EE566 Solid State Devices

Spring 2005
Dept of Electrical Engineering
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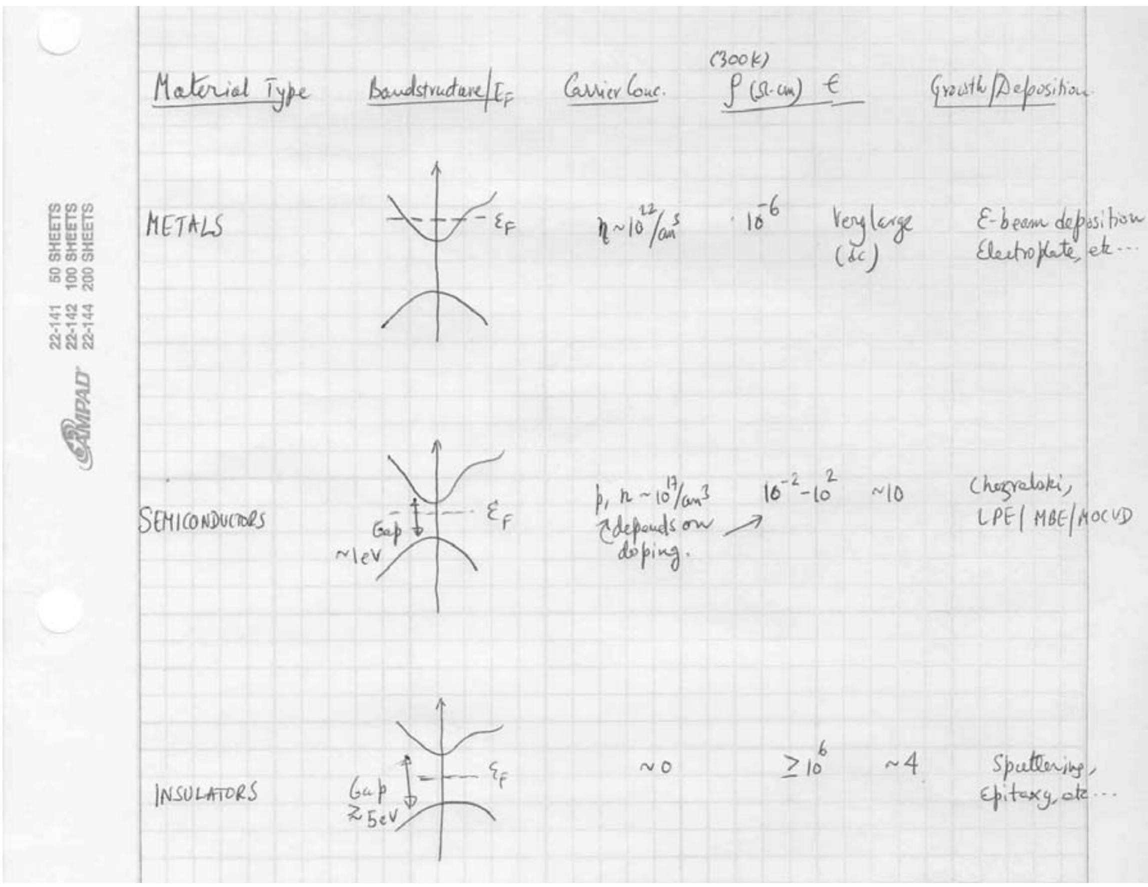
Assignment I - SOLUTIONS

Problem I -



Material Type	Bandstructure/E_F	Carrier Conc.	ρ (Ω-cm) (300K)	ϵ	Growth/Deposition
METALS	E_F	$n \sim 10^{22}/cm^3$	10^{-6}	Very large (dc)	E-beam deposition, Electroplate, etc...
SEMICONDUCTORS	Gap ~1eV, E_F	$p, n \sim 10^{17}/cm^3$ depends on doping	$10^{-2} - 10^{2}$	~10	Czochralski, LPE/MBE/MOCVD
INSULATORS	Gap $\gtrsim$ 5eV, E_F	~0	$\geq 10^{6}$	~4	Sputtering, Epitaxy, etc...

