EE 566 – Solid State Devices
Spring 2006 – Debdeep Jena
Assignment 1 – Solutions

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<< Graphics`
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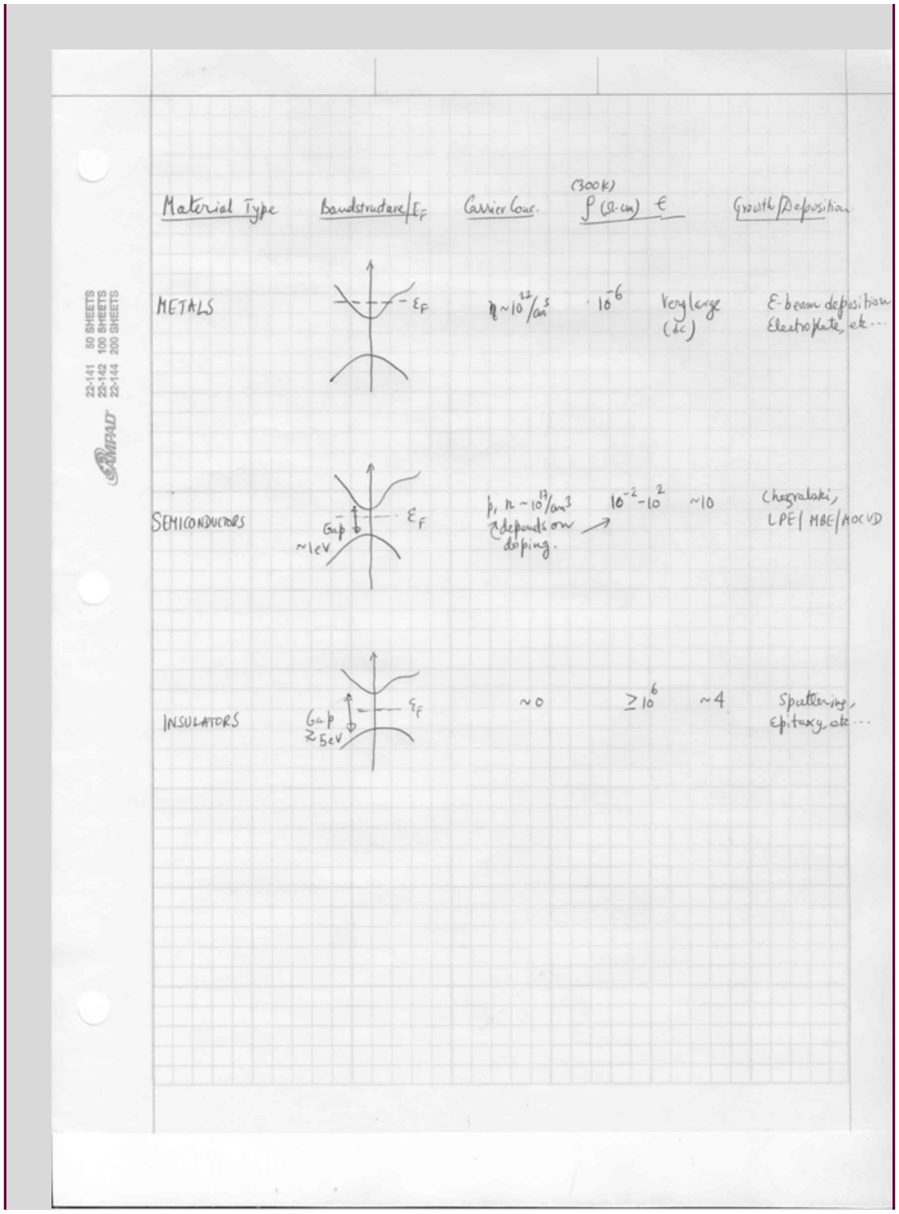

Material Type	Bandstructure/E_F	Carrier Conc.	ρ (Ω-cm) (300K)	ϵ	Growth/Deposition
METALS	ε_F	$n \sim 10^{22}/cm^3$	10^{-6}	Very large (dc)	E-beam deposition, Electroplate, etc...
SEMICONDUCTORS	ε_F; Gap $\sim 1eV$	$p, n \sim 10^{17}/cm^3$ (depends on doping.)	$10^{-2} - 10^{2}$	~ 10	Czochralski, LPE/MBE/MOCVD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

