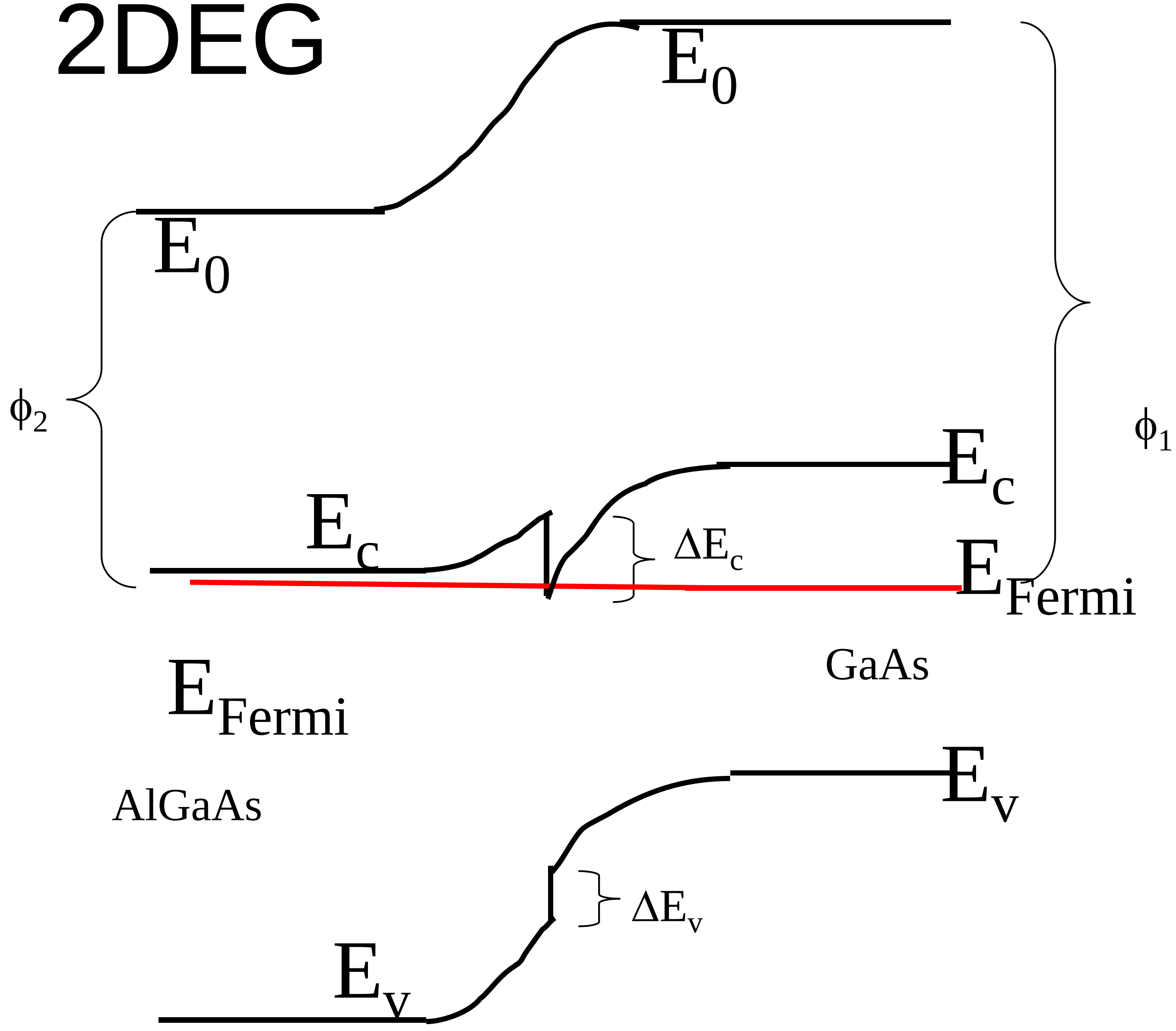
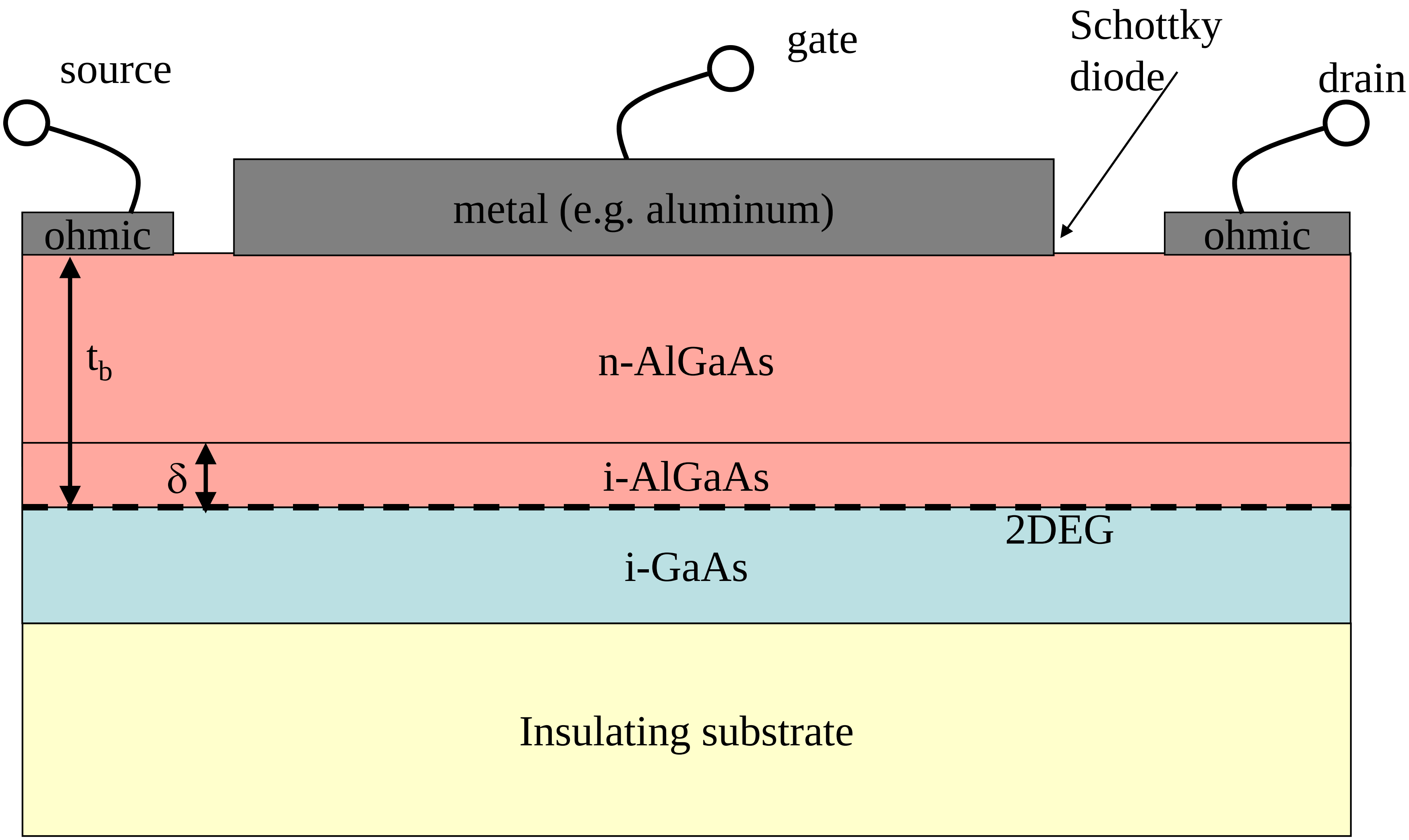
Lecture 9: High electron mobility transistor (HEMT)

