Int. J. Appl. Engng Ed. Vol. 7, No. 1, pp. 71–75, 1991
Printed in Great Britain.

0742–0269/91 $3.00+0.00

Innovative Analysis of Semiconductor Junctions using a Personal Computer*†

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The purpose of this paper is to provide an alternative and innovative method of studying the semiconductor PN junctions which form the basis of all modern electronic devices. We have developed a student-oriented computer program which can be used for analyzing the characteristics of a semiconductor junction made of silicon, germanium or gallium arsenide on a personal computer. The program is written in FORTRAN 77 and the graphics have been incorporated using a package called GRAFMATIC. The program has been used to study the ideal static and dynamic current-voltage characteristics of the step PN junctions under forward and reverse bias conditions at different operating temperatures. The effects of varying the doping concentrations and the junction cross-sectional areas have also been studied. It can also be used to study the dependence of the reverse-bias breakdown voltage of the junction on the donor and acceptor concentrations. The program has also been used to analyze the effects of the generation and recombination in the depletion layer. The software modules have been run successfully on microcomputers and are suitable for inclusion in microcomputer-based microelectronics education.

INTRODUCTION

DURING the last few years, the latest technological advancements and the low cost of personal computers has led to their increasing use in computer-based instruction (CBI) in several disciplines such as calculus [1], statistics [2], computer programming [3–6], French language [7], physics [8], chemistry [9], engineering [10–14], and so on. In the area of engineering curricula, although CBI has not and perhaps will not replace the traditional methods of education, yet it offers some significant advantages. Research has shown that students using CBI demonstrate increased motivation [15] and that increased motivation translates into improved achievement of course objectives. Furthermore, particularly for the engineering education, CBI makes it possible to train students in problem-solving skills by designing programs that require student problem solving through realistic simulations in a wider range of applications and using various types of problem-solving approaches [16,17]. In short, the CBI method using personal computers seems to best complement the engineering education.

Microelectronics is an area within electrical/electronics engineering that deals with solid state devices such as p-n diodes, p-n-p and n-p-n transistors, metal-semiconductor field effect transistors (MESFETs), metal-oxide-semiconductor field effect transistors (MOSFETs) and so on, and their fabrication and characterization on the very large scale integrated (VLSI) chips. Understanding of PN junctions is essential to the study of all solid state electronic devices. In this paper, a student-oriented computer program which can be used to study the characteristics of a PN junction on a personal computer is described. The program has been used to study the various characteristics of PN junctions made of silicon (Si), germanium (Ge) or gallium arsenide (GaAs).

PROGRAM DEVELOPMENT

We have developed a program called 'Microcomputer Simulation of Semiconductor Junction Characteristics' (MSSJC) which can be used to study the forward and reverse-bias current-voltage (I-V) characteristics of the step PN junctions and the dependence of the breakdown voltage of a PN junction on the doping concentrations. The program supports PN junctions made of any one of the three semiconductor materials: Si, Ge or GaAs. The user has the option of including the effects of recombination for the forward bias or those of generation for the reverse bias. The program can also be used to study the dependences of the I-V characteristics on temperature, electron doping concentration, hole doping concentration and the cross section area of the PN junction. The results can be displayed graphically on the monitor screen

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[*] Paper accepted 11 June 1990. Some of the results were presented at the 'ISMM International Conference on Microcomputer Applications' at Los Angeles, California on 14–16 December 1989.

[†] The program is available for distribution and can be obtained by writing to the intellectual Properties Office of the Michigan Technological University.

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for anyone of the chosen variables. The various symbols and constants (in MKS units) used in the equations below are defined as follows:

A = Cross sectional area of the PN junction
D_n = Diffusion constant for electrons
D_p = Diffusion constant for holes
$E_g(T)$ = Energy gap in the semiconductor material at T(°K)
$E_g(0)$ = Energy gap at 0 °K
I_0 = Saturation current
L_n = Electron diffusion length
L_p = Hole diffusion length
M_e = Effective mass of the electrons in the conduction band in the material
M_h = Effective mass of the holes in the valence band in the material
N_c = Effective density of states in the conduction band
N_v = Effective density of states in the valence band
n_i = Intrinsic carrier density
N_a = Doping concentration of holes
N_d = Doping concentration of electrons
p_{no} = Equilibrium hole density on the N side of the PN junction
n_{p0} = Equilibrium electron density on the P side of the PN junction
T = Temperature in °K
τ_n = Electron carrier lifetime
τ_p = Hole carrier lifetime
μ_n = Intrinsic mobility of electrons
μ_p = Intrinsic mobility of holes
V = Voltage, in volts
ϕ_T = Voltage equivalent of temperature
ψ_0 = Diffusion potential
K_s = Dielectric constant of the material
h = Planck's constant = 6.625×10^{-34} J.s
K = Boltzmann's constant = 1.38×10^{-23} J/°K
q = Electron charge = 1.6×10^{-19} C
ϵ_0 = Permittivity of free space = 8.854×10^{-14} F/cm
π = 3.142
α = 4.73×10^{-4}
β = 636.0.

