EE566 Solid State Devices

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Dept of Electrical Engineering
University of Notre Dame
Instructor: Debdeep Jena (djena@nd.edu, x8835)

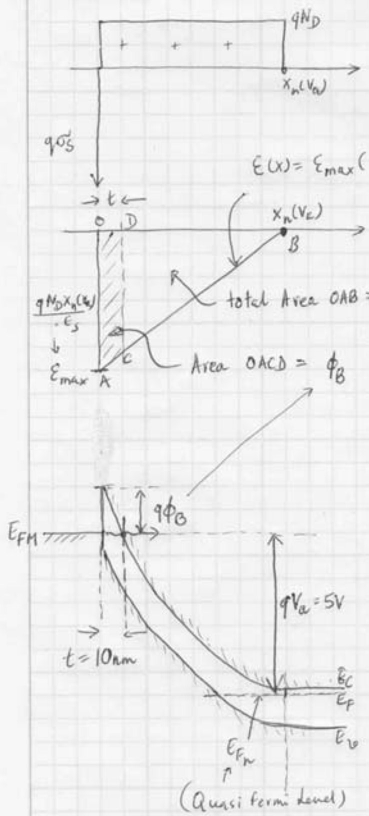
Assignment 3
SOLUTIONS

Assignment 3 · EE 566 SOLID STATE DEVICES, SPRING 2005 02/16/05

SOLUTIONS

PROBLEM 1 (3.7, MKC).

See the charge-field-band diagram.



Electric field: $\mathcal{E}(0) = \mathcal{E}_{max}$

$$\frac{1}{2}\mathcal{E}_{max}\, x_n(V_a) = \phi_i - V_a$$

$$OACD \rightarrow \frac{1}{2}\left[\mathcal{E}_{max} + \mathcal{E}(t)\right] * t = \phi_B$$

$$\mathcal{E}(x) = \mathcal{E}_{max}\left(1 - \frac{x}{x_n(V_a)}\right) \longrightarrow \mathcal{E}(t) = \mathcal{E}_{max}\left(1 - \frac{t}{x_n(V_a)}\right)$$

$$\therefore \mathcal{E}_{max}\left[2 - \frac{t}{x_n(V_a)}\right] = \frac{2\phi_B}{t}$$

total Area $OAB = (\phi_i - V_a) = \frac{1}{2}\mathcal{E}_{max}\, x_n(V_a)$

Area $OACD = \phi_B$

Also, $$x_n(V_a) = \frac{\epsilon_s \mathcal{E}_{max}}{qN_D} = \frac{2(\phi_i - V_a)}{\mathcal{E}_{max}}$$

Therefore, we get

$$\mathcal{E}_{max}\left[2 - \frac{t \cdot \mathcal{E}_{max}}{2(\phi_i - V_a)}\right] = \frac{2\phi_B}{t}$$

$$\mathcal{E}_{max}^2 - \frac{4(\phi_i - V_a)}{t}\mathcal{E}_{max} + \frac{4\phi_B(\phi_i - V_a)}{t^2} = 0$$

$$\therefore \mathcal{E}_{max} = \frac{2(\phi_i - V_a)}{t}\left[1 \pm \sqrt{1 - \frac{\phi_B}{\phi_i - V_a}}\right]$$

→ ONLY REASONABLE SOLN:

$\mathcal{E}_{max} = 6.72 * 10^5$ V/cm

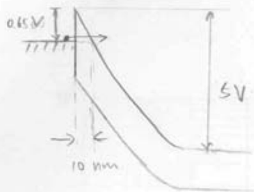
(other is $\mathcal{E}_{max}' = 1.93 * 10^7$ V/cm $\gg \mathcal{E}_{breakdown}$)

$$\Rightarrow \boxed{N_D = \frac{\epsilon_s \mathcal{E}_{max}^2}{2q(\phi_i - V_a)} \sim 3 * 10^{17}/cm^3}$$

b) From fig 1-15 in MKC, for $N_D \sim 3 * 10^{17}/cm^3$, $\boxed{\rho \sim 5 * 10^{-2}\ \Omega \cdot cm}$

c) Shown above.

PROBLEM 2 - Solution by A. Wang -



$$\frac{df}{dV} = -\frac{1}{4\pi\sqrt{LC}}\,\frac{1}{C}\,\frac{dC}{dV} = 0.22\times10^{6}\ \mathrm{Hz/V}$$

$$\therefore\quad N(x_d) = \frac{(C/A)^3}{q\epsilon_s\, d(C/A)/dV}, \qquad \frac{C^3}{A^2 N(x_d) q \epsilon_s} = \frac{dC}{dV}$$

$$\frac{-1}{4\pi\sqrt{LC}}\,\frac{1}{C}\,\frac{C^3}{A^2 N(x_d)\, q\epsilon_s} = -0.22\times10^{6}$$

