EE566 Solid State Devices

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Dept of Electrical Engineering
University of Notre Dame
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Assignment 9

SOLUTIONS

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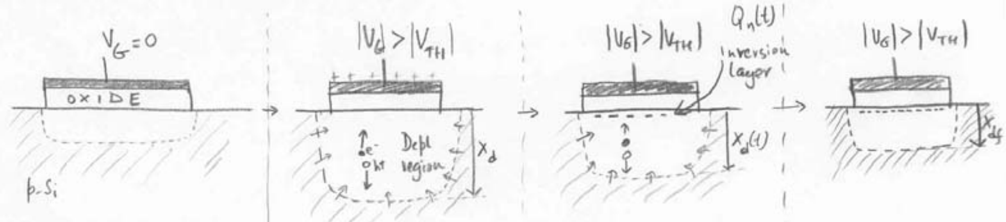
PROBLEM 3 — MOS Capacitor



$\boxed{t=-\infty}$ Steady State

$\boxed{t=0}$: Inversion charge does NOT form immediately

$\boxed{t=t}$: Inversion layer partially formed from thermally generated ehp's in depl. region ($np < n_i^2$)

$\boxed{t=\infty}$: Inversion layer completely formed. $x_{depl} = x_{df}$ is max. depletion thickness @ eqm.

A pictorial view of the mechanism (of DRAM opⁿ).

$$\frac{dQ_n}{dt} = -\frac{q n_i (x_d - x_{df})}{2\tau_0} \rightarrow \text{use this, \& simple charge conservation}$$

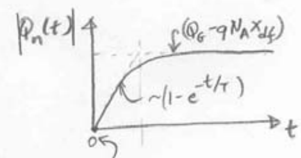
$$|Q_n(t)| + q N_A x_d(t) = |Q_G|$$

get — in — eliminate $x_d(t)$

(a)
$$Q_n + \underbrace{\left(\frac{2\tau_0 N_A}{n_i}\right)}_{'T'} \frac{dQ_n}{dt} = -[Q_G - q N_A x_{df}]$$

(b) Solve:
$$\int_{Q_n(0)=0}^{Q_n(t)} \frac{dQ_n}{(Q_n + Q_G - q N_A x_{df})} = -\int_{t=0}^{t} \frac{dt}{T}$$

$$\ln\left(\frac{Q_n(t) + Q_G - q N_A x_{df}}{Q_G - q N_A x_{df}}\right) = -t/T$$