PROBLEM 2

$$q = 1.6 * 10^{-19} \quad \text{(* Electron charge, Coulomb *)}$$

$$hbar = \frac{6.63}{2\pi} * 10^{-34} \quad \text{(* Reduced Planck's constant, J.s *)}$$

$$kb = 1.38 * 10^{-23} \quad \text{(* Boltzmann constant, J/K *)}$$

$$m0 = 9.1 * 10^{-31} \quad \text{(* Electron rest mass, Kg *)}$$

$$meGaN = 0.2 * m0 \quad \text{(* Electron effective mass, CB *)}$$

$$mhGaN = 1.4 * m0 \quad \text{(* Hole effective mass, VB *)}$$

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

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

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

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

(* In energy scale, Ev is set to zero,
and Ec=Ev+Eg=3.4 eV. Ef is in eV too! *)

$$Eg = 3.4 \quad \text{(* Bandgap of GaN, eV. Also conduction band edge!*)}$$

$$Ea = 0.16 \quad \text{(* Acceptor ionization energy, eV *)}$$

$$Ed = Eg - 0.01 \quad \text{(* Donor activation energy, eV *)}$$

$$ND = 10^{16} \quad \text{(* Donor atom volume density, cm}^{-3}\text{ *)}$$

$$NA = 10^{19} \quad \text{(* Acceptor atom volume density, cm}^{-3}\text{ *)}$$

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

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

(* 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 *)

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(*----------SET Directory TO Export Data---------------*)
SetDirectory["C:\Documents and Settings\Debdeep Jena\My
   Documents\Transfer\PostPhD\Universities\NotreDame\Teaching\
   CourseMaterial\06_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"]
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```
(* 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}]
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{Ef → 0.117157}
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root[T_] :=
 FindRoot[NDp[Ef, T] + p[Ef, T] - (NAm[Ef, T] + n[Ef, T]) == 0, {Ef, 0}]
r[T_] := Ef /. root[T]
```

