Automated measurements of junction characteristics to evaluate parameters for semiconductor diodes


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Using National Instrument’s LabVIEW (Laboratory Virtual Instrument Engineering Workbench), a graphical programming language, we have measured the junction characteristics of different diodes in the temperature range 273-373 K. The PCI-6024E Data Acquisition Board and BNC-2120 for the acquisition of the data have been used. LabVIEW’s Controls and Functions enable one to control the experiment, measure the parameters, analyze and process the data. Ideality factor $\eta$, reverse saturation current $I_0$, and material constant $B$ have been evaluated using $I-V$ characteristics. The barrier height $\Phi_B$ and the band-gap energy $E_G$ have been measured and compared using both $I-V$ and $C-V$ characteristics. For Schottky diode, the series resistance $R_s$ and $\Phi_B$ can be calculated using the Norde method. The band-gap energy has been measured using constant current source. Here, we have characterized $p-n$ junction diodes viz. 1N5402, 1N5408, 1N4148, and 6A4. In addition, LabVIEW may be used to characterize other junction diodes like zener diode, LED, varactor diode, Schottky diode, etc.

Keywords: Semiconductor diode junction characteristics, LabVIEW automation

1 Introduction

LabVIEW (Laboratory Virtual Instrument Engineering, Workbench) is a graphical programming language where icons serve the purpose of text syntax. LabVIEW contains a comprehensive set of tools, called Virtual Instruments (VIs), for controlling, acquiring, analyzing, displaying and storing data. LabVIEW consists of a front panel, wherein one can build user-interface with controls and indicators, and block diagrams, which have codes to control the front panel, acquisition and processing of data. Obtaining the junction characteristics like current-voltage ($I-V$), current-voltage-temperature ($I-V-T$), capacitance-voltage ($C-V$), and capacitance-voltage-temperature ($C-V-T$) is time-consuming and requires knowledge of text-based language for interfacing and acquisition of data. To overcome this we have developed the LabVIEW-based automation system.

The LabVIEW program for studying the junction characteristics consists of three sections viz., $I-V$ characteristics, $C-V$ characteristics and determination of the band-gap energy using a constant current source. The program has the features of control over the parameters like temperature and voltage and an analysis of the data procured. It controls the range and incremental steps of the voltage and temperature and can auto-stop the experiment at a pre-defined temperature and stipulate the number of snaps (a whole set of readings) for a given temperature. It can also control the time-delay between two observations and furthermore, it allows the selection of the temperature-sensor device. In addition, the program can handle the storage of data, file-path, display of graphs (with selection of curve-fitting method) and results.

Figure 1 shows the block diagram of the system in which the temperature sensor can be a Semiconductor Temperature Sensor (STS) i.e. LM35DZ, a Thermocouple, or a Thermister, depending upon the type of application. PCI-6024E Data Acquisition Board and BNC-2120 Connector Block are the interfacing instruments/tools between device under test (DUT) circuit and computer. The DUT circuit is different for each characterization part. VI controlled voltage source has been used for $I-V$ measurement whereas a constant current source, using IC LM 334, has been used for determining the band-gap energy. $C-V$ measurement has been carried out using reverse biased voltage and an incremental voltage at radian frequencies $\omega_1$ and $\omega_2$ (ref. 2).

2 Theory

2.1 Forward bias $I-V$ characteristics

The current $I$ in a $p-n$ junction is given by:

\[ I = I_0 \left[ \exp \left( \frac{qV}{\eta kT} \right) - 1 \right] \]  

\[ \text{...}(1) \]
where \( q, V, \eta, k, T \) and \( I_0 \) are the electronic charge, junction voltage, ideality factor, Boltzmann’s constant, temperature in Kelvin, and reverse saturation current, respectively. \( I_0 \) is given by:

\[
I_0 = BT^3 \exp\left(-\frac{E_g}{\eta kT}\right)
\]  

(2)

where \( E_g \) is the band-gap energy and \( B \) is the material constant. The ideality factor can be obtained using \( \ln I \) versus \( V \) plot from the following equation:

\[
\eta = \frac{q}{kT} \left( \frac{d \ln I}{dV} \right)^{-1}
\]  

(3)

In addition, \( \ln I_0 \) is given by the intercept of the above plot under the condition, \( \exp(qV/\eta kT)>>1 \).