Problem 2 -

EE 566 – Solid State Devices
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Assignment 1 – Solutions

In[1]:=
```
<< Graphics`
```

In[2]:=
```
q = 1.6*10^-19          (* Electron charge, Coulomb *)
hbar = 6.63/(2π)*10^-34 (* Reduced Planck's constant, J.s *)
kb = 1.38*10^-23        (* Boltzmann constant, J/K *)
m0 = 9.1*10^-31         (* Electron rest mass, Kg *)
meGaN = 0.2*m0          (* Electron effective mass, CB *)
mhGaN = 1.4*m0          (* Hole effective mass, VB *)
```

$$Nc[T\_] = 2*\left(\frac{meGaN*kb*T}{2*\pi*hbar^2}\right)^{\frac{3}{2}}*10^{-6}$$ (* CB edge Effective DOS, cm^{-3} *)

$$Nv[T\_] = 2*\left(\frac{mhGaN*kb*T}{2*\pi*hbar^2}\right)^{\frac{3}{2}}*10^{-6}$$ (* VB edge Effective DOS, cm^{-3} *)

$$F[\eta\_] = Abs\left[\frac{2}{\sqrt{\pi}}\int_0^{\infty}\frac{\sqrt{x}}{1+Exp[x-\eta]}\,dx\right]$$

(* Fermi-Dirac Integral of order j=1/2 *)

In[11]:=
```
(* In energy scale, Ev is set to zero, and Ec=Ev+Eg=3.4eV. Ef is in eV too! *)
Eg = 3.4          (* Bandgap of GaN, eV.  Also conduction band edge!*)
Ea = 0.16         (* Acceptor ionization energy, eV *)
Ed = Eg - 0.01    (* Donor activation energy, eV *)
ND = 10^14        (* Donor atom volume density, cm^-3 *)
NA = 10^18        (* Acceptor atom volume density, cm^-3 *)
```

In[16]:=

$$NDp[Ef\_, T\_] = \frac{ND}{1+2*Exp\left[\frac{q*(Ef-Ed)}{kb*T}\right]}$$ (* Ionized donor density, cm^{-3} *)

$$NAm[Ef\_, T\_] = \frac{NA}{1+4*Exp\left[\frac{q*(Ea-Ef)}{kb*T}\right]}$$ (* Ionized acceptor density, cm^{-3} *)

$$n[Ef\_, T\_] = Nc[T]*F\left[\frac{q*(Ef-Eg)}{kb*T}\right]$$ (* Free electron density in cm^{-3} dependent on Ef *)

$$p[Ef\_, T\_] = Nv[T]*F\left[\frac{q*(0-Ef)}{kb*T}\right]$$ (* Free hole density in cm^{-3} dependent on Ef *)

```
(*----------SET Directory TO Export Data---------------*)
SetDirectory[
 "C:\Documents and Settings\Debdeep Jena\My Documents\Transfer\PostPhD\Universities\
   NotreDame\Teaching\CourseMaterial?5_Spring_EE_566_SSD\Assignments\Mathematica"]
FermiLevelPlot =
 Table[{Ef, NDp[Ef, 300], NAm[Ef, 300], n[Ef, 300], p[Ef, 300], NDp[Ef, 300] + p[Ef, 300],
   NAm[Ef, 300] + n[Ef, 300]}, {Ef, -0.2, 3.6, 0.05}]
Export["FermiLevelPlot.txt", FermiLevelPlot, "Table"]
```

