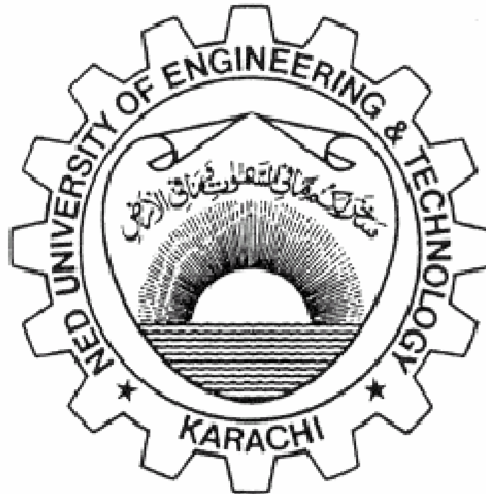
# LABORATORY WORK BOOK
## For The Course
## EL-433 SOLID STATE DEVICES

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# EL-433 SOLID STATE DEVICES

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# 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

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## LAB # 1

**OBJECT**: Program to compute Number of atoms/$cm^3$ in cubic crystals of silicon atom

### EXERCISE:

Construct a MATLAB program that computes the number of atoms/$cm^3$ 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 A (1A=10 exp -8)since there are eight Si atoms per unit cell and the volume of the unit cell is a^3 it follows that there are 8/a^3 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 <= $\Delta E$ <= 0.2eV. All f(E)versus ΔE 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,