In the program, the current flowing through the PN junction is calculated by using the equation [18–21].

$$I = I_0\,[e^{v/\phi_t} - 1] \tag{1}$$

where

$$I_0 = qA\left[\frac{D_p p_{no}}{L_p} + \frac{D_n n_{po}}{L_n}\right] \tag{2}$$

$$L_p = \sqrt{D_p \tau_p} \tag{3}$$

$$L_n = \sqrt{D_n \tau_n} \tag{4}$$

$$D_p = \frac{kT\mu_p}{q} \tag{5}$$

$$D_n = \frac{kT\mu_n}{q} \tag{6}$$

$$p_{no} = \frac{n_i^2}{N_d} \tag{7}$$

$$n_{po} = \frac{n_i^2}{N_a} \tag{8}$$

$$n_i = \sqrt{N_c N_V}\, e^{-(Eg/2kT)} \tag{9}$$

$$N_c = 2\left[\frac{2\pi\, M_e\, kT}{h^2}\right]^{3/2} \tag{10}$$

$$N_v = 2\left[\frac{2\pi\, M_h\, kT}{h^2}\right]^{3/2} \tag{11}$$

and

$$\phi_T = \frac{kT}{q} \tag{12}$$

The energy gaps at temperature T(°K) for Si, Ge and GaAs are calculated by using the equations [19]:

$$E_g(T) = \left[E_g(0) - \frac{\alpha\, T^2}{\beta + T}\right](1.6 \times 10^{-19}) \tag{13}$$

$$E_g(T) = (0.75 - 2.66667 \times 10^{-4}\, T)\,(1.6 \times 10^{-19}) \tag{14}$$

and

$$E_g(T) = (1.5 - 3.33333 \times 10^{-4}\, T)\,(1.6 \times 10^{-19}), \tag{15}$$

respectively. Additional currents due to recombination and generation are given by [18,21]:

$$I_{\text{Rec}} = \left[\frac{q\,A\,n_i\,x_{\text{dr}}}{2\,\tau_P}\right] e^{V/2\phi_T} \tag{16}$$

and

$$I_{\text{Gen}} = \left[\frac{q\,A\,n_i\,x_{\text{dg}}}{2\,\tau_P}\right] e^{V/2\phi_T} \tag{17}$$

where

$$x_{\text{dr}} = \left[\frac{2\text{K}_s\,\epsilon_0\,\psi_0\,N_a}{q\,N_d\,(N_a + N_d)}\right]^{1/2} + \left[\frac{2K_s\,\epsilon_0\,\psi_0\,N_d}{q\,N_a\,(N_a + N_d)}\right]^{1/2} \tag{18}$$

$$x_{\text{dg}} = \left[\frac{2\text{K}_s\,\epsilon_\text{o}\,(\psi_0 + V)}{q\,N_d}\right]^{1/2} + \left[\frac{2\text{K}_s\,\epsilon_0\,(\psi_0 + V)}{q\,N_a}\right]^{1/2} \tag{19}$$

and

$$\psi_0 = \phi_T \ln\left[\frac{N_d N_a}{n_i^2}\right] \tag{20}$$

The dependence of the breakdown voltage (BV) on the doping concentration was determined by using the expression [18]

$$\mathrm{BV} = \frac{K_s \epsilon_o E_c^2}{2qN_d}$$

where the critical field (E_c) for Si, Ge and GaAs was determined by fitting with the known experimental data [20].

