

LAB MANUAL

“Transient Current Technique – A Dynamic Characterization Method”



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CHAPTER 1.

INTRODUCTION

1.1. SILICON DETECTOR

Particle detectors are devices, or instruments that can detect track, momentum, energy, etc. of the incident particles. There are 3 types of detectors: solid, liquid, gas. Our study is focused on solid semiconductor silicon detectors because of various advantages over liquid and gaseous detectors. The energy required for the generation of electron hole pairs is comparatively smaller. These have high density of atoms and therefore are compact. They have a smaller size and can be carried easily from one place to another. Silicon is chosen because it is easily available and its natural oxide can act as both insulating and passivating layers. It can be operated at room temperature. Also it has a developed electronics technology.

In solids, when many atoms come together to form a crystal lattice, their individual wave functions overlap and their individual energy levels become degenerate and form energy bands consisting of energy levels separated by very small energies, which can be effectively taken as continuous. The highest energy band which has occupied states is called valence band and the lowest completely unoccupied band is called conduction band, with an energy gap between the two bands, which does not allow any energy state. Depending on the energy gap between valence and conduction band, a solid state body is classified as conductor, insulator or semiconductor. A semiconductor is a material that has an energy band gap not so large enough and the electrons can be thermally excited to the conduction band from the valence band. Silicon is a semiconductor with an energy band gap of 1.12 eV at 300 K.

The density of electrons is defined by the integration of the product of density of available electron states in the conduction band and the Fermi-Dirac distribution, over all energy range. Fermi energy (E_F) is defined as that energy level at which the probability of the electron occupying a state is exactly half at all temperatures, except 0 K and is 1 for energies lower than E_F and 0 for for energies greater than E_F , at 0 K.

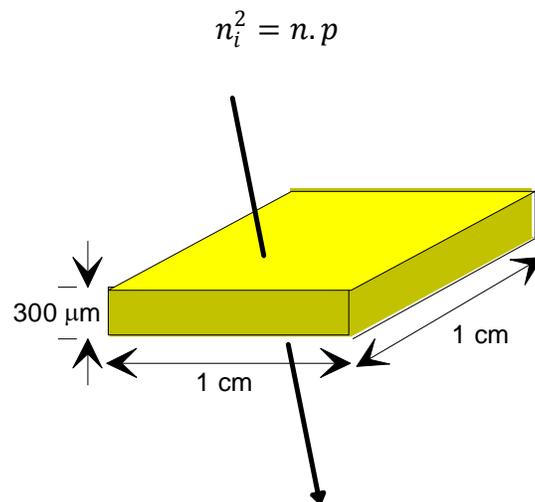
$$n = \int g_e(E).f(E).dE$$

$$g_e(k).dk = 2 * \frac{1}{8} * \frac{4.\pi.k^2}{\left(\frac{k}{a}\right)^3}.dk$$

$$E = \frac{1}{2m}.\left(\frac{hk}{2\pi}\right)^2$$

$$f(E) = \frac{1}{\exp\left(\frac{E - E_F}{kT}\right) + 1}$$

Similarly, density of holes in the valence band can be calculated. For an intrinsic semiconductor, the electrons in the conduction band are thermally excited. Hence, the number of electrons in the conduction is equal to the number of holes in the valence band. However, in an extrinsic semiconductor, either trivalent or pentavalent impurities are added, that makes the semiconductor p-type or n-type because of excess of hole or electrons carriers, respectively. For both the case, the law of mass action states that the product of number of electrons in the conduction band and the number of holes in the valence band is constant at a fixed temperature and is independent of amount of donor and acceptor impurity added. For silicon, the intrinsic carrier density at room temperature is approximately 10^{10} cm^{-3} .



When a particle is incident on a block of silicon, it creates electron hole pairs by ionization. A minimum ionizing particle deposits the least energy in the lattice. It leads to creation of ~ 80 e-h

pairs/ μm in silicon. Then, for a 300 μm thick detector, the number of charge carriers created will be 24,000. This is known as the signal.

Now, in a simple piece of semiconductor of 300 μm thickness, the number of free charge carriers is very large $3 * 10^8$. This is the noise. Since, the signal to noise ratio is so small, it cannot be used as a particle detector. Therefore, we use a pn junction in the reverse bias mode, which has current because of the minority carriers, which for a 300 μm thick junction can be calculated to be equal to 3. This gives a good signal to noise ratio.

A pn junction is formed by diffusing p-type impurities on a n-type wafer or vice versa. The majority carriers (electrons in n-type, holes in p-type) diffuse to the other side because of the density gradient, leaving behind ions. This region of positive and negative ions formed is called depletion region. The electric field and the potential developed in this region can be calculated using the Poisson's equation. Also the depletion width can be calculated. The diagrammatical view is shown in *Figure 1*.

$$\nabla^2 \phi = -\frac{\rho}{\epsilon}$$

$$\rho = -e \cdot N_A \text{ (p - type)}, e \cdot N_D \text{ (n - type)}$$

$$E = -\nabla \phi$$

$$N_A w_p = N_D w_n : \text{Charge neutrality}$$

$$w = w_p + w_n$$

$$\Delta V = \frac{e}{2\epsilon} (N_D w_n^2 + N_A w_p^2)$$

$$w = \sqrt{\frac{2\epsilon \Delta V}{e N_{eff}}}$$

$$N_{eff} = |N_A - N_D|$$

In the presence of an external source, in the above equations ΔV is simply replaced by $\Delta V + V$.

The above theory has been generated from [R1, R2, R3, R4].

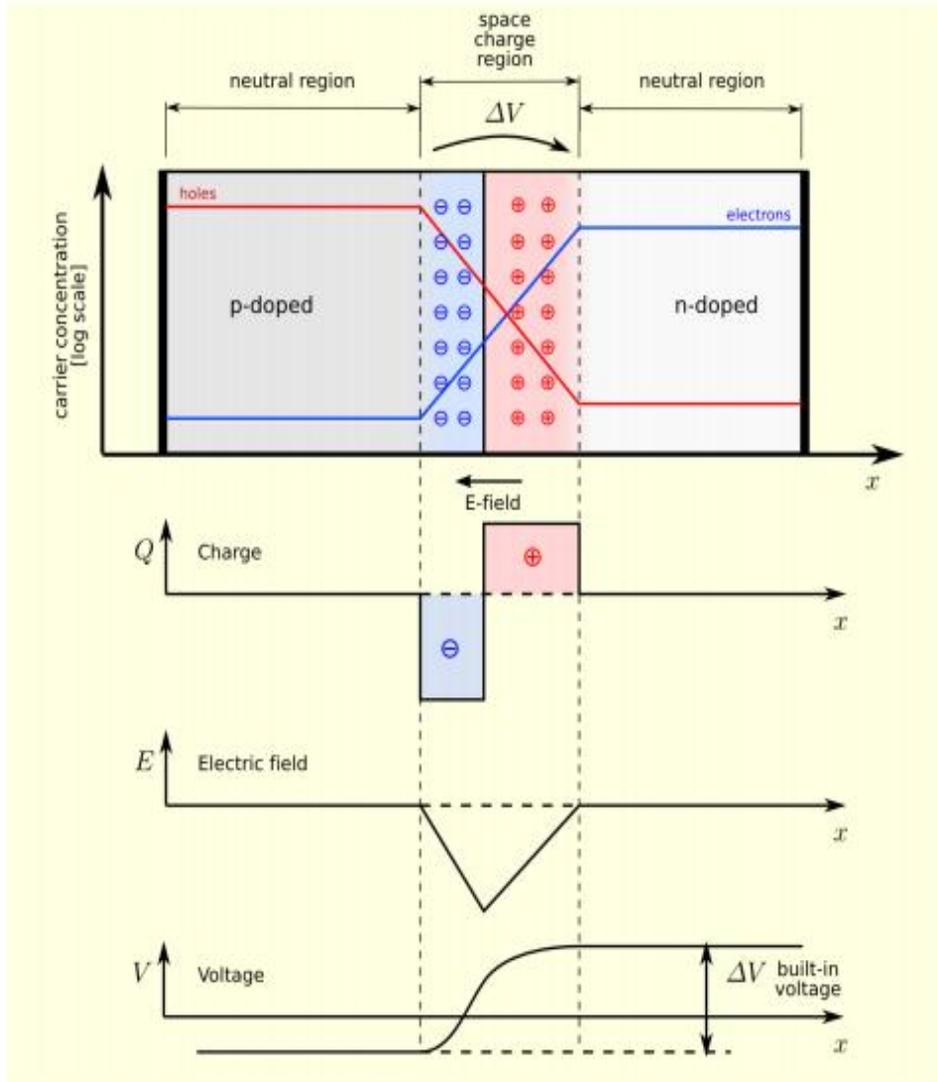


Figure 1.1: Formation of depletion region in a PN diode. The charge density, electric field and the potential profiles developed in the depletion region are shown.

Silicon detectors are presently being used in various experiments like CMS, ATLAS, ALICE, LHCb, etc. and in different configurations like pad diodes, strip detectors, double sided strip detectors, pixel detectors, low gain avalanche detectors (LGADs), 3D columnar detectors, 3D

double sided columnar detectors, avalanche photodiodes (APD), high voltage complementary metal oxide semiconductor (HV-CMOS), etc. These are shown in *Figure 2*.

1.4 About Silicon Diodes:

Due to their simple geometrical layout, planar diodes (also called pad diodes or pad sensors) are commonly used as test structures to investigate material properties. They can be reasonably well approximated with simple assumptions. This facilitates the calculation of certain quantities necessary for transport simulations and offers the possibility to study certain aspects of the material with a well defined geometry.

A sketch of a typical pad diode is shown in *Figure 1.3*.

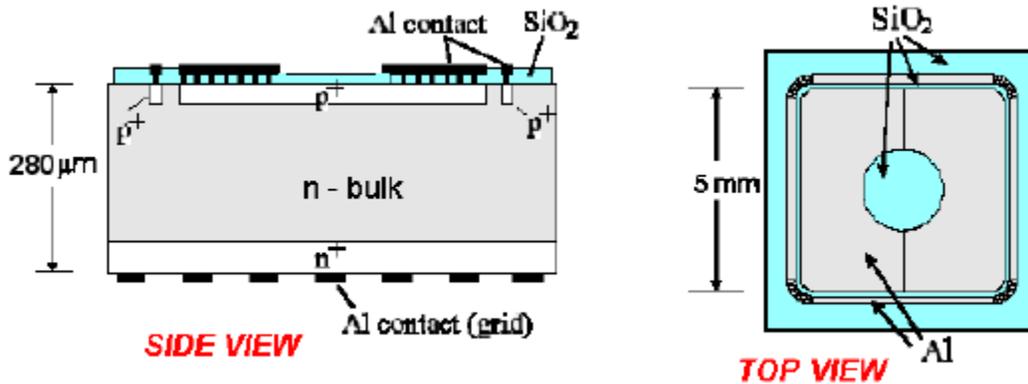


Figure 1.2: Sketch of a pad diode.

The Sensor used is a silicon detector, a reverse biased p-n Junction diode. The diodes have a basic double-sided p⁺-n⁺ or n⁺-p⁺ diode structure. The component area is surrounded with a guard ring to define the active volume precisely and prevent skewing of the leakage current measurements. With no guard ring, the electric field could reach the dicing edge of the sample. Then, large external currents could be pulled into the diode.

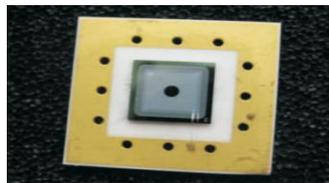


Figure 1.3: A diode sample on a ceramic plate prepared for TCT measurements.

The contact pad on the front side has an opening in the middle, thus enabling direct illumination of the diode. The opening in the pad, the guard ring, and the bonding wires can be seen in *Figure 1.4* where a diode is glued on the ceramic plate. The size of the diode samples is 8 mm x 8 mm, although the active detecting volume is sized 5 mm x 5 mm.

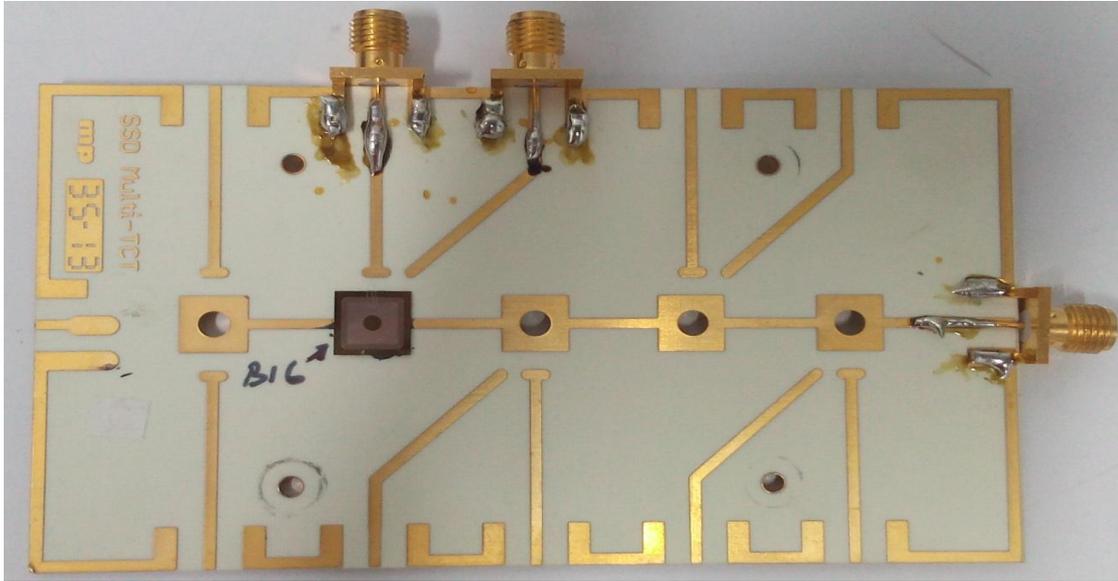


Figure 1.4: Picture showing Silicon Diode mounted on Ceramic PCB.

The above Figure shows the diode Glued on Ceramic PCB using Silver Glue and then is bonded to develop a connection to SMA connector.

1.5 Etching of Detectors from Back Side:

Diodes are etched from back side using NaOH(conc.) solution i.e. aluminum coating is removed or etched from the bulk silicon of the detector. Back side of diode is usually coated with aluminum oxide and in order to collect current produced in the detector due to electrons we will need to take TCT characteristics of diode from the back side and for taking the measurements the silicon must be exposed to laser.

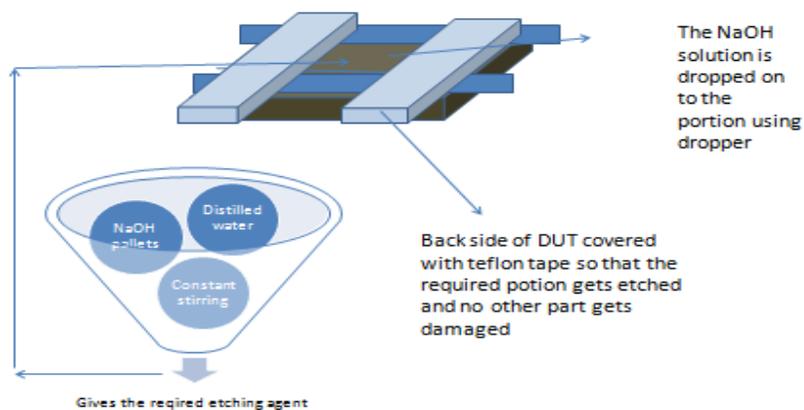
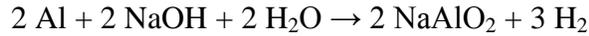


Figure 1.5: Picture showing etching of diode.

Reaction involved in etching process:

Sodium aluminate is also formed by the action of sodium hydroxide on elemental aluminum which is an amphoteric metal. The reaction is highly exothermic once established and is accompanied by the rapid evolution of hydrogen gas. however the species produced in solution is likely to contain the $[\text{Al}(\text{OH})_4]^-$ ion or perhaps the $[\text{Al}(\text{H}_2\text{O})_2(\text{OH})_4]^-$.



Sodium aluminate is soluble in water as well in alcohol also.

Etching procedure:

1. Concentrated solution of NaOH is prepared using distilled water.
2. Require portion to be etched kept free and rest of the portion is covered using Teflon tape so that it doesn't gets damaged.
3. DUT is cleaned using acetone.
4. And NaOH solution is dropped using a dropper.
5. This process is repeated twice to get desired etching.
6. And finally it is cleaned using Acetone.

TCT MEASUREMENTS

1.1 About TCT:

The Transient Current Technique (TCT) is a well established technique to determine effective trapping times in irradiated/ un-irradiated silicon diodes. It can also be used to determine the field distribution in these devices. TCT utilizes the drift of electron hole pairs created inside a reverse biased diode either by ionizing radiation or laser light. These charge carriers drift under the influence of the electric field and induce a current in the readout circuit. The current pulse contains information about the amount of drifting charge and its drift velocity.

The principle of TCT measurements is to observe the signal created by drifting charge carriers in the silicon detector bulk. The free charge carriers are generated in consequence of illuminating the detector by red laser light. If the front side implantation of the reverse-biased diode is illuminated, the charge carriers that are collected from the front side drift to the contact faster than the read-out electronics can respond. On the other hand, the carriers opposite in sign drift through the whole detector to the back side. This transient current is the measured signal. If a reverse-biased detector is being illuminated from the front side, the measured signal originates from the charge carriers equal in sign to the majority carriers in the bulk as presented in below figure. The figure shows how the TCT signal in a p-type detector is caused by holes when illuminated from the front side. Illumination from the back side results in a signal originating from electrons.

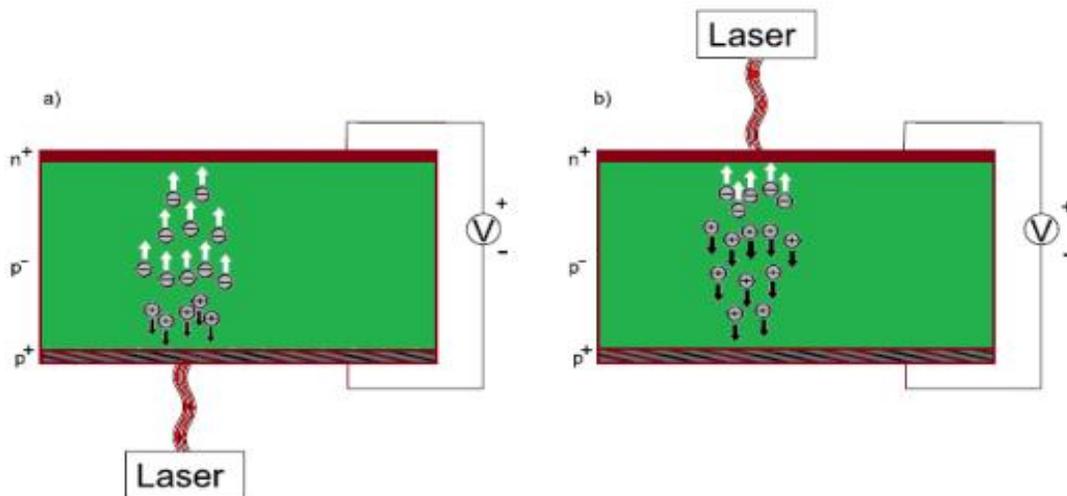


Figure 1.1 a) The back side of n⁺-p-p⁺ diode is being illuminated, and the resulting TCT signal comes from electrons. b) Illumination of the front side of the same diode structure results in a TCT signal caused by holes.

Experiment No. 1

Aim: To study the signal formation in Si detector using Transient Current Technique of the given Un-Irradiated Diode.

Theory:

Transient Current Technique (TCT) is one of the important methods to characterize silicon detectors and is based on the time evolution of the charge carriers generated when a laser light is shone on it. For red laser, charge is injected only to a small distance from the surface of the detector. For such a system, one of the charge carriers is collected faster than the readout time of the electronics and therefore, the effective signal at the electrodes is decided by the charge carriers that traverse throughout the active volume of the detector. So, for a detector with n-type substrate, with front-side laser illumination, the output signal is the electron signal and with rear-side laser illumination, the output signal is the hole signal.

The TCT setup at Delhi University is interfaced through interfacing software in LabVIEW.

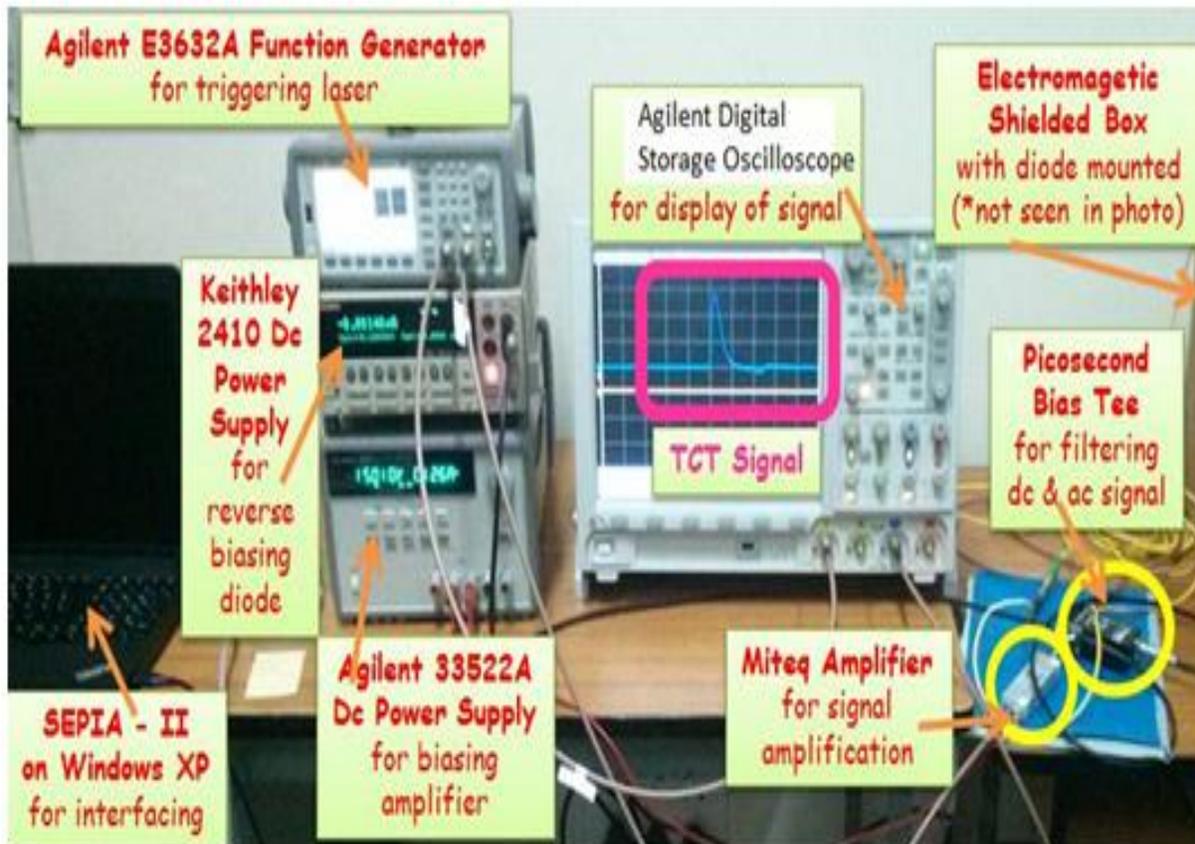


Figure 1.6: Picture showing Setup of TCT measurement set up in a class 1 clean Bench.

Apparatus:

DU has joined the RD50 organization and has developed a working Red Laser TCT setup in collaboration with CERN PH Detector Lab as shown in *Figure 1.1*.

Instrument Used :

1. PDL 828 “SEPIA II” multi channel Picosecond Quant Laser Controller
2. Laser Aperture or Laser Head
3. Agilent E3632A function generator
4. Agilent 33522A DC power supply
5. Keithley 2410 Source Meter
6. DSO 7104B
7. Miteq amplifier
8. Pico second Bias tee
9. Electromagnetic shielded box

Laser controller (Pico quant PDL 828 Sepia II)

- Provide current to the laser diode.
- Controls supply voltage.
- Controls laser output power Controls lasing wavelengths for red laser 660nm and infrared laser 1060nm.



Figure1.4 Showing laser controller.

PARAMETER	VALUE	UNIT
Frequency	50/60	hz
Power	130-250	watt
Voltages	100-250	volts

Table1.1 Parameters of laser controller.

Laser Aperture

They are building around a variety of different diode type, which allows offering these heads at many wavelengths with different power values and spectral widths. The laser heads come with collimating optics and can be fitted with optical fiber. All laser heads emit picoseconds pulses with a (FWHM) around 100 ps or below at the "low power level", which is close to the lasing threshold. The pulse width itself cannot be controlled directly, but does depend on the selected

power level of the diode. At maximum driving current (“high power level”), the pulse width broadens due to shoulders or additional peaks.



Figure 1.5 Laser Aperture.

PARAMETER	VALUE	UNIT
wavelength	375-1990	nm
peak power	Up to 1	watt
pulse rate	< 100	ps
frequency	80	MHz

Table 1.2 Parameters of laser aperture.

Power Supply

The Agilent E3632A DC power supply feature a combination of programming capabilities and linear power supply performance that makes it ideal for power systems applications.

This power supply has two ranges, allowing more voltage at a lower current.

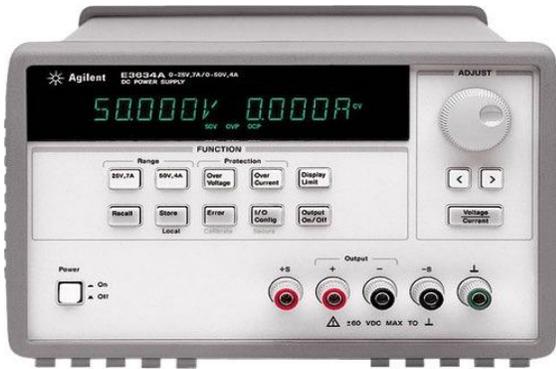


Figure 1.6 Power supply.

PARAMETER	VALUE	UNIT
Resistance	50	Ω
Power	80-200	watt
Voltage/current	0-15/7 0-30/4	Volts/ampere

Table 1.3. Parameters of power supply.

Bias Tee Picoseconds 5531

Bias tee is an ideal capacitor that allows AC through system but blocks the DC bias. Bias tees are designed to operate over a range of signal frequencies. The reactance is chosen to have minimal impact at the lowest frequency.

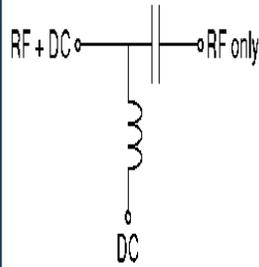


Figure 1.7 Bias Tee.

PARAMETER	VALUE	UNIT
Resistance	3	k Ω
Capacitance	2.2	nF
Impedance	50	Ω
Frequency	750	KHz
Pulse rate	35, 45 max.	ps
Voltage	1500 max.	volts
Current	2 max.	mA
Bandwidth	10	GHz

Table 1.4. Parameter of bias tee

Agilent 33522A Function generator:

The function generators' large graphical display allows for simultaneous parameter setup, signal viewing and editing. The generator also offers more precise functions and true point-by-point arbitrary waveforms that are alias-protected for exceptional accuracy.



Figure 1.8 function generator

Parameter	Value	Unit
Impedance	50	Ω
Frequency	30	MHz
Power	< 45	watt
Pulse rate	16-100	ps
Voltage	100-240	volts

Table 1.5. Function generator Parameters

Keithley 2410 Source Meter:

Source Meter models provide precision voltage and current sourcing as well as measurement capabilities. The power source characteristics include low noise, precision, and read back. The multi meter capabilities include high repeatability and low noise. In operation, these instruments can act as a voltage source, a current source, a voltage meter, a current meter, and an ohmmeter.



Figure 1.9 Source meter.

Parameter	Vaule	Unit
Voltage	100-240	volts
Frequency	50-60	Hz

Table 1.6 Parameters of source meter.

Amplifier

Amplifier is an electronic device that increases the power of a signal. An amplifier modulates the output of the power supply to make the output signal stronger than the input signal.



Figure 1.10 Miteq Amplifier.

Parameter	Value	Unit
Frequency	10 ⁴ -1300	MHz
Gain	58	dB min
Voltage	15	volts
Current	135	mA

Table 1.7 Parameter of amplifier

Software Used:

The measurements were controlled by custom written LabVIEW software on a personal computer which also stores the measurement data to the storage disk.

Wires and Connectors:

In the setup of TCT coaxial wires with different connectors (such as BNC, LEMO, SMA, Banana), optical fiber, USB's and GPIB's are used for serial Communication. A table containing wire and connectors used information with the specific device is listed below:-

SR. NO	DEVICES	CONNECTIONS WIRES	CONNECTO RS	MADE WIRES
1	<i>KEITHLEY 2400</i>	from I/O port to Bias-T (BNC-BNC)	Dual Banana (at K2400)	HUBER+SHUNER RG 58 C/U 50 OHM 521342 WP

		GPIB to KUSB	-	E74020-C 9U AWM STYLE-2464 VW-1 80°C SR-PVC 300V IEEE-488 26 AWG
2	AGILENT 33522A	From sync o/p to channel 1 of DSO(BNC-BNC)	-	BEDEA # 1084 RG 58 --- MADE IN GERMANY --- 93016205
3		from channel-setup 1 to sepia triggering IN (BNC-BNC)	-	RG 142/2 X 11BNC/1000mm ITEM No. :84233630
		GPIB to KUSB	-	E74020-C 9U AWM STYLE-2464 VW-1 80°C SR-PVC 300V IEEE-488 26 AWG
	AGILENT E3632A	From o/p(+) to preamp	-	
		From o/p(-) to preamp	-	
		GPIB to KUSB	-	E74020-C 9U AWM STYLE-2464 VW-1 80°C SR-PVC 300V IEEE-488 26 AWG
A	PDL 828 SEPIA II	From PDL to computer(USB)	-	
		PDL photodiode(LEMO-BNC) to	-	
4		from sync out in PDL to photo diode (BNC-BNC)	BNC(M)-BNC(M)	RG 142/2 X 11BNC/1000mm ITEM No. :84233630
		Thick black wire from laser output to laser head input	-	
	LASER HEAD	2 optical fiber	Pigtail	
i	DSO 7104B	from Channel 3 to Pre-Amplifier (SMA-SMA)	BNC-SMA (at DSO)	RG 142/2 X 11SMA/2000mm ITEM No. :84233636
B		From DSO to	-	

		computer(USB)		
ii	BIAS T	From diode to Bias T (SMA-SMA)	-	RG 142/2 X 11SMA/2000mm ITEM No. :84233636
	PRE AMPLIFIER	Bias T to preamp	SMA(M)-SMA(M)	

Table 1.8 Wires and Connectors used in TCT setup.

Block Diagram:

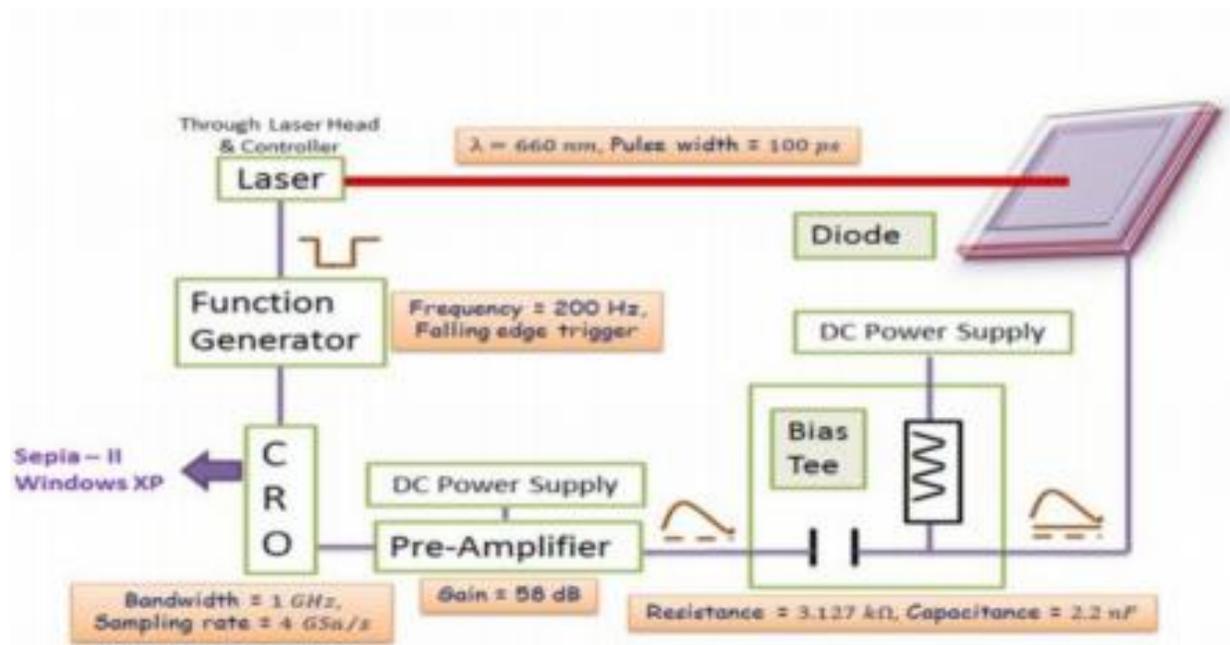


Figure 1.10: Block Diagram showing connections for TCT set-up.

1.4 Steps/Procedure for Measurement:

First, the DUT is kept in the electromagnetically shielded chamber with the help of screws making sure that the distance between optical lens and the PCB is 4 cm. The contact pad on the front side of the sensor has an opening in the middle where the laser should be illuminated and for that the Sepia software in computer should be opened.

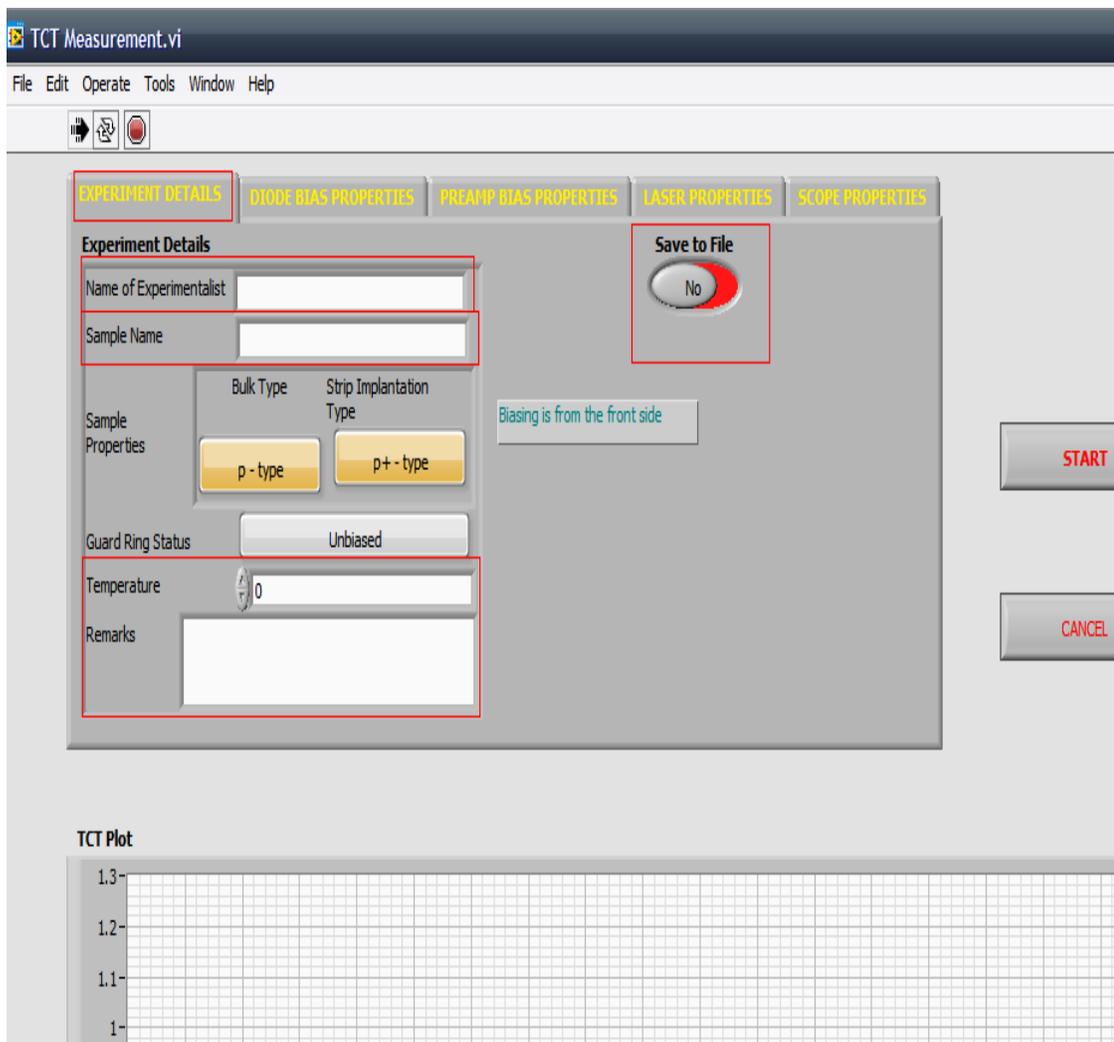
Sepia II Software:

1. Open the software “SEPIA IP” from start menu.
2. Make sure that the laser controller is active i.e. the key is turned on.

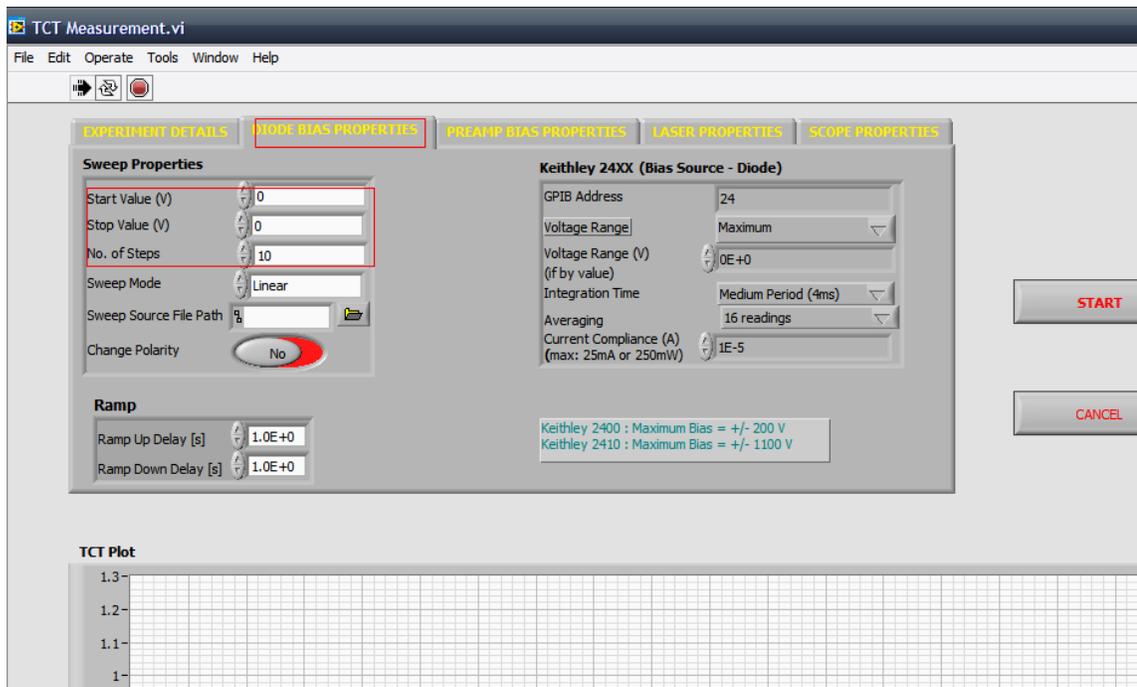
3. Set the intensity 80%.
4. Change the frequency to 80Mhz which is visible to eye, press apply button and move the Optical Lens stand so that the laser is shone within the small circular spot on the detector.
5. Then again change the frequency to Falling Edge and press Apply button and then quit.

For LabVIEW software:

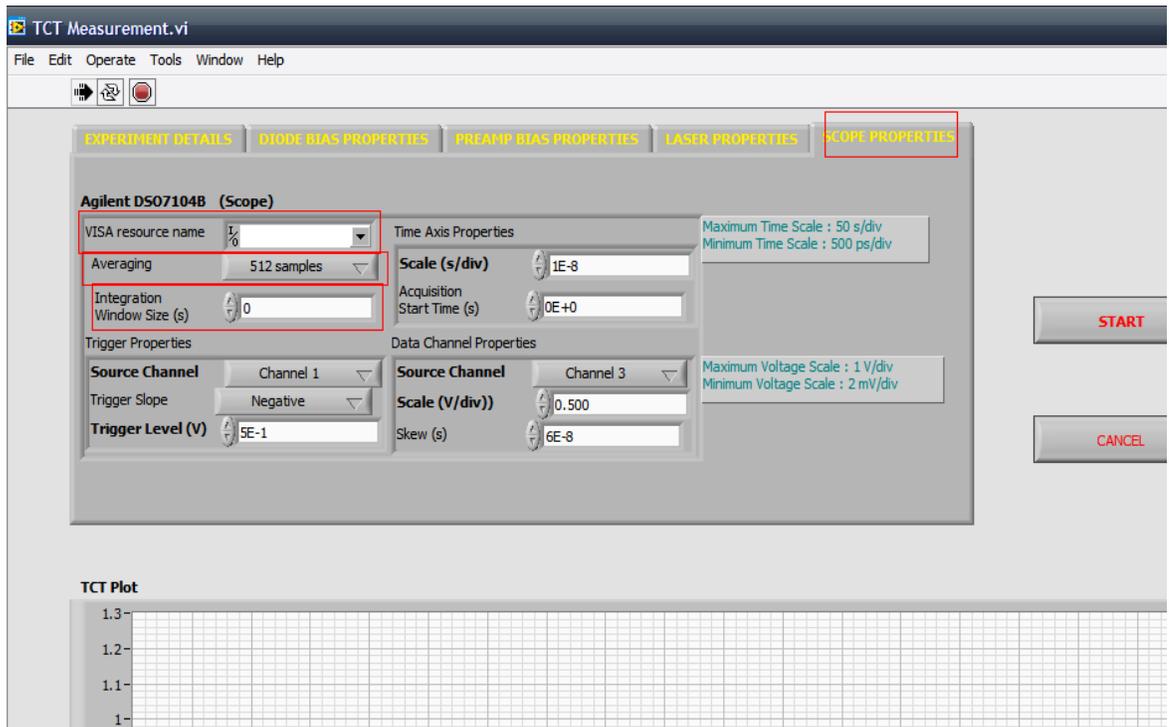
1. Open the folder SERC School on Desktop then TCT->bin->”TCT Measurement.exe” and press enter.
2. In the window tab “Experimental Details” enter the name of operator, diode name, set the Bulk Type, Temperature, remarks if any and press Save button to ensure that the data should be saved in a text file.



3. Then go into the “Diode Bias Properties” tab and enter the start, stop and no. of steps value.



- Then directly move to the “Scope Properties” Tab where you will have to select DSO VISA resource name from drop down menu (DSO7104b), set the averaging of 1024, and set the integration window to 25E-9.



5. No other settings should be touched.
6. Now press the start button.
7. The data will be saved on the folder named "TCT" with name as mention in "name of operator" followed by date.

Precautions:

1. Remember to set the compliance before running the experiment.
2. Make a manual check for identification of the polarity of the detector substrate.

RESULTS AND DISCUSSION

Discussion:

The red TCT signal from the electrons and the holes can provide an insight to the charge collected, the full depletion voltage, the electric field profile, the drift velocity, effective doping density, etc. of the detector substrate. Hence, the red TCT setup is a very important and useful tool in determining the change in the electrical properties of the detector with irradiation. Below is a sample plot of front-side red laser TCT signal (electron signal) for p-in-n type pad diode, at different bias voltages.

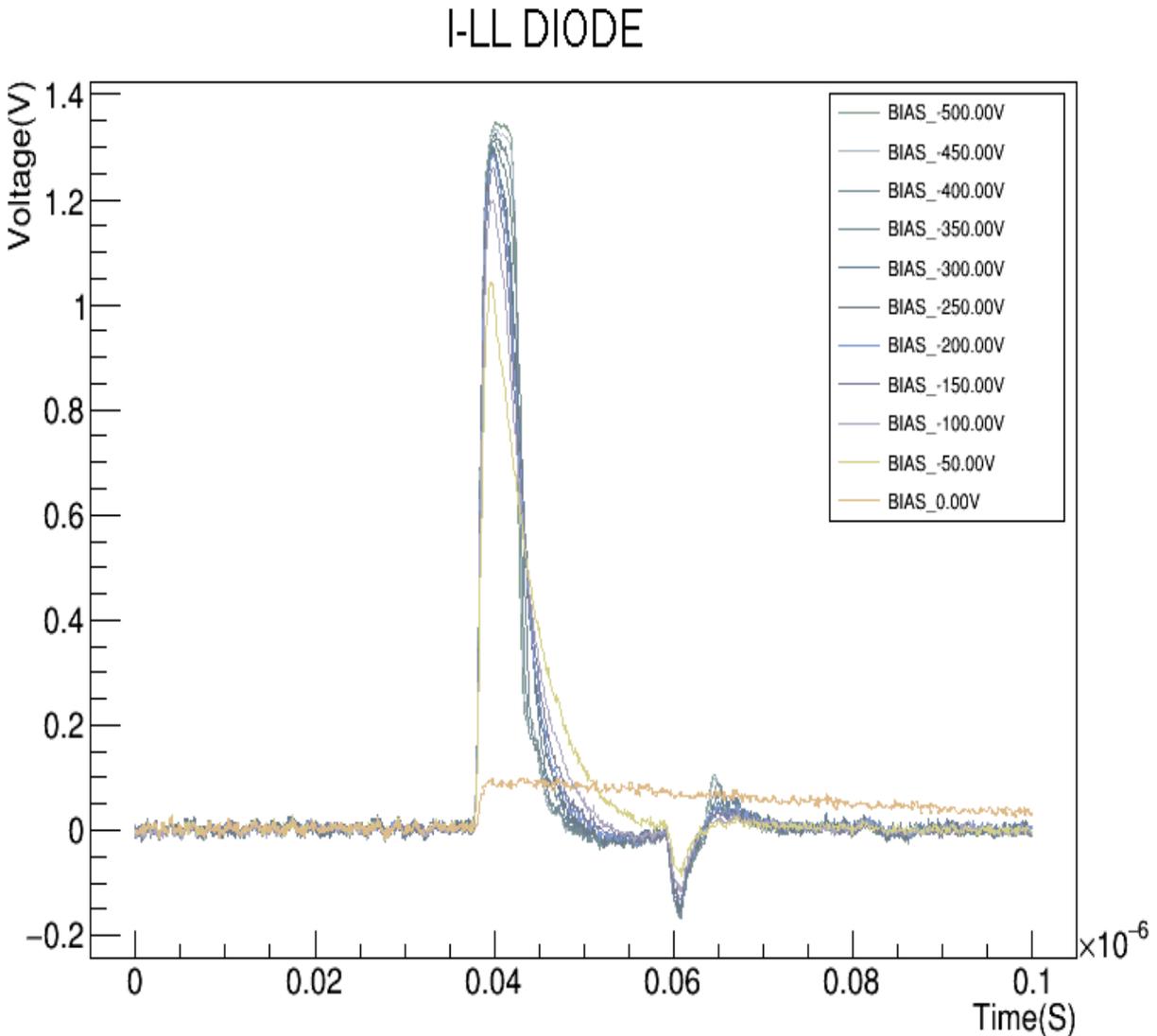


Figure1.1 The electron tct signal at different bias voltages from 0 V to -500 V of a I11 diode illuminated with red laser from front side.

I9 Diode

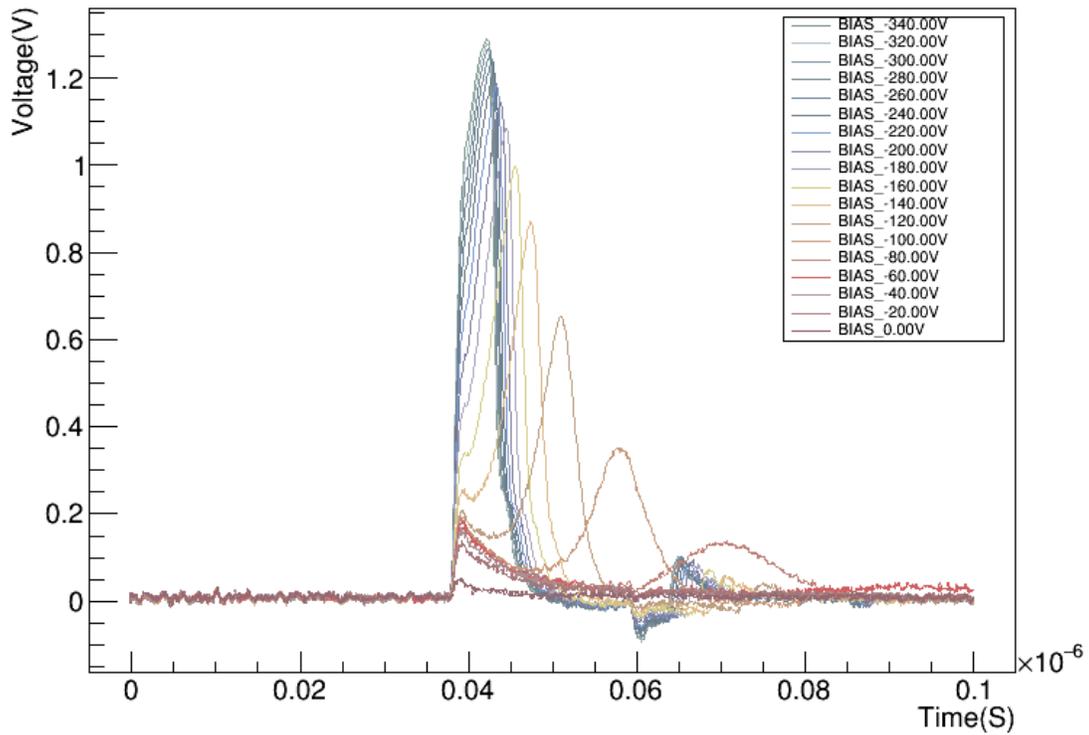


Figure1.2 The electron tct signal at different bias voltages from 0 V to -340 V of a I9 diode illuminated with red laser from front side.

I-13 Diode

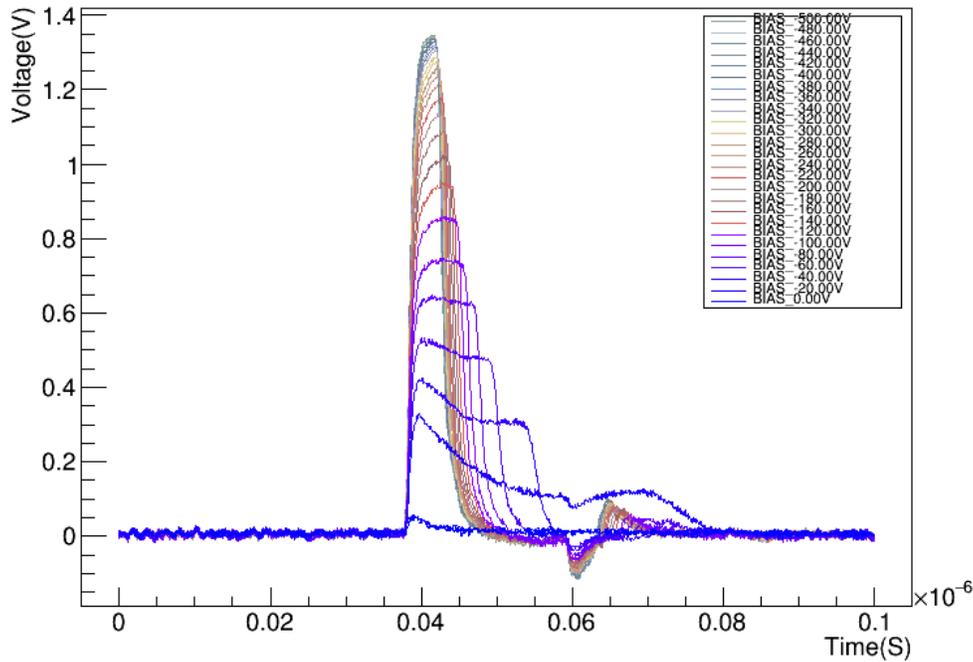


Figure1.3 The electron tct signal at different bias voltages from 0 V to -500 V of a I13 diode illuminated with red laser from front side.

