PN-Junction-
Material Characteristics

Lab Manual

M.Sc Physics (Sem II)
Solid State Physics Lab

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Objective: To study the material characteristics of a *pn*-junction diode.
(i) Reverse Saturation Current, I_s and material constant, η
(ii) Energy Band Gap, E_g
(iii) Depletion Layer Capacitance, C_d .

Apparatus Required: PN-Junction setup Model PN-1, Sample: BC 109C (Base Emitter Junction), CRO, and Oven provided with the setup.

Figure 1: PN junction Setup

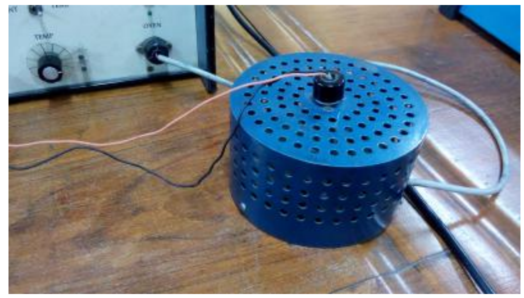

Figure 2: Oven

Figure 3: CRO

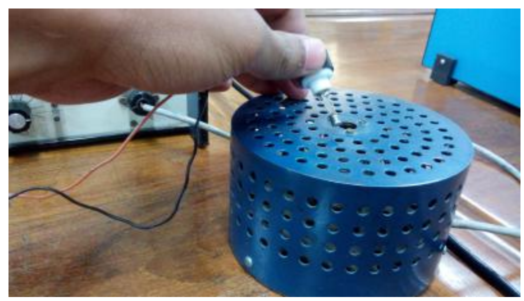

Figure 4: Sample BC 109C

Theory:
This experiment is divided into three parts. In the first part of the experiment we will be calculating the reverse saturation current, I_s and the material constant, η.
Diode current equation for a forward biased diode is given as:

$$I = I_s \left[\exp \frac{qV}{\eta kT} - 1 \right]$$

where I is the diode current, V is the voltage across the junction, q is the electronic charge= 1.6×10^{-19}, η is a material constant, k is the boltzmann constant= $1.38 \times 10^{-23} m^2 kg s^{-2} K^{-1}$ and T is the temperature.
For small voltages between 0.5-1V, the exponential term varies from 1.55×10^4 to 2.41×10^8. Therefore, we can neglect '1' and rewrite the equation as

$$I = I_s \exp \frac{qV}{\eta kT} \tag{1}$$

or

$$\ln I = \ln I_s + \frac{qV}{\eta kT}$$

Therefore, if we plot $\ln I$ versus V we get the slope as $\frac{q}{\eta kT}$ and the intercept as $\ln I_s$. So we can get the reverse saturation current from the intercept and the calculate η from the slope.

For the second part of the experiment, we need an expression for the reverse saturation current I_s , which depends strongly on temperature, but not on V. It can be shown that I_s is proportional to the $\exp \frac{-E_g}{\eta kT}$ and T^m where E_g is the energy band gap and m is a constant. Therefore, we can write I_s as

$$I_s = AT^m \exp \frac{-E_g}{\eta kT} \tag{2}$$

Combining Eq 1 and 2 we get,

$$I = AT^m \exp \frac{qV - E_g}{\eta kT}$$

Taking the logarithmic on both sides

$$\implies \ln I = \ln A + m \ln T + \frac{qV - E_g}{\eta kt}$$

For I = constant take the derivative w.r.t T

$$\begin{aligned} &\implies 0 = 0 + \frac{m}{T} - \frac{qV - E_g}{\eta kT^2} + \frac{q}{\eta kt}\frac{\mathrm{d}V}{\mathrm{d}T} \\ &\implies qV - E_g = \eta mkT + qT\frac{\mathrm{d}V}{\mathrm{d}T} \\ &\implies \boxed{E_g = qV - \eta mkT - qT\frac{\mathrm{d}V}{\mathrm{d}T}} \end{aligned} \tag{3}$$

where m, η are constants.
Therefore, if we plot junction voltage, V versus Temperature, T, we can get $\frac{\mathrm{d}V}{\mathrm{d}T}$ from the slope and find an equation for $V(T)$ using the least square fitting. Thus E_g at room temperature can be easily calculated by substituting the obtained values.