USING 'MSSJC'

The program 'MSSJC' has been used to study the dependences of the current-voltage characteristics of Si, Ge and GaAs PN junctions under forward- and reverse-bias conditions on the various parameters such as temperature, doping concentration of electrons or holes and cross sectional area of the PN junction. It has also been used to study the dependences of the reverse-bias breakdown voltages for any PN junction on the doping concentrations of electrons or holes on the N- or P-side, respectively. The program allows the option of including or excluding the effects of recombination under the forward-bias or those of generation under the reverse-bias conditions. Unless otherwise changed by the user, the program chooses the following typical values for the various parameters: temperature = 300 °K, doping concentration of electrons on the N-side = $1\times10^{16}/\mathrm{cm}^3$, doping concentration of holes on the P-side = $1\times10^{16}/\mathrm{cm}^3$ and cross sectional area of the PN junction = 0.01 cm^2. Effective masses of electrons and holes depend on the material chosen. For Si, Ge and GaAs these are 3×10^{-31}, 2×10^{-31} and 5.73×10^{-31} kg, respectively for electrons and 4.55×10^{-31}, 2.82×10^{-31} and 4.55×10^{-31} kg, respectively for holes. Lifetimes of electrons and holes depend on the material also. For Si, Ge and GaAs these are 2.5×10^{-3}, 1×10^{-3} and 1×10^{-6} seconds, respectively for electrons as well as holes. In the results presented below, the effects of recombination/generation have been included and typical values are chosen for all the parameters except for the one being varied.

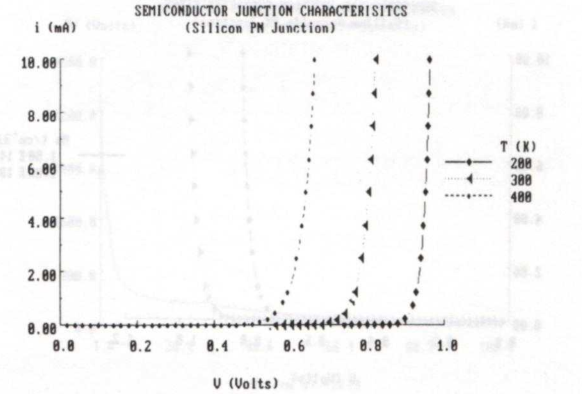

Fig. 1. The monitor screen showing the forward-bias I-V characteristics for the silicon PN junctions at temperatures of 200, 300 and 400°K.

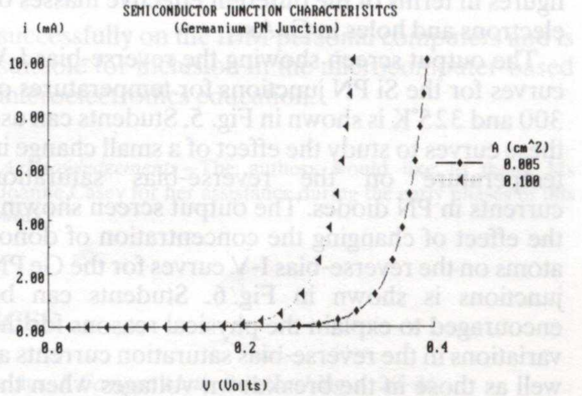

Fig. 2. The monitor screen showing the forward-bias I-V characteristics for the germanium PN junctions for two values of the cross sectional area.

The output screen showing the forward-bias I-V curves for the Si PN junctions for temperatures of 200, 300 and 400°K is shown in Fig. 1. Students can use these curves to study the dependence of the threshold voltage for a given PN junction on the temperature. For the Ge PN junction, the forward-bias I-V curves for two different values of the junction cross sectional area are shown in Fig. 2. It can be noticed from this figure that the threshold voltages for Ge are much lower than those for Si or GaAs. Students can be encouraged to explain this difference in terms of the energy gaps of the three materials. The output screens showing the forward-bias I-V curves for the GaAs PN junctions for electron and hole concentration values of 1×10^{14} and $1\times10^{18}/\mathrm{cm}^3$ are shown in Figs 3 and 4, respectively. Students can be encouraged to analyze the small differences between these two

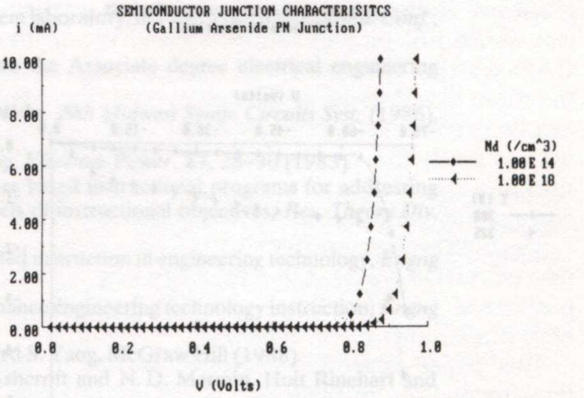

Fig. 3. The monitor screen showing the forward-bias I-V characteristics for the gallium arsenide PN junctions for donor concentrations of 1×10^{14} and $1\times10^{18}/\mathrm{cm}^3$.

