EE-612:
Lecture 14:
V_T Engineering

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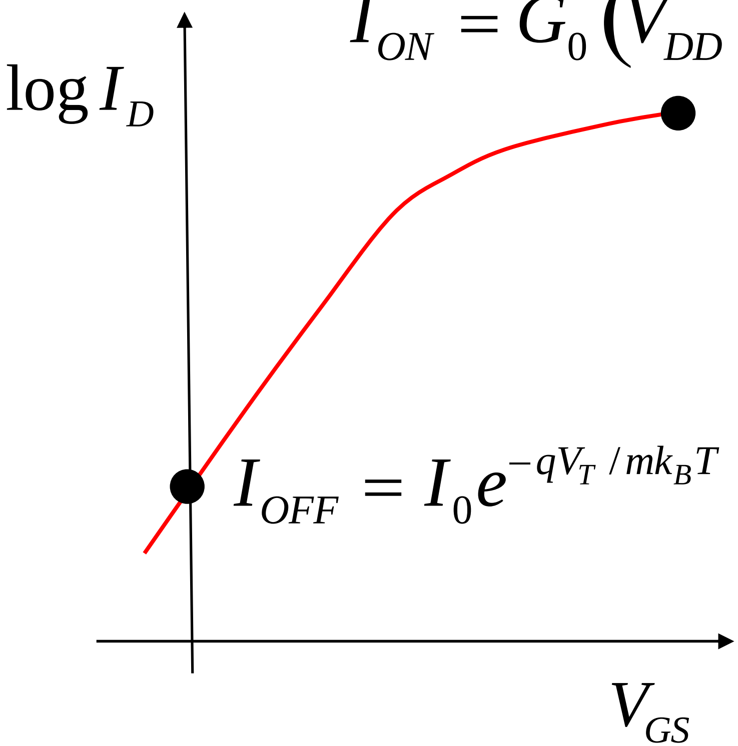
objective

The doping profiles in modern MOSFETs are complex. Our goal is to develop an intuitive understanding of how non-uniform doping profiles affect the threshold voltage and 2D electrostatics.

outline

1) V_T Specification
2) Uniform Doping
3) Delta-function doping, $x_C = 0$
4) Delta-function doping, $x_C > 0$
5) Stepwise uniform
6) Integral solution

threshold voltage specification



$$I_{ON} = G_0 \left(V_{DD} - V_T\right)^{\alpha}$$

$$I_{OFF} = I_0 e^{-qV_T / mk_B T}$$

1) ***I_{OFF}***
largest value that designers can live with.

2) ***I_{ON}***
smallest value for required system performance.

3) ***V_{DD}***
smallest value consistent with I_{ON} target.

ITRS: 2008 (HP)

High-performance logic: 2008 (59 nm node - bulk planar)

i) physical gate length: 22 nm

ii) EOT_{elec} = 1.21 nm

iii) V_{DD} = 1.0V

iv) I_{OFF} = 0.71 μA/μm

v) Ion = 1513 μA/μm

vi) V_T(sat) = 0.094V

ITRS 2007 edition
Table PIDS 2a
www.itrs.net

$V_T \approx 9.4\% V_{DD}$

ITRS: 2008 (LSP)

Low Standby Power logic: 2009 (59nm node - bulk planar)

