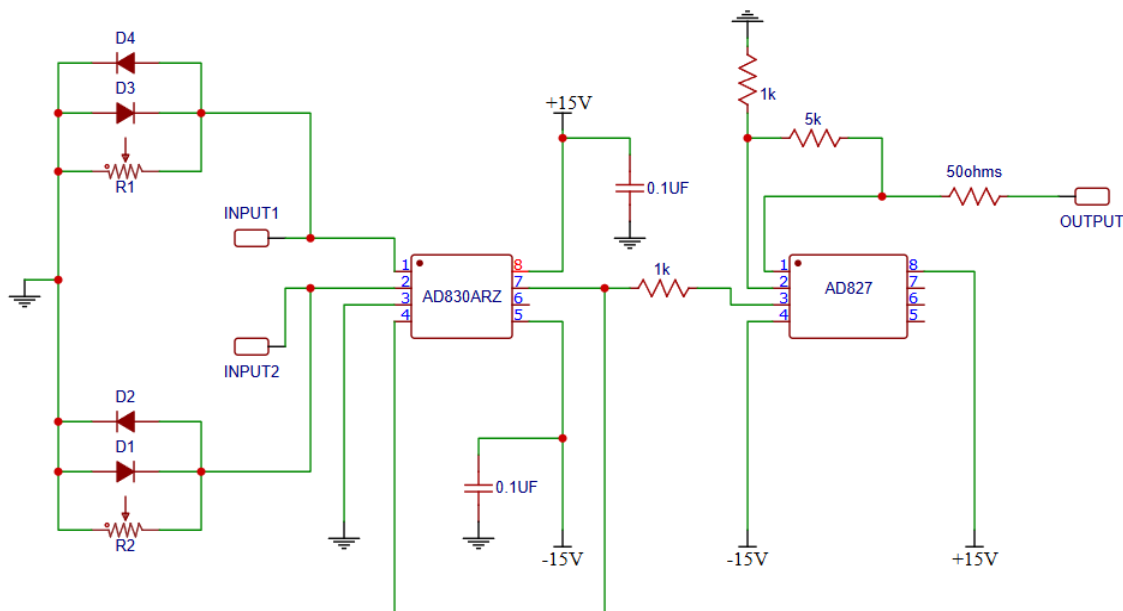


Figure 4.12 A cascading 2-Stage system of amplifiers consisting of a differential amplifier and a 16dB gain amplifier. The two grounded bridge networks are at the left most of the schematic.

The first stage utilizes a high CMRR, wide-bandwidth video amplifier AD830ARZ from Analog Devices, configured as a unity-gain differential amplifier. This amplifier has a unity gain bandwidth of 85 MHz and a CMRR of 60 dB at 4 MHz.

The second stage is a non-inverting amplifier, built using a high-speed operational amplifier AD827 from Analog Devices. This stage provides a gain of 16 dB (based on the resistor value in the feedback path), ensuring that the photocurrent signal is amplified above the noise floor of the digital oscilloscope.

To measure the output, an oscilloscope probe equipped with a hook and a sawtooth ground grabber can be used. The probe hook should be connected at the node following the $50\ \Omega$ resistor of the amplifier, which represents the output, while the sawtooth grabber should be connected to the common ground. If all connections and the power supply are verified to be functioning correctly but no output is observed, the issue may stem from inappropriate values of resistors R1 or R2. Extremely high or low resistance values can result in a significant DC offset, potentially shifting the signal outside the oscilloscope's baseline display range. Additionally, it is important to ensure that the oscilloscope's time scale is appropriately set and that the trigger level is correctly positioned to enable accurate signal capture. The amplifier electronics circuitry was placed inside a shielded enclosure as shown in Figure 4.13.

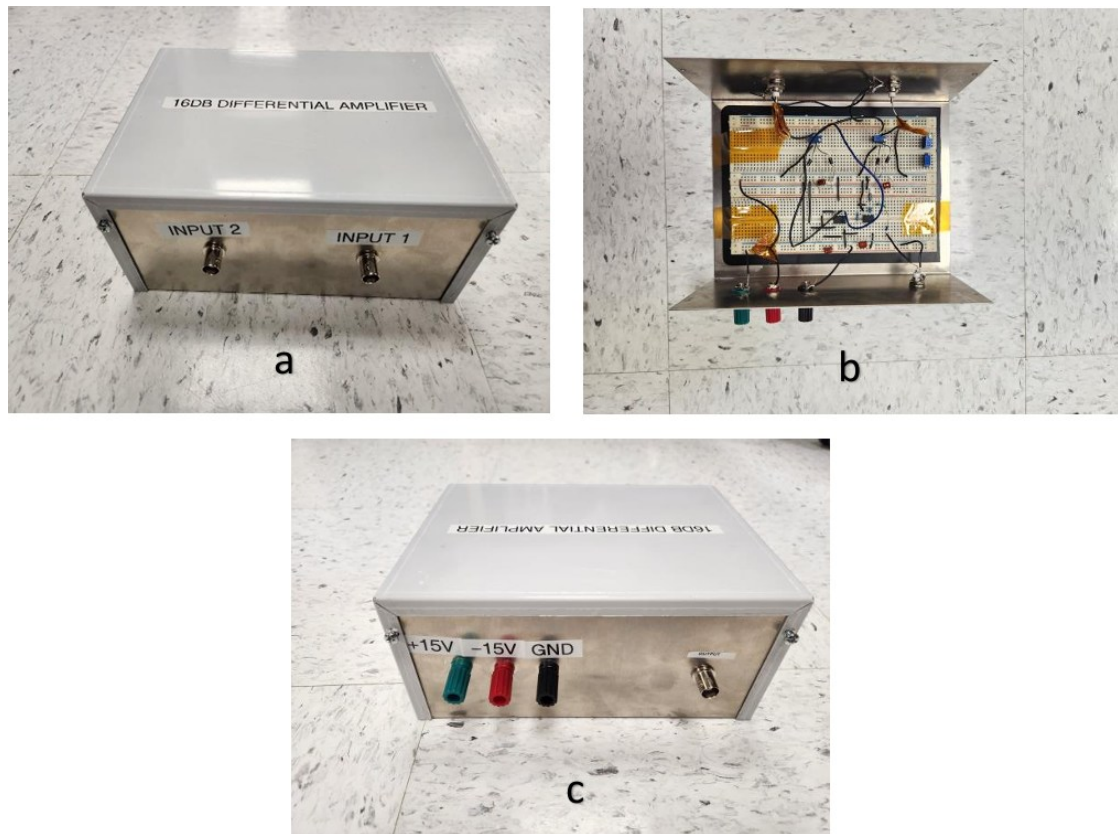


Figure 4.13 Images showing the Amplifier enclosed in a shielded box. (a) shows the front view of the Amplifier with the INPUT 1 and INPUT 2 terminals which are the connections for the output signal that is collected from the sample in the sample box and the Air Capacitor output signal displacement current signal respectively. (b) shows the internal connections of the amplifier inside the enclosure. (c) is the Rear View containing the connections for the 15V power supply, ground and the Output knob at the far right.

4.9 Laser

A nitrogen gas laser (MNL 100) was used to photoinject charge carriers into the sample for the transient photoconductivity measurements. This laser produces ultraviolet pulses at a central wavelength of 337.1 nm with a pulse width of approximately 3–4 ns (FWHM). Each pulse carries about 80 μ J of energy, corresponding to a peak optical power of roughly 25 kW. The output is quasi-monochromatic (spectral bandwidth $\sim$ 0.1 nm) and originates from the N₂ gas excitation line. These short, intense UV pulses provide an almost instantaneous generation of charge carriers in the photoconductive sample, effectively serving as a fast “injection” current pulse at time $t \approx 0$ in the TOF experiment. The laser ensures consistent pulse generation and a long operating lifetime without the need for an external gas supply.

