Semiconductor Devices and Models II
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Homework No 2. Solutions

1. The data in Fig. 1 are the measured current-voltage characteristics of a silicon *p-n* junction diode at very small biases (much smaller than V_{th}, where V_{th} is the thermal voltage (assume temperature T = 25 ^{o}C). (The current is in μA in the graph and in A in the table, the voltage is in V.) Using the empirical diode equation

$$I = I_s\left(\exp\frac{V}{\eta V_{th}} - 1\right)$$

extract the ratio $I_s/(\eta V_{th})$ from the slope of the diode characteristics.

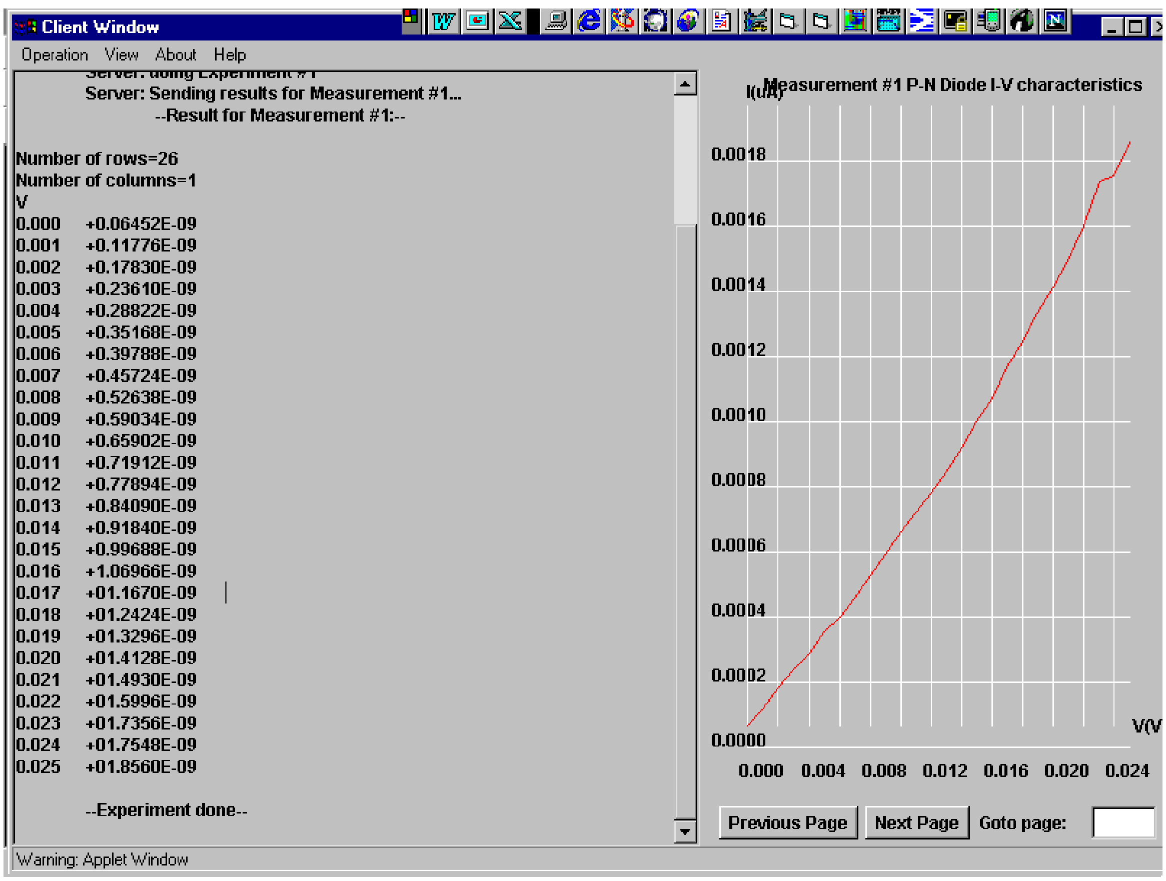


Figure 1

In the linear range ($V << V_{th}$, where V_{th} ~ 26 mV is the thermal voltage, $I \sim I_s V/(\eta V_{th})$. From the data in Fig. 1s, we find

