EE566 Solid State Devices

Spring 2006
Dept of Electrical Engineering
University of Notre Dame
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Assignment 9

SOLUTIONS

Problem 1: Solutions

Sol. by Ze Zhang

HW 9

Problem 1 Solutions

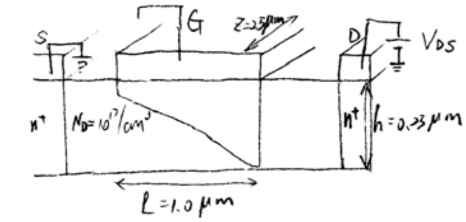


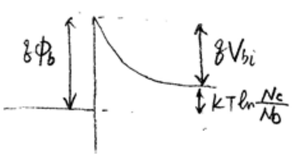
Figure 1. GaAs n-channel MESFET

a) Pinch off voltage:

$$V_p = \frac{qN_D h^2}{2\epsilon_s} = \frac{1.6\times10^{-19}\,coul \times 10^{17}/cm^3 \times (0.23\times10^{-4})^2\,cm^2}{2\times 8.85\times10^{-14}\,F/cm \times 12.9} \approx 4.38V$$

Built in voltage:

$$V_{bi} = \phi_b - \frac{kT}{q}\ln\frac{N_c}{N_D} = 0.8V - 0.026V\ln\frac{4.7\times10^{17}}{10^{17}} \approx 0.76V$$



So threshold voltage:

$$V_{TH} = V_{bi} - V_p = 0.76V - 4.4V = -3.62V$$

b) For $V_{GS} = -1.5V$

$$V_{DS}(sat) = V_p - V_{bi} + V_{GS} = 4.38V - 0.76V - 1.5V = 2.12V$$

For $V_{GS} = -3.0V$

$$V_{DS}(sat) = V_p - V_{bi} + V_{GS} = 4.38V - 0.76V - 3.0V = 0.62V$$

c) For $V_{GS} = -1.5V$, $V_{DS}(sat) = 2.12V$

$$I_D(sat) = \frac{e\mu_n N_d Z h}{L}\left[\frac{V_p}{3} - V_{bi} + V_{GS} + \frac{2(V_{bi}-V_{GS})^{3/2}}{3V_p^{1/2}}\right]$$

$$= \frac{1.6\times10^{-19}\times 6000\,cm^2/V\cdot S \times 10^{17}/cm^3 \times 25\times10^{-4}\times 0.23\times10^{-4}\,cm^2}{1\times10^{-4}\,cm}\left[\frac{4.38V}{3} - 0.76V - 1.5V + \frac{2(0.76V+1.5V)^{\frac{3}{2}}}{3\times\sqrt{4.4V}}\right]$$

$$\approx 16.8\,mA$$

(d) For $V_{GS} = -3.0\,V$, $V_{DS}(sat) = 0.62\,V$

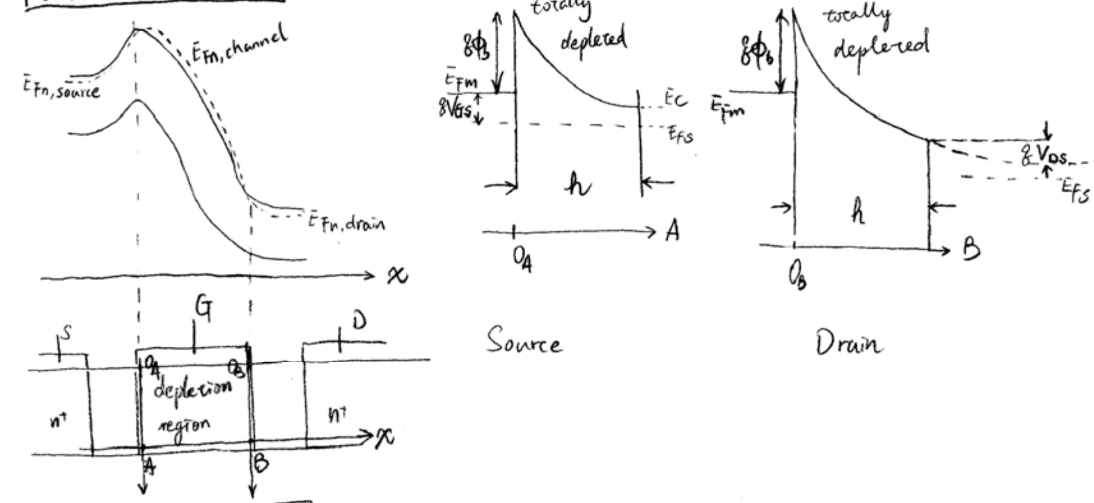
$$I_D(sat) = \frac{e\mu_n N_d Z h}{L}\left[\frac{V_p}{3} - V_{bi} + V_{GS} + \frac{2(V_{bi}-V_{GS})^{3/2}}{3V_p^{1/2}}\right]$$