The MNL 100 was triggered externally using a TTL electrical pulse (approx. +5 V amplitude, $\geq$ 100 ns duration) generated by the PCIe 6361 counter and applied to its trigger input. Upon receiving this trigger, the internal power switch rapidly discharges the laser’s 12 kV capacitor, resulting in an optical pulse after a fixed delay of about 1.3 μ s. The timing jitter between the trigger signal and the emitted laser pulse is very small (<2.5 ns), ensuring excellent pulse-to-pulse timing stability. In this setup, the trigger logic for the laser was programmed and controlled through a LabVIEW-based system. The TTL trigger was sent to the laser at the precisely desired moment. Because the MNL 100 requires only a single TTL pulse to fire (the charging and firing sequence is handled internally by its controller), the synchronization was straightforward.

For added reliability, and to prevent any high voltage switching transients from coupling into the sensitive measurement circuitry, the trigger line was optically isolated from the laser. In the experimental geometry, the laser beam was directed onto the top electrode of the photoconductor sample to ensure carriers were injected just inside the illuminated surface. The absorption of this UV pulse in the semiconductor creates a dense cloud of electron-hole pairs at the electrode interface, i.e., it instantaneously photoinjects charge into the sample. Immediately following the laser flash, these photogenerated carriers are subjected to the applied electric field across the sample and begin to drift through the material. The resulting transient photocurrent is measured as a function of time, constituting the photocurrent signal. The short duration of the MNL 100 pulse ($\sim$ 3.5 ns) means that the generation of carriers can be considered practically instantaneous relative to the transit times (typically microseconds or longer) of the carriers, thus defining a clear start time for the transient. By controlling the laser firing time via the LabVIEW software, we could precisely align this photo injection event with other timing-critical elements of the experiment (such as the switch trigger).

4.10 Signal Capture and Analysis

In this investigation, the transient photocurrent signal was captured using a Tektronix MDO4104-3 digital oscilloscope. The setup was relatively straightforward and involved a manual acquisition process. The PCIe 6361 counter board installed in the PCI bus of the computer was configured with LabVIEW to control the TTL pulses with timed accuracy for the laser and the HV switch. When a TTL pulse was sent to both the nitrogen laser and the HV switch, the oscilloscope was simultaneously triggered to record the resulting photocurrent waveform. The MDO4104-3, equipped with a USB interface, allowed the captured waveform to be directly saved onto a USB flash drive in .csv format for later analysis. After capturing the waveform, the file was transferred to a PC where it was opened and processed using Microsoft Excel. Basic filtering and parameter extraction were carried out within Excel for measurements. This semi-manual process, although not automated, proved sufficient for accurate signal analysis and was aided by the high-resolution storage and display capabilities of the MDO4104-3 oscilloscope.

4.11 Overview of TOF and IFTOF Methods

In earlier studies, the influence of As and Cl additions on the charge transport behavior of stabilized a-Se photodetector films was investigated using either xerographic or standard TOF techniques. In the xerographic method, an electrostatically charged a-Se photoconductor is photo-discharged, and the residual surface potential is monitored to estimate the carrier range, denoted as $\mu\tau$ [49][50]. However, this approach is limited by the specific model used to interpret the surface potential decay, providing only an approximate measure of $\mu\tau$ in the film. Moreover, due to the inability to consistently apply high negative surface voltages on a-Se films, studying the electron range as a function of alloy composition becomes particularly difficult.

Conventional TOF techniques allow for analysis of carrier transport for both electrons and holes in a-Se-based films. The deep trapping time, τ , is often estimated by reducing the applied field until the carrier transit time t_t becomes comparable to τ . When this condition is met, the photocurrent decays exponentially with a time constant indicative of the trap lifetime [51][52]. However, extracting τ directly from the shape of the photocurrent curve is not always accurate. This is because in a-Se alloys, photogeneration is strongly field-dependent, if the applied field is too low, the photocurrent may vanish entirely. Additionally, in films with exceptionally long carrier lifetimes, the resulting photocurrent signal can become too weak to reliably extract the decay constant. Another complication is that the shape of the TOF transient may not accurately reflect a genuine exponential decay. Distortions in the signal may arise due to field-dependent

photogeneration, space-charge effects, or dispersion mechanisms, all of which can obscure the true trapping behavior.

In this investigation, both TOF and IFTOF techniques were employed to examine how the alloy composition influences the mobility-lifetime product ($\mu\tau$) and the trapping time (τ) in amorphous selenium films. The IFTOF method was particularly advantageous for determining $\mu\tau$ values because it enables a more accurate assessment of both hole and electron lifetimes within the bulk of the photoconductor material. For the purpose of this study, all samples used had a fixed composition of 0.3% As and 4 ppm Cl and as previously mentioned these samples were sourced from Analogic, Montreal. The deposition of these films was carried out on glass substrates using standard vacuum coating techniques. Each glass substrate was pre-coated with a thin, conductive layer of Indium Tin Oxide (ITO), which served as the bottom electrode for subsequent photoconductivity measurements.

4.12 Charge Carrier Transport in Stabilized a-Se

The intrinsic charge transport behavior of stabilized amorphous selenium photoconductors was evaluated using both TOF and IFTOF transient photoconductivity techniques. These techniques monitor the transient current generated when a brief, intense pulse of light injects a narrow sheet of charge into a biased a-Se sample. By adjusting the polarity of the bias on the sample, it is possible to investigate either hole or electron transport in the material. The duration of the I-mode pulse obtained from the TOF measurement reflects the transit time of the charge carriers, which in turn allows for the estimation of their drift mobility (μ).

In the IFTOF method, the carrier drift and resulting photocurrent are intentionally interrupted while the carriers are still in transit. This approach enables the measurement of the trapping time (τ) of charge carriers by analyzing the photocurrent signal before and after the interruption period, particularly at regions with deep traps. Accurate interpretation of these transient experiments requires the assumption that the internal electric field generated by the applied voltage V is uniform across the film, and may be represented as V/L , where L is the film thickness. Once a bias is applied, some charge is injected at the electrode interfaces and accumulates within the a-Se layer, forming a space charge that influences the electric field distribution in the sample. As this space charge develops, it eventually distorts the uniformity of the internal field. The point in time at which this deviation begins, termed the space charge formation time (t_{sc}), marks the end of the field's uniformity and is typically considered the boundary for accurate transient analysis [53].

In a-Se films, t_{sc} typically occurs around 100 ms [30]. In the current study, the laser pulse used for photoexcitation can be triggered a few microseconds (10-20 us) after the application of the external bias. This delay was introduced to allow sufficient time for the internal electric field in the sample to reach a uniform state prior to carrier injection, ensuring reliable TOF measurements. Evidence of field uniformity can be found by examining the shape of the TOF photocurrent pulse in samples exhibiting long carrier lifetimes. In such cases, a nearly rectangular-shaped current pulse suggests constant carrier velocity and a uniform electric field. Additionally, plotting the hole transit time t_T against $1/V$ typically yields a linear relationship in stabilized a-Se, further supporting the assumption of a uniform field during TOF experiments [29]. However, if the laser pulse occurs significantly after t_{sc} , the photocurrent may show either an increase or decrease depending on the polarity of the accumulated space charge. This behavior was similarly noted in Cl-doped selenium samples by Kasap and Juhasz [41]. A comparable effect may be observed in repeated TOF measurements conducted at a fixed repetition rate over a long period, where residual space charge accumulates [54]. When examining hole transport, space charge buildup near the positive electrode can reduce the electric field strength in that region, much like what occurs in space charge limited conduction observed in insulating materials. Under these conditions, the observed photocurrent begins to mirror the shape of the electric field distribution in the film, which is governed by the Poisson equation: $dE/dx = \rho/\epsilon$, where ρ is the charge density. To neutralize these effects, the sample was periodically discharged between successive TOF and IFTOF measurements. This can be done by repeatedly illuminating the sample while it was shorted, thereby promoting recombination of photogenerated carriers and clearing any built-up space charge from previous measurements.