In the third part of the experiment we will be studying the variation of depletion layer capacitance with reverse bias voltage.
The depletion layer between the n- and p-sides of a pn junction diode serves as an insulating region that separates the two diode contacts. Thus, the diode in reverse bias exhibits a depletion-layer capacitance, sometimes more vaguely called a junction capacitance, analogous to a parallel plate capacitor with a dielectric between the contacts. In reverse bias the width of the depletion layer is widened with increasing reverse bias V, and the capacitance is accordingly decreased. Thus, the junction serves as a

voltage-controllable capacitor. In a simplified one-dimensional model, the junction capacitance is:

$$C_d = K\epsilon_0 \frac{A}{w(V)}$$

where A is the area, $w(V)$ is the width of the depletion layer which is a function of reverse bias voltage, V, K is the dielectric constant and ϵ_0 is the permittivity of free space.
We will observe the variation of depletion layer capacitance with reverse bias voltage. From the above relation we can see that C_d is inversely proportional to V.
To do this we use the circuit shown below,

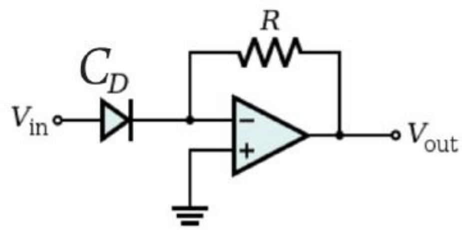

Figure 5: Circuit Diagram

We use an op-amp in inverting mode with V_{in} being the input voltage, and the diode in place of R_{in}. If the diode has capacitance C_d then the reactance, χ_c is given as $\frac{1}{j\omega C_d}$.
Also, the gain of op-amp in inverting mode is given as $\frac{V_{out}}{V_{in}} = \frac{-R_f}{R_i}$. Therefore, the output voltage V_1 for an input signal of voltage V and frequency, ω_1 is given as:

$$V_1 = \frac{-R}{\chi_c} V$$
$$\implies V_1 = -Rj\omega_1 C_d V \tag{4}$$

Similarly, the output voltage V_2 for an input signal of voltage V and frequency, ω_2 is given as:

$$V_2 = -Rj\omega_2 C_d V \tag{5}$$

from eq 4 and 5, we get

$$V_2^2 - V_1^2 = r^2\omega_2^2 C_d^2 V^2 - R^2\omega_1^2 C_d^2 V^2$$
$$\implies V_2^2 - V_1^2 = \left(\omega_2^2 - \omega_1^2\right) R^2 C_d^2 V^2$$
$$\implies C_d = \frac{1}{VR}\frac{\sqrt{V_2^2 - V_1^2}}{\sqrt{\omega_2^2 - \omega_1^2}}$$

In the apparatus being used,
V=200mV
R=100kΩ
$\omega_1 = 2\pi\times$ 5kHz
$\omega_2 = 2\pi\times$ 20kHz

which gives,

$$\boxed{C_d = 0.41\sqrt{V_2^2 - V_1^2}\text{pF}} \tag{6}$$

Procedure:
Experiment I:
1. Connect the diode to the PN-junction setup as shown in the Figure 1.
2. Increase the current in small steps and note down the corresponding junction voltage.
3. Calculate $\ln I$ and plot a graph between $\ln I$ and Junction Voltage, V.
4. Find out the intercept, $\ln I_s$ and calculate I_s from it.
5. Calculate the slope and use it to calculate η using the formula:

$$\eta = \frac{qV}{slope \times kT}$$

Experiment II:
1. Connect the oven to the setup.
2. Increase the temperature in small steps using the knob on the setup and note down the corresponding junction voltage.
3. Plot a graph of junction voltage, V versus Temperature, T.
4. Find a least square linear fitting for the plot, and use it to calculate the band gap, E_g using eq 3.

Experiment III:
1. Connect the CRO to the setup.
2. For this experiment the diode is to be connected to the left socket.
3. Set the display 2 to BIAS mode.
4. Measure and note down the peak to peak output voltage in the CRO for different bias voltages and frequencies.
5. Use eq 6 to calculate C_d and plot a graph of C_d versus Junction voltage, V.

