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HIGH EFFICIENT PIN PHOTODIODE FABRICATION
AND
EVALUATION FOR MEDICAL APPLICATIONS

DOCTOR OF PHILOSOPHY
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ABSTRACT

HIGH EFFICIENT PIN PHOTODIODE FABRICATION AND EVALUATION FOR MEDICAL APPLICATIONS

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EMRE DOĞANCI

BOLU ABANT İZZET BAYSAL UNIVERSITY

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Today, radiation safety has become an extremely important issue. Therefore, tracking the doses of radiation that people who work in radiated environments are instantly exposed to is extremely important. While passive dose measuring devices used for this purpose are successful in measuring the dose exposure rate, reading the dose information that these devices measure is a considerable waste of time. For this reason, it is extremely important to get the dose information in the medium instantly. Semiconductor-based sensors have been studied extensively in the literature, and the results have shown that silicone-based photodiodes are very successful in instantaneous dose mortality, and Si-PIN PDs are well-designed to measure instant dose speeds. However, the architectural design of a Si-PIN PD, which is planned to be used in radiation sensing, and the knowledge of the variables necessary for the production of this structure are critical. In the literature, the radiation responses of produced Si-PIN PDs are studied, but the data shared on production is quite insufficient. In this study, the Si-PIN PD architecture was designed using Silvaco software tools. The electrical properties of the designed Si-PIN PDs have been studied using ATLAS software to obtain the most suitable original Si-PIN PD architecture for use in dosimeters. The variables of the production stages have been determined using the Silvaco ATHENA tool so that the resulting architecture can be produced in a laboratory environment. After the completion of the design, electrical tests of Si-PIN PDs were carried out, X-rays test of Si-PIN PD's were performed in ion chamber conditions. Subsequently, radiation spectroscopy from ^{204}Tl , ^{90}Sr sources was analyzed. The results show that Si-PIN PDs are promising for future use in healthcare applications.

KEYWORDS: Silicon PIN Photodiode, Fabrication, X-Ray Detection, ^{90}Sr Detection, ^{204}Tl Detection

ÖZET

YÜKSEK VERİMLİ PIN FOTO DİYOT ÜRETİLMESİ VE TIBBİ UYGULAMALAR İÇİN DEĞERLENDİRİLMESİ

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Günümüzde radyasyon güvenliği son derece önemli bir konu haline gelmiştir. Bu yüzden, radyasyonlu ortamlarda çalışan kişilerin anlık olarak maruz kaldığı radyasyon dozlarının takibi son derece önemlidir. Bu amaç için kullanılan pasif doz ölçen aygıtlar, doza maruz kalma oranını ölçme hususunda başarılı olsalar da, bu aygıtların ölçtüğü doz bilgisini okumak oldukça fazla zaman kaybına neden olmaktadır. Bu nedenden dolayı, anlık olarak ortamda bulunan doz bilgisine ulaşmak son derece önemlidir. Yarı iletken tabanlı sensörler literatürde oldukça fazla çalışılmaktadır ve elde edilen sonuçlar, silikon tabanlı fotodiyotların anlık doz ölçme hususunda oldukça başarılı sonuçlar verdiğini göstermiştir ve Si-PIN PD'ler sahip oldukları yapı sayesinde, anlık olarak doz hızlarını ölçebilme konusunda öne çıkmaktadır. Ancak, radyasyon algılamalarında kullanılması planlanan bir Si-PIN PD'nin mimari tasarımı ve bu yapının üretimi için gerekli değişkenlerin bilinmesi kritik öneme sahiptir. Literatürde, üretilen Si-PIN PD'lerin radyasyon cevapları çalışılmasına rağmen, üretim hususunda paylaşılan veriler oldukça yetersizdir. Bu çalışmada, Silvaco yazılım araçları kullanılarak, Si-PIN PD mimarisi tasarlanmıştır. Tasarımı yapılan Si-PIN PD'lerin elektriksel özellikleri ATLAS yazılımıyla incelenerek doz metrelerde kullanılabilecek en uygun özgün bir Si-PIN PD mimarisi elde edilmiştir. Elde edilen mimarinin, laboratuvar ortamında üretilmesi için Silvaco ATHENA aracı kullanılarak, üretim aşamalarının değişkenleri belirlenmiştir. Tasarımı tamamlanan, Si-PIN PD'lerin elektriksel testleri gerçekleştirildikten sonra, İyon odası koşullarında, Si-PIN PD'lerin X-ışını testleri gerçekleştirilmiştir. Daha sonra, ^{204}Tl , ^{90}Sr kaynaklarından yayılan radyasyon spektroskopisi analiz edilmiştir. Elde edilen sonuçlar, Si-PIN PD'lerin sağlık uygulamalarında kullanılabilmesi hususunda gelecek vaat ettiğini göstermiştir.

ANAHTAR KELİMELER: Silikon PIN Fotodiyot, Üretim, X-ışını Dedeksiyonu, ^{90}Sr Dedeksiyonu, ^{204}Tl Dedeksiyonu

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LIST OF ABBREVIATIONS AND SYMBOLS

CB	: Conduction Band
VB	: Valance Band
N_a	: Acceptor Concentration
SCL	: Space charge layer
n_i	: Intrinsic Carrier Concentration
N_d	: Donor Concentration
C-V	: Capacitance - Voltage
Q	: Electron Charge
C_j	: Junction Capacitance
V_{biased}	: Biased Voltage
I-V	: Current - Voltage
G_{nr}	: Non- Radiative Generation Rate
V_{th}	: Thermal Velocity
N_T	: Density of Deep State
τ_{eff}	: Effective Life Time
τ_p	: Effective Life Time of Hole
τ_n	: Effective Life Time of Electron
E_G	: Band Gap
L_n or L_p	: Distance for Electron or Hole
D_n and D_p	: Diffusion Coefficient of Electron and Holes
P_o	: Incident Optical Power
P(x)	: Optical Power Function of Distance
λ_c	: Cutoff Wavelength
R	: Spectral Response
t_{diff}	: Diffusion Time
t_d	: Duration Required for the Carriers Generated in the Depletion Region

t_R	: RC time constant
NIEL	: Non-Ionizing Energy Loss
FET	: Field Effect Transistor
Q_{pulse}	: Pulse Charge
V_{out}	: Signal Output Voltage
E	: Electric Field
MCA	: Multi Channel Analyzer
Pre-Amp	: Previous Amplifier
SCA	: Charge Sensitive Amplifier
FWHM	: Full Wave Half Maximum
I_d	: Dark Current
I_{ph}	: Photo Current
R	: Spectral Response

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1 INTRODUCTION

1.1 An Overview of Semiconductor Device

Several significant semiconductor technologies have been derived from processes that were invented centuries ago. The lithography process, which dates back to 1798, involved the initial transfer of a pattern or image from a stone plate (1). Table 1 presents a chronological listing of several significant semiconductor technologies. In the year 1918, Czochralski devised a technique for the growth of nanocomponent materials using a liquid-solid process. The Czochralski growth method is widely employed for the cultivation of a majority of crystals utilized in the production of silicon wafers (2).

Table 1. Chronological list of semiconductor devices

Year	Semiconductor Device	Inventors
1874	Metal-Semiconductor Contact invent	Braun
1907	LED	Round
1947	Invention of Bipolar transistor	Bardeen, Brattain, and Shockley
1949	Discovery of p-n junction	Shockley
1952	As a new devices Thyristor	Ebers
1954	Study about Solar Cell	Chapin, Fuller, and Pearson
1957	Heterojunction bipolar transistor	Kroemer
1958	Tunnel Diode	Esaki
1960	Field effect transistor (MOSFET)	Kahng and Atalla
1962	Discovery of Laser	Hall et al.
1963	Laser with Heterostructure	Kroemer, Alferov and Kazarinov
1963	Transferred-electron diode	Gunn
1965	IMPATT diode invention	Johnton, DeLoach, and Cohen
1966	MESFET	Mead
	Nonvolatile Semiconductor	
1967	memory	Kahng and Sze
1970	Charge-coupled device	Boyle and Smith
1974	Resonant tunnelling diode	Chang, Esaki, and Tsu
1980	MODFET invention	Mimura et al
2004	Improvement of 5 nm MOSFET	Yang et al.

The phenomenon of impurity atom diffusion in semiconductors holds significant relevance in the realm of device fabrication and processing. Fick examined the fundamental principles of diffusion and drift theory in 1855 (3,4). Pfann (1952) introduced the concept of employing diffusion techniques for modifying the conductivity characteristics of silicon in a patent document dating back to 1952. The application of photo resist on silicon oxide with lithography

process to semiconductor-device fabrication was initially introduced by Andrus in 1955 (5,6). The utilization of photosensitive etch-resistant polymers, commonly referred to as photoresist, was employed by the researcher for the purpose of pattern transfer. Lithography plays a pivotal role in the semiconductor industry. The ongoing expansion of the industry can be attributed directly to advancements in lithographic technology. Lithography plays a substantial role in the economy, accounting for more than 35% of the total cost associated with integrated-circuit production at present. The oxide masking technique was pioneered by Frosch and Derick in 1957, as documented in the provided references. It has been discovered that the presence of an oxide layer effectively inhibits the diffusion of the majority of impurity atoms(7). In the aforementioned year, Sheftal (1968) successfully developed the epitaxial growth process utilizing the chemical vapor deposition technique. Epitaxy refers to a crystal growth technique wherein a thin layer of semiconductor materials is deposited onto a crystal surface possessing an identical lattice structure to that of the crystal (8). Shockley (1958) proposed a technique involving ion implantation for the purpose of doping semiconductors(9). The process of ion implantation exhibits the inherent ability to accurately regulate the quantity of dopant atoms that are introduced into a material (10). The combined utilization of diffusion and ion implantation techniques can effectively synergize the process of impurity doping. As an illustration, the process of diffusion can be employed in high-temperature scenarios involving deep junctions, while ion implantation can be utilized in lower-temperature situations pertaining to shallow junctions (11).

A semiconductor material is a homogeneous crystalline substance that exhibits an energy band structure. In the context of an infinitely large crystal, this band structure represents a continuous range of energy states. In practical terms, this implies that the crystal's dimensions are considerably larger than its lattice parameter, typically exceeding a few dozen nanometers. Broadly speaking, the energy configuration of a semiconductor is characterized by a valence band that corresponds to states of molecular bonding, and a conduction band that represents states of molecular anti-bonding. The energy interval spanning from the upper limit of the valence band to the lower limit of the conduction band is referred to as the prohibited band, or more frequently recognized as the bandgap. An electron that is

within the valence band is typically found in its lowest energy state and is confined to a specific atom within the crystal lattice. Conversely, an electron located within the conduction band is in an excited state, where it experiences minimal interaction with the crystalline structure (12,13).

1.2 Types of Radiation Detectors

1.2.1 Passive Dosimetry Technologies

Thermoluminescence detectors (TLD) are based on the premise that the energy absorbed by a crystal is later emitted as optical radiation when the crystal is heated. TLD dosimeters are capable of quantifying low levels of radiation exposure, ranging from 100 μSv to 10 Sv. Nevertheless, once the individual wears the dosimeter for a specific duration (many weeks or months), an examination of the dosimeters is conducted to ascertain the cumulative dose received. Furthermore, intricate calibration procedures are implemented to enable the reuse of TLD dosimeters. Due to the protracted nature of dose analysis calibration, it is inadvisable for individuals to employ TLD dosimeters as personal dosimeters. Another well-known detector is optically induced luminescence (OSL) dosimetry. The fundamental principles underlying OSL. In OSL, the primary distinction is in the utilization of light photons rather than heat to extract electrons from the traps. OSL involves the excitation of luminescent materials using certain wavelengths of light. This process allows the trapped electrons inside the crystal structure to be released from their traps and generate a luminous glow at the recombination centers. The phenomenon is referred to as OSL signal, and its magnitude varies directly with the amount of radiation exposure. Unlike TLD dosimeters, OSL dosimeters do not require heating. Hence, the temperature sensitivity of the material constituting the foundation of the OSL dosimeter is insignificant, making its utilization more prevalent compared to TLD dosimeters. The OSL dosimeters, which have a dosage range of 10 μSv -10 Sv, are highly responsive to different levels of radiation exposure. Nevertheless, OSL dosimeters do not provide immediate feedback to the user, unlike TLD dosimeters. Hence, employing OSLs in personal dosimeters is not beneficial. When atomic radiation is put on film, it basically goes through a browning process. The amount of energy it gets changes its pixels, which is why this happens. When the film gets darker, it changes how much light it reflects or lets through. The changes that happen are directly related to the amount of radiation that hits the picture. Using this ratio, the film that has been through several steps

can be used to figure out the amount that was exposed. Film dosimeters that can measure doses between 100 μSv and 10 Sv can pick up on different amounts of radiation. Still, radiographic and radio chromic films are the ones that are used most often in film dosimetry. The main problem with film dosimeters is that they can be damaged by UV light and weather (14–20).

1.2.2 Active Dosimetry Technologies and Its Significands

Throughout history, the significance of radiation safety has remained paramount. The prioritization of workers' safety has been emphasized in several sectors, ranging from healthcare facilities to nuclear power stations. Therefore, it is crucial to ascertain the daily level of exposure in surroundings where radiation is present. The passive dosimeter systems discussed in the preceding chapter are extensively employed for assessing the magnitude of radiation exposure. Nevertheless, passive dosimeters do not provide real time dose information. At specific intervals, these dosimeters are retrieved from their owners and subjected to analysis. This laborious process jeopardizes the safety of individuals working in surroundings exposed to radiation (21,22).

The introduction of active personal dosimeters in the early 1990s marked the beginning of a new era in radiation detection. Unlike passive dosimeters, these devices provide the individual with direct reports of the dose information (23). Currently, the active personal dosimeters operating with the Geiger Müller Pipe (GM) gas detector are quite unusual. While GM dosimeters have relatively high sensitivity in the 50 keV to 3000 keV energy range, GM-based detectors can detect radiation at a dose of up to 10 Sv and a dose rate of 100 mSv/h (24,25).

A silicon photomultiplier (SiPM) is the current, small shape of a photomultiplier sensor. Silicon photodiodes and Geiger mode detection have been used together since 1965, and today's use includes SiPMs that hold all of the pixels. As a 'PN' solid state device, a silicon photodiode speeds up a photon that comes from a scintillator crystal to make an electrical output through an avalanche of electrons. SiPM is made up of separate parts that are each dozens of micrometers across. When there are of photodiodes in 1000 mm² (APDs), they can cover a large area. APDs in a SiPM all work in Geiger mode and are linked together with a shutdown resistance. The device works in Geiger mode, but SiPM is an analog

device because all micro cells are read in parallel, and signals can be made for an area of one square millimeter that ranges from a single photon to up to 1000 photons (26,27).

Si-PM-based detectors can detect dosage ranges between 0.1 μSv and 10 Sv and radiation in the energy range of 20 keV to 2000 keV when used with a scintillator is today's most important technology (28,29). However, while Si-PM is efficient, the fabrication stages are quite costly due to their complex architectures.

Silicon pin photodiodes, which can instantly measure ionized radiation, are in the literature. These photodiodes, thanks to their architecture, are able to operate under high voltage and are very successful in detecting ionized radiation. Thus, with a simpler architecture compared to Si-PM, Silicon PIN photodiodes are much easier to manufacture, at a lower cost, and are the best alternative to SI-PMs (30–32).

1.3 Silicon PIN Photodiode Usage for Radiation Applications

For photodiode detectors, the new p-type, intrinsic region, n-type (PIN) arrangement has been used. In a photodiode, an intrinsic area with a high resistivity makes the depletion region wider without causing reverse voltage, which lowers the capacitance. Also, the PIN photodiode goes into full depletion mode when the reverse voltage is low, which means it has little power to work (33,34). For many years, different semiconductor materials like Silicon (Si), Indium Gallium Arsenide (InGaAs), and Germanium (Ge) have been used to make PIN photodiodes with different physical arrangements. The materials used have a direct effect on how the PIN light diode works and how it looks. III-V materials like Gallium Arsenide and Indium Gallium Arsenide are often chosen for longwave electronics uses like radar and transmission systems. However, Silicon is the best material for a radiation detector because it is cheap, has a band structure, has a long carrier lifetime, and can sense a wide range of frequencies. Also, it's easy to grow a good layer of silicon dioxide on top of silicon (35–37). A lot of study has been done on how to stop the leakage current that makes the PIN photodiode not work in a straight line. This current was cut down a lot with a flat structure and silicon dioxide passivation (38,39). It was also found that a floating guard ring could cut down on leakage current (40). To improve the efficiency of PIN photodiodes, fabrication techniques like thermal deposition, ion implantation, and different dopant concentrations were

also used. The capacitance was lowered to the pico-farad level. This is how the fast detection reaction was made possible (41). Quantum efficiency is another important factor for PIN photodiode. This is affected by many things, such as the band gap, the thickness of the p-type dopant, and the intrinsic region and n-type dopant. The spectral range of Silicon PIN photodiodes was found to be between 190 nm and 1100 nm, and the near-infrared region has the highest quantum efficiency (42,43). Because of these advances in the PIN photodiode, important findings have been made in the areas of energy physics, radiation sensors, personal dosimeters, diagnostic radiology, and digital picture use. This makes PIN photodiodes more appealing to businesses (44,45).

A short explanation of the Silicon PIN photodiode is that it creates pairs of electrons and holes in the depletion region when radiation hits the active area of the photodiode. These carriers move in the opposite direction along the depletion region's electric field and make up an electric current. This current may change depending on the conditions outside and differences in the structure (33).

The sensitivity of silicone PIN photo diodes to radiation has attracted the attention of many researchers, and the performance of silicon PIN photo diode under X-rays has been studied in literature. The results showed that silicone pin photodiodes have a linear response and are suitable for dosimeter applications (30,46). In radio tests using ^{55}F and ^{109}Cd radiation sources, the Silicon PIN photodiode was found to be sensitive to the X-rays emitted from these sources (47). Roseli Künzel (2004) conducts spectroscopic analysis on X-rays generated by a mammography apparatus. He corrected the findings using the CdZnTe detector and demonstrated that the silicon photodiode could be used for mammographic X-ray detection (48).

Moloi (2009) conducted a study on the Si-PIN photodiode they manufactured, examining its performance under varying neutron currents. The following describes the present characteristics of the Si-PIN photodiode when it is subjected to both forward and reverse biasing. In addition, he examined the behavior of capacitors in relation to voltage. The Si-PIN photodiode structure remained intact despite exposure to radiation (49).

Extensive research has been conducted on silicone PIN photodiodes in gamma-ray experiments up to this point. The Silicon PIN photo diodes were incapable of solely detecting gamma rays. Thus, the detection of gamma rays by Si-PIN photodiodes necessitates the use of a scintillator. La(Br) and Csl(Tl) scintillators have demonstrated high efficacy in gamma ray detection when paired with silicone-based PIN photodiodes (50,51). However, Silicon PIN photodiodes have yielded highly successful results in detecting beta particles without the use of scintillator materials (52,53).

In this study, Si-PIN PDs for medical applications were designed and simulated fabrication steps by using TCAD software. Designed Si-PIN PDs with different active areas were fabricated and evaluated electrically and radiologically.

2 AIM AND SCOPE OF THE STUDY

Passive sensor technologies are now employed as dosimeters effectively measures radiation. However, dose information can only be acquired by analyzing these dosimeter devices in a laboratory setting at specific intervals. This scenario presents a significant hazard in areas exposed to radiation. To minimize these risks, it is necessary to develop novel technology product dosimeter systems that have the capability to promptly notify the user. A highly recommended substitute for these systems is Si-PIN PD.

The objective of this study is to design the Si-PIN PDs with three different sensitive areas using the Silvaco ATLAS and ATHENA software, to evaluated the performance of these devices following the fabrication. The dimensions of the PDs were selected as 10x10 mm², 12x12 mm², and 20x20 mm², respectively. The spectral responses of the Si-PIN photodiodes were analyzed and electrical properties were investigated with Silvaco software. The lithographic masks for Si-PIN PDs with optimal electrical characteristics for medical applications were designed. The results obtained from the fabricated Si-PIN PDs were compared with the outcomes of a simulation analysis of the Si-PIN PDs. Following the completion of the electrical tests, the Si-PIN PDs underwent X-ray testing. The obtained spectra for the ⁹⁰Sr and ²⁰⁴Tl radiation sources from the Si-PIN photodiodes was analyzed.

2.1 Semiconductors Basics as Detector

Today, radiation detectors play an important role in preventing the harmful effects of radiation. Gas based detection systems are widely used. When radiation traverses a gas, it has the ability to ionize the gas molecules, as long as the energy it carries exceeds the ionization potential of the gas. The created pairs can be induced to travel in opposing directions with the application of an external electric field. The outcome is an electrical pulse that can be quantified by a corresponding measuring apparatus. Gas-filled detectors have been constructed using this particular approach. Typical components of a gas-filled detector of the traditional kind include a gas enclosure, positive and negative electrodes, and a gas-filled chamber. The electrodes are subjected to a significant disparity in the electrical potential; this disparity can range from less than one hundred volts to several thousand volts, depending on the design and operational mode of the detector. An electrical pulse is produced at the electrodes as a result of a disturbance in the externally applied electric field generated by the creation of charge pairs, which is triggered by the interaction between radiation and the gas. Following this, an examination of the resultant charge, current, or voltage at one of the electrodes, in combination with adequate calibration, offers substantial insights into the energy and/or intensity of the particle beam. Despite the considerable usefulness exhibited by these systems in various applications, their usage remains limited due to several factors. The production of a restricted number of electron-ion pairs in a gas medium poses a notable obstacle for high-resolution systems functioning under conditions of minimal radiation. The inefficiency observed in this context can be ascribed to the high concentration of target atoms per unit volume in the gas subjected to the incident radiation. This suggests that the utilization of liquids or solids, as opposed to other substances, would likely result in a higher likelihood of charge pair generation. Nevertheless, it is evident that the process of charge pair creation is influenced by a multitude of parameters, extending beyond the only consideration of density. Nevertheless, one sort of solid has been shown to have considerably superior charge pair generation capabilities than gases. Semiconductors exhibit electrical conduction characteristics that lie between those of conductors and insulators. Diamond is a solid material that has been discovered to possess exceptional capabilities in charge pair creation. The category of detectors utilizing solid materials as their active sensing media is commonly referred to as solid state

detectors, a designation that is occasionally limited to semiconductor detectors (54–56).

Semiconductors are crystalline solids characterized by the presence of covalent bonds that hold atoms together. Semiconductors are given this designation due to their electrical conduction characteristics, which are situated between those of insulators and conductors. Germanium and Silicon are widely employed as semiconductor materials in various applications. Silicon has been the predominant material used in the fabrication of semiconductor detectors (57).

Thanks to quantum physics, we are aware that an atom's electrons can only occupy specific energy levels. Discreteness or quantization is actually not restricted to solitary atoms in any way. For instance, the covalent interaction between atoms in semiconductors leads to the creation of distinct energy levels that are permissible. However, the valence band and conduction band, commonly known as the two bands, serve the purpose of categorizing these energy levels collectively. In contrast to the conduction band, which encompasses energy levels at higher energies, the valence band exhibits a significant quantity of closely spaced energy levels at lower energies. The energy level diagram is characterized by the presence of a forbidden gap, which serves as a demarcation between the two bands. Essentially, electrons are not permitted to acquire any energy within this particular energy band. Later in our study, we will discover that this statement holds true solely for ideal semiconductors that are completely free from any impurities. However, it is important to note that every actual semiconductor possesses at least one energy level within the band gap. The electrons in the valence band exhibit strong bonding with their respective atoms, necessitating a minimum energy equivalent to the band gap for them to undergo a transition to the conduction band. In contrast, the electrons in the conduction band are essentially free to roam about and are just very loosely coupled. These electrons participate in the conduction of electricity. In the ground state of an ideal semiconductor, the conduction band would be empty and the valence band would be fully populated with electrons (58,59).

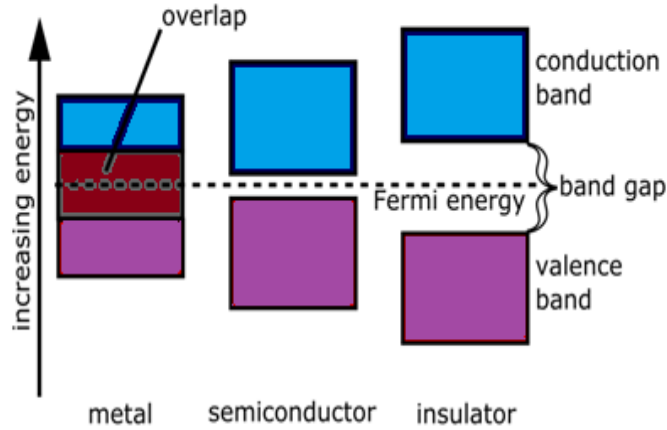


Figure 2.1 Energy band diagram of materials

An electron transfers a net positive charge from the valence band to the conduction band. A hole is an effective positive charge that participates in electrical conduction and behaves like a genuine particle. It should be highlighted, nevertheless, that when we refer to a hole moving, we imply the transfer of a net positive charge from one location to another as a result of an electron moving. It is incorrect to think of a hole as a defined mass, localized positive charge (60).

2.2 Intrinsic Materials

An intrinsic semiconductor refers to a semiconductor crystal that possesses an ideal state, devoid of any impurities or lattice defects. At absolute zero temperature (0 K), the absence of charge carriers may be observed in this particular material. This is due to the fact that the valence band is occupied by electrons, while the conduction band remains unoccupied. At higher temperatures electron-hole pairs are created as valence band electrons are stimulated thermally over the band gap to the conduction band. The only charge carriers present in intrinsic material are the electron-hole pairs (EHPs).

The process of generating EHPs can be qualitatively understood by examining the rupture of covalent bonds inside the crystal lattice (Figure 2.2). When a valence electron of silicon is dislodged from its location within the bonding structure, it acquires mobility within the lattice, thereby generating a conduction electron and leaving behind a vacant bond (hole). The energy necessary for bond dissociation is represented by the band gap energy, denoted as E_g . This model facilitates the visualization of the physical mechanism underlying the production of

EHPs. However, for the purpose of quantitative calculations, the energy band model proves to be more effective. A significant challenge encountered in the "broken bond" paradigm is to the apparent localization of the free electron and the hole inside the lattice, which can be misleading. In reality, the spatial distribution of the free electron and the hole extends across many lattice spacings, necessitating their treatment within the framework of quantum mechanics through the utilization of probability distributions (57,61).

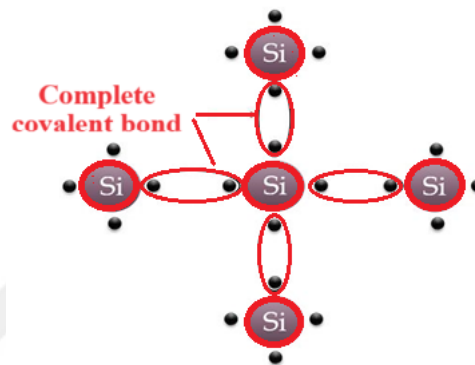


Figure 2.2. Intrinsic semiconductor material

2.3 Extrinsic Material

In conjunction with the thermally generated intrinsic carriers, it is feasible to deliberately introduce impurities into the semiconductor crystal to generate carriers. The technique known as doping is often employed to modulate the conductivity of semiconductors. The introduction of impurities into a crystal lattice, commonly known as doping, can induce a significant shift in the population of charge carriers, resulting in a pronounced prevalence of either electrons or holes. Consequently, two distinct categories of doped semiconductors exist, namely n-type semiconductors, which are primarily characterized by an abundance of electrons, and p-type semiconductors, which are predominantly characterized by an abundance of holes.

When a crystal is intentionally doped to alter the equilibrium carrier concentrations n_n and p_0 , deviating from the intrinsic carrier concentration n_i , the material is classified as extrinsic. The introduction of impurities or lattice defects into a crystal that is otherwise considered perfect results in the creation of new energy levels within the band structure. These levels typically emerge within the band gap. As an illustration, the inclusion of an impurity originating from column

V of the periodic table (namely, P, As, and Sb) results in the introduction of an energy level that is in close proximity to the conduction band in the materials Ge or Si (Figure 2.3). At a temperature of absolute zero, the conduction band of this level is occupied by a significant number of electrons, and the amount of thermal energy needed to stimulate these electrons to transition to a higher energy state is minimal (13).

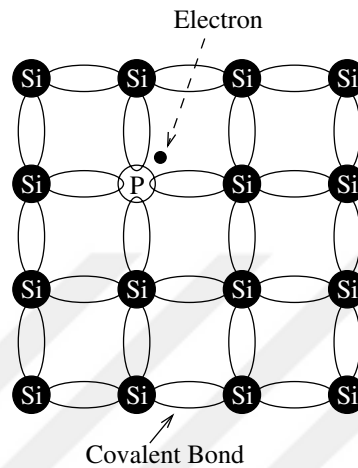


Figure 2.3. Adding impurity on silicon lattice (13)

If the additional element has a lower electron count compared to the semiconductor, it has the potential to either form a bond that is one less than the atoms of the semiconductor, or it may obtain an electron from the semiconductor lattice to achieve structural compatibility. In every situation, a surplus of vacancies or holes is created. When a significant quantity of impurity atoms is introduced, there is an increase in the number of holes relative to the quantity of free electrons present in the valence band. Interestingly enough, if an external electric field is now given to the material, these holes start floating and generate an electric current. A semiconductor material that contains an acceptor impurity is commonly referred to as a p-type semiconductor. The introduction of acceptor impurities has the overall consequence of causing the Fermi level to move closer to the valence band. This implies that the presence of unbound positive charges inside the material's bulk is greater in comparison to the negative charges. Boron is a prevalent illustration of an acceptor impurity capable of inducing p-type conductivity in silicon. Figure 2.4 illustrates the impact of doping on a conventional silicon lattice.

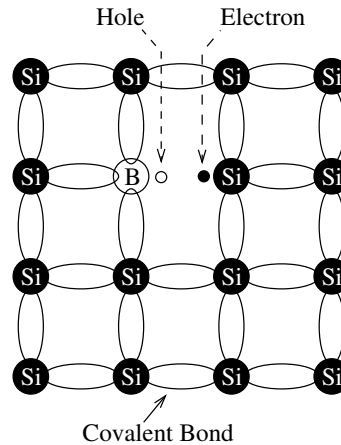


Figure 2.4. Adding Boron in Silicon lattice (13)

In the semiconductor lattice, a silicon atom forms covalent connections with four surrounding silicon atoms, utilizing its four valence electrons. When a boron atom, which possesses three valence electrons, is introduced into the lattice, it endeavors to integrate itself into the existing structure. However, due to its deficit of one electron, it is only capable of forming three covalent bonds with silicon atoms. The fourth site can be considered to possess a positive hole due to its significant attraction for attracting a free electron. In point of fact, the hole is essentially relocated to its original position when a free electron in the lattice fills the vacancy. This occurs when the void is occupied by the free electron. Because an inherent silicon lattice contains only a small number of free electrons, the addition of a relatively small quantity of boron atoms within the lattice's bulk can greatly enhance the abundance of p-type charges, so changing the material into a p-type semiconductor. This is because the presence of free electrons in an inherent silicon lattice is extremely rare (58).

2.4 Basic Structure of PN Junction Diode

Figure 2.5 (a) shows the n and p-types of the Si. There is a sharp break between the p and n regions. This is the metallurgical junction, M. In the n-region, there are fixed ionized donors and free electrons (in the conduction band, CB). In the p-region, there are fixed ionized acceptors and holes (in the valence band, VB). Because there is a difference in the number of holes from the p-side (where $p = p_{p0}$) to the n-side (where $p = p_{n0}$), the holes move to the right, enter the n-region, and join up with the electrons (majority carriers) (57,61–63).

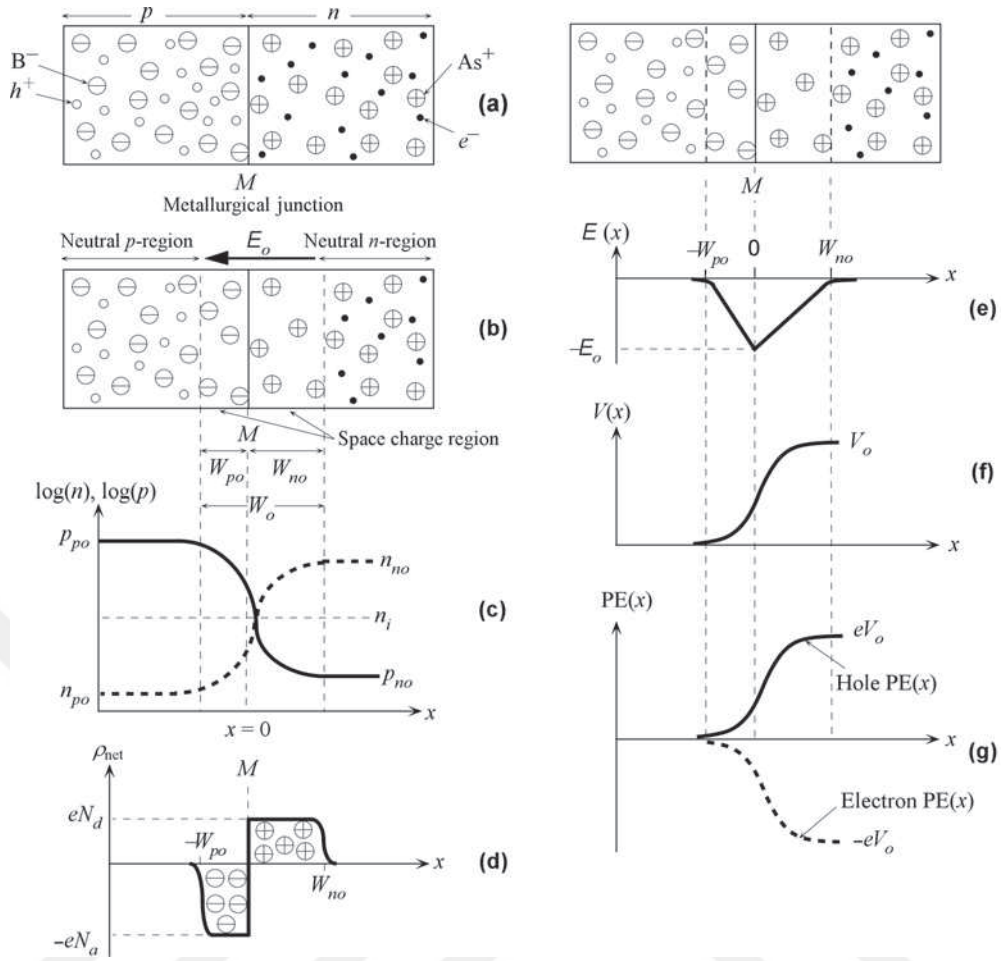


Figure 2.5. a) PN junction b) p and n side before creatin contact c) Carrier concentration d) Net charge space density e) Electric field in pn junction f) Potential changes in pn junction g) Hole and electron potential representation (62)

Consequently, the region on the n side adjacent to the junction experiences a depletion of majority carriers, leading to an exposure to positively charged donor ions at a concentration of N_a . In a similar vein, the presence of an electron concentration gradient facilitates the movement of electrons through diffusion towards the left. The regions next to the junction point, M, exhibit a deficiency of free carriers in comparison to the p and n regions of the cluster that are situated at a greater distance from the junction. Consequently, the formation of a space charge layer (SCL) occurs surrounding M. SCL is also called as depletion region that is depicted in Figure 2.5b. The profiles of hole and electron concentrations are depicted using a logarithmic vertical concentration scale (Figure 2.5c). This valid under equilibrium conditions. Namely, there is no bias and photo excitation. Concentration can be expressed (Equation 1) (57,63).

$$pn = n_i^2 \quad (1)$$

Where n_i is intrinsic carrier concentration, p is p type concentration and n is n type concentration. In equilibrium conditions, it is same in everywhere. When, the depletion region is expanded.

$$-x = W_{p0} \quad x = W_{n0} \quad (2)$$

Total depletion region width can be expressed with Equation 3,

$$W_T = W_{p0} + W_{n0} \quad (3)$$

Where, W_T , W_{p0} , and W_{n0} are total depletion width, p region width and n region width, respectively.