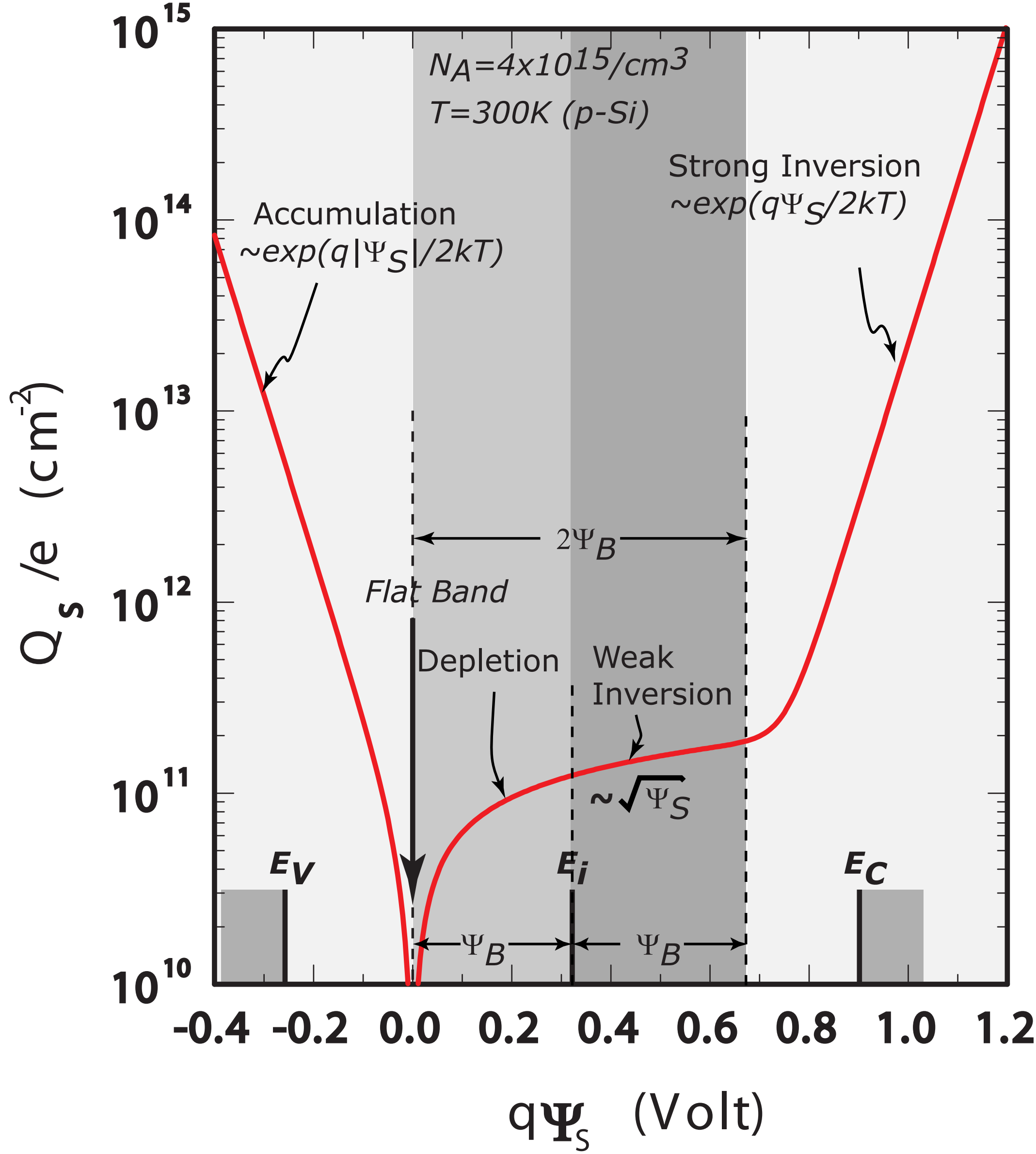


No inv. charge at $t=0$

$$\Rightarrow \boxed{Q_n(t) = -(Q_G - q N_A x_{df})(1 - e^{-t/T})}$$

$$T = 2\tau_0 * \frac{N_A}{n_i} = (2*10^{-6}\,s) * \left(\frac{10^{15}/cm^3}{10^{10}/cm^3}\right) \approx \boxed{0.2\,\text{seconds}}$$

Since the time reqd' to form the layer is in the order of seconds, one can come back to the MOS capacitor after many clock cycles & find what had been stored there before ⇒ it is a memory...



$N_A=4x10^{15}/cm^3$
T=300K (p-Si)
Strong Inversion
$\sim exp(q\Psi_S/2kT)$
Accumulation
$\sim exp(q|\Psi_S|/2kT)$
$2\Psi_B$
Flat Band
Depletion
Weak Inversion
$\sim\sqrt{\Psi_S}$
E_V
E_i
E_C
Ψ_B
Ψ_B
10^{15}
10^{14}
10^{13}
10^{12}
10^{11}
10^{10}
Q_s/e (cm^{-2})
-0.4 -0.2 0.0 0.2 0.4 0.6 0.8 1.0 1.2
$q\Psi_S$ (Volt)

ASSIGNMENT (9)

(9)

Problem 3 — Soln by Anjali Bhartaur

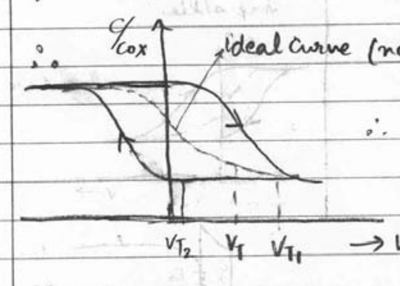
8.14 a(i) Considering field aided movement of positive ions in the insulator

We know that $\Delta V_{FB} = -\frac{1}{C_{ox}} \int_0^{x_{ox}} \frac{x}{x_{ox}} \rho(x)\, dx$

where $\rho(x)$ is the oxide charge sheet density ~~density~~.