i) physical gate length: 37 nm

ii) EOT_{elec} = 1.93 nm

iii) V_{DD} = 1.1V

iv) I_{OFF} = 3.3 x 10^{-5} μA/μm

v) Ion = 569 μA/μm

vi) V_T(sat) = 0.567V

ITRS 2007 edition
Table PIDS 3a
www.itrs.net

$V_T \approx 52\% V_{DD}$

outline

1) V_T Specification

2) Uniform Doping

3) Delta-function doping, $x_C = 0$

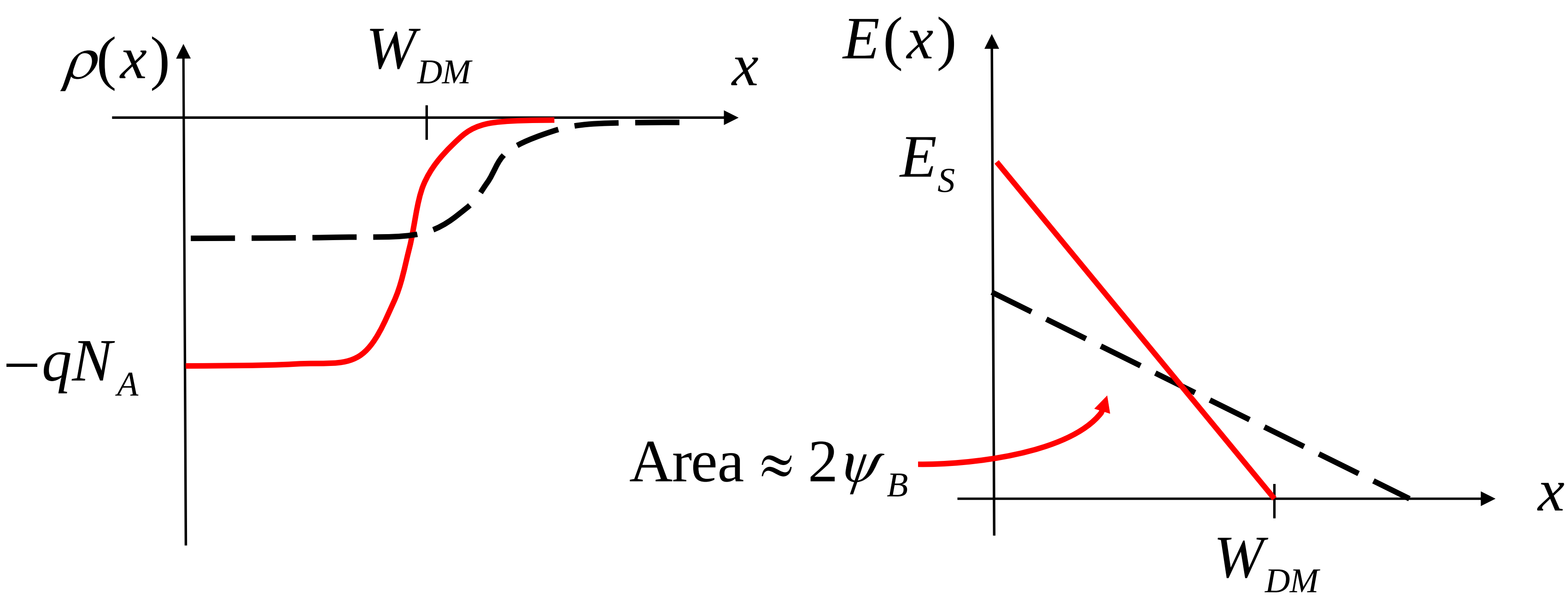
4) Delta-function doping, $x_C > 0$

5) Stepwise uniform

6) Integral solution

uniform doping

$$dE/dx = -qN_A/\varepsilon_{Si}$$



- N_A controls W_{DM} **and** E_S
- lighter N_A gives bigger W_{DM} and smaller E_S
- ψ_B relatively insensitive to N_A

uniform doping (ii)

W_{DM} controls short channel effects

$$\text{need } L / mW_{DM} > 2$$

E_S controls threshold voltage

$$V_T = V_{FB} + 2\psi_B - Q_{DM} / C_{ox}$$
$$= V_{FB} + 2\psi_B + \varepsilon_{Si} E_S / C_{ox}$$

***both** are set by the doping density*

$$W_{DM} = \sqrt{4\varepsilon_{Si}\psi_B / qN_A} \quad E_S = qN_A W_{DM} / \varepsilon_{Si} = \sqrt{4qN_A\psi_B / \varepsilon_{Si}}$$

uniform doping (iii)

High N_A *gives small* W_{DM} and good short channel effects, but V_T may be too high.