Obviously, from positive ions to negative ions, i.e., in the -x direction, the internal electrical field E_0 is trying to redirect the holes to the p region and the electrons to the n region. Evidently, an increasing number of vacancies exhibit a rightward trajectory, concomitantly with the dispersion of electrons towards the left, while the internal volume surrounding M expands until an equilibrium state is ultimately attained. The equilibrium between the lateral diffusion of holes and their rotational motion to the right, which is influenced by the electric field in the E_0 region, is maintained. The distribution and flow of electrons will also exhibit equilibrium. The net space charge density within the semiconductor's diameter, denoted as $\rho_{net}(x)$ in Figure 2.5d remains the same for p- and n- zones with equal doping. In order to maintain overall charge neutrality, it is necessary for the total charge on the left side to be equal to the total charge on the right side Equation (4):

$$N_a W_{p0} = N_d W_{n0} \quad (4)$$

If, acceptor concentration is larger than donor concentration $N_a > N_d$, $W_{n0} > W_{p0}$ indicates that the extinction region is more n-soft by p-softer dope. In fact, in the case of $N_a \gg N_d$, the extinction part is located almost entirely next to n. The electric field $E(x)$ in Figure (2.5e) is related to space charge density. We can now find the electric field by integrating $\rho_{net}(x)$ across the device. As the electric field across the pn junction changes, the negative field denotes a vector quantity oriented in the

negative x-axis direction. It should be noted that the magnitude of $E(x)$ reaches its maximum value, denoted as E_0 , at the point M.

The determination of the potential $V(x)$ at any given point x involves the integration of the electric field, as it is defined by the Equation 5:

$$E = -\frac{dV}{dx} \quad (5)$$

Setting the potential on the p-side at a distant location from M (Figure 2.5e) as the reference point of zero, while applied voltage is zero. It should be noted that on the n-side, the potential attains a value denoted as V_o , commonly referred to as the built-in potential. The behavior of an abrupt pn junction $\rho_{\text{net}}(x)$ can be approximately characterized using step functions, as depicted in Figure 2.5 d. By employing the step form of $\rho_{\text{net}}(x)$ as depicted in (Figure 2.5d) and performing integration, the values of the electric field E_0 and the built-in potential V_o can be determined with Equation 6 and Equation 7 (64).

$$V_o = -\frac{1}{2} E_0 W_0 = -\frac{eN_a N_d W_0^2}{2\varepsilon(N_a + N_d)} \quad (6)$$

2.4.1 Operation Mode of PN Diode with External Voltage

PN-diodes can operate in two distinct modes, namely the photovoltaic mode and the photoconductive mode. Semiconductor detectors predominantly function in photovoltaic mode; however, it is both feasible and pragmatic to fabricate a detector that operates in a theoretically photovoltaic mode. The two operation modes are explicated in the present parts. Nevertheless, due to the limited practicality of photovoltaic mode in radiation detectors, we will not allocate significant attention to its discussion.

2.4.2 Photovoltaic Mode

In order to almost completely stop current flow through the circuit, a very high load resistance is provided along the connecting point in this mode. This results in a potential difference throughout the diode. The incoming radiation produces pairs of electron holes moving in opposite directions within the extinction zone, under the influence of the connective potential. We can say this a reverse current due to radiation. As a result of this load flow, there is a decrease in the connection barrier, which initiates another current, but this time the current will be in the

opposite direction of the current. There is relatively little current flowing through the circuit because the diode is essentially linked to an open circuit (extremely high load resistance). This means that The reverse current must balance the forward current, or the potential difference along the diode must change as a result of the reversal current's alteration of the energy barrier. Subsequently, this voltage can be quantified using a very responsive apparatus. This operating mode does not necessitate the pre-voltage of the connecting point by an external source.. The good thing about this operation mode is that there is basically no leaking current along the connection point, and therefore its noise is extremely low. Noise, however, is not the only important factor to be taken into account in order to create a perception. For radiation detection reasons, this mode is not good because of things like the thin depletion area and the non-linear response. This mode's biggest problem is that the output voltage isn't a straight-line function of the stored energy. This makes it hard to use the detector for spectroscopic tasks. As was already said, these are the reasons why this method of action is not used to find radiation. Most solar cells are made in the photovoltaic form. (13,65).

2.4.3 Photoconductive Mode

Typically, radiation detectors are operated in this particular mode. A significant reverse voltage is applied across the diode, resulting in the formation of a substantial depletion region at the junction. The passage of radiation through the extinction region results in the generation of electron-hole pairs along its path. The aforementioned loads exhibit opposing movements and generate a quantifiable electric current. The quantity of load pairs produced by incident radiation is contingent upon the cumulative energy, thereby establishing a direct relationship between the measured current and the energy conveyed by the radiation.

2.4.3.1 Forward Biased

As shown in Figure 2.6, when the pn connection is forward biased, the size of the barrier potential decreases. Thus, transmission band electrons on the n side and valence bond holes on the p side are allowed to spread along the connection. Once confronted, they significantly increase their minority carrier concentrations, and the excess carrier then reconnects with the reverse loaded majority carriers. Recombination of excess minority carriers is the mechanism by which optical radiation is produced.

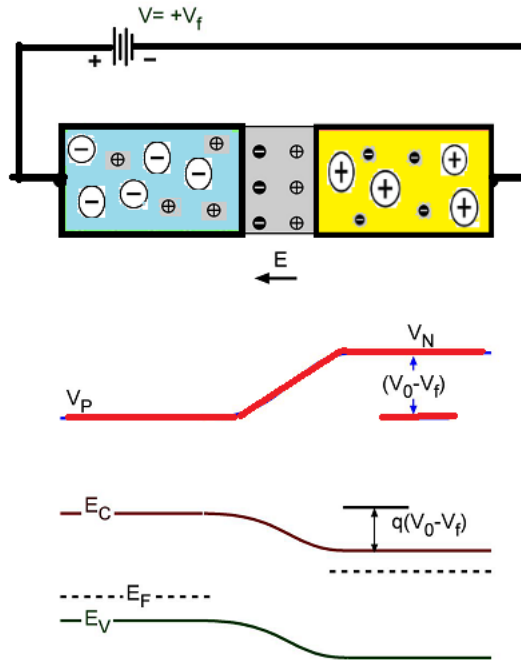


Figure 2.6. Schematic representation of forward biased pn junction and its band diagram

In an forward biased pn junction, radiation detectors are not used in applications because the depletion area is narrowed (66).

2.4.3.2 Reverse Biased

Typically, radiation detectors are run in this particular mode. A significant reverse bias is employed across the diode, resulting in the formation of a substantial depletion region at the junction. The passage of radiation through the extinction region results in the generation of electron-hole pairs along its path (Figure 2.7).

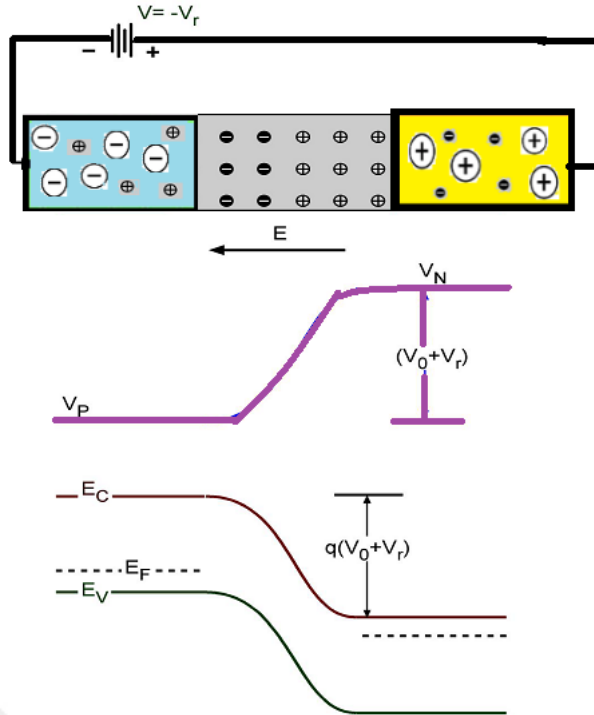


Figure 2.7. Schematic representation of reversed biased pn junction and its band diagram

The aforementioned charges exhibit opposing movements, resulting in the generation of a quantifiable electric current. The quantity of charge pairs produced by incident radiation is contingent upon the amount of stored energy, thereby establishing a proportional relationship between the measured current and the energy conveyed by the radiation. The reverse prediction of pn-ventricles offers three primary advantages in the context of radiation detection.

- Enhance the spatial extent of the depletion region.
- Enhance the signal-to-noise ratio.
- Capacitance decreases

Charge pairs are not exclusively generated by incident radiation within the depletion zone. Indeed, the likelihood of generating an electron-hole pair remains constant, irrespective of whether the region is depleted or not. One advantage of the depletion zone is its limited presence of free-load pairs. Consequently, the absence of such pairs within this zone results in reduced leakage flows originating from its

internal components (67,68). This phenomenon will be discussed in current-voltage characterization part.

2.5 Advantage of P-I-N Structure Compared to PN Structure

Semiconductor p-n structures (Figure 2.8) have the potential to be utilized for radiation detection. Although a basic pn junction diode can serve as a radiation detector, it is important to acknowledge that this approach is with its limitations. One of these limitations is the limited depletion region, charge pairs are generated in all materials, but the ones produced within the depletion zone exhibit the ability to generate a quantifiable current. Hence, it is recommended that the extent of the depletion region be maximized in order to facilitate the efficient absorption and retention of radiation energy. The ability to increase voltage to exceedingly high levels may be limited by the potential risk of crystal structure degradation. Hence, in the case of a basic pn-junction, the extent of the depletion region cannot surpass the threshold determined by the breakdown voltage of the crystal lattice. One potential approach to address this issue involves employing a material with a sufficiently low thickness to ensure its complete depletion under moderate voltage conditions. Indeed, this practice is typically employed in detectors composed of semiconductor materials with a thickness ranging from 100 to 300 μm . Second one is high capacitance, Because the capacitance goes down as the width of the depletion region increases, simple pn diodes that work at moderate voltages have high capacitances. If you want to use the junction as a detector, this effect is definitely not what you want. Third one is slow response, PN detectors are utilized in a state of complete depletion. However, it is important to note that this approach is only feasible with detectors of minimal thickness. As previously demonstrated, the application of a substantial potential across the junction is necessary to expand the depletion region. The generation of electron-hole pairs within the non-depleted region poses a significant challenge for thicker detectors that are unable to achieve full depletion. The nonlinearity of the detector's response is not the sole consequence of this phenomenon, as it also engenders a deceleration in the detector's performance due to the disparate movement of charges across distinct regions (69,70).

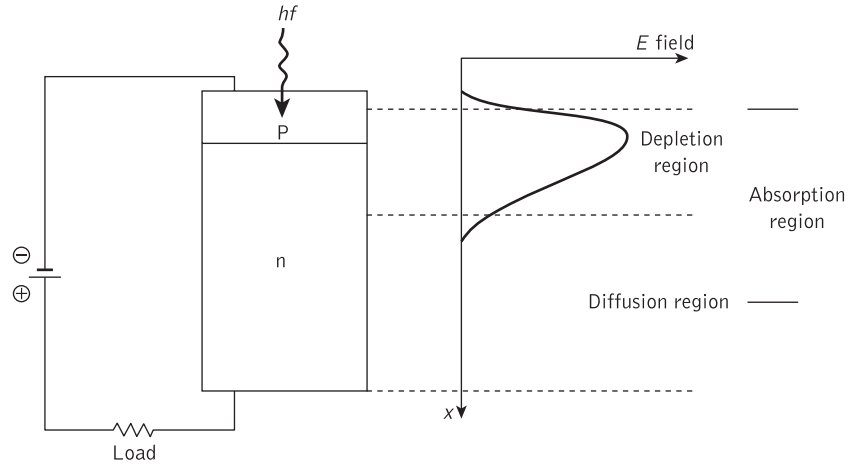


Figure 2.8. Depletion and absorption regions schematic representation of PN photodiode

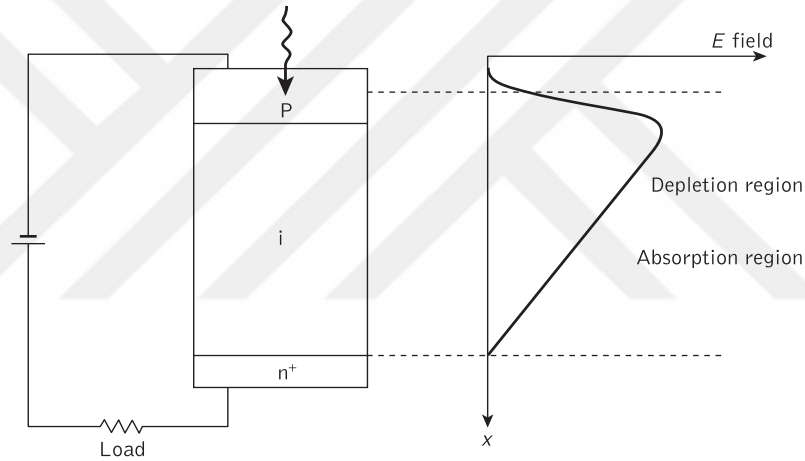


Figure 2.9. Depletion and absorption regions schematic representation of PIN photodiode

Incorporating an intrinsic layer made of a semiconductor material in between the p and n materials, as shown in Figure 2.9, is one method that can effectively increase the depletion width. This method can be seen in action in the figure. The PIN structure, also known as the P-type, Intrinsic type, and N-type configuration, is one that is utilized frequently in semiconductor detectors. The incorporation of an intrinsic material within the middle has a number of important advantages, one of the most significant of which is that it effectively establishes the depletion width to be equal to the width of the intrinsic region. By utilizing this strategy, it is possible to achieve a sizeable expansion of the depletion width without the

necessity of employing an excessively high level of reverse bias. This solution addresses the majority of the issues that are typically associated with basic pn junctions in an efficient and effective manner (13,70).

2.5.1 Capacitance-Voltage Characterization

There are fundamentally two distinct forms of capacitance that are linked to a junction. The first is the junction capacitance resulting from the dipole in the transition region. The second is the charge storage capacitance that occurs when the voltage lags behind the current due to charge storage effects. When designing p-n junction devices to work with time-varying signals, it is crucial to account for both of these capacitances. Under forward bias, charge storage capacitance predominates, while under reverse bias, junction capacitance does. The capacitance of a p-n junction is a limiting factor in many of its potential uses.

Negative charge comes from the uncompensated acceptor ions on the p side, and positive charge comes from the ionized donors on the n side of the transition region. The resulting dipole's capacitance is a little trickier to calculate than that of standard parallel plates (Equation 7).

$$C = \left| \frac{dQ}{dV} \right| \quad (7)$$

Nonlinearity is observed in the charge Q on either side of the transition region as a function of the applied voltage (dV). By reexamining the equations for the width of the transition region (W) and the resulting charge, it can be shown that these quantities depend on one another in a nonlinear fashion. The value of W at equilibrium was determined to be in (Equation 8).

$$W = \left[\frac{2\varepsilon V_0}{q} \left(\frac{N_a + N_d}{N_a N_d} \right) \right]^{\frac{1}{2}} \quad (8)$$

Therefore, the correct expression for the size of the biased transition region is depicted in (Equation 9):

$$W = \left[\frac{2\varepsilon(V_0 - V_{bi})}{q} \left(\frac{N_a + N_d}{N_a N_d} \right) \right]^{\frac{1}{2}} \quad (9)$$

The applied voltage, denoted by V , may be either positive or negative depending on whether the bias is forward or reverse. As was hypothesized, the forward bias causes the transition region to expand, whereas the reverse bias causes it to contract. Because the unbalanced charge Q on either side of the junction varies with the width of the transition region, the charge on a capacitor varies in tandem with the applied voltage. This is because the width of the transition region varies. Both the doping level and the transition region can be used to express Q in a mathematically meaningful way (Equation 10).

$$|Q| = qAX_{n0}N_d = qAX_{p0}N_A \quad (10)$$

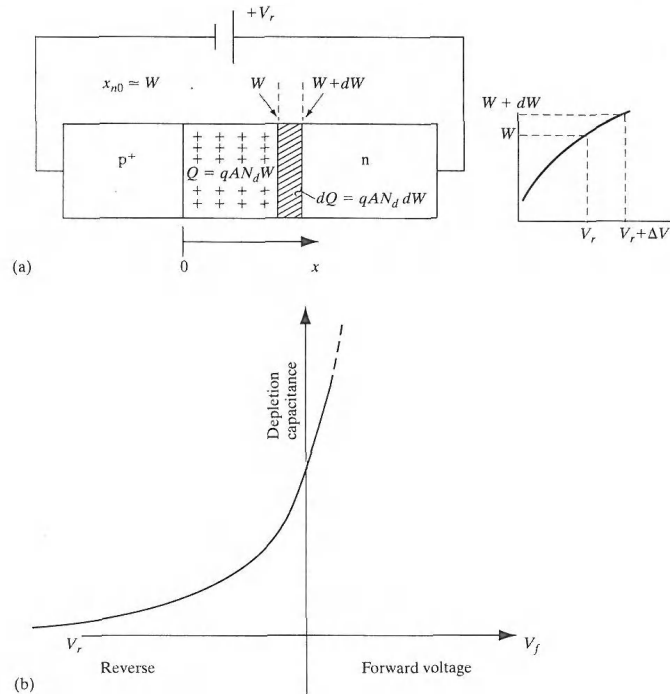


Figure 2.10. a) Representation of depletion region with reverse biases b) Capacitance characteristics of pn junction

Because C_j is proportional to $(V-V_0)^{1/2}$, the value C_j represents a capacitance that varies with the applied voltage (Figure 2.10). The use of variable capacitors in tuned circuits is just one of the numerous significant applications for these components. The p-n junction device, which exploits the voltage-variable characteristics of C_j , The form of the parallel plate capacitor formula is obtained from the expressions

for C and V, despite the fact that the dipole charge is distributed in the transition region of the junction (Equation 11) (57,71,72).

$$C_j = \epsilon A \left[\frac{dQ}{2\epsilon(V_0 - V)} \right] = \frac{A}{2} \left[\frac{2q\epsilon}{(V_0 - V)} \frac{N_d N_a}{N_d + N_a} \right]^{1/2} = \epsilon \frac{A}{W} \quad (11)$$

2.5.2 Current- Voltage Characterization

Near to a PN junction, there exists a region characterized by the presence of steady-state ionized impurities. This region exhibits a negative charge on the P side and a positive charge on the N side, while lacking free charge carriers (Figure 2.11).

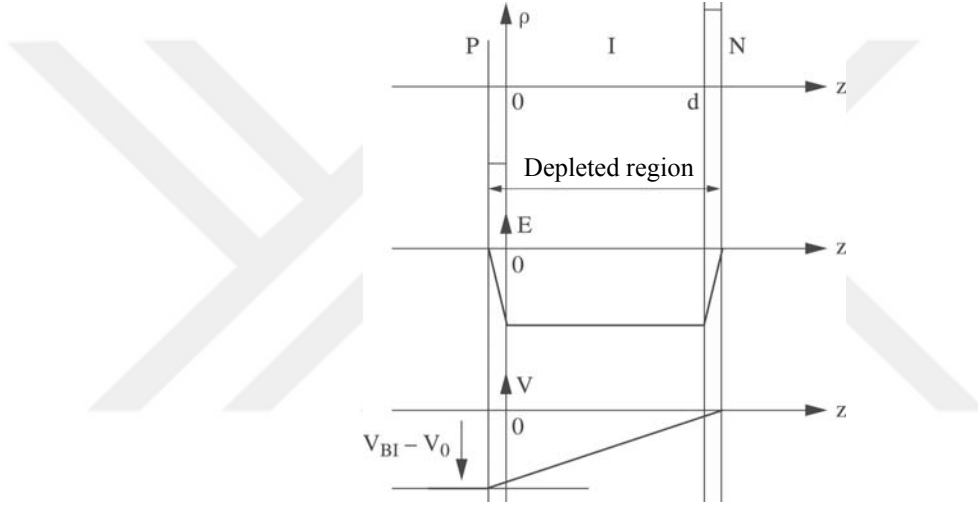


Figure 2.11. The distribution of electric field and potential across a reverse-biased Si-PIN diode.

This region is commonly referred to as the space charge region (SCR). Through the process of double integration in the z direction, the Poisson equation can be effectively incorporated (Equation 12).

$$\frac{d^2V}{dz^2} = \frac{\rho(z)}{\epsilon} \quad (12)$$

Given the charge density $\rho(z)$ and the dielectric constant ϵ , it is possible to derive the electric field E and potential V profiles across the structure. In the scenario of a sudden PN junction, the extent of the depleted region fluctuates according to the expression $(V_{bi}-V)$, where V_{bi} represents the inherent or diffusion potential existing in the absence of any external bias applied to the diode, and V denotes the voltage across the diode's terminals. Consequently, the capacitance of the junction exhibits

a decrease as the magnitude of the reverse-bias voltage increases (Discussed in section 2.5.1). Figure 2.11 depicts the examination of a Si-PIN PD structure, illustrating the profiles of the fixed charge density, electric field, and potential across the structure in a sequential manner.

The extent of the depleted region into the P and N regions is minimal, and for practical purposes, it aligns with the I region. The thickness of the I region, denoted as d in the subsequent sections of this section, is a crucial parameter in defining a Si-PIN PD (73,74).

When a voltage is applied to a photodiode in a state of low illumination, the resulting V-I curve exhibits similarities to that of a conventional rectifying diode, as depicted in Figure 2.12.

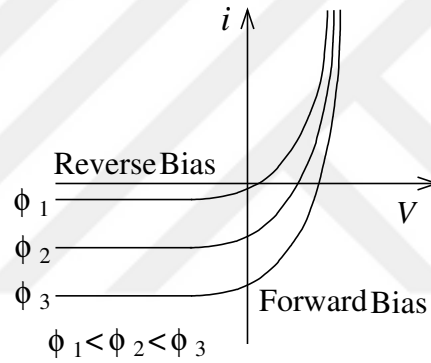


Figure 2.12. I-V characteristics of Si-PIN photodiode

Nevertheless, upon the incidence of light on the photodiode, the curve within the undergoes Φ_1 shift to Φ_2 and Φ_3 . Furthermore, as the intensity of the incident light increases, the characteristic curve becomes increasingly parallel to the light density. When the terminals of the photodiode are connected, a photo current that is directly proportional to the intensity of light will flow from the anode to the cathode, denoted as I_{sh} . When the circuit is activated, an open circuit voltage, denoted as V_{op} will be generated at the anode with a positive polarity (13).

The dark current comprises multiple components, encompassing non-radiative currents that necessitate energy for their conduction, such as the Shockley-Read-Hall (SRH) process, as well as the tunneling current, which exhibits flow without the requirement of energy. Figure 2.13 illustrates the depiction of the two processes occurring in a sharp $p^+ - i - n^-$ homojunction (75,76).

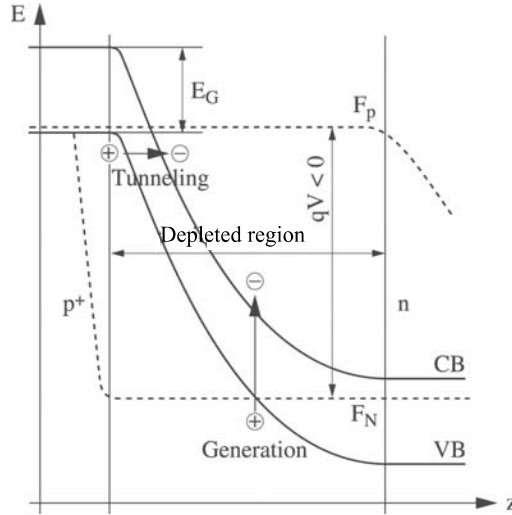


Figure 2.13.Valance band (VB) and conduction band (CB) characteristics of depleted p⁺-i-n junction. The process of generation, as depicted in the depleted zone (64).

$$G_{nr} = \frac{n_i V_{th} N_T}{2} = \frac{n_i}{\tau_{eff}} \quad (13)$$

Where, G_{nr} , n_i , V_{th} , N_T , τ_{eff} are non-radiative generation rate, intrinsic concentration, thermal velocity, density of deep state, and effective life time respectively. Dark current (I_d) can be expressed with Equation 14.

$$I_D = AdG_{nr} = \frac{Adn_i}{\tau_{eff}} \quad (14)$$

The expression for the generation contribution in the neutral p and n regions can be formulated as follows:

$$I_D = n_i^2 Aq \left(\frac{L_n}{N_A \tau_n} + \frac{L_p}{N_D \tau_p} \right) \quad (15)$$

It is mostly n_i that affects the generation of current, which changes very quickly with band gap E_G and temperature kT .

Tunneling current is also important for Si-PIN PD, it is expressed with Equation (16).

$$I_{\text{tunnelling}} = A \frac{\sqrt{2m^* q^3 EV}}{4\pi^3 \hbar^3} e^{\left(-\sqrt{\frac{2m^* E_g^2}{4qhE}}\right)} \quad (16)$$

The electric field in the depleted area, $E=V/d$, stays the same for a PIN diode. The $I_{\text{Tunneling}}$ may rise very quickly with the voltage V across the diode's ends for a certain material. This is mostly because E rises. It also goes up when E_g goes down, which means that the tunneling current's effect on the dark current is most noticeable in photodiodes made of materials with a small bandgap (64,76).

2.5.2.1 BREAKDOWN PHENOMENON

Zener Breakdown:

When a junction with a high doping concentration is subjected to reverse bias, the energy bands intersect at relatively low voltages. Specifically, the conduction band on the n-side becomes adjacent to the valence band on the p-side. When the bands intersect, the numerous unoccupied states on the conduction band of the n-side align with the abundant occupied states on the valence band of the p-side. The phenomenon of electron tunneling can occur when the strength of the barrier separating two bands is relatively weak. The Zener effect refers to the phenomenon wherein electrons undergo tunneling from the valence band of the p-side to the conduction band of the n-side, hence resulting in the generation of a reverse current that flows from the n-side to the p-side. In order to facilitate the phenomenon of tunneling current, it is important to establish a narrow barrier with restricted height, which effectively separates a substantial population of electrons from a significant number of unoccupied states. The probability of tunneling is contingent upon the width of the barrier. In order to achieve optimal performance, it is imperative for the metallurgical junction to possess a well-defined sharpness, while concurrently exhibiting a high level of doping. This combination ensures that the transition zone, denoted as W , is confined to a limited extent on each side of the junction. The occurrence of tunneling is precluded in cases where the junction lacks sharpness or if either side of the junction exhibits a minimal level of doping. The Zener effect can be conceptualized as the phenomenon of field ionization occurring at the junction of the host atoms. In the context of a densely doped junction, the

application of reverse bias results in the generation of a significant electric field within the region denoted as W. When this electric field reaches a critical strength, it has the potential to exert a force on the electrons involved in covalent bonding, leading to their detachment from the bonds and subsequent acceleration towards the n side of the junction. The magnitude of the electric field necessary for inducing ionization of this nature is around 10 V/cm (77,78).

Avalanche Breakdown:

In the case of lightly doped junctions, the phenomenon of electron tunneling can be considered unimportant. Instead, the breakdown mechanism mostly occurs through the process of impact ionization, wherein energetic carriers cause the ionization of host atoms. Typical lattice-scattering occurrences can lead to the generation of electron-hole pairs (EHPs) provided that the scattered carrier possesses adequate energy. For instance, in the event that the electric field percentage within the transition area is substantial, an electron that enters from the p side has the potential to be accelerated to a sufficiently high level of kinetic energy, hence leading to an ionizing collision with the lattice. Carrier multiplication occurs as a consequence of a solitary contact, whereby the initial electron and the subsequently generated electron are both propelled towards the n side of the junction, while the generated hole is propelled towards the p side. If carriers created within the transition area also undergo ionizing collisions with the lattice, the degree of multiplication can reach significant levels. As an illustration, it is possible for an electron entering a lattice to undergo a collision, resulting in the formation of an electron-hole pair (EHP). Each of these charge carriers possesses the potential to generate an additional EHP, and subsequently, each of these newly formed EHPs can also give rise to more EHPs, therefore initiating a cascading effect. The observed phenomenon can be classified as an avalanche process, since it is characterized by the ability of each incoming carrier to trigger the generation of a significant quantity of further carriers(77,78). Zener and avalanche breakdown is shown on Figure 2.14.

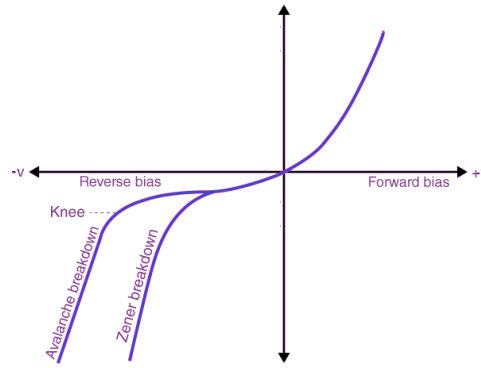


Figure 2.14. Breakdown characteristics of Si-PIN PD

2.5.3 Spectral Response

When a photon with an energy that matches or exceeds the energy range of the semiconductor material's band is incident, it has the ability to transfer its energy to the material, causing an electron to transition from the valence band to the conduction band. The aforementioned procedure generates photocarriers, which are free electron-hole pairs resulting from the photon-induced production of load carriers. The photodetector is often engineered to predominantly generate these carriers within the depletion region (depleted inner region) this in discussed in Figure 2.12.

As the load carriers traverse the material, a portion of the electron holes will undergo recombination, resulting in their annihilation. Load carriers often exhibit a matching L_n or L_p distance for electrons and holes, respectively, on average. The term used to describe this distance is referred to as the diffusion length. The duration required for an electron or hole to reestablish its connection is referred to as the carrier lifetime, denoted as τ_p and τ_n for electrons and holes, respectively. The concepts of "lifes" and "diffusion lengths" are closely related to the following propositions.

$$L_n = (D_n \tau_n) \quad L_p = (D_p \tau_p) \quad (17)$$

In where D_n and D_p . diffusion coefficient of electron and holes respectively.

The absorption of optical light in semiconductor materials follows an exponential law (Equation 18).

$$P(X) = P_o (1 - e^{-\alpha_s(\lambda)x}) \quad (18)$$

α_s =Absorption coefficient, P_o = Incident optical Power, $P(x)$ = optical power function of distance.

The dependency of the optical absorption coefficient on the wavelength is shown in Figure 2.15 for various photodiode materials (43,79,80).

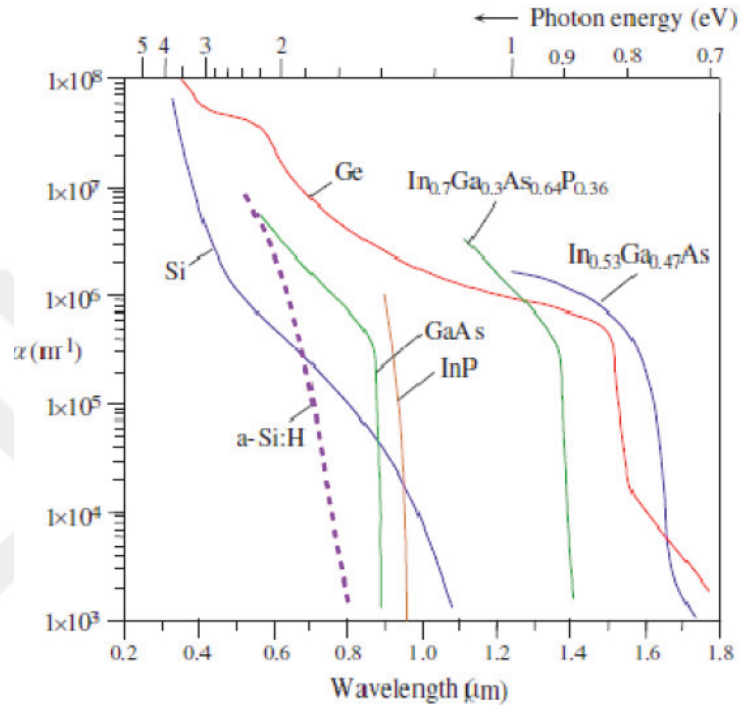


Figure 2.15. The absorption coefficient α is examined as a function of wavelength λ across different semiconductors.