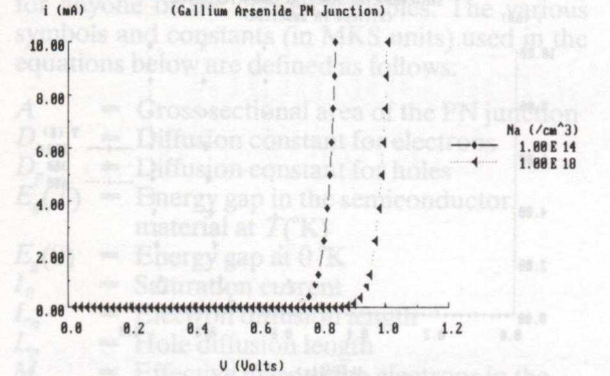

Fig. 4. The monitor screen showing the forward-bias I-V characteristics for the gallium arsenide PN junctions for acceptor concentrations of 1×10^{14} and $1\times10^{18}/\mathrm{cm}^3$.

figures in terms of the different effective masses of electrons and holes in GaAs.

The output screen showing the reverse-bias I-V curves for the Si PN junctions for temperatures of 300 and 325°K is shown in Fig. 5. Students can use these curves to study the effect of a small change in temperature on the reverse-bias saturation currents in PN diodes. The output screen showing the effect of changing the concentration of donor atoms on the reverse-bias I-V curves for the Ge PN junctions is shown in Fig. 6. Students can be encouraged to explain the physical reasons for the variations in the reverse-bias saturation currents as well as those in the breakdown voltages when the concentration of free electrons in the material is changed. The output screen showing the reverse-bias I-V curves for cross-sectional areas of 0.005 and 0.1 cm^2 of the GaAs PN junctions is shown in Fig. 7. Students can note that only the reverse-bias current and not the breakdown voltage depends on the cross sectional area, as expected. The monitor screens showing the dependences of the reverse-bias breakdown voltages on the concentrations of electrons or holes in the range 1×10^{14} to $1\times10^{16}/\mathrm{cm}^3$ for the Si, Ge and GaAs PN junctions are shown in Figs 8, 9 and 10, respectively. From these results, students can see that under similar conditions, the reverse-bias breakdown voltage for Ge PN junctions is the lowest while that for the GaAs PN junction is the highest. Students can be encouraged to think about the suitability of using Si, Ge or GaAs PN diodes for different applications.

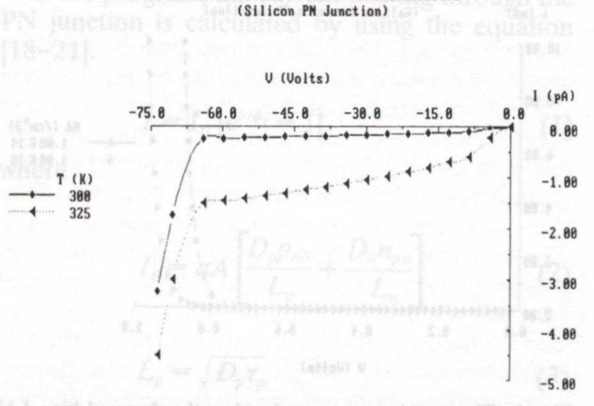

Fig. 5. The monitor screen showing the reverse-bias I-V curves for the silicon PN junctions at temperatures of 300 and 325°K.