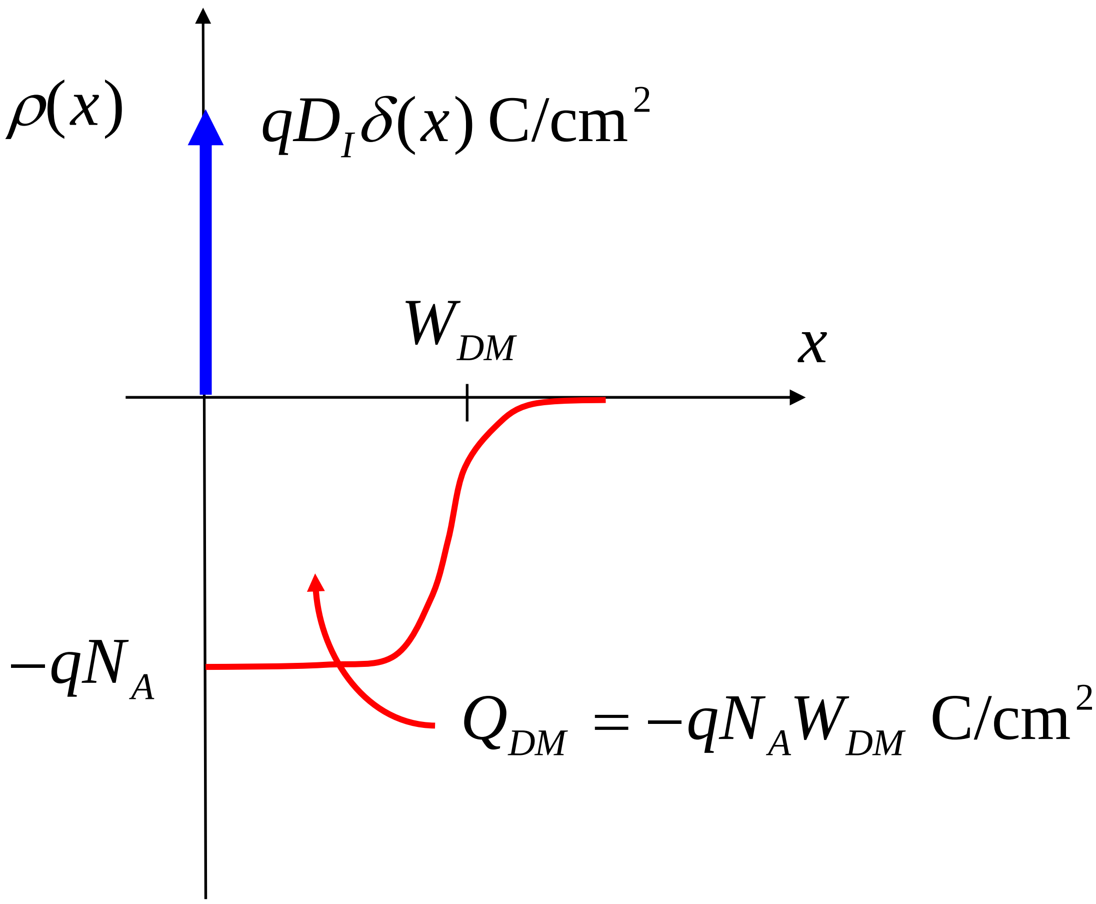
We would like to control W_{DM} and V_T independently.

Solution: non-uniform doping.

outline

1) V_T Specification
2) Uniform Doping
3) **Delta-function doping, $x_C = 0$**
4) Delta-function doping, $x_C > 0$
5) Stepwise uniform
6) Integral solution

delta function at the surface



D_I: dose (cm^{-2})

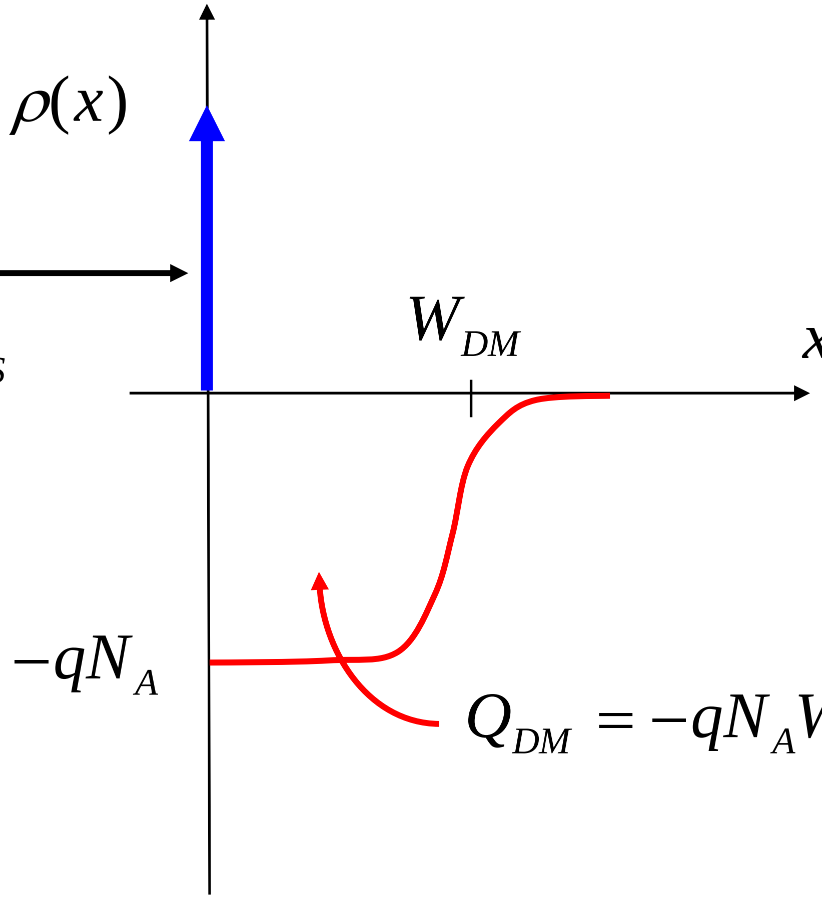
>0 (As^+, P^+)
<0 (B^-)

