Introduction

The work book emphasizes on the experiments related to the solid state theory of Fermi level, diodes & BJT. These experiments are tested on the most useful tool namely MATLAB. The name MATLAB stands for matrix laboratory. MATLAB is a high-performance language for technical computing. It integrates computation, visualization, and programming in an easy-to-use environment where problems and solutions are expressed in familiar mathematical notation. Typical uses include:

- Math and computation
- Algorithm development
- Data acquisition Modeling, simulation, and prototyping
- Data analysis, exploration, and visualization
- Scientific and engineering graphics
- Application development, including graphical user interface building

MATLAB is an interactive system whose basic data element is an array that does not require dimensioning. This allows you to solve many technical computing problems, especially those with matrix and vector formulations, in a fraction of the time it would take to write a program in a scalar non-interactive language such as C or Fortran.
# Solid State Devices Laboratory

## CONTENTS

<table>
<thead>
<tr>
<th>LAB#</th>
<th>LIST OF EXPERIMENTS</th>
<th>PAGE #</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Program to compute Number of atoms/cm$^3$ in cubic crystals of silicon atom</td>
<td>04</td>
</tr>
<tr>
<td>2</td>
<td>Program to plot f(E) versus Energy for different temperatures</td>
<td>05</td>
</tr>
<tr>
<td>3</td>
<td>Compute &amp; plot $V_{bi}$ as a function of doping ($N_A$ or $N_D$)</td>
<td>07</td>
</tr>
<tr>
<td>4</td>
<td>Program to generate an energy band diagram of a pn junction</td>
<td>09</td>
</tr>
<tr>
<td>5</td>
<td>Program to construct a plot of a square law relationship ($I_{Dsat}/I_{DO}$ versus $V_G/V_P$) of FET</td>
<td>12</td>
</tr>
<tr>
<td>6</td>
<td>Program to construct a plot of the depletion width versus the impurity concentration</td>
<td>14</td>
</tr>
</tbody>
</table>
OBJECT: Program to compute Number of atoms/cm³ in cubic crystals of silicon atom

EXERCISE:

Construct a MATLAB program that computes the number of atoms/cm³ in cubic crystals. Use MATLAB input function to enter the number of atoms/unit-cell & the unit cell side length.

THEORY:

In Silicon(Si) at room temperature the unit cell side length (a) is 5.43 Å (1Å=10 exp -8) since there are eight Si atoms per unit cell and the volume of the unit cell is a³ it follows that there are 8/a³ or almost exactly 5 exp 22 atoms/cubic cm in the Si lattice.

MATLAB CODE:

```
N = input('input number of atoms/unit cell, N = ');  
A = input('lattice constant in angstrom, a = ');  
Atmden = N*(1.0e24)/(a^3);  
```

Program output:

input number of atoms/unit cell, N = 8  
lattice constant in angstrom, a = 5.43  
Atmden = 4.9968e + 22
LAB # 2

OBJECT: Program to plot $f(E)$ versus Energy for different temperatures

EXERCISE:
Successively setting $T = 100, 200, 300$, and then $400$ K, compute and plot $f(E)$ versus $\Delta E = E - E_F$ for $0.2$ eV $5 \leq \Delta E \leq 0.2$eV. All $f(E)$ versus $\Delta E$ curves should be superimposed on a single set of coordinates.

THEORY:

THE FERMI FUNCTION:

Fermi function $f(E)$ specifies how many of the existing states at the energy $E$ will be filled with an electron, or equivalently, $f(E)$ specifies, under equilibrium conditions, the probability that an available states at an energy $E$ will be occupied by an electron.

Mathematically speaking the Fermi function is simply a probability density function. in mathematical symbols,

$$f(E) = \frac{1}{1+\exp{(E-E_F)/kT}}$$

where

$E_F$=Fermi energy of Fermi level

$k$=boltzmann constant ($k=8.62 \ exp \ -5 \ ev/k$)

$T$=temperature

MATLAB CODE:

```matlab
%Fermi Function Calculation, f(\Delta E, T)
% Constant
k=8.617e-5;
%Computation proper
for ii=1:4;
    T=100*ii;
    kT=k*T;
dE(ii,1)=-5*kT;
for jj=1:101
    f(ii,jj)= 1/(1 +exp(dE(ii,jj)/kT));
dE(ii,jj+ 1)=dE(ii,jj)+0.1*kT;
```
end
end
dE=dE(1:4,1:101); %This step strips the extra dE value
%plotting results
close
plot(dE',f');grid;
xlabel(‘E-EF(eV)’);
text(0.05,0.2,’T= 400K’);
text(-.03,0.1,’T=100K’);

Program Output:
LAB # 3

OBJECT: Compute & plot $V_{bi}$ as a function of doping ($N_A$ or $N_D$)

EXERCISE:

Most real diodes are very heavily doped on one side of the junction. In computing the built-in voltage of $p$-$n$ and $n$-$p$ step junctions, it is common practice to assume that the Fermi level on the heavily doped side is positioned at the band edge; i.e., $E_f = E_y$ in a $p$ material and $E_f = E_c$ in an $n$ material. Making the cited assumption, compute and plot $V_{bi}$ as a function of the doping ($N_A$ or $N_D$) on the lightly doped side of Si $p$-$n$ and $n$-$p$ step junctions maintained at 300 K. The plot is to cover the range $10^{14}/cm^3 < N_A$ or $N_D > 10^{17}/cm^3$.