All TOF photocurrent waveforms display a trailing edge or "tail," which arises from the spreading of carriers within the charge packet as they move through the sample. The extent of this tail becomes more pronounced as the carrier transit time t_T increases. Therefore, it is essential to adopt a standardized approach for measuring the pulse width to ensure meaningful comparisons of carrier mobility across various samples and electric field strengths. One commonly used approach is the half peak magnitude method. This technique determines the pulse width by measuring the time interval between the initial rise of the photocurrent and the point on the trailing edge where the signal drops to half of its maximum value. In instances where the TOF signal decays significantly, the magnitude of the tail is identified at the "knee" of the waveform, where the slope noticeably changes.

IFTOF measurements were used to determine the mean charge carrier lifetime in the bulk of stabilized a-Se x-ray photoconductor layers. The photocurrent magnitude is directly proportional to the average concentration of mobile photo-injected carriers and their drift velocity, given by $i(t) \approx ep(t)v_d(t)$. If the experiment is conducted under small signal conditions, meaning the injected charge $p(t)$ is much smaller than the charge already present on the electrodes, then the drift velocity v_d remains constant. This is because the mobility is a material property and the electric field remains uniform. At time t_1 , the applied electric field is removed, causing the carrier drift to stop. While the charge packet stays in place, carriers are gradually lost due to trapping. As a result, when the field is reapplied at time t_2 , the recovered photocurrent is lower in magnitude. By comparing the photocurrent signal amplitudes measured at times t_1 and t_2 , it is possible to estimate the ratio of corresponding voltage signal during the period before and after the electric field was turned off. Hence from equation (4.14) and (4.15) we have:

$$\frac{i(t_2)}{i(t_1)} = \frac{v(t_2)}{v(t_1)} = \exp\left(-\frac{t_i}{\tau_c}\right) \quad (4.18)$$

where $t_i = t_2 - t_1$ is the duration of the field interruption.

Plotting $\frac{v(t_2)}{v(t_1)}$ on a semilogarithmic scale against t_i yields a straight line. The slope of this line provides a measure of the deep carrier trapping lifetime

4.13 Results using Time-of-Flight technique

The Three samples used and their thickness are shown in table 4.1.

Table 4.1 Samples used in the experimental setup and their thicknesses.

SN#	Sample Reference number according to Analogic	Sample Sequence	Thickness (um)
1	029-201-2	Sample 1	200
2	029-202-2	Sample 2	176
3	029-203-2	Sample 3	195

The hole mobility (μ_h) values for the three samples were determined as follows: sample 1 exhibited a hole mobility of $0.145493 \text{ cm}^2/\text{V}\cdot\text{s}$ (Figure 4.14), sample 2 had a mobility of $0.14030221 \text{ cm}^2/\text{V}\cdot\text{s}$ (Figure 4.16), and sample 3 showed the highest mobility of $0.1538982 \text{ cm}^2/\text{V}\cdot\text{s}$ (Figure 4.18). Among the three, sample 3 demonstrated the highest hole mobility, suggesting that charge transport via holes was more efficient in this sample compared to the others. In contrast, sample 2 had the lowest hole mobility. When comparing the thickness, the thickness of sample 3 is more than sample 2 but less than sample 1. These results may reflect on the variations in composition of the samples leading to such outputs.

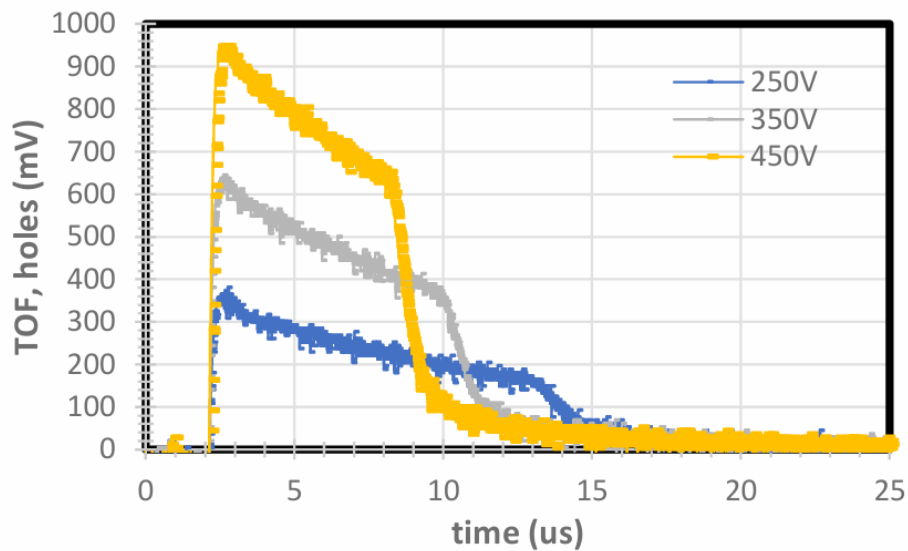


Figure 4.14 Sample 1 TOF for holes at voltages 250V, 350V and 450V

The mobility values were calculated by using equation (4.17) for each waveform. Multiple photocurrent signals were recorded at different bias voltages, but for clarity, 3 outputs have been shown in all the images. After having calculated mobility for each TOF photocurrent output signal, their average was taken and recorded. In the same way, the mobility of the electrons for each sample was also calculated.