Now, considering ~~a~~ p-type Si as substrate. If we apply positive V_G, then we can expect the movement of positive ions ~~in~~ away from the oxide, ~~perhaps~~ into the Si substrate. This would cause $\rho(x)$ in the oxide to decrease, increasing ΔV_{FB} and thus increasing V_{TH}.

Now, consider the case, when we are in inversion and we decrease V_G, initially $\rho(x)$ is much lesser ~~than~~, as it was steadily decreasing when we went from accumulation to inversion. Hence, the retrace path would be below that of the forward path.



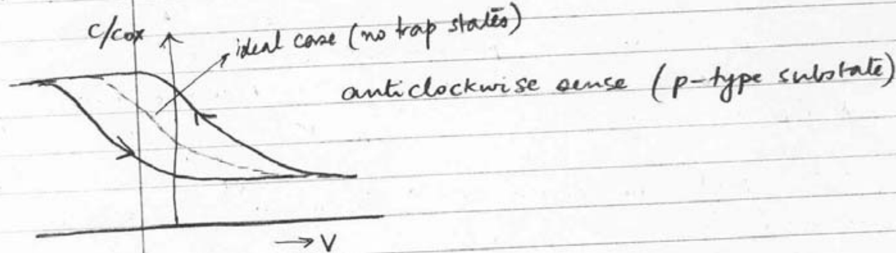
$\therefore$ clockwise sense. (p-type Si substrate)

(ii) Considering trapping of free carriers from the channel in the traps at the oxide - Si interface

$\rightarrow$ contd..

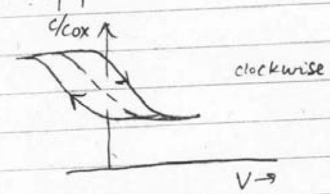
$$\Delta V_{FB} = \frac{-1}{C_{ox}} \int_0^{x_{ox}} \frac{x}{x_{ox}} \rho(x)\, dx$$

Now, as we increase V_G (for a p-Si substrate), the channel starts forming ($\rho(x)$ decreases), and the trap states start getting filled. But to start with we have trap states with positive charge, which decreases V_{FB}, decreasing V_{TH}. Also, when going from inversion to accumulation, it is more difficult to empty a trap, than to fill it. Hence, we observe that the C-V curve has ~~an~~ an anti-clockwise sense.

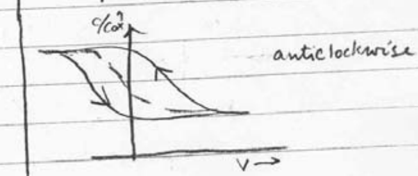


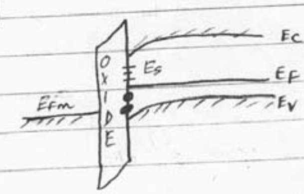
b) P-type

(i) Field added movement of positive ions



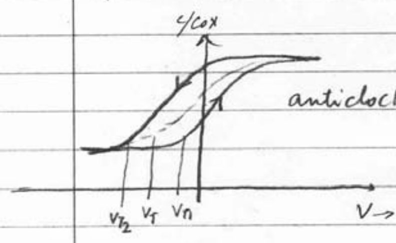
(ii) Trapping of free charge in trap states