As clearly seen in the curves, α is strongly linked to the wavelength. Therefore, a particular semiconductor material can only be used in a limited range of wavelengths. The upper cutting wavelength λ_c is determined by the material's bandwidth energy E_g . If the electron is expressed in the unit of volt (eV), the λ is given in the μm unit (Equation 19).

$$\lambda_c = \frac{hc}{E_g} = \frac{1.24}{E_g(\text{eV})} \quad (19)$$

The wavelength at which silicon exhibits optimal cutting performance is around $1.06 \mu\text{m}$. In the case of longer wavelengths, the energy carried by photons is inadequate to induce the excitation of an electron from its valence band to the conduction band. The photo-tape is severed at the lower end of the electromagnetic spectrum because to the significantly higher values of absorption coefficient at

shorter wavelengths. In this particular scenario, the photons undergo absorption in close proximity to the surface of the photodetector, resulting in the formation of electron-hole pairs. Notably, the recombination period of these pairs is exceedingly brief. Consequently, the carriers that are generated are reestablished prior to their assembly by the photodetector circuit.

If the width of the extinction area is denoted as w , the total power absorbed inside a distance w can be calculated using Equation (21).

$$P(w) = P_o (1 - e^{-\alpha_s w}) \quad (20)$$

$$I_p = \frac{q}{h\nu} P_o (1 - e^{-\alpha_s w})(1 - R_f) \quad (21)$$

The optical power incident on the photodetector can be expressed as the product of the electric charge (q) and the photon energy ($h\nu$). Quantum activity and reaction speed are two significant attributes of a photodetector. The values of these parameters are contingent upon the bandwidth of the material, the wavelength at which the device operates, as well as the contribution and thickness of the p, i, and n areas inside the device. The quantum efficiency, denoted as n , is the quantity of electron-hole carrier pairs generated per photon energized by $h\nu$ (Equation 22) (81,82).

$$n = \frac{\# \text{ of electron - hole pairs}}{\# \text{ of incident photons}} = \frac{\frac{I_p}{q}}{\frac{P_o}{h\nu}} \quad (22)$$

Silicon PIN photodiode performance evaluated with responsivity that is relative with quantum efficiency (Equation 23).

$$R = \frac{I_p}{P_{\text{incident}}} \quad (23)$$

Ideal spectral response characterization of Si-PIN photodiode (Figure 2.16)(83)

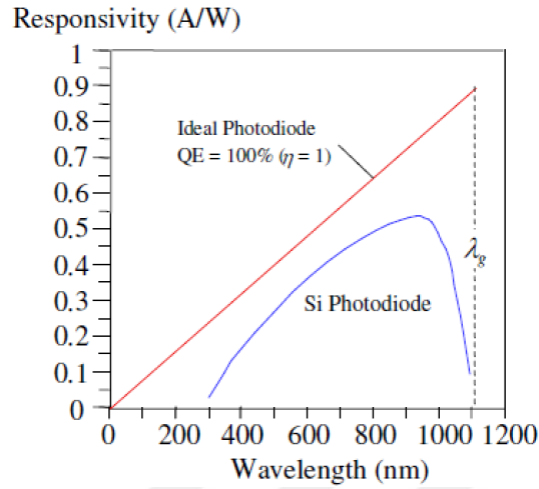


Figure 2.16. Spectral response characteristics related to quantum efficiency of Si-PIN photodiode

2.5.4 Transient Characterization

Reaction time is an additional characteristic that plays a crucial role in determining the performance of a photodiode. The photodiode exhibits a finite response time when subjected to an abrupt alteration in the intensity of light. The conventional practice is to quantify the response time as a t_{rise} , denoting the duration necessary for the output to transition from 10% to 90% of its ultimate magnitude (Figure 2.17).

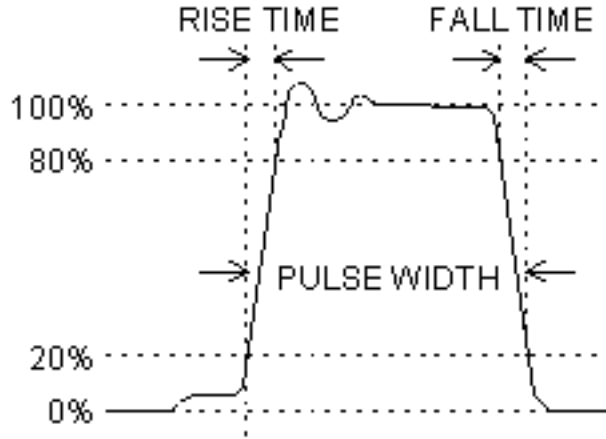


Figure 2.17. Rise Time and Fall Time behavior

The determination of the total rise time involves three distinct components. The first component is known as the diffusion time, denoted as t_{diff} . This time interval represents the duration required for carriers generated within the neutral region to traverse through diffusion and reach the depletion zone. The second factor pertains to the duration required for the carriers generated in the depletion region to traverse the distance and reach the electrode, which is facilitated by the presence of an electric field. Thank you for your input. The RC time constant, denoted as t_{RC} , represents the duration required for a capacitor to reach 63% of its maximum charge or to discharge to 37% of its initial voltage within an RC circuit. The total upgrade time can be computed by considering the three aforementioned components.

$$t_{rise} = \sqrt{t_d^2 + t_{diff}^2 + t_{RC}^2} \quad (24)$$

When the diode is completely depleted or functioning under a significant level of depletion, the dissipation time becomes negligible. The stability of the RC time, as well as the values of terminal capacitance and load resistance (R_L), are influenced by the photodiode. The capacitance of a photodiode, denoted as terminal capacitance, is determined by the combined values of its package capacity and bonding capacity. In most cases, the package capacity is the primary contributor to the overall capacitance (34).

2.6 Ionized Radiation Effect on Silicon P-I-N photodiode

The detrimental flaws induced by radiation primarily arise from atomic substitution, which perturbs the integrity of the lattice structure. The aforementioned imperfections have the potential to be dispersed or concentrated in close proximity to the trajectory of the incoming radiation. Point defects are faults that arise due to the separation of atomic shifts. This form of clustering is called a cluster fault. One notable characteristic of these cluster flaws is their propensity to render a significant portion of the material nonfunctional. The primary mechanism of damage involves the displacement of an atom by an incoming particle originating from the surrounding cage region. The phenomenon being referred to is commonly known as Non-Ionizing Energy Loss, abbreviated as NIEL. In contrast, NIEL has a non-proportional relationship with the overall energy absorbed within the semiconductor material. Instead, it mostly relies on the characteristics of the radiation, such as its type and energy. Nevertheless, it is important to acknowledge that atoms that undergo replacement due to the impact of incoming radiation have the potential to induce additional harm. This damage does not fall within the scope of the non-ionizing energy loss spectrum. The impact of this action is not very noticeable for all incoming forms of radiation since the type of damage is determined by the energy spectrum of these reactive atoms. For instance, when charged particles enter, they often generate recoil atoms that have a distribution with an extended tail at low energy levels. This increases the likelihood of secondary point defect creation rather than cluster formation. So in this scenario, NIEL scaling would be a good approach to overall damage. However, when it comes to high-energy neutrons, the feedback spectrum is more acute towards the high energy tip, and so the NIEL scaling should be carefully evaluated. Whatever the exact process of degradation, the ultimate effect is a detector performance decline (56,84).

2.6.1 Radiation related leakage current

One profound result of radiation damage is a change in the stream of reverse biases. The obvious reason for this is the rise or decrease in the number of free charging pairs in the depletion zone. The decrease in leakage current, commonly noticed during first radiation, is mostly due to the creation of charging traps in the

restricted energy gap. The leakage current can exhibit a large increase after continuous radiation, as the chance of creating the charging pair grows with the application of more energy levels in the restricted zone.

The dose of radiation included in the leak that caused the damage was determined to depend on the volume and temperature to which the detector was exposed. The integrated radiation dosage, of course, depends on the particle movement, which is simply the integrated radiation density. At a specific temperature, the change in leakage current can be expressed ΔI_{leak} particle current Φ and volume V dependence.

$$I_{leak} = aV\Phi \quad (25)$$

where a is the so-called damage coefficient, which varies with particle type and energy. Both the leakage current I_{before} before irradiation and the leakage current I_{after} after irradiation can be used in this equation (85,86).

$$I_{after} = I_{before} + aV\Phi \quad (26)$$

2.6.2 Type Inversion

The phenomenon of type inversion has been documented in high resistivity n-type silicon following extended exposure to high-energy particles, with an integrated fluence of approximately $10^{13}/\text{cm}^2$. The concentration of donors reduces gradually with exposure, ultimately leading to the observation of a change to top-type behavior. Several theoretical models propose that the observed change is attributed to the creation of deep acceptor levels within the bandgap due to radiation exposure. These acceptor levels are situated toward the center of the bandgap and exhibit electrical activity upon the application of voltage to the detector. In detectors featuring a p^+-i-n^+ structure, a noteworthy outcome of the type inversion is the effective displacement of the rectifying contact from one side of the detector to the other side. After the inversion, the device has the ability to maintain its operation despite the applied voltage having the same polarity. However, over time, the increasing concentration of acceptors results in an elevation of the voltage threshold needed for complete depletion. This threshold finally surpasses the levels that lead to breakdown(87,88).

2.6.3 Radiation Detection with Semiconductor Detector

When utilizing a semiconductor detector, such as silicon, for the purpose of measuring ionized radiation, the resulting output signal manifests as a feeble electrical disturbance characterized by a pulse duration spanning several tens of nanoseconds. The detector element is a capacitive device, thus exhibiting a significantly elevated level of empowerment. Hence, it is imperative to consider the performance of the front booster that is to be connected while amplifying this output signal.

Integrators employing operational upgrading modes that utilize feed capacity are extensively employed in such applications. Given the high input impedance of these amplifiers, they effectively incorporate and transform weak load effects into voltage effects, thereby enhancing the signal, and subsequently deliver a low impedance output. As a result of this procedure, the term "charge amplifier" is utilized to refer to such amplifiers. Typically, the initial phase of a charge amplifier entails the utilization of a low-noise Field-Effect Transistor (FET). The open-cycle gain is carefully adjusted to a sufficiently high level in order to ensure that the amplification process remains unaffected by the capacitance of the detector. The output phase serves as a low-impedance buffer for transmitting an external phase signal over a lengthy cable connection (30)

When ionizing radiation interacts with a semiconductor detector made of Si, it generates pulses of electrical signals known as Qs signal load beats. The width of these pulses is proportional to the energy of the incident particles. As a result of the load generation, there is an increase in potential at the input end of the load-lift, and a potential with reverse polarity is observed at the output end (Figure 2.18). Nevertheless, due to the substantial open-cycle gain of the amplifier, the output end potential effectively operates in a feedback loop, resulting in the input end potential rapidly approaching zero (31).

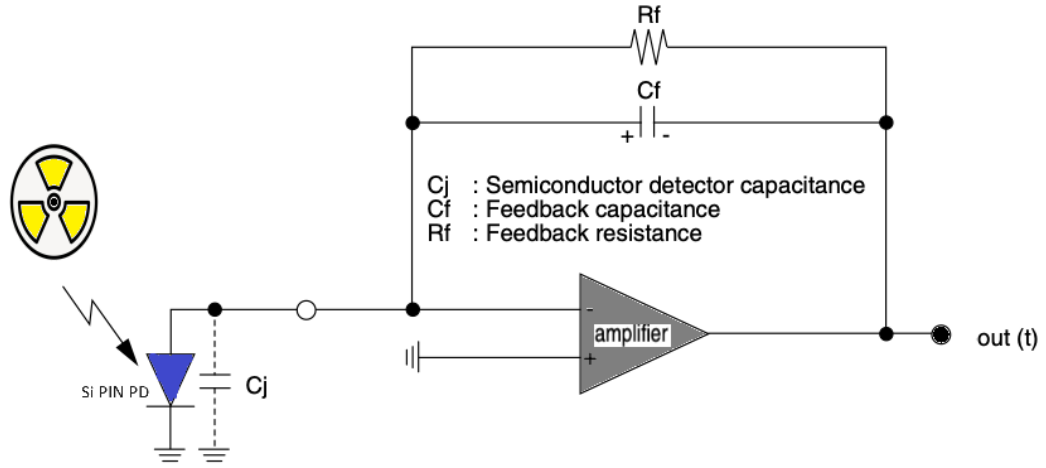


Figure 2.18. Si-PIN PD operation under ionized radiation

Output voltage can be written with Equation 27 if $0 \leq t < t_0$

$$V_{out}(t) = - \frac{Q_{pulse}}{C_f} \times \frac{1 - e^{-\frac{t}{\tau}}}{\frac{t_0}{\tau}} \quad (27)$$

On the other hand, $t > t_0$ output voltage can be calculated with Equation 28.

$$V_{out}(t) = - \frac{Q_{pulse}}{C_f} \times \frac{1 - e^{-\frac{t}{\tau}}}{\frac{t_0}{\tau}} e^{-\frac{t}{\tau}} \quad (28)$$

Sometimes the word "sensitivity" is used instead of "gain" when referring to this. The output voltage (mV) for each MeV of particle energy that is shined on a detector is used to measure sensitivity. How strong the signal charge is from a semiconductor detector depends on the particle energy going in, like soft X-rays and gamma rays, as well as the semiconductor material.

$$Q_{pulse} = \frac{E * e'}{e_{creation}} \quad (29)$$

Where E , e , e_{creation} are radiation particle energy, electron charge and minimum energy for creation electron holes pairs (31,84).

$$\text{Sensitivity} = \frac{V_{\text{out}}}{E} = \frac{\frac{Q_{\text{pulse}}}{C_f}}{Q_{\text{pulse}} \cdot \frac{e_{\text{creation}}}{e}} = (\text{mV/MeV}) \quad (30)$$

2.6.4 Counting Statistics and Energy Measurement

All laboratory measurements contain sources of uncertainty or error. Some of them come from measurement systems. Others are caused by the radioactive deformation itself, because the radioactivity itself is a statistical process of change, and its formation is entirely random. If we want to make a single measurement of the progressive variable, that is, a statistical event, then two questions are asked.

1. Accuracy of measurement
2. The result of a single measurement is "how close to the real value"

The probability of degradation of n of a sample containing N radioactive nuclei within a certain time interval should be calculated as $P(n)$.

The literature provides a comprehensive list of systems that can be employed for the measurement of nuclear radiation energies. Typically, the electronic signals originating from the detector are directly routed to the front amplifier. The charge pulse from the detector is transformed into voltage pulses. The amplifier facilitates the amplification of voltage to the millivolt range of the front amplifier. In order to establish a correlation between the radiation energy and the pulse height, it is necessary for the amplifier to exhibit linearity. The multi-channel analyzer (MCA) enables the observation of a histogram displaying multiple pulse heights acquired from the process of a complex degradation (Figure 2.22) (13,32,56).

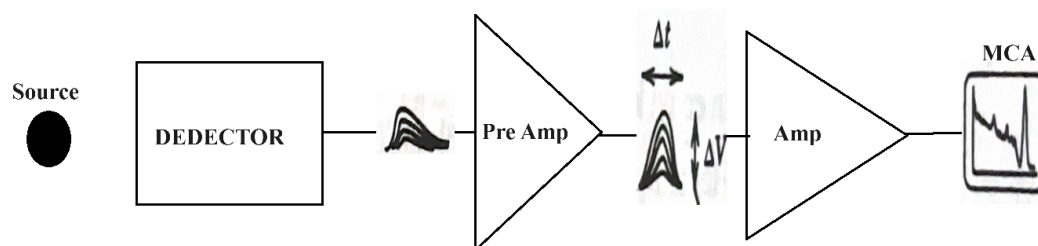


Figure 2.19. Detection system with Si-PIN PD sensor

2.6.5 X-ray Detection with Si-PIN PD

X-ray spectroscopy has the potential to serve as a viable alternative to a less complex silicon p-i-n diode. This configuration involves the inclusion of non-injecting contacts, labeled as p and n, on both surfaces of a high-resistance i-zone. The purpose of these contacts is to effectively reduce the leak current to a level that is lower than what can be observed with a standard diode. A thickness of approximately 300-500 μm is generally considered adequate to achieve favorable detection efficiency within the energy range of 20 to 30 keV. In order to effectively detect the limited number of electron-hole pairs produced by a low-energy X-ray photon, it is imperative to minimize the noise level of the detector to the utmost extent. Consequently, these diodes are frequently subjected to cooling measures in order to mitigate the current to levels of even greater insignificance. A compact thermoelectric chiller is frequently employed to achieve a cooling temperature of approximately $-55\text{ }^{\circ}\text{C}$. The p-i-n diodes have been effectively utilized in the measurement of fluorescent X-rays and are readily accessible in the market (46,89–91).

2.6.6 Strontium-90 (^{90}Sr)

^{90}Sr , a radioactive isotope generated through nuclear fission, poses significant environmental and health concerns as it is found in the nuclear serpentine. ^{90}Sr undergoes a notable decay process with a decay energy of 0.546 MeV, resulting in the formation of ^{90}Y . Silicon PIN photodiodes have demonstrated efficacy in detecting beta emissions. A Si-PIN photodiode with ^{90}Sr as the radiation source has a sensitivity spanning from 320 nm to 1100 nm in real-world scenarios. This photodiode is enclosed in a lightproof metal box to provide insulation. It is capable of measuring dark current in units of nA and pF. Additionally, it can withstand

reverse polarization forward voltage of up to 30 V. When an ionizing particle, such as a beta particle emitted during the decay of ^{90}Sr , penetrates the sensitive region of the photodiode, numerous electron-hole pairs are generated. The cathode and anode of the diode gather these pairs to create a signal. The signal width is directly proportional to the electron's energy, but it is limited by the maximum energy threshold set by the thickness of the diode's active region. Nevertheless, the photodiode's output exhibits a notable deficiency in generalization and necessitates amplification. A load-sensitive front amplifier, also known as a current-to-voltage converter, is utilized to transform the current signal generated by the detector into a corresponding voltage signal. The output of this CSP is directly proportional to the total load from the detector. It is characterized by a prolonged decrease in quality after a rapid initial increase in time. In order to enhance the feasibility of analyzing these signals, they undergo amplification through a shaping amplifier and are transformed into symmetrical bell-shaped waveforms, resulting in a substantial improvement in the ratio between the signal and the noise.

The efficacy of this system in detecting beta particles, such as those emitted by Sr-90, has been verified. Nevertheless, there exist constraints on the range of energy frequencies that can be observed. Low-energy beta particles are unable to penetrate the protective window, whereas higher-energy particles can pass through the entire sensitive area without being fully absorbed, suggesting a detectable maximum energy of approximately 1 MeV (92).

The simplified Fermi function is applicable for determining the overall spectrum of ^{90}Sr and ^{90}Y .

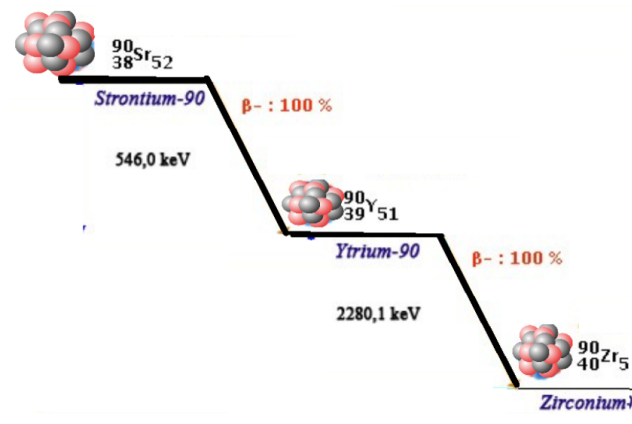


Figure 2.20. ^{90}Sr decay Shema

This is the visual representation depicted in Figure 2.21. The particle possesses an energy level of approximately 2.2 MeV, equivalent to the energy released during the β -decay of ^{90}Y . The energy level typically ranges around 0.3 MeV. The decay of $^{90}\text{Sr} + ^{90}\text{Y}$ results in the release of two β -particles, which corresponds to the emission probability distribution. The spectroscopic analysis of β -emission from ^{90}Sr experiments confirms the accuracy of our pure analytical spectrum. Due to the functionality of the instruments, the alterations are predominantly observable at lower energy levels. To determine the amount of energy that will be stored in the diode and to prevent excessive absorption of β -particles by the source material, it is crucial to have precise knowledge of the spectrum (93).

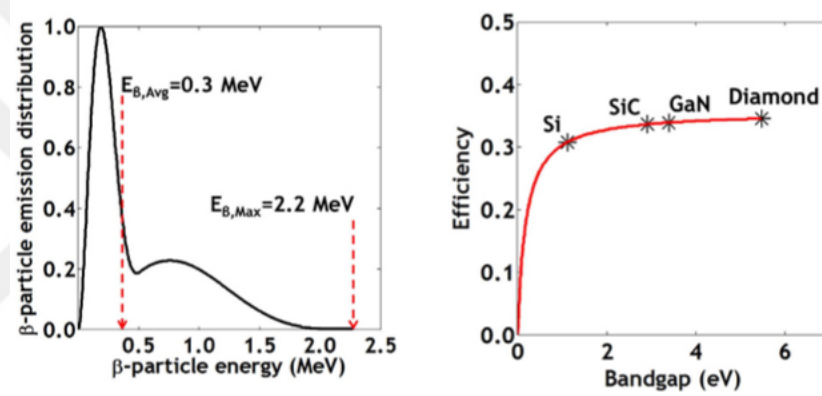


Figure 2.21. Beta spectrum and beta particle efficiency of devices with different materials (93)

2.6.7 Thallium-204 (^{204}Tl)

^{204}Tl , a radioactive thallium isotope, is crucial in numerous scientific and industrial contexts. With a half-life of around 3.78 years, this substance is well-suited for utilization in nuclear medicine, particularly in stress testing. Heart illness diagnosis. Ensuring safety and effectiveness in these applications requires the crucial real-time detection of ^{204}Tl . Real-time detection allows for immediate evaluation of the dispersion and density of the isotope, guaranteeing precise diagnosis and reducing patients' radiation exposure. Furthermore, the use of live monitoring of ^{204}Tl in industrial settings can effectively avert environmental pollution and guarantee the well-being of workers. The precision and lucidity of

this detection are crucial for overseeing the utilization of the isotope, diminishing its possible risks, and exploiting its advantageous applications (94,95).

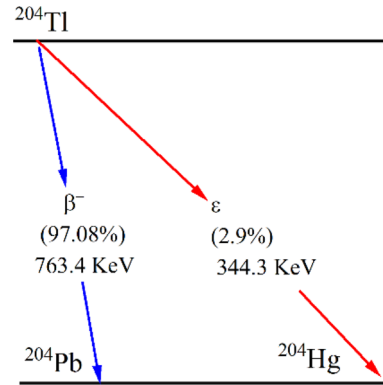


Figure 2.22. ^{204}Tl decay shema (96)

2.7 Device Simulation with Silvaco

Silvaco is a prominent supplier of software tools utilized for simulating and designing semiconductor devices and processes. The device simulation package, commonly referred to as ATLAS and ATHENA, enables the modeling and analysis of semiconductor devices, including transistors, diodes, and solar cells. This software package is renowned for its comprehensive assortment of physical models capable of simulating diverse phenomena in semiconductor devices, encompassing electrical, thermal, and optical behaviors. Silvaco's tools are extensively utilized by engineers and researchers to create and enhance semiconductor devices, facilitating comprehension of device physics, performance estimations, and reliability assessments. Silvaco's simulations possess exceptional flexibility and precision, rendering them highly valuable in the semiconductor sector, particularly for advanced research and development of novel semiconducting technologies (56,97).

2.7.1 Atlas Tool (Device Modelling and Characterization)

The Atlas tool developed by Silvaco is a sophisticated software package designed for the simulation of semiconductor devices. It provides the ability to model the performance of different semiconductor devices under varied circumstances. Specifically, the Atlas 2D module is utilized for the creation and examination of silicone diode structures, as well as for conducting DC analysis. Understanding the properties of semiconductors is crucial in the field of research

and development. The operations necessitate the utilization of a fundamental module known as "SPICES".

The utilization of the Atlas tool entails a series of sequential actions, including the submission of input data in the form of text files generated by DECKBUILD, an integral component of the Silvaco software ecosystem. This includes input files, expressions that provide the simulation settings, and model coefficients. The outputs from Atlas simulations are divided into two categories: Standard Output and Standard Error Output. The former includes the results obtained from simulated expressions, while the latter consists of error warnings.

The simulation process with Atlas has multiple steps, including construction specification, material and model requirements, numerical technique specifications, solution specifications, and result analysis. An example of how Atlas can be applied is in simulating the sophisticated properties of Schottky diodes. This encompasses the fabrication of the device architecture, modeling the Schottky barrier height, and evaluating advanced predictive characteristics. The simulation entails the identification of areas and electrodes, the determination of boundary conditions such as Ohmic and Schottky connections, and the determination of the doping distribution in the semiconductor material.

The Atlas software enables the simulation of I-V characteristic curves and the selection of appropriate numerical models, such as the Gummel and Newton techniques, to solve the equation system used in the simulation. The device is capable of calculating DC, AC tiny signals, and transient solutions. Additionally, it has the ability to display these results by drawing the device structure and characteristics using commands in the DECKBUILD window (ref). ATLAS supports three distinct methods for defining a device structure reading a pre-existing structure from a file is the initial method. Either a prior ATLAS run or another program, such as DEVEDIT or ATHENA, generates the structure. The mesh, geometry, electrode positions, and doping of the structure are specified in a MESH statement. As an illustration:

MESH INFILE=<filename>

The second option is to transmit the input structure from ATHENA or DEVEDIT using the Automatic Interface feature of DECKBUILD.

When executing within the ATHENA and ATLAS DECKBUILD environments, you can take advantage of an automated interface that connects the two software products. To load the whole network, geometry, and contribution from ATHENA to ATLAS, please follow the steps outlined. Firstly, Gather and shape the electrode material at ATHENA. Secondly, Utilize the term "electrode" within ATHENA to designate the specific sites of contact. To designate a specific area, provide the X and Y coordinates along with markers. Subsequently, the entire region is transformed into an electrode. Often, simply the X coordinates are required. For instance, there exists a unique circumstance in the lowermost part of the framework to signify a point of communication.

Electrode Name: Anode X=1 Y=-2

Electrode Name: Cathode Backside

By changing the value of the QSCV parameter in the SOLVE expression, the quasistatic capacitance can be calculated. Subtracting the adjacent forecaster's electrode charge from the current and then dividing the result by the voltage increase yields the quasistatic capacitance. By using an electrode and Gauss's current theory, we can determine the load density. On the halfway point between the two forecast points, this provides the capacity. Since the voltage increase ought to be adequate, ATLAS does not adjust the output to account for this. Hence, this minor slide can be disregarded. You can also get close to the continuous derivative with a little voltage boost. According to the METHOD statement, QSCV can handle CARRIERS=0, 1, or 2. The total capacitance and capacitance for each electrode can be determined by connecting them using the COMMON parameter of the CONTACT expression. For a connected electrode, setting MULT and FACTOR causes the capacitance to be computed at the right prediction points and stored according to the prediction applied to the COMMON electrodes. The C-V curve may need to be shifted or scaled in this instance (98,99).

2.7.2 Athena Tool (Process Simulation)

A file is run by ATHENA that tells it how to do the simulation, the meshing, and the models. The file's contents are expressions that each ask the simulation to do something or set a feature of it. This part talks about the language of commands that can be used to manage ATHENA.

`<command> <parameters> = <value>`

Command, parameters and value refers to command name, parameter name, and parameters value respectively. As parameters, various materials may be specified in a variety of expressions. Standard and usage-defined materials are both accessible at ATHENA. The description of a sentence dictionary includes the general name MATERIAL, which denotes that only one of the standard material names or user-defined material from the following list may be specified. By including the MATERIALS generic name in the syntax: description expression, it is possible to specify a combination of user-defined and standard materials (Figure 2.23).

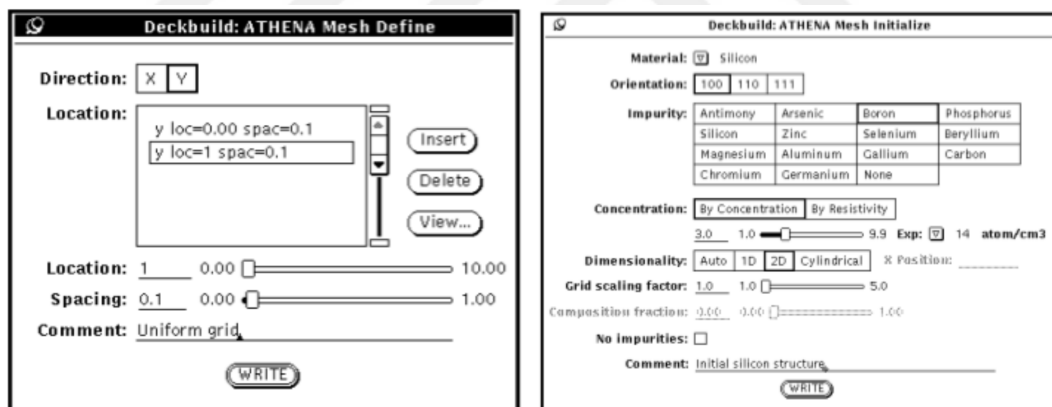


Figure 2.23. Determining mesh and selection of the material as a substrate (100)

To establish the background doping, simply select the desired impurity box (such as Boron) by clicking on it. The operationalization of the background impurity concentration specification will occur at this juncture. If the "None" box is chosen, the concentration information will become inactive and will be shown in grayscale along with the other available options on the menu. You have the ability to select the desired concentration by utilizing the slider(100).

Structures with multiple layers can be created using conformal deposition. Any situation where the precise shape of the deposited layer is not crucial can be

modeled using conformal deposition, the simplest deposit model. When the amount of doping redistribution that occurs during oxidation is minimal, planar or quasi-planar semiconductor regions can be oxidized instead of deposited using conformal deposition. From the Commands menu in DECKBUILD and the ATHENA Deposit Menu, choose Process→Deposit→Deposit to set the conformal deposition step (Figure 2.24).

Deckbuild: ATHENA Deposit

Type: Conformal Machine Display: Basic parameters Grid Impurities

Material: ☒ Polysilicon
User defined: _____

Thickness (μm): 0.50 0.00 1.00

Grid specification:

☒ Total number of grid layers: 10 1 20

☒ Nominal grid spacing (μm): 0.02 0.00 1.00

☒ Grid spacing location (μm): 0.2 0.00 1.00

☐ Minimum grid spacing (μm): 0.01 0.00 1.00

☒ Minimum edge spacing (μm): 0.001 0.01 1.00

Impurity concentrations (atom/cm3):

☐ Antimony: 1.0 1.0 9.9 Exp: 11

☐ Arsenic: 1.0 1.0 9.9 Exp: 11

☐ Boron: 1.0 1.0 9.9 Exp: 11

☒ Phosphorus: 5.0 1.0 9.9 Exp: 19

☐ Silicon: 1.0 1.0 9.9 Exp: 11

☐ Zinc: 1.0 1.0 9.9 Exp: 11

☐ Selenium: 1.0 1.0 9.9 Exp: 11

☐ Beryllium: 1.0 1.0 9.9 Exp: 11

☐ Magnesium: 1.0 1.0 9.9 Exp: 11

☐ Aluminum: 1.0 1.0 9.9 Exp: 11

☐ Gallium: 1.0 1.0 9.9 Exp: 11

☐ Carbon: 1.0 1.0 9.9 Exp: 11

☐ Chromium: 1.0 1.0 9.9 Exp: 11

☐ Germanium: 1.0 1.0 9.9 Exp: 11

Composition fractions:

☐ Initial composition fraction: 0.00 0.00 1.00

☐ Final composition fraction: 0.00 0.00 1.00

Comment: Poly deposition _____

WRITE

Figure 2.24. Impurity deposition with ATHENA deposition menu

To adjust the doping level, select the Phosphorus or Boron options and utilize the slider and the Exp menu to input specific values, such as 1.5×10^{11} . By modifying the parameters for the Nominal grid spacing and the Grid spacing location, it is possible to generate a non-uniform grid in the deposited layer. To create a more detailed grid on regions, choose 0.0 as the starting point (at the surface), set the Nominal grid spacing, and specify a total of grid layers. For electrode metal deposition, the same menu can be used.

The deposition region and metal etch regions can be defined as the subsequent stage in the simulation of the tutorial process. To configure the geometrical, etch

step, choose the Process→Etch→Etch... option from the DECKBUILD Command menu. Figure 2-15 displays the ATHENA Etch Menu (Figure 2.25) (100).

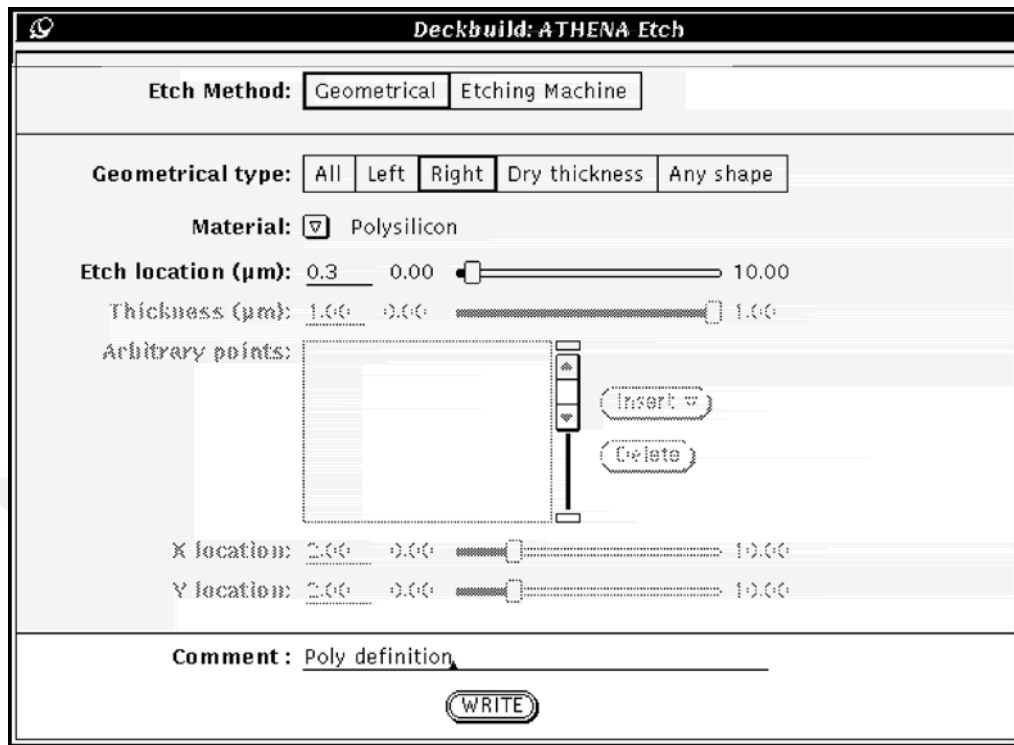


Figure 2.25. ATHENA etching menu(100)

Etching regions can be determined by using x and y location parameters (Figure 2.26).