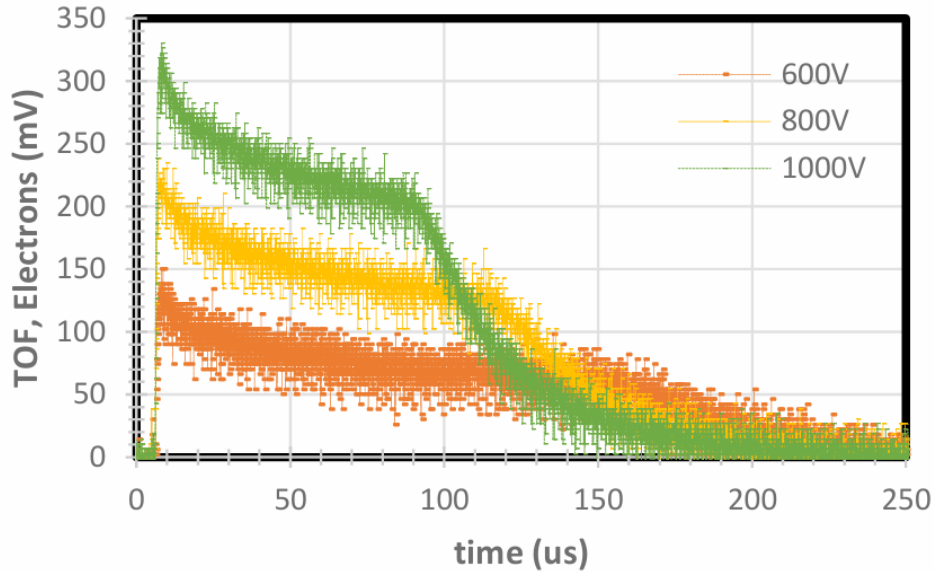


Figure 4.15 Sample 1 TOF for electrons at voltages 600V, 800V and 1000V

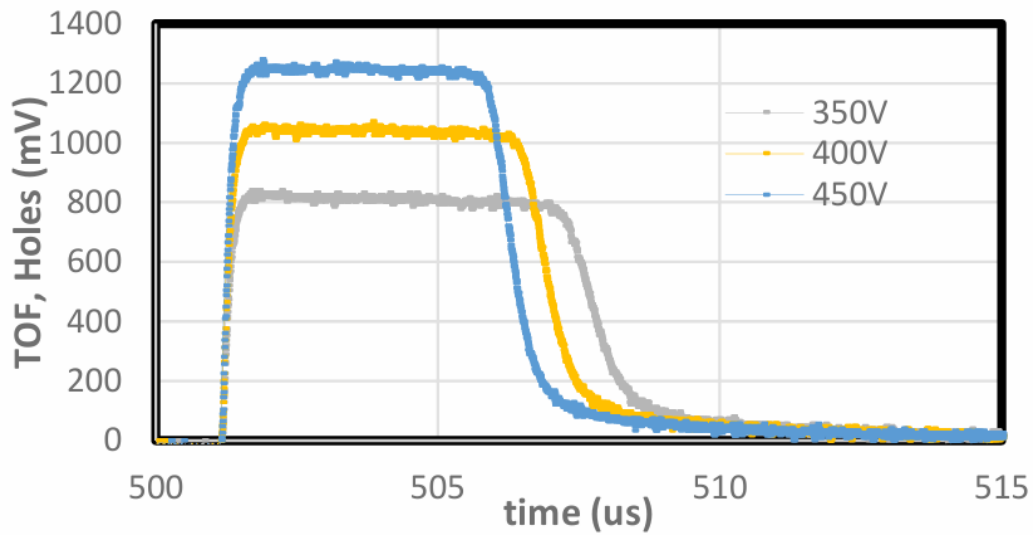


Figure 4.16 Sample 2 TOF for holes at voltages 350, 400V and 450V

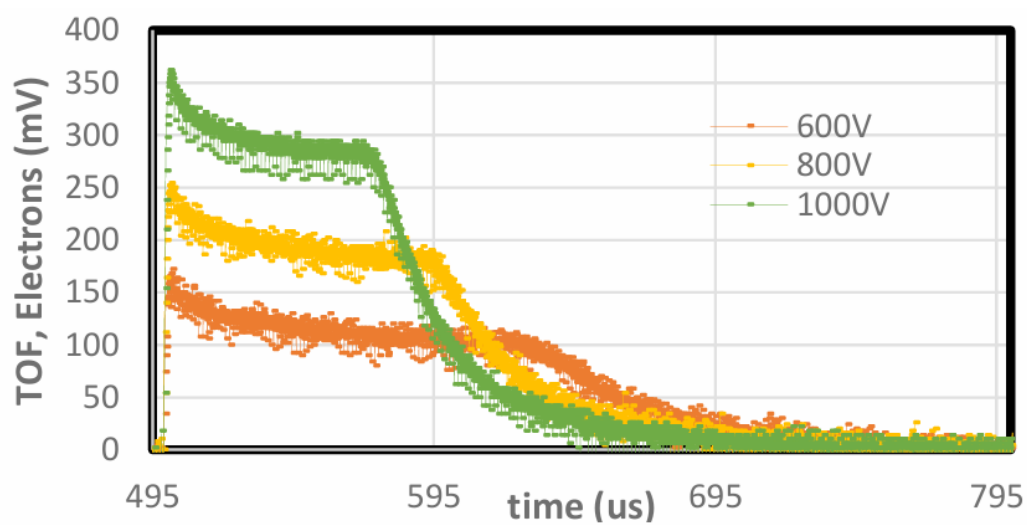


Figure 4.17 Sample 2 TOF for electrons at voltages 600V, 800V and 1000V

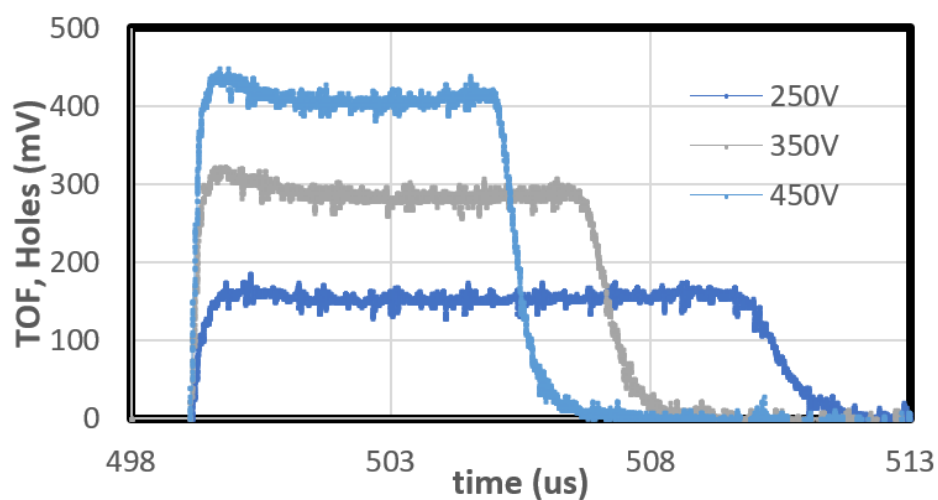


Figure 4.18 Sample 3 TOF for holes at voltages 250, 350V and 450V

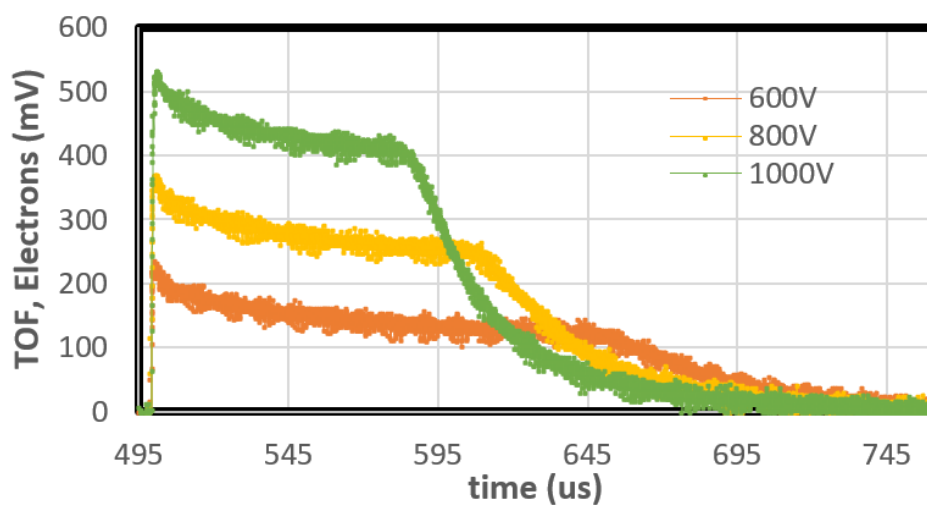


Figure 4.19 Sample 3 TOF for electrons at voltages 600V, 800V and 1000V

The electron mobility (μ_e) values for the three samples have very similar values. sample 1 had an electron mobility of $0.00347543 \text{ cm}^2/\text{V}\cdot\text{s}$ (Figure 4.15), sample 2 exhibited the lowest electron mobility at $0.00316318 \text{ cm}^2/\text{V}\cdot\text{s}$ (Figure 4.17), and sample 3 recorded a mobility of $0.00342636 \text{ cm}^2/\text{V}\cdot\text{s}$ (Figure 4.19). Sample 2 demonstrated the lowest value for charge transport. In contrast, sample 1 showed the highest electron mobility. Sample 3 had mobility value closer to that of sample 1 compared to sample 2.