2DEG

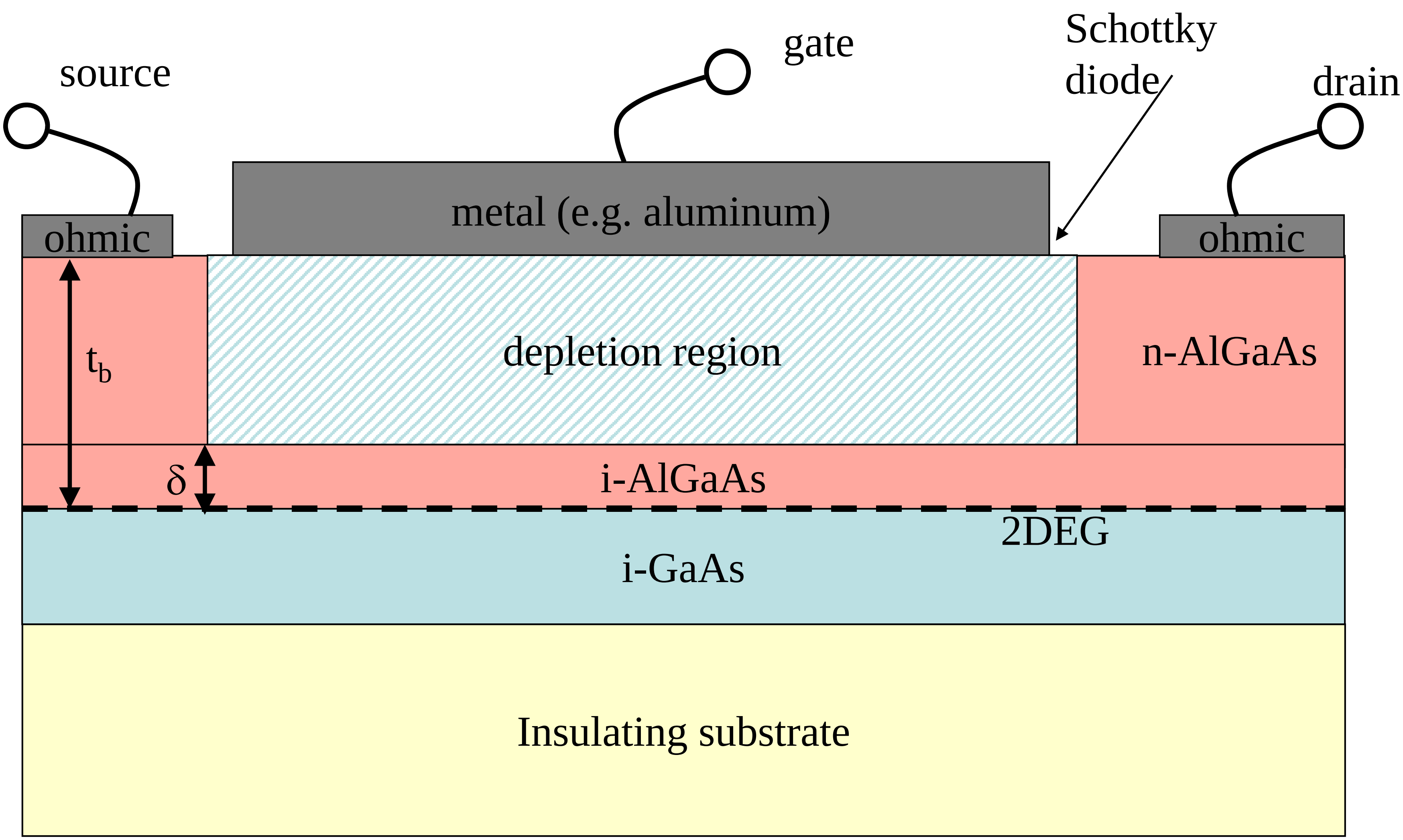


E_0
E_0
ϕ_2
ϕ_1
E_c
E_c
ΔE_c
E_{Fermi}
E_{Fermi}
GaAs
AlGaAs
E_v
E_v
ΔE_v

HEMT:


source
gate
Schottky
diode
drain
ohmic
metal (e.g. aluminum)
ohmic
t_b
n-AlGaAs
δ
i-AlGaAs
2DEG
i-GaAs
Insulating substrate

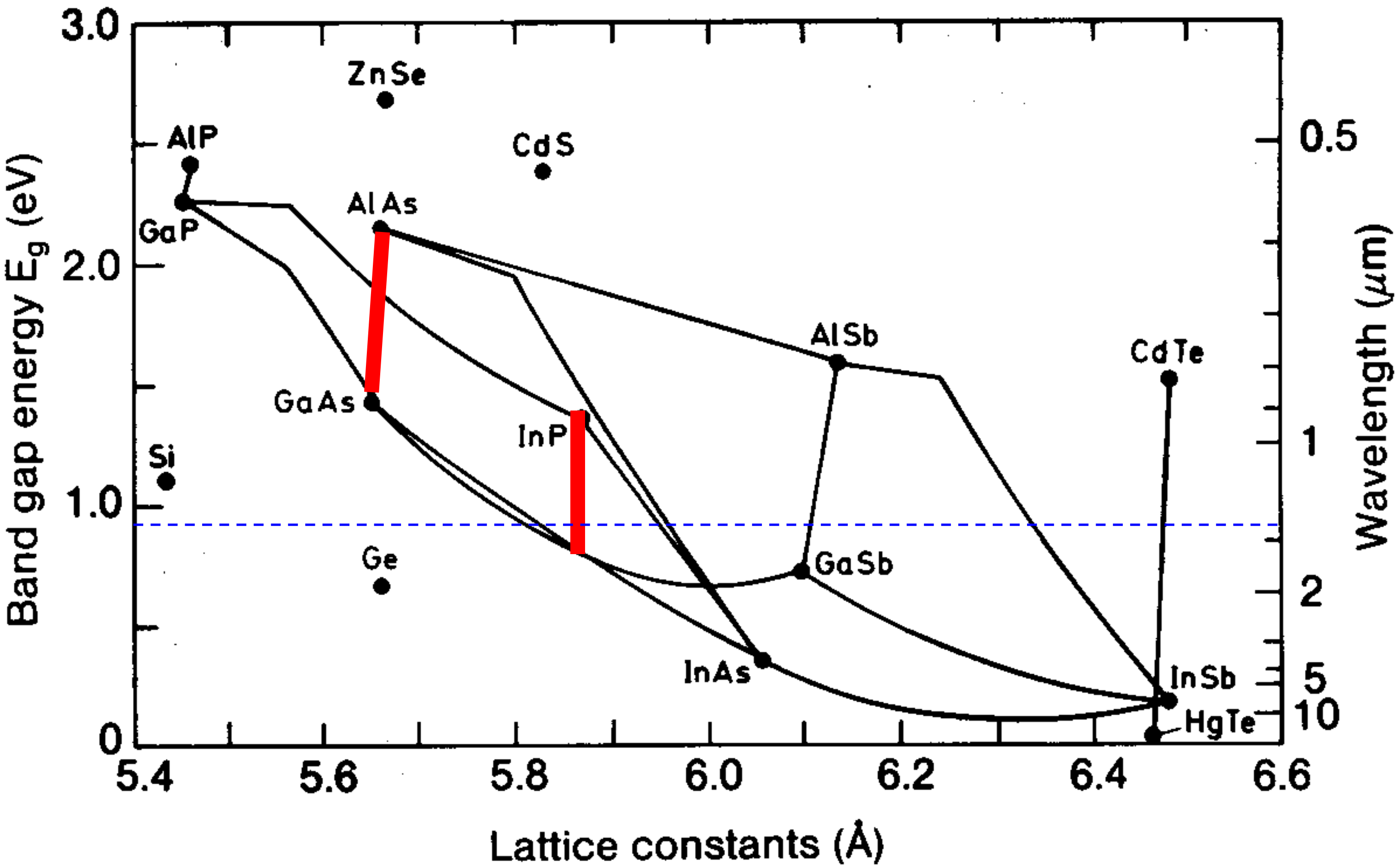
HEMT:


source
gate
Schottky
diode
drain
metal (e.g. aluminum)
ohmic
ohmic
depletion region
n-AlGaAs
t_b
δ
i-AlGaAs
2DEG
i-GaAs
Insulating substrate

