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DETERMINATION OF CARRIER TEMPERATURE FROM JUNCTION I(V) MEASUREMENTS

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ABSTRACT
The carrier temperature differs from the lattice temperature in operating silicon junctions.
This paper describes a practical experiment that can be performed by undergraduate students to introduce and understand the concept of the carrier temperature or the Kinetic temperature. An application is proposed, for the determination of the semiconductor energy gap at T=0 K, $E_g(0)$, from the analysis of the pn junction current-voltage characteristic.
Keywords: semiconductor, silicon, energy gap, carriers temperature, junction, thermal potential

I. INTRODUCTION

Ideal pn silicon junction *I(V)* characteristics are often described in low injection conditions by a one exponential model [1-4]:

$$I = I_0 \exp\left(\frac{V}{V_T}\right) \tag{1}$$

where I is the load current, V is the junction voltage. In Eq. (1), the thermal potential $V_T = kT_c/e$ introduces the carrier temperature T_c and I_0 is the reverse diode saturation current. Ideal junction signifies that the series resistance R_s is low, thus the ohmic potential drop in the neutral regions is negligible compared to the applied voltage ($R_s I << V$), and that space charge recombination currents are negligible compared to the carrier diffusion currents. An expression of I_0 for the low injection behavior may be written in the form [1, 2]:

$$I_0 = I_{0L} n_i^2, \tag{2}$$

where I_{0L} is determined from the description of the carrier diffusion processes. The intrinsic carrier concentration n_i is dependant on both the energy gap E_g and the carrier temperature:

$$n_i = (N_c N_v)^{1/2} \exp\left(-\frac{E_g}{2kT_c}\right) \tag{3}$$

A recent work [5] has also derived Eq. (1) from the description of carrier distributions at low and high injection conditions. The current appeared as the sum of the contribution of each part of the pn junction, the p region, the n region and the space charge region. Each region was described by its own behavior, either low or high injection, thus the total contribution corresponds to a combination of behavior and characteristics.
We present here an experimental method based on current-voltage, *I(V)*, measurements at various lattice temperature values, T, varying from 92 K to 422 K. The description of *I(V)* curves by Eq. (1) leads to determine carrier temperature values, T_c, different from T values. In addition, measurements of the junction voltage needed to obtain the same low injection level current, at each temperature, are shown to enable the determination of the silicon energy gap value.

II. EXPERIMENTAL PROCEDURE AND RESULTS

The experimental study was realized with the measuring setup shown in Fig. 1-a. The silicon pn junction is the emitter-base junction of the NPN 2N2222A transistor. The transistor metal package (TO-18) should be cut open to enable even heat flow around the transistor chip. Encapsulating a transistor holder and a thermocouple with the corresponding wiring in a plaster body makes a heat/cold resistant holder, which is shown in Fig. 1-b. The tip of the thermocouple (or the sensing end) is placed close to the transistor. The current-voltage measurements were made in two different ways. A controlled oven is used to heat the sample from room temperature to the desired higher temperature (from 300 K to 422 K). For decreasing the transistor temperature from room temperature, liquid nitrogen is used and the distance of the transistor from the surface of the liquid nitrogen determines the desired temperature (from 300K to 92K). The sample temperature is monitored on the temperature control unit display (REX CB100 equipped with a thermocouple of type K which can hold until 1150°C and having a 0.3 % of precision.), and the *I(V)* measurements are acquired once the temperature is stable at the desired temperature, in heating coil or liquid nitrogen. The *I(V)* characteristics are measured at different temperature values using a Keithley Model 2400 General-Purpose SourceMeter. The LabTracer software was used to acquire all *I(V)* data.