```
p[0.117157, 300]
(* This is the Hole concentration,
 the semiconductor is obviously p-type *)
```

4.45615×10^{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)"}]
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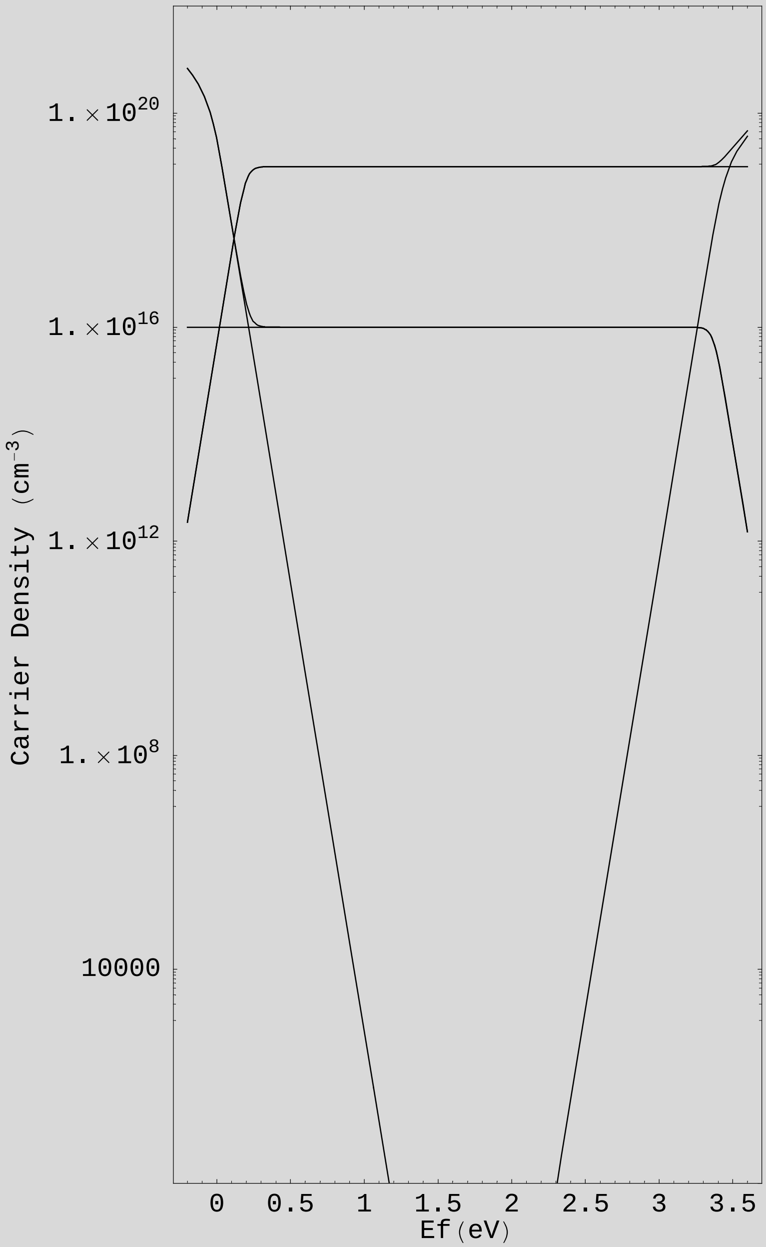
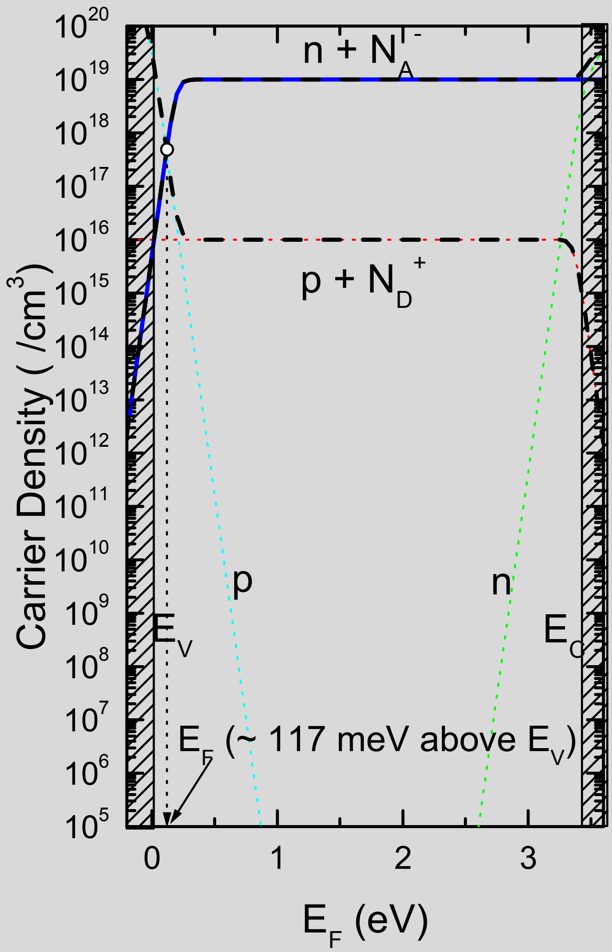

1. × 10^20
1. × 10^16
1. × 10^12
1. × 10^8
10000
Carrier Density (cm^-3)
0 0.5 1 1.5 2 2.5 3 3.5
Ef (eV)

- Graphics -



PROBLEM 3

Simple problem - use Vegards ' s law to interpolate the bandgap for the alloy. Investigate what does one mean by the negative bandgap ??

PROBLEM 4

Apply Gauss ' s law (or Poisson equation) to the junction, and calculate the charge – field – band diagram. The charge profile should be neutral, and thereafter the problem is simple. Note that the electric field profile determines the profile of the potential V (x). Since $V(x) = -\int_{-\infty}^{x} F(x)\, dx$, the potential changes fastest where the electric field is the highest in magnitude. Here, the field reaches it ' s maximum value at the metal – semiconductor