Many possible variations

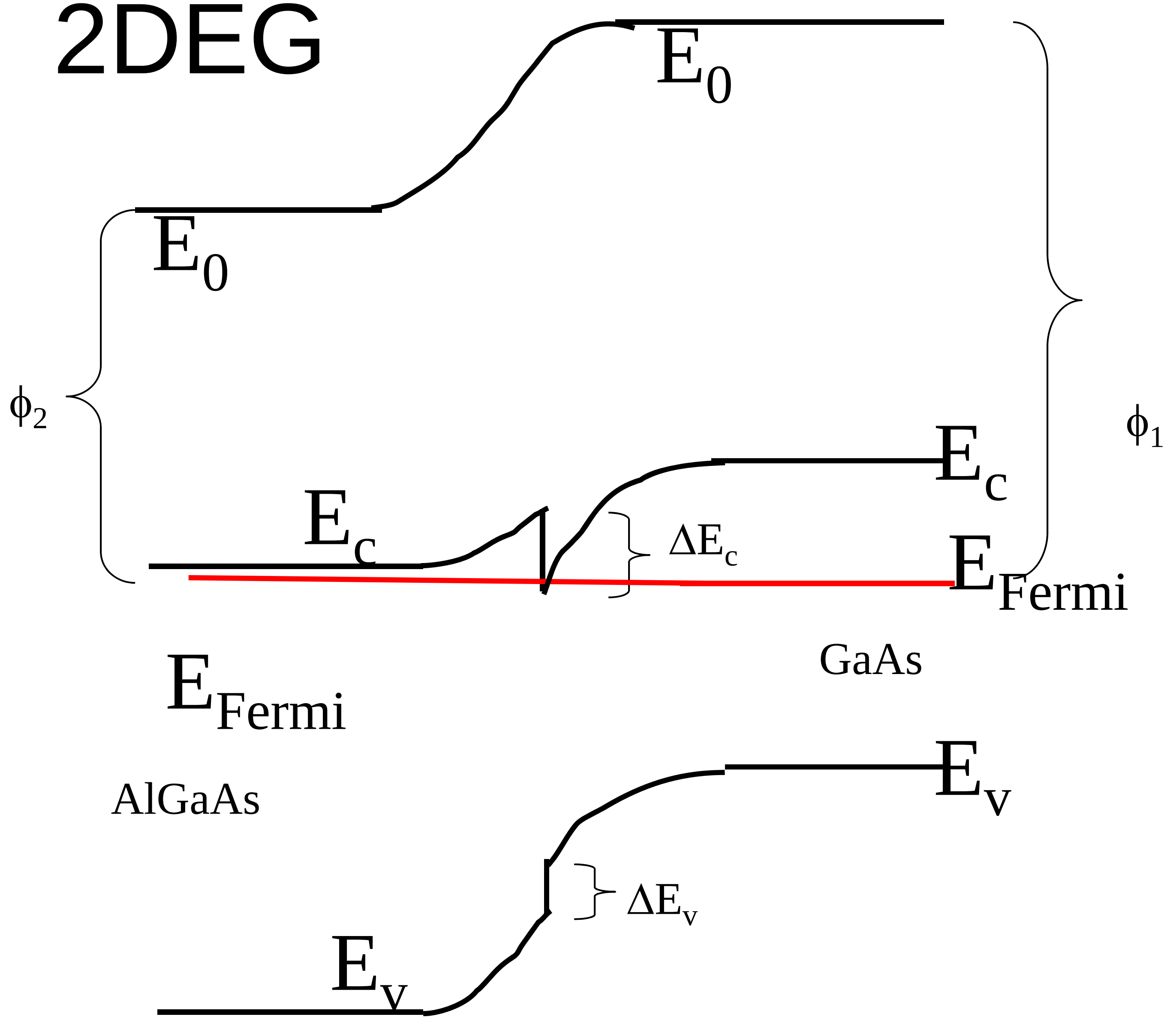
- “Quantum well” is also popular.
- Highly doped material under ohmics for low contact resistance
- InP based materials
- GaN based materials
- (pHEMT: strained materials)

Band gaps

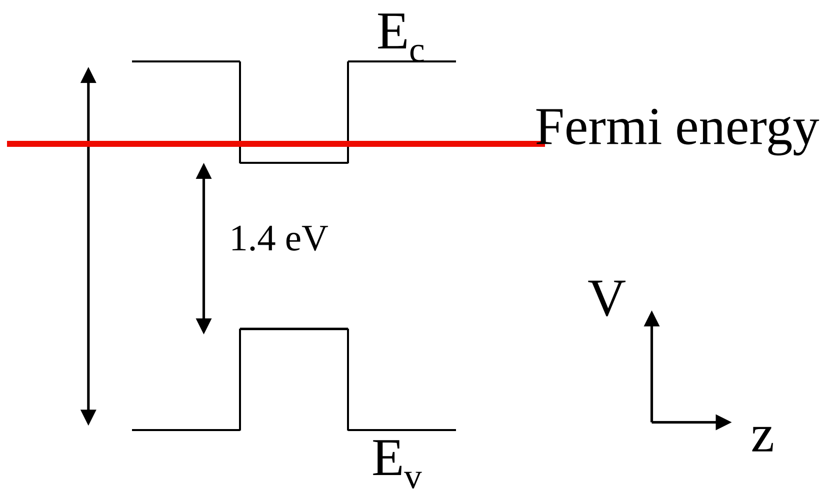


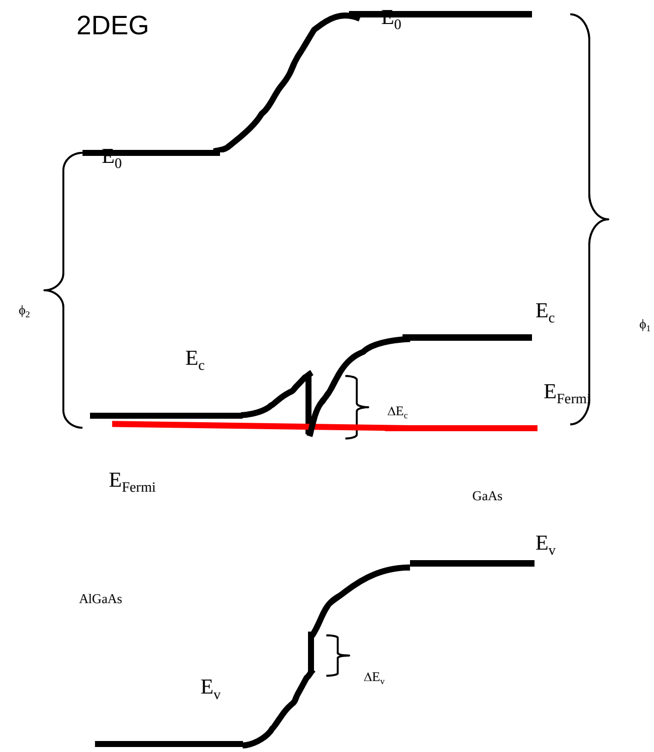
3.0
2.0
1.0
0
Band gap energy E_g (eV)
5.4
5.6
5.8
6.0
6.2
6.4
6.6
Lattice constants (Å)
0.5
1
2
5
10
Wavelength (μm)
ZnSe
AlP
CdS
GaP
AlAs
AlSb
CdTe
GaAs
InP
Si
Ge
GaSb
InAs
InSb
HgTe

2DEG


E_0
E_0
ϕ_2
ϕ_1
E_c
E_c
ΔE_c
E_{Fermi}
E_{Fermi}
GaAs
AlGaAs
E_v
ΔE_v
E_v

Triangle vs. square well:





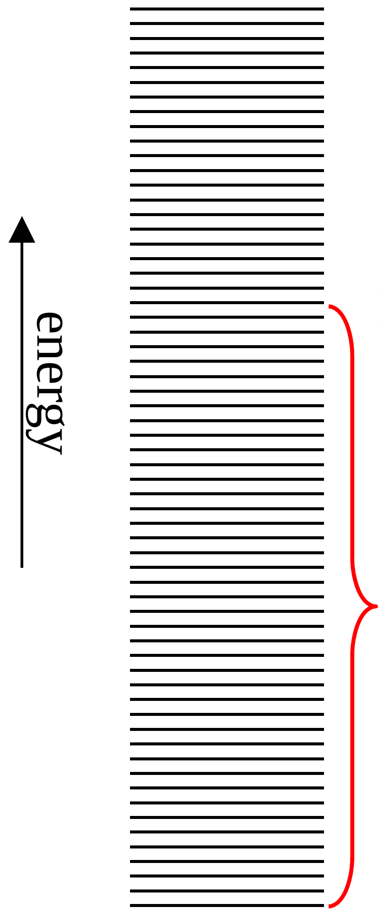
(Draw both bound states on board.
In particular discuss figure 5.21 from Liu.)
Also discuss shallow vs. wide wells on board.
(Typically 100 angstroms works.)