Observations:

Experiment I:

Reverse Saturation Current and material constant

Temperature: 295K
Least Count of ammeter = 0.01mA = 10uA
Least Count of voltmeter = 0.001V

Current, I (uA)	Junction Voltage, (V)	ln(I)
100	0.637	4.605
200	0.663	5.298
300	0.678	5.704
400	0.689	5.991
500	0.697	6.215
600	0.704	6.397
700	0.71	6.551
800	0.715	6.685
900	0.719	6.802
1000	0.723	6.908
2000	0.75	7.601
3000	0.766	8.006
4000	0.778	8.294
5000	0.787	8.517
6000	0.794	8.700
7000	0.801	8.854
8000	0.806	8.987
9000	0.812	9.105
10000	0.817	9.210

Table 1: Reverse Saturation Current

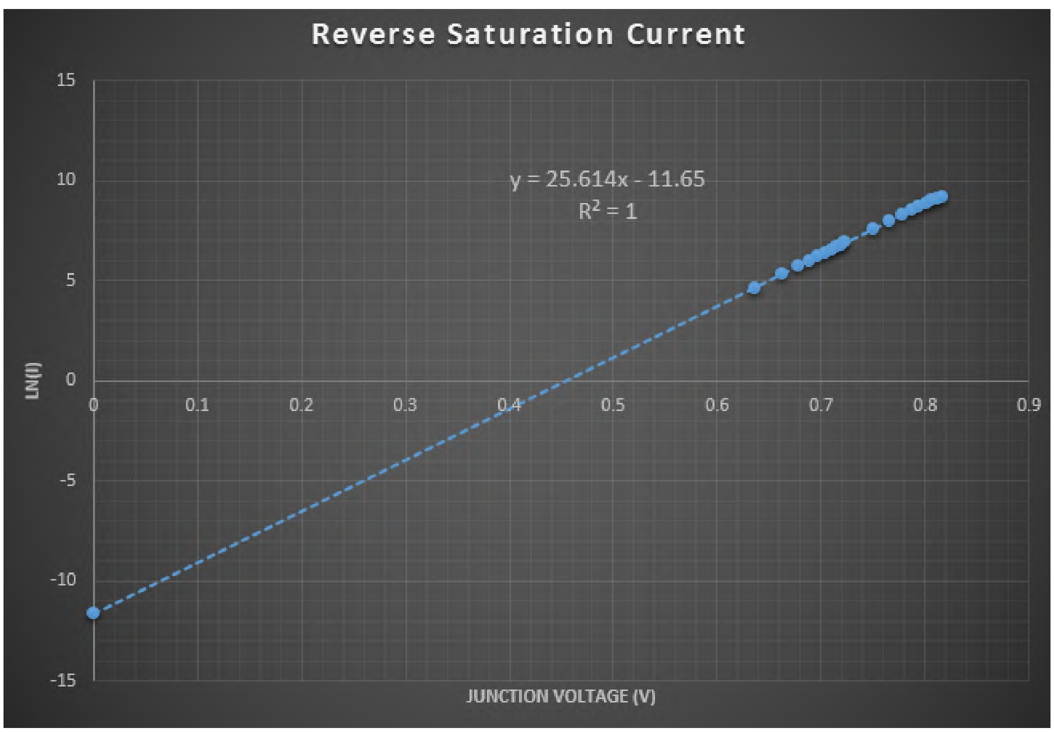

Figure 6: Reverse Saturation Current(Graph)

From figure 6 we get,

$$\ln I_s = -11.65$$

Therefore,

$$I_s = 8.71 \times 10^{-6} \mu A$$
$$\implies \boxed{I_s = 0.08 \times 10^{-10} A}$$

Slope of the curve, $\frac{\Delta \ln I}{\Delta V} = 25.614$
Plugging the above value of the slope in the following equation:

$$\eta = \frac{q}{kT} \frac{\Delta V}{\Delta \ln I}$$
$$\implies \eta = \frac{q}{kT} \times \frac{1}{slope}$$
$$\implies \eta = \frac{1.602 \times 10^{-19}}{1.381 \times 10^{-23} \times 295 \times 25.641}$$
$$\implies \boxed{\eta = 1.533}$$

Experiment II:

Temperature dependence of Junction Voltage

Least Count of thermometer = 1K
Least Count of voltmeter = 0.001V
I = 1mA (constant for the set)

Temperature(K)	**Junction Voltage (V)**
305	0.703
313	0.692
320	0.684
328	0.671
336	0.658
340	0.652
344	0.648
353	0.635
360	0.625
365	0.616