interface, therefore the slope of V (x) should be the highest there. The slope of V (x) should decrease continuously from $x = 0$ to $x = x_{d2}$. I use F (x) for electric field in the following

$F(x) = 0, \; x < 0$

$$F(x = 0) = -|F_{max}| = -\frac{[\rho_1 * x_{d1} + 2 * \rho_1 * (x_{d2} - x_{d1})]}{\epsilon_S} = -\frac{\rho_1 (2 x_{d2} - x_{d1})}{\epsilon_S},$$

$$F(x) = F(x = 0) + \frac{1}{\epsilon_S} \int_{x=0}^{x} (\rho_1)\, dx =$$

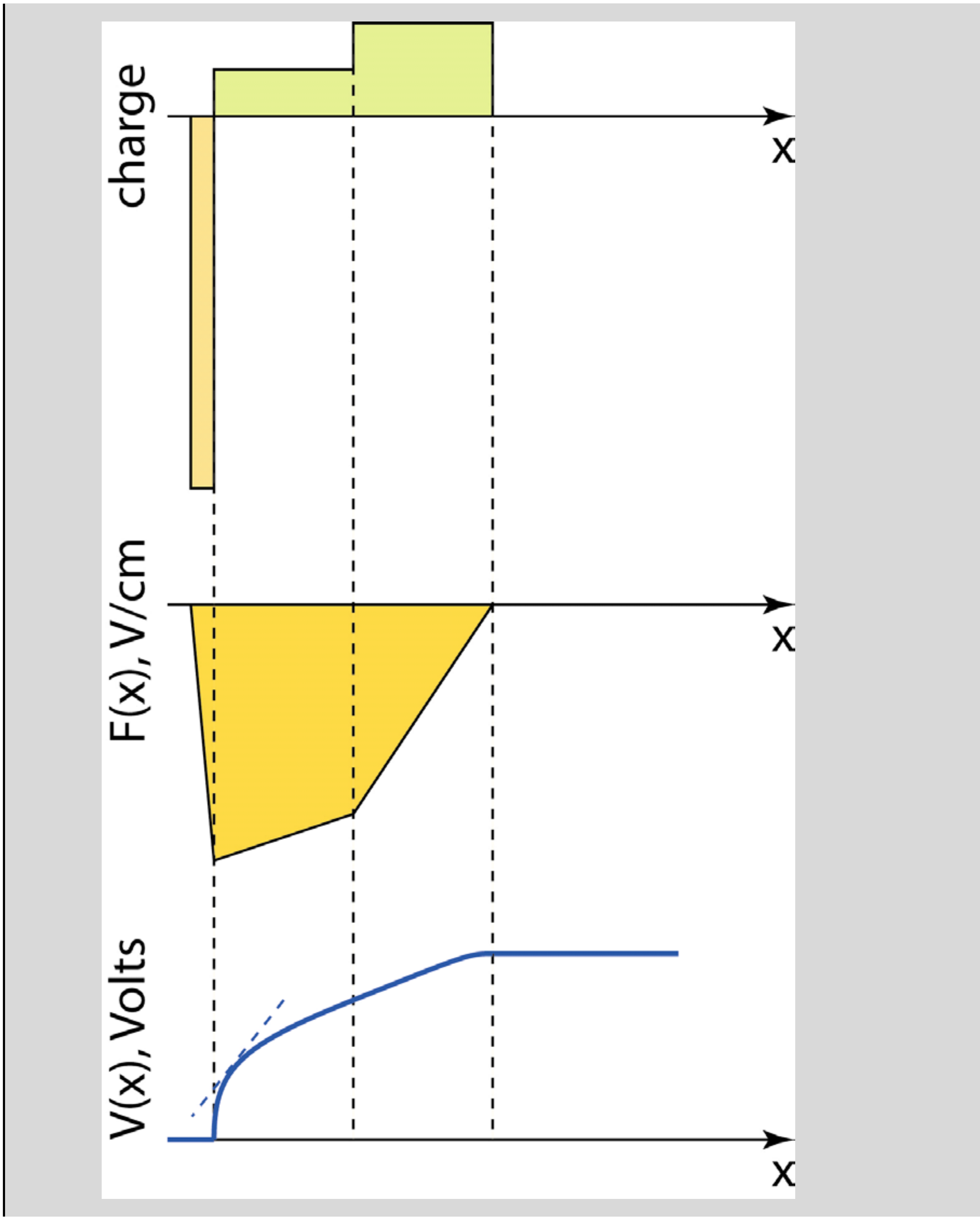
$$-\frac{\rho_1 (2 x_{d2} - x_{d1})}{\epsilon_S} + \frac{(\rho_1 * x)}{\epsilon_S} = -\frac{\rho_1 [2 x_{d2} - (x_{d1} + x)]}{\epsilon_S} \quad \text{for } 0 < x < x_{d1},$$

$$F(x) = F(x_{d1}) + \frac{1}{\epsilon_S} \int_{x=x_{d1}}^{x} (2 \rho_1)\, dx =$$

$$-\frac{2 \rho_1 * (x_{d2} - x_{d1})}{\epsilon_S} + \frac{2 \rho_1 (x - x_{d1})}{\epsilon_S} = -\frac{2 \rho_1 (x_{d2} - x)}{\epsilon_S} \quad \text{for } x_{d1} < x < x_{d2},$$

$F(x) = 0, \; x > x_{d2}$

Similarly, the potential can be evaluated as $V(x) = -\int_{-\infty}^{x} F(x)\, dx$ for each x.


charge
x
F(x), V/cm
x
V(x), Volts
x