Fermi energy in 2 dimensions

$$\#\,\text{electrons} = \int_0^{E_f} N_{\mathrm{E}}\,\mathrm{dE} = \int_0^{E_f} L^2 \frac{m}{\pi\hbar}\,dE$$

$$\#\,\text{electrons} = L^2 \frac{m}{\pi\hbar} E_f$$

$$\boxed{\Rightarrow E_f = \frac{\hbar\pi}{m}\left(\frac{\#\,\text{electrons}}{L^2}\right) = \frac{\hbar\pi}{m} n}$$



$E=E_{Fermi}$

All these states are filled with electrons.

$E=0$

In GaAs, 10^{11}cm^{-2} gives

$E_f \sim 1\text{-}10$ meV

But 10^{12}cm^{-2} gives more than first subband.

Discuss “subband”, how above integral gets modified.

Problem

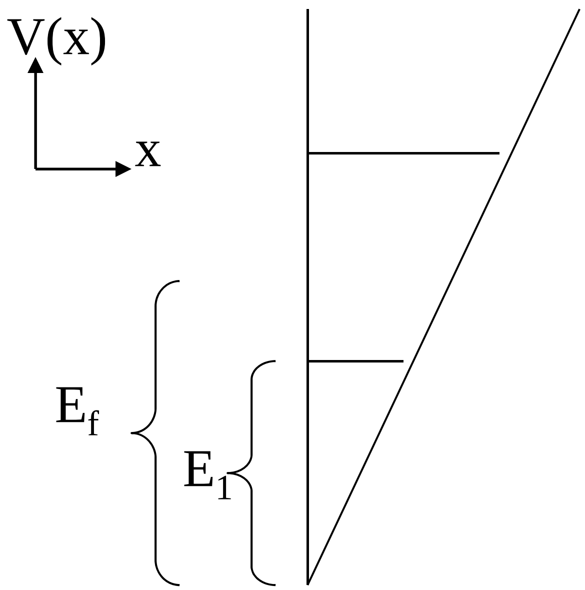
- Presence of electrons changes shape of potential well.
- We need a way to account for this.
- Will do NOW.
- Why? We want to know how many electrons there are!
- Later, we want to know how gate voltage changes that.

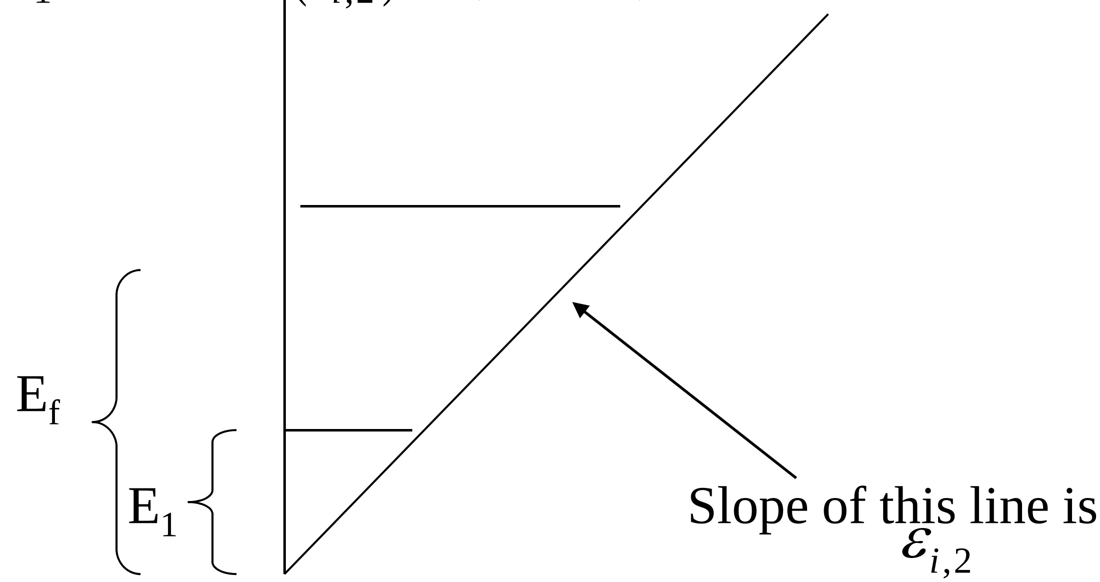
Trianglular wells

From quantum mechanics:

$$E_n \approx \left(\frac{h^2}{8\pi^2 m^2}\right)^{1/3}\left(\frac{3\pi}{2}e\varepsilon_{i,2}\right)^{2/3}\left(n-\frac{1}{4}\right)^{2/3}$$

$$E_1 \approx 4\cdot 10^{-5}\left(\varepsilon_{i,2}\right)^{2/3}(V/cm)$$

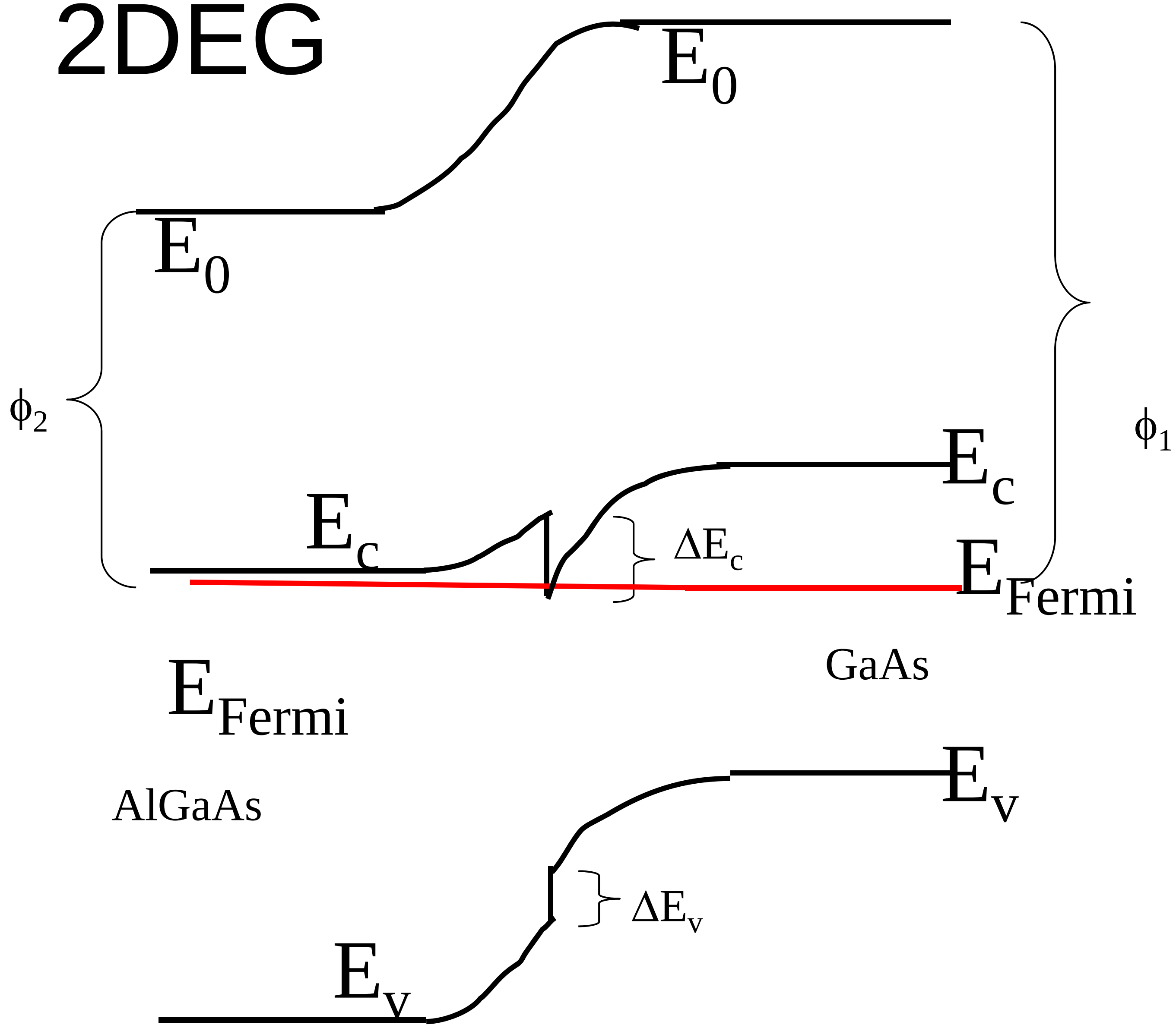




$$E_f = \frac{\hbar^2\pi}{m}n_s \rightarrow \left(E_f - E_1\right) = \frac{\hbar\pi}{m}n_s$$

Note: Lecture 10 had error of hbar.