$I = 0.0629 + 57.2514\ V$, where current I is in nA and voltage V is V

Hence $g_o = I_s/(\eta V_{th}) = 57.25$ nS

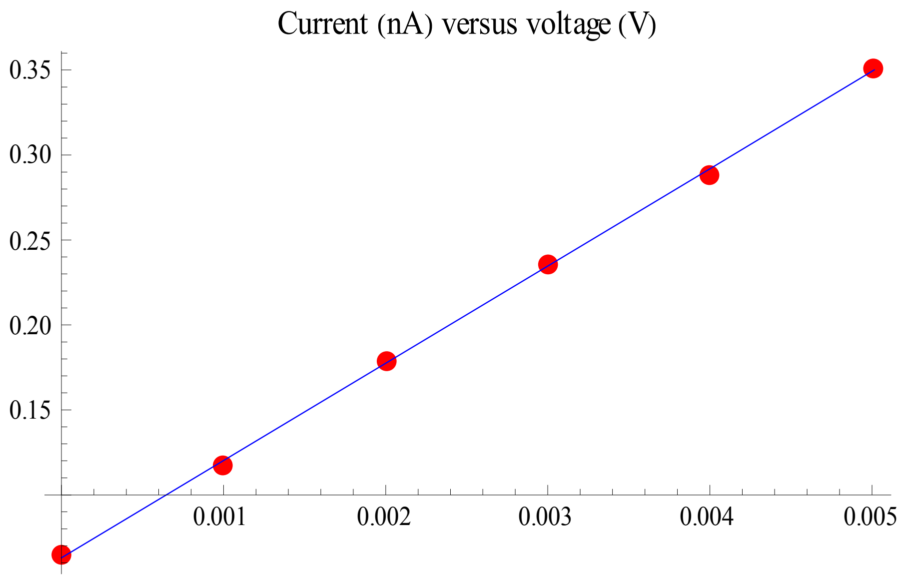


Figure 1s.

2. **Fig. 2 shows the measured current-voltage characteristics of the same silicon p-n junction diode at biases in the range between 0.1 V and 0.5 V. Re-plot the measured characteristic in a semilog scale and extract I_s and η**