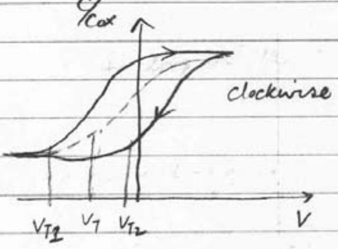
n-type substrate

(i) Field movement of positive ions

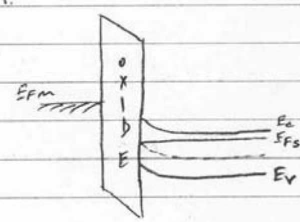


Here, as in the ideal case V_T is negative. On decreasing $\rho(x)$, $V_{FB} \uparrow$, $\therefore V_{TH} \uparrow$. Same reasoning as that for p-type, except here the sense becomes opposite

(ii) Trapping of free charges in trap states



Here, the free charges are holes. Thus, when we reach inversion we have $\rho(x)$ ~~becoming +ve~~ increasing. Thus, on retracing, we see that $V_{TH} \uparrow$. $\therefore$ clockwise rotation.



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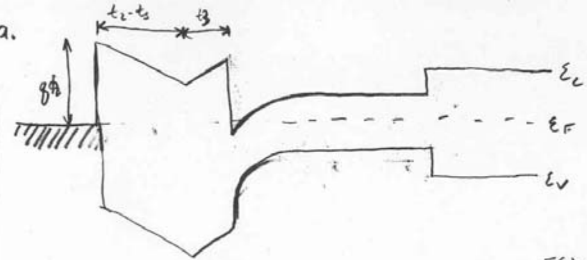
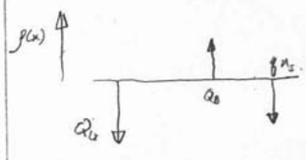
continued.

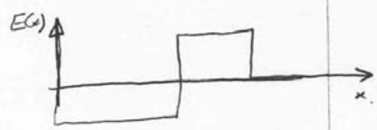
'bound'.

By Nespor

a.







$Q_G = Q_0 - qn_s$

tracking the energy.

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

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

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

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

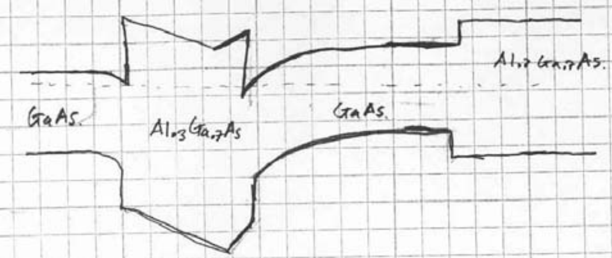
$$n_s = \frac{\frac{\epsilon_s}{q}(\Delta\mathcal{E}_c - q\phi_B) + \frac{Q_0}{q}(t_2-t_3)}{(t_2+a)}.$$

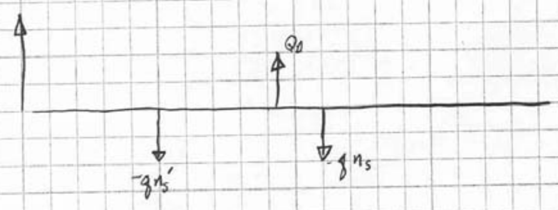
$\Delta\mathcal{E}_c = .79x\ eV$
$= (.79*.3)\ eV = .2370\,eV.$ $\qquad a_{GaAs} \approx 50\text{Å}$

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

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

b. Band Diagram.





$Q_0 = qn_s + qn_s'$

3 states $-52\,meV$, $21\,meV$, $71\,meV$

$$-\frac{qn_s'}{\epsilon}(a+t_1-t_3) + \frac{Q_0-qn_s'}{\epsilon}(t_3+a) = 0$$

$$-\left(\frac{Q_0-qn_s}{\epsilon}\right)(a+t_1-t_3) + \frac{qn_s}{\epsilon}(t_3+a) = 0$$

$$qn_s\,(t_1+2a) = Q_0\,(a+t_1-t_3)$$

$$qn_s = \frac{Q_0\,(a+t_1-t_3)}{t_1+2a}$$

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

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

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 ...

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

See solns ... → I get $\boxed{-0.23 \text{ volts}}$

d. The only advantage 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.