$$f(E) = 1/( 1+\exp (E-Ef)/kT )$$

where

Ef=Fermi energy of Fermi level

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

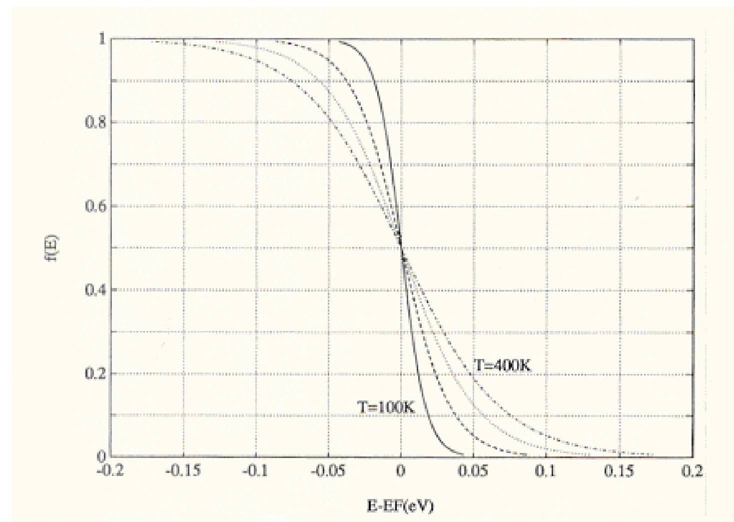
T=temperature

**MATLAB CODE:**

```
%Fermi Function Calculation, f(ΔE, T)
% Constant
k=8.617e-5;
%Computation proper
forii=l :4;
   T= l00*ii;
   kT=k*T;
   dE(ii,1)=-5*kT;
  forij=1:101
        f(ii,jj)= 1/(1 +exp(dE(ii,jj)/kT));
        dE(ii,jj+ 1)=dE(ii,jj)+0.l *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., *Ef* = Ey in a *p* + material and *Ef* = Ec in an *n* + material. Making the cited assumption, compute and plot *Vbi* as a function of the doping *(N* A or *No)* 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 $10^{14}/cm3 < N$ A or $ND > 10^{17}/cm3$.

**THEORY:**

Specifically considering a *p + -n* junction, we can write

$$(Ei - \mathrm{Ef})_{\text{p-side}} \text{ assumed} = Ei - \mathrm{Ef} = E_G/2$$

$$(Ef - \mathrm{Ej})_{\text{n-sjde}} = kT\, In(N_D/nj)$$

$$Vbi = 1/q[(Ei-Ef)p+(Ef-Ei)n]$$

$$V_{bi} = E_G/2 + KT/q \ln (N_D/n_i) \text{ in volts.}$$

For *n +-p* junctions, *NA* simply replaces *ND,* yielding a computationally equivalent relationship.

**MATLAB CODE:**

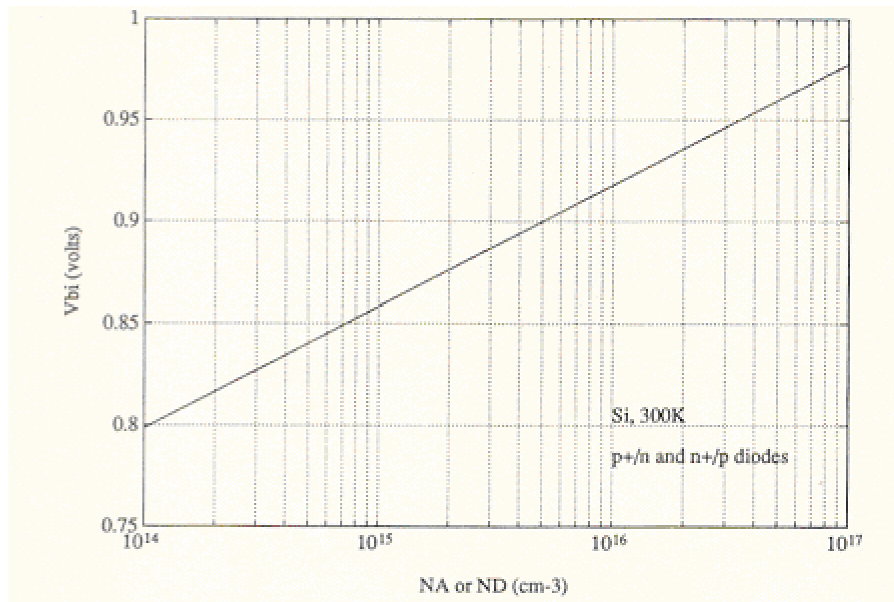
```
%Vbi Computation (p+/n and n+/p junctions)

%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 "Dia- gram 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

Vbi=kT *ln((NA*ND)/ni^2)

Where ni=intrinsic carrier concentration

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

Xn=sqrt(2*KS*e0/q*NA*Vbi/(ND*(NA+ND))) ;

Where KS=dielectric constant of Si

e0=permittivity of free space

q=charge of electron

depliton width of p side can be calculated as:

Xp=sqrt(2*KS*e0/q*Nd*Vbi/(NA*(ND+NA)));