4.14 Results using Interrupted Field Time-of-Flight technique

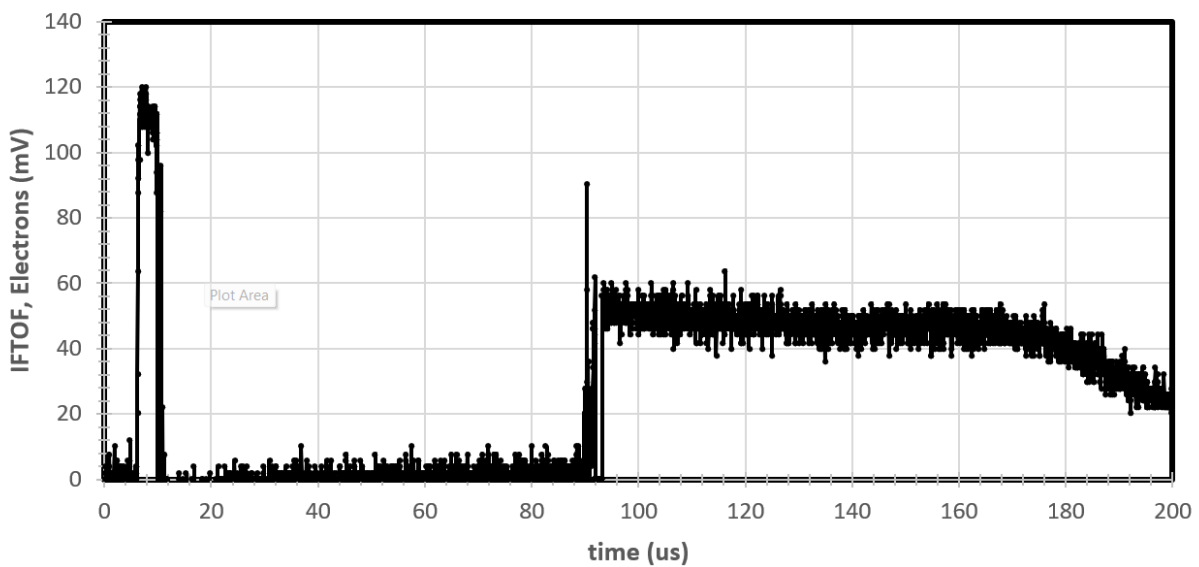


Figure 4.20 Electrons IFTOF for sample 1 of thickness 200um. The interruption time in this case was 80us with an applied voltage of 1000V.

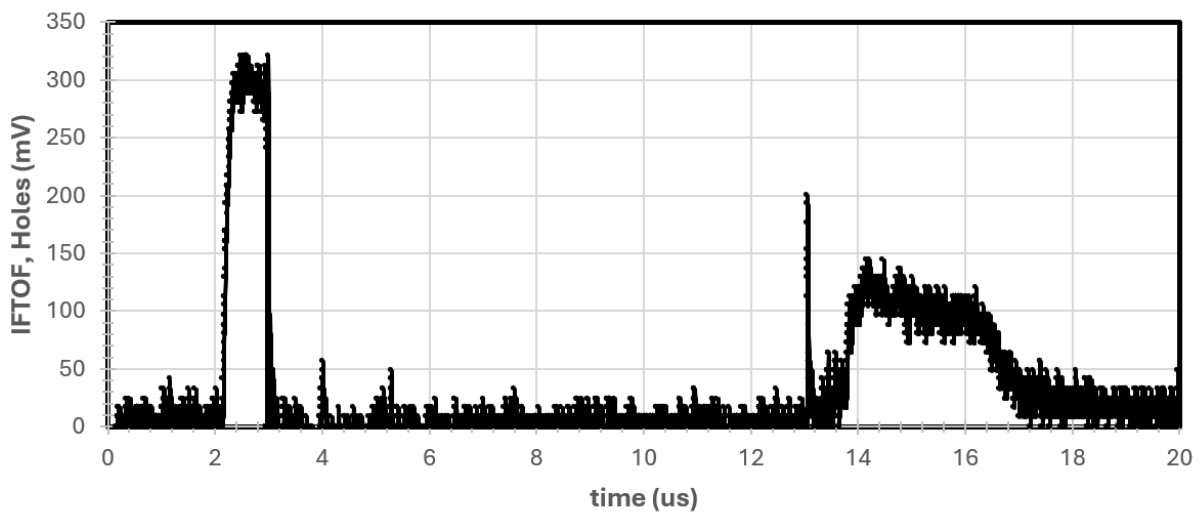


Figure 4.21 Holes IFTOF for sample 1 of thickness 200um. The interruption time in this case was 10us with an applied voltage of 700V.

Typical IFTOF waveforms for both electrons and holes are shown in Figure 4.20 and Figure 4.21. The samples used for these figures was sample 1 with a thickness of 200 μm for holes and for electrons. The interruption time in Figure 4.20 was 80 μs for electrons, and in Figure 4.21 was 10 μs for holes. The IFTOF measurements were repeated on the same sample with varying t_i in order to get different values for the fractional recovered photocurrent signal $v(t_2)/v(t_1)$. Once multiple corresponding readings were taken for the fractional recovered photocurrent signal and the interruption time t_i , the two were plotted against each other giving an exponential curve corresponding to the theoretical expression from equation (4.18). However, if this linear plot is converted to a semi-logarithmic plot, then we observe a straight line which shows the correctness of the experimental data with the theoretical values as shown in the figures below.

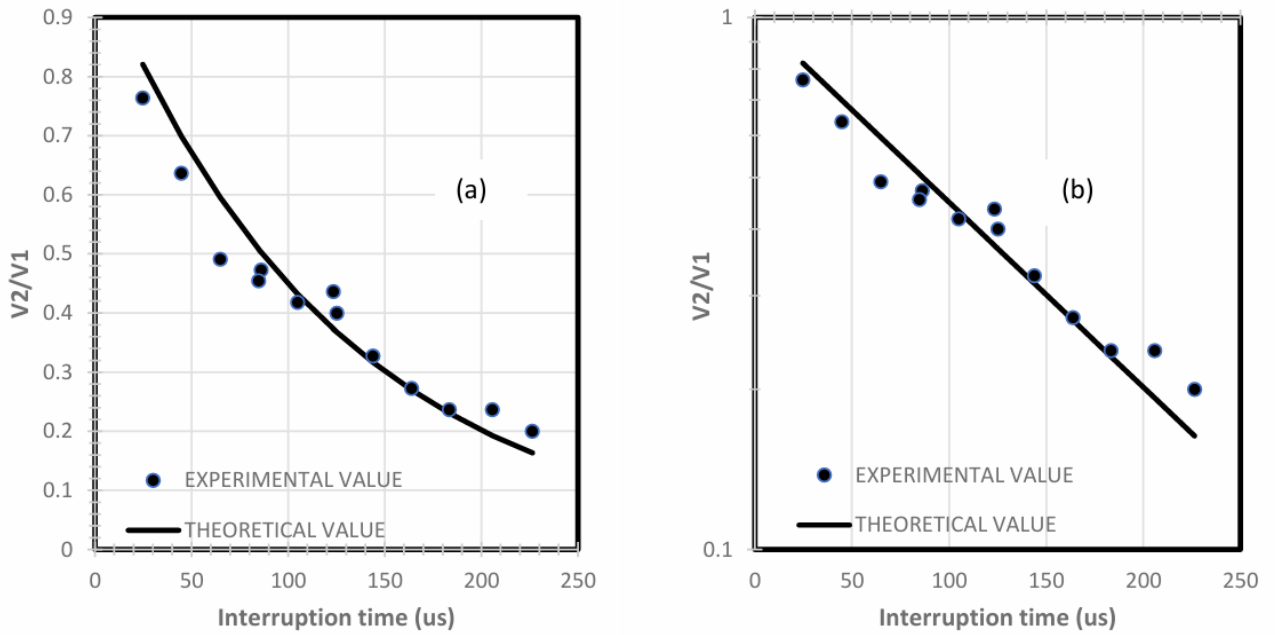


Figure 4.22 (a) Fractional recovered photocurrent signal vs the interruption time for electrons in a-se sample 1. (b) Semilogarithmic plots of fractional recovered photocurrent i_2/i_1 vs. interruption time. The electron lifetime value is 125 μs .