2DEG



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E_c
ΔE_c
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E_{Fermi}
E_{Fermi}
GaAs
AlGaAs
E_v
ΔE_v
E_v

Poisson equation

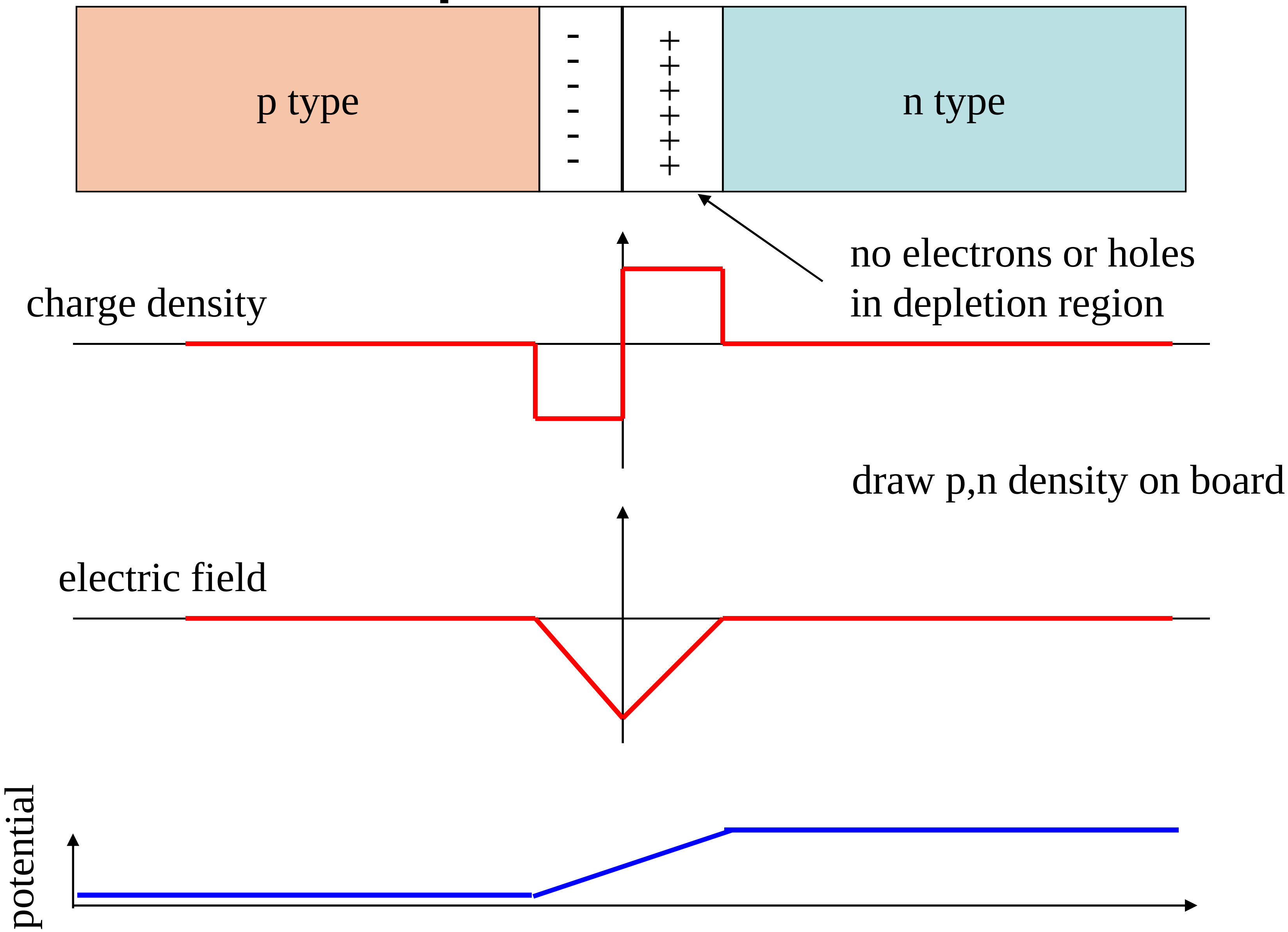
Actually first of Maxwell's four equations:

$$\vec{\nabla} \cdot \vec{E} = -\frac{\rho}{\varepsilon}$$

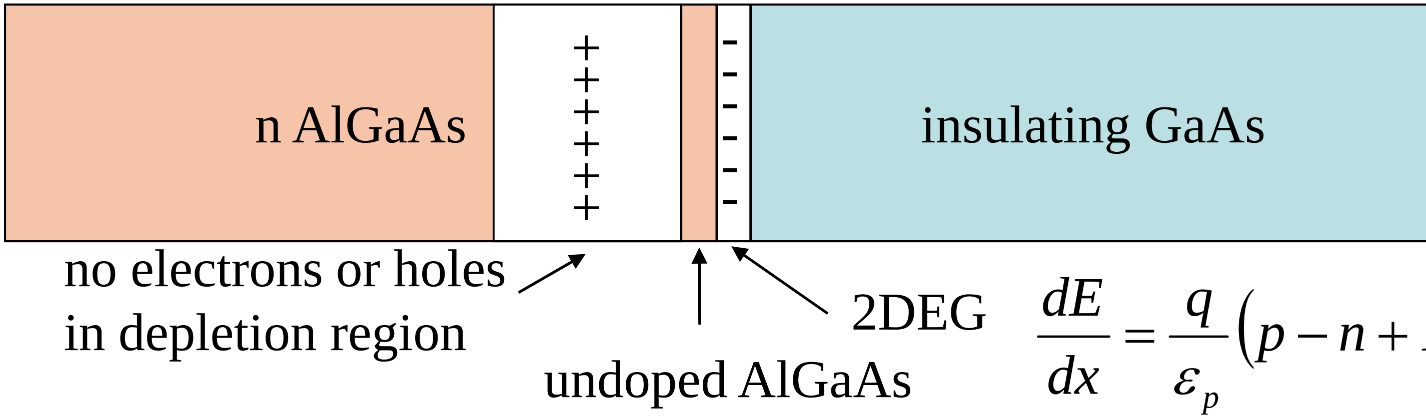
In the x-direction only:

$$\frac{dE}{dx} = \frac{q}{\varepsilon_p}\left(p - n + N_d^+ - N_a^-\right)$$

p n diode

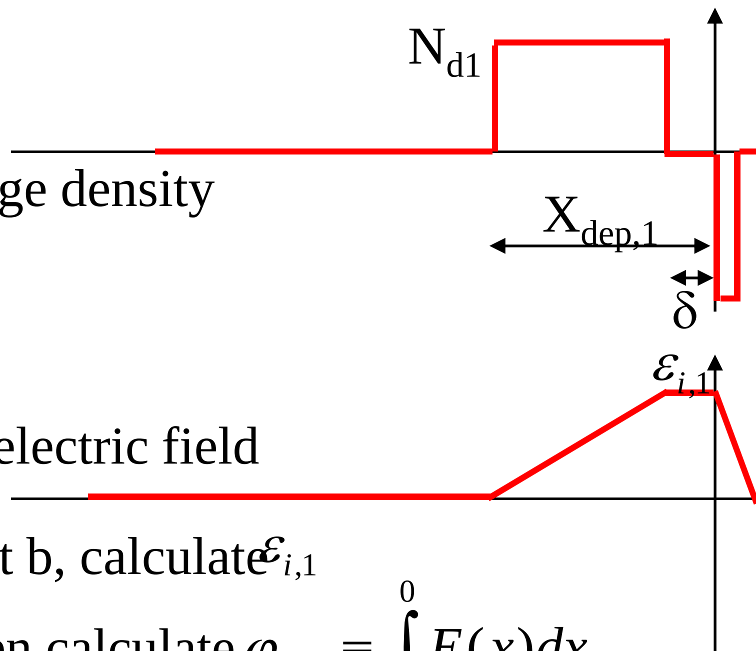

p type
n type
no electrons or holes in depletion region
charge density
draw p,n density on board
electric field
potential