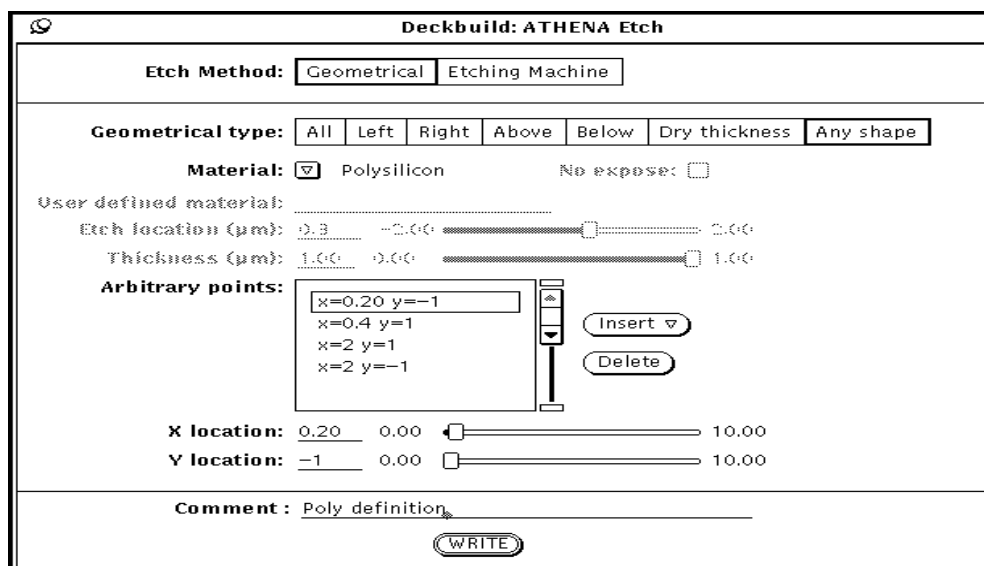


Figure 2.26. ATHENA menu for specific regions etches

3 MATERIALS AND METHODS

3.1 Device Simulation

It is aimed to design diodes with low capacitance and current by using the "Silvaco TCAD" simulation program. To achieve these goals, firstly, the production processes of diodes were simulated using "SILVACO ATHENA". Silvaco ATLAS program was used to determine the current-voltage (I-V), capacitance-voltage (C-V) and spectral response behaviors of these devices.

3.2 Proses Simulation and Creating Mesh Structure with Athena

A high resistance Pure Floating Zone (FZ) substrate is used in the fabrication of Silicon PIN photo diodes. The FZ substrate cannot be determined directly in the ATHENA software. Therefore, the resistor properties of substrate were defined for the diode to be designed. When 10 k Ω -cm resistance was entered into the ATEHA software, the ion density of the substrate was calculated as 1×10^{11} cm⁻³. The substrate thickness is 500 μ m, and the N type (100) was chosen as the type Figure 3.1.

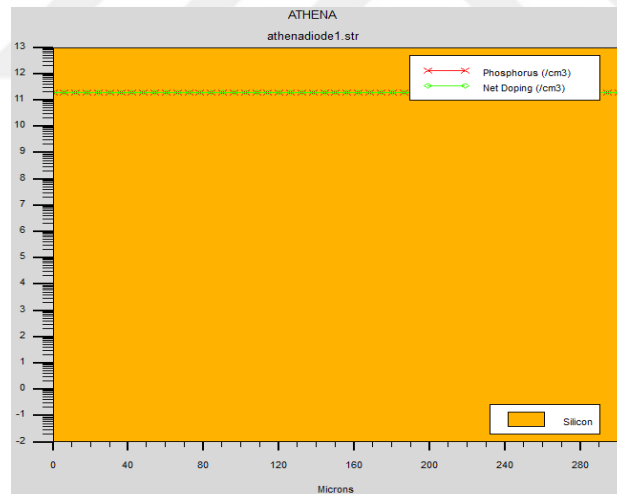


Figure 3.1. Mesh structure of substrate

After determining the substrate that is planned to be used in the production stages of the diodes, the initial oxide (SiO₂) layer of 1 μ m thickness, which will act as a mask, was grown Figure 3.2.

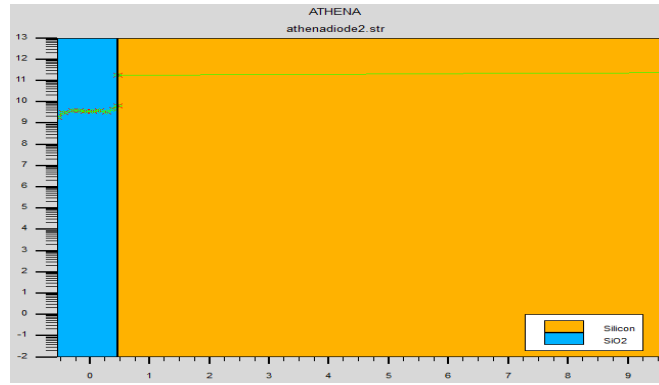


Figure 3.2. Initial oxide growing on substrate

3.2.1 Etching Process and Phosphor Doping

After the initial oxide growth process was completed, the N^{++} region was formed by doping phosphorus on the back surface of the Substrate. During the doping process, an oxide layer with a thickness of 120 nm was formed on the back surface of the Substrate (Figure 3.3a). After doping, the ion profile was obtained (Figure 3.3b). For the N^{++} region, $1.5 \times 10^{16} \text{ cm}^{-3}$ ion doping was carried out at a depth of 1-2 μm .

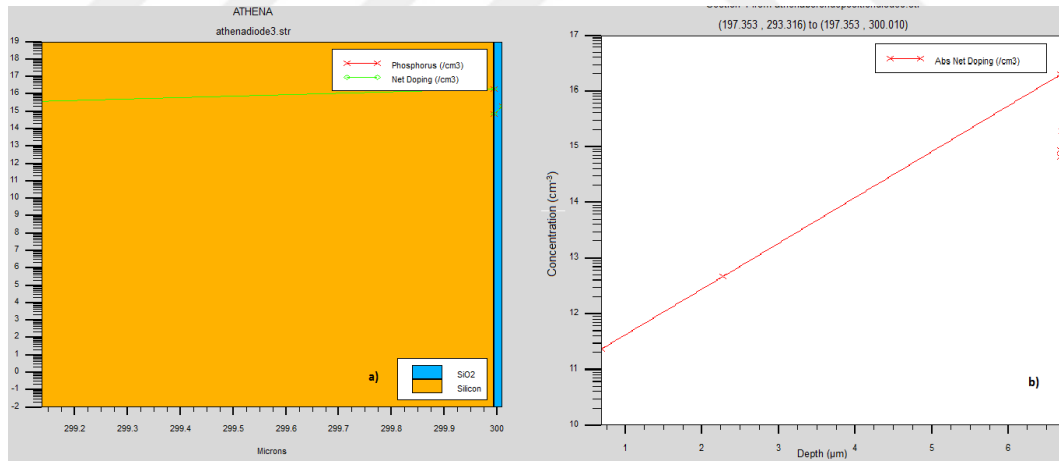


Figure 3.3. a) Phosphorus doped substrate, **b)** Ion profile of doping process

3.2.2 Etching Process and Boron Doping

The process of forming the active area and guard rings on the front surface of the substrates, whose phosphorus doping process has been completed, has been started. At this stage, the active area dimensions are designed to be 10x10 mm^2 , 12x12 mm^2 and 20x20 mm^2 . In Silicon PIN photo diodes (Si-PIN PD) designs, if the breakdown voltage is desired to be lower than -50 V, one protection ring is

usually sufficient. However, if it is desired to obtain a more stable diode at higher voltages, more than one protection ring is needed (101). For this reason, simulation studies of diodes with different numbers of protection rings were carried out in simulation studies and their I-V, C-V characterization were examined. As a result of the examinations, it was concluded that the Si-PIN PD structure with 4 guard rings is the most suitable structure. I-V and C-V behaviors of diode structures with different structures are detailed in the characterization section.

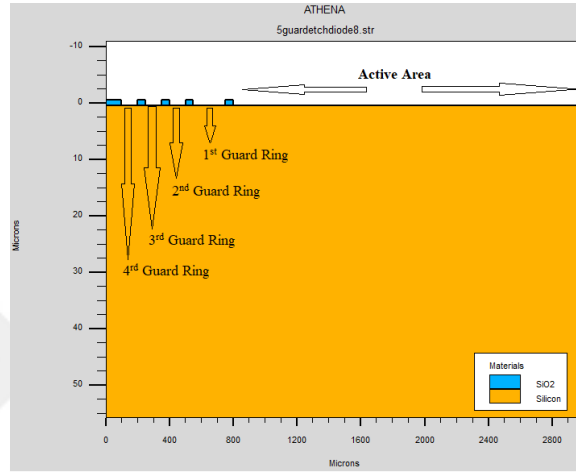


Figure 3.4. Determination of regions of active and guard rings

After the locations of the active region and guard rings areas were determined, P^{++} regions were created by Boron deposition (Figure 3.5a). After doping process, the peak ion density was determined as $2.5 \times 10^{18} \text{ cm}^{-3}$ at 110 nm depth (Figure 3.5b).

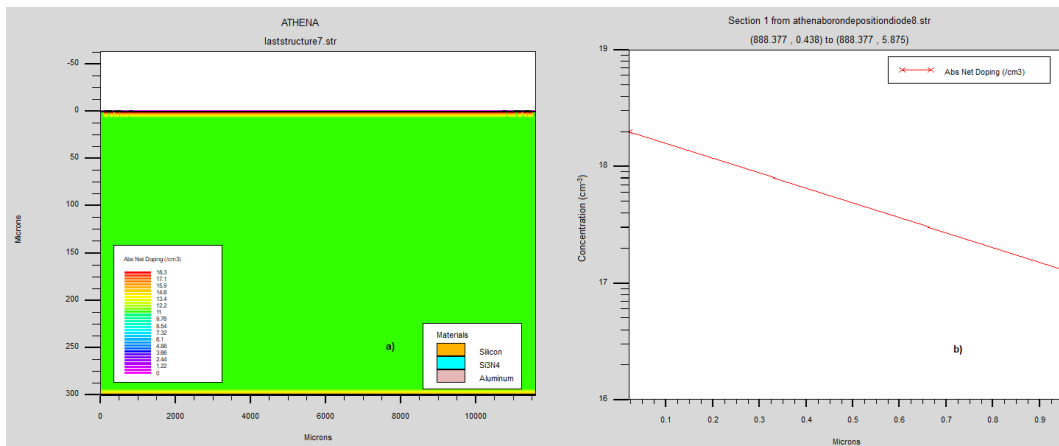


Figure 3.5. a) Phosphorus doped substrate, **b)** Ion profile of doping process

3.2.3 Metallization Process

After the boron doping process, The Si-PIN PD's metal contacts were formed by coating a layer of aluminum (Al) that was 1 μm thick on both the front and back sides of the substrate. Since the back surface will be completely covered with Al, aluminum etching has not been carried out on the back surface. The etching process has been performed on the front surface to selectively retain Al on the active area and guard rings. To mitigate the presence of surface current on the Silicon PIN photo diode structure with metal contacts, a layer of SiO_2 measuring 120 nm is applied to the front surface of the diode structure. In the next step, the SiO_2 layer on the metal contacts was removed. The fabrication simulation of the Si-PIN PD has been completed (Figure 3.6).

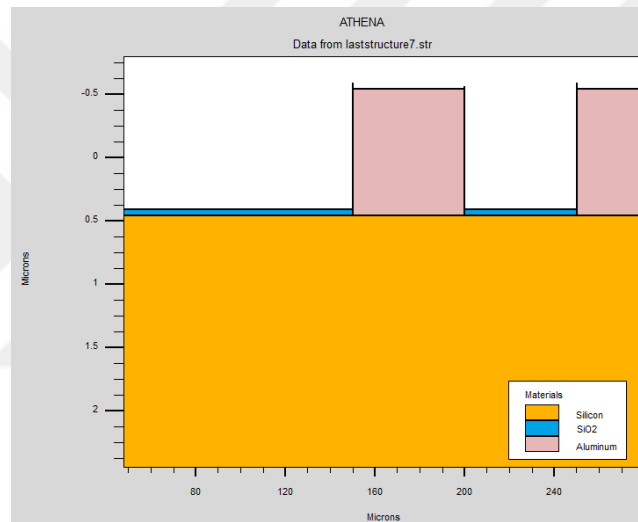


Figure 3.6. Aluminum and SiO_2 coating process

3.3 Device Characterization (ATLAS)

3.3.1 Current-Voltage Characterization

For device simulators, extracting reverse bias leakage currents for diodes offers some challenging numerical issues. These issues arise because of constraints on numerical precision. Double-precision arithmetic is used in ATLAS and the vast majority of other device simulators to calculate terminal currents. About 16 decimal places can be calculated with double precision. Extraction of reverse bias leakage currents for diodes presents device simulators with a number of complex numerical challenges. Due of limitations on numerical precision, these problems arise. Terminal currents are calculated utilizing double-precision arithmetic in ATLAS and the vast majority of other device simulators. With double precision,

approximately 16 decimal places are calculable. Current as low as 10^{12} A/micron to 10^{16} A/micron can be measured as a result of internal scaling. Unfortunately, this is near to or below the average leakage current of photodiodes. As a result, the printed current cannot be relied upon as an accurate estimation of the device leakage current, as they are prone to a high level of numerical noise. Two estimation methods exist for reverse leakage current.

The reverse behavior of diodes can theoretically be determined by either diffusion current in the neutral zones or recombination currents in the depletion region. With the assistance of ATLAS, these two mechanisms can be studied. Reverse leakage current can be estimated in two different ways.

One of two theoretical effects—diffusion currents in the neutral zones or recombination currents within the depletion region—can theoretically govern diodes' reverse behavior. Both of these mechanisms can be investigated with the help of ATLAS.

3.3.2 Capacitance-Voltage Characterization

The Quasistatic Capacitance is determined by the value of the QSCV parameter in the SOLVE statement. The electrode's quasistatic capacitance under a ramping bias can be calculated by subtracting the charge at one bias from the charge at the adjacent bias and dividing the result by the rise in voltage. Gauss's flux theorem is applied to the electrode to calculate the charge density. This value determines the capacitance at the center of the gap between the two bias points. Since the voltage increment is judged to be accurate enough, ATLAS does not rectify the output for this problem. As a result, this tweak is meaningless. Similarly, a moderate voltage boost will approximate the continuous derivative with high accuracy. Carrier support for the QSCV method can be specified in the METHOD declaration as 0, 1, or 2. Capacitance values for both electrodes and the whole circuit will be calculated when the CONTACT statement's COMMON parameter is used to link the electrodes. Capacitance at the linked electrode's relevant bias locations is computed and stored as a function of the bias given to the COMMON electrode when the MULT and FACTOR parameters are set. It's important to think about the possibility of scaling or altering the C-V curve in this case.

3.4 Photo Mask Design

Mask design was made using the "Clew in" drawing program of the photo diode structure determined by simulation studies. Three masks were designed for the fabrication stages.

1st Mask: Creation of active area and guard rings.

2nd Mask: Creation of metal contact areas.

3rd Mask: SiO₂ passivation.

Since the back surface of the substrate will be completely covered with phosphorus and the N⁺⁺ region will be formed, mask design for the back surface of the diodes is not needed. The Si-PIN PD structure with an active area of 10x10 mm², 12x12 mm², 20x20 mm², which is formed by the alignment of all masks, is shown in Figure 3.6 and its structural dimensions are shown in Table 1.

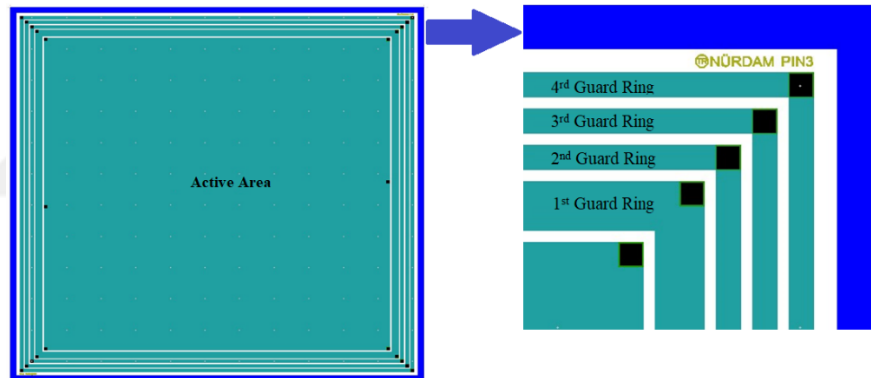


Figure 3.6. Si-PIN PD architectural structure

Table 2. Structural dimensions of the designed Si-PIN PD.

	Width (μm)	Thickness (μm)	Gaps among Guard Rings (μm)
1st Guard Ring	200	200	50
2nd Guard Ring	100	100	50
3rd Guard Ring	100	100	50
4rd Guard Ring	100	100	50

Si-PIN PDs, whose design has been completed, are placed on a 6 inch substrate as in (Figure 3.7). Thus, Si-PIN PDs of all sizes can be produced on the same substrate.

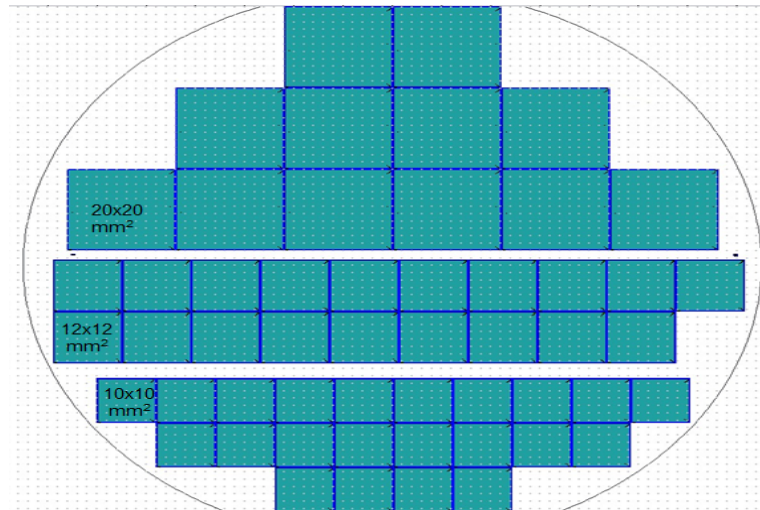


Figure 3.7. View of three different sizes of Si-PIN PDs on 6 inch substrate

3.5 Fabrication Process

3.5.1 Radio Corporation of America (RCA) Cleaning

N-type silicon substrates with 500 μm thickness, 10 $\text{k}\Omega\text{-cm}$ resistance and 100 crystal orientation were chosen to be used in the fabrication of Si-PIN PDs. It is extremely important to clean these substrates before fabrication. Because the slightest contamination on the substrates will affect the performance of the planned Si-PIN PDs or cause them to not work at all. In order to prevent this situation, the substrates were cleaned in three stages: organic, ionic and oxide cleaning.

Organic Cleaning:

In order to clean the organic pollution on the substrate, a chemical solution consisting of Pure water, Hydrogen peroxide, Ammonium solution at a ratio of 5:1:1 was prepared. This solution was then heated to 60 $^{\circ}\text{C}$. The 4 lower substrate, which are planned to be used in production, were kept in the solution that came to thermal equilibrium for 17 min. and the substrate were washed with pure water, thus the organic cleaning phase was completed.

Ionic Cleaning:

The substrates, whose organic cleaning process has been completed, have been subjected to ionic cleaning application. Thus, it is aimed to remove the ionic pollution on the substrate. In line with this goal, a 6:1:1 ratio of pure water, hydrochloric acid, hydrogen peroxide solution was prepared and heated up to 60 $^{\circ}\text{C}$. The lower stones were kept in the solution that came to thermal equilibrium for 17 min. and the lower stones were washed using distilled water. Thus, the ionic cleaning process is completed.

Oxide Cleaning:

After the ionic cleaning steps are successfully completed, it is aimed to clean the naturally growing oxide layer on the substrates and for this process, a solution consisting of pure water and hydrofluoric acid in a 100:1 ratio was prepared. The substrates were kept in this solution for 15 s and then washed with distilled water. The substrates, whose washing process was completed, were dried with the help of nitrogen gas.

3.5.2 Initial Oxide Growth

It is aimed to grow a 1000 nm thick silicon oxide (SiO_2) layer, which will act as a mask during the production stages, on the silicon substrates. In line with this goal, a thermal diffusion furnace was used for the 1000 nm oxide growth process. Since the SiO_2 layer will only act as a mask, the oxide quality is not very important. Therefore, it is aimed to enlarge the layer by wet oxidation method. The recipe to be used in diffusion furnaces was checked using the "Silvaco ATEHA" simulation tool. The simulation showed the SiO_2 thickness as 1030 nm. Using a simulation-controlled recipe, the substrates were covered with SiO_2 using a diffusion furnace at 1000 °C (Figure 3.8). After the oxidation process was completed, the enlarged oxide thickness was measured with an ellipsometer (Figure 3.9). SiO_2 thickness was measured as 932 nm. The thickness difference of 68 nm can be ignored as it will not have any negative impact on device performance.

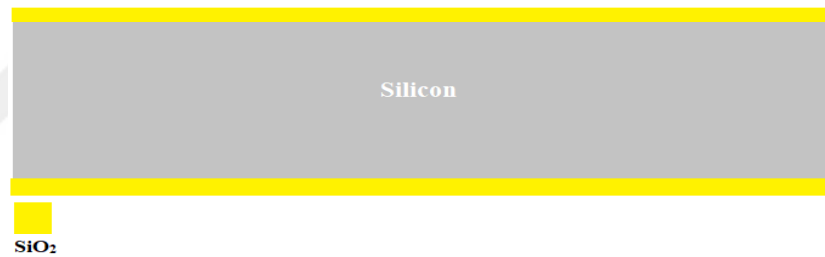


Figure 3.8. Schematic representation of the structure whose SiO_2 growth

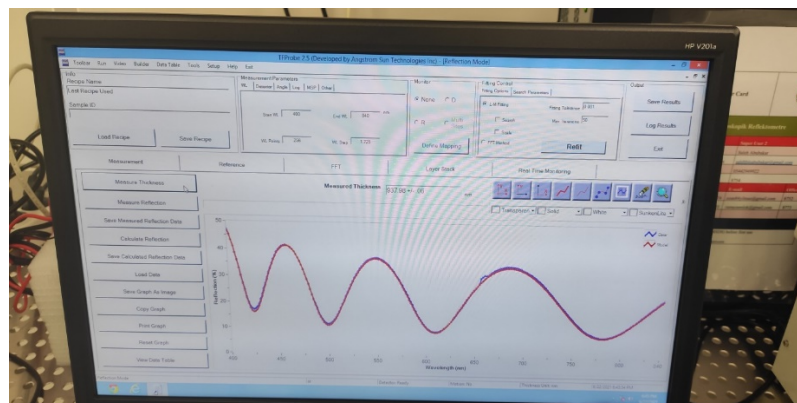


Figure 3.9. Measurement of SiO_2 thickness with an ellipsometer.

3.5.3 First Photo Lithography Process for Phosphor Deposition

Phosphorus doping is aimed for the N^{++} region to be located on the back surface of the substrate. In line with this goal, the 932 nm thick SiO_2 layer on the back surface of the substrate should be removed. Therefore, the front surface of the substrate was covered with photoresist (PR) of 1 μm thickness by spin coating method (Figure 3.10). The substrate was then heated at 135 °C for 3.5 min.

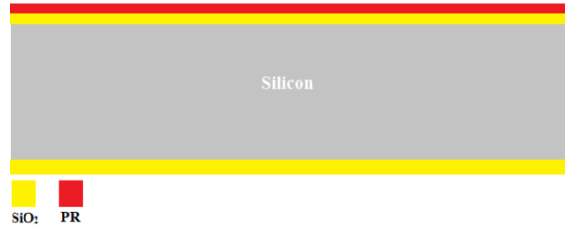


Figure 3.10. Schematic representation of the substrate covered with PR

The back surface of the substrate, whose PR coating process has been completed, should be removed. For this process, a buffer solution (BF) consisting of 235 gr Ammonium Fluoride, 130 ml Purified water and 120 ml hydro fluoric acid was prepared. The substrates were kept in this solution for 13 minutes and the SiO_2 layer on the back surface was removed. In the next step, the substrate was placed in the PR removing solution (Remover) and the PR on the anterior surface of the substrate was removed (Figure 3.11).

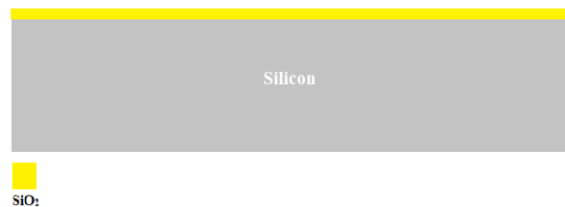


Figure 3.11. Structure with SiO_2 layer removed from its back surface

Before the doping process, the sample doping was analyzed by secondary ion spectroscopy (SIMS) measurement to check the suitability of the recipe we prepared in the diffusion furnaces. The ion density obtained in Figure 3.12 was determined to be suitable for our fabrication.

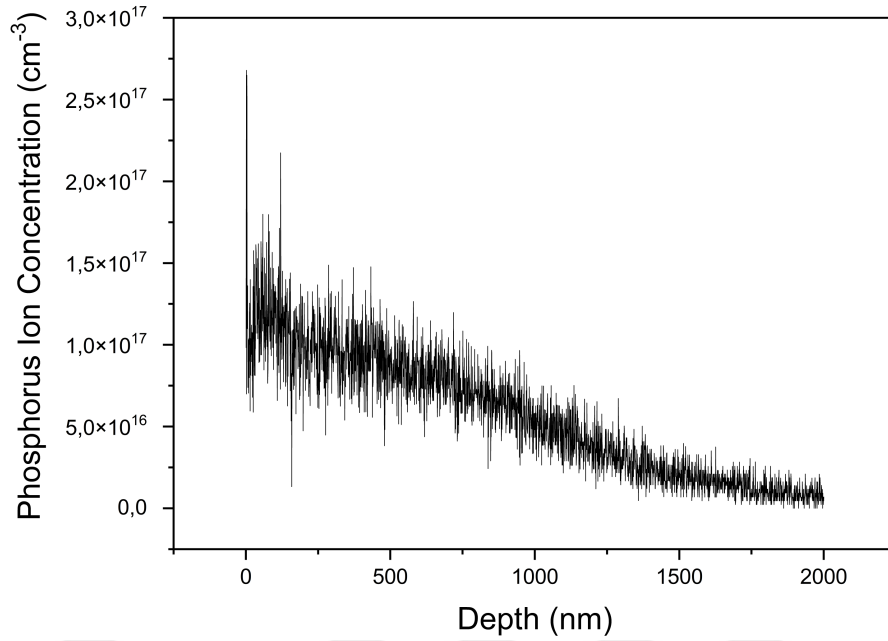


Figure 3.12. SIMS analysis for Phosphorus

The rear surface of the substrate prepared for the doping process is shown in Figure 3.13. Phosphorus was doped by using diffusion furnaces. 130 nm SiO₂ was grown on rear surface during the thermal doping process.

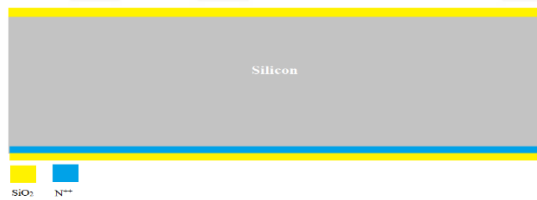


Figure 3.13. Schematic representation of the N⁺⁺ region-formed structure

In order to understand whether the doping process was successful or not, the resistance measurement of the sample substrate placed in the furnace before doping was performed in Table 2, Figure 3.14 and after doping in Table 3, Figure 3.15. We expect that the resistance of the substrate will decrease in a successful phosphorus doping.

Table 3. Substrate resistance measurement before phosphorus doping

Point	X	Y	R_s (Ω/sq)	Resistivity (Ωcm)	V/I	Thickness (μm)
1	0	0	87981.6	9399.1	19752.1	500
2	65	0	92949.4	8647.5	20371.3	500
3	0	65	115661.5	1083.1	23564.7	500
4	-65	0	92573.6	9628.7	20202.6	500
5	0	-65	174430.0	8721.5	38203.0	500

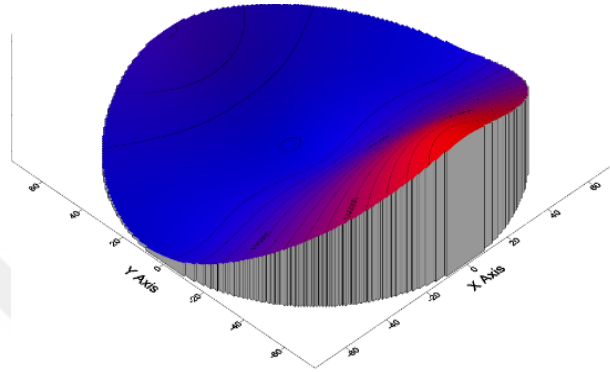


Figure 3.14. Graph of the resistance change on the substrate before phosphorus doping

Table 4. Substrate resistance changes after Phosphorus deposition

Point	X	Y	R_s (Ω/sq)	Resistivity (Ωcm)	V/I	Thickness (μm)
1	0	0	16.141762	0.807088	3.58399	500
2	65	0	15.893636	0.794682	3.515991	500
3	0	65	16.057873	0.802894	3.525136	500
4	-65	0	15.810337	0.790517	3.524766	500
5	0	-65	11.934164	0.596708	2.693879	500

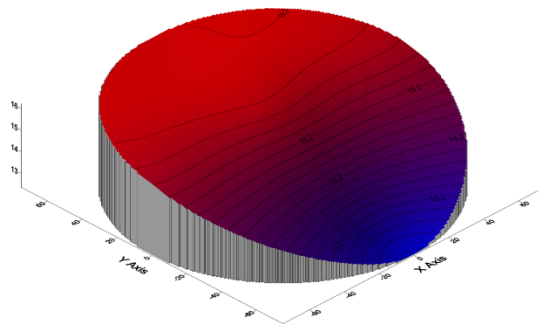


Figure 3.15. Resistance distribution on substrate after phosphorus doping

3.5.4 Second Photo Lithography Process for Creation active region and guard rings

After the successful creation of the N^{++} region, it was aimed to create a P^{++} region on the anterior surface of the substrate. In line with this goal, the front and back surfaces of the substrate were coated with PR using the spin coating method for the first lithography process of the last structure shown in (Figure 3.16). Next, the first mask was aligned to the front face using the mask alignment system for identifying the regions of P^{++} and the guard rings (Figure 3.17).

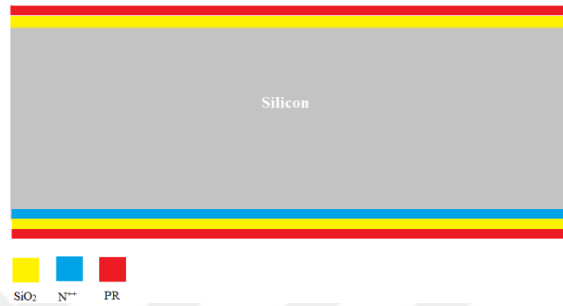


Figure 3.16. PR coating on the front and back surface of the substrate by spin coating method

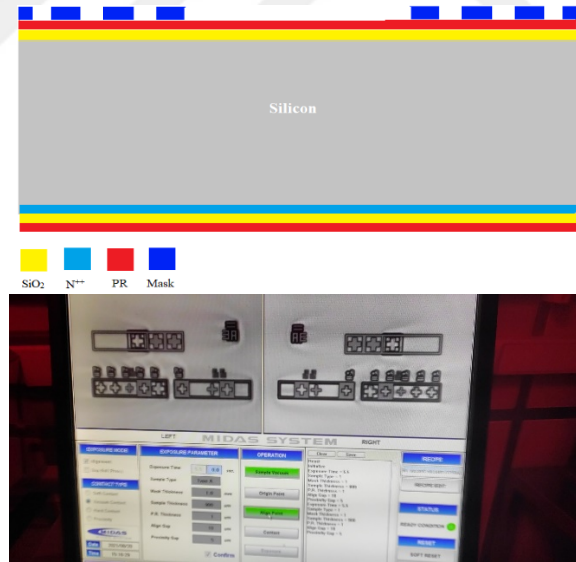


Figure 3.17. Alignment of the first mask for creation P^{++} and guard rings

After alignment of the mask, ultraviolet light was irradiated from the open areas of the mask and the PR in these areas was refuted, then the refuted PR was removed with the developer solution. After the PR removal process, the SiO₂ layers in these regions were removed with the BF solution. The PR layer remaining in

other parts of the building was cleaned with the help of a special lifting solution, and the substrate were made ready for Boron doping (Figure 3.18).

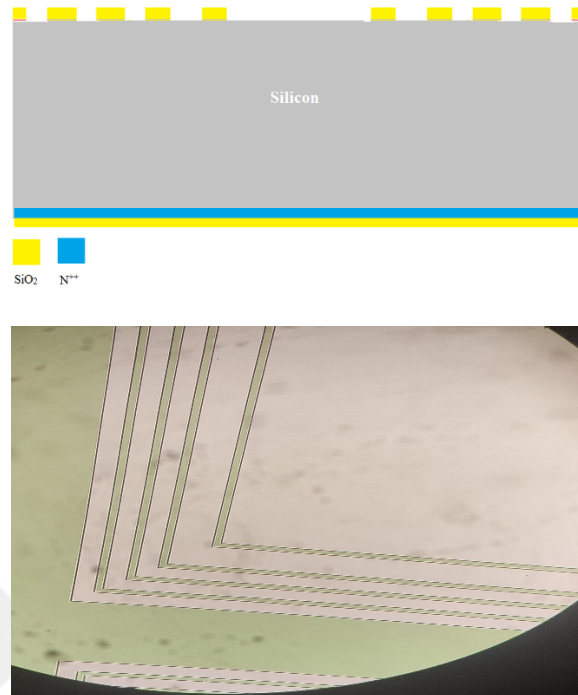


Figure 3.18. Structure before boron doping

Before the boron doping process, trial doping was made and the ion density of the recipe to be used for doping was examined by SIMS measurement (Figure 3.19).