$$\frac{C^2}{A^2 4\pi\sqrt{LC}\; q\epsilon_s \times 0.22\times10^{6}} = N(x_d)$$

$$C = A\cdot\epsilon_s/x_d$$

$$\therefore\quad \frac{A^2\epsilon_s^2/x_d^2}{A^2 4\pi\sqrt{L\cdot A\epsilon_s/x_d}\; q\epsilon_s \times 0.22\times10^{6}} = N(x_d)$$

$$\frac{(11\times8.854\times10^{-12})^{\frac{1}{2}}/x_d^{2}}{4\times3.14\times\sqrt{2\times10^{-3}\times10^{-7}/x_d}\times1.6\times10^{-19}\times0.22\times10^{6}} = N(x_d)$$

$$1.58\times10^{12}\, x_d^{-\frac{3}{2}} = N(x_d)$$

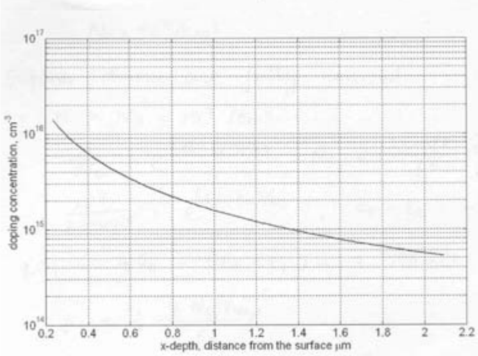
at $V=0$, $\quad C = 41.8\times10^{-12} = A\cdot\frac{\epsilon_s}{x_d}$, $x_d = 2.33\times10^{-7}\,\mathrm{m}$

$= 233\,\mathrm{nm}$

$C = 4.65\times10^{-12} = A\cdot\frac{\epsilon_s}{x_d}$, $x_d = 2.09\times10^{-6}\,\mathrm{m}$

$= 2.09\,\mu\mathrm{m}$

The doping profile is plotted on the next page.



PROBLEM 3 - Solution by Jengxiao Jin -

Problem3

a) We know that the thickness of depletion area can be calculated using equation

$$\frac{q^2 N_D x_d^{\ 2}}{2\varepsilon_s} + kT \ln\left(\frac{N_c}{N_D}\right) = q\phi_B$$

Now, $q\Phi_B$ = 1eV, N_D= 1e17/cm^3, N_C=2.2e19/cm^3, so we can get the depletion distance

x_d = 1.21e-7 m

For such a depletion area, we know that the highest electric field exists at the junction, and its value is

$$E = \frac{qN_d d}{\varepsilon_{GaN}} = \frac{1.6\times10^{-19}\times10^{23}\times1.21\times10^{-7}}{8.9\times8.854\times10^{-12}} = 2.5\times10^{7} V/m$$

The breakdown field for GaN is about 5e6 V/cm, that is 5e8V/m, so the electric field at the surface of the semiconductor is smaller than the breakdown voltage F_{BR}.

b) Now we know that as reverse voltage changes, the capacitance doesn't change, which means the depletion area also doesn't change, so we can know that before reverse bias voltage is added, the whole GaN area has already been depleted, thus we know that

$$t_{cap} < x_{depl} = 1.21\times10^{-7} m$$

If we know the value of the capacitance, then we can get the value of t_{cap} by doing calculation

$$t_{cap} = \frac{C}{\varepsilon_{GaN}}$$

c) To achieve breakdown, we should have an electric field that equals to F_{BR} at the surface of the semiconductor. Under reverse bias V_R, we can calculate the electric field

$$E = \frac{qN_d t_{cap}}{\varepsilon_{GaN}} + \frac{V_R}{t_{cap}}$$

Let E equals breakdown field value F_{BR}=5e6 V/cm when V_R=38.4V, and we can get the value of t_{cap},

$$t_{cap} = 8\times10^{-8} m \ or \ 2.42\times10^{-6} m$$

Since t_{cap}<x_{depl}=1.21e-7m, we can get the value of t_{cap} is 8e-8 m or 80nm.

The Charge-Field_Band diagrams are simple and should be drawn in a complete solution.
Remember "Kroemer's Lemma of Proven Ignorance"...

PROBLEM 4 - Comments by me and a possible solution by L. Chuanxin -

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PROBLEM 4

As you must have realized, the desired specifications are rather difficult to satisfy. Requirement (b) for the Schottky diode to be unaffected by visible light rules out Si, Ge, and almost all Zinc-Blende III-V semiconductors, since their bandgaps lie in or below the visible energies (~2-3eV or 400nm-800nm).

Therefore, one has to opt for a wide-bandgap semiconductor - GaN, $Al_xGa_{1-x}N$, AlN, or ZnO are some possible choices. Diamond is another attractive choice. Typically, wide bandgap semiconductors are difficult to dope p-type.