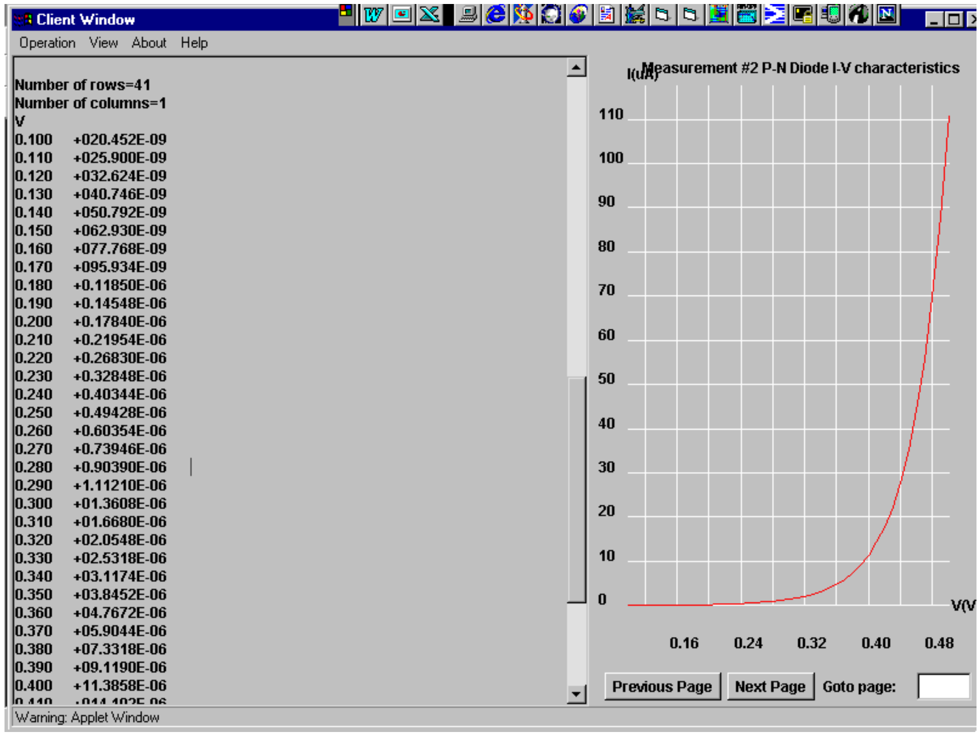


Figure 2

Plotting the data on a semilog scale, we obtain

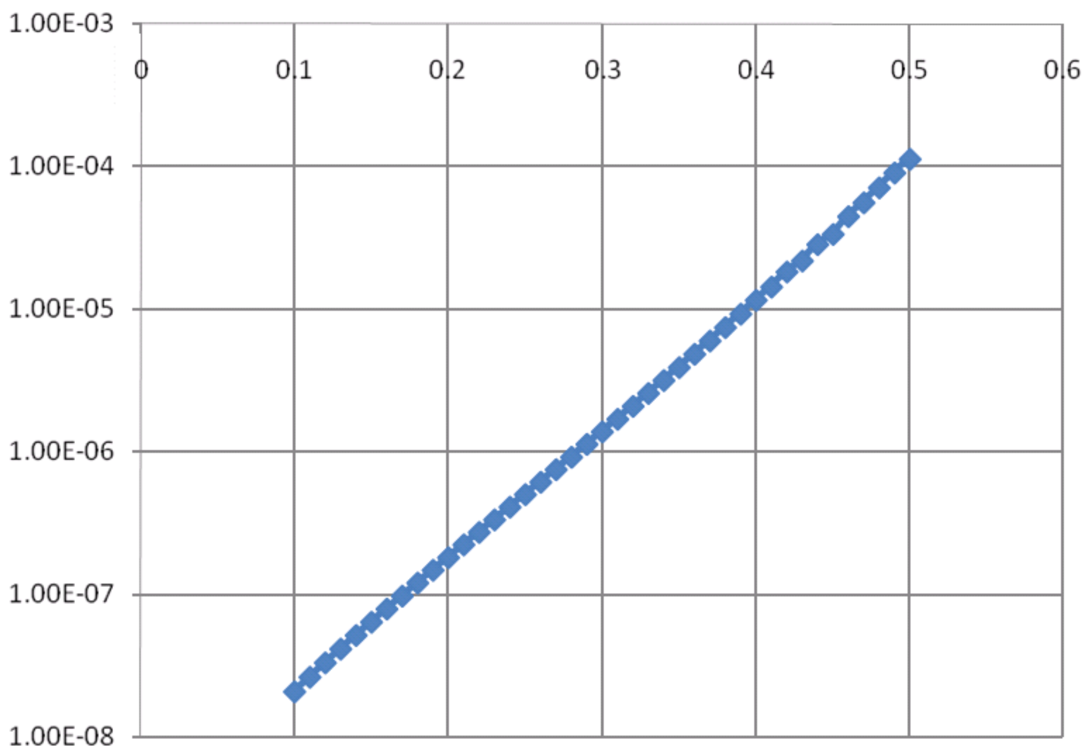


Fig. 2s. *I* (A) versus *V* (V)