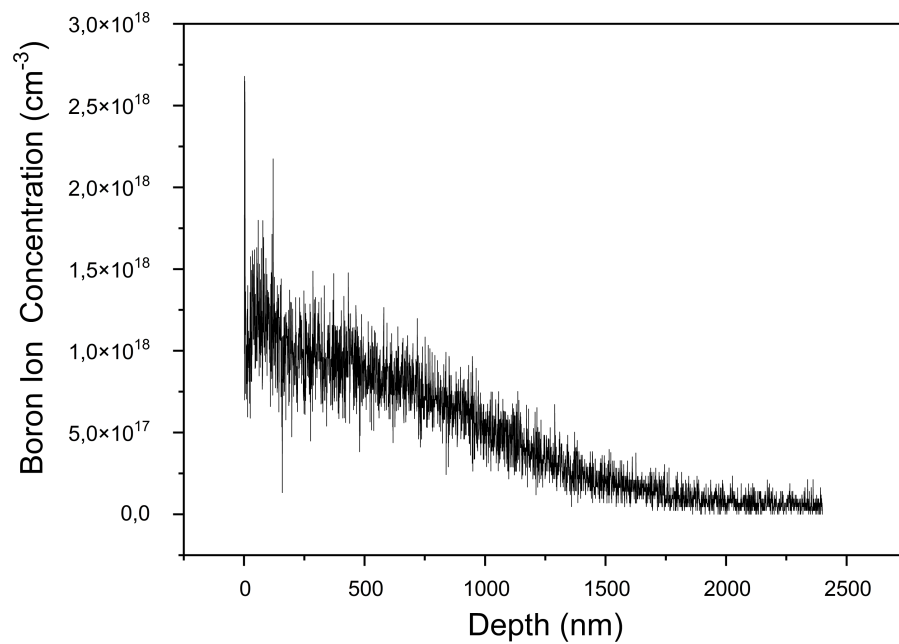


Figure 3.19. SIMS analysis of boron ion distribution with depth

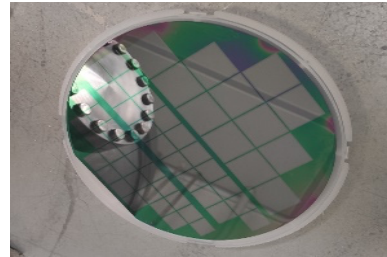
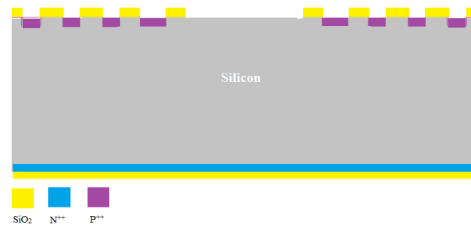


Figure 3.20. Formation of P⁺⁺ and guard rings by boron doping

After doping, resistance measurements were made on the substrate. The obtained substrate resistance values were compared with the substrate resistance values before doping in Table 5 and Table 6.

Table 5. Substrate resistance measurement before doping

Point	X	Y	Rs (Ω/sq)	Resistivity (Ωcm)	V/I	Thickness (μm)
1	0	0	129799.0	8489.9	28053.4	500
2	65	0	136407.2	9820.4	28165.0	500
3	0	65	180638.6	9031.9	33331.6	500
4	-65	0	103694.6	1084.7	23786.1	500
5	0	-65	679844.3	8992.2	-29552.8	500

Table 6. Substrate resistance measurement after doping

Point	X	Y	Rs (Ω/sq)	Resistivity (Ωcm)	V/I	Thickness (μm)
1	0	0	69.333847	3.466692	15.530652	500
2	65	0	77.229973	3.861499	17.21328	500
3	0	65	69.434166	3.471708	15.509208	500
4	-65	0	74.55027	3.727514	16.678165	500
5	0	-65	77.374527	3.868726	17.269159	500

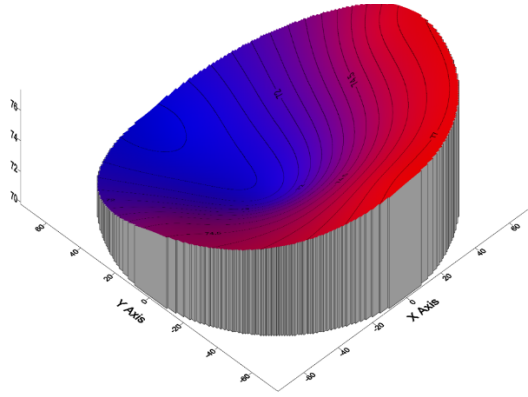


Figure 3.21. Substrate resistance after boron ion deposition

3.5.5 Third Photo Lithography Process for Metal Contact

After the completion of the thermal deposition processes, the P-I-N structure was successfully formed. In the obtained structure, metal contact formation process was performed to read the electric current passing through the P^{++} and N^{++} regions. During the process, 1 μm thick Aluminum (Al) was coated on the front and back surfaces of the substrate using the RF sputtering method (Figure 3.22).



Figure 3.22. The structure formed after the Al coating process

In order to determine the metal points of the substrate whose metal deposition has been completed, PR was coated on the front and back surfaces of the structure and a metal mask was applied on the front surface. By irradiating UV light from the open areas of the mask, the PR in these areas was refuted. After rotting, the substrate

was placed in the developer solution and the rotting PR was removed (Figure 19a and Figure 19b and Figure 19c).

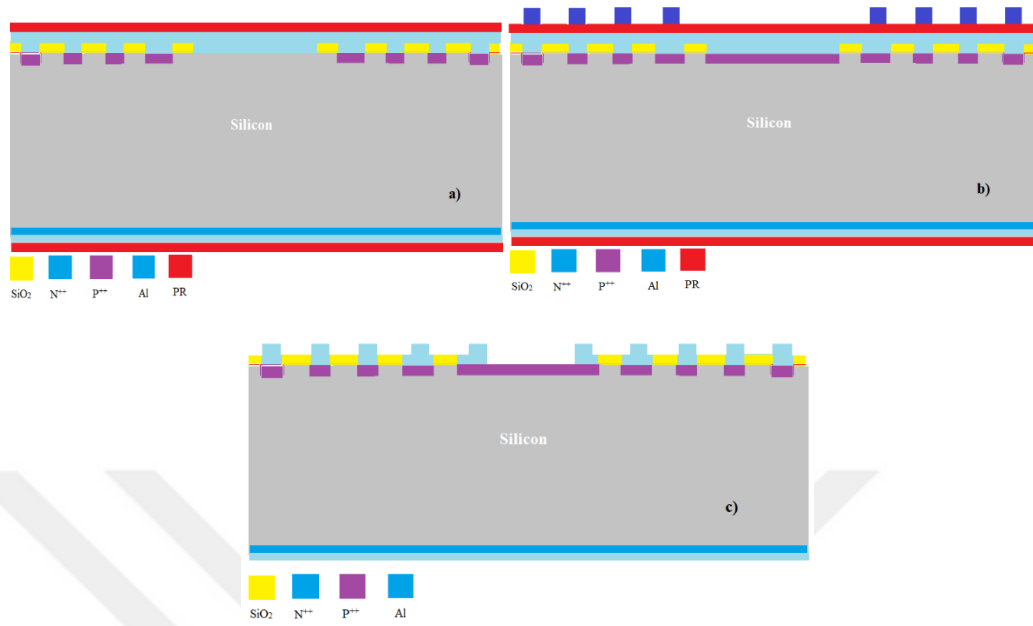


Figure 3.23. a) Application of the metal mask **b)** Removal of PR from the opened areas **c)** Metal contact structure

3.5.6 Surface Passivation

The current formed on the surface of the photodiode increases the leakage current of the photodiode. The photodiode will have more signal noise due to this increase, which will negatively affect the performance of the photodiode. To prevent this, the surface of the photodiode was coated with 151.72 ± 0.10 nm SiO₂ using a dry oxidation method.

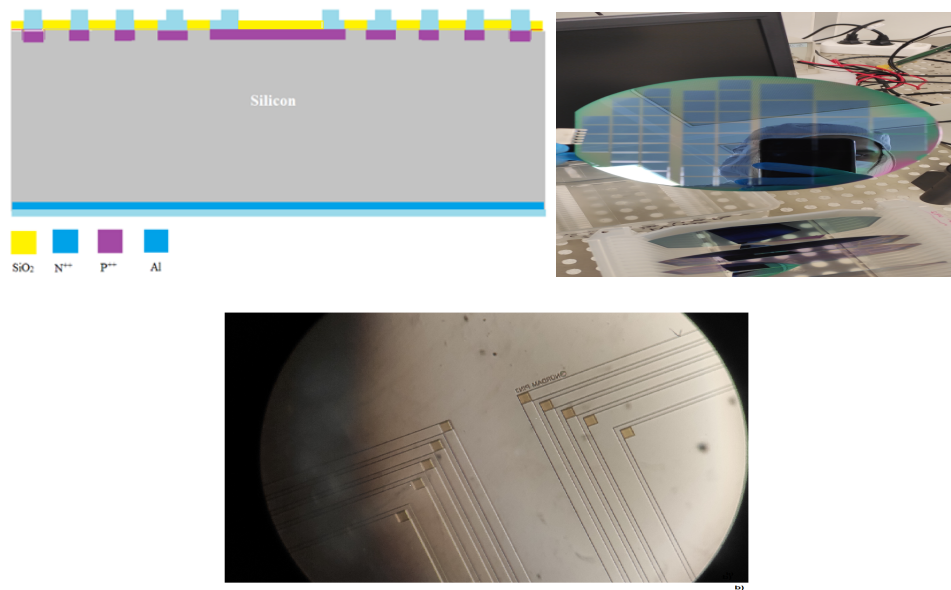


Figure 3.24. Silicon PIN Photodiode Structure

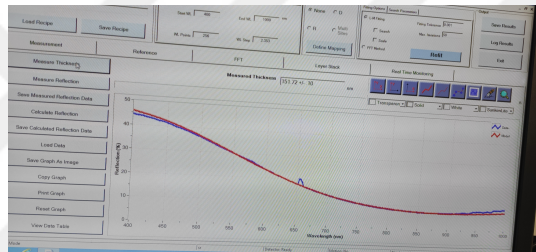


Figure 3.25. Thickness measurement of SiO_2 layer

3.5.7 Packaging of Fabricated Silicon PIN photodiodes

Produced photodiodes must be packaged so that they can be integrated into the electronic circuit. Due to the large size of the photodiodes, a package was created using Solidworks software (Figure 3.26).

3.6 Characterization of Silicon PIN Photodiodes

3.6.1 Current- Voltage Measurement

The dark current values of Si-PIN PDs with $10 \times 10 \text{ mm}^2$, $12 \times 12 \text{ mm}^2$ and $20 \times 20 \text{ mm}^2$ active areas completed were measured by using KEITHLEY SCR 200 on probe station (Figure 3.28). During the experimental process, 18 Si-PIN PD samples were prepared from photodiodes with three different sensitive regions. The dark environment of these samples grouped according to the size of the sensitive region and the current-voltage (I-V) values are measured at room temperature. The regions of Si-PIN PDs taken for measurement are detailed in (Figure 3.29).



Figure 3.28. Probe station system to measure I-V of Si-PIN PD

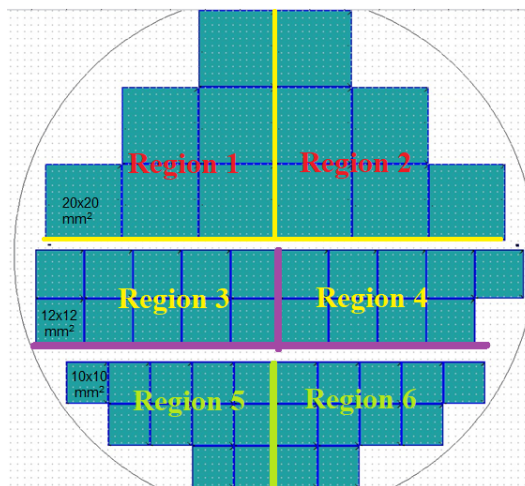


Figure 3.29. Regions of the selected Si-PIN PDs

3.6.2 Capacitance -Voltage Measurement

The produced Si-PIN PDs were grouped into six units according to the size of the active area and a total of eighteen C-V measurements of the Si-PIN PDs' were carried out using HIOKI 3532-50 LCR tester and KIKUSUI bipolar power supply PBZ40-10 (Figure 3.30). C-V analyses of photodiodes were performed using voltage up to -30 V at a frequency of 1 MHz.



Figure 3.30. C-V measurement system

3.6.3 Current -Voltage and Rise Time Measurements under Light

The elevation times of Si-PIN PDs were achieved by experimental installation in Figure 3.31. In the experimental scheme, a -25 V voltage was applied to the photodiode. 100 kHz light pulses have been produced by connecting the 650 nm point red light source to the Hp 8116A signal generator, and these pulses were illuminated in the active sensor region of the Si-PIN PD. The time analysis of the resulting signal was analyzed using the Tektronix MDO 4 series oscilloscope.

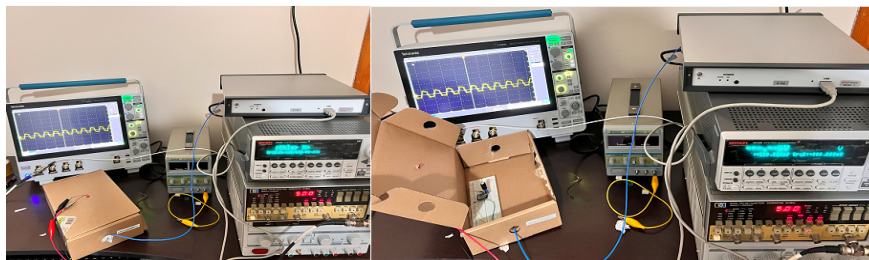
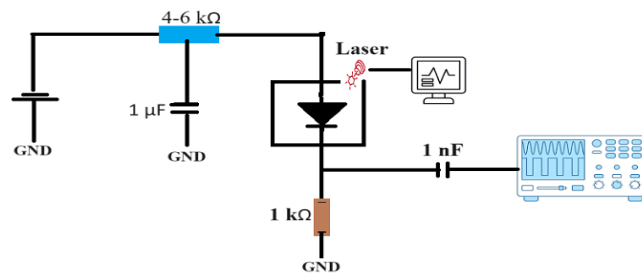


Figure 3.31. Rise time measurement setup

Figure 3.32 analyses the on/off characteristics of photodiodes under dark environment. The active corner area of the diode was illuminated using laser light with 650 nm and 532 nm wavelengths. Using the Keithley source meter on current and off current are determined. At the same time, the on/off time of the photodiode was observed with an oscilloscope.

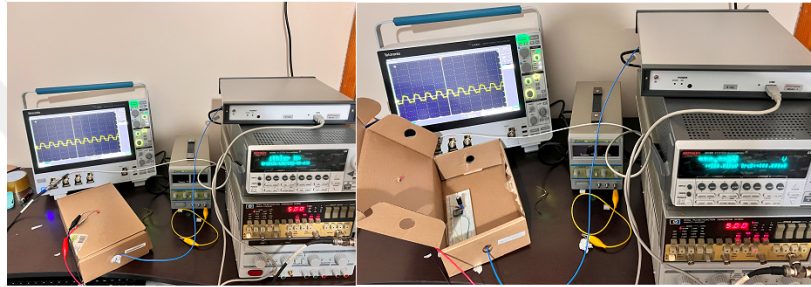
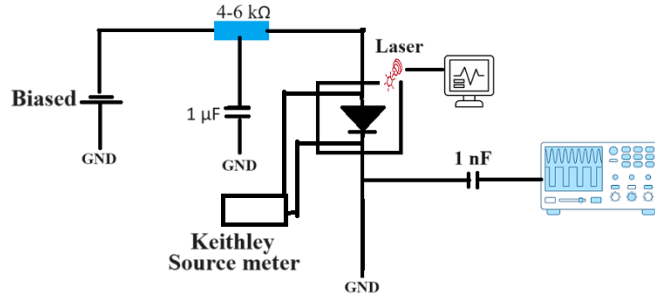


Figure 3.32. On-Off current measurement

3.7 Radiation Response of Si-PIN Photodiode

3.7.1 Si-PIN Photodiode Response Measurement under Sr-90, and Thallium-204

Si-PIN PDs produce very little current order of nA under the radiation source, so it is quite difficult to read this current correctly and understand the signal. The signal generated by the Si-PIN PDs under the radiation source is readable by the wave-shaping amplifier (Micod LTD CA 25) after being amplified with the (Micod LTD CSA 250) pre-amplifier with a gain of 10^6 (Figure 3.33). The photon current converted from current to voltage by elevation was analyzed using the Tektronix MDO 4 series 500 MHz Digital Oscilloscope. The noise level (65 mV) observed from the oscilloscope screen, the trigger voltage is assumed, and this value is entered in the multi-channel analyzer (MCA) as the limit voltage (Figure 3.34).

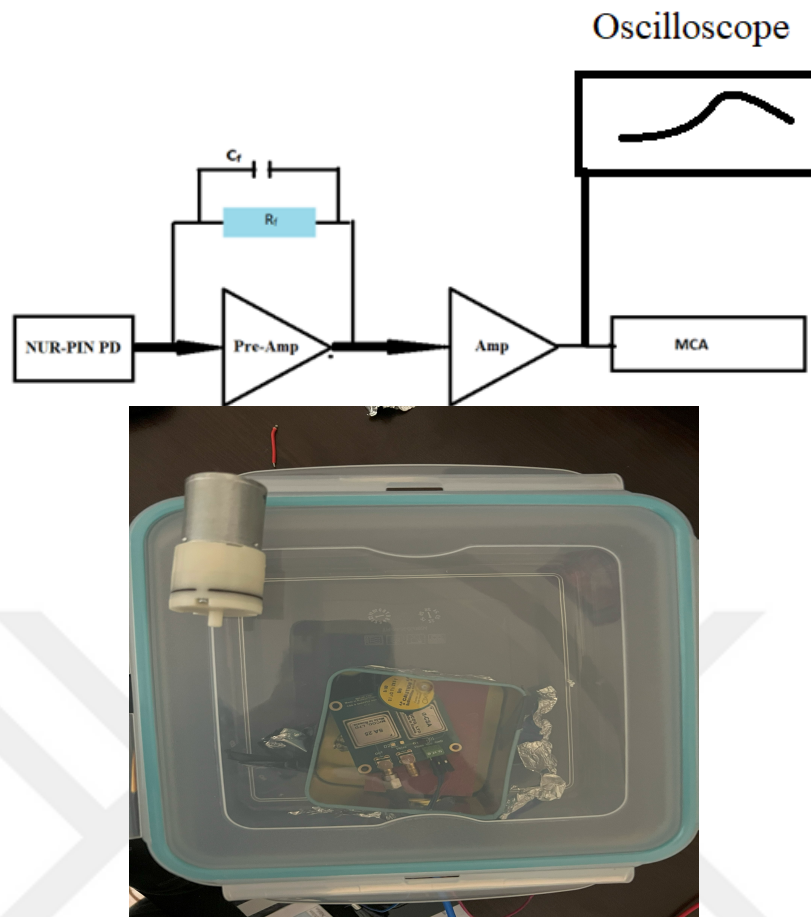


Figure 3.33. Schematic representation of experimental setup and amplifier circuit

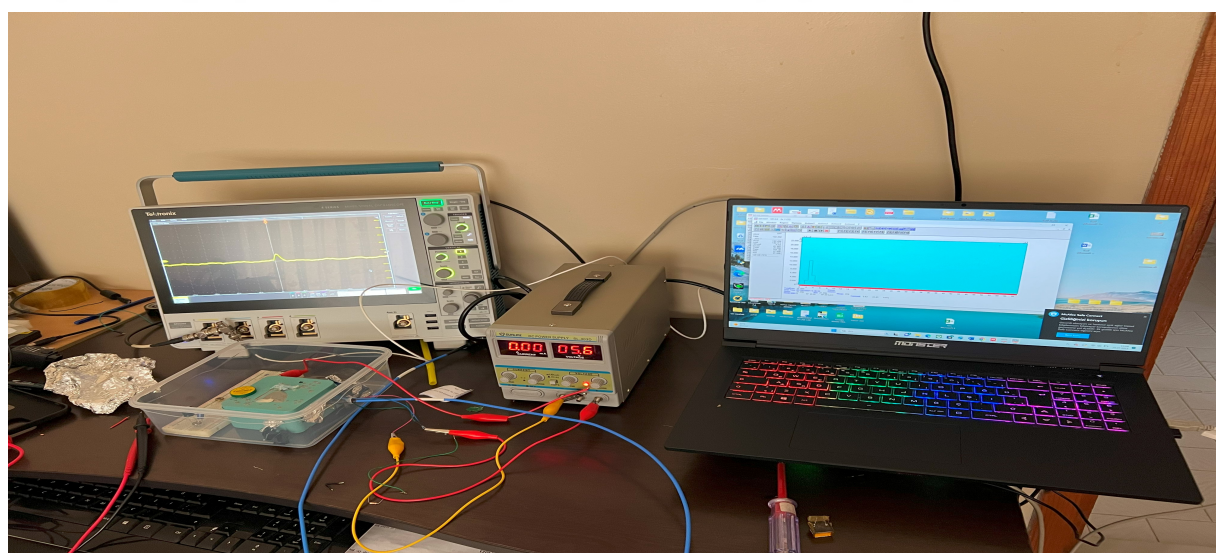
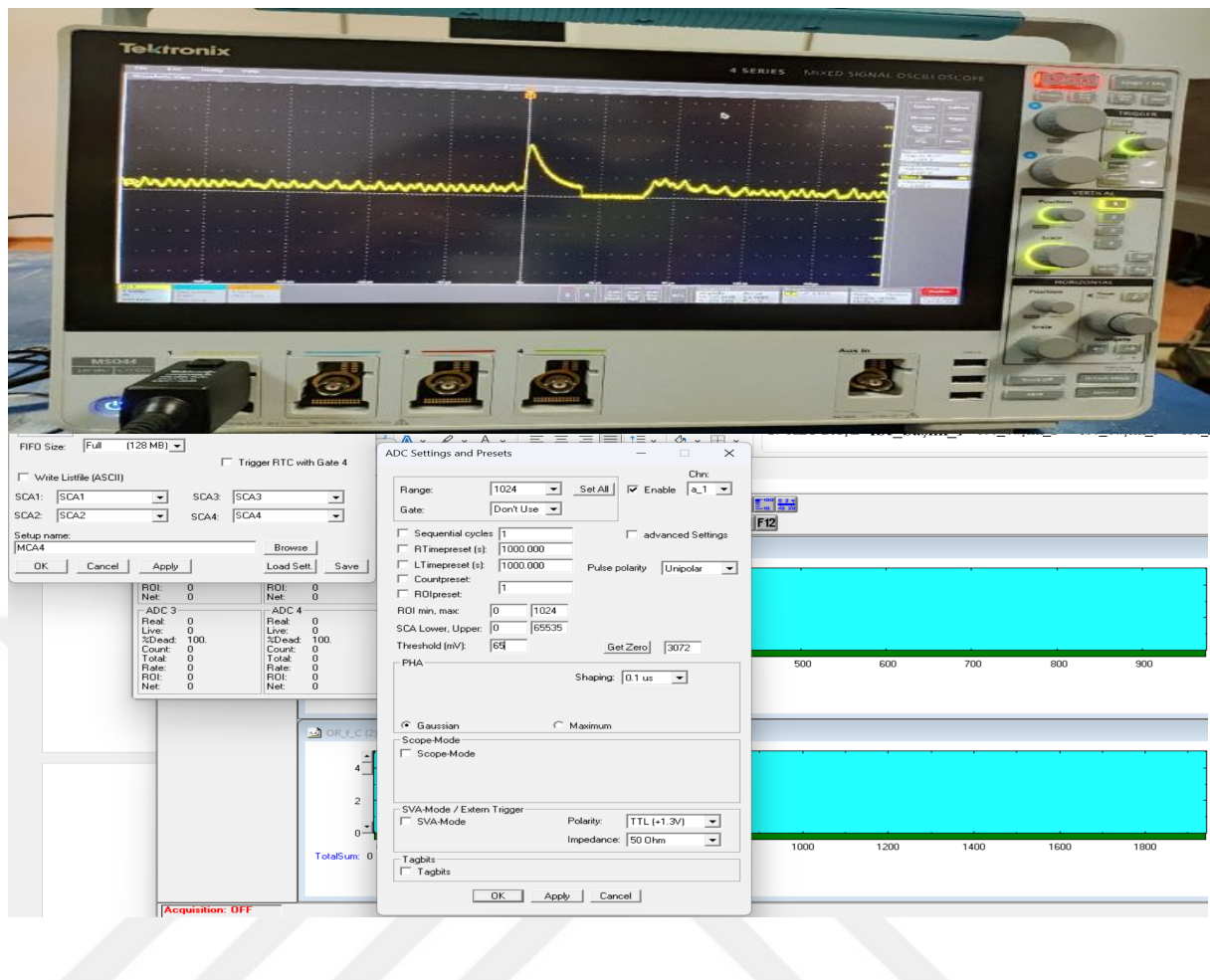


Figure 3.34. Pictures of Oscilloscope and MCA

3.7.2 X-Ray Measurement of Si-PIN Photodiode.

Si-PIN PDs have been performed X-ray tests. For experimental operations, the Italray Pixel HF X-ray device, located in the ion room at the Ankara Institute of Nuclear Sciences, was used for experimental research at 50 kW power, radiographic power range 40-150 kVp characteristics. Experimental setup is shown in (Figure 3.35 and Figure 3.36).

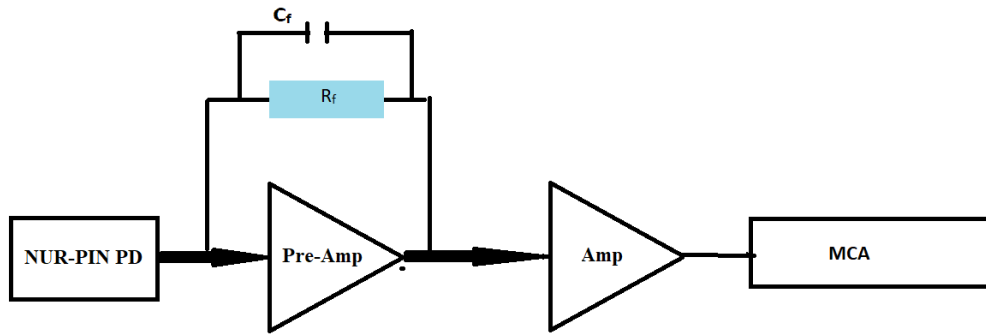


Figure 3.35. Schematic representation of experimental setup.



Figure 3.36. X-Ray tests at ion room.

4 RESULTS AND DISCUSSION

4.1 Investigation of Electrical Characterization of Si-PIN PDs

The electrical behavior of Si-PIN PDs with a different structure created using the Silvaco software ATLAS tool. A photodiode must have a low dark current and capacitance value to have high reaction and resolution under ionized radiation. Thus, in the device simulation studies I-V, C-V, Responsivity results were studied.

4.1.1 I_d -V and C-V Characterization of Si-PIN PDs With Two Guard Rings

A diode structure with $10 \times 10 \text{ mm}^2$, $12 \times 12 \text{ mm}^2$, $20 \times 20 \text{ mm}^2$ active area and two Guard has been created. When I_d -V and C-V behaviors of this structure were studied, it was found that the I_d values of the diode increased very slowly as the voltage increased. However, I_d of Si-PIN PDs at -90V, which are shown in Table 6, is not desired level. More than 10 nA dark current can cause electronic noise that effects the detectors resolution negatively (Figure 4.1).

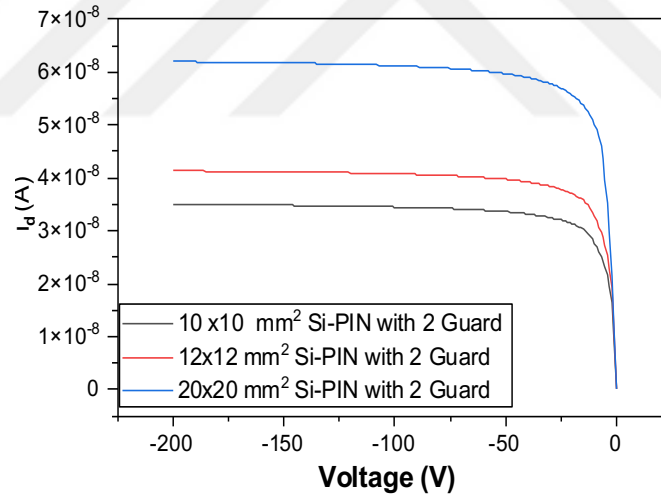


Figure 4.1. I_d -V characteristics of Si-PIN PDs with Two Guard Rings

When the C-V values of Si-PIN PDs were analyzed, the capacitance values for photo diodes with three different dimensions of active fields decreased to -20 V along with voltage increases, and when the voltage was further increased, there was little decrease in the capacitance values. This capacitance behavior indicates that the diodes reached depletion mode at -20 V (Figure 4.2). Obtained capacitance values are given in Table 7.

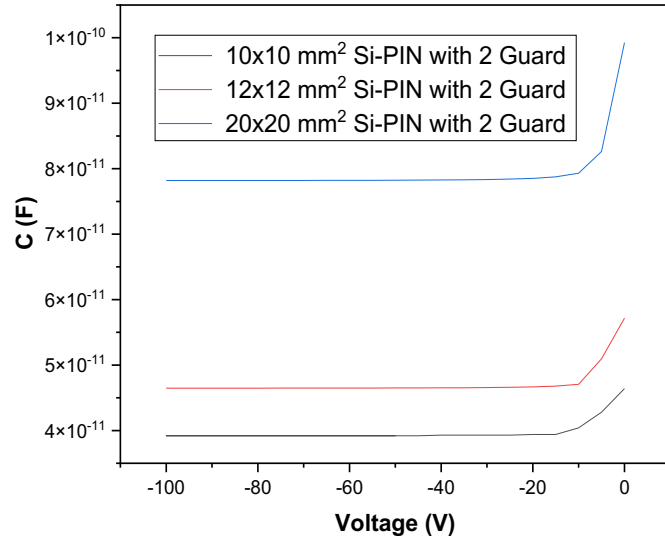


Figure 4.2. C-V characteristics of Si-PIN PDs with Two Guard Rings

Table 7. I_d -V and C-V values for Si-PIN PDs with Two Guard Rings

Active Area (mm ²)	10x10	12x12	20x20
I_d (nA) @-90V	34	40	61
Capacitance (pF) @-90V	40	46	78

Although the capacitance values of Si-PIN PDs with two guard rings match the literature values, the dark current values are higher than the median Si-PIN PD used in radiation sensing (102). The increase in the number of guard rings in the Si-PIN PD structure is clearly stated in the literature, where it reduces dark current (103,104). In this context, Si-PIN PD examined dark current values by increasing the number of guard rings.

4.1.2 I_d -V and C-V Characterization of Si-PIN PDs with Three Guard Rings

One more Guard Ring was added to the photodiode structure because the dark current values of the Si-PIN PDs with two guard rings were not at the desired level. The distances between the protective rings have been changed. The distance between each protective belt was increased from 30 μm to 40 μm . SiO_2 was also amplified to the diode surface at different thickness to better eliminate the current

from the surface, and a drop in the Si-PIN PD dark current values was observed (Figure 4.3).

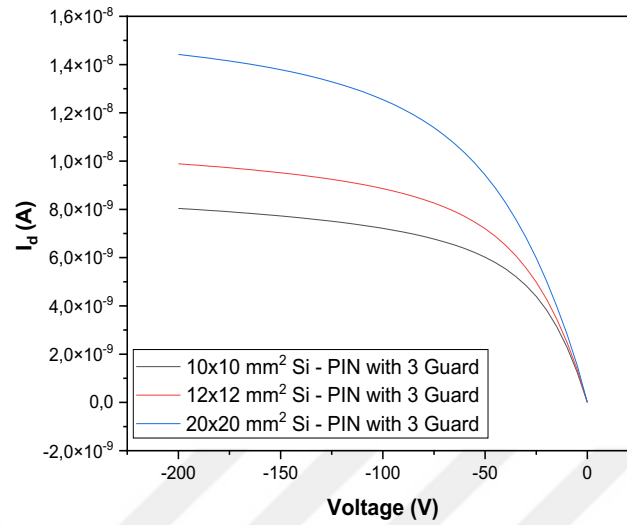


Figure 4.3. I_d -V characteristics of Si-PIN PDs with Three Guard Rings

When the dark current value of Si-PIN PDs with three Guard ring are examined, the current value for the device with an active area of 10x10 mm² and 12x12 mm² at -90 V varies from 1 nA to 10 nA. But when the active area is 20x20 mm², the dark current is 12 nA. There was no significant difference in the capacitance values of three guard rings Si-PIN PDs compared to the two guard rings Si-PIN PDs (Figure 4.4).