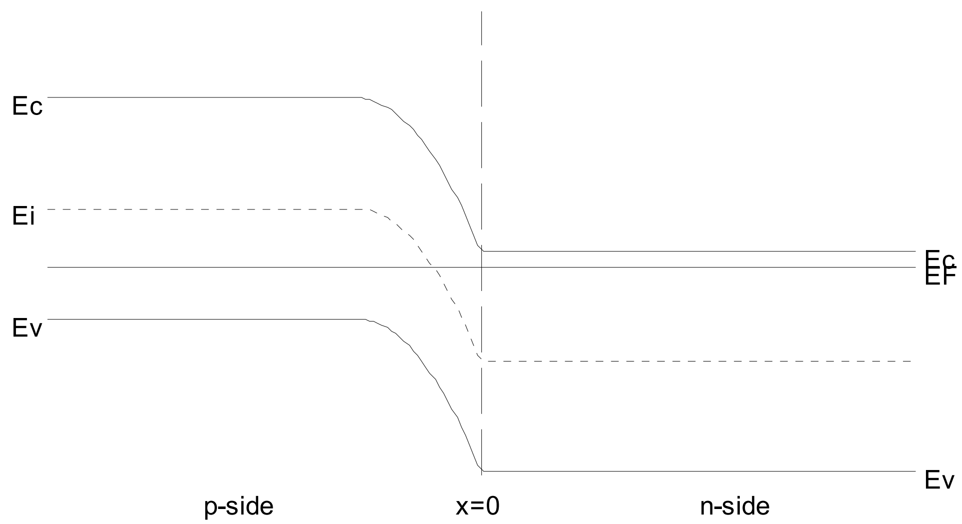
**MATLAB CODE**

```
% 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



# LAB # 5

## OBJECT:

Program to construct a plot of a square law relationship ($I_{dsat}/I_{do}$ versus $V_G/V_P$) of FET

## EXERCISE:

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

## THEORY:

In phenomenological theory

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

If
z = Vbi/vp
x = Vg/Vp

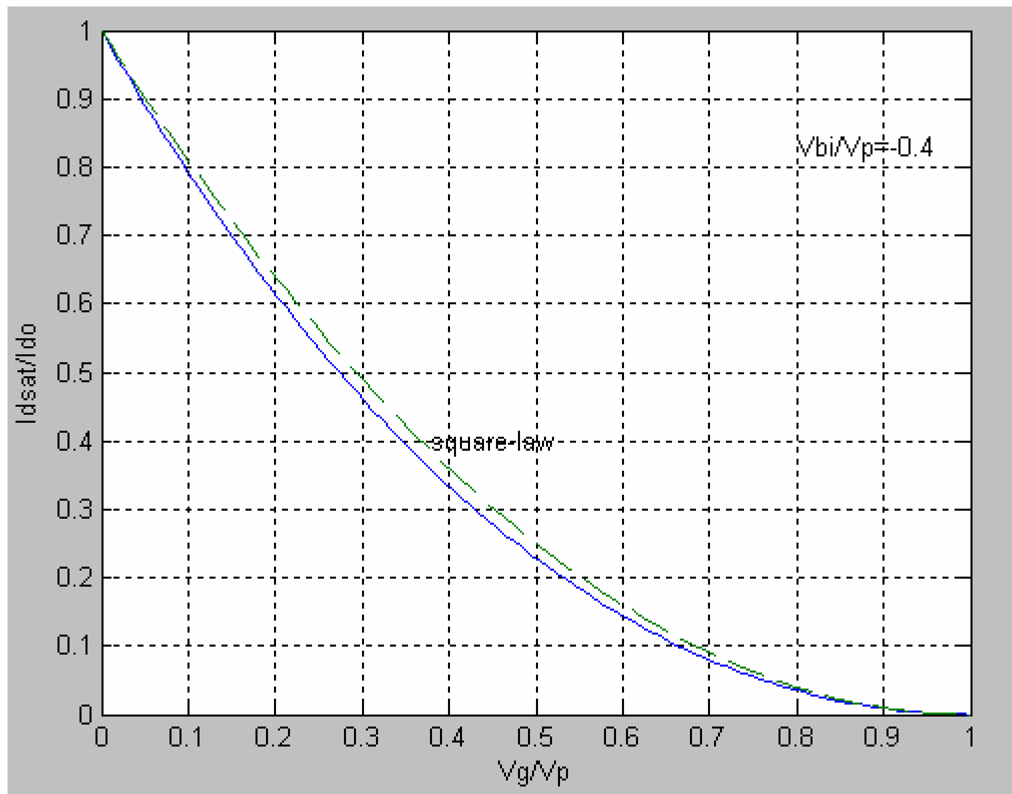
$$Idast/Ido= \frac{x-1-2/3(z-1)[1-((z-x)/(z-1))^{3/2}]}{-1-2/3(z-1)[1-((z)/(z-1))^{3/2}]}$$

According to the square law relationship;
Idsat/Ido = (1-Vg/Vp)^2

## MATLAB CODE:

```
%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)).^(1.5));
den = -1-(2/3)*(z-1)*(1-(z./(z-1)).^(1.5));
yP = num./den;
%square law theory
yS = (1-x).^2;
% plotting result
Close
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 pr ND) on the lightly doped side of Si p+ -n and n+ -p step junctions maintained at 3ook.include curves for Va=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

$$V_{bi}=E_G/2+kT/q*\ln(N_D/n_i)$$

If NA=ND

$$(N_A+N_D)/N_A*N_D=1/N_B$$

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

## MATLAB CODR :

```
%this program calculates and plots the depletion width vs impurity
%constants and prameters
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(.38,.26,'VA=0.5v')
text(.38,.76,'VA=-10v')
text(.77,.82,'Si,300K')
text(.77,.79,'p+/nandn+/p')
set(gca,'DefaultTextUnits','data')
```

**PROGRAM OUTPUT:**