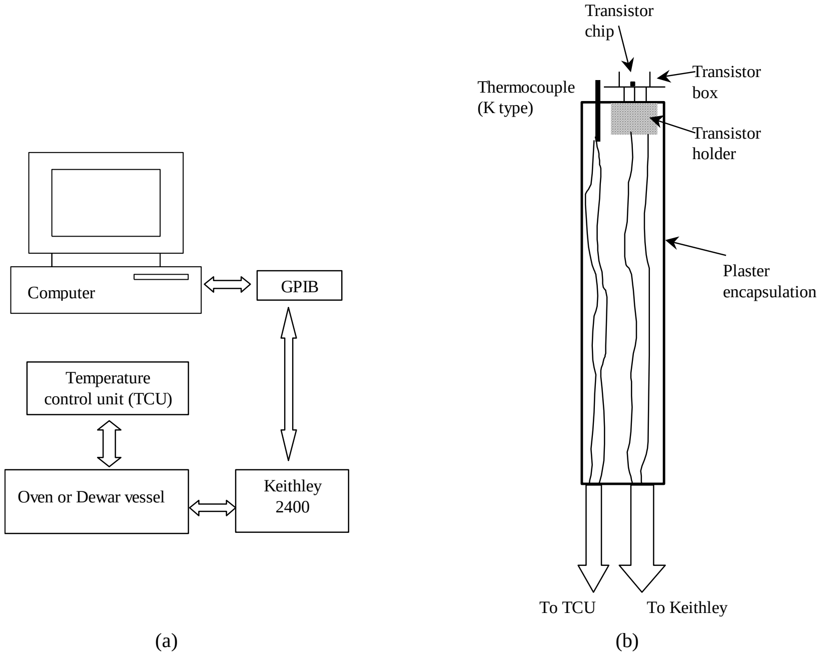

Fig. 1: The measuring cell.

The *I(V)* characteristics, measured at eight temperature values as shown in Table 1, are reported in the semi logarithmic plots of Fig. 2.

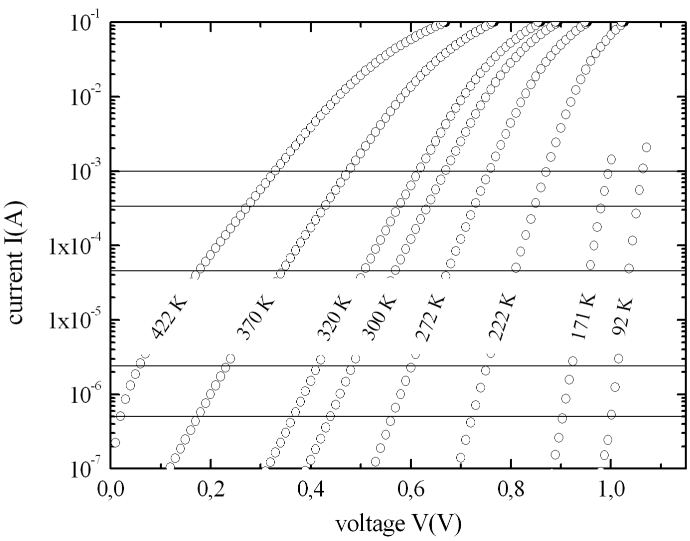

Fig. 2: Current-voltage characteristics in semi logarithmic plot for eight different temperature values as reported in Table 1.

Using Eq. (1) and the plot of *Log(I)* versus the applied voltage *V* it is easy to obtain the values of the thermal potential [4] V_T from the slope of the most linear part of the plot. The experimental reverse saturation current I_0 is determined from the intersection with *Log(I)* axis. The extraction software is the graphical interface Microcal origin 5.0 using defined fitting procedure. Results are displayed in Table 1.

Table 1. Experimental results for the reverse saturation current I_0 , the thermal potential V_T and the computed values of the carrier temperature T_c.