$$= \frac{1.6\times10^{-19}\,\text{coul}\times 6000\,\text{cm}^2/\text{V}\cdot\text{s}\times10^{17}/\text{cm}^3\times 25\times10^{-4}\times 2.25\times10^{-4}\,\text{cm}^2}{1\times10^{-4}\,\text{cm}}\left[\frac{4.38V}{3} - 0.76V - 3.0V + \frac{2\times(0.76V+3.0V)^{3/2}}{3\sqrt{4.38V}}\right]$$

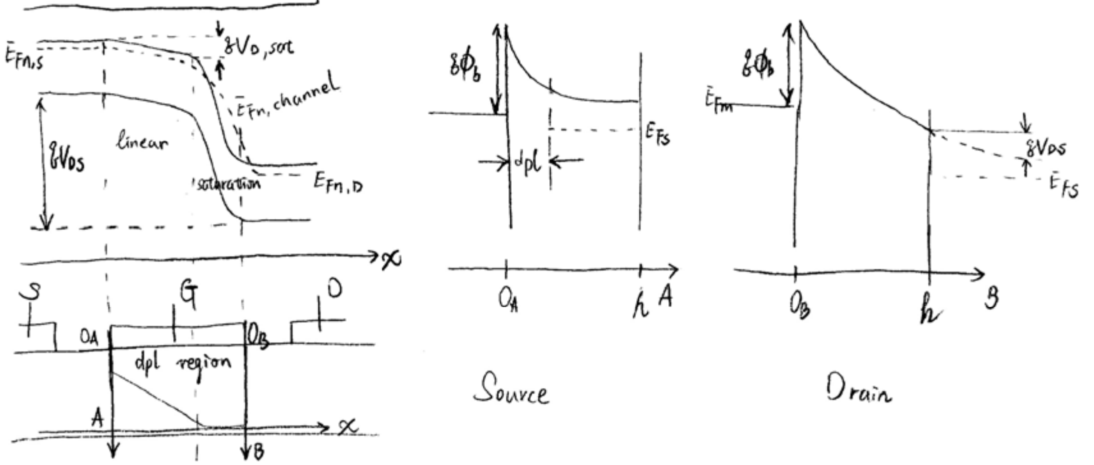
$$\approx 1.35\,mA$$

$\boxed{\text{Sketch}}$

$\boxed{\text{i) } V_{GS} < V_T,\ V_{DS} > V_{D,sat}}$



$\boxed{\text{ii) } V_{GS} > V_T,\ V_{DS} > V_{D,sat}}$

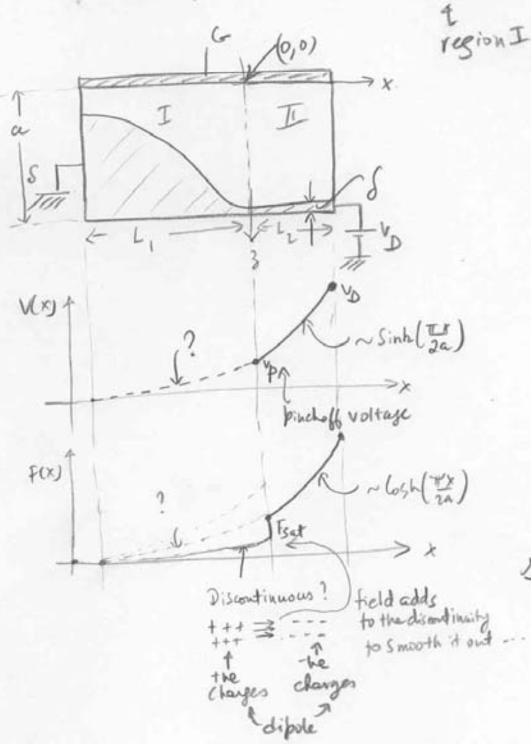


Problem 2: Solutions

MESFET 2-D problem:

The problem was assigned to ensure you read the paper. The main difficulty with the 2-region model is matching the Field $\left(\frac{\partial V}{\partial x}\Big|_{(0,a^-)} = \frac{\partial V}{\partial x}\Big|_{(0,a^+)} \right)$

region I. ↑ Region 2, $= F_{sat}$



A simple-minded solution by calculating $V(x, z=a)$, with $\begin{cases} V(x=-L_1, z=a) = 0 \ \& \\ V(x=0, z=a) = V_p = \frac{qN_d a^2}{2\varepsilon_s} \end{cases}$

fails to match the electric fields. (Believe me, I did this myself too ☺).

⇓