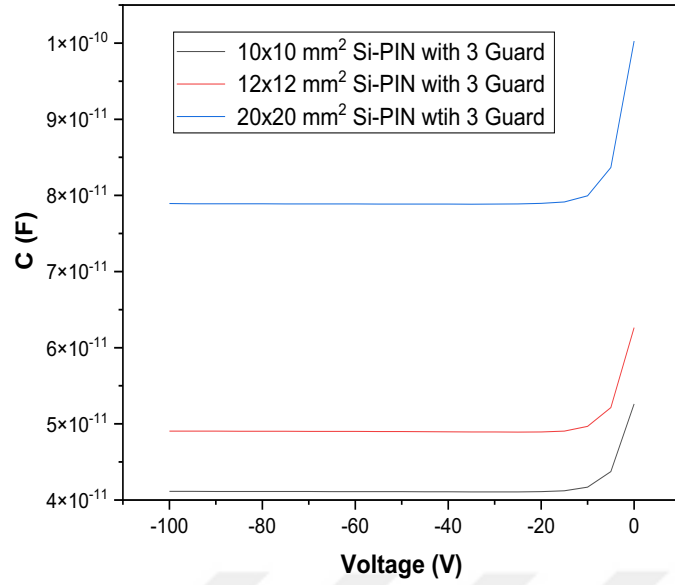


Figure 4.4. C-V characteristics of Si-PIN PDs with Three Guard Rings

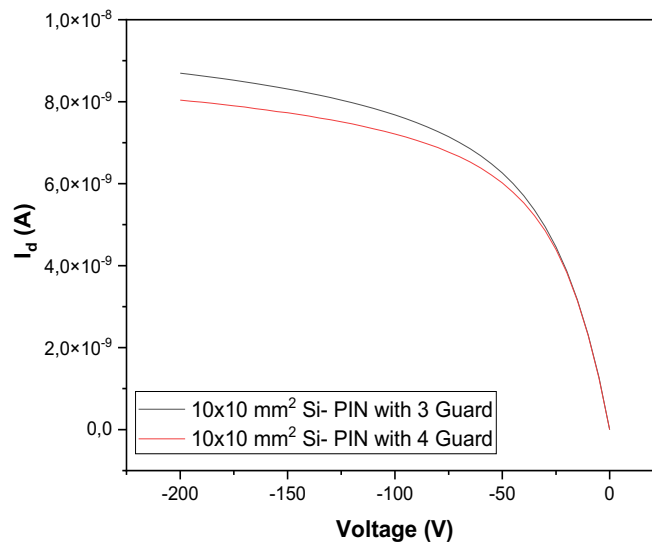
4.1.3 I_d -V and C-V Characterization of Si-PIN PDs with Four Guard Rings

The observed result aligns with what was anticipated. The capacitance value of a photodiode is influenced by several key parameters, namely the active area length of the diode, the thickness of the substrate utilized in the diode's design, and the ion profile contribution (41,72). The design of the Si-PIN PDs, featuring three guard rings, has remained unaltered in terms of the thickness of the substrate and the dimensions of the active field. The joining profiles exhibit similarity to the two-guard ring Si-PIN PDs, with the exception that the depth of the P^{++} region has been decreased from 300 nm to 200 nm. The present scenario gives rise to a disparity in capacitance values of such magnitude that this alteration will be disregarded. The dark current and capacitance values obtained are presented in (Table 8).

Table 8. I_d -V and C-V values for Si-PIN PDs with Three Guard Rings

Active Area (mm ²)	10x10	12x12	20x20
I_d (nA) @ -90V	7	8.65	12
Capacitance (pF) @ -90V	41	49	78

When conducting an analysis of the electrical characteristics of Si-PIN PDs equipped with three guard rings, it is observed that the capacitance values align with the intended specifications. The measured dark current value of a photo diode with a relatively small active area of 12x12 mm² did not meet the expected value in terms of current values. Therefore, the objective is to mitigate the voltage-induced current escalation in the SI-PIN PD structure by incorporating an additional protective loop. To achieve this objective, the Si-PIN PD was incorporated into a guard ring of comparable dimensions, while also increasing the spacing between the guard rings by 50 μ m. The specific measurements pertaining to the structure can be found in the section dedicated to mask design. The ion density of the P⁺⁺ zone in four Si-PIN PDs with protective rings was found to be 2.5×10^{18} cm⁻³ at a depth of 110 nm. Additionally, the N⁺⁺ zone density is expected to be 1×10^{16} cm⁻³ within a range of 1-2 μ m. Figure 4.5 presents a comparative analysis of the electrical characteristics exhibited by four Si-PIN PDs equipped with three guard rings, in contrast to three Si-PIN PDs also equipped with four guard rings.



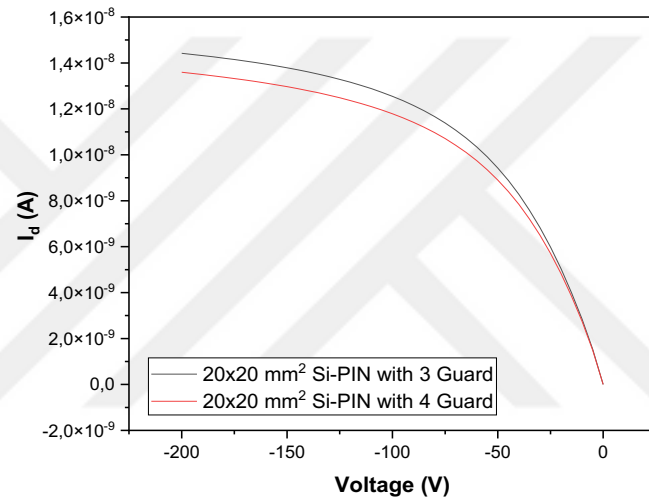
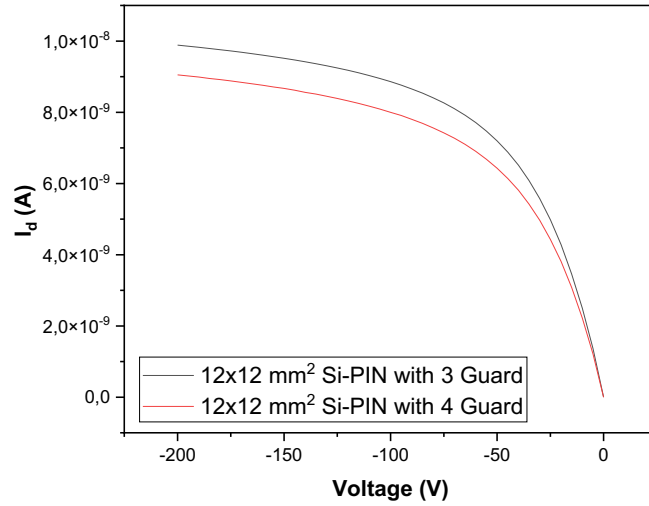


Figure 4.5. Comparison of the I_d -V characterization of the four guard ring Si-PIN PD and three guard rings

When I-V behaviors were investigated, four guard-ringed Si-PIN PDs with active areas of $10 \times 10 \text{ mm}^2$, $12 \times 12 \text{ mm}^2$, and $20 \times 20 \text{ mm}^2$ increased more slowly than anticipated. Additionally, dark currents were found at -90 V between 1 nA and 10 nA. These values are consistent with the values in the expected electrical performance (40).

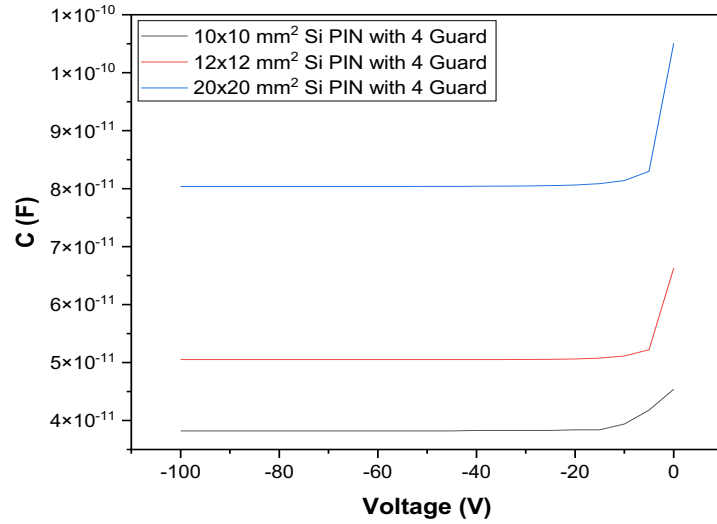


Figure 4.6. C -V characterization of Si-PIN PD with four guard rings

Noise current calculations have been conducted for this diode architecture, as the I-V and C-V values are at the desired level. The major source of noise in photoconductive diodes is the noise current. It is anticipated that the noise current will be on the order of $10^{-14} \text{ A}/(\text{Hz})^{1/2}$, as photo diodes with optimal characteristics exhibit excellent sensitivity to low levels of light. The calculation of the noise flow of the finalized construction was performed utilizing Equation 31

$$I_n = \sqrt{2q (I_{light} + I_{dark}) \Delta f} \quad (31)$$

Where, I_n , I_{dark} , I_{light} , Δf are noise current, dark current, light induced current and band width of Si PIN PDs

Once the fabrication process of photo diodes has been finalized, a layer of black resin will be applied to the sensing portions of the diodes. This protective coating serves the purpose of confining their sensitivity solely to ionized radiation. Hence, in the context of radiation measurements, the noise stream of the photo diodes will remain unaffected by the presence of light. Hence, solely the dark current was employed in the computation of the diode's noise current. Based on the acquired data, it can be observed that the noise currents exhibited by the diodes exhibit a range between $3.98 \times 10^{-14} \text{ A}/(\text{Hz})^{1/2}$ and $4.60 \times 10^{-14} \text{ A}/(\text{Hz})^{1/2}$, with variations contingent upon the dimensions of the active region. The noise flow data pertaining to the diodes are provided in (Table 8).

The Si-PIN PDs, which have been engineered for operation in the presence of ionizing radiation, possess a broad range of applications. Hence, it is crucial to consider the spectral response characteristics exhibited by the Si-PIN PD that have been constructed when exposed to light. The spectral responses of photodiodes with four guard rings, $10 \times 10 \text{ mm}^2$, $12 \times 12 \text{ mm}^2$ and $20 \times 20 \text{ mm}^2$, have been observed to be between 0.5 A/W and 0.6 A/W under light with wavelengths of 800 nm and 960 nm. Since the material and structure used in the design of photo diodes with three different active fields are the same, the spectral response behavior of the diodes is expected to be the same. The results of the simulation show that the spectral response behavior of Si-PIN PDs with three different active regions is the same as $\pm 1 \text{ A/W}$ deviation (Figure 4.7). The deviation was caused by small slides in the diode structures (Mesh) created during the simulation as the area of diode sensing expanded. Obtained spectral responsivity results are consistent with literature (37,43). The spectral response behavior of diodes is detailed in (Table 9).

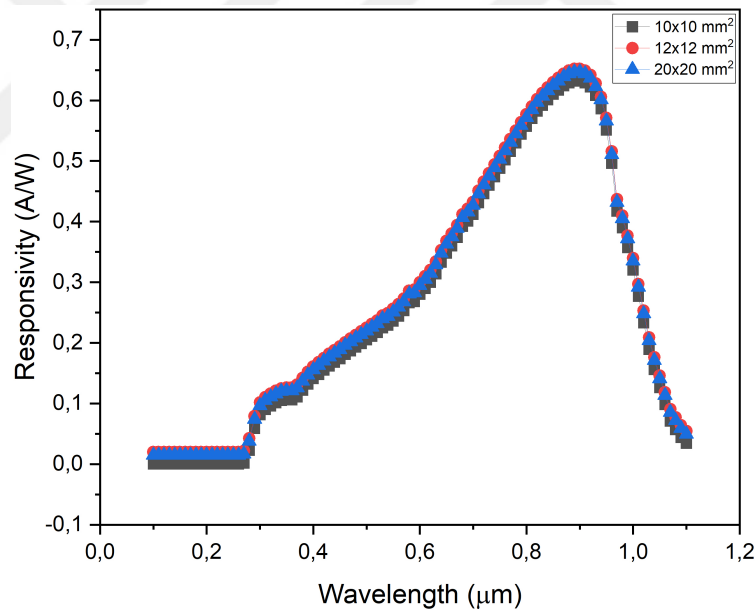


Figure 4.7. Spectral response of Si-PIN PD

Table 9. Specification of Si-PIN PD with four guard rings

	Commercial Diodes (105,106)	10x10 mm²	12x12 mm²	20x20 mm²
I_d (nA) @-90	1-30	7.49	8.72	10
Capacitance (pF) @-90	20-120	39	51	80
Spectral Response (800nm-960nm) A/W	0.55 – 0.6	0.62 ± 1	0.62 ± 1	0.62 ± 1
Rise Time (ns) @-90 V, RL=50 Ω	20-200	86	112	176
Noise Current 10⁻¹⁴ (A/Hz^{1/2})	6.45	3.98	4.30	4.60

4.2 I_d-V Characteristics of fabricated Si-PIN PD

I_d-V analyses of the fabricated Si-PIN PDs were performed in a dark environment. The Si-PIN PDs are produced in three different sizes, 20x20 mm², 12x12 mm² and 10x10 mm². Four Si-PIN PDs were selected from each size in the six regions of the silicon substrate (Figure 3.29).

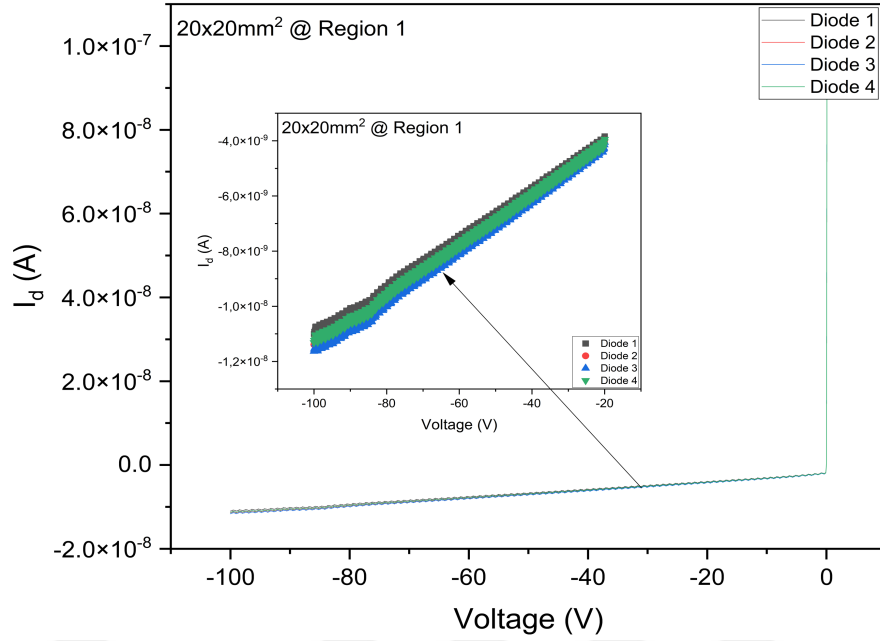


Figure 4.8. Si-PIN PD I-V characteristics from region 1 on silicon substrate

The first four Si-PIN PDs with an active area of $20 \times 20 \text{ mm}^2$ are selected from region one. The values of the dark current of these diodes at room temperature are applied in reverse voltage (measured in photo conductor mode). According to the data obtained, although the dark current values of the Si-PIN PDs have exceeded 10 nA at -90 Volt , there is a level that can be ignored (Figure 4.8). When different current values were compared between the diodes, the current change was determined to be the highest at 2.88% (Table 10).

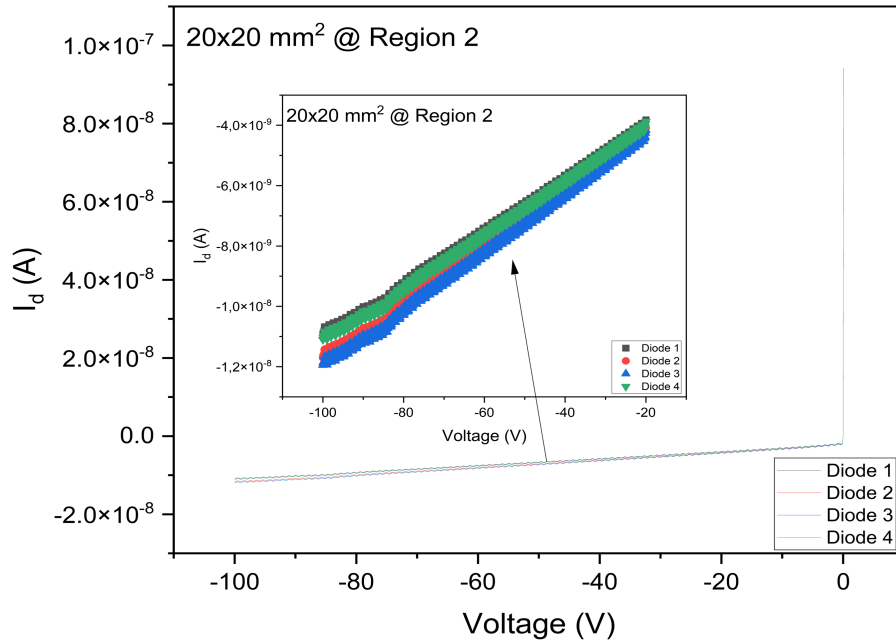


Figure 4.9. Si-PIN PD characteristic from region 2 on silicon substrate

The second four Si-PIN PDs with an active area of 20x20 mm² are selected from the region two of the substrate. The dark current value of the selected Si-PIN PDs varied between 10.10 nA and 10.98 nA when applied to -90 Volt voltage at room temperature (Figure 4.9). The dark current value of the diode number three is higher compared to other diodes. The main reason for this difference is that the pollution in the bottom region where the diode is located causes a significant discharge in diode surface flow (38,107,108). Comparing the dark current values of the diodes in the second region with those of the first region shows a deviation of 0.028% (Table 10). This result is relatively low for diodes with a large active area. Because they're diodes with a large sensitive area. It covers a fairly large area on the substrate. This shows that, despite the situation in question, the fabrication stages are extremely homogeneous.

Table 10. I_d-V Characteristics of fabricated 20x20 mm² Si-PIN PD

Active Area 20x20(mm²)	Region 1	Region 2
	I_d (nA) @ -90 V	I_d (nA)@ -90 V
Diode 1	-10.06	-10.10
Diode 2	-10.42	-10.70
Diode 3	-10.64	-10.93
Diode 4	-10.35	-10.15

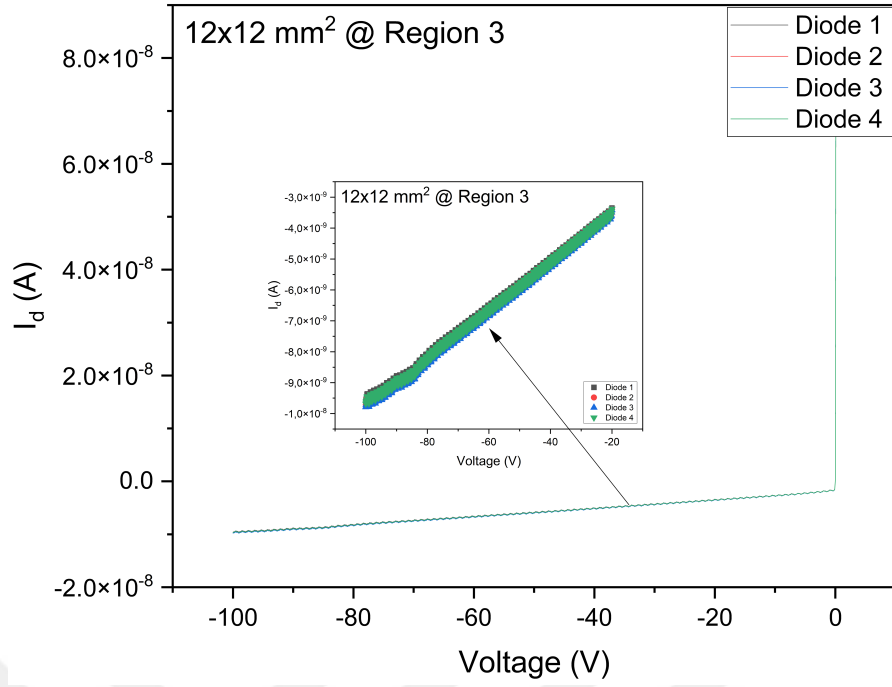


Figure 4.10. Si-PIN PD characteristic from region 3 on silicon substrate

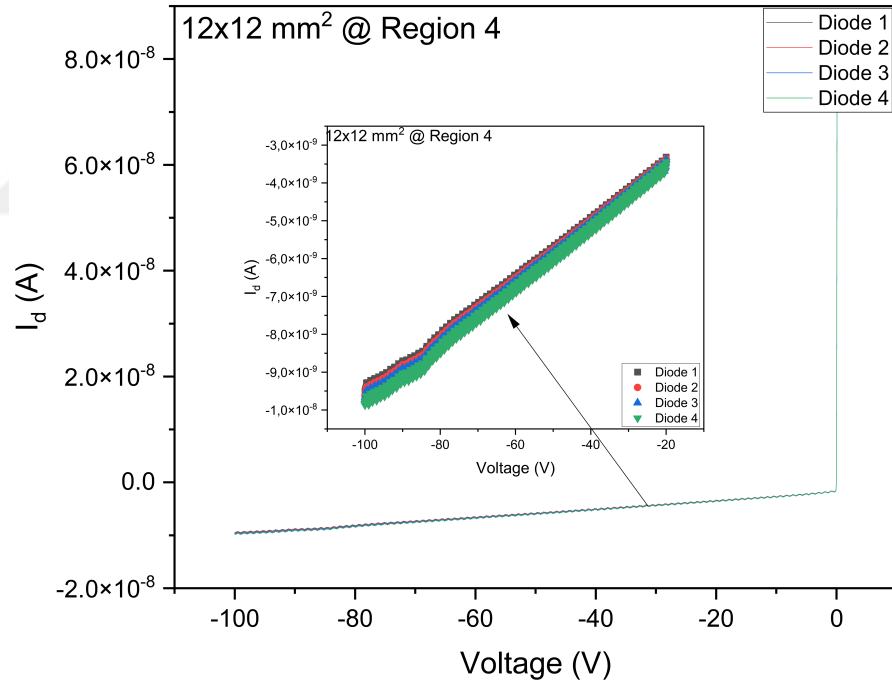


Figure 4.11. Si-PIN PD characteristic from region 4 on silicon substrate

Eight Si-PIN PDs selected from the third and fourth regions of the silicone substrate are grouped among themselves. These diodes, with a sensor area size of $12 \times 12 \text{ mm}^2$, have dark current values determined at room temperature. (Figure 4.10 and 4.11). When the dark current values of the diodes in the third region were analyzed, they varied between 8.78 and 8.95 nA at -90 V, while the current behavior

of the fourth region varied from 8.70 to 9.02 nA at -90 V. A comparison between the dark current values of diodes in the third and fourth regions revealed a marginal change of less than 2%. The magnitude of this depth is of such insignificance that it can be disregarded. Furthermore, it is observed that Si-PIN PDs featuring an active area measuring 12x12 mm² exhibit a reduced dark current in comparison to Si-PIN PDs with a larger active area of 20x20 mm² (Table 11). According to mathematical principles, a reduction in the active sensor region of a photodiode corresponds to a decrease in the values of dark current (38,109).

Table 11. I_d -V Characteristics of fabricated 12x12 mm² Si-PIN PD

Active Area 12x12 (mm ²)	Region 3	Region 4
	I_d (nA) @ -90 V	I_d (nA) @ -90 V
Diode 1	-8.78	-8.70
Diode 2	-8.88	-8.80
Diode 3	-8.95	-8.89
Diode 4	-8.85	-9.02

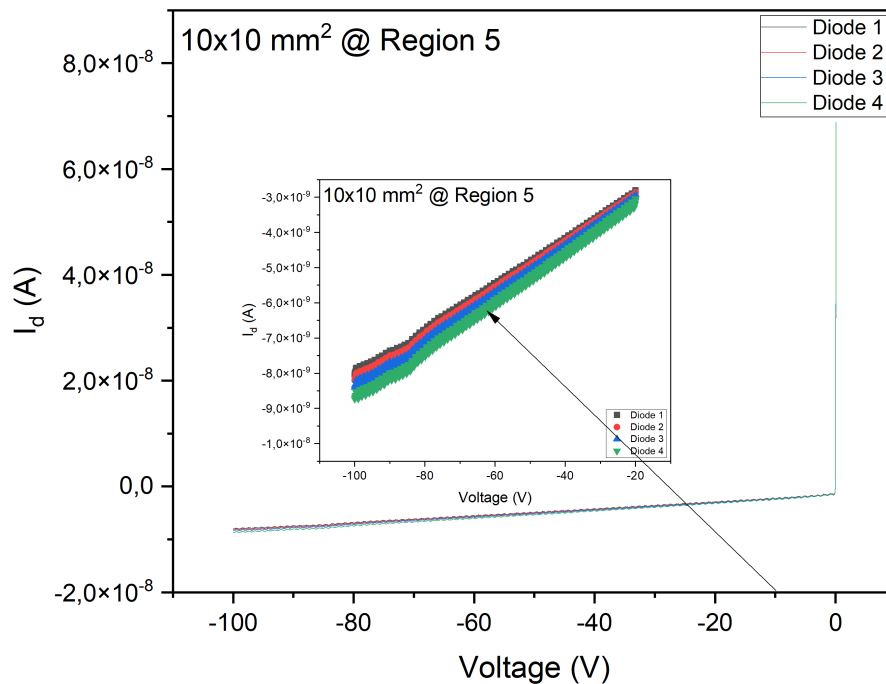


Figure 4.12. Si-PIN PD characteristic from region 5 on silicon substrate

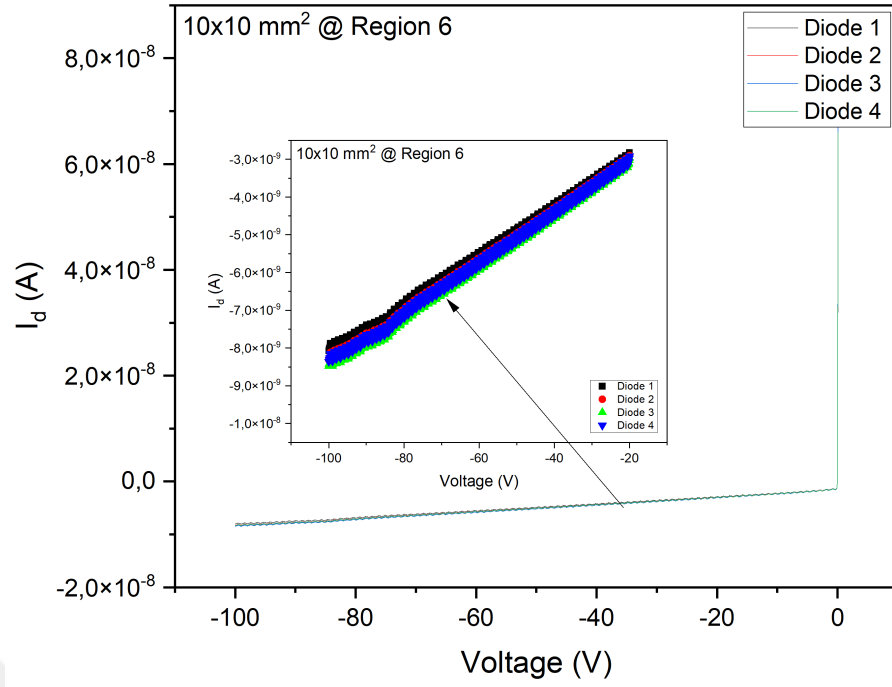


Figure 4.13. Si-PIN PD characteristic from region 6 on silicon substrate

When the current values of Si-PIN PD with an active sensor area of $10 \times 10 \text{ mm}^2$ taken from the fifth and sixth zones of the silicon substrate were studied, the dark current value of the SI-PIN PDs in the fifth region varied from 7.36 nA to 7.98 nA when -90 V was applied (Figure 4.12). The current between the diodes is at most 8.4%. The current behavior of the four different diodes from the sixth region varied between 7.32 nA and 7.64 nA at -90 V (Figure 4.13), and the current change of the Si-PIN PDs from the Sixth region was around 4.4%. When the diodes taken from the region five and six were compared to each other, no significant current change was observed (Table 12).

Table 12. I_d -V Characteristics of fabricated 10x10 mm² Si-PIN PD

Active Area 10x10 (mm²)	Region 5	Region 6
	I_d (nA) @ -90 V	I_d (nA) @ -90 V
Diode 1	-7.36	-7.38
Diode 2	-7.50	-7.60
Diode 3	-7.68	-7.76
Diode 4	-7.98	-7.64

The dark current values of twenty-four different Si-PIN PDs have been studied with different active area sizes taken from different regions of the substrate. In theory, a Si-PIN PD is not expected to generate current in a dark environment. but it's very sensitive to the silicon temperature in which the photo diodes are made. It is stimulated by the effect of an electron temperature inside the silicon, even at room temperature, and can easily pass through the valance to conduction band. This condition produces a small amount of current if it contains diodes. Temperature is not the only factor causing the dark current, it is influenced by the current in the surface of the diode, the width of the sensing area of the architecture, the doping processes in production processes, and many variables such as the production of dark current by Si-PIN PDs (38,75,109,110). It is not possible to completely eliminate the dark current at this stage, but it is very important to keep the dark stream of the photo diode at an ideal level. The literature and commercial Si-PIN PDs have defined this level as 1-10 nA (50,111). The dark currents of the Si-PIN PDs with 10x10 mm² and 12x12mm² active areas produced remained below 10nA even at -90 V. The dark current values of Si-PIN PDs with a active area of 20x20 mm² are slightly above or equal to 10 nA at a voltage of -90 V. However, deviations in these current values are at a level that can be ignored. Because during the radiation tests, the maximum voltage of -25 V will be applied to the Si-PIN PDs. At this voltage, the luminous values of the Si-PIN PDs are at the highest level of 5.5 nA, which is below the target value.

4.3 C-V Characteristics of Fabricated Si-PIN PD

In this part of the study, capacitance voltage analyses of fabricated Si-PIN PDs. In this direction, a total of twenty-four Si-PIN PDs with three different photosensitive area have been selected from the six regions on the substrate. Capacitance measurements of photodiodes with $20 \times 20 \text{ mm}^2$ photo sensitive area were shown in Figure 4.14 and Fig. 4.15 by adjusting the 1MHz frequency. With the applied reverse voltage, the depletion regions of Si-PIN PDs have expanded as expected(41). Since the capacitance value of the photodiode is inversely proportional to the width of the depletion width, an exponential decrease of photodiodes capacitance with increases the applied reverse voltage has been observed(57). The capacitance values of the photodiodes were rapidly reduced to -25 V, and when they reached -30 V, the capacitance change occurred in very small proportions. This electrical behavior indicates that the photodiodes operate in full depletion mode at -30 V volts. The capacitance values of Si-PIN PDs operating at full depletion voltage were measured at the highest 112.3 pF in region one and the lowest 115.4 pF. In region two, the lowest is 114 pF and the highest 114.5 pF (Table 13).

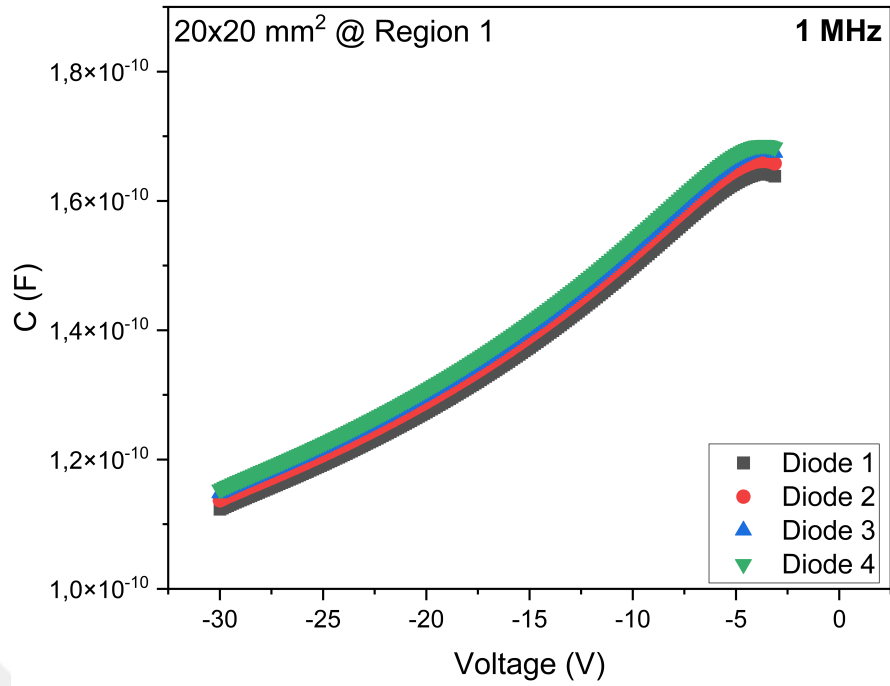


Figure 4.14. Si-PIN PD characteristic from region 1 on silicon substrate

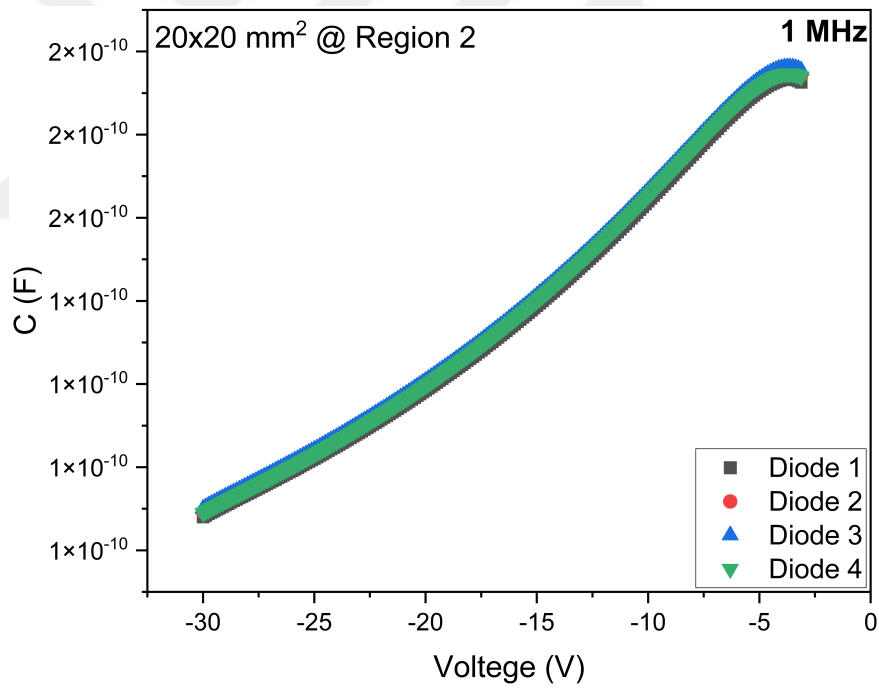


Figure 4.15. Si-PIN PD characteristic from region 2 on silicon substrate

Table 13. C-V values of fabricated 20x20 mm² Si-PIN PD

Active Area 20x20 (mm ²)	Region 1	Region 2
	Capacitance (pF) @ -30 V	Capacitance (pF) @ -30 V
Diode 1	112.3	114
Diode 2	113.7	114.6
Diode 3	114.8	115
Diode 4	115.4	114.5

Capacitance behavior of Si-PIN PDs with an active area of 12x12 mm² is shown in Figure 4.16 and Fig. 4.17. Because the architecture of the diodes is the same, the full depletion mode at -30 V has become fashionable. In full depletion mode, the lowest capacitance value of Si-PIN PDs in region one was 71 pF, while the highest was 76.4 pF. When the capacitance behavior of photodiodes in region two was analyzed, the lowest capacitance was measured at 71.12 pF and the highest at 78 pF (Table 14).