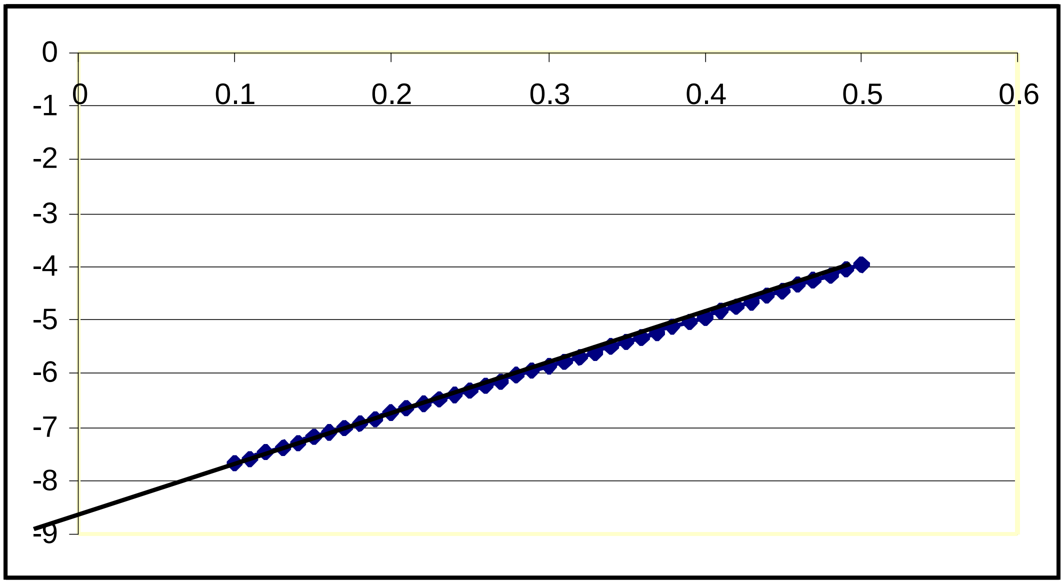


Fig. 3s. Log (I,A) versus V(V) for finding the intercept

Ln (I) = Ln (I_s) + V/(ηV_{th}) and Log (I) = Ln (I_s)/2.3 + V/(2.3ηV_{th})

Hence from the slope and intercept in Fig. 3s, we find $I_s \sim 2.3$ nA, $\eta V_{th} = 0.041$ V, $\eta = 1.58$

Hence,

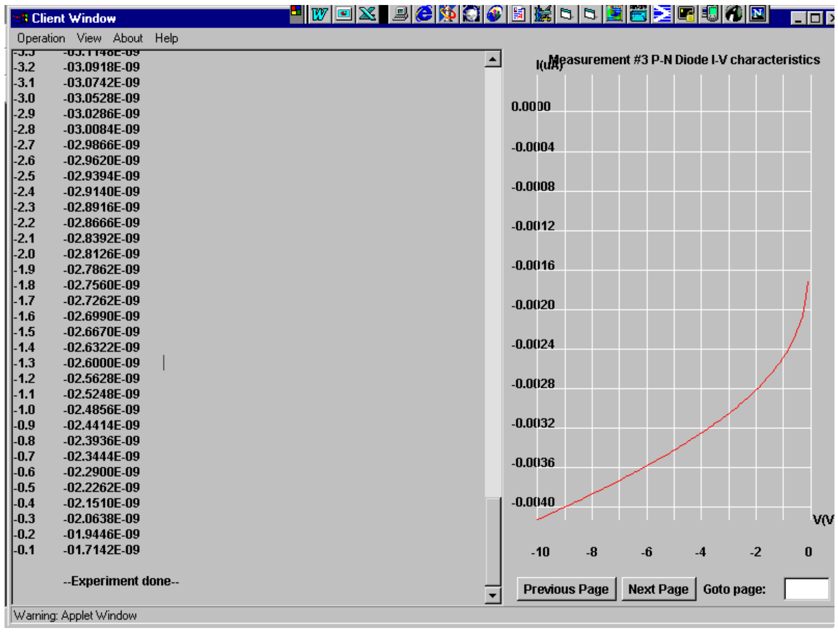
3. What does the value of η reveal about the current mechanism?

This value of η shows that recombination current must play an important role.

4. Compare the ratio of $I_s/(\eta V_{th})$ extracted from the I-V characteristics at very low voltages and from the semi log plot.

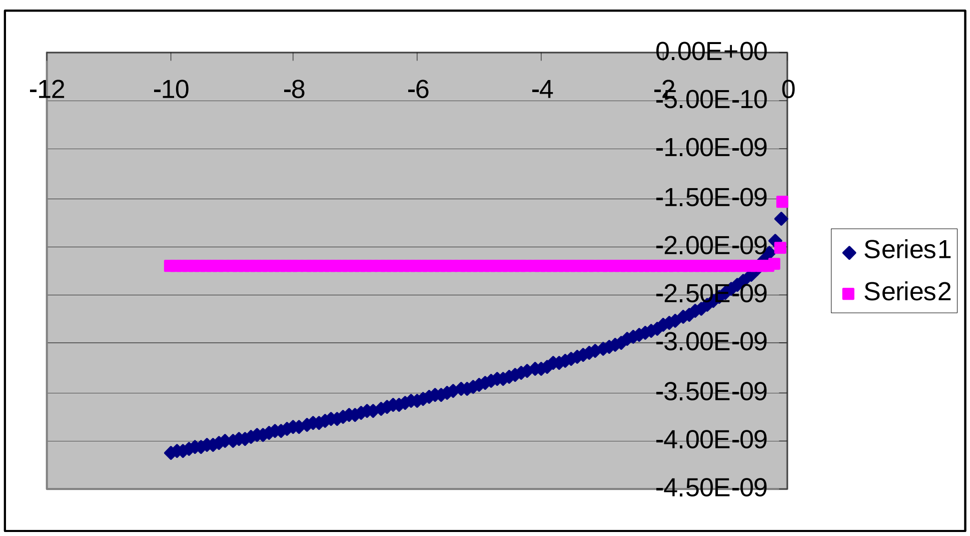
The ratio of $I_s/(\eta V_{th})$ extracted from the I-V characteristics at very low voltages is approximately 57 10^{-9} A/V. The value of ηV_{th} extracted from the semi log plot is 0.041 V. The intercept of the semi log plot yields $I_s \sim 2.3$ nA for the ratio of $I_s/(\eta V_{th})$ ~ 56 10^{-9} A/V. Hence, these values agree with each other. The accuracy of the semi log plot does not allow for a more accurate comparison.