Hint for HW #5.8



$$\frac{dE}{dx} = \frac{q}{\varepsilon_p}\left(p - n + N_d^+ - N_a^-\right)$$

$$\rightarrow \frac{dE}{dx} = \frac{q}{\varepsilon_p} n$$



$$\int_0^{Xdep2} \frac{dE}{dx} dx = \int_0^{Xdep2} \frac{q}{\varepsilon_p} n dx = \frac{q}{\varepsilon_p} n_s$$

$$LHS = \int_{E(0)}^{E(Xdep2)} dE = E(Xdep2) - E(0) = E(0) \equiv \varepsilon_{i,2}$$

Part b, calculate $\varepsilon_{i,1}$

Then calculate $\varphi_{bi,1} \equiv \int_{-\infty}^{0} E(x)dx$

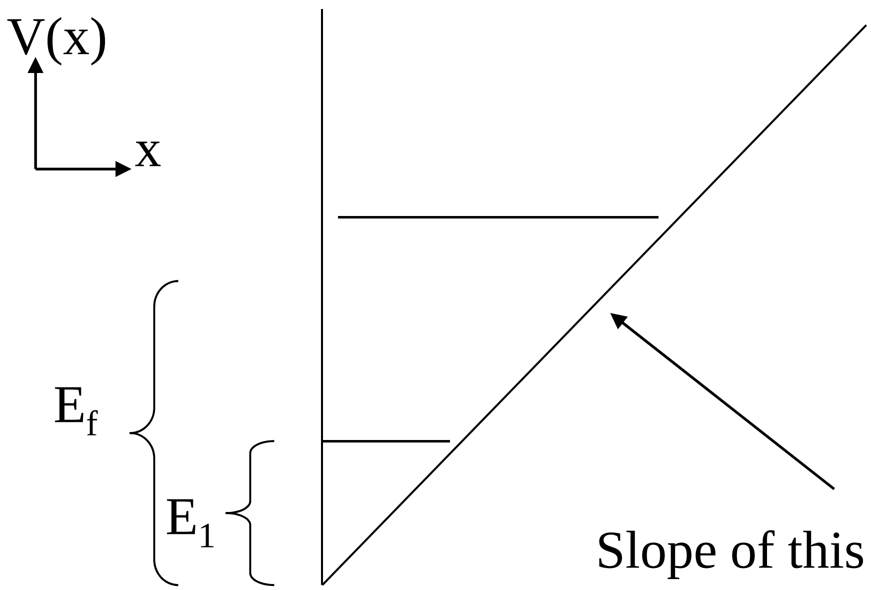
Then eliminate $X_{dep,1}$

$$\varepsilon_{i,1} = \varepsilon_{i,2}$$

$$\Rightarrow \varepsilon_{i,2} = \frac{q}{\varepsilon_p} n_s$$

Trianglular wells

$$E_1 \approx 4 \cdot 10^{-5} \left(\varepsilon_{i,2}\right)^{2/3} (V / cm)$$



$$\left(E_f - E_1\right) = \frac{\hbar \pi}{m} n_s$$

$$\varepsilon_{i,2} = \frac{q}{\varepsilon_p} n_s$$

$$E_1 \approx 4 \cdot 10^{-5} \left(\frac{q}{\varepsilon_p} n_s\right)^{2/3} (V / cm)$$

Slope of this line is
$\varepsilon_{i,2}$

Discuss intuitively: adding electrons changes slope which changes Fermi energy.

That gives one relationship between E_f and n_s.
To solve for both of them, you need another relationship: HW 5.8

From HW 5.8

You will find:

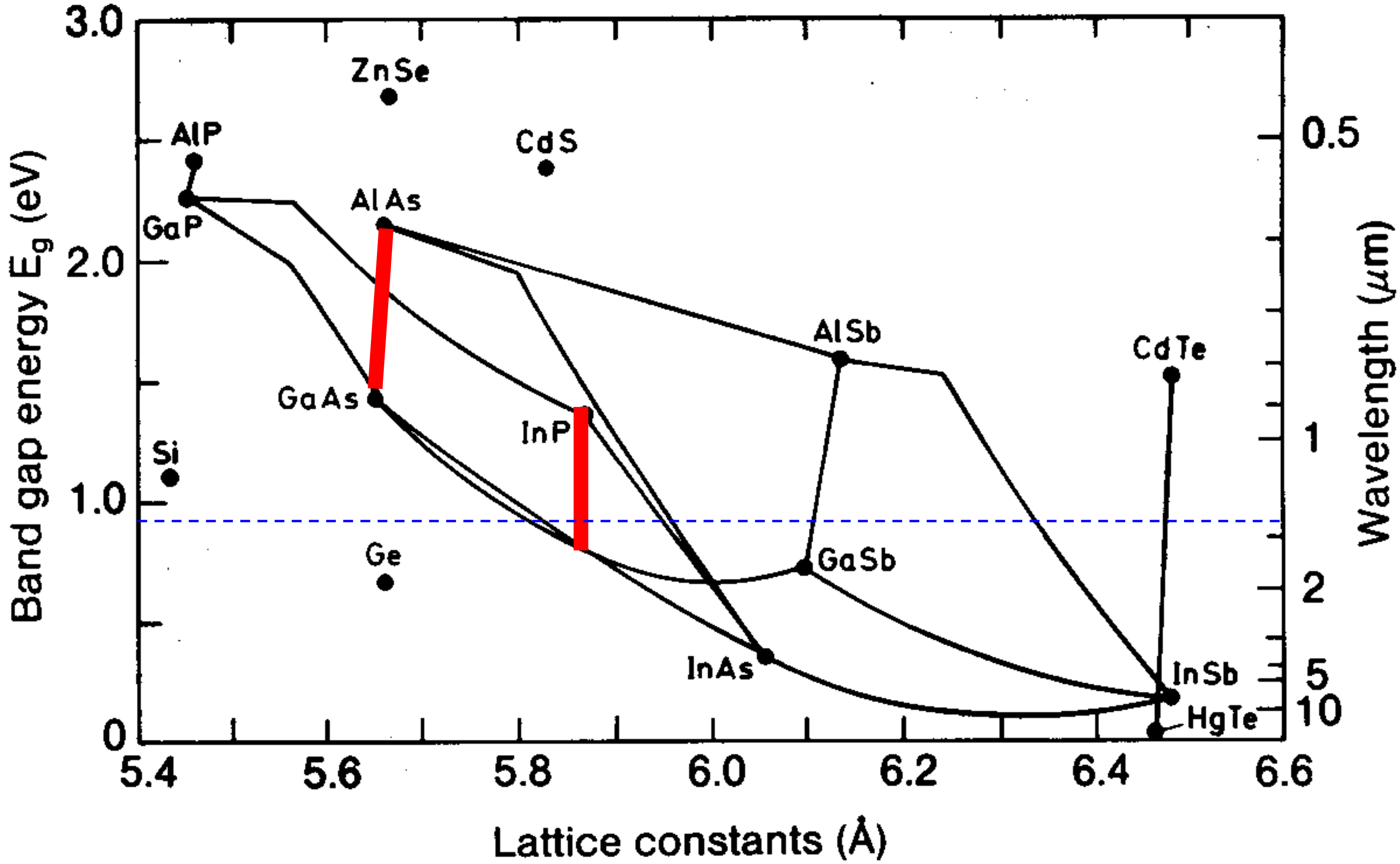
$$n_s \propto \sqrt{\Delta E_c}\sqrt{N_d}$$

Want to engineer material so that ΔE_c large.
For GaAs, there is a limit.

For $In_xGa_{1-x}As/In_xAl_{1-x}As$,
use strained layers to get larger ΔE_c (discuss).
(InP has higher mobility, peak velocity than GaAs.)

Called pseudomorphic HEMT: pHEMT.