If there is a field discontinuity, it can create a charge-dipole to smoothen it out!

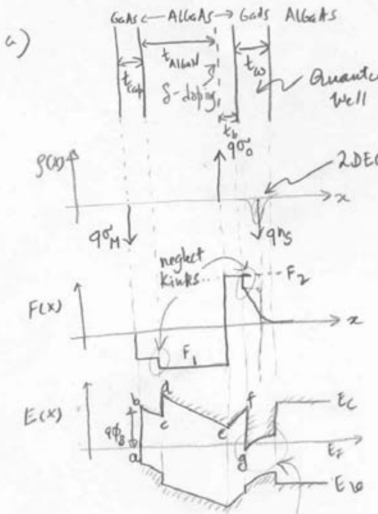
Check this out in pg 129a figs (d) & (f) ...

Problem 3: Solutions

We need $n_s = 10^{12}/cm^2$, what's the reqd. sheet doping?

Assume sheet doping $= q\sigma_0'$ coul/cm^2

a)



Charge conservation: $q\sigma_M' + qn_s = q\sigma_0'$

Go around the loop in the band diagram

$E_F \to a \to b \to c \to d \to e \to f \to g \to E_F$

$+ \phi_B - F_1 * t_{cap} + \Delta E_c - F_1 * t_{AlGaN} + F_2 * t_b - \Delta E_c + (E_0 - E_c) + (E_F - \varepsilon_0) = 0$

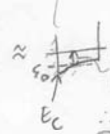
$F_1 = \frac{q\sigma_M}{\epsilon_s}$, $\quad F_1 = \frac{q\sigma_M'}{\epsilon_s}$, $\quad F_2 = \frac{qn_s}{\epsilon_s}$

ⓐ $\boxed{\varepsilon_0 - \varepsilon_c = \text{Ground-state of a q-well.} \approx 25\,meV}$

(assume ∞-well, $t_w = 15nm$) (See pg 33 of NOTES)

Can assume Δwell too...

also, $q\sigma_M' = q(\sigma_0' - n_s)$



2D DOS $= \frac{m^*}{\pi\hbar^2}$

$(\varepsilon_F - \varepsilon_0) * g_{2D}(\varepsilon) \approx n_s$

$\therefore$ ⓑ $\boxed{(\varepsilon_F - \varepsilon_0) \approx \frac{\pi\hbar^2 n_s}{m^*}}$