(assume net p-type doping ($Q_S < 0$))

electrostatics

$$D_S = \varepsilon_{Si} E_S = -Q_S$$

$$Q_S = Q_{DM} + qD_I$$

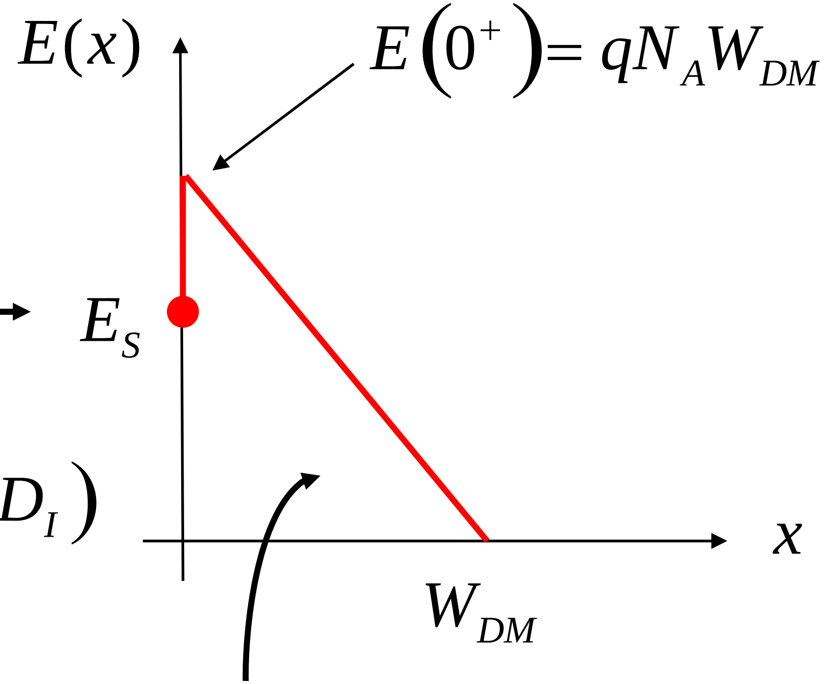


$$Q_{DM} = -qN_A W_{DM} \ \mathrm{C/cm^2}$$

(assume net p-type doping ($Q_S < 0$))

electrostatics (ii)

$$E\left(0^{+}\right) = qN_A W_{DM} / \varepsilon_{Si}$$



$$\varepsilon_{Si} E_S = -Q_S$$
$$= \left(qN_A W_{DM} - qD_I\right)$$

$$E_S = E\left(0^{+}\right) - qD_I / \varepsilon_{Si}$$

Area $= 2\psi_B$
did not change

electrostatics (iii)

$$W_{DM} = \sqrt{4\varepsilon_{Si}\psi_B / qN_A}$$ does not depend on D_I

$$V_T = V_{FB} + 2\psi_B - \left(Q_{DM} + qD_I\right)/C_{ox}$$

$$\Delta V_T = -qD_I / C_{ox}$$

i) select N_A for $L / mW_{DM} > 2$

ii) select D_I for desired V_T

W_{DM} and V_T can be selected independently!