Figure 4.22 (a) shows the plot of the fractional recovered photocurrent signal vs the interruption time using the experimental data and compared with the theoretical value for electrons in sample 1. In case of the theoretical value, arbitrary values for the electron lifetime were taken until the best fit curve was obtained in comparison to the experimental values. In Figure 4.22 (b), the

straight line verifies the validity of equation (4.18). Figure 4.23,4.24,4.25,4.26,4.27 depict the results for the IFTOF experiment for different carriers and samples.

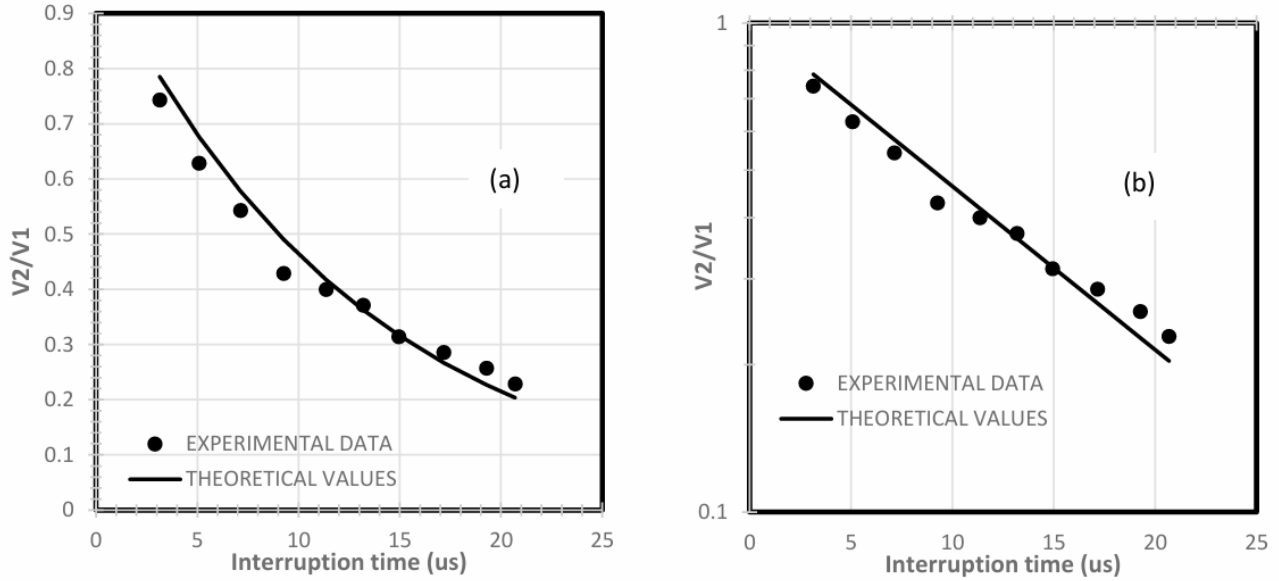


Figure 4.23 (a) Fractional recovered photocurrent signal vs the interruption time for holes in a-se sample 1. (b) Semilogarithmic plots of fractional recovered photocurrent i_2/i_1 vs. interruption time. The hole lifetime value is 13 μ s.

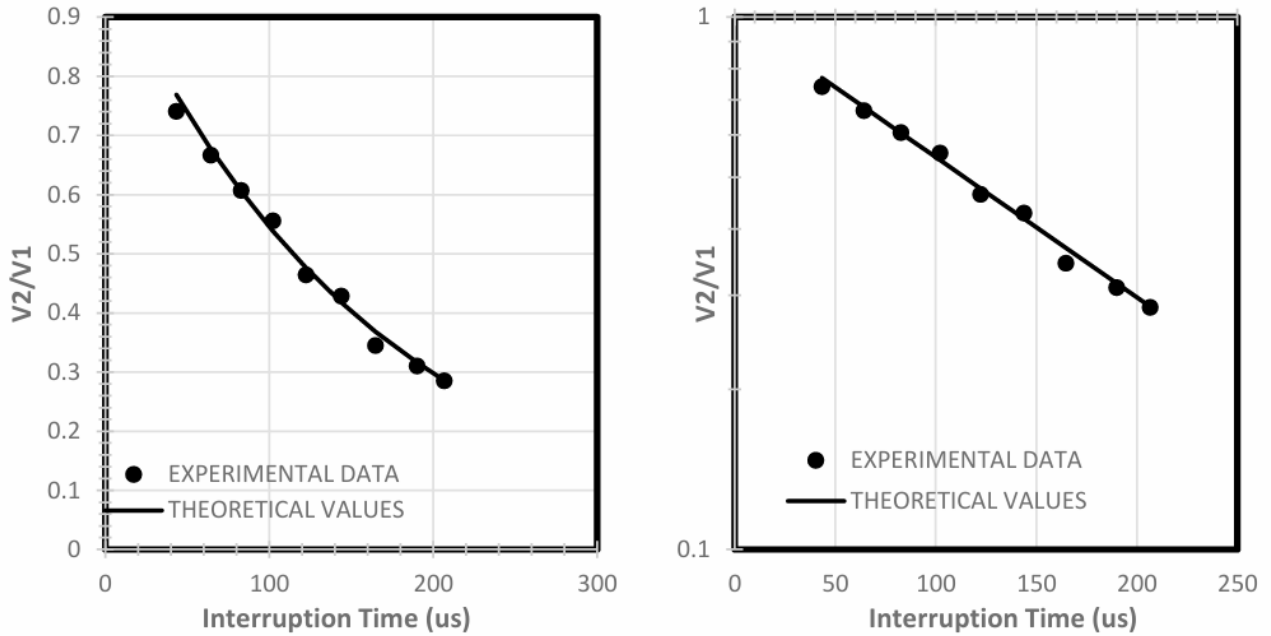


Figure 4.24 (a) Fractional recovered photocurrent signal vs the interruption time for electrons in a-se sample 2. (b) Semilogarithmic plots of fractional recovered photocurrent i_2/i_1 vs. interruption time. The electron lifetime value is 165 μ s.