$\Rightarrow$

$$\phi_B - \frac{q(\sigma_0' - n_s)}{\epsilon_s}(t_{cap} + t_{AlGaN}) + \frac{qn_s}{\epsilon_s} t_b + \underbrace{(\varepsilon_0 - \varepsilon_c)}_{25meV}/q + \underbrace{(\varepsilon_F - \varepsilon_0)}_{\frac{\pi\hbar^2}{m^*} n_s}/q = 0$$

approx...

$$\Rightarrow \boxed{\sigma_0 \approx \frac{\epsilon_s}{q(t_{cap} + t_{AlGaN})}\left[\phi_B + \frac{\varepsilon_0 - \varepsilon_c}{q}\right] + n_s * \left\{1 + \frac{t_B + \pi \frac{\hbar^2 \epsilon_s}{q^2 m^*}}{t_{cap} + t_{AlGaN}}\right\}}$$

Effective Bohr Radius

$$\approx 2.1 * 10^{12} + 1.9 * 10^{12}$$

$\boxed{\sigma_0 \approx 4 * 10^{12}/cm^2}$ ⇐ Note: This is a crude estimate. If you assume a Δ-Quantum well, you'll get $\sigma_0' \approx 3*3 * 10^{12}/cm^2$.

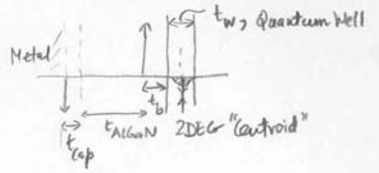
The method is more important here.

Prob 2 : Contd ...

(3)

(b)

$$\left(\frac{g_m^{Sat}}{W}\right)_{max} = C_g v_{Sat} \approx \left(\frac{\epsilon_s}{t_{M\to 2DEG}}\right) * (v_{Sat}) \leftarrow \text{Short-channel transconductance...}$$

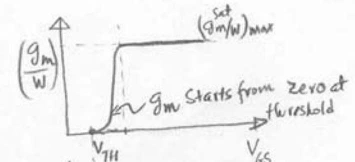


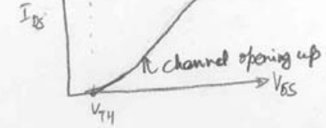
$$t_{M\to 2DEG} = t_{Cap} + t_{AlGaN} + t_b + \underset{\text{approximate}}{t_w/2}$$

$$\left(\frac{g_m^{Sat}}{W}\right)_{max} \approx \frac{13 * 8.85 * 10^{-14} * 10^7}{(5+30+2+7.5)*10^{-7}} \ \frac{S}{cm} = 2.58\ S/cm$$

$$= 258\ S/m$$

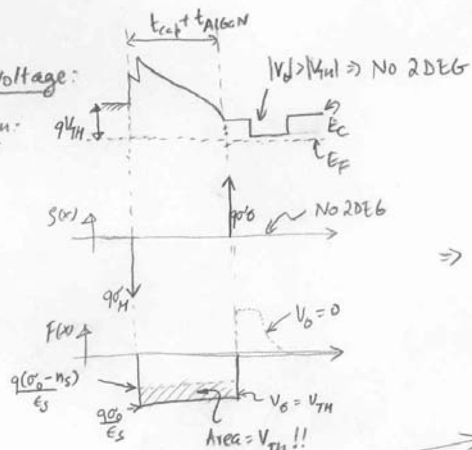
$$\boxed{\left(\frac{g_m^{Sat}}{W}\right)_{max} \approx 258\ mS/mm}$$ Constant at saturation region.