The Richardson constant \( A^* \), series resistance \( R_s \) and the barrier height \( \Phi_B \) of the Schottky diode may be calculated using the modified Norde technique for Schottky diode. This method does not require the exact knowledge of the effective mass. In this method, one defines the function \( F_1 \) as:

\[
F_1 = \frac{qV}{2(kT)} - \ln\left(\frac{I}{T^2}\right)
\]  

(4)

\( F_1 \) has a distinct minimum \( F_1_m \) at each temperature; the corresponding voltage \( V_m \) and current \( I_m \) are used to calculate the series resistance using:

\[
R_s = \frac{kT}{q} \left( \frac{2 - \eta}{I_m} \right)
\]  

(5)

A plot of \( 2F_1_m + (2 - \eta)\ln(I_m/T^2) \) against \( (q/kT) \) gives a straight line. We may find the experimental value of Richardson constant from the equation:

\[
A^* = \frac{1}{A} \exp\left[\left(\frac{2-\text{intercept}}{\eta}\right) - 1\right]
\]  

(6)

where \( A \) is the effective diode area. One can also find theoretically the Richardson constant from the equation \( A^* = 4\pi q m^* k^2 / h^3 \), where \( m^* \) is the effective mass. The barrier height is given by:

\[
\Phi_B = \frac{\text{slope}}{\eta}
\]  

(7)

### 2.2 Band-gap energy measurement

We can also determine the band-gap energy and the material constant, \( B \), using the constant current source method. From Eqs (1) and (2), we have:

\[
V = \frac{E_g}{q} - \left[\ln\left(\frac{BT^3}{I}\right)\right] \frac{\eta kT}{q}
\]  

(8)

The graph of \( \ln I \) versus \( V \) represents a straight-line with \( E_g = q \) (Intercept). Furthermore, the material constant, \( B \), can be obtained from:

\[
B = \frac{I}{T^3} \exp\left(\frac{q(\text{Slope})}{\eta k}\right)
\]  

(9)

### 2.3 C-V characteristics

Figure 1 shows the circuit for the measurement of the C-V characteristics. The outputs of the operational amplifier \( V_1 \) and \( V_2 \) can be given by Eqs [(10) and (11)], which are obtained for two different
frequencies \( \omega_1 \) and \( \omega_2 \), respectively, where, \( C_D \) is the depletion capacitance and \( G_D \) is the leakage resistance of the DUT.

\[
V_1 = -V \left( G_D + j \omega_1 C_D \right) R \quad \text{(10)}
\]

\[
V_2 = -V \left( G_D + j \omega_2 C_D \right) R \quad \text{(11)}
\]

where \( R \) is the feedback resistance and \( V \) is the input signal of the same magnitude for both \( \omega_1 \) and \( \omega_2 \). From the Eqs 10 and 11, we have:

\[
C_D = \frac{\sqrt{V_2^2 - V_1^2}}{VR(\omega_2^2 - \omega_1^2)} \quad \text{(12)}
\]

Intersection of the plot of \( 1/C^2 \) versus \( V \) on \( V \)-axis (X-axis at \( 1/C^2 \)) gives the barrier height.

### 3 LabVIEW Programming

Figure 2 shows a flowchart of the program. It gives only the main functions of the program; the details of the characterization parts have been left out.

Figure 3 shows the front panel view containing controls and indicators and Fig. 4 shows the block diagram containing codes.