If one is able to dope GaN p-type, it might be possible to get a surface barrier height of ~2 volts with certain metals. However, in real world, there are certain constraints. (See the attached solutions...)

For an ideal GaN - Metal contact, (No surface pinning), n-GaN - Pt (if $\phi_M = 6.35eV$) can give the required condition, but this is rarely seen in practice...

Another option suggested was to design the Schottky diode such that appreciable 'tunneling' occurs @ 2Volts. However, tunneling in a Schottky occurs mainly to carry reverse-bias current...

There might be other possible ways too...

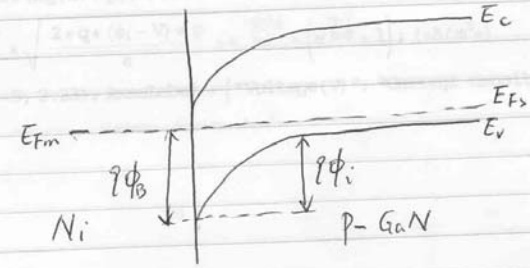
oblem 4. metal : Ni

Semiconductor: P-GaN

Acceptor density: $\sim 10^{20}\ cm^{-3}$ Hole concentration: $\sim 10^{18}\ cm^{-3}$

Acceptor: Mg

$q\phi_m(Ni) = 5.15 eV$ $q\chi(GaN) = 4.1 eV$



$$q\phi_B = q\chi + E_g - q\phi_B = 2.39 eV$$

The acceptors with the doping concentration of around $10^{20}\ cm^{-3}$ can generate holes which have the concentration of approximately $10^{18}\ cm^{-3}$

$$\phi_i = \phi_B - \frac{kT}{q} \ln\left(\frac{N_V}{P}\right) \doteq 2.3 V$$

$\therefore$ a) $V_{turn\text{-}on} \approx \phi_i \sim 2 V$

b) $E_g(GaN) = 3.4 eV >$ energy of visible light

(*Ni/p-GaN*)

$q = 1.6 * 10^{-19}$; (*C*)

$d = 4 * 10^{-4}$; (*m^2/s*)

$nv = 4.6 * 10^{19} * 10^{6}$; (*m^3*)

$k = 1.38 * 10^{-23}$; (*J/K*)

$T = 300$; (*K*)

$p = 10^{18} * 10^{6}$; (*m^3*)

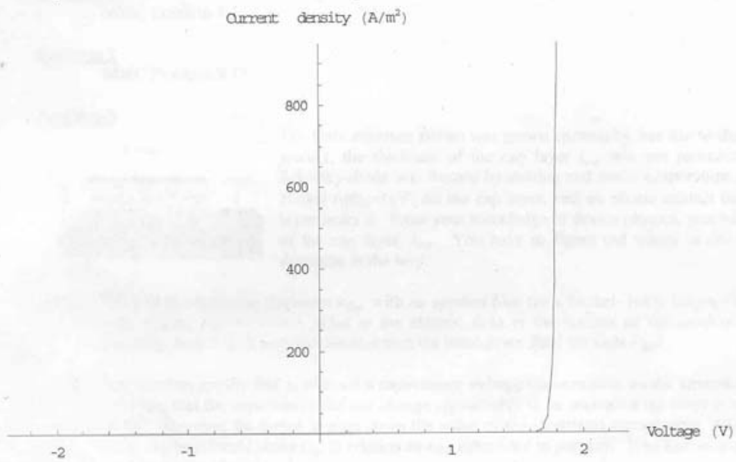
$\epsilon = 9 * 8.85 * 10^{-12}$; (*F/m*)

$\phi_B = 4.1 + 3.44 - 5.15$; (*V*)

$\phi_i = \phi_B - 0.026 * \mathrm{Log}[nv / p]$; (*V*)

$$J = \frac{q^2 * d * nv}{k * T} * \sqrt{\frac{2 * q * (\phi_i - V) * p}{\epsilon}} * e^{\frac{-q * \phi_B}{k * T}} * \left(e^{\frac{q * V}{k * T}} - 1\right);\ (*A/m^2*)$$

Plot[J, {V, -5, 2.23}, AxesLabel → {"Voltage(V)", "Current density(A/m^2)"}]



$\mathcal{E}_{BR} = 5 \times 10^{6}$ V/cm for GaN

$$X_d = \sqrt{\frac{2 \epsilon_s \phi_i}{q \cancel{N_A} p}} = \sqrt{\frac{2 \times 9 \times 8.85 \times 10^{-14} \times 2.3}{1.6 \times 10^{-19} \times 10^{18}}} = 47.9\ nm$$

$$|V_{BR}| = \frac{1}{2} \mathcal{E}_{BR} X_d = \frac{1}{2} \times 5 \times 10^{6} \times 47.9 \times 10^{-7} \approx 12\ V$$

$$\boxed{V_{BR} \approx 12\ V}$$