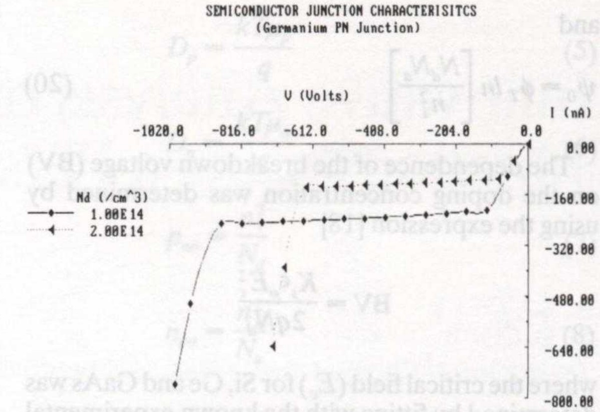

Fig. 6. The monitor screen showing the reverse-bias I-V curves for the germanium PN junctions for donor concentrations of 1×10^{14} and $2\times10^{14}/\mathrm{cm}^3$.

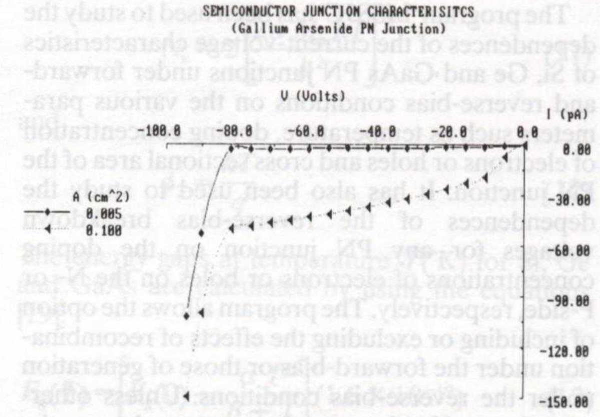

Fig. 7. The monitor screen showing the reverse-bias I-V curves for the gallium arsenide PN junctions for junction cross sectional areas of 0.005 and 0.1 cm^2.

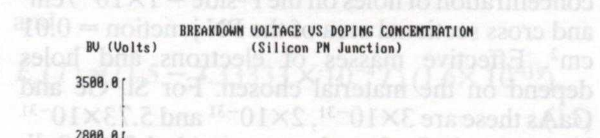

Fig. 8. The monitor screen showing the dependence of the reverse-bias breakdown voltage on the doping concentration in the range $10^{14}-10^{17}/\mathrm{cm}^3$ for the silicon PN junctions.

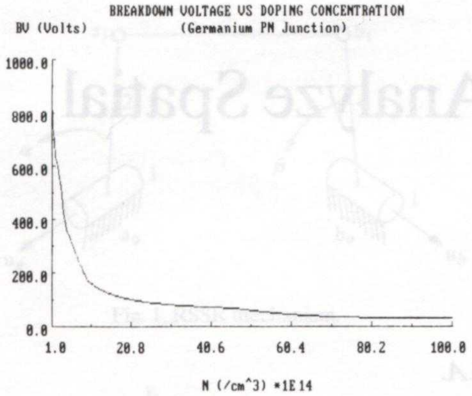

Fig. 9. The monitor screen showing the dependence of the reverse-bias breakdown voltage on the doping concentration in the range $10^{14}-10^{17}/\mathrm{cm}^3$ for the germanium PN junctions.

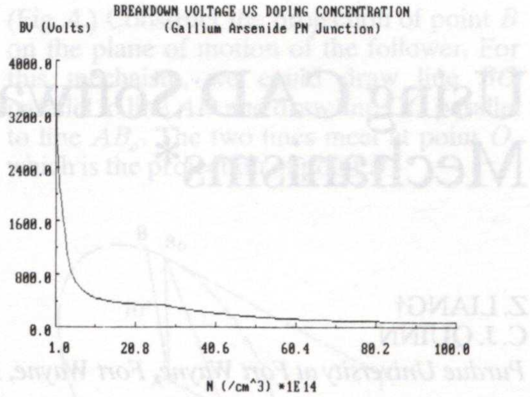

Fig. 10. The monitor screen showing the dependence of the reverse-bias breakdown voltage on the doping concentration in the range $10^{14}-10^{17}/\mathrm{cm}^3$ for the gallium arsenide PN junctions.

SUMMARY

We have developed a student-oriented program which can be used to analyze the behaviors of Si, Ge and GaAs PN junctions under forward and reverse-bias conditions for several values of the junction parameters. The program has been run successfully on the IBM personal computers and is suitable for inclusion in the microcomputer-based microelectronics education.

Acknowledgements—The authors would like to thank Ms Joanne Casey for her assistance during the early phases of this work.

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