Figure 5 shows the temperature control section of the program. This section acquires temperature from the temperature sensor device with given sampling information. It displays the temperature on the front panel and triggers the characterization program at specified steps of temperature, known as the ‘Auto Data Acquisition Mode.’ In the Auto Data Acquisition Mode, one can also obtain the data manually by pressing the ‘Acquire Manually’ button. If the temperature exceeds the specified maximum limit, it stops the program.

#### 3.1 I-V characteristics

This section of the program procures the \( I-V \) characteristics of the device (Fig. 6). In this program, one can select the curve-fitting method; we have used the Levenberg-Marquardt algorithm to determine the least-squares set of coefficients that best-fit the set of input data points \((X,Y)\) as expressed by a non-linear function \( y = f(x,a) \), where \( a \) is the set of coefficients. Formula Node is used to solve equations and handle manipulations with arrays.

#### 3.2 C-V characteristics

By selecting the \( C-V \) tab, we can obtain the \( C-V \) characteristics as shown in Fig. 7. In this section, sub-VI ‘CV control’ is used for data acquisition and control. Incremental voltage \( V \) with radian frequencies \( \omega_1 \) and \( \omega_2 \) is given manually when sub VI window appear for seeking it. A sub-VI, named ‘CV process’, performs data processing and calculation for these characteristics.

### 4 Experimental Set-up

Before starting the experiment, the system needs to be set for Traditional NI-Daq Virtual Channels and connection of respective DUT circuit with BNC’s channels. To increase the current drive capacity and prevent the BNC-2120 from damage, we have used buffers. Figure 8 shows the picture of the experimental set-up of the system. Temperature sensor can be LM 35DZ, thermocouple, or thermister.
Fig. 3 — Front panel view of the program showing the controls and indicators

Fig. 4 — Block diagram view of the program showing graphical programming
depending upon the application. We have performed this experiment using LabVIEW 7.1 on the window platform. For easy accessibility, we have stored the data in Microsoft Excel format. Once the program runs, one should select the respective tabs and set all the values for the relevant parameters. If one wants to perform the temperature characteristics one switches to Auto Data Acquisition Mode and increases the temperature gradually; at a specified maximum limit of the temperature the program will stop with results on front panel and in files. In $C-V$ measurement, set the frequency and enter the relevant parameter whenever program demands.

One can modify the system for auto-temperature control instead of the hot plate as used by us. In $C-V$ measurement, we apply the incremental voltage at radian frequency $\omega$ using BNC’s function generator because of the incapability of our PCI-6024 card, but this can also be programmed using higher sampling rate DAQ card for output frequency of about 25 kHz. The constant current source is made using LM334, which can be replaced by a programmable current source. One can modify and change the DUT circuits’

![Fig. 5 — Program for the temperature control part of the system](image)

![Fig. 6 — Subprogram used for determining the $I-V$ characteristics](image)

![Fig. 7 — Subprogram used for determining the $C-V$ characteristics](image)

![Fig. 8 — Experimental setup used for determining the diode characteristics](image)

![Fig. 9 — $I-V$ characteristics of the diode 1N 4148 at 358 K](image)
connection by a single socket connection for the diode manually.

5 Results
Junction characteristics of different diodes have been measured in the temperature range 273-373 K. Some diodes need low temperatures of about 50K for noticeable change in $\eta$, $R_s$, $I_0$ etc. with temperature. We have not performed the experiment for such temperature ranges. The graphs shown in Fig. 9 to 12 were obtained online during the experiment. In Table 1, the results for some diodes are presented. The results obtained by this system are closer to ‘actual’ values as we have compared result$^{2,5}$ of 1N 4007.

6 Conclusions
The experimental method developed for the characterization of semiconductor junctions at a particular controlled temperature can be generalized to other experiments where control of temperature (and/or other parameters) is necessary. It also shows the versatility and simplicity of the LabVIEW compared with the text-based language (wherein the above problem would be quite a formidable one for an average undergraduate student). The applicability on any semiconductor junction is another beneficial feature of this system.

References