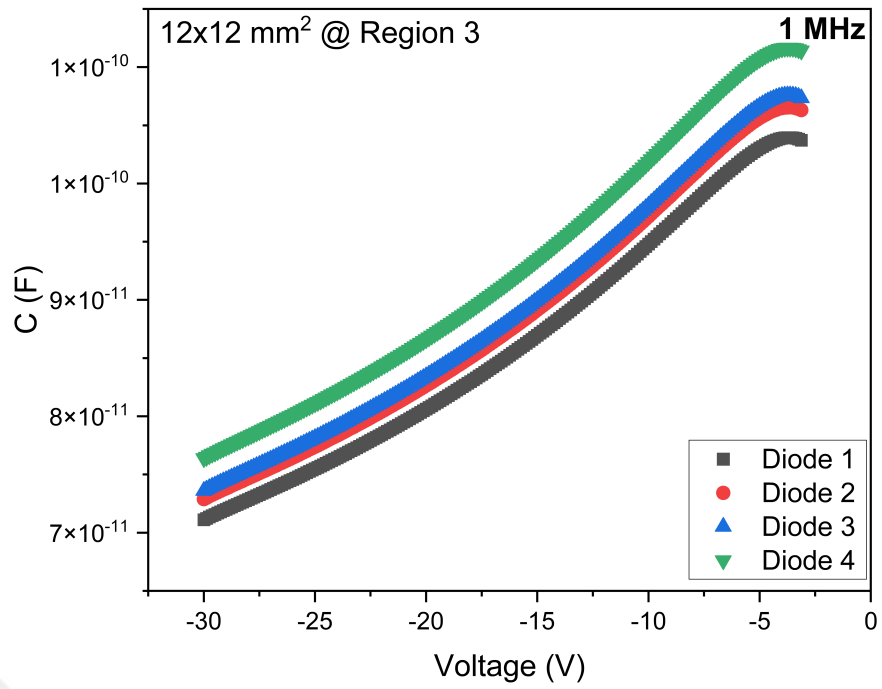


Figure 4.16. Si-PIN PD characteristic from region 3 on silicon substrate

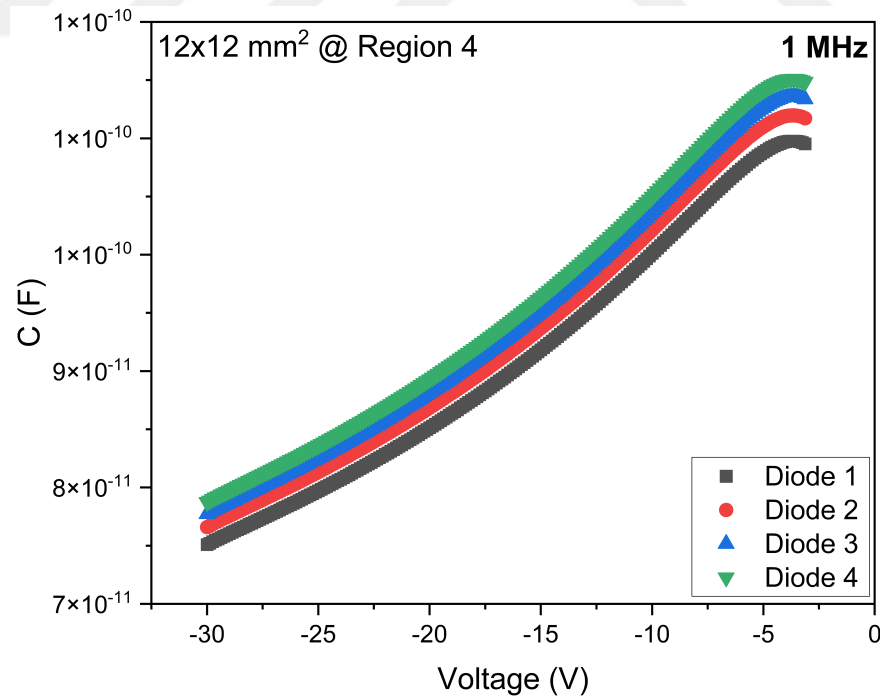


Figure 4.17. Si-PIN PD characteristic from region 4 on silicon substrate

Table 14. C-V values of fabricated 12x12 mm² Si-PIN PD

Active Area 12x12 (mm ²)	Region 3	Region 4
	Capacitance (pF) @ -30 V	Capacitance (pF) @ -30 V
Diode 1	71	71.12
Diode 2	73	71.51
Diode 3	73.6	76.6
Diode 4	76.4	78

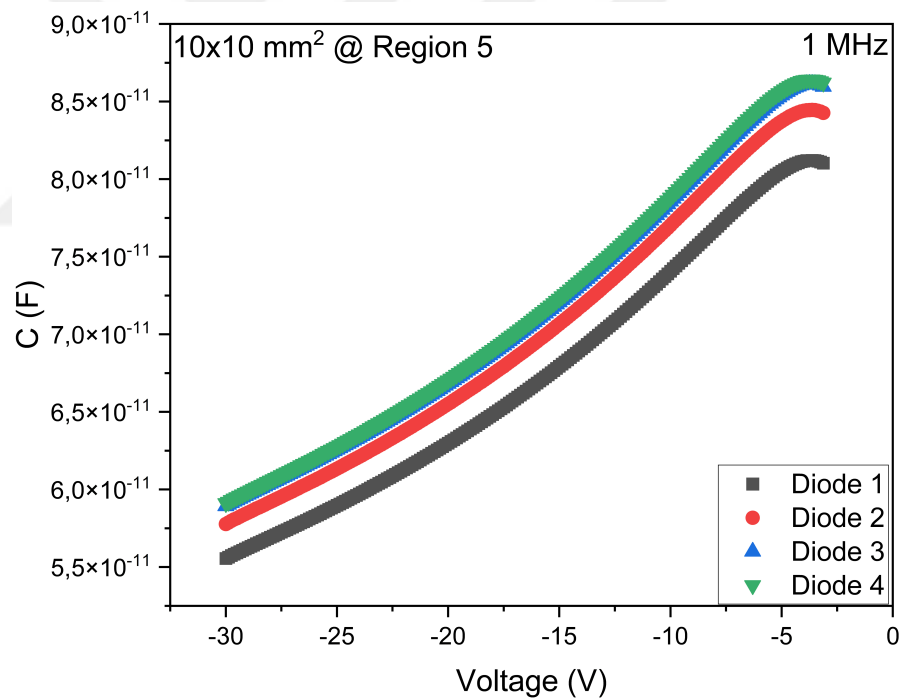


Figure 4.18. Si-PIN PD characteristic from region 5 on silicon substrate

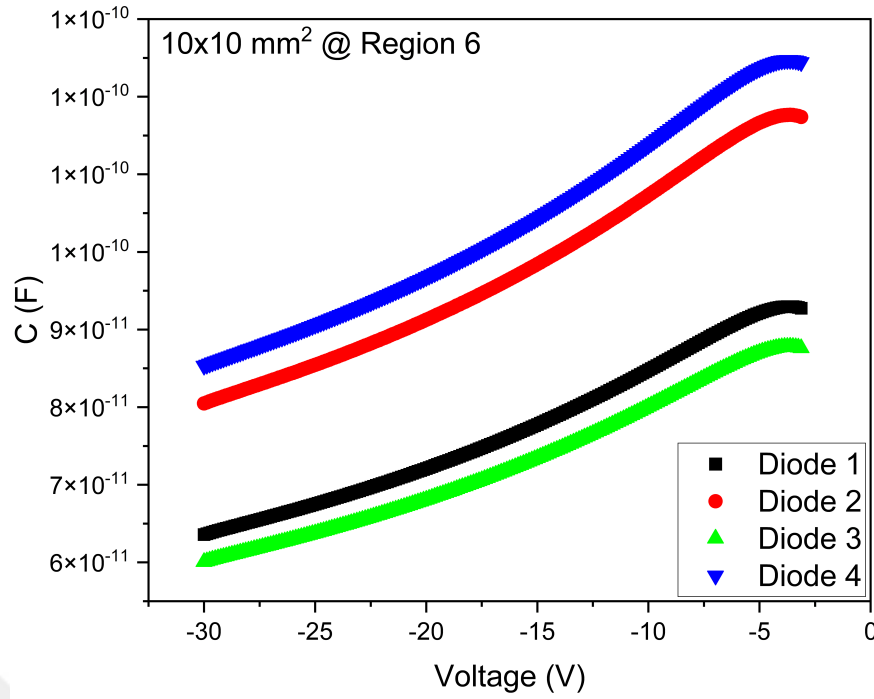


Figure 4.19. Si-PIN PD characteristic from region 6 on silicon substrate

The capacitance values of photo diodes with $10 \times 10 \text{ mm}^2$ photo sensitive area selected from region 5 and region 6 have been analyzed (Figure 4.16 and Figure 4.17). The capacitance values of the photo diodes selected from region 5 were measured at the lowest 55.6 pF and the highest 59.4 pF. For diodes selected from region 6, the lowest is 63 pF and the highest is 85.3 pF at full depletion voltage - 35. The difference between the lowest and highest capacitance values of the selected photodiodes from zone 6 was observed at 35%. It has been determined that this difference is only in diodes selected from region 6 and that during the boron-deposition process, region 6 is not homogeneously contributed(112).

Table 15. C-V values of fabricated 10x10 mm² Si-PIN PD

Active Area 10x10 (mm²)	Region 5	Region 6
	Capacitance (pF) @ -30 V	Capacitance (pF) @ -30 V
Diode 1	55.6	63
Diode 2	57.8	80.5
Diode 3	59	60
Diode 4	59.4	85.3

Si-PIN PDs were taken from six different regions on the substrate were analyzed by applying reverse voltage at 1 MHz frequency. When the capacitance values obtained as a result of the analyses (Table 13, Table 14 and Table 15) are compared with the results of the simulation (Table 9). 42% in Si-PIN PDs with 20x20mm² active sensitive area of the resulting difference %42.5, Si-PIN PDs with an active sensitive area of 12x12 mm² were defined as 39.4 % and 10x10 mm² Si-PIN PDs as % 61.53. It is quite normal that there is such a difference between the capacitance values of the simulation results and the actual produced Si-PIN PDs. While the production processes are designed in simulation, the input processes can be carried out extremely homogeneously and at the desired depth with ease. However, in the actual fabrication phase, it is quite difficult to control such a precision of thermal diffusion processes. The biggest factors that affect the capacitance values of a photodiode are the size of the active region, the thickness of the depletion region, and the rate of ion deposition. Thus, differences in the concentration of deposition the production process are sufficient reasons for the resulting change in the capacitance results (57,113). Furthermore, when comparing the results, we evaluate -90 V data in simulation studies. In actual production results, capacitance values at -30 V were used. This reverse voltage difference is not sufficient for the difference in capacitance values. Because the diodes reach the full depletion range at -30 V voltage, and the capacitance values of Si-PIN PDs vary by a maximum of 1 pF when the voltage is higher than the full depletion voltage.

4.4 I_{ph} -V Characteristic of fabricated Si-PIN PD

In the section, the objective is to examine the performance of completed Si-PIN PDs under the light. For this purpose, those with the lowest dark current of Si-PIN PDs taken from different regions of the altar have been selected for light testing. Light tests of Si-PIN PDs were performed using 532nm and 650nm light sources. Photo current-voltage (I_{ph} -V) and Spectral response at -5 volts of a photo diode with an active area of 20x20 mm² were analyzed at 650 nm light in Figure 4.20 and Figure. 4.21.

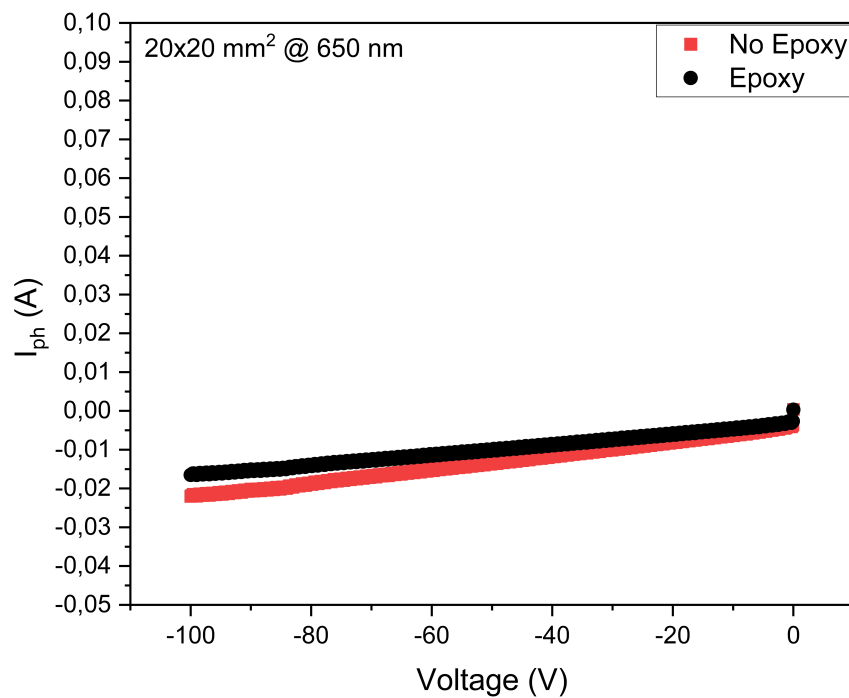


Figure 4.20. I_{ph} -V characteristics under 650 nm laser light of 20x20mm² Si-PIN PD

When I_{ph} -V behavior was studied, the current value of the Si-PIN PD increased from nano-ampere to milli-ampere. After covering with transparent epoxy of the active area of the same Si-PIN PD, the current of the photo diode was measured again, and a decrease in the photon flow of the Si- PIN PD was observed (Figure 4.20). This decrease in the I_{ph} is due to the fact that less photons reach the active region of the photodiode, as laser light That was diffracted, passes through the epoxy. The obtained photo characteristics is consisted with literature reported in (114).

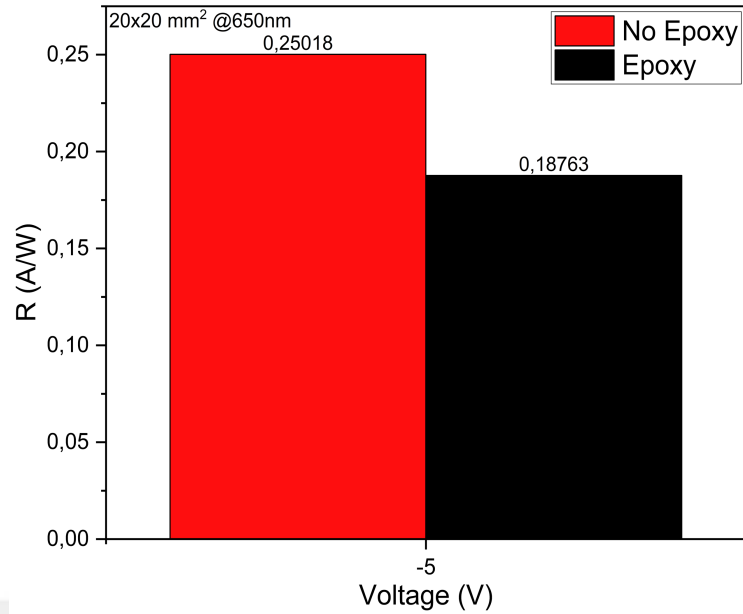


Figure 4.21. Spectral Response under 650 nm laser light of 20x20mm² Si-PINPD

The spectral response (R) of Si-PIN PDs with an active area of 20x20 mm² has been calculated. The spectral response of the non-epoxy-coated Si-PIN PD was calculated at 0.25018 A/W. When the active field of the Si-PIN PD is covered with epoxy, the spectral response is reduced by 35% to 0.1873 A/W (Figure 4.21).

When I_{ph} -V analysis of Si-PIN PDs was done using a 532nm light source, the I_{ph} value came from the mA scale. However, this current value was less than the I_{ph} value obtained under 650 nm light (Figure 4.22). A diode decreasing the photon current is expected to have a theoretically low spectral response. The spectral response of the Si-PIN PD at 532nm light is defined as 0.15511 A/W. When covered with epoxy, the spectral response was 0.08617 A/W (Figure 4.23). The results of fabricated pin photo diodes are almost same reported in (115,116).

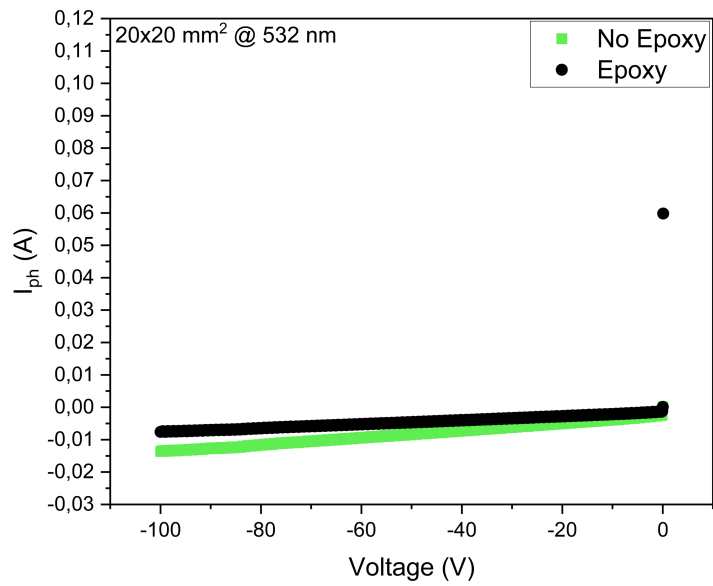


Figure 4.22. I_{ph} -V characteristics under 532 nm laser light of 20x20 mm² Si-PIN PD

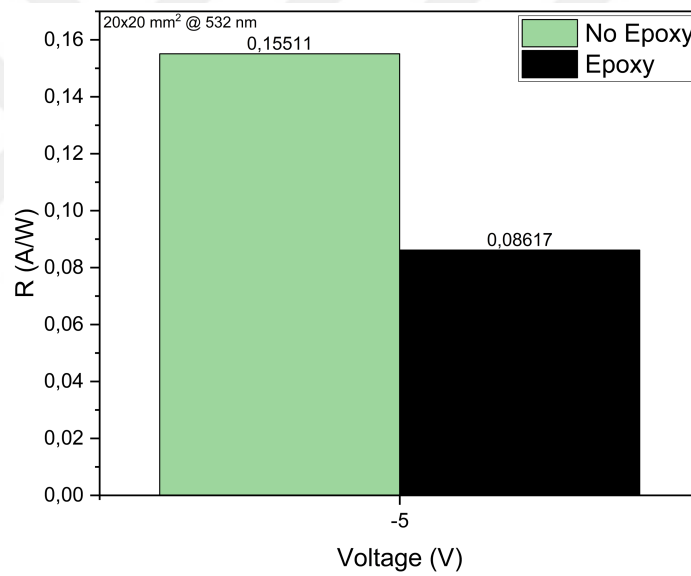


Figure 4.23. Spectral Response under 532 nm laser light of 20x20 mm² Si-PIN PD

When an I_{ph} -V analysis of a Si-PIN PD with an active area of $12 \times 12 \text{ mm}^2$ is performed under 650 nm light. The current characteristic of the Si-PIN PD has been observed to differ from the current behavior of a Si-PIN PD with an active area of $20 \times 20 \text{ mm}^2$. When this situation was analyzed, the current behavior of the diode, which was not covered with epoxy, reached the expected level of milli amperes. However, when diodes were coated with epoxy, more flow loss was observed than diodes with an active area of $20 \times 20 \text{ mm}^2$ (Figure 4.24). When the diode surface was analyzed, it appeared that the epoxy in the active diode field was slightly thicker and that air bubbles were present. This situation affected the reach of laser light to the diode surface and caused a current loss. Thus, a Si-PIN PD with an active area of $12 \times 12 \text{ mm}^2$ has a lower spectral response which was observed as 0.22 A/W. But, It decreased 0,17 A/W(115).

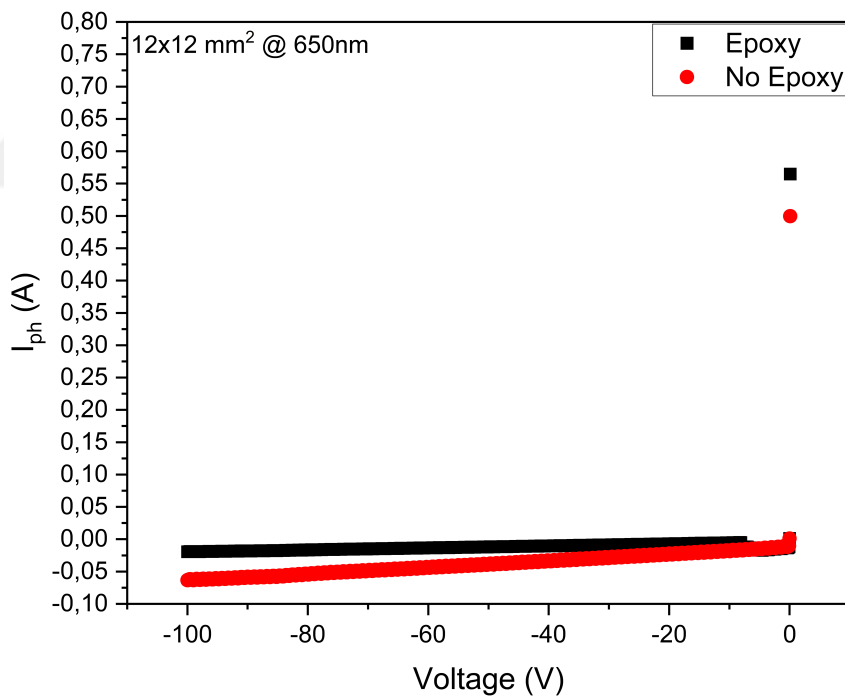


Figure 4.24. I_{ph} -V characteristics under 650 nm laser light of $12 \times 12 \text{ mm}^2$ Si-PIN PD

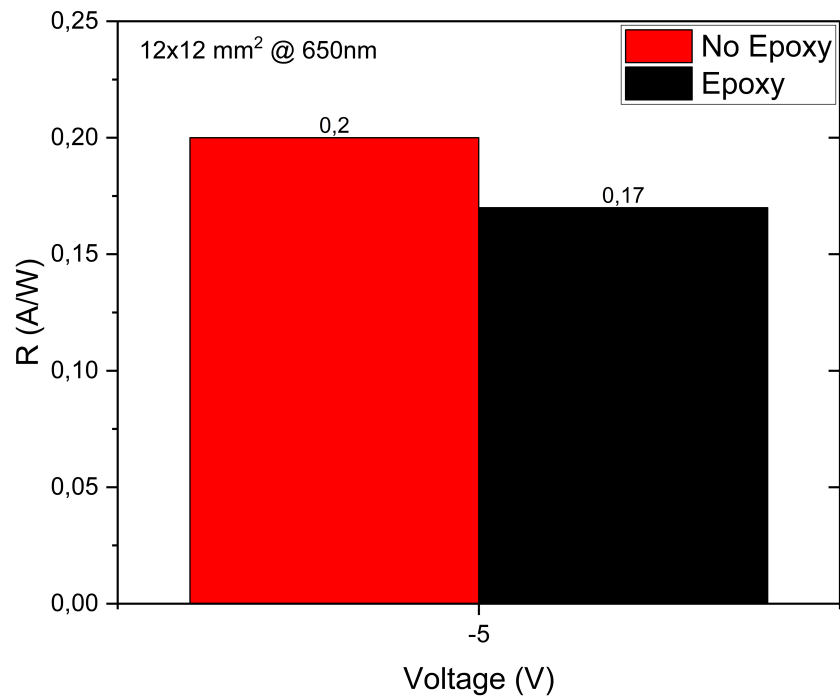


Figure 4.25. Spectral response under 650 nm laser light of 12x12 mm² Si-PIN PD

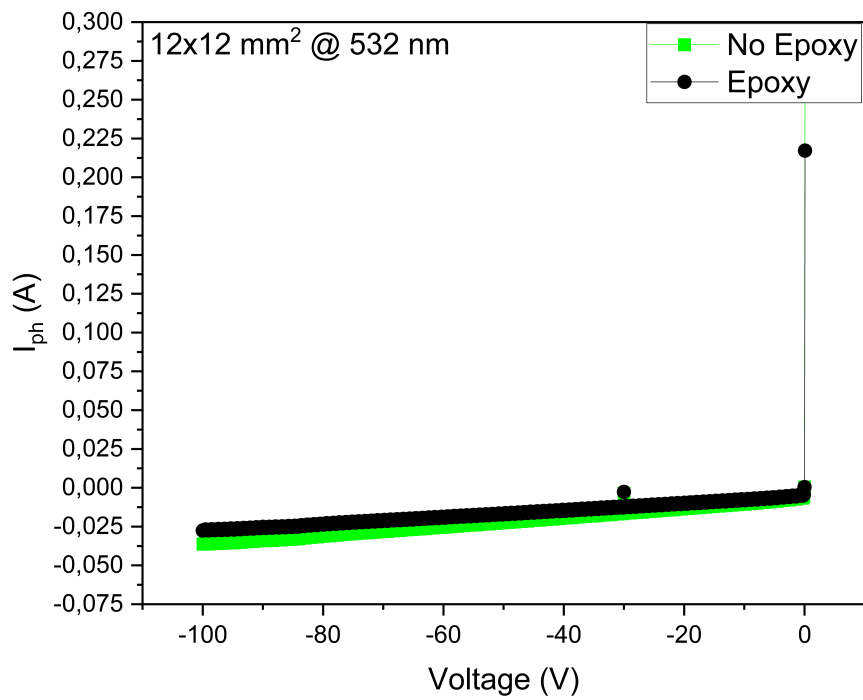


Figure 4.26. I_{ph}-V characteristics under 532 nm laser light of 12x12mm² Si-PIN PD

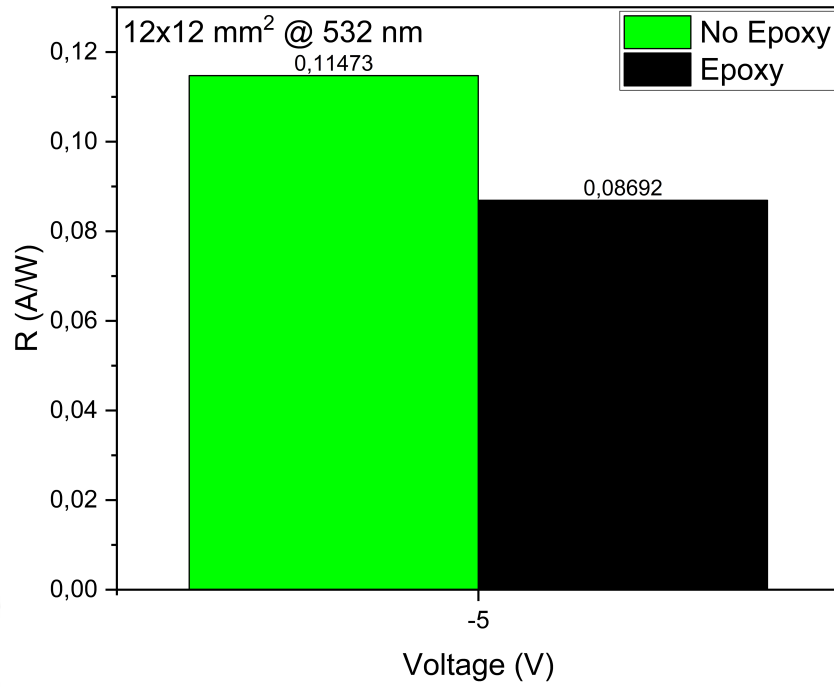


Figure 4.27. Spectral response under 532 nm laser light of 12x12 mm² Si-PIN PD

When the electrical responses of a Si-PIN PD with an active region of 12x12 mm² are examined under light with a wavelength of 532 nm. As expected, the Si-PIN PD is similar to the diode behavior of the 20x20 mm² Si-PIN PD. Also, when compared to the spectral response under 650 nm light. The spectral response measured at 532 nm light is lower than 0.11473 A/W. It is compatible with the data obtained when compared to the simulation studies. However, when the Si-PIN PD is covered with epoxy, this value drops to 0.08 A/W (Figure 4.26 and Figure 4.27).

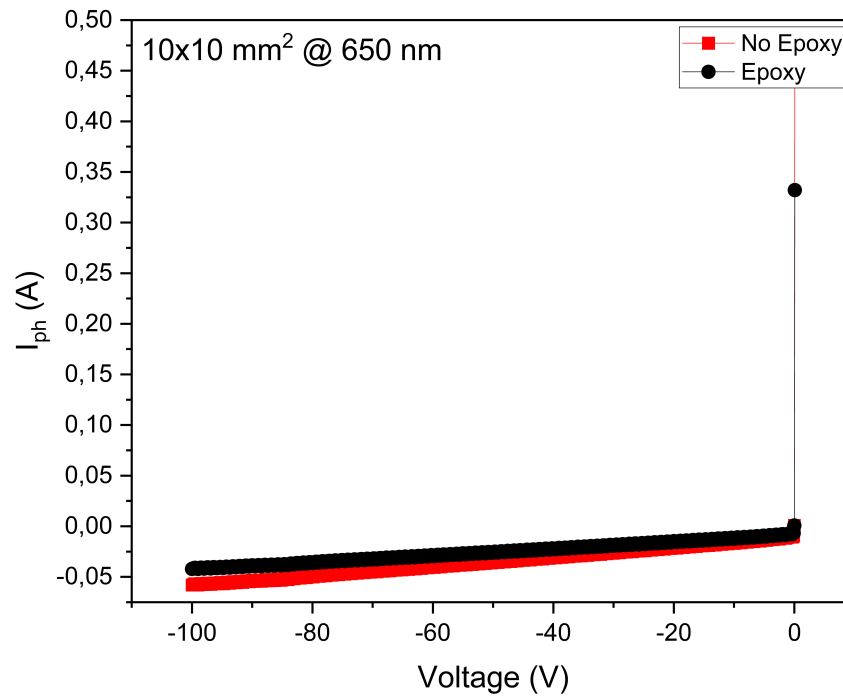


Figure 4.28. I_{ph}-V characteristics under 650 nm laser light of 10x10 mm² Si-PIN PD

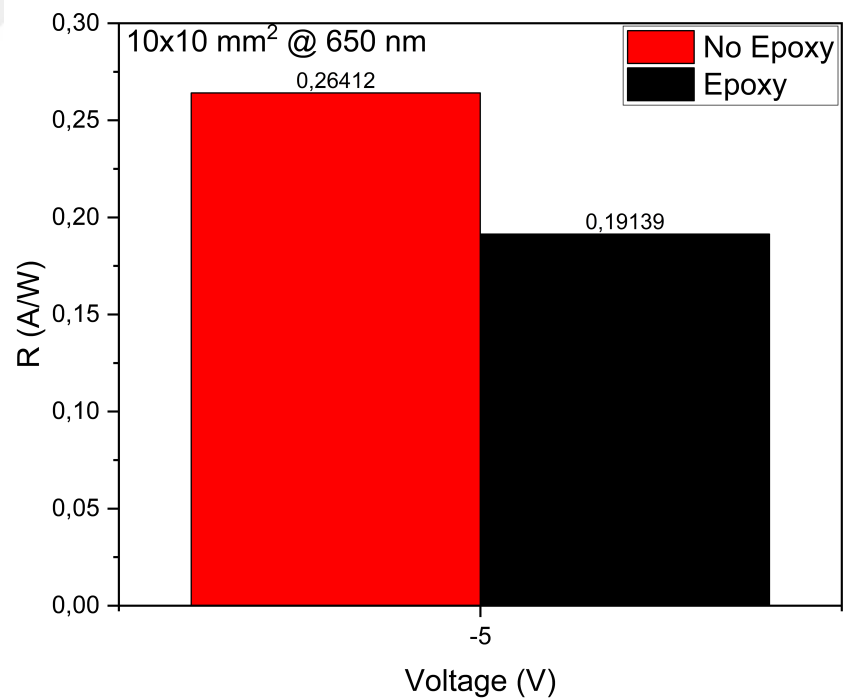


Figure 4.29. Spectral response under 650 nm laser light of 10x10 mm² Si-PIN PD

The Si-PIN PD with an active area of $10 \times 10 \text{ mm}^2$ is under two light sources with 650nm and 532nm wavelengths. electrical behavior has been studied. The current value of the Si-PIN PD is below the two light sources, at the milli ampler level (Figure 4.28 and Figure 4.30). This is similar to the current behavior of the other two different dimensions of the Si-PIN PD. When the spectral responses of the $10 \times 10 \text{ mm}^2$ Si-PIN PD were studied, the spectrum response of the none epoxy Si- PIN PD was determined to be 0.26412 A/W, and 0.19139A/W when covered with epoxy (Figure 4.29 and Figure 4.31)(117).