Band gaps



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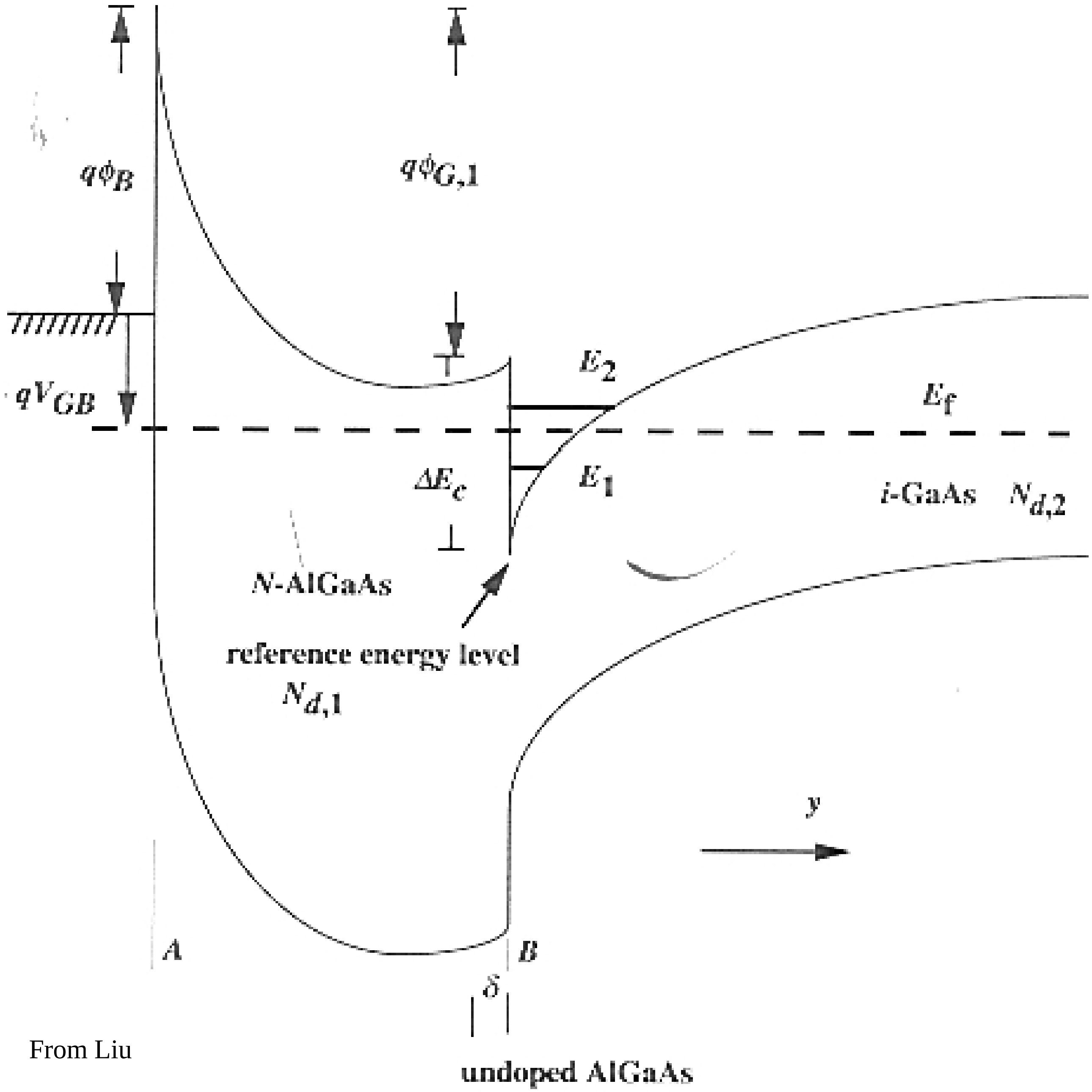
GaSb
InAs
InSb
HgTe

n_s vs E_f

After all that mumbo-jumbo, we know it is complicated.
We approximate it many times as:

$$E_f(n_s) = E_{f,0} + a \cdot n_s$$

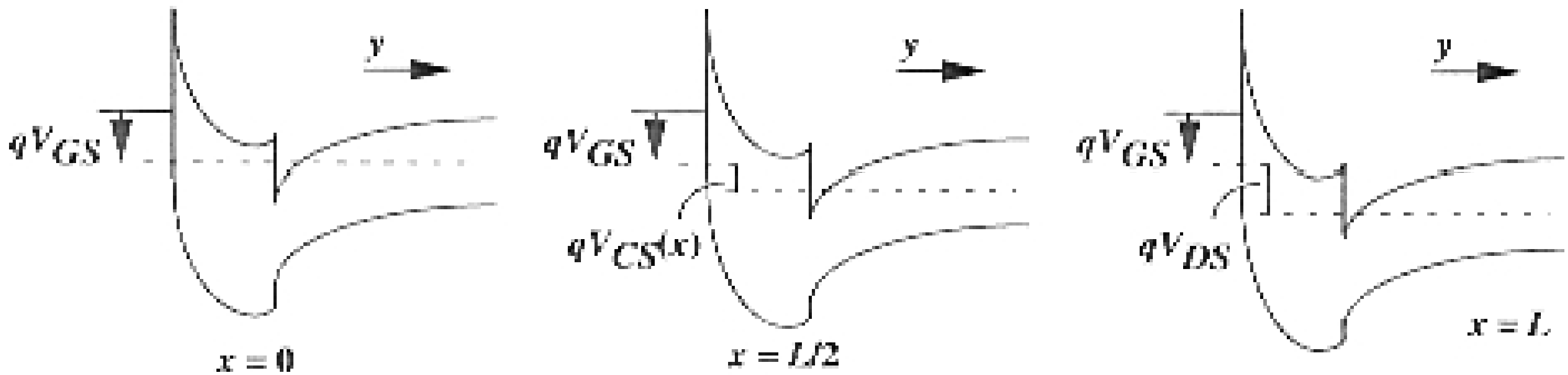
Gate



Gate changes E_f with respect to reference energy. This changes density.

From Liu

Vary gate voltage



Changes Fermi energy which changes density.

(Draw better pictures on board.)

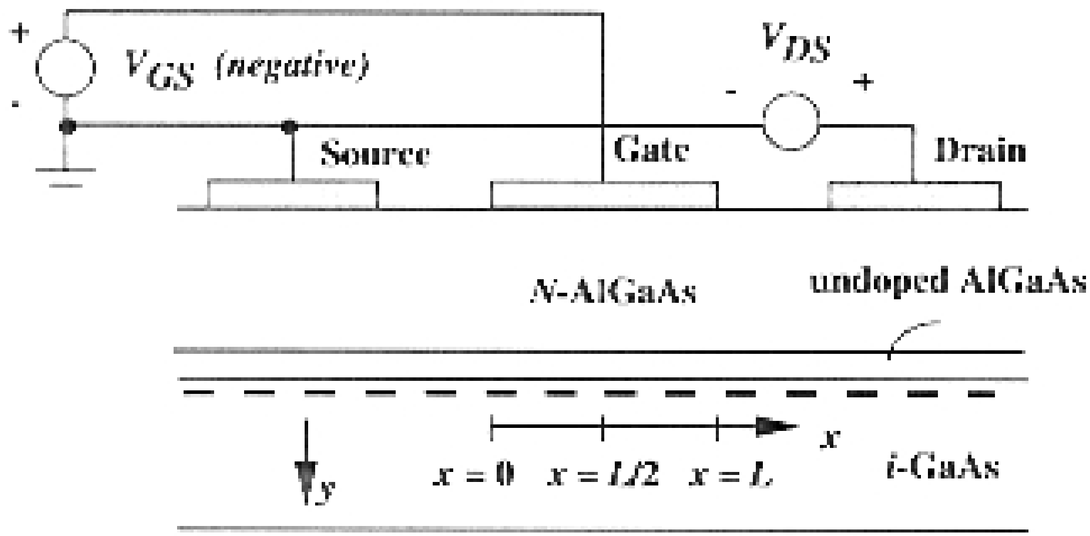
From Liu.