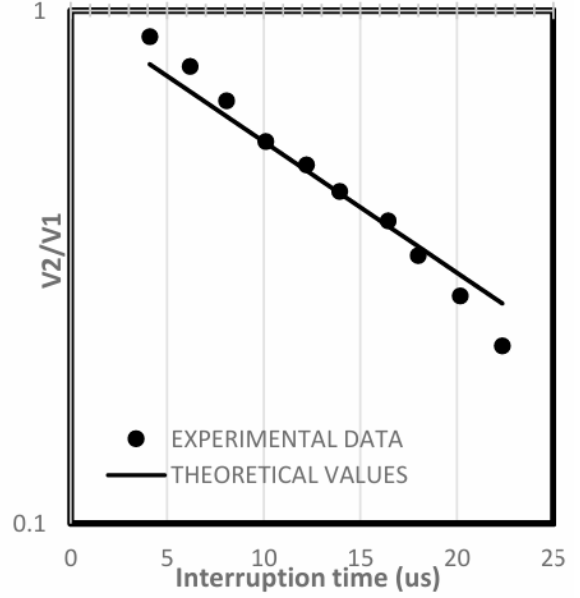
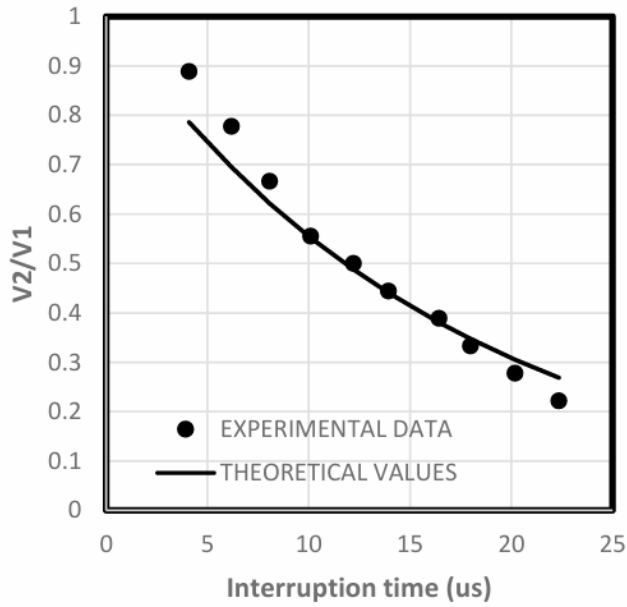


Figure 4.25 (a) Fractional recovered photocurrent signal vs the interruption time for holes in a-se sample 2. (b) Semilogarithmic plots of fractional recovered photocurrent i_2/i_1 vs. interruption time. The hole lifetime value is $17\mu\text{s}$.

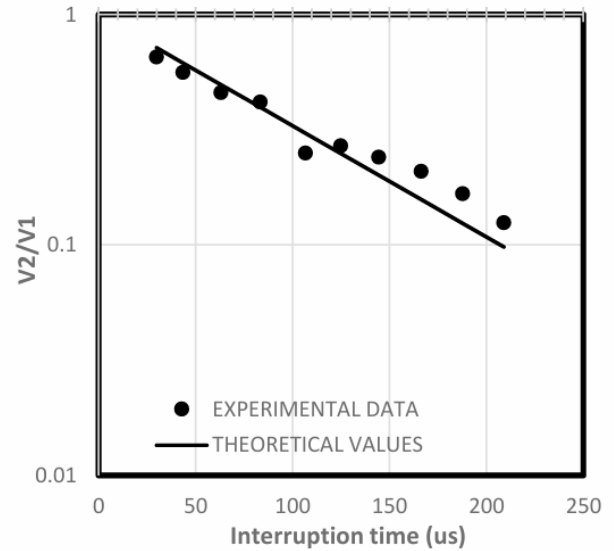
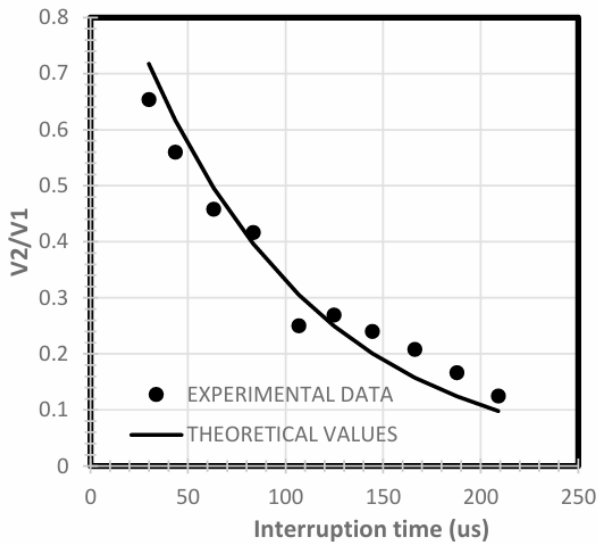


Figure 4.26 (a) Fractional recovered photocurrent signal vs the interruption time for electrons in a-se sample 3. (b) Semilogarithmic plots of fractional recovered photocurrent i_2/i_1 vs. interruption time. The electron lifetime value is $90\mu\text{s}$.

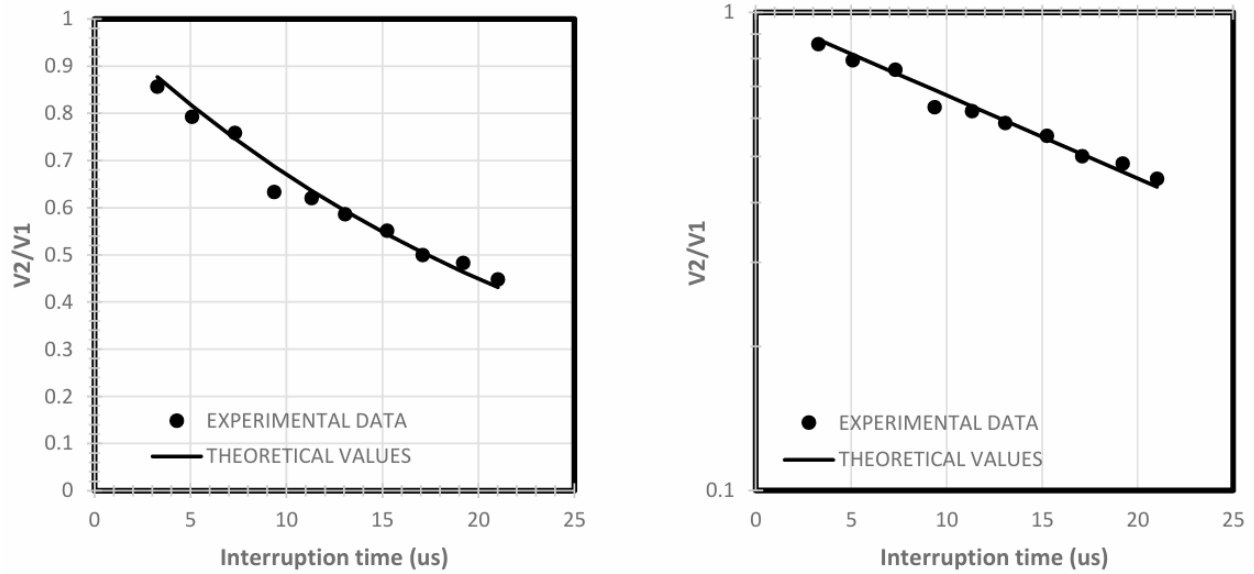


Figure 4.27 (a) Fractional recovered photocurrent signal vs the interruption time for holes in a-se sample 3. (b) Semilogarithmic plots of fractional recovered photocurrent i_2/i_1 vs. interruption time. The hole lifetime value is $25\mu\text{s}$.

4.15 Comparative Analysis and Discussion

Table 4.2 Comparison of TOF results of the three samples used to measure electron and hole mobility. Conditions fixed during the experiment are stated.