THEORY:

Specifically considering a $p$-$n$ junction, we can write

$$ (E_i - E_f)_{p\text{-side assumed}} = E_i - E_f = E_G/2 $$

$$ (E-f - E_j)_{n\text{-side}} = kT \ln(N_D/n_j) $$

$$ V_{bi} = \frac{1}{q} [(E_i - E_f)_{p} + (E_f - E_i)_{n}] $$

$$ V_{bi} = \frac{E_G}{2} + \frac{kT}{q} \ln \left( \frac{N_D}{n_i} \right) \text{ in volts.} $$

For $n$-$p$ junctions, $N_A$ simply replaces $N_D$, yielding a computationally equivalent relationship.

MATLAB CODE:

```matlab
%Vbi Computation (p+/n and n+/p junctions)
%Constants
EG=1.12;
kT=0.0259;
ni=1.0e10;
%Computation
ND=logspace(14,17);
Vbi = EG/2 + kT*log(ND/ni);
```
%Plotting
close
semilogx(ND, Vbi); grid
axis([1.0e14 1.0e17 0.75 1])
xlabel('NA or ND (cm-3)');
ylabel('Vbi (volts)');
text(le16,0.8,'Si,300K')
text(le16,0.78,'p+/n and n+/p diodes')

Program Output:
LAB # 4

OBJECT: Program to generate an energy band diagram of a pn junction

EXERCISE:

Once a quantitative relationship has been established for the electrostatic potential, it becomes possible to construct a fully dimensioned energy band diagram. The "Diagram Generator" program that follows draws the equilibrium energy band diagram for a nondegenerately doped Si step junction maintained at room temperature. The user is prompted to input the p- and n-side doping concentrations. Run the program trying different $NA$ and $ND$ combinations. It is informative to include at least one combination each where $NA >> ND$, $NA = ND$, and $NA << ND$. The asymmetrical junctions are of particular interest because the resultant "one-sided" diagrams differ from those normally included in textbooks. The user might also consider modifying the program so that it draws the energy band diagram for an arbitrary applied bias.

THEORY:

Built in potential can be calculated as

$$V_{bi} = kT \times ln((NA \times ND)/n_i^2)$$

Where $n_i$=intrinsic carrier concentration

deployment width of n side is determined by the help of given formula;

$$X_n = \sqrt{2 \times KS \times e_0 / q \times NA \times V_{bi} / (ND \times (NA+ND))}$$

Where $KS$=dielectric constant of Si

$e_0$=permittivity of free space

$q$=charge of electron

depletion width of p side can be calculated as:

$$X_p = \sqrt{2 \times KS \times e_0 / q \times Nd \times V_{bi} / (NA \times (ND+NA))}$$
MATLAB CODE

% Equilibrium Energy Band Diagram Generator
%(Si, 300K, nondegenerately doped step junction)

%Constants
T=300; % Temperature in Kelvin
k=8.617e-5; % Boltzmann constant (eV/K)
e0=8.85e-14; % permittivity of free space (F/cm)
q=1.602e-19; % charge on an electron (coul)
KS=11.8; % Dielectric constant of Si
ni=1.0e10; % intrinsic carrier conc. in Silicon at 300K
EG=1.12; % Silicon band gap (eV)

%Control constants
xleft = -3.5e-4; % Leftmost x position
xright = -xleft; % Rightmost x position
NA=input ('Please enter p-side doping , NA = ');
ND=input ('Please enter n-side doping , ND = ');

%Computations
Vbi = k*T*log((NA * ND)/ni^2);
xN=sqrt(2*KS*e0/q*NA*Vbi/(ND*(NA+ND))); % Depletion width n-side
xP=sqrt(2*KS*e0/q*ND*Vbi/(NA*(NA+ND))); % Depletion width p-side
x = linspace(xleft, xright, 200);
Vx1 =(Vbi-q*ND.*(xN-x).^2/(2*KS*e0).*(x<=xN) ).*(x>=0);
Vx2=0.5*q*NA.*(xP+x).^2/(KS*e0).*(x>=-xP & x <0);
Vx=Vx1+Vx2; % V as a function of x
VMAX = 3; % Maximum Plot Voltage
EF=Vx(1)+VMAX/2-k*T*log(NA/ni); % Fermi level