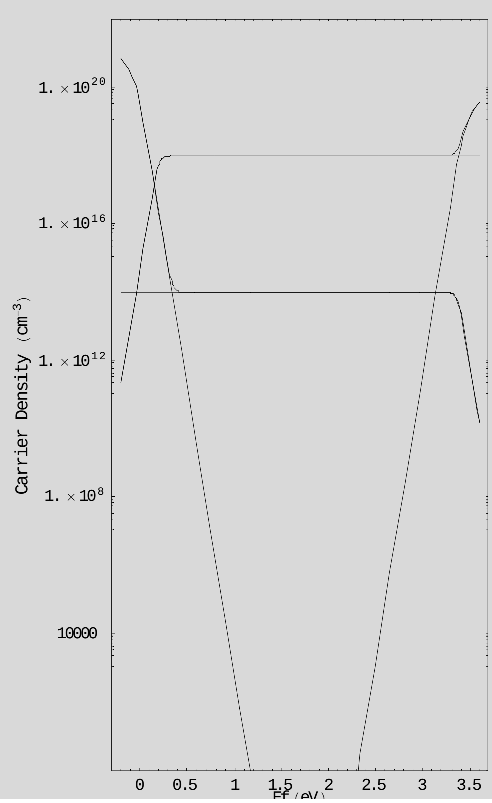
```
(* Numerical Solution of the charge-
  neutrality equation gives us the Fermi Level in eV.  Note that you can do this
   for any general temperature and doping densities. *)
FindRoot[NDp[Ef, 300] + p[Ef, 300] - (NAm[Ef, 300] + n[Ef, 300]) == 0, {Ef, 0}]
```

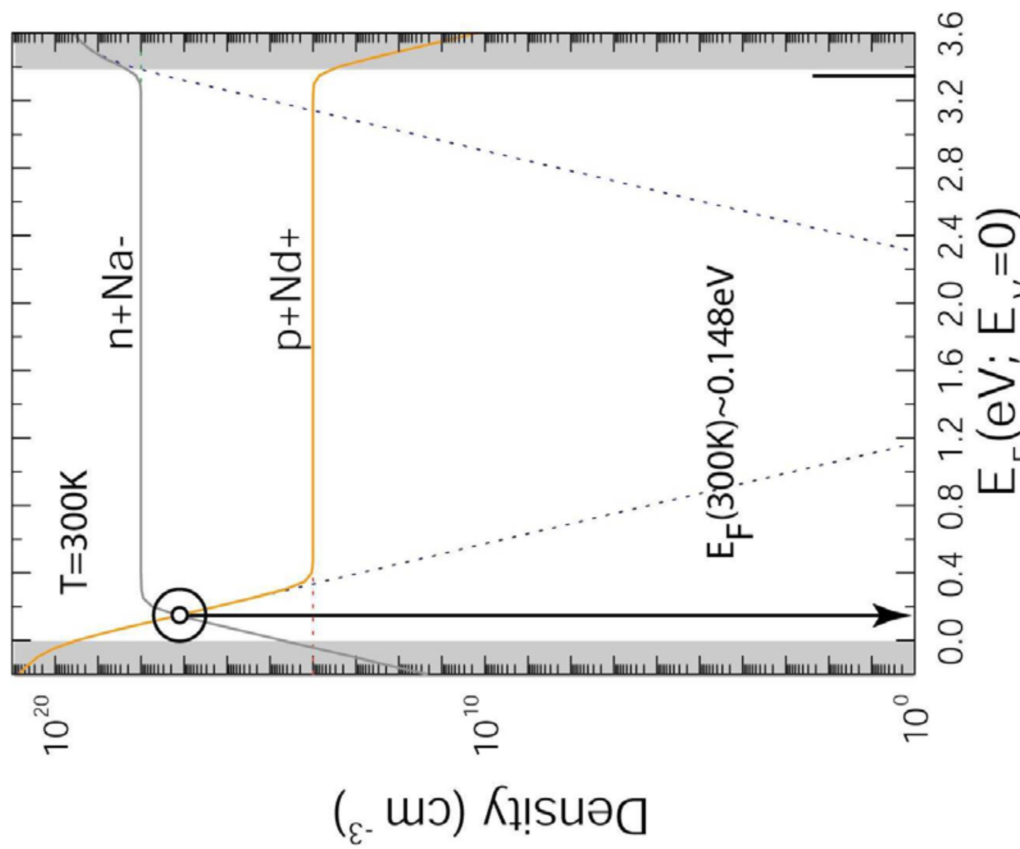
{Ef → 0.147989}

```
p[0.147989, 300]
(* This is the Hole concentration, the semiconductor is obviously p-type *)
```