outline

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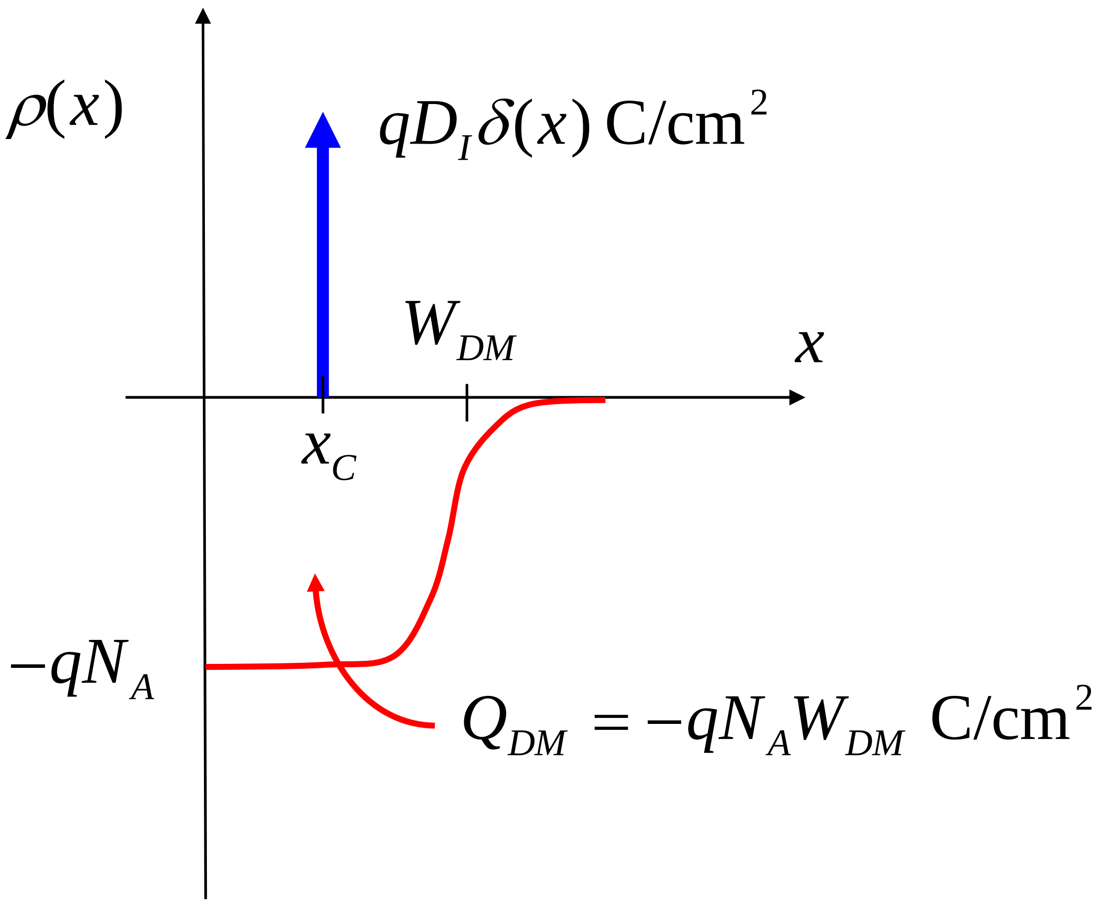
5) Stepwise uniform