Threshold Voltage:

Approximate solution.



$$\Rightarrow \ |V_{TH}| = \left\{\frac{q\sigma_0}{\epsilon_s} - \frac{q(\sigma_0 - n_s)}{\epsilon_s}\right\} * (t_{cap} + t_{AlGaN})$$

$$= \frac{q n_s}{\epsilon_s} * (t_{cap} + t_{AlGaN})$$

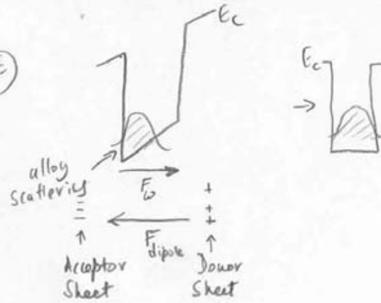
$$= 0.48 \text{ Volts}$$

Note:

$$|V_{TH}| = \frac{q n_s \leftarrow \text{2DEG charge}}{\left[\epsilon_s / (t_{cap} + t_{AlGaN})\right] \leftarrow \text{capacitance}}$$

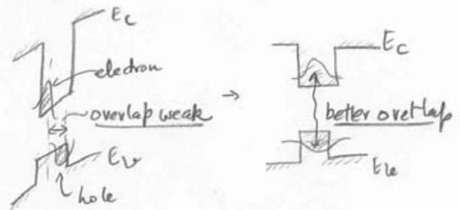
$\therefore$ $\boxed{V_{TH} \approx -0.48 \text{ Volt}}$

(c)



One can dope an "inverse" Sheet dipole to cancel the electric field in the well. It needs an equal & opposite donor-acceptor Sheet (or δ-) doping as shown.

(d)



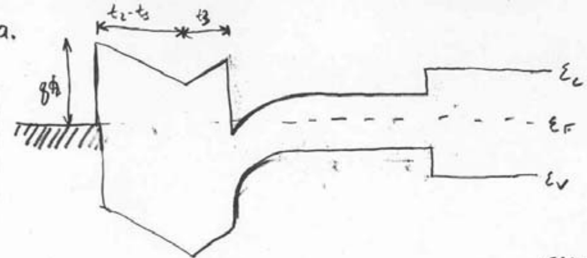
If there is an electric field in a QWell, & you want to use it for an optical device, the electron & holes are pushed in opposite directions & the chances of them recombining & giving out photons is reduced. This is called the Quantum-Confined Stark Effect (QCSE). So for good optical devices, it is highly desirable to have flat wells so that e-h overlap is high.

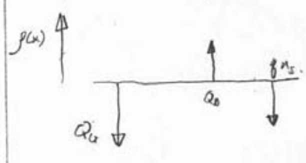
If I flatten the well for the HEMT though with doping, ionized impurity scattering will increase, & chances are that mobility will go down. However, alloy scattering, which occurs due to penetration of 2DEG wavef^n into the barrier is reduced, since the 2DEG is pushed away from the surface...

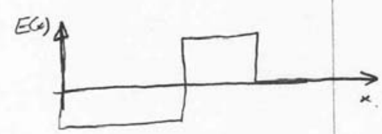
It's always give and take ☺

Problem 4: Solutions

a.







$Q_G = Q_0 - q n_s$

tracking the energy.

$$q\Phi_B - \frac{Q_G(t_2-t_3)}{\epsilon_s} + \frac{(Q_0 - Q_G)(t_3+a)}{\epsilon_s} - \Delta\mathcal{E}_c = 0$$

$$q\Phi_B - \Delta\mathcal{E}_c - \left(\frac{Q_0}{\epsilon} - \frac{q n_s}{\epsilon_s}\right)(t_2-t_3) + \frac{q n_s}{\epsilon_s}(t_3+a) = 0$$

$$q\Phi_B - \Delta\mathcal{E}_c - \frac{Q_0}{\epsilon_s}(t_2-t_3) + \frac{q n_s}{\epsilon_s}(t_2+a) = 0.$$

$$q n_s = \frac{\epsilon_s(\Delta\mathcal{E}_c - q\Phi_B) + Q_0(t_2-t_3)}{(t_2+a)} \qquad Q_0 = q\,(3.5*10^{19}\,cm^{-3})(1*10^{-7}\,cm)$$