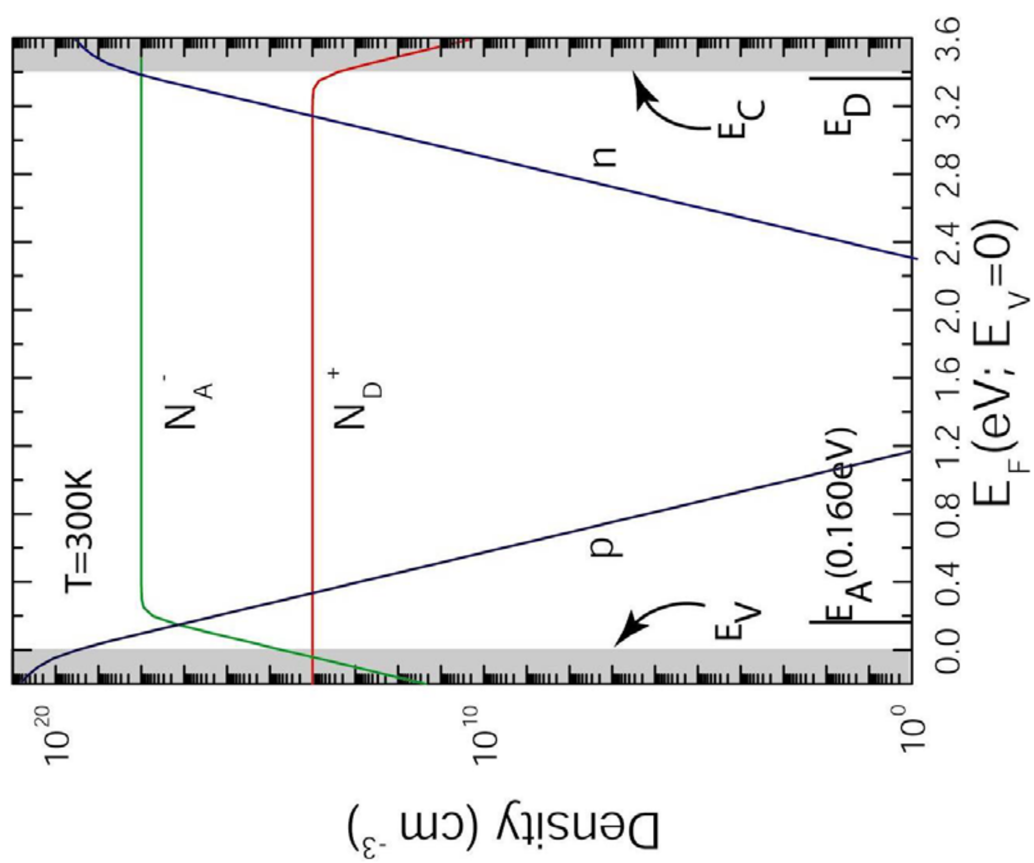
Out[20]= 1.35713×10^{17}

```
(*----You can do a Graphical Solution also - See the attached figures,
 which are basically the plot below labeled and suitably commented upon----*)
LogPlot[{NDp[Ef, 300], NAm[Ef, 300], n[Ef, 300], p[Ef, 300], NDp[Ef, 300] + p[Ef, 300],
  NAm[Ef, 300] + n[Ef, 300]}, {Ef, -0.2, 3.6}, PlotRange → {10^0, 10^22}, Frame → True,
 AspectRatio → 2, FrameLabel → {"Ef(eV)", "Carrier Density (cm^-3)"}]
```





T=300K
n+Na-
p+Nd+
E_F(300K)~0.148eV
Density (cm^-3)
10^20
10^10
10^0
0.0 0.4 0.8 1.2 1.6 2.0 2.4 2.8 3.2 3.6
E_F(eV; E_V=0)



T=300K
N_A^-
N_D^+
p
n
E_V
E_C
E_A(0.160eV)
E_D
Density (cm^-3)
10^20
10^10
10^0
0.0 0.4 0.8 1.2 1.6 2.0 2.4 2.8 3.2 3.6
E_F(eV; E_V=0)