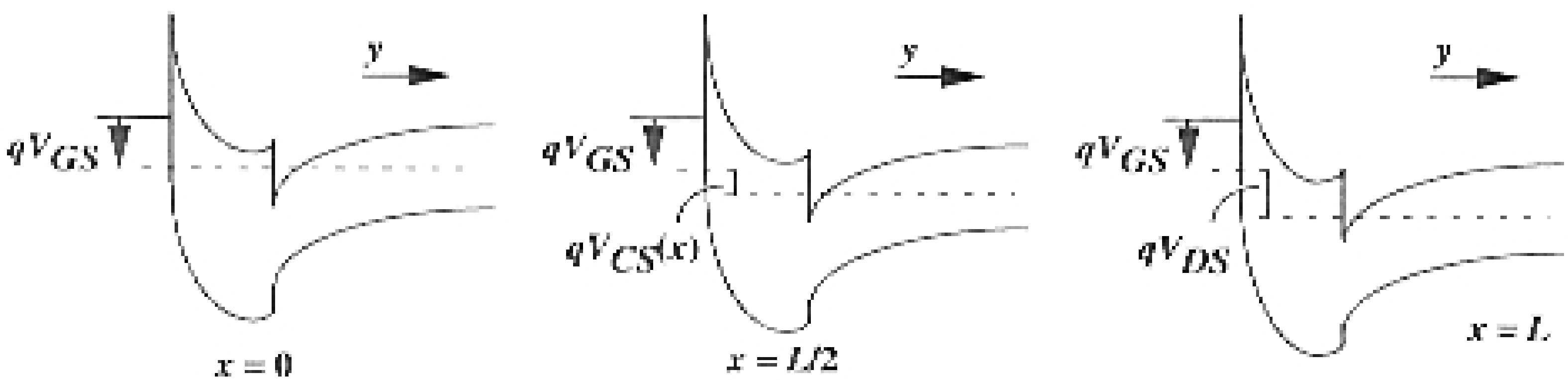
Density

$$en_s = \frac{\varepsilon}{t_b + \varepsilon a / e^2}\left(V_{GB} - V_T\right)$$

$$V_T \equiv \phi_B + \frac{E_{f,0}}{e} - \frac{eN_{d,1}}{2\varepsilon}(t_b - \delta)^2 - \frac{\Delta E_c}{e}$$

HEMT analysis





From Liu.

Density

$$en_s = \frac{\varepsilon}{t_b + \varepsilon a / e^2}\left(V_{GB} - V_T\right)$$

$$\rightarrow en_s(x) = C_{ox}\left(V_{GS} - V_T - V_{CS}(x)\right)$$

$$C_{ox} \equiv \frac{\varepsilon}{t_b + \varepsilon a / e^2}$$

$$V_{CS}(0) = 0$$

$$V_{CS}(L) = V_{SD}$$

Current

J is 2d, n_s is 2d. (Discuss).

$$J = e \cdot \mu \cdot n_s \cdot E$$

$$I_D = J \cdot (width) = e \cdot \mu \cdot n(x) \cdot E(x) \cdot W$$

$$I_D = \mu \cdot C_{ox}\left(V_{GS} - V_T - V_{CS}(x)\right) \cdot E(x) \cdot W$$

$$= \mu \cdot C_{ox}\left(V_{GS} - V_T - V_{CS}(x)\right) \cdot \frac{\partial V_{CS}(x)}{\partial x} \cdot W$$

Integrating:

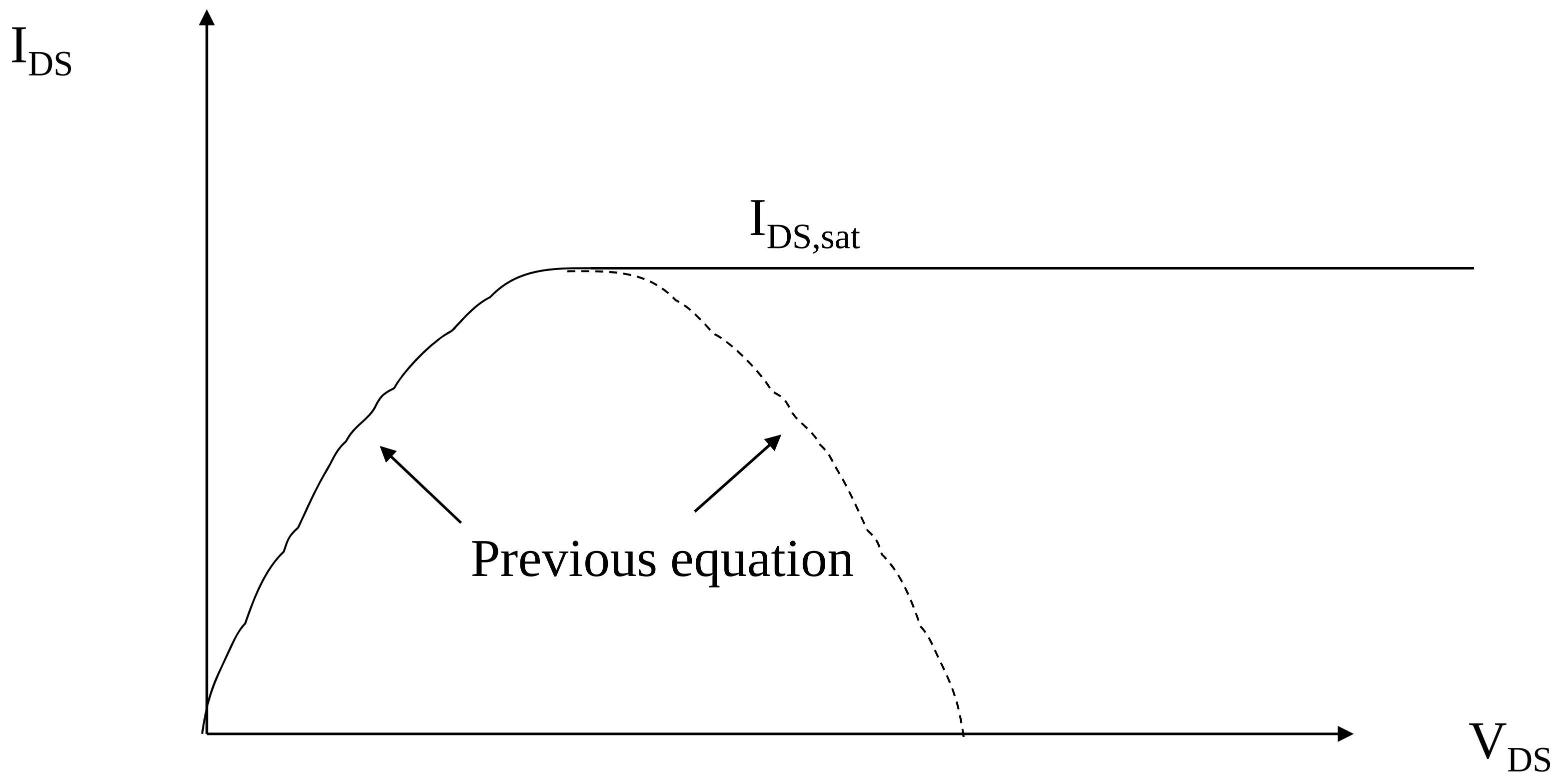
$$I_D = \mu \cdot C_{ox}\left(V_{GS} - V_T - V_{CS}(x)\right) \cdot \frac{\partial V_{CS}(x)}{\partial x} \cdot W$$

$$\int_0^L I_D dx = \int_0^L \mu \cdot C_{ox}\left(V_{GS} - V_T - V_{CS}(x)\right) \cdot \frac{\partial V_{CS}(x)}{\partial x} \cdot W dx$$

$$= \int_{V_{CS}(0)}^{V_{CS}(L)} \mu \cdot C_{ox}\left(V_{GS} - V_T - V_{CS}(x)\right) \cdot \partial V_{CS}(x) \cdot W = doable$$

$$\boxed{I_D = \frac{W \cdot \mu \cdot C_{ox}}{L}\left[(V_{GS} - V_T)V_{DS} - \frac{{V_{DS}}^2}{2}\right]}$$

Conclusion:



Channel potential:

$$J = e \cdot \mu \cdot n_s \cdot E$$

$$I_D = J \cdot (width) = e \cdot \mu \cdot n(x) \cdot E(x) \cdot W$$

Since we are in 2d, no position dependent thickness b(x). Life is easier.
It can be shown that:

$$V_{CS}(x) = (V_{GS} - V_T)\left[1 - \sqrt{1 - \frac{x}{L}\left(1 - \alpha^2\right)}\right]$$

$$\alpha \equiv \begin{cases} 1 - V_{DS}/V_{DS,sat} & \text{for} \quad V_{DS} < V_{DS,sat} \\ 0 & \text{for} \quad V_{DS} > V_{DS,sat} \end{cases}$$

Velocity saturation

- Just like MESFETs
- Important in short channel HEMTs
- Need to model channel as to regions: saturated and unsaturated
- Qualitative IVs are similar