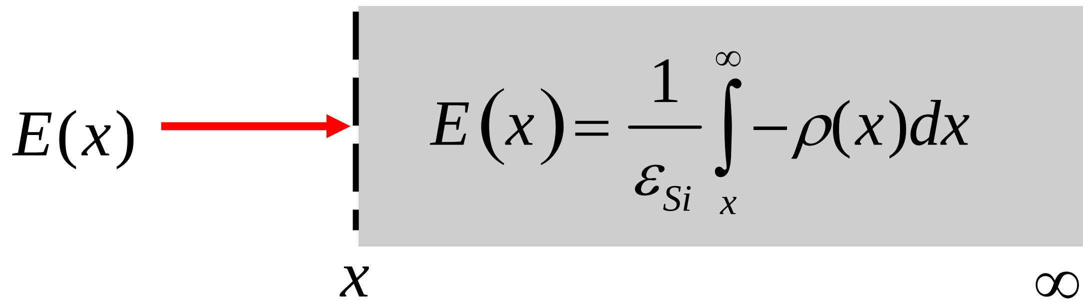
6) Integral solution

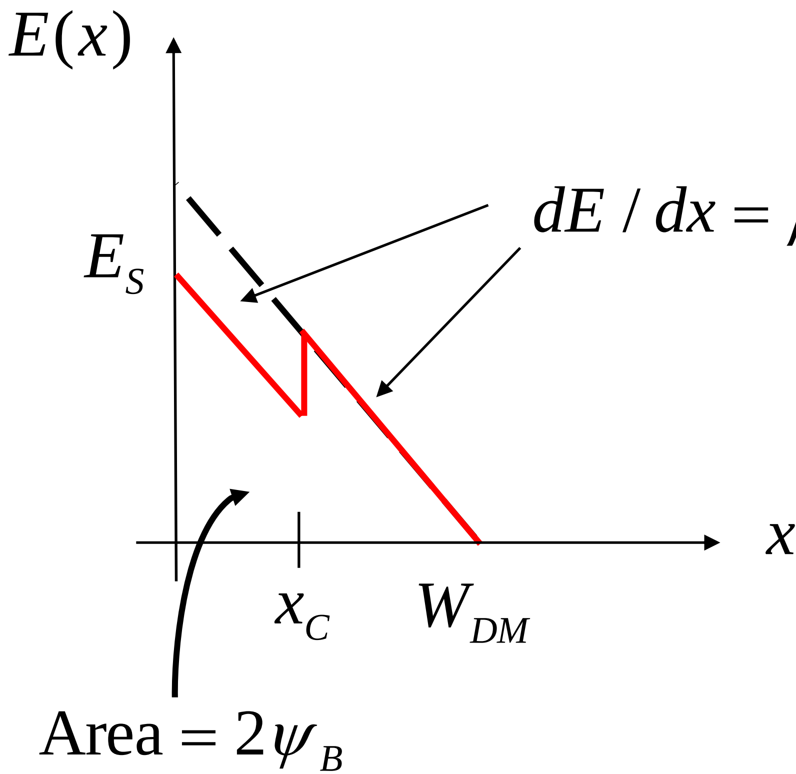
delta function at $x = x_C$



(assume net p-type doping ($Q_S < 0$))

electrostatics





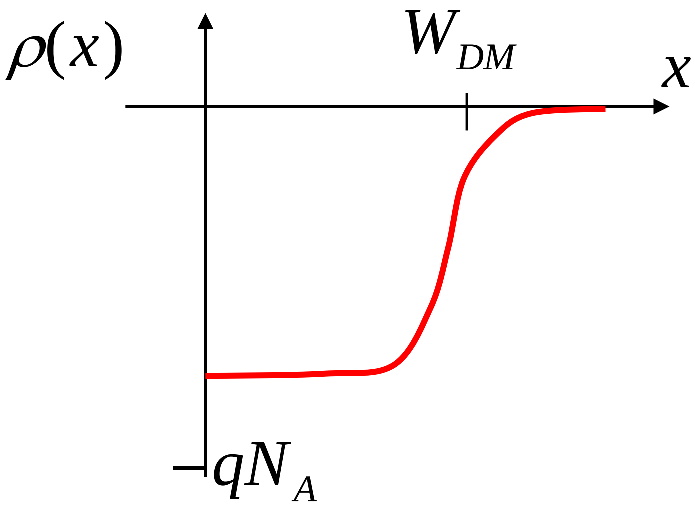
E_S decreased

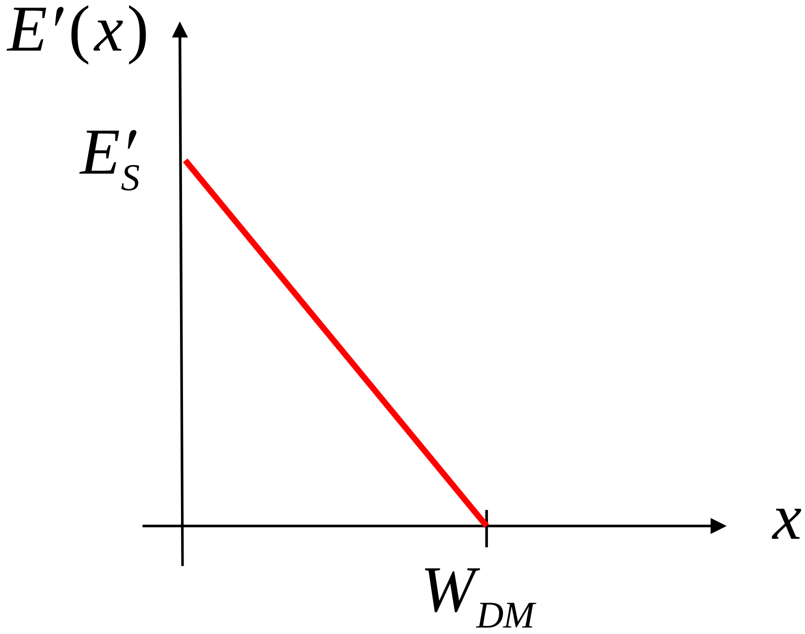
V_T decreased

How is W_{DM} affected?

electrostatics (ii)