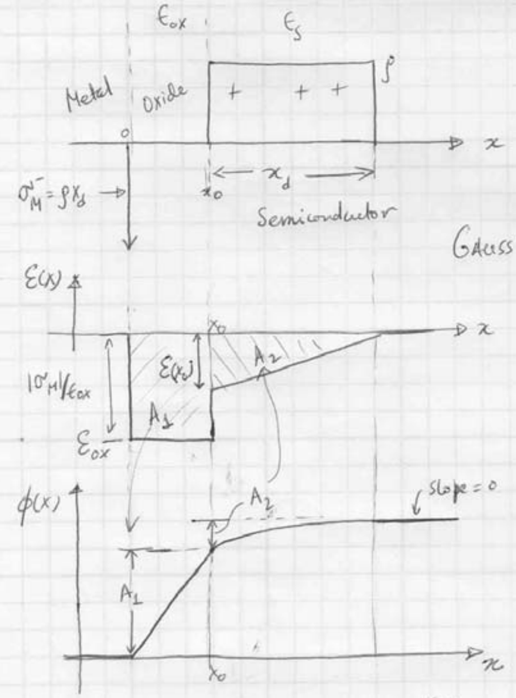
<u>Problem 3</u> -

The *majority* carriers will flow from the hot probe to the cold probe inside the semiconductor. Thus, from the direction of the current flow, the carrier-type can be determined. This is the so-called "hot-probe" technique of finding whether a semiconductor is n- or p-type.

The current may be modeled as diffusive current, but it is not entirely correct. Please see the following for more information -
http://ece-www.colorado.edu/~bart/book/hotprobe.htm

Problem 4 -

A1.4 Just apply Gauss' Law - easy problem!



Sheet charge on metal

$\sigma_M^- = \rho X_d$, negative (by charge neutrality).

Gauss' LAW ⇒ ∴ $|\mathcal{E}_{ox}| = \frac{\sigma_M^-}{\epsilon_{ox}} = \frac{\rho X_d}{\epsilon_{ox}}$

@ $x = x_0$,

$\mathcal{E}_{ox} \cdot \epsilon_{ox} = \mathcal{E}(x_0) \cdot \epsilon_s$

⇒ $|\mathcal{E}(x_0)| = \frac{\epsilon_{ox}}{\epsilon_s} \mathcal{E}_{ox}$

$|\mathcal{E}(x_0)| = \frac{\rho X_d}{\epsilon_s}$.

∴ $\mathcal{E}(x) = |\mathcal{E}(x_0)|\left[\frac{x - x_0}{x_d} - 1\right]$

$|\mathcal{E}(x)| = |\mathcal{E}(x_0)|\left[\frac{x - x_0 - x_d}{x_d}\right]$ for $x_0 \le x \le x_0 + x_d$.

(a)

∴ $\mathcal{E}(x) = 0$ for $x \le 0$

$= -\frac{\rho X_d}{\epsilon_{ox}}$ for $0 \le x \le x_0$

$= -\frac{\rho x_d}{\epsilon_s}\left(\frac{x - x_0 - x_d}{x_d}\right)$ for $x_0 \le x \le x_0 + x_d$

(b) $\phi(x) = -\int_{-\infty}^{x} dx\, \mathcal{E}(x)$

$= 0$ for $x \le 0$

$= +\frac{\rho x_d x}{\epsilon_{ox}}$ for $0 \le x \le x_0$

$= \frac{\rho x_d x_0}{\epsilon_{ox}} + \frac{\rho x_d}{\epsilon_s}\left\{\frac{x^2 - x_0^2}{2x_d} - \left(\frac{x_0 + x_d}{x_d}\right)(x - x_0)\right\}$ for $x_0 < x \le x_0 + x_d$

$= \frac{\rho x_d x_0}{\epsilon_{ox}} + \frac{\rho x_d^2}{2\epsilon_s}$ for $x \ge x_0 + x_d$.

(c) $\phi(0) - \phi(x_0) = -\frac{\rho x_d x_0}{\epsilon_{ox}}$ = Area A_1

(d) $\phi(x_0) - \phi(x_0 + x_d) = -\frac{\rho x_d^2}{2\epsilon_s}$ = Area A_2

(e) Superposition → Will yield same results!