5. Figure 3 shows the measured diode current-voltage characteristic for voltages from 0 to - 10 V. Compare these characteristics with the predicted reverse characteristic obtained from the ideal diode equation. Is agreement good? If not, estimate the contribution from the generation current.



The next figure shows the comparison with the empirical diode equation

$$I = I_S\,(e^{(\frac{V}{\eta V_{TH}})} - 1)\,.$$



6. Comment on the accuracy of the diode equation in describing the device characteristics of real *p-n* diodes.

As seen from the above figure, the agreement in the reverse bias region is very bad because of the contribution from the generation current in the depletion region under the reverse bias conditions.

4-3-4. Design a Si p^+-n junction diode with the reverse saturation current smaller than 1 nA at room temperature at - 5 V and forward current at 0.5 V of approximately 1 mA at T = 300K. Specify the device dimensions and indicate doping levels. **Hint:** Assume reasonable values of parameters. Use eq. (4-3-21) and choose x_n << X_n << L_p where X_n is the length of the n-region, x_n is the width of the depletion region, and L_p is the hole diffusion length. (You may estimate L_p to be on the order of 50 µm.)

Solution:

Let us choose $N_a = 10^{18}$ cm^{-3}, $N_d = 10^{15}$ cm^{-3}.
At 300 K, $n_i \approx 10^{10}$ cm^{-3}. Then

$$V_{bi} = \frac{k_B T}{q} \ln \frac{N_a N_d}{n_i^2} = \frac{k_B T}{q} \ln \frac{10^{18} 10^{15}}{10^{20}} = 0.0258 \times \ln\left(10^{13}\right) = 0.773(V)$$

$$x_n(V=0) = \sqrt{\frac{2\varepsilon_s V_{bi}}{q N_d}} = \sqrt{\frac{2 \times 1.05 \times 10^{-10} \times 0.773}{1.602 \times 10^{-19} \times 10^{21}}} = 1(\mu m)$$

Let us choose X_n = 10 µm so that x_n << X_n << L_p. Assuming that the hole mobility in Si is μ_p = 200 cm^2/Vs, we find $D_p = \mu_p k_B T/q$ = 200x0.0258 = 5.17 cm^2/s. $p_{no} = n_i^2/N_d = 10^5$ cm^{-3}. Then we find from eq. (4-3-34):

$$j \approx \frac{q D_p p_{no}}{X_n}\left[\exp\left(\frac{V}{V_{th}}\right) - 1\right] =$$

$$\frac{1.602 \times 10^{-19} \times 5.17 \times 10^5}{10^{-4}}\left[\exp(38.7 \times V) - 1\right] =$$

$$8.28 \times 10^{-10}\left[\exp(38.7 \times V) - 1\right]\left(\frac{A}{cm^2}\right)$$

At 0.5 V, the current density is equal to 0.21 A/cm^2. Hence, the diode area should be equal to $10^{-3}/0.21 \approx 0.0048$ cm^2. If the diode has a circular shape, this corresponds to the radius of 0.0389 cm. The reverse current at – 5 V is approximately 0.0048*8.28*$10^{-10} \approx$ 0.0038 (nA), well within the specs.