Table 2: Temperature Dependence of Junction Voltage

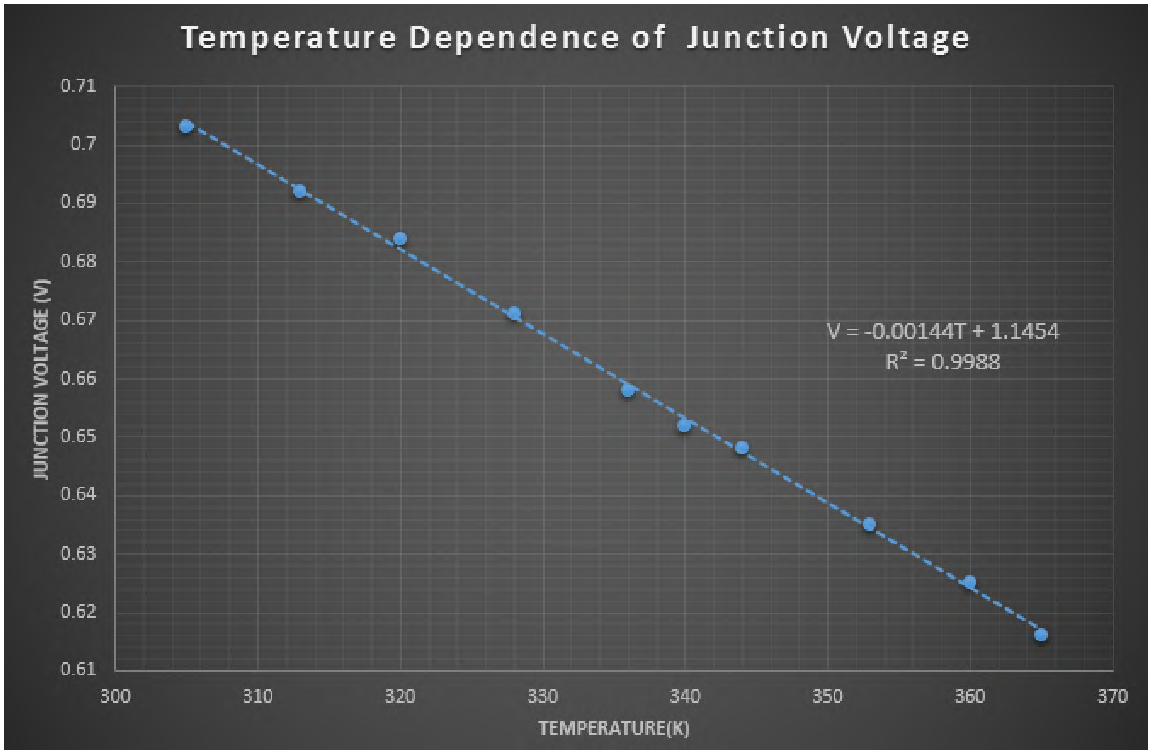

Figure 7: Temperature Dependence of Junction Voltage(Graph)

We know, from eq 3
Energy band gap, $E_G = q\left(V(T) - T\frac{\mathrm{d}V}{\mathrm{d}T} - \frac{m\eta kT}{q}\right)$
From figure 7,

$$V(T) = -0.00144T + 1.145$$

Therefore, at $T = 295K$,

$$V(T) = 0.720\mathrm{V}$$

also $\frac{\mathrm{d}V}{\mathrm{d}T} = -1.44 \times 10^{-3} V/K$

For Si:

$$m = 1.5, \eta = 2$$

therefore at $T = 295K$

$$\frac{m\eta kT}{q} = 0.076\mathrm{V}$$

Plugging the above values back in E_G,

$$E_G = \left(0.720 - [295(-1.44 \times 10^{-3})] - 0.076\right)\mathrm{eV}$$
$$\implies E_G = (0.720 - [-0.424] - 0.076)\,\mathrm{eV}$$
$$\implies E_G = (0.720 + 0.424 - 0.076)\,\mathrm{eV}$$
$$\implies \boxed{E_G = 1.068\mathrm{eV}}$$

Experiment 3:

Depletion Layer Capacitance:

Least Count of Voltmeter = 0.01V

Bias Voltage (V)	$\mathbf{V_1}(\omega_1 = \mathbf{5kHz})$ **(mV)**	$\mathbf{V_2}(\omega_2\mathbf{=20kHz})$ **(mV)**	**Depletion Layer Capacitance** $\mathbf{C_d}$ **(pF)**
0.00	0.300	1.30	5.18×10^2
0.52	0.200	0.80	3.17×10^2
1.00	0.160	0.64	2.54×10^2
2.00	0.120	0.52	2.07×10^2
3.02	0.100	0.40	1.58×10^2
4.01	0.090	0.34	1.34×10^2
5.00	0.084	0.30	1.18×10^2
6.00	0.076	0.28	1.10×10^2
7.00	0.072	0.27	1.06×10^2
8.02	0.064	0.25	0.99×10^2