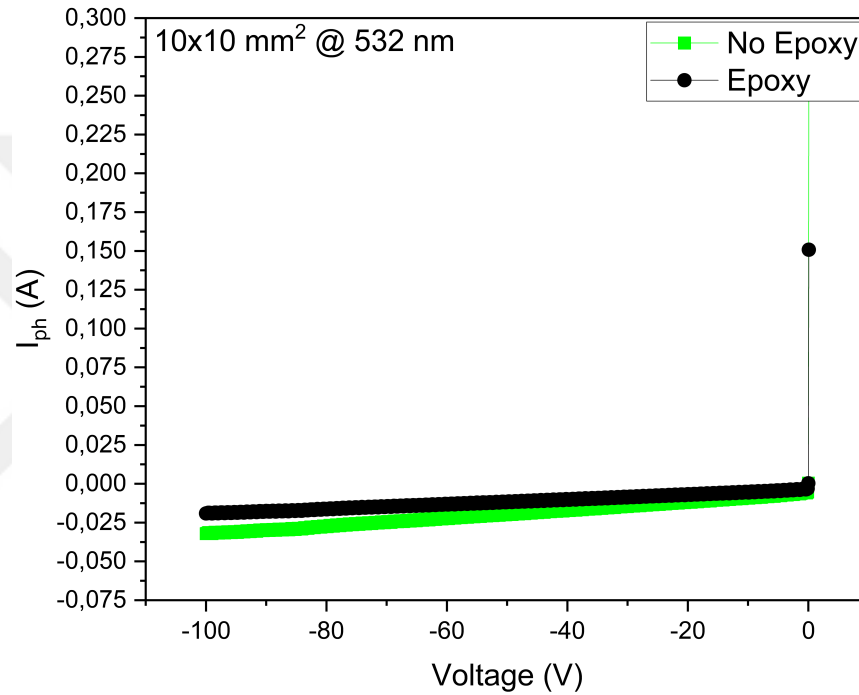


Figure 4.30. I_{ph} -V characteristics under 532 nm laser light of $10 \times 10 \text{ mm}^2$ Si-PIN PD

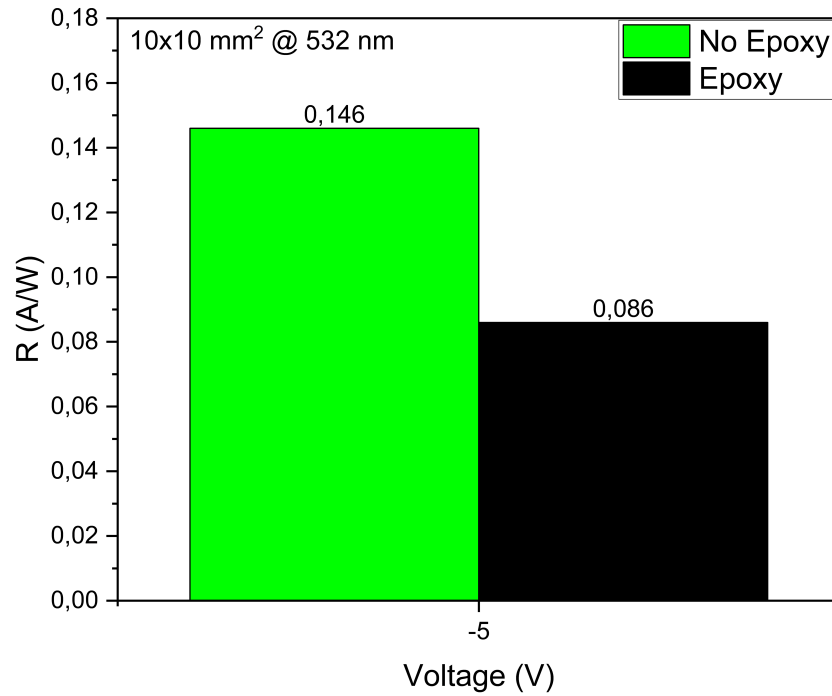


Figure 4.31. Spectral response under 532 nm laser light of 10x10 mm² Si-PIN PD

4.4.1 On-Off Current Characteristics

On-Off current analysis of Si-PIN PDs with 10x10 mm², 12x12 mm² and 20x20 mm² active area was performed under light with 650 and 532 nm wavelengths (Figure 4.32, Figure 4.33 and 4.35). This is when the falling light of the photo diode with three different active fields is switched on. The switching times of Si-PIN PDs are measured at 85 ns, 100 ns and 145ns, respectively. The larger the size of the Si-PIN PDs, the slower the annotation time is seen. This situation has been associated with an increase in junction capacitance of the Si-PIN PD. Because, The Si-PIN PDs is semiconductor devices that exhibit bipolar behavior, which arises from the modulation of conductivity due to the injection of minority carriers. The maximum transition frequency that can be employed in power conversion is constrained by the recombination and enhancement of minority carriers during transition intervals. The primary factor responsible for the energy variation in Si-PIN PD during closure is the reverse recycling load. Furthermore, the presence of diode overvoltage resulting from the loss of inductions also plays a role in the overall transition energy. The level of tension rises significantly as a result of the combined influence of the peak recursive current and the diode's dI/dt , which is regulated by the RC time constant. The speed at which the diode transitions to the downward state is influenced by factors such as the diode's parasitic capacitance and circuit loss induction (118)

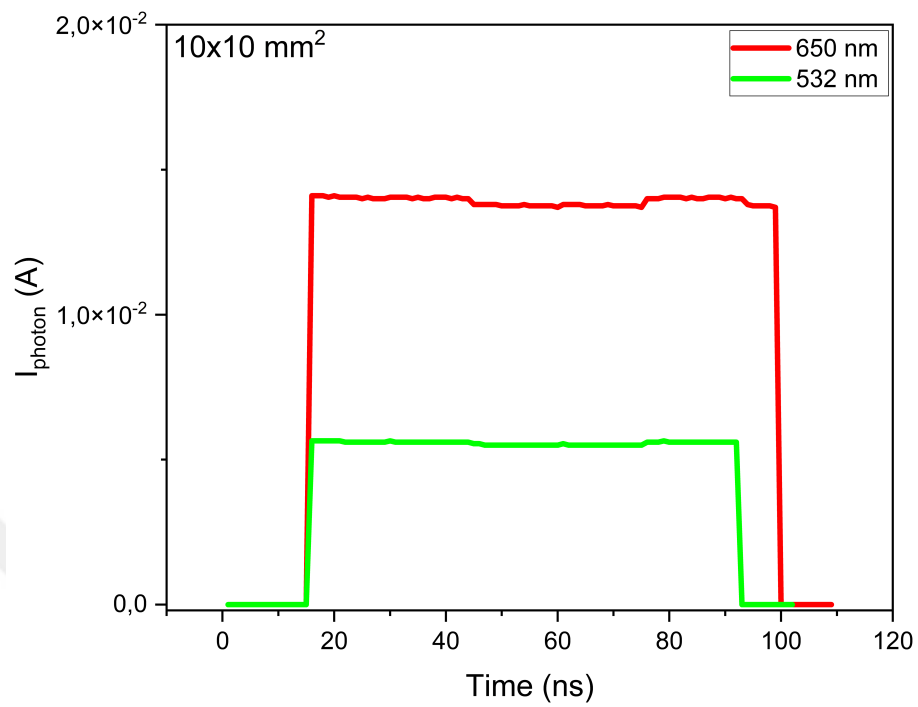


Figure 4.32. On-Off Current Measurement of 10x10mm² Si-PIN PD

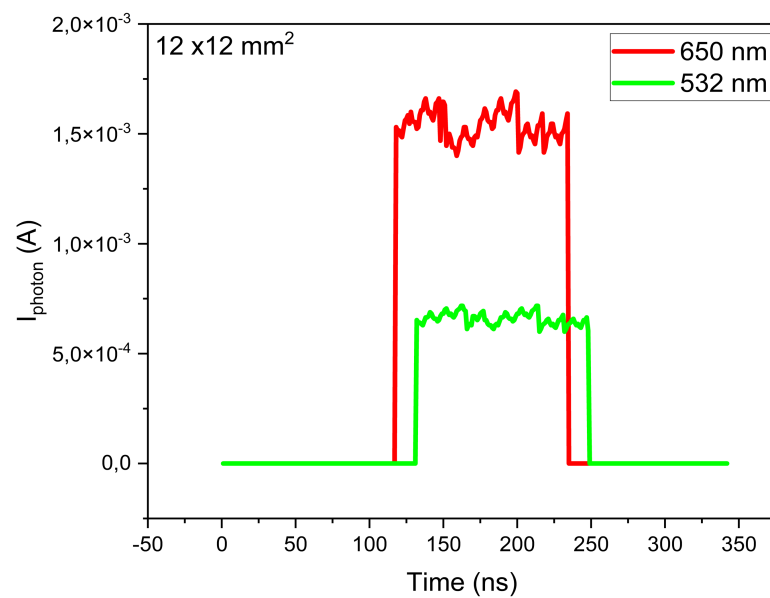


Figure 4.33. On-Off Current Measurement of 12x12mm² Si-PIN PD

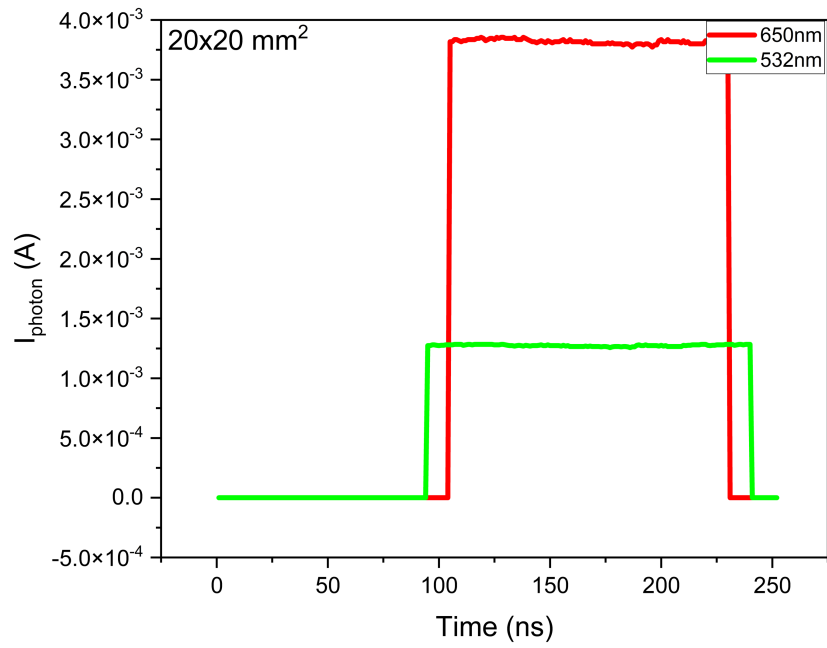


Figure 4.34. On-Off Current Measurement of 20x20 mm² Si-PIN PD

4.5 Transient Time of Si-PIN PD

The rise times of a Si-PIN PD with three different active area under 650 nm light have been analyzed. Figure 4.35, Figure. 4.36 and Figure.4.37 is depicted that, As the active area of diodes increases, the rise time period increases. Because the rise time of the photodiode depends on variables such as diffusion time, transit time, and RC time constant (Equation 24). Therefore, when a photodiode runs in full depleted mode, the RC time constant is dominated by its backup capacity, and the Terminal capacity is the sum of the diode's capacity and the package capacity. When the diodes have increased in size, the capacitance has increased, so an increase has been observed at times of increasing (119,120)

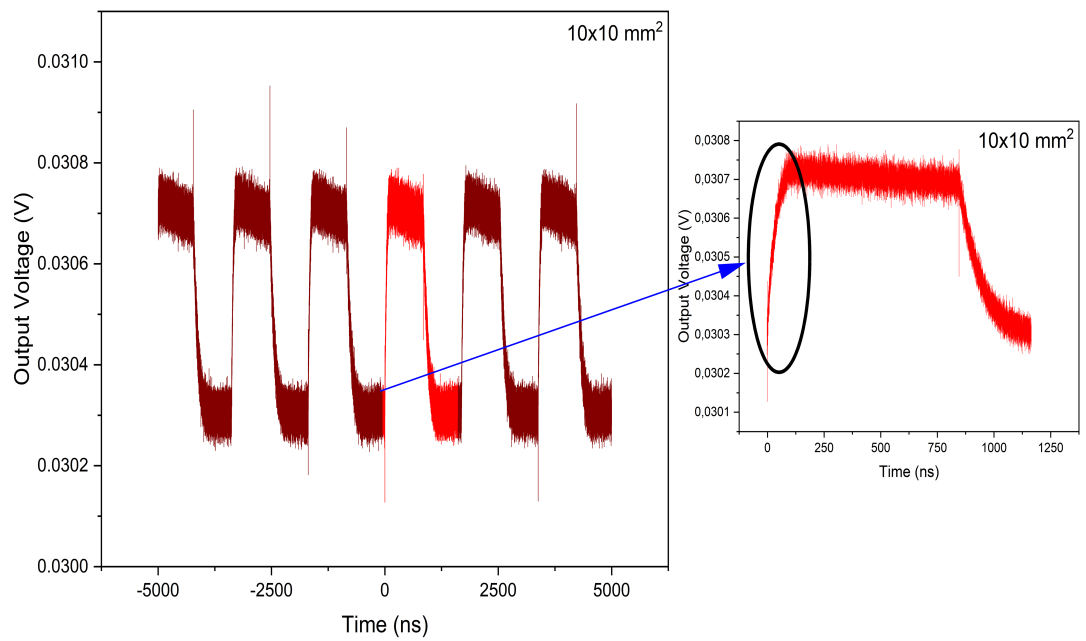


Figure 4.35. Transient time measurement result of 10x10 mm² Si-PIN PD

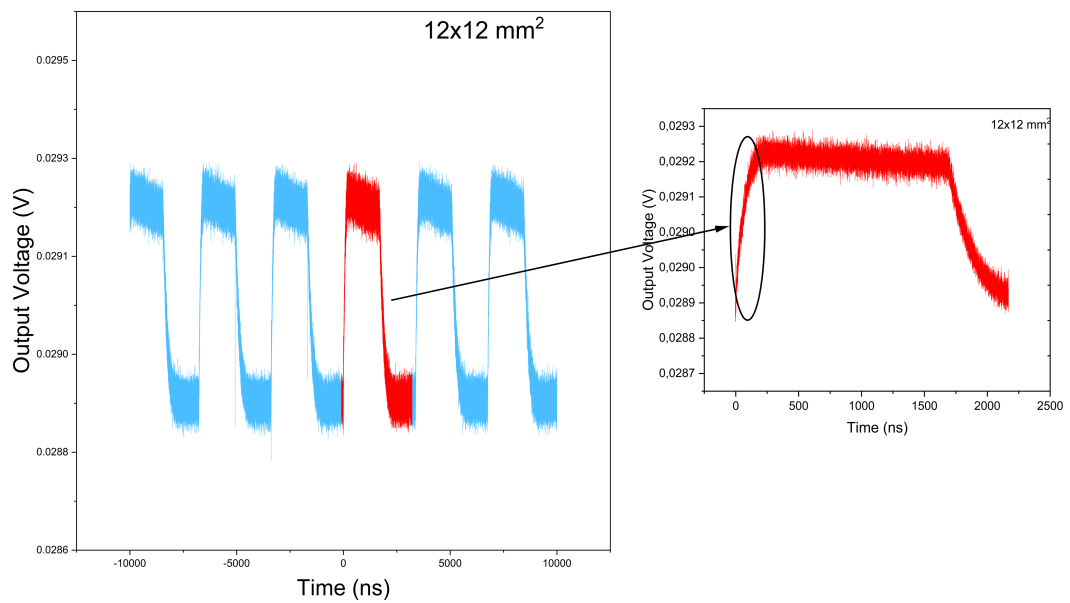


Figure 4.36. Figure 4.35. Transient time measurement result of 12x12 mm² Si-PIN PD

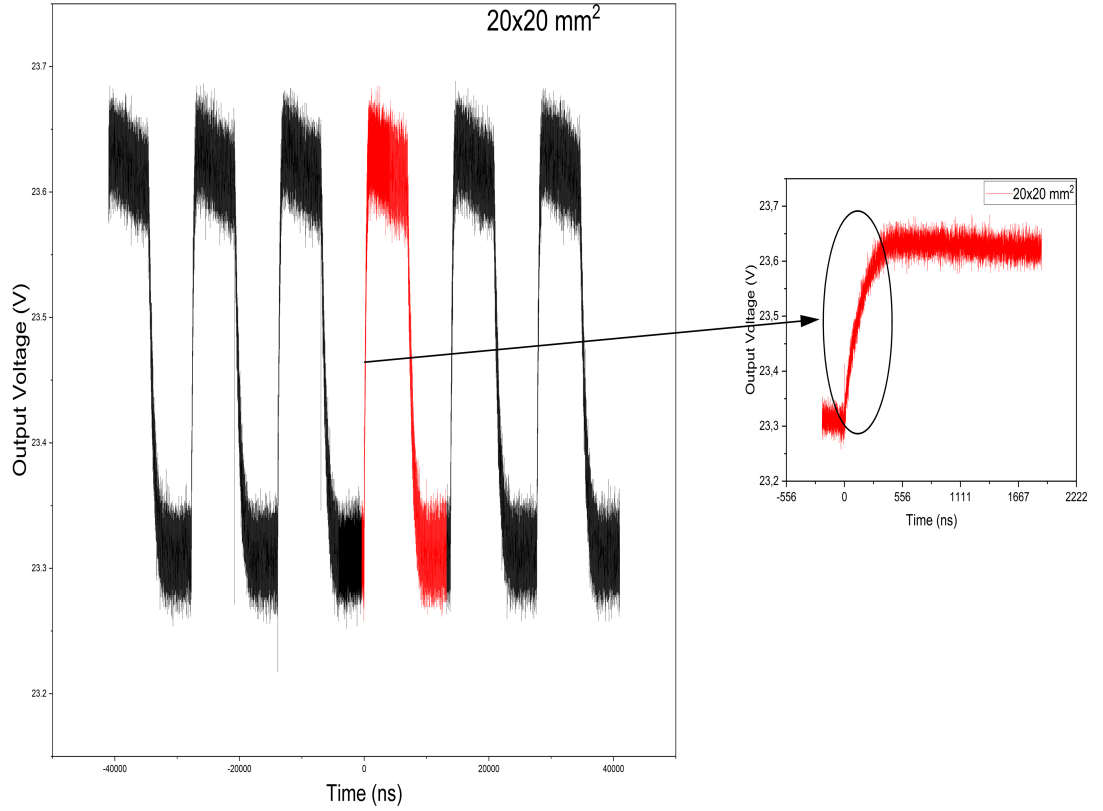


Figure 4.37. Transient time measurement result of 20x20 mm² Si-PIN PD

4.6 X-Ray Measurement with Si-PIN PD

The radiation tests of Si-PIN PDs were conducted using X-rays with energies ranging from 15 keV to 60 keV and tube current is 20 mas (Figure 4.38). The obtained results demonstrate that the produced Si-PIN PDs are sensitive to X-rays with energies ranging from 17 to 40 keV, with the highest signal being observed under X-rays with an energy of 30 keV. However, as the size of the photosensitive region of the photodiode increases, the obtained signals have decreased. Because the increase in the active sensing regions of photodiodes, the values of dark current have increased. As a result, the signal-to-noise ratio of the diodes has decreased. Another important factor that affects signal loss is the increased capacitance effect caused by the diode(120,121).

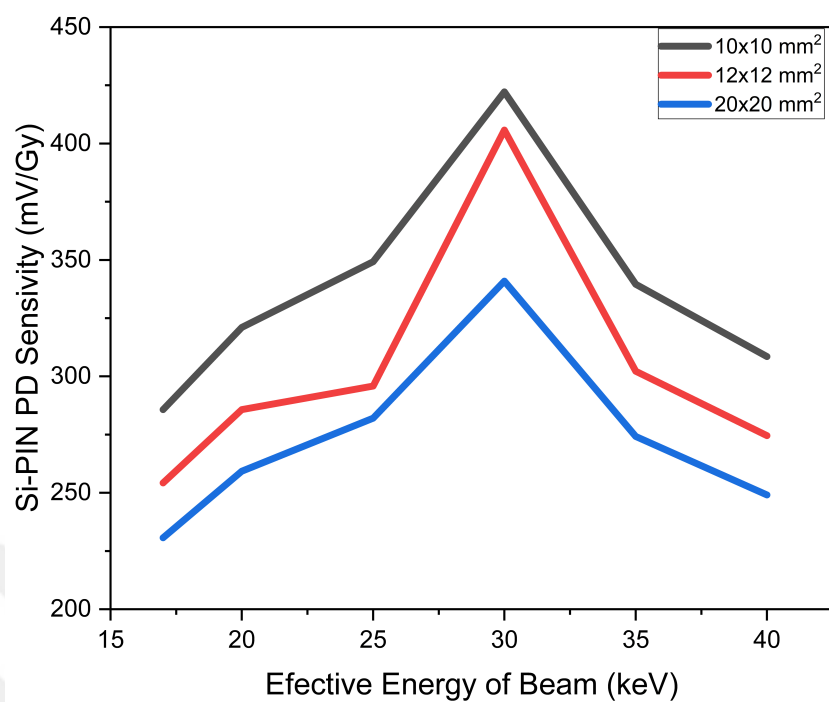


Figure 4.38. Si-PIN PD sensitivity under different X-ray energy

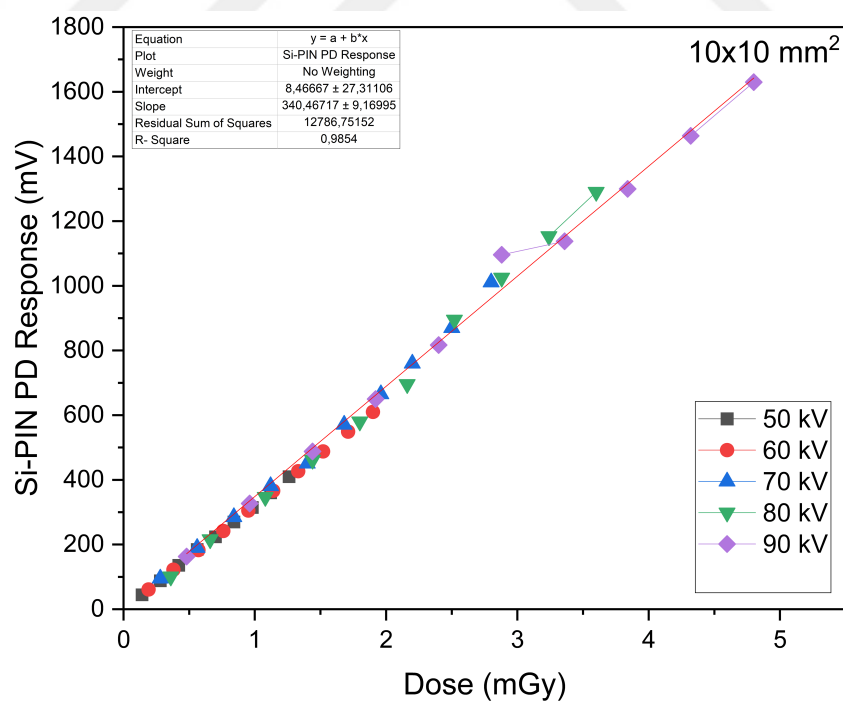


Figure 4.39. Response of Si-PIN PD with 10x10 mm² with radiation dose

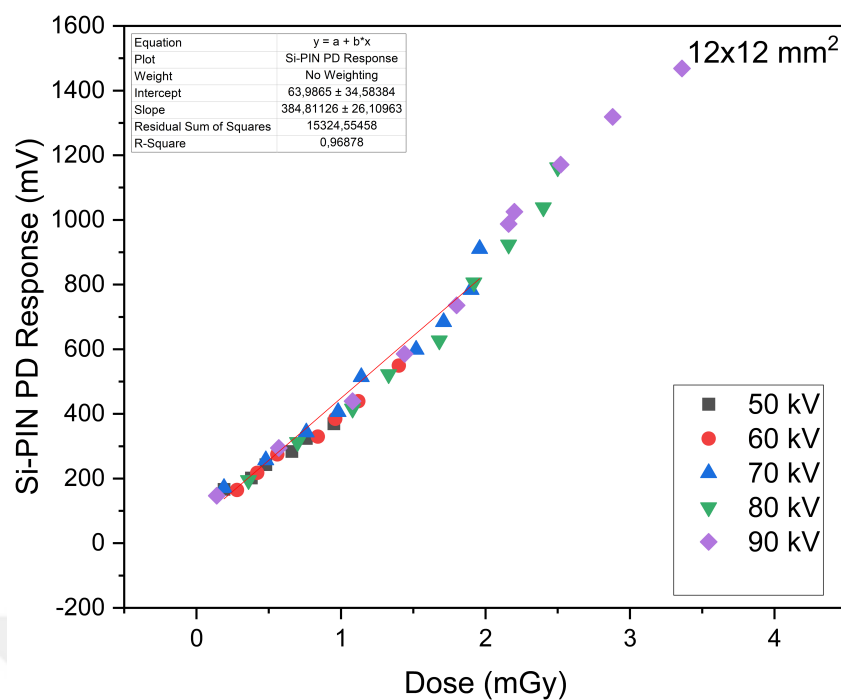


Figure 4.40. Response of Si-PIN PD with 12x12 mm² with radiation dose

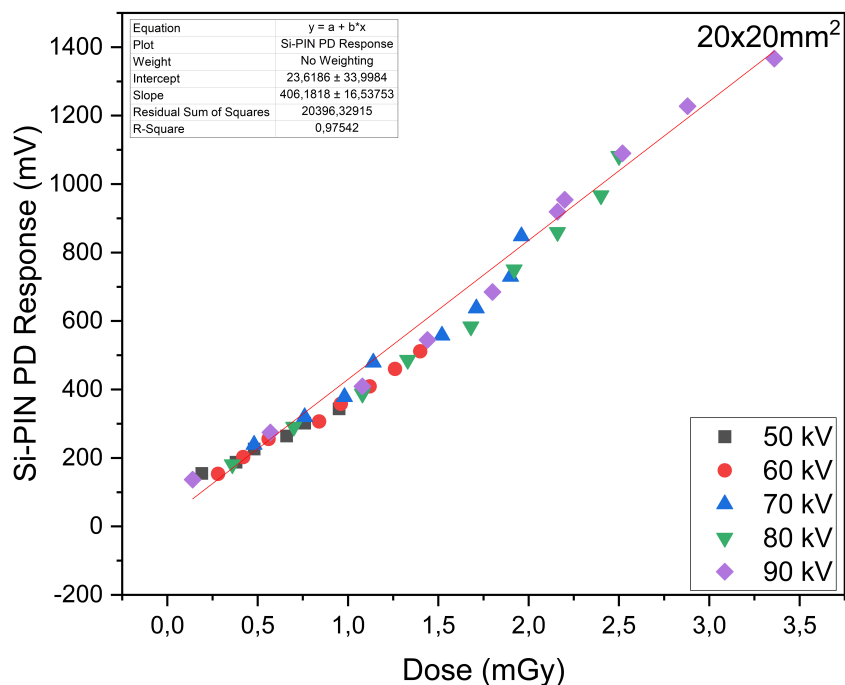


Figure 4.41. Response of Si-PIN PD with 20x20 mm² with radiation dose

The Si-PIN PD were examined based on the radiation dose ratio. At this level, the picture in question exhibits an inherent sensitivity with an elevated dosage rate. Figures 4.39, 4.40, and 4.41 illustrate the relationship between the radiation dose ratio and the sensitivity of the photo diodes. Based on the acquired data, the Si-PIN PD achieved the highest accuracy with a 10x10 mm² detection, reaching a R value of 0.9854. Other sizes, such as 12x12 mm² and 20x20 mm², were also evaluated. The Si-PIN PD exhibit R values of 0.96878 and 0.97542 respectively. This result is consistent with reported in (91)

4.7 ⁹⁰Sr and ²⁰⁴Tl tests with fabricated Si-PIN PD

The spectroscopy of the radiation emitted by the 204 Tl beta source was analyzed using Si-PIN PDs with three different active regions (Figure 4.42). In 600-second and measurements, the behavior of X-ray pixels (Kalpha, Kbeta) and beta particles has been clearly observed and is consistent with the results in the literature(122). These peaks are clearly visible with the 10x10 mm² and 12x12 mm² Si-PIN PD, while the spectral X-rays and beta peaks taken with the 20x20 mm² Si-PIN PD are not clear enough. When we analyzed this situation, it was observed that the signal noise of the 20x20 mm² Si-PIN PD was very high. The fact that this noise is over many radiation signals has prevented us from seeing the spectrum clearly. The fabricated Si-PIN PDs were also tested for beta particles using a source of strontium radiation. The ⁹⁰Sr spectra taken for 600 seconds with -25 reverse voltage are shown in Figure 4.43. A full decay chain was seen for each ⁹⁰Sr particle, which led to the creation of ⁹⁰Y and its subsequent decay into stable Zr. Although the main part of the peak is mostly made up of beta particles released when ⁹⁰Sr breaks down, the secondary peak below is typical of the breakdown of ⁹⁰Y and gradually fades at a much higher energy level. This obtained spectrum is consistent with studies that were reported in (52,123,124)

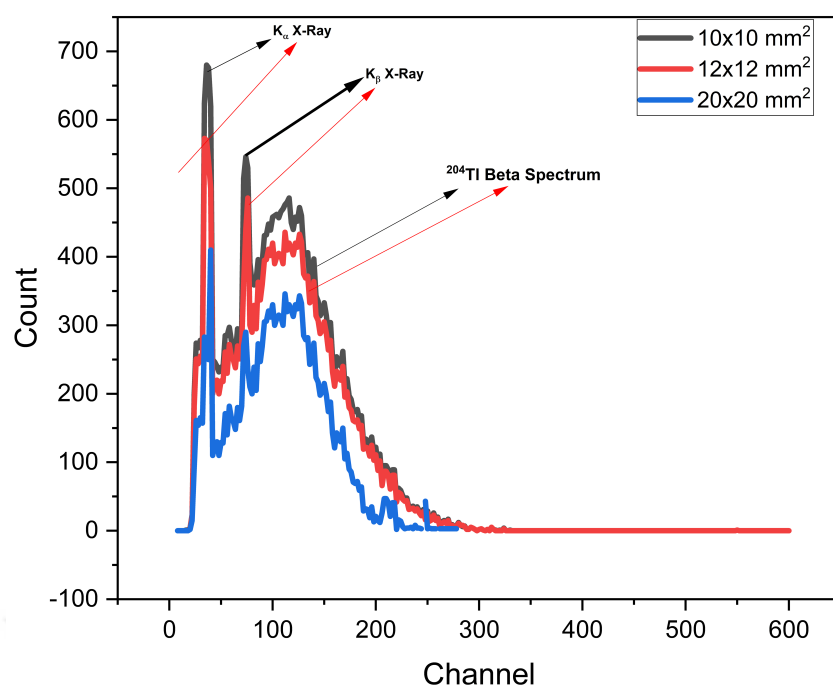


Figure 4.42. ^{204}Tl spectrum with fabricated Si-PIN PD

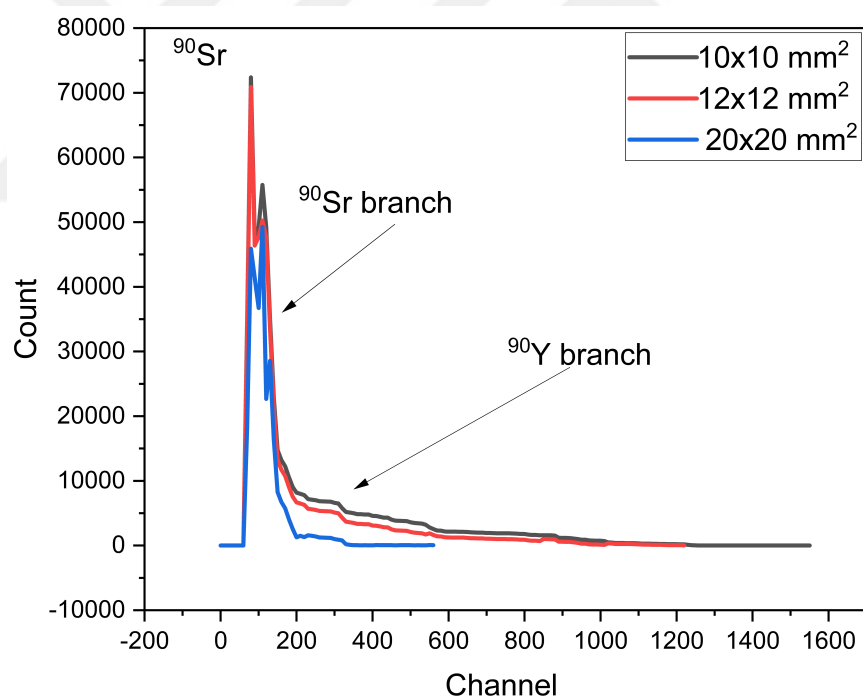


Figure 4.43. ^{90}Sr spectrum with fabricated Si-PIN PD

5 CONCLUSIONS AND RECOMMENDATIONS

The fabrication processes of Si-PIN photodiodes (PDs) with three different active sensor areas, measuring $10 \times 10 \text{ mm}^2$, $12 \times 12 \text{ mm}^2$, and $20 \times 20 \text{ mm}^2$, were identified by using the Silvaco TCAD Athena tool. Subsequently, the electrical characteristics of Si-PIN PDs device were investigated by using ATLAS tool. The Si-PIN PDs, which were created using computer-aided design, were produced following the manufacturing guidelines provided by the ATHENA device. The analysis of the electrical characteristics of the Si-PIN PDs were carried out. In their final state, performances of Si-PIN PD were scrutinized for X-ray and analyzed the radiation spectra emitted by radioactive sources of ^{90}Sr and ^{104}Tl .

1. The electrical characteristics of the fabricated diodes closely resemble those of the diodes generated by simulation. Discrepancies in the electrical characteristics of the received Si-PIN photodiodes have been detected. The non-uniform ion-contributing processes during manufacture resulted in variations across different regions of the base, hence impacting the electrical characteristics of the diodes. Enhancing the production phases can enhance the performance of diodes.
2. Electrical investigations were conducted on Si-PIN PDs having three different active areas. The capacitance values of the largest active field were observed to be greater than those of the other dimensions. The radiation performance of the $20 \times 20 \text{ mm}^2$ photo diode was adversely impacted by this condition.
3. The Si-PIN PDs that were produced exhibited dark current levels $< 10 \text{ nA}$, even under a voltage of -90 Volts . This outcome has resemblance to the Si-PIN PDs now produced for commercial purposes. Nevertheless, the dark current values can be reduced to lower levels by employing ion implantation.
4. In this study, the packaging appliances used for packaging the fabricated Si-PIN PDs were produced using a 3D printer. A copper conductor tape was used to retrieve the rear contact point from the diodes. This process has caused the diodes to produce an additional electronic noise. By improving the packaging tools, the diode's signal resolution can be increased.

5. The Si-PIN PDs produced in this study can be used to detect X-rays between 17 to 40 keV energy. The Si-PIN PDs fabricated in this study can be used to detect X-rays with 17 to 40 keV energy. In addition, as the dose ratio increases, the electrical signal of the Si-PIN PDs is linear.
6. A spectroscopy of radiation from ^{90}Sr and ^{204}Tl radioactive sources was obtained using Si-PIN PDs. The resolution of the spectrum can be increased by using a better vacuum system.
7. The Si-PIN PDs have an inadequate thickness of the depletion region for the purpose of achieving gamma-ray spectroscopy. Therefore, gamma spectroscopy has not been carried out. Gamma rays can be detected by the Si-PIN PD by gamma-rays transformed into visible light. In this procedure, it is necessary to integrate the Si-PIN PDs' with the scintillator. Subsequent investigations will involve conducting radiation testing using a sensor.

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