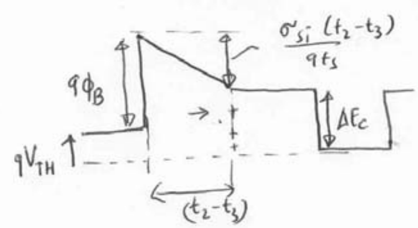
also, $t_g \downarrow \Rightarrow C_g \uparrow \Rightarrow \frac{g_m^{sat}}{W} = C_g v_{sat} \uparrow$

So Larger gain ...

Rework it to get -

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

$= -0.23$ Volts.

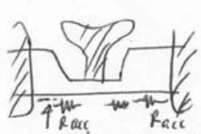


Note: Under the gate, $n_S \downarrow$, but $C_g \uparrow \Rightarrow$

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

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

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

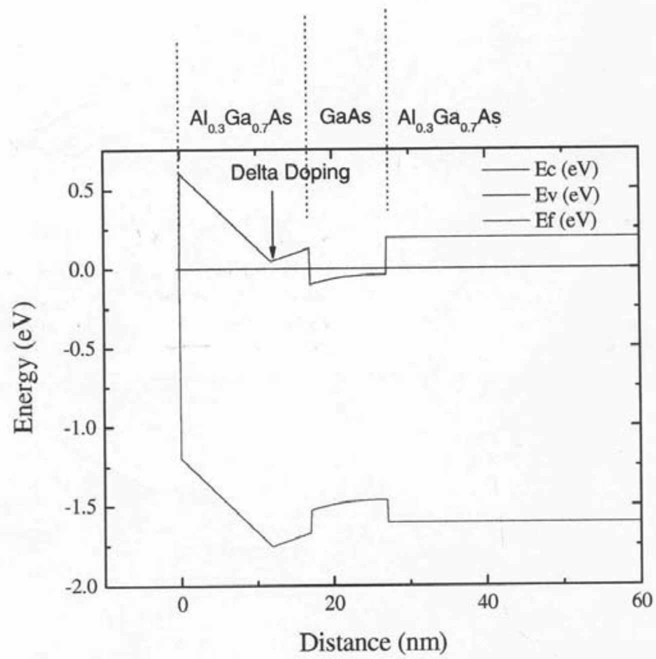


n_S is large ⇒ $R_{acc} \downarrow$.

(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
```

Simulations 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

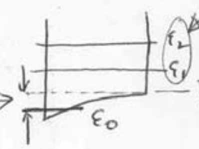
45Ang. algaas x=0.300 ns= 3.271E+10 cm-2 ps= 0.000E+00 cm-2

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

substrate slope=0

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



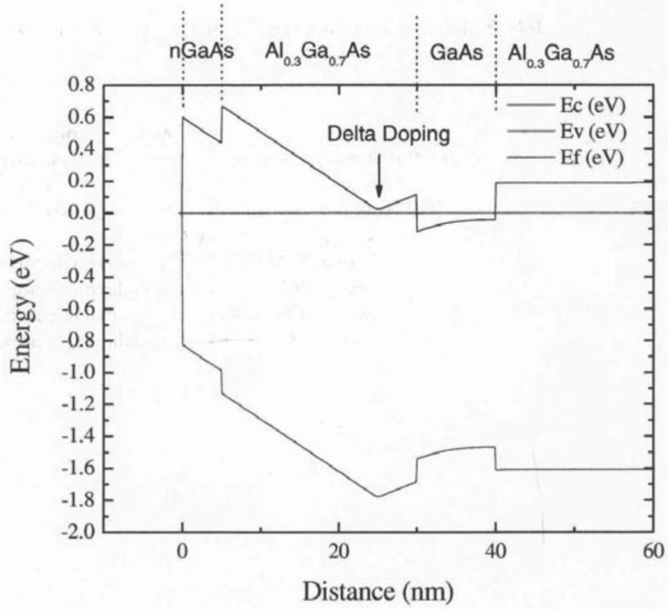
Temperature = 300.0K
Schrodinger solution from 0.000E+00 Ang. to 9.500E+02 Ang.

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

(b) 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
```



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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