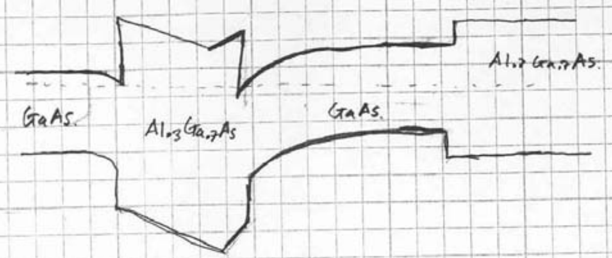
$$n_s = \frac{\frac{\epsilon_s}{q}(\Delta\mathcal{E}_c - q\Phi_B) + \frac{Q_0}{q}(t_2-t_3)}{(t_2+a)}$$

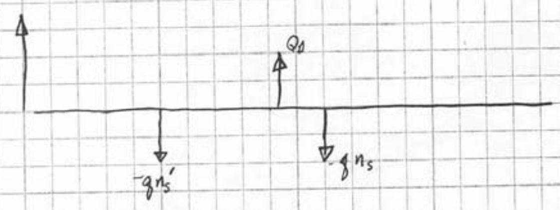
$\Delta\mathcal{E}_c = .79x\ eV$
$= (.79*.3)\ eV = .2370\,eV$ $\qquad a_{GaAs} \approx 50\text{Å}$

$n_s = 3.13*10^{12}\ cm^{-2}$

1D Poisson $\Rightarrow 7.023*10^{11}\ cm^{-2}$

b. Band Diagram.





$$Q_d = qn_s + qn_s'$$

3 states
-52 meV
21 meV
71 meV

$$-\frac{qn_s'}{\epsilon}(a+t_1-t_3) + \frac{Q_D - qn_s'}{\epsilon}(t_3+a) = 0$$

$$-\left(\frac{Q_D - qn_s}{\epsilon}\right)(a+t_1-t_3) + \frac{qn_s}{\epsilon}(t_3+a) = 0$$

$$qn_s\,(t_1+2a) = Q_D\,(a+t_1-t_3)$$

$$qn_s = \frac{Q_D\,(a+t_1-t_3)}{t_1+2a}$$

from 1D poisson $\Rightarrow 1.69 * 10^{12}\ cm^{-2}$

$$n_s = 6 * 10^{12}\ cm^{-2}$$

too large??

c. $C_g = \frac{q\,dn_s}{\partial V_{gs}}$

$$qn_s = \frac{\epsilon_s(\Delta E_c - q\phi_B - qV_g)}{(t_2+a)}$$

$$C_g = \frac{\epsilon_s}{t_2+a} * W * L$$

$$g_m = \frac{\partial I_D}{\partial V_{gs}}$$

$$I_D = q\,n_s\,v_{sat}\,W.$$

$$\frac{\partial I_D}{\partial V_{gs}} = \frac{q\epsilon_s}{t_2+a}\,v_{sat}\,W.$$

$$q n_s = \frac{\epsilon_s(\Delta E_c - q\phi_B - qV_{gs}) + Q_D(t_2 - t_3)}{(t_2 + a)}$$

$$0 = \frac{\epsilon_s(\Delta E_c - q\phi_B - qV_{TH}) + Q_D(t_2 - t_3)}{(t_2 + a)}$$ ✓

Method correct . . .

$$\boxed{V_{TH} = \frac{1}{q}(\Delta E_c - q\phi_B) + \frac{Q_D(t_2 - t_3)}{q\epsilon_s}} \approx -.3700\,V$$

See soln below . . .

→ I get $\boxed{-0.23 \text{ volts}}$

d. The <u>only advantage</u> of using a gate recess process is a reduction in access resistance to the 2DEG Region. Without the gate-recess region there would be an ohmic contact to the 2DEG followed by a large ohmic resistance. With the gate recess this is mitigated because you now have a 2DEG from S→D.