%Plot Diagram
close
plot (x, -Vx+EG/2+VMAX/2);
axis ([xleft xright 0 VMAX]);
axis ('off'); hold on
plot (x, -Vx-EG/2+VMAX/2);
plot (x, -Vx+VMAX/2,'w:');
plot ([xleft xright], [EF EF], 'w');
plot ([0 0], [0.15 VMAX-0.5], 'w--');
text(xleft* 1.08,(- Vx(1)+ EG/2 + VMAX/2-.05),'Ec');
text(xright* 1.02,(- Vx(200)+ EG/2 + VMAX/2-.05),'Ec');
text(xleft* 1.08,(- Vx(1)-EG/2+ VMAX/2-.05),'Ev');
text(xright* 1.02,(- Vx(200)-EG/2+ VMAX/2-.05),'Ev');
text(xleft* 1.08,(- Vx(1)+ VMAX/2-.05),'Ei');
text(xright* 1.02, EF-.05,'EF');
set(gca, 'DefaultTextUnits' , 'normalized ')
text(.18, 0,'p-side');
text(.47, 0, 'x=0');
text(.75, 0,'n-side');
set(gca,'DefaultTextUnits','data')
hold off

**PROGRAM OUTPUT:**

Please enter p-side doping, NA = 10E14
Please enter n-side doping, ND = 10E17
OBJECT:
Program to construct a plot of a square law relationship (Idsat/Ido versus Vg/Vp) of FET

EXERCISE:
Construct a matlab program to plot square law relationship (Idsat/Ido vs Vg/Vp) of FET

THEORY:
In phenomenological theory

\[
\frac{\text{Idsat}}{\text{Ido}} = \frac{\text{Vg/Vp}-1-2/3(\text{Vbi/Vp})^3/2}{1-2/3(\text{Vbi/Vp})^3/2}
\]

If

\[
z = \frac{\text{Vbi}}{\text{Vp}} \quad \text{x = Vg/Vp}
\]

\[
\frac{\text{Idsat}}{\text{Ido}} = x-1-2/3(z-1)[1-((z-x)/(z-1))^3/2]
\]

According to the square law relationship;

\[
\frac{\text{Idsat}}{\text{Ido}} = (1-\text{Vg/Vp})^2
\]

MATLAB CODE:

```matlab
%computational parameters
z = -0.4;   %z=Vbi/Vp
x = linspace(0,1);   %x=Vg/Vp
num = x-1-2/3(z-1)[1-((z-x)/(z-1))^3/2]
-1-2/3(z-1)[1-((z)/(z-1))^3/2]

%square law theory
yS = (1-x).^2;

% plotting result
plot(x,yP,x,yS,'--');grid
xlabel('Vg/Vp');
ylabel('Idsat/Ido');
text(0.38,0.4,'square-law')
text(0.8,0.83,'Vbi/Vp=-0.4')
```
Program Output:
LAB#6

OBJECT:

Construct a plot of the depletion width (w) versus the impurity concentration (NA or ND).

EXERCISE:

Construct a MATLAB program to plot depletion width (w) versus the impurity concentration (NA or ND) on the lightly doped side of Si p+ -n and n+ -p step junctions maintained at 300K. Include curves for V_a=0.5v,0v, and -10v covering the range 10exp14/cm^3<NA or ND<10exp17/cm^3.

THEORY:

The vbi associated with the p+ -n and n+ -p step junction is computed using the relationship

\[ V_{bi} = \frac{E_G}{2} + kT/q \ln(\frac{ND}{ni}) \]

If NA=ND

\[ \frac{(NA+ND)}{NA*ND} = \frac{1}{NB} \]

Where NB is the doping (NA or ND) on the lightly doped side of the junction.

MATLAB CODR:

```matlab
% this program calculates and plots the depletion width vs impurity constants and parameters
T=300; %temp in kelvin
k=8.617e-5; %boltzman constant(ev/k)
e0=8.85e-14; %permitivity of free space(F/cm)
q=1.602e-19; %charge on an electron(coul)
ks=11.8; %dielectric constant of Si at 300K
ni=1e10; %intrinsic carrier conc. in Si at 300K
eg=1.12; %band gap of Si(ev)
%choose variable values
NB=logspace(14,17); %doping ranges from 1e14 to 1e17
VA=[0.5 0 -10]; %VA values set
%depletion width calculation
Vbi=eg/2+k*T.*log(NB./ni);
w(1,:)=1.0e4*sqrt(2*ks*e0/q.*(Vbi-VA(1))./NB);
w(2,:)=1.0e4*sqrt(2*ks*e0/q.*(Vbi-VA(2))./NB);
```
w(3,:) = 1.0e4 * sqrt(2 * ks * e0 / q * (Vbi - VA(3)) / NB);

% plot
close
loglog(NB, w, '-'); grid
axis([1.0e14 1.0e17 1.0e-1 1.0e1])
xlabel('NA or ND')
ylabel('width (micrometers)')
set(gca, 'defaultTextUnits', 'normalized')
text(0.38, 0.26, 'VA = 0.5v')
text(0.38, 0.76, 'VA = -10v')
text(0.77, 0.82, 'Si, 300K')
text(0.77, 0.79, 'p+/n and n+/p')
set(gca, 'DefaultTextUnits', 'data')

**PROGRAM OUTPUT:**