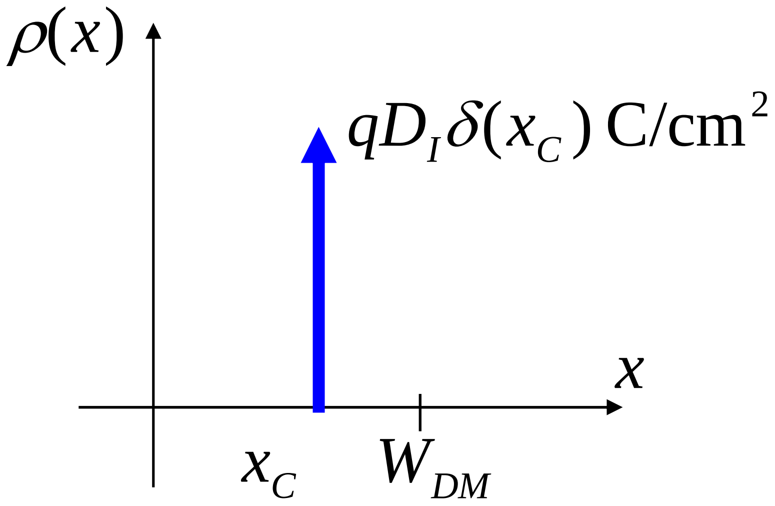
$dE / dx = \rho / \varepsilon_{Si}$ solve by superposition

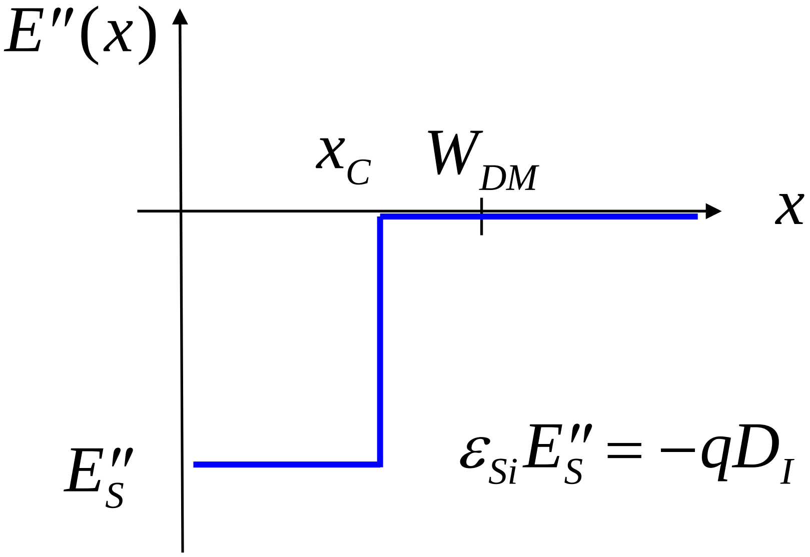




$$\psi'_S = \frac{1}{2} E'_S W_{DM} = \frac{1}{2} \left(\frac{qN_A W_{DM}}{\varepsilon_{Si}} \right) W_{DM}$$

electrostatics (iii)





$$\psi''_S = E_S x_C = \left(\frac{-qD_I}{\varepsilon_{Si}}\right) x_C$$

electrostatics (iv)

$$2\psi_B = \psi_S' + \psi_S'' = \frac{1}{2}\left(\frac{qN_A W_{DM}}{\varepsilon_{Si}}\right) W_{DM} - \frac{qD_I}{\varepsilon_{Si}} x_C$$

$$W_{DM} = \sqrt{\frac{2\varepsilon_{Si}}{qN_A}\left(2\psi_B + qD_I x_C / \varepsilon_{Si}\right)}$$

$$V_T = V_{FB} + 2\psi_B - \left(Q_{DM} + qD_I\right)/C_{ox}$$

$$V_T = V_{FB} + 2\psi_B + \frac{1}{C_{ox}}\sqrt{2qN_A\varepsilon_{Si}\left(2\psi_B + qD_I x_C / \varepsilon_{Si}\right)} - \frac{qD_I}{C_{ox}}$$

electrostatics (v)

$$W_{DM} = \sqrt{\frac{2\varepsilon_{Si}}{qN_A}\left(2\psi_B + qD_I x_C / \varepsilon_{Si}\right)}$$

$$V_T = V_{FB} + 2\psi_B + \frac{1}{C_{OX}}\sqrt{\frac{2\varepsilon_{Si}}{qN_A}\left(2\psi_B + qD_I x_C / \varepsilon_{Si}\right)} - \frac{qD_I}{C_{OX}}$$