Table 3: Depletion Layer Capacitance as a function of Bias Voltage

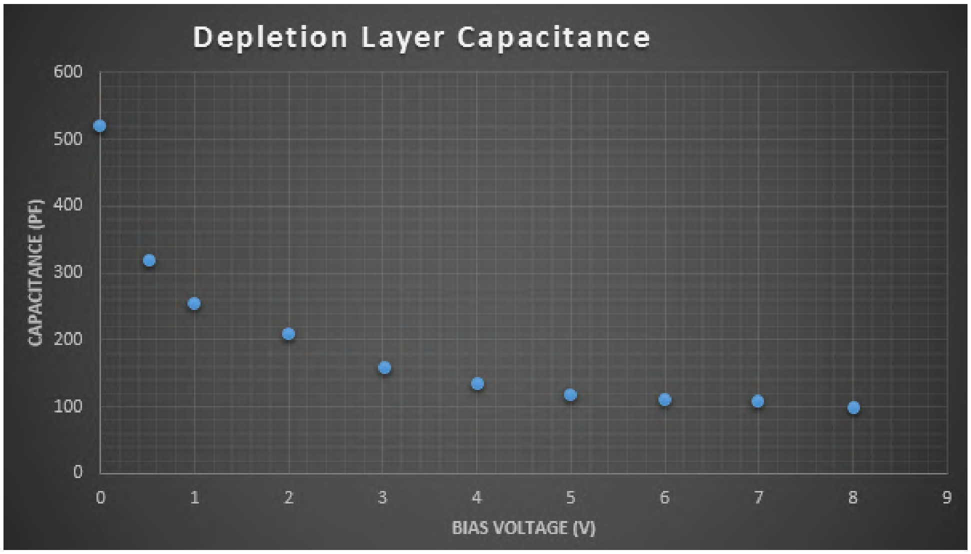

Figure 8: Depletion Layer Capacitance(Graph)

Result:
The experimentally obtained values are $I_s = 0.08 \times 10^{-10}A$, $\eta = 1.53$ and the energy band gap $E_g = 1.068eV$.
The dependence of depletion layer capacitance on reverse bias voltage was also observed and plotted.

Precautions:
1. Ensure the p-side is made positive w.r.t the n-side for the first two experiments and that the diode is reverse biased for the third experiment.

2. While doing the experiment do not exceed the ratings of the diode. This may lead to damage of the diode.
3. Connect voltmeter and Ammeter in correct polarities.
4. Do not switch ON the power supply unless you have checked the circuit connections as per the circuit diagram.
5. Temperature T should be noted down in Kelvin.
6. Observations must be taken when the temperature is decreasing in the second experiment.
7. The reverse voltage must be less than breakdown voltage.
8. We took the energy band gap to be independent of temperature which is not strictly true, therefore the value we obtained has some error in it.

Viva Voce:
1. What is the need for doping?
2. How depletion region is formed in the PN junction?
3. What is leakage current?
4. What is break down voltage?
5. What is an ideal diode? How does it differ from a real diode?
6. What is the effect of temperature in the diode reverse characteristics?
7. What is cut-in or knee voltage? Specify its value in case of Ge or Si?
8. What are the difference between Ge and Si diode.
9. What is the capacitance formed at forward biasing?
10. What is the relationship between depletion width and the concentration of impurities?
11. How does the I-V characteristic of a heavily doped diode differ from that of a lightly doped diode? Why does the I-V characteristics differ?
12. For any diode, how does the I-V characteristic change as temperature increases?
13. For the same doping concentration, how does the I-V characteristic of a wide band gap (E_g) semiconductor compare to a narrow band gap semiconductor (say GaAs vs. Si)?

References:

- http://users.df.uba.ar/acha/Lab5/bandgap_diodos.pdf
- http://www.sestechno.com/pro1/2n.pdf
- https://en.wikipedia.org/wiki/P%E2%80%93n_junction
- Geeta Sannon- B.Sc Practical Physics
- http://kamaljeeth.net/newsite/index.php?route=product/product/getProductAttachmentFile&attachment_id=335

Author Notes:

- This Lab Manual was created for the Solid States Physics Lab during the II Semester of M.Sc Physics course at University of Delhi.

- Despite extreme caution, some errors or typos may have crept in inadvertently. If you find an error or have a correction or suggestion, then you can either email (manassharma07@live.com) me or drop a comment on this post: http://www.bragitoff.com/2017/02/pn-junction-material-characterisitcs-experiment-lab-manual/ on my blog: http://bragitoff.com.
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