T (K)	I_0 (A)	V_T (x10^{-3} V)	T_c (K)
92	2.04×10^{-59}	8.29	96.17
171	3.84×10^{-39}	12.20	141.53
222	1.16×10^{-23}	18.88	219.02
272	4.51×10^{-17}	24.37	282.71
300	1.25×10^{-13}	28.86	334.80
320	4.02×10^{-12}	31.13	361.14
370	6.14×10^{-9}	38.94	451.79
422	1.29×10^{-6}	49.38	572.85

The last column in Table 1 gives computed values of the carrier temperature using $T_c = eV_T/k$.
Table 1 points out that the carrier temperature T_c is different from the experimentally imposed lattice temperature T. Further more, Table 1 shows that T_c=T for a temperature value close to 230 K. This result may be related to the temperature dependent carrier-lattice interaction [6], and have a relation with Debye temperature. These results are displayed in Fig. 3; at low temperature the behavior is quadratic, compared to the quasi-linear variation at higher temperature.

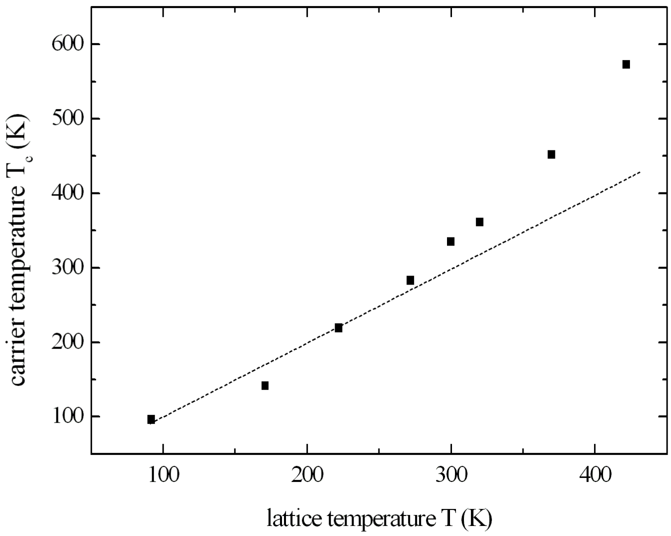

Fig. 3: The carrier temperature in low injection versus the lattice temperature. The dotted curve is the experimental data, and the dashed curve is $T_c = T$.

These results may be applied to describe the temperature dependence of the junction *I(V)* characteristic. It can be done with an additional experiment that considers measurements, at different temperatures, of the voltage values applied to the junction in order to obtain a steady current.
From the same measurement displayed in Fig. 2, the student could use horizontal lines to determine the variation of the junction voltage at constant current.
Using Eqs. (1), (2) and (3), the applied junction voltage V, for a steady value I=I_{cst}, may be obtained in the form:

$$V = V_T \ln\left(\frac{I_{cst}}{I_{0L}\left(N_c N_v\right)}\right) + \frac{E_g}{e} . \quad (4)$$

The temperature dependence of voltage V is related [2] to the variations with temperature of the energy gap E_g which is given by Varshni's equation [7]:

$$E_g\left(T\right) = E_g\left(0\right) - \frac{\alpha T^2}{\left(\beta + T\right)} . \quad (5)$$

where $E_g(0)$ is the energy gap limit at 0 K, and α and β are related to the semiconductor properties.

Our results are based on the observation from Eqs. (4) and (5) that as temperature decreases towards the absolute zero, the voltage goes towards the value [1, 8] $E_g(0)/e$ at 0 K.