IFTOF RESULTS COMPARISON			
	τ_e (us)	τ_h (us)	Conditions fixed during experiment
Sample 1	125	13	Holes : Laser Intensity at 1.5%. Applied Bias at 700V. R1 0.742KOhms, R2 0.975KOhms. One Thick OD Filter used Electrons: Laser Intensity at 8%. Applied Bias at 1000V. R1 1.5KOhms, R2 11.96KOhms
Sample 2	165	17	Holes : Laser Intensity at 1.5%. 1 Thick OD Filter Used. R1 0.74KOhms, R2 0.9KOhms, Electrons: Laser Intensity at 8%. 1Thick <u>OD Filter</u> used. R1 1.5KOhms, R2 11.96KOhms.
Sample 3	90	25	Holes: Applied Bias at 500V. Laser Intensity at 1.5%. R1 0.742KOhms, R2 0.975KOhms. 1 Thick OD Filter. Electrons: Applied Bias at 1000V. Laser Intensity at 8%. R1 1.5KOhms, R2 11.96KOhms. 1 Thick OD Filter Used.

Table 4.3 Comparison of TOF results of the three samples used to measure electron and hole mobility. Conditions fixed during the experiment are stated.

TOF RESULTS COMPARISON			
	μ_e (cm ² /V·s)	μ_h (cm ² /V·s)	Conditions fixed during experiment
Sample 1	0.00347543	0.145493	Holes : 71.5% Laser Intensity. R1 0.9KOhms R2 0.6KOhms. 2 OD Filters Electrons: 71.5% Laser Intensity. R1 3.5KOhms R2 3.3KOhms. 2 OD Filters
Sample 2	0.00316318	0.14030221	Holes : 71.5% Laser Intensity. R1 0.9KOhms, R0.6KOhms. 2 OD Filters Electrons: 71.5% Laser Intensity. 2 OD Filters R1 3.5KOhms, R2 3.3KOhms.
Sample 3	0.00342636	0.1538982	Holes: 20% Intensity. R1 0.9KOhms R2 0.6KOhms 2 OD Filters Electrons: 20% Intensity. R1 3.5KOhms R2 3.3KOhms. 1 Thick OD Filter

The electron and hole transport properties of the three samples were analyzed based on their respective mobility and lifetime values. The data were taken while keeping certain factors fixed in order to obtain proper results. For example, as shown in Table 4.2, for sample 1, the R1 and R2 values while measuring hole mobility are much smaller compared than when measuring electron mobility for the same sample. This is because holes are much more sensitive and can be easily observed with relatively lower amplification requirements and voltage bias whereas electrons require a higher R1 and R2 value and hence, higher amplification in order to bring the signal above the noise floor. Moreover, in Table 4.3, it can be noticed that while performing IFTOF for holes and electrons, despite having the lowest laser intensity possible from the laser used, an additional OD filter was needed to further bring down the intensity to avoid interference from space charge effect.

For electron transport, sample 2 exhibited the lowest electron mobility (0.00316318 cm²/V·s) and the longest electron lifetime (165 μ s). Conversely, sample 3 had the shortest electron lifetime (90 μ s), despite having a higher electron mobility (0.00342636 cm²/V·s) compared to sample 1. Sample 1, with an electron mobility (0.00347543 cm²/V·s) closer to sample 3 and an intermediate electron lifetime (125 μ s), appears to have more limited electron transport properties compared to sample 2.

For hole transport, sample 3 demonstrated the most efficient charge conduction, with the highest hole mobility (0.1538982 cm²/V·s) and a hole lifetime of 25 μ s. sample 2, in contrast, had the lowest hole mobility (0.14030221 cm²/V·s) and a shorter hole lifetime (17 μ s), which suggests a more significant limitation in hole conduction. Interestingly, sample 1 exhibited a hole lifetime (13 μ s) lower than both sample 2 and sample 3, yet its hole mobility (0.145493 cm²/V·s) was lower than that

of sample 3. These findings can align with the effects of how arsenic and chlorine concentrations can compensate for each other, meaning an increase in hole lifetime may come at the expense of a slight reduction in hole mobility.

Chapter 5: Summary and Conclusions

5.1 Summary

In this thesis we have examined the charge transport properties in a-Se photodetectors, using Time-of-Flight and Interrupted Field Time-of-Flight experimental techniques specifically for measurement of carrier mobility and lifetime and modelling of charge collection efficiency under non-uniform electric field. The idea stems from the need to improve the efficiency of direct-conversion X-ray detectors (such as stabilized amorphous selenium and emerging perovskites) for medical and industrial imaging. Issues like trapping-induced charge loss, space-charge field distortion, and consequent image lag/ghosting can affect how charge carriers move and are collected under certain fixed conditions.

In summary, the Time-of-Flight (TOF) and Interrupted-Field Time-of-Flight (IFTOF) measurement system was developed to characterize charge transport in stabilized a-Se. This allowed reliable measurement of deep trapping lifetimes in a-Se despite the large bias voltages and transient interference inherent to IFTOF. Using this setup, electron and hole transport properties were measured for multiple a-Se samples of varying thickness. All samples had the same alloy composition. The TOF results demonstrated the expected order of magnitude disparity between hole and electron mobility in a-Se. Holes were far more mobile ($\sim 10^{-1} \text{ cm}^2/\text{V}\cdot\text{s}$) than electrons ($\sim 10^{-3} \text{ cm}^2/\text{V}\cdot\text{s}$), consistent with established literature. Meanwhile, the IFTOF results yielded corresponding carrier lifetimes in the microsecond range for both carrier types. Importantly, the variations in mobility and lifetime among the samples did not follow a clear monotonic trend with thickness. This suggests that film quality and other factors may have had a more pronounced impact on transport properties than the sample thickness alone. In fact, subtle differences observed between samples hinted at a trade-off: a sample exhibiting a higher hole mobility tended to show a shorter hole lifetime, and vice versa. This behaviour is consistent with the known effects of dopants in stabilized a-Se. For example, increasing the concentration of certain deep trapping centres can prolong carrier lifetimes at the cost of reduced drift mobility. Thus, one practical insight from the measurements is that the As/Cl doping concentrations can be tuned to favour either electron or hole transport depending on application needs. This is especially useful in direct conversion imagers, where one type of carrier often dominates the signal (holes in the case of a-Se), optimizing doping for that carrier can improve sensitivity and mitigate lag/ghosting effects.

Furthermore, we developed models for the CCE under non-uniform field conditions. the CCE in radiation detectors under non-uniform electric field deviates significantly from the well-known HCE in equation (3.12). The deviation has been quantified in terms of trapped charge ratio (r or r_{tr}), normalized attenuation depth and carrier lifetimes. Two models for the CCE estimation have been developed that lead to the same results: the first is based on carrier packet drift analysis, while the second numerically solves the continuity and Poisson equations. The space charge due to ionized dopants in the bulk photoconductor layer were considered and the trapped charges due to the photogenerated carriers in the bulk photoconductor layer were also considered. In most cases, the CCE under non-uniform electric field deteriorates from HCE. The CCE under non-uniform electric field can be improved for some normalized carrier lifetimes provided that the irradiation (photons or particles) absorption occurs mostly near the top electrode. The theoretical model has been applied to the published experimental results in perovskites X-ray detectors, and space charge concentration and carrier transport properties have been estimated. The results obtained can be used to develop a strategy to enhance the CCE under non-uniform electric field in the photoconductor layer of a radiation detector.

5.2 Future Work

Future work could focus on expanding the model beyond the planar geometry to accommodate more complex configurations and transient simulations can be implemented. Moreover, validating the TOF and IFTOF using actual X-ray exposure instead of only laser-based excitation used in this study to confirm the mobility, lifetime and even charge collection efficiency and performing these tests under different environmental factors, for example, performing measurements at different temperatures, to assess the detector's performance stability. Furthermore, exploring different materials such as CZT and by investigating them, it can provide a comparison with a-Se charge transport properties and further the scope for research.

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