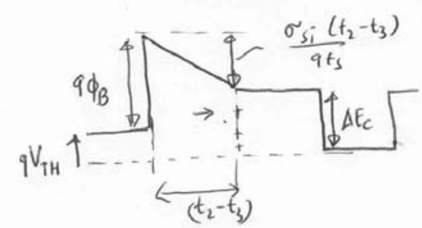
also, $t_g \downarrow \Rightarrow C_g \uparrow \Rightarrow \frac{g_m^{sat}}{W} = C_g v_{sat} \uparrow$

So larger gain . . .

Rework it to get -

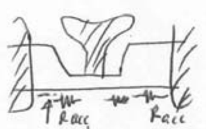
$$\boxed{V_{TH} = q\phi_B - \frac{\Delta E_c}{q} - \frac{\sigma_{si}(t_2 - t_3)}{q\epsilon_s}}$$

$$= -0.23 \text{ Volts}.$$



Note: Under the gate, $n_s \downarrow$, but $C_g \uparrow \Rightarrow$

good! $\boxed{g_m^{sat} \uparrow \text{ due to recess}}$



n_s is large $\Rightarrow R_{acc} \downarrow$.

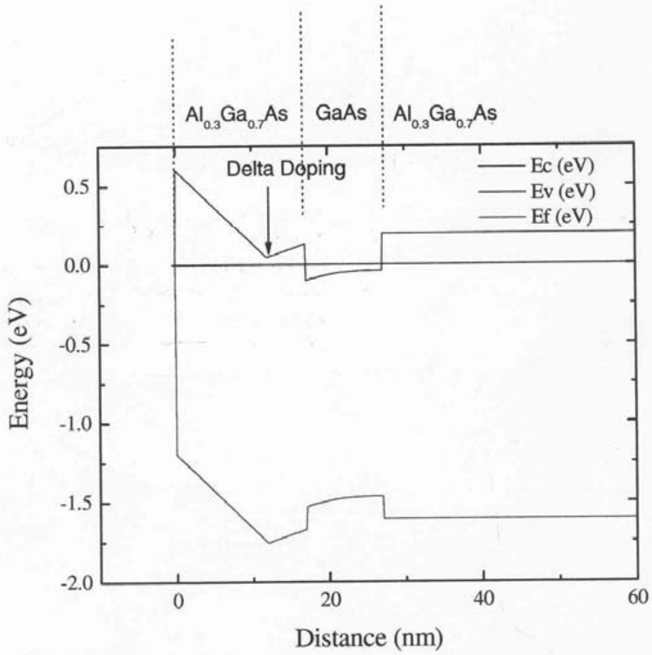
Away from gate, $n_s \uparrow$ in regions with cap

$\Rightarrow$ $\boxed{\text{Access resistance} \downarrow}$ → good!

(a) B-B' section

```
surface schottky=0.6   v1
AlGaAs       t=115   x=.3                  dy=1
AlGaAs       t=10    x=.3   Nd=3.5e19      dy=0.1
AlGaAs       t=45    x=.3                  dy=1
GaAs         t=100                         dy=1
AlGaAs       t=700   x=.3                  dy=10
substrate
fullyionized
v1 0.0
schrodingerstart=0
schrodingerstop=1000
temp=300K
```

Simulation by K. Pang



.status file:

number of iterations to converge = 22

Final correction to bands = 0.371E-06eV

maximum error in poisson equation= 0.519E-05
Don't worry, be happy! The convergence is good!

Structure Sheet Resistance = 8.985E+02 Ohms/square

layer sheet concentrations

surface schottky

115Ang. algaas x=0.300 ns= 4.928E+08 cm-2 ps= 0.000E+00 cm-2

10Ang. algaas x=0.300 ns= 5.665E+08 cm-2 ps= 0.000E+00 cm-2

45Ang. algaas x=0.300 ns= 3.271E+10 cm-2 ps= 0.000E+00 cm-2

100Ang. gaas ns= 7.627E+11 cm-2 ps= 0.000E+00 cm-2

700Ang. algaas x=0.300 ns= 2.075E+10 cm-2 ps= 7.295E-16 cm-2

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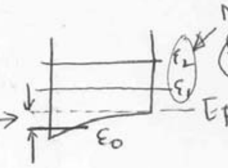
substrate slope=0

Not occupied, since $\varepsilon > \varepsilon_F$!