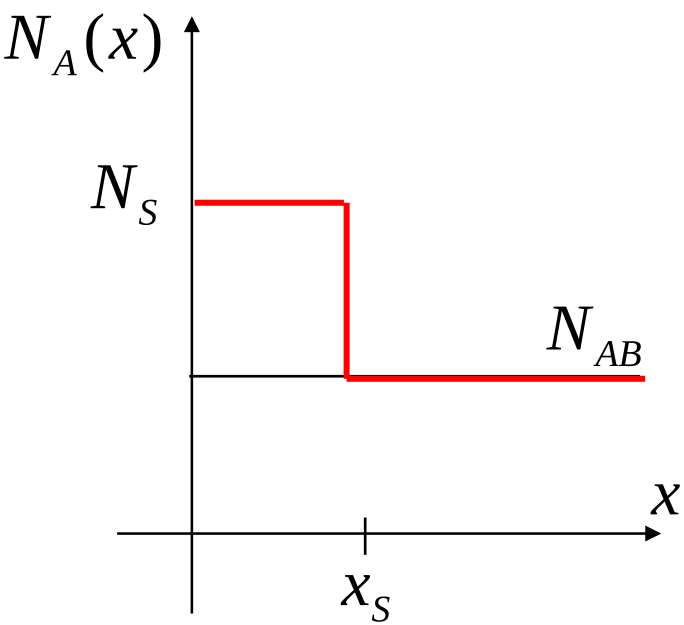
When $x_C > 0$, both W_{DM} and V_T are affected, but when x_C is close to 0, we get a large change in V_T and a small change in W_{DM}

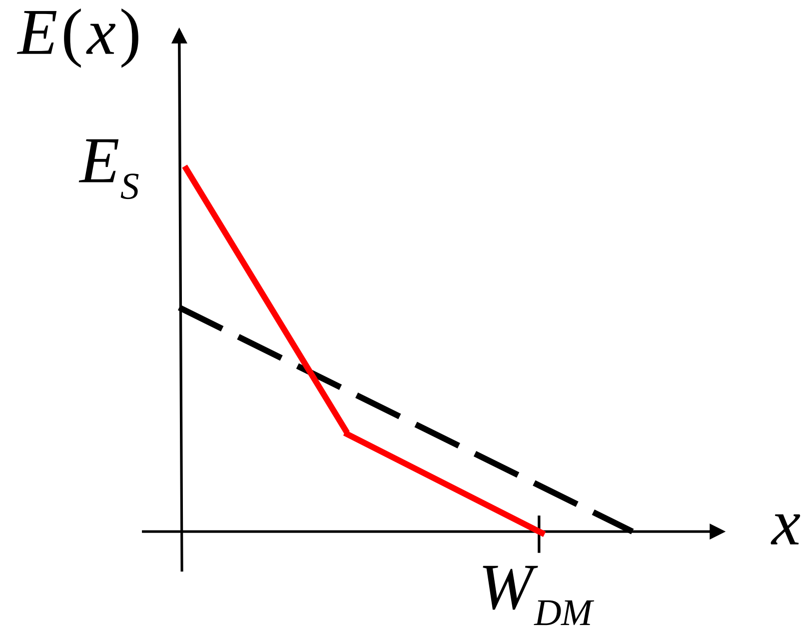
outline

1) V_T Specification
2) Uniform Doping
3) Delta-function doping, $x_C = 0$
4) Delta-function doping, $x_C > 0$
5) **Stepwise uniform**
6) Integral solution

stepwise constant doping

$$dE / dx = -qN_A / \varepsilon_{Si}$$

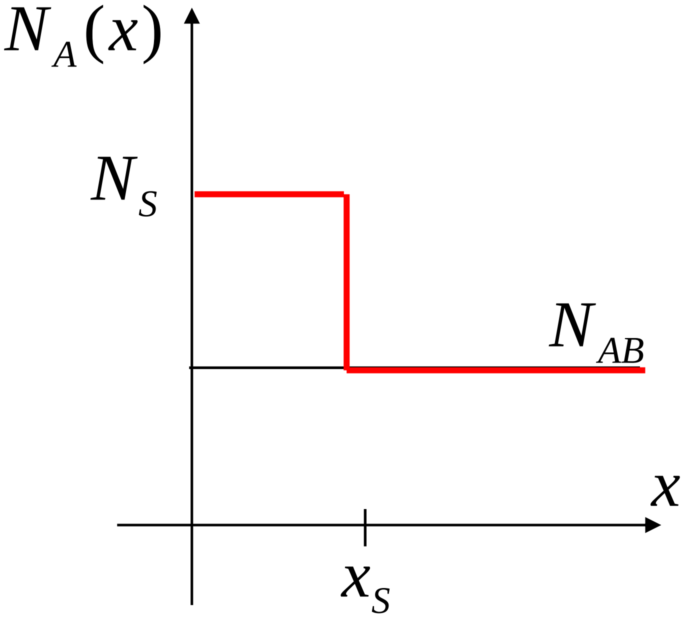




$$\text{Area} \approx 2\psