Reproducibility tests for measurements with CV-IV and TCT setups

Author: Shudhashil Bharthuar
Summer job project in PH-EP SSD group, CERN
Supervisors: Esteban Curras Rivera, Moritz Oliver Wiehe, Sofia Otero Ugobono, Michael Moll

Keywords: TCT, CV-IV, reproducibility test, systematic error

Summary

The entire project is based on checking the reproducibility of measurements done with the CV-IV and TCT setups by changing different factors or parameters (such as temperature and frequency for CV-IV setup and temperature with laser intensity for IR laser and Red laser for TCT setup) that vary during data acquisition. We thereby, measure the systematic error of the experimental systems under these varying conditions and also can check for the consistency of results. One can infer to the standard deviation \( \sigma \) in order to check the consistency of the results.

Contents

1 Introduction 3

2 Silicon Detectors 3
   2.1 p-n Junction 4
   2.2 Particle Detectors 8

3 Characterization techniques 9
   3.1 CV/IV MEASUREMENT 9
   3.2 Diode sample layout 12
      3.2.1 Passivation 12
      3.2.2 Bias Ring 12
      3.2.3 Guard Ring(s) 12
3.3 TCT MEASUREMENT ............................................. 13

4 Samples and Measurements ..................................... 15
  4.1 Sample Specifications .......................................... 15
  4.2 Measurements Performed ...................................... 16

5 Results and discussion .......................................... 17
1 Introduction

Characterisation of solid state detectors can be done with the help of CV-IV and TCT (Transient current technique). With the help of the CV-IV setup one measures the change in capacitance by varying Voltage and also the change in current with voltage. From the IV plot, we get to know the leakage current and the breakdown voltage for the sensor and from the CV plot we get to know the value of end capacitance once the silicon bulk gets fully depleted. On plotting $1/C^2$ versus Voltage, we get the value of full depletion voltage from the point of inflection in the curve.

Since most of the time we do one set of measurement per sensor keeping the varying parameters constant, we dont know till what extent our measurements are true or consistent with the real values. Therefore, by repeating the measurements with different varying conditions, we can determine the systematic error of the set up. Systematic error (or systematic bias) refers to the consistent, repeatable error associated with an equipment or experimental design. The changing factors in an IV measurement are temperature and in CV measurement, the changing factor is temperature and frequency. Similarly for TCT set up, the varying parameters are temperature and laser intensity which can be altered by changing the shutter opening for both red and Infra-red lasers.

This report presents a theoretical background for silicon particle detectors, a brief description about the characterization of silicon sensors using CV/IV and Transient Current Technique (TCT) measurements as well as the practical measurements. In the end, the results are discussed along with a summary of the contents.

2 Silicon Detectors

Silicon is an element that has revolutionized the development of the electronics and is known to be a very important and multi-usable material, dominating the technology today. Silicon is a semiconductor which isolates at low temperatures and shows a measurable conductance at higher temperatures. Silicon sensors have a very good intrinsic energy resolution since for every 3.6 eV energy released by the particle crossing the medium, one electron-hole pair is produced. Compared to a gaseous detector wherein about 30 eV is required to ionize a gas molecule in which one gets 10 times the number of particles in Silicon. Silicon particle detectors used in LHC experiments are in principle reverse biased p-n junction diodes. Without any impurities, the concentration of electrons (n) in the conduction band and holes in the valence band are equal to the intrinsic concentration.

The mechanism to alter the conductivity behavior of intrinsic silicon is by inserting additional states in the forbidden region to increase the probability to excite electrons or holes in the Fermi-Dirac sense:doping. In order to understand the electrical conduction mechanism, one has to know about the mobility $\mu$ and the drift velocity $= \mu E$ where $E$ is the applied electric field. It is not difficult to convince that the conduction depends upon the the amount of free charges available and their ability and ”motivation” to move. Conductivity of the silicon material comes to:

$$\sigma = e[\mu_en + \mu_hp] \quad (1)$$
and therefore:

\[ \rho = \frac{1}{e[\mu_e n + \mu_h p]} \] (2)

Microscopically, \( \mu \) is given by:

\[ \mu_{e,h} = \frac{e \tau_s}{m^*_{e,h}} \] (3)

where \( \tau_s \) is the time between scattering processes:

a) at crystal defects due to undesired impurities which is not dominant before irradiation but gets dominant after irradiation

b) at impurities such as doping atoms that are introduced intentionally

c) at phonons due to thermally simulated lattice vibrations

### 2.1 p-n Junction

A p-n junction is generally fabricated by the diffusion or implantation of acceptor or donor impurity atoms into n type or p type substrate silicon, respectively. By thermally joining, p-type and n-type together electrons move to the lower Fermi levels and holes to the higher, thereby building up a space charge region SCR, where in equilibrium, the Fermi energy \( E_F \) is constant everywhere. In order to visualize it, you can see Figure 1. wherein the band diagrams for p-type and n-type region are shown along with their Fermi levels \( E_{F-p} \), \( E_{F-n} \) separately. The dashed lines shows the Fermi level \( E_{F-i} \) of the intrinsic sensor. Secondly, on joining the parts, the electrons move the material with lower energy while the opposite is true for holes. The last diagram shows a state of equilibrium wherein a space charge is built up and the potentials are shifted accordingly but the Fermi energy is kept constant everywhere [4].

![Figure 1: p-n Junction showing formation of the space charge region (SCR)](image-url)

Let’s now try to get a mathematical feeling of the device. At the p-n junction diffusion and recombination produces a space charge region thereby creating an electric field \( E \) and
preventing further diffusion. Figure 2. shows how a dynamic equilibrium is created wherein the field current and diffusion flow of both the charge carriers are compensation each other at the p-n junction.

The Poisson equation describes the electrostatic potential \(\phi(x)\):

\[
\frac{d^2 \phi}{dx^2} = -\frac{1}{\epsilon_{SC}\epsilon_0}\rho(x) \tag{4}
\]

Assuming complete ionization, the charge density with the impurity density of acceptor and dopant, respectively is derived as follows:

\[
\rho(x) = -q[n(x) - p(x) + N_A - N_D] \tag{5}
\]

The space charge width however is given by:

\[
w = x_p - x_n \tag{6}
\]

And, electric field strength \(|E|\) n-type region and p-type region respectively are given as:

\[
|E_n(x)| = +\frac{qN_D}{\epsilon_{SCR}\epsilon_0}(x + x_n); \quad |E_p(x)| = +\frac{qN_A}{\epsilon_{SCR}\epsilon_0}(x - x_p) \tag{7}
\]

On integrating equation (6) and (7) twice leads us to the parabolic behavior of the potential \(\phi(x)\) with boundary condition given by: \(\phi(x=0) = 0\) gives us:-

\[
\phi_n(x) = -\frac{1}{2} |E_{\text{max}}| x_n \left[ \left( \frac{x}{x_n} \right)^2 + 2 \frac{x}{x_n} \right]; \quad \phi_p(x) = +\frac{1}{2} |E_{\text{max}}| x_p \left[ \left( \frac{x}{x_p} \right)^2 - 2 \frac{x}{x_p} \right] \tag{8}
\]

\[
V_{\text{diffusion}} = \phi_p(x_p) - \phi_n(x_n) = \frac{1}{2} |E_{\text{max}}| w = \frac{1}{2\mu\rho\epsilon}w^2 \tag{9}
\]

The entire system is defined by energy barriers which are completely defined by the doping concentrations. Creation of large volumes with pure doping concentration difference is technically impossible; \(V_{\text{diffusion}}\) is of the order of a few to some hundred of millivolts with SPR of some ten of microns. An additional technique is needed to increase the depleted region. An external voltage would disturb the equilibrium and lead to generation and recombination of electrons/holes. As shown in figure 3, depending upon the magnitude along with the polarity of the external voltage applied, the intrinsic potential barrier either increases or decreases.
Figure 2: The above diagram displays: (a) A simple visualization of the atomic and charge distribution. (b) The doping profile. (c) The mobile charge density. (d) The space charge density. (e) The electric field configuration. (f) The electric potential. (g) Electron energy across the pn-junction. All the states are depicted in their equilibrium state without any external applied voltage.

As shown in figure 3, depending upon the magnitude along with the polarity of the external voltage applied, the intrinsic potential barrier either increases or decreases. Silicon sensors are operated in reverse bias mode. For the detectors, charge carriers that are created in the SCR region are collected at the junction while those are generated in the non-depleted region are recombined with free majority carriers or with the generation partner and are
eventually lost. Therefore, an external voltage is applied $V_{\text{external}}$ such that the whole volume or the bulk of the silicon is completely depleted. With $V_{\text{external}} = V_{\text{bias}} + V_{\text{diffusion}}$ and equation (9) results to:

$$w = \sqrt{2\varepsilon \mu \rho V_{\text{bias}}}$$

(10)

Alternatively,

$$V_{\text{fulldepletion}} = V_{FD} = \frac{D^2}{2\varepsilon \mu \rho}$$

(11)

$V_{FD}$ is one the important parameters describing the minimal operation value for the voltage the sensor has to sustain without undergoing any current breakdown.

Figure 3: The barrier decreases in forward bias case as the majority carriers flow freely through the diode and increases for reverse-bias case as well as the same goes with the depletion width that increases.

The diode is partially depleted at low reverse bias voltages. In these circumstances, the total leakage current can be expressed as the summation of the diffusion current $J_s$ from the non-depleted area and the generation current $J_{\text{gen}}$ from the SCR. The leakage current also is affected by other parasitic currents such as the surface generation current. This can however be neglected along with other non-ideal conditions such as tunneling of charge carriers between energy states in the band gap and the series resistance in the
junction structure. In particle detectors, the minority carrier concentration also remains significantly lower than the density of the majority carrier concentrations thus excluding the high injection case. Consequently, $J_{\text{gen}}$ becomes the dominant component of the leakage current when diodes are fully depleted. Hence, the total leakage current of a fully depleted detector can be given by:

$$J_{\text{gen}} = \frac{qn_i W}{\tau_{\text{gen}}}$$  \hspace{1cm} (12)

where $\tau_{\text{gen}}$ denotes the lifetime of the generated charge carriers and $n_i$ is the intrinsic carrier concentration given as:

$$n_i^2 = n_p = N_C N_V e^{-\frac{E_g}{K_B T}}$$  \hspace{1cm} (13)

wherein $N_C$ and $N_V$ are the effective density of states for conduction band and valence band respectively. $E_g$ is the band gap of silicon, $K_B$ is the Boltzmann’s constant and $T$ is the temperature.

### 2.2 Particle Detectors

At the LHC, collision events take place after an interval of 25 ns. However, the signal needs to be read out in each interval. This can be achieved by reading out the drift current caused by the electric field. Detectors used have a lightly doped bulk material with thin, high resistivity and highly doped implantations. Traditionally detectors have been fabricated from n-type bulk of silicon. The frontal side is doped with acceptor type impurities and thereby creating a $p^+$-type implantation and a $n$ implantation is formed at the back side creating the donor doping. Hence, the pn junction is generated closer to the front side of the detector.

The band gap of Silicon is 1.17 eV but an additional energy is required to excite the electrons from the valence band to the conduction band. In the process electron-hole pairs are generated. Consequently, excited phonons with a certain energy are needed to compensate the momentum changes. Therefore, the minimum energy for ionizing silicon diode structures is 3.67 eV at room temperature. Minimum ionizing particles create in a fully depleted 300 $\mu$m thick silicon detector about 22000 electrons which corresponds to approximately 70 electron-hole pairs per micron. In order to achieve measurable signals from such level of carrier concentration, the practical implementations of detectors are volume devices. This enables collection of carriers from entire detector bulk [1].

Single electron drifting through a 300 $\mu$m thick detector at an average electric field of $10^4$ V/cm are collected in approximately 10 ns, where as the collection time for the holes is approximately 25 ns. The collection times of the charge carries depends on their drift velocities, which on the other hand is determined by the mobilities of electrons and holes, respectively. Thus the time needed to collect induced charge carriers with temperature as the mobility of electrons and holes increases with decreasing temperature. Also, if the trapping probability of the charge carriers is high, not all the induced charge carriers can be collected and the total amount of the remaining free carriers can be read out in even shorter time than stated above [5].
3 Characterization techniques

Since the reproducibility tests were done with CV-IV and TCT setups, the report includes description of these two methods.

3.1 CV/IV MEASUREMENT

The depletion voltage can be determined experimentally by measuring the capacitance as a function of applied voltage (CV). The pn junction in the semiconductor bulk can be considered as a parallel plate capacitor of size of the depletion region. The geometrical capacitance for a parallel plate capacitor is given by:

\[ C = \frac{\varepsilon A}{d} \]  \hspace{1cm} (14)

where A is the square of the capacitor’s plate and d is the thickness of the capacitor (=depletion region). On the other hand, using equation 14 can be defined as:

\[ C = A \sqrt{\frac{\varepsilon q N_{\text{eff}}}{2V}} \] \hspace{1cm} (15)

This function will describe the behavior of the capacitance until the full depletion will happen after that it becomes constant. The full depletion voltage is the value of voltage when the capacitance becomes constant. Measured CV data should be plotted as \( C^{-2} \) vs. V and the crossing point of the two linear fits will give the value of the depletion voltage [shown in figure 5].

In reality even in the fully depleted region some phenomena leading to the movement of charge carriers can occur. Silicon is mainly thermal pair production resulting in existence of leakage current

\[ I_{\text{leakage}} = qGd = \frac{qn_i d}{\tau_g} \] \hspace{1cm} (16)

where G is the generation rate, \( n_i \) is the intrinsic carrier concentration and \( \tau_g \) is the lifetime of generated electron-hole pairs.
Primary generated electrons enquired enough kinetic energy begin to create more electron-hole pairs, and this process escalates as multiplication of charge carriers and result in fast significant increase of leakage current. This phenomenon is called avalanche breakdown. It is possible to find the leakage current at full depletion voltage using the value of $V_{fd}$ determined during CV measurements.

The following two figures show the circuit diagram for IV and CV measurements respectively.

The probe station at the PH-DT laboratory consists of a dry air supply in order to maintain the humidity levels at low temperatures up to -20°C. This prevents condensation of air humidity on the metallic contact of the sensors. It also consists of the JIG that secures the sensors by means of vacuum on the chuck. Along with the vacuum supply, there’s also high voltage power supply at the bottom conducting surface of the sensor. There are two needles that are held on a plate next to the chuck by the help of micro manipulators. On of the needle is used to ground the guard ring where as the other needle is connected to the pad in order to read the current from the metallic contact at the top of sensor (the pad). Both the micro manipulators are can be adjusted along the -X, -Y and -Z directions.
by the help of fine adjustment screws. The measurement equipment is controlled by the PC via the interface on LabView software. The measurement equipment of the probe station includes [2]:

1) Keithley 6517A (KE6517A) : This device has a voltage source with a range of +/-1000V, a maximum current of 1mA and an additional electrometer which is completely isolated from the voltage source. The electrometer is used for all current measurements.

2) ISEG: This device is a DC-DC converter with a output range of -6000V TO 0V or 0V to +6000V with a maximum current of 10mA. The voltage source of the Keithley 6517A is used as input voltage.

3) Hewlett Packard 4284A (HP4284A): The LCR meter is used for capacitance measurements. It has a test frequency range from 20Hz to 1MHz. The device has a maximum signal voltage level of 1 Volts.

4) Isobox: This is a circuit board which adds the signal from the HP4284A to the high bias voltage.

Figure 7: Circuit diagram showing CV measurement

Figure 8: CV-IV set up in EH-DT SSD lab
3.2 Diode sample layout

Silicon sensors that were used for this project are based on a diode structure consisting of n- and p- doped silicon layers forming a pn junction [shown in Figure 8]. The pad structure includes the main contact pad with round optical opening and the metal layer on the back. To reduce surface currents across the conductive sensor edge the front pad is surrounded by the guard ring. In the n-type samples heavily p-doped front implant forms the on-junction with the n-doped bulk. The back side is also heavily n-doped to build an ohmic contact.

![Figure 9: Diode layout (Top view)](image)

The ring structures surrounding the active area including the sensor out edge are discussed in this subsection as well as passivation.

3.2.1 Passivation

Passivation is the final step to protect the sensor from the environment. It often consists of a crude form of $\text{SiO}_2$, sputtered on the sensor or a film of polyamide. Only the bonding and the testing areas (Al) are later opened. In contrast to the passivation needs in the industry, the material for the sensor protection has to be without contaminants. A small charge concentration in the passivation can change the well-designed field configuration on the implants and the Si-$\text{SiO}_2$ interface. For example, negative charge concentration can evoke a surface inversion layer, opening a hole conduit from strip to strip decreasing inter strip resistance.

3.2.2 Bias Ring

The bias ring and the backplane are the main contacts to apply the bias voltage. The bias ring runs around the whole active area of the sensor to ensure the homogeneous potential for all the strips. It either connects to all the bias resistors, therefore supplying the implants with voltage, via the punch-through effect. The bias ring is not ultimately necessary for DC-coupled sensors where the potential can be applied via a read chip connection.

3.2.3 Guard Ring(s)

The guard ring shapes the field inside the sensitive area to minimize the edge effects and guarantees a defined homogeneous potential for all the strips, including the edge ones. Two
basic connection schemes can be applied. First, a direct connection of the guard ring to a certain potential, often GND, provides a drain for the leakage currents from the edges of the detector. The second configuration uses one or more "floating" guard rings to adapt potential, especially for high voltages, where the voltage drops from outside to inside.

3.3 TCT MEASUREMENT

Transient Current Technique (TCT) exploits the signal induced in electrodes by motion of non-equilibrium free charge carriers in a semiconductor structure. The excitation of these electron-hole pairs can be done through pulse biasing, ionizing particle or light pulses. CERN R&D collaborations such as RD-48, RD39, RD-42, RD-50) is devoted to understanding and improving semiconductor materials used in tracking detectors at the LHC and recently its envisaged upgrade HL-LHC, extensively used TCT for characterization of materials with large fluences of radiation exposure. The basic schematic view of TCT system for studying pad detectors is show below [3].

Figure 10: Schematic view of a typical TCT system used for studies of pad sensors

The detector is connected to input of the transimpedance amplifier. Its output is fed to the oscilloscope. There are two ways of connecting the detector to the amplifier. Either back of the electrode of the detector is at high potential and the front of the electrode at ground or high potential is brought to the front side through so called bias-T which decouples detector bias voltage from the input to the amplifier (AC coupling). The former option has an advantage of avoiding additional components which would distort the signal, but usually results in more complicated grounding scheme as backside of the sensor has to be physically separated from the shielding which protects the sensors from the RF pickup.

As the drift velocities of charge carriers within silicon bulk are in the range of $10^6$-$10^7$ cm/s, which sets the typical time scale of the induced currents from ns to few tens ns. This in turn sets a requirement of both electronics and laser. For most of the systems the rise time of the measured induced current is determined by the capacitance of the electrode and the input impedance of the amplifier. In TCT measurements an average response to many laser pulses is taken into consideration which thereby diminishes the noise. Along with the wavelength of the laser that determined the penetration depth in the sensor, the pulse
width is equally important. TCT systems use lasers typically with pulses shorter than a few hundred picoseconds in order to resolve the evolution of pulses from typically few 100 µm thick structures.

In a silicon un-irradiated detector we have a fixed constant fixed positive charge in one side (n⁺ implant) and negative in p bulk. This as a result generates a linear electric field in the bulk. So, the space charge regions consists a fixed ions in silicons. However, radiation produces certain defects in silicon. These defects can be electrically active an/or trap carriers. A trapped carrier does not contribute to the detectable signal anymore. Some of these defects are charged when they trap electrons or holes. Now, since we have more electrons traveling in one direction and more holes in the opposite direction, there will be more trapping of electrons on one side and more holes trapped in the opposite side. A linear space charge arises leading to the formation of a double junction.

In TCT, the signal we measure is the current induced by the movement of the carriers. Simon Ramo (1913-2016) demonstrated that the induced current in a system of electrodes can be calculated considering the drift velocity of the carrier which is weighted by a magnitude (so called weighting electric field) that depends on the position of the particle. In a two electrode system, the velocity profile corresponds to the E-field profile given by:

\[ I(t) = q_e V_{\text{drift}} E_W \]  \hspace{1cm} (17)

wherein \( q_e \) is the electron charge, \( V_{\text{drift}} \) is the drift velocity of the carrier and \( E_W \) is the weighting electric field/ Ramo field.

![Fig. 11: Silicon sensor with Red front (a) and Red back (b) illumination](image)

The detector properties that can extracted from the pulse shapes:

1) Sign and the concentration of the space charge which decreases or increases of the velocity during the movement of the charge is related to the changes in the electric field strength which in turn is related to the space charge.

2) If the detector is fully depleted, the current pulse ends after the end of the drift which can be seen as the knee in the induced current pulse (as one can notice in figure 11 (a) at \( U = 30V \)). For voltages below full depletion voltage, the current approaches asymptotically \( I_m = 0 \) (as shown in figure 11 (a) at \( U=10V \)).

3) Induced charge is given as \( Q = \int I(t) dt \). It is difficult to achieve the same intensity and illumination spot therefore the charge \( Q \) is usually relatively with respect to the other voltages only.
In the TCT setup we make use of two lasers namely, red and Infrared lasers with wavelengths 650 nm and 1030 nm respectively. The setup has an integrated: SPA-TCT (Single Photon Absorption-TCT) which makes use of red and infra-red lasers as well as Edge-TCT using Infra-red laser only. In SPA-TCT red, one can employ a short penetration depth laser wherein all the carriers are deposited in few µm from the surface that allows to study drift of one kind of carriers. There’s no spatial resolution along beam direction and single photon generates a single electron-hole pair. In case of SPA-TCT infrared, one employs a long penetration depth laser giving rise to a homogeneous distribution along "Rayleigh length". It’s similar to Minimum Ionizing Particles (MIPs) through different $\frac{dE}{dx}$ that can be incident from top, bottom or edge. In edge-TCT an IR beam is injected from the side of the detector. Detector can be probed as a function of depth. Continuous carrier trail along the beam. The figure below shows the experimental set up of the TCT+ set up at EH-DT SSD laboratory.

![Figure 12: TCT+ set up in EH-DT SSD lab](image)

4 Samples and Measurements

4.1 Sample Specifications

In order to check for the reproducibility, non-irradiated samples were taken as they are without any defects. For the CV-IV set up, two samples with n-type bulk; one with a resistivity of 1 kΩ-cm and depletion voltage of 280 Volts and another with a resistivity of 2 kΩ-cm and depletion voltage of 131 Volts were taken. For the TCT+ set-up, two pin diodes with resistivity 12 kΩ-cm and depletion voltage of approximately 40 Volts.

The PCB for the silicon sensor used for TCT measurement consists of three connectors. The single connector at the top (as shown in figure 13 (iii) & (iv) is connected to ground. Out of the other two connectors below; one of them is connected to the CIVIDEc amplifier which is connected to the top metallic surface of the pad and the other connector is connected
to the PT1000 which is a Platinum resistance thermometer (PRT) that offers an excellent accuracy over a wide temperature range (from -200 to +850 °C).

4.2 Measurements Performed

While performing measurements with the CV-IV set up, the factors that one can vary are temperatures during an IV measurement and frequency along with temperature in a CV measurement. The temperature that can attained with the set up goes from -20 °C to 25 °C. Maintaining low temperatures of -20 °C is crucial especially for irradiated samples.

Similarly, for the TCT+ setup one can vary the temperature and laser intensity by changing the value of the shutter opening for both red and infra-red lasers. For this particular project, both measurements were done with red and infra-red lasers with front illumination.

The measurements performed for studying the reproducibility test were as follows:

- **CV/IV**
  - For IV: at -20 °C, 0 °C, 20 °C (5 set each)
  - For CV: 1kΩ & 10kΩ at -20 °C (5 set each)
  - 1kΩ & 10kΩ at 0 °C (5 set each)
  - Voltage range: 0-400V
  - (2 ROUNDS OF MEASUREMENTS)

- **TCT**
  - For IR-laser (front illumination): (5 set each)
  - At -20 °C, 0 °C, 20 °C with shutter opening: 3mm
  - At -20 °C, 0 °C, 20 °C with shutter opening: 3.5mm
  - At -20 °C, 0 °C, 20 °C with shutter opening: 4mm

Note: While performing a second round of IV measurement for sensor (i), there was a
spark due to the presence of some static charge on the conducting surface of the sensor. Also, round 1 and round 2 of measurements were performed on different days!

5 Results and discussion

For CV-IV measurements, the data for a set of five measurements under similar conditions as mentioned were plotted on the same graph. For IV measurement, we plot leakage current from the pad with respect to Voltage. For CV measurements, since the software gives us an average capacitance value for five consecutive measurements at the same voltage, we observe that the capacitance does not differ to a great extent while plotting CV plots for a set of five measurements at same conditions. However, we see a lot of variation in consecutive measurements while plotting $1/C^2$ versus Voltage. The full depletion voltage can also be determined from the point of inflection of the curve in $1/C^2$ vs V plot.

Figure 14: IV analysis curves for sensor (i) and (ii) with resistivity of 1kΩ-cm and 2kΩ-cm respectively showing the plots for different measurements along with their sigma ($\sigma$) values at a temperature of 20°C.

Figure 14 shows the IV plot for a set of five measurements for both the sensors with resistivity of 1kΩ-cm and 2kΩ-cm respectively at a temperature of 20°C. The sigma values are of the same range of the order of $10^{-11}$ amperes. Also, one can observe the measurements lie within a confidence level of $3\sigma$ and is consistent for both the sensors at the same temperature. However, at lower temperatures, the leakage current value decreases which isn’t within the resolution range of the pico-ammeter we use for measuring current (shown in Figure 15).

Since, measurements at different voltage values are independent of each other. Therefore, in order to calculate the error (sigma) for every voltage value, we took the standard deviation at each voltage reading for five consecutive set of measurements. Therefore, we don’t have an average value of sigma rather a range of sigma values considering that their order is the same as we change the ramp up the voltage values. Measurements at -20°C are consistent for the simple reason that the value of sigma is of the same order of $10^{-11}$ which is high in comparison
Figure 15: IV analysis curves for sensor (i) with resistivity of 1kΩ-cm showing the plots for the five set measurements performed on two separate days along with their sigma ($\sigma$) values at a temperature of -20°C.

to the value of leakage current at that temperature; although the leakage current value is a lot reduced in comparison to that at 20°C. All the measurements lie within a confidence level of $4\sigma$. Similarly, for IV measurements performed at 0°C, the leakage current is of the same order as of that at -20°C and the readings lie within a confidence level of $4\sigma$ [see Appendix.].

From $1/C^2$ versus V plots we get the value of depletion voltage as well as we get know the precision of this value. Figure 16 shows a similar plot at 20°C with a frequency of 1 kHz measured at two separate days. We can observe that the depletion voltage value varies within an approximation of less than 5% showing the consistency of measurements at 20°C at lower frequencies.

Nevertheless, at lower temperatures we observe an inconsistency in reproducibility of capacitance value as well the depletion voltage varies within an approximation of 10% which is higher than that at higher temperatures. The variation was a lot more during the first round of measurement with high sigma values. However, the measurements lie within a confidence level of $2\sigma$ (shown in Figure 17).

The rest of the plots for different temperatures and frequency values are given in Appendix.
Figure 16: CV analysis curves for sensor (ii) with resistivity of 2kΩ-cm showing the plots for the five set measurements performed on two separate days along with their depletion voltage values for separate measurements at a temperature of 20°C.

Figure 17: CV analysis curves for sensor (ii) with resistivity of 2kΩ-cm showing the plots for the five set measurements performed on two separate days along with their depletion voltage values for separate measurements at a temperature of -20°C.

For measurements with TCT+ set up, the value of charge collection at different voltages were obtained by integrating the induced current signal curves from 0 to 25 ns. As five set of measurements were performed at different temperatures by changing the shutter values for both red and infra-red lasers, the error can be calculated from standard deviation values at individual voltages. Just as in case of CV-IV measurements, even for TCT measurements, since charge collection efficiency at a different voltages is independent of each other, the
stand deviation (sigma value) is also independent at different voltages. Therefore, we get a range of sigma value within the same order.

Figure 18: Charge collection vs voltage plots for five set of measurements with infra-red laser with a shutter opening of 3mm. The sigma values are mentioned in the plots.

Figure 19: Charge collection vs voltage plots for five set of measurements with infra-red laser with a shutter opening of 3.5mm. The sigma values for the first and second round of measurements lie within the range of (0.64-7.29) and (1.04-5.88) respectively.

Figure 18 shows the charge collection (relative value; therefore its not mentioned in coulombs) versus voltage plot from 0 to 400 Volts. The laser used here is infra-red laser with a shutter opening of 3mm. One can observe that the measurements lie within a confidence level of $3\sigma$. The measurements however, deviate within 25%. On increasing the shutter
value, keeping the same temperature, the sigma value decreases and the measurements lie within a confidence level of $4\sigma$ (shown in figure 19).

The charge collection increases with an increase in voltage. However, beyond the full depletion voltage, the value of charge collection remains constant. On increasing the temperature, by keeping the value of shutter opening constant, we observe that the charge collection values beyond the full depletion voltage also increases for infrared laser but we don’t observe the same for red laser [see the plots in appendix]. The reason is that for red laser we are probing a few microns either from the top or bottom of the bulk. As a result of which the number of electron/holes that are collected is always constant as the penetration depth does not change with the temperature and so does the absorption coefficient remains constant with temperature for red laser within the silicon bulk. For infra-red laser, the photons pass through the entire bulk of the material and since its got a longer wavelength, the absorption coefficient changes with temperature. So on increasing the temperature the absorption coefficient for photons in infra-red laser increases with increasing temperature. Therefore the charge collection value also increases with increasing temperature within the silicon bulk (considering the shutter opening is kept constant).

The sigma $\sigma$ values for both CV-IV and TCT+ set up measurements under varying factors are tabulated as follows:

### IV MEASUREMENT

<table>
<thead>
<tr>
<th>W336-111-1kOhm-cm-Wf04-F10</th>
<th>$\sigma$ for 20C ($\times 1.0e-11$)</th>
<th>$\sigma$ for 0C ($\times 1.0e-11$)</th>
<th>$\sigma$ for -20C ($\times 1.0e-11$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Round 1</td>
<td>0.58-0.72</td>
<td>0.09-0.14</td>
<td>0.18-0.39</td>
</tr>
<tr>
<td>Round 2</td>
<td>(Burnt)</td>
<td>0.01-0.13</td>
<td>0.52-0.93</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>W336-111-2kOhm-cm-Wf04-B11</th>
<th>20C ($\times 1.0e-11$)</th>
<th>0C ($\times 1.0e-8$)</th>
<th>-20C ($\times 1.0e-8$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Round 1</td>
<td>0.63-0.83</td>
<td>0.0001-0.3323</td>
<td>0.002-0.453</td>
</tr>
</tbody>
</table>

### CV MEASUREMENT

<table>
<thead>
<tr>
<th>W336-111-1kOhm-cm-Wf04-F10</th>
<th>$\sigma$ for 20C ($\times 1.0e20$)</th>
<th>$\sigma$ for 0C ($\times 1.0e21$)</th>
<th>$\sigma$ for -20C ($\times 1.0e19$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ROUND 1 ( @ 1kHz)</td>
<td>0.35-2.19</td>
<td>0-1.08</td>
<td>0-4.47</td>
</tr>
<tr>
<td>ROUND 2 ( @ 1kHz)</td>
<td>0-1.95</td>
<td>0-7.07</td>
<td>0-5.48</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>W336-111-1kOhm-cm-Wf04-F10</th>
<th>$\sigma$ for 20C ($\times 1.0e19$)</th>
<th>$\sigma$ for 0C ($\times 1.0e21$)</th>
<th>$\sigma$ for -20C ($\times 1.0e21$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ROUND 1 ( @ 10kHz)</td>
<td>0.084-8.367</td>
<td>0-1.443</td>
<td>0-1.403</td>
</tr>
<tr>
<td>ROUND 2 ( @ 10kHz)</td>
<td>0-1.52</td>
<td>0-1.02</td>
<td>0-5.48</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>W336-111-2kOhm-cm-Wf04-B11</th>
<th>$\sigma$ for 20C ($\times 1.0e20$)</th>
<th>$\sigma$ for 0C ($\times 1.0e19$)</th>
<th>$\sigma$ for -20C ($\times 1.0e19$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ROUND 1 ( @ 1kHz)</td>
<td>0-9.35</td>
<td>0-9.53</td>
<td>0.123-8.032</td>
</tr>
</tbody>
</table>
a) For 7859-WL-A63-PN4

<table>
<thead>
<tr>
<th></th>
<th>σ for 3mm</th>
<th>σ for 3.5mm</th>
<th>σ for 4mm</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Infra-Red</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Round 1)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-20°C</td>
<td>4.16-27.51</td>
<td>0.83-6.38</td>
<td>0.39-5.35</td>
</tr>
<tr>
<td>0°C</td>
<td>7.77-23.77</td>
<td>0.64-7.76</td>
<td>0.48-15.50</td>
</tr>
<tr>
<td>20°C</td>
<td>5.45-24.56</td>
<td>0.87-6.99</td>
<td>0.54-10.33</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>σ for 3.5mm</th>
<th>σ for 4mm</th>
<th>σ for 4.5mm</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Red</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Round 1)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-20°C</td>
<td>2.68-17.04</td>
<td>0.47-4.63</td>
<td>0.49-4.01</td>
</tr>
<tr>
<td>0°C</td>
<td>0.96-21.47</td>
<td>0.57-5.71</td>
<td>0.39-11.40</td>
</tr>
<tr>
<td>20°C</td>
<td>3.07-17.28</td>
<td>0.56-4.86</td>
<td>0.94-4.65</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>σ for 3mm</th>
<th>σ for 3.5mm</th>
<th>σ for 4mm</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Infra-Red</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Round 2)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-20°C</td>
<td>1.74-20.98</td>
<td>1.02-6.62</td>
<td>0.79-4.54</td>
</tr>
<tr>
<td>0°C</td>
<td>3.35-25.42</td>
<td>0.57-6.14</td>
<td>0.55-3.96</td>
</tr>
<tr>
<td>20°C</td>
<td>2.54-18.91</td>
<td>1.01-7.86</td>
<td>0.62-4.23</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>σ for 3.5mm</th>
<th>σ for 4mm</th>
<th>σ for 4.5mm</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Red</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Round 2)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-20°C</td>
<td>2.69-20.59</td>
<td>0.62-7.19</td>
<td>0.76-4.82</td>
</tr>
<tr>
<td>0°C</td>
<td>3.74-15.78</td>
<td>0.97-5.38</td>
<td>0.73-4.91</td>
</tr>
<tr>
<td>20°C</td>
<td>1.72-14.53</td>
<td>0.62-7.19</td>
<td>0.75-4.11</td>
</tr>
</tbody>
</table>

b) For PIN4-W2-D8-4-Run-7859

<table>
<thead>
<tr>
<th></th>
<th>σ for 3mm</th>
<th>σ for 3.5mm</th>
<th>σ for 4mm</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Infra-Red</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Round 1)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-20°C</td>
<td>3.35-19.98</td>
<td>0.39-6.78</td>
<td>0.85-4.83</td>
</tr>
<tr>
<td>0°C</td>
<td>3.20-25.99</td>
<td>1.89-11.39</td>
<td>5.18-26.41</td>
</tr>
<tr>
<td>20°C</td>
<td>2.39-25.75</td>
<td>0.64-7.29</td>
<td>0.87-6.66</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>σ for 3.5mm</th>
<th>σ for 4mm</th>
<th>σ for 4.5mm</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Red</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Round 1)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-20°C</td>
<td>2.65-25.77</td>
<td>1.21-7.78</td>
<td>0.63-5.81</td>
</tr>
<tr>
<td>0°C</td>
<td>3.24-21.87</td>
<td>0.82-5.66</td>
<td>0.61-5.88</td>
</tr>
<tr>
<td>20°C</td>
<td>1.70-21.49</td>
<td>1.10-39.09</td>
<td>0.96-5.44</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>σ for 3mm</th>
<th>σ for 3.5mm</th>
<th>σ for 4mm</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Infra-Red</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Round 2)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-20°C</td>
<td>3.73-22.29</td>
<td>1.00-5.88</td>
<td>0.35-4.70</td>
</tr>
<tr>
<td>0°C</td>
<td>4.53-17.46</td>
<td>0.57-5.71</td>
<td>0.37-7.59</td>
</tr>
<tr>
<td>20°C</td>
<td>2.54-18.91</td>
<td>1.04-5.88</td>
<td>0.71-5.03</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>σ for 3.5mm</th>
<th>σ for 4mm</th>
<th>σ for 4.5mm</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Red</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Round 2)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-20°C</td>
<td>2.98-21.59</td>
<td>0.46-6.64</td>
<td>0.28-4.35</td>
</tr>
<tr>
<td>0°C</td>
<td>2.56-22.31</td>
<td>0.86-6.06</td>
<td>2.15-10.55</td>
</tr>
<tr>
<td>20°C</td>
<td>1.58-24.32</td>
<td>0.93-6.55</td>
<td>0.49-3.82</td>
</tr>
</tbody>
</table>
References


7859-WL-A63-PIN4 – Red front @ (20C & 3.5mm, 4mm & 4.5mm)
PIN4-W2-D8-4-Run-7859 – Red front @ (20°C & 3.5mm, 4mm & 4.5mm)

---

**PIN4-W2-D8-Run-7859 Charge-collection vs. Voltage With red laser @ 20°C & shutter opening: 3.5mm**

- 1st measurement
- 2nd measurement
- 3rd measurement
- 4th measurement
- 5th measurement
- Mean value

**PIN4-W2-D8-Run-7859 Charge-collection vs. Voltage With red laser @ 20°C & shutter opening: 4mm**

- 1st measurement
- 2nd measurement
- 3rd measurement
- 4th measurement
- 5th measurement
- Mean value

**PIN4-W2-D8-Run-7859 Charge-collection vs. Voltage With red laser @ 20°C & shutter opening: 4.5mm**

- 1st measurement
- 2nd measurement
- 3rd measurement
- 4th measurement
- 5th measurement
- Mean value
a) For 7859-WL-A63-PIN4

<table>
<thead>
<tr>
<th>Infra-Red (Round 1)</th>
<th>σ for 3mm</th>
<th>σ for 3.5mm</th>
<th>σ for 4mm</th>
<th>Red (Round 1)</th>
<th>σ for 3.5mm</th>
<th>σ for 4mm</th>
<th>σ for 4.5mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>-20°C</td>
<td>4.16-27.51</td>
<td>0.83-6.38</td>
<td>0.39-5.35</td>
<td>-20°C</td>
<td>2.68-17.04</td>
<td>0.47-4.63</td>
<td>0.49-4.01</td>
</tr>
<tr>
<td>0°C</td>
<td>7.77-23.77</td>
<td>0.64-7.76</td>
<td>0.48-15.50</td>
<td>0°C</td>
<td>0.96-21.47</td>
<td>0.57-5.71</td>
<td>0.39-11.40</td>
</tr>
<tr>
<td>20°C</td>
<td>6.45-24.56</td>
<td>0.87-6.99</td>
<td>0.54-10.33</td>
<td>20°C</td>
<td>3.07-17.28</td>
<td>0.56-4.86</td>
<td>0.94-4.65</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Infra-Red (Round 2)</th>
<th>σ for 3mm</th>
<th>σ for 3.5mm</th>
<th>σ for 4mm</th>
<th>Red (Round 2)</th>
<th>σ for 3.5mm</th>
<th>σ for 4mm</th>
<th>σ for 4.5mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>-20°C</td>
<td>1.74-20.98</td>
<td>1.02-6.62</td>
<td>0.79-4.54</td>
<td>-20°C</td>
<td>2.69-20.59</td>
<td>0.62-7.19</td>
<td>0.76-4.82</td>
</tr>
<tr>
<td>0°C</td>
<td>3.35-25.42</td>
<td>0.57-6.14</td>
<td>0.55-3.96</td>
<td>0°C</td>
<td>3.74-15.78</td>
<td>0.97-5.38</td>
<td>0.73-4.91</td>
</tr>
<tr>
<td>20°C</td>
<td>2.54-18.91</td>
<td>1.01-7.86</td>
<td>0.62-4.23</td>
<td>20°C</td>
<td>1.72-14.53</td>
<td>0.62-7.19</td>
<td>0.75-4.11</td>
</tr>
</tbody>
</table>

b) For PIN4-W2-D8-4-Run-7859

<table>
<thead>
<tr>
<th>Infra-Red (Round 1)</th>
<th>σ for 3mm</th>
<th>σ for 3.5mm</th>
<th>σ for 4mm</th>
<th>Red (Round 1)</th>
<th>σ for 3.5mm</th>
<th>σ for 4mm</th>
<th>σ for 4.5mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>-20°C</td>
<td>3.35-19.98</td>
<td>0.39-6.78</td>
<td>0.85-4.83</td>
<td>-20°C</td>
<td>2.65-25.77</td>
<td>1.21-7.78</td>
<td>0.63-5.81</td>
</tr>
<tr>
<td>0°C</td>
<td>3.20-25.99</td>
<td>1.89-11.39</td>
<td>5.18-26.41</td>
<td>0°C</td>
<td>3.24-21.87</td>
<td>0.82-5.66</td>
<td>0.61-5.88</td>
</tr>
<tr>
<td>20°C</td>
<td>2.39-25.75</td>
<td>0.64-7.29</td>
<td>0.87-6.66</td>
<td>20°C</td>
<td>1.70-21.49</td>
<td>1.10-39.09</td>
<td>0.96-5.44</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Infra-Red (Round 2)</th>
<th>σ for 3mm</th>
<th>σ for 3.5mm</th>
<th>σ for 4mm</th>
<th>Red (Round 2)</th>
<th>σ for 3.5mm</th>
<th>σ for 4mm</th>
<th>σ for 4.5mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>-20°C</td>
<td>3.73-22.29</td>
<td>1.00-5.88</td>
<td>0.35-4.70</td>
<td>-20°C</td>
<td>2.98-21.59</td>
<td>0.46-6.64</td>
<td>0.26-4.35</td>
</tr>
<tr>
<td>0°C</td>
<td>4.53-17.46</td>
<td>0.57-5.71</td>
<td>0.37-7.59</td>
<td>0°C</td>
<td>2.56-22.31</td>
<td>0.86-6.06</td>
<td>2.15-10.55</td>
</tr>
<tr>
<td>20°C</td>
<td>2.54-18.91</td>
<td>1.04-5.88</td>
<td>0.71-5.03</td>
<td>20°C</td>
<td>1.58-24.32</td>
<td>0.93-6.55</td>
<td>0.49-3.82</td>
</tr>
</tbody>
</table>
Analysed data for CV-IV setup:
W336-111-1kOhm-cm-wf04-F10-IV- measurement @ 20°C & W336-111-2kOhm-cm-B11- IV measurement at 20°C, 0°C & -20°C

The graphs above illustrate the current-voltage (I-V) characteristics for two different samples:

- **W336-111-1kOhm-cm-wf04-F10-IV** measured at 20°C (23.07.2018)
- **W336-111-2kOhm-cm-wf04-B11-IV** measured at 20°C (20.07.2018)

Each graph shows the I-V data for five measurements, labeled as 1st, 2nd, 3rd, 4th, and 5th measurement. The data is presented in.logarithmic scale, and the mean value is indicated by a red line. Additional graphs show measurements at 0°C and -20°C.
W336-111-1kOhm-cm-wf04-F10-CV measurement @ 1kHz & 10kHz, temperature: -20°C
### IV MEASUREMENT

<table>
<thead>
<tr>
<th>W336-111-1kOhm-cm-Wf04-F10</th>
<th>σ for 20C ( x 1.0e-11 )</th>
<th>σ for 0C ( x 1.0e-11 )</th>
<th>σ for -20C ( x 1.0e-11 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Round 1</td>
<td>0.58-0.72</td>
<td>0.09-0.14</td>
<td>0.18-0.39</td>
</tr>
<tr>
<td>Round 2</td>
<td>(Burnt)</td>
<td>0.01-0.13</td>
<td>0.52-0.93</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>W336-111-2kOhm-cm-Wf04-B11</th>
<th>20C ( x 1.0e-11 )</th>
<th>0C ( x 1.0e-8 )</th>
<th>-20C ( x 1.0e-8 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Round 1</td>
<td>0.63-0.83</td>
<td>0.0001-0.3323</td>
<td>0.002-0.453</td>
</tr>
</tbody>
</table>

### CV MEASUREMENT

<table>
<thead>
<tr>
<th>W336-111-1kOhm-cm-Wf04-F10</th>
<th>σ for 20C ( x 1.0e20 )</th>
<th>σ for 0C ( x 1.0e21 )</th>
<th>σ for -20C ( x 1.0e21 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>ROUND 1 ( @ 1kHz)</td>
<td>0.35-2.19</td>
<td>0-1.08</td>
<td>0-4.47</td>
</tr>
<tr>
<td>ROUND 2 ( @ 1kHz)</td>
<td>0-1.95</td>
<td>0-7.07</td>
<td>0-5.48</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>W336-111-1kOhm-cm-Wf04-F10</th>
<th>σ for 20C ( x 1.0e19 )</th>
<th>σ for 0C ( x 1.0e21 )</th>
<th>σ for -20C ( x 1.0e21 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>ROUND 1 ( @ 10kHz)</td>
<td>0.084-8.367</td>
<td>0-1.443</td>
<td>0-1.403</td>
</tr>
<tr>
<td>ROUND 2 ( @ 10kHz)</td>
<td>0-1.52</td>
<td>0-1.02</td>
<td>0-5.48</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>W336-111-2kOhm-cm-Wf04-B11</th>
<th>σ for 20C ( x 1.0e20 )</th>
<th>σ for 0C ( x 1.0e19 )</th>
<th>σ for -20C ( x 1.0e19 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>ROUND 1 ( @ 1kHz)</td>
<td>0-9.35</td>
<td>0-9.53</td>
<td>0.123-8.032</td>
</tr>
</tbody>
</table>