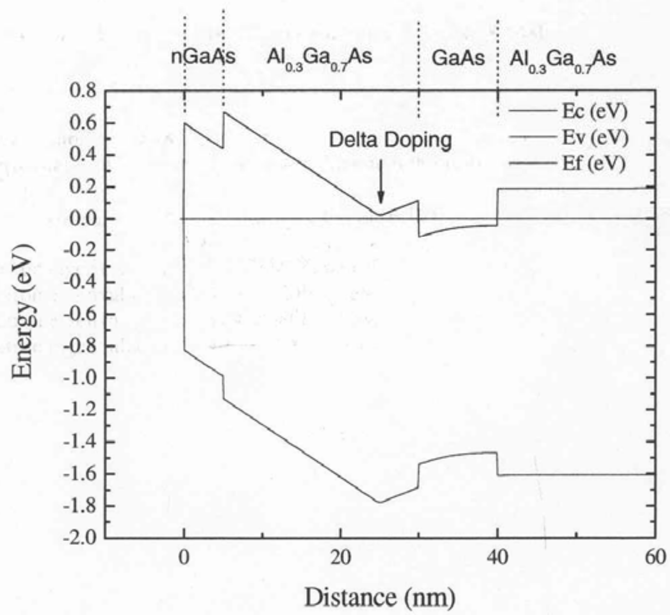
Temperature = 300.0K
Schrodinger solution from 0.000E+00 Ang. to 9.500E+02 Ang.

The following subband energies were found (E-Ef):

ε_0 electron eigenvalue 1 = -15.037920E-03 eV ← only "Quantum Confined" state
ε_1 electron eigenvalue 2 = 68.996940E-03 eV
ε_2 electron eigenvalue 3 = 158.793900E-03 eV
ε_3 electron eigenvalue 4 = 202.757300E-03 eV

(a) A-A' section

surface schottky=0.6 v1
GaAs t=50 Nd=7e17 dy=1
AlGaAs t=195 x=.3 dy=1
AlGaAs t=10 x=.3 Nd=3.5e19 dy=0.5
AlGaAs t=45 x=.3 dy=1
GaAs t=100 dy=1
AlGaAs t=700 x=.3 dy=10
substrate
fullyionized
v1 0.0
schrodingerstart=0
schrodingerstop=1000
temp=300K



.status file
number of iterations to converge = 23
Final correction to bands = 0.191E-06eV
maximum error in poisson equation= -0.501E-05
Don't worry, be happy! The convergence is good!

Structure Sheet Resistance = 5.267E+02 Ohms/square

layer sheet concentrations

surface schottky

50Ang. gaas ns= 1.514E+03 cm-2 ps= 0.000E+00 cm-2

195Ang. algaas x=0.300 ns= 1.161E+10 cm-2 ps= 0.000E+00 cm-2

10Ang. algaas x=0.300 ns= 7.741E+09 cm-2 ps= 0.000E+00 cm-2

45Ang. algaas x=0.300 ns= 9.548E+10 cm-2 ps= 0.000E+00 cm-2

100Ang. gaas ns= 1.248E+12 cm-2 ps= 0.000E+00 cm-2

700Ang. algaas x=0.300 ns= 3.089E+10 cm-2 ps= 8.548E-15 cm-2

----

substrate slope=0

Temperature = 300.0K
Schrodinger solution from 0.000E+00 Ang. to 9.900E+02 Ang.

The following subband energies were found (E-Ef):

electron eigenvalue 1 = -37.178800E-03 eV
electron eigenvalue 2 = 44.572720E-03 eV
electron eigenvalue 3 = 91.408380E-03 eV
electron eigenvalue 4 = 168.793100E-03 eV