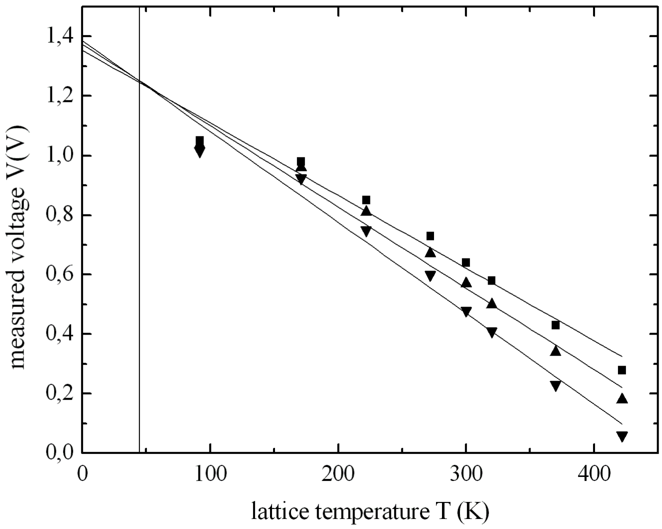

Fig. 4: Dependence of the values of the voltage across the junction on the lattice temperature *T*. The data indicated by squares, up triangles and down triangles correspond respectively to current at 3.35×10^{-4} A, 4.57×10^{-5} A and 2.40×10^{-6} A. The solid straight lines result from least-square fitting procedure applied to the separated data sets.

Figures 4 and 5 represent the values of the measured applied voltage across the junction as a function of temperature, respectively T and T_c, for steady values $I=I_{cst}$ of the injected current in low injection conditions. The lines in both figures represent a computed fit. All the lines in Fig. 5 intercept the T_c=0 K voltage axis at the same point $V(0)$ = 1.2 V. This result is in agreement with the above observation since the value of voltage V at 0 K corresponds to the value of the energy gap at 0 K, $E_g(0)$. This value could be compared with the literature [7, 2] determinations ($E_g(0)$ = 1.17 eV). It is not the case in Fig. 4 where the lines do not intercept at 0 K and more delicate extrapolation is needed.

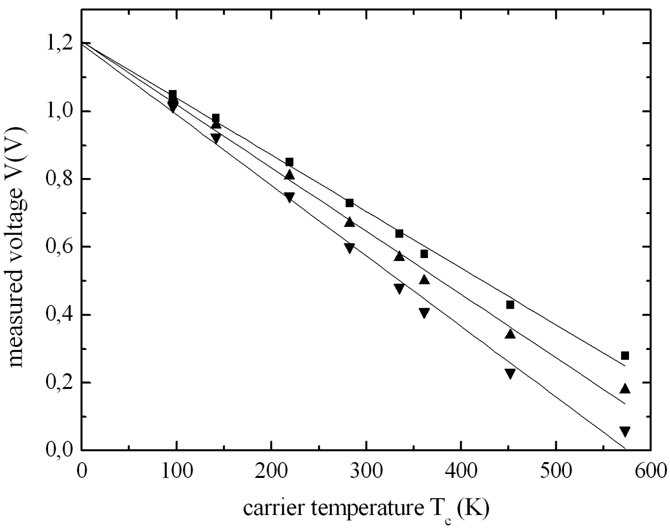

Fig. 5: Dependence of the values of the voltage across the junction, on the carrier temperature T_c. The data indicated by squares, up triangles and down triangles correspond respectively at 3.35×10^{-4} A, 4.57×10^{-5} A and 2.40×10^{-6} A. The solid straight lines result from least-square fitting procedure applied to the separated data sets.

This additional experiment points out the difference between the carrier temperature and the lattice temperature.

III. DISCUSSION AND CONCLUSION

Experimental values in Fig. 3 (square symbols) show two types of variations of the carrier temperature in silicon, linear at temperature higher than 200 K and a quadratic approach for temperature lower than 200K; these observations were made by Varshni [7] for the forbidden energy gap, who introduced Eq. (5) to fit these results. The introduction of the carrier temperature results in a new description, which is of importance for the understanding of optical properties of semiconductor devices, but a discussion of this point is not the aim of this work. The use of the carrier temperature gives rise to correct predictions of e/k in Inman work.

Experiments have been described which lead students to introduce the concept of carrier temperature which is related to the excitation of carriers since thermal agitation induces a dominant process of carrier generation. The concept is applied to the description of *I(V)* measurements. Furthermore, the described method is of simple use and introduces a practical way to experiment on temperature dependence of semiconductor properties.

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