I-6 Diode

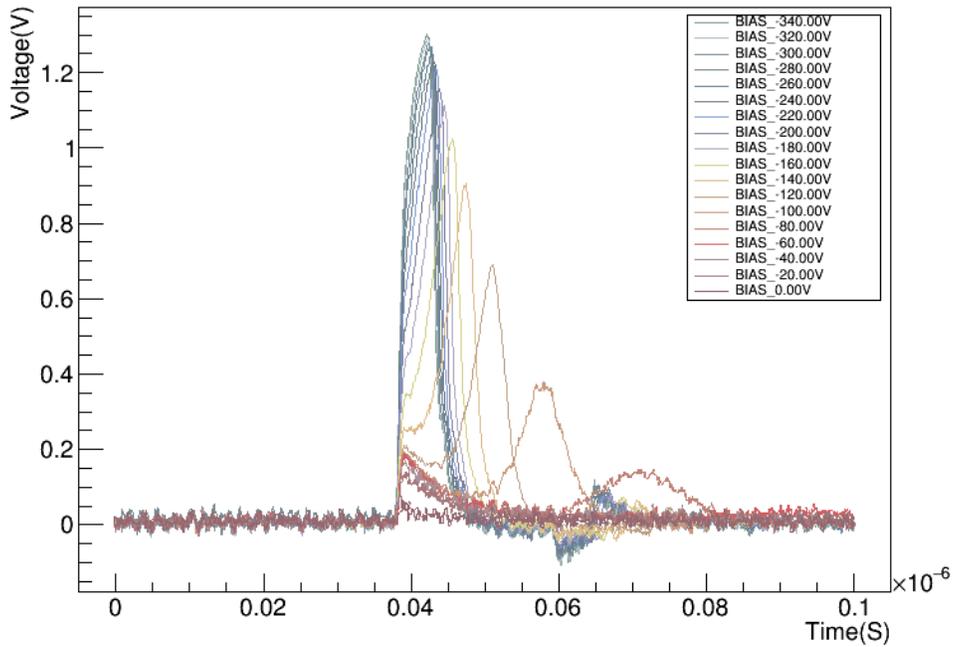


Figure1.4 The electron tct signal at different bias voltages from 0 V to -340 V of a I6 diode illuminated with red laser from front side.

N1 Diode Front side

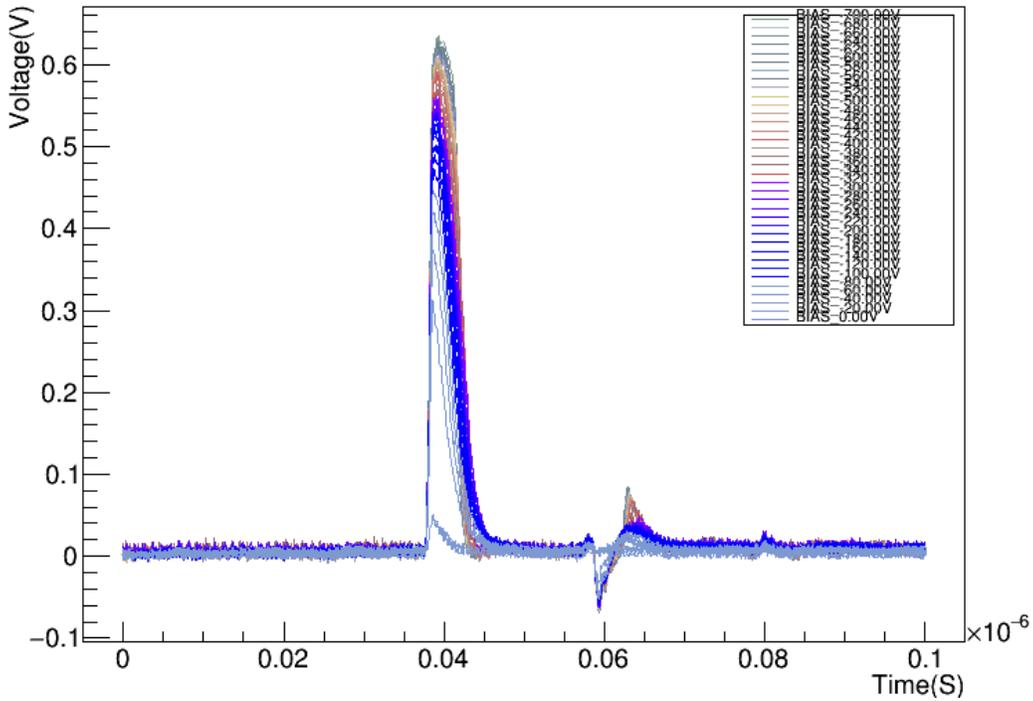


Figure1.5 The electron tct signal at different bias voltages from 0 V to -700 V of a N1 diode illuminated with red laser from front side.

N1 Diode Back side

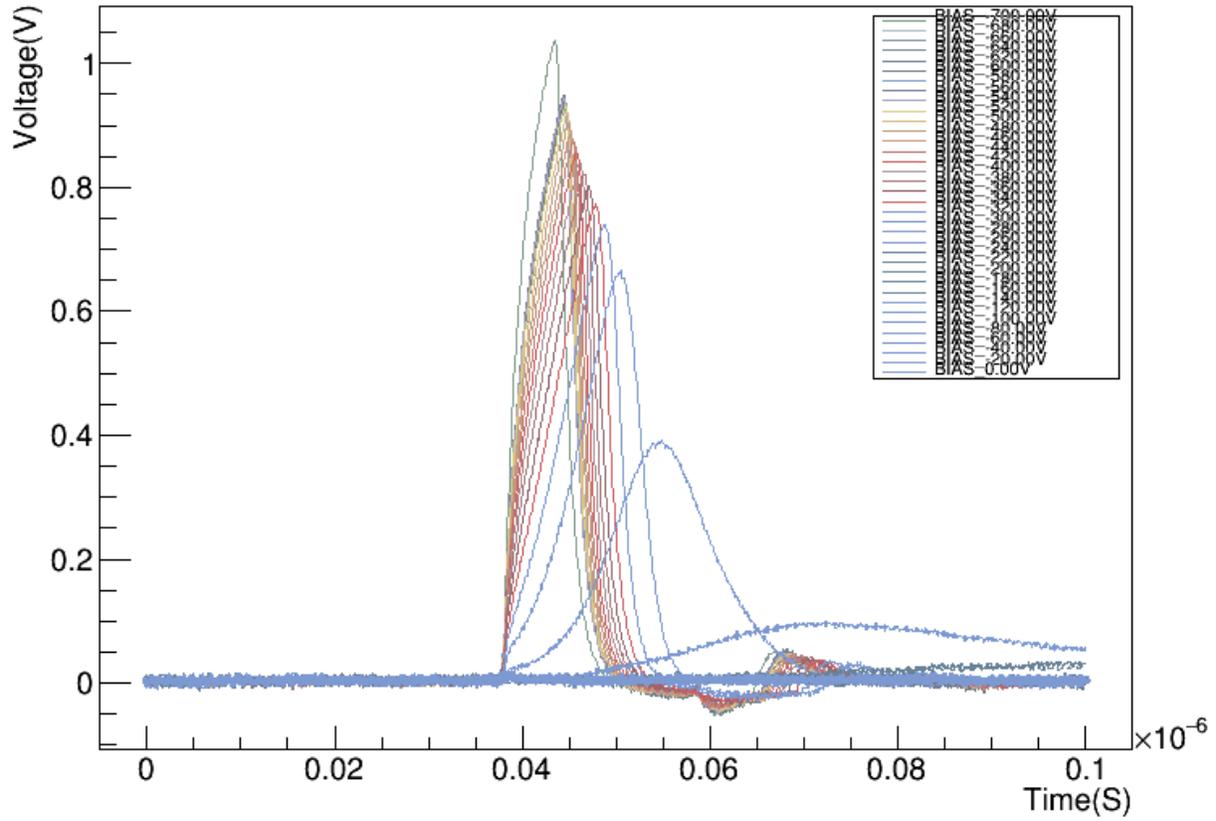


Figure 1. 6 The electron tct signal at different bias voltages from 0 V to -700 V of a N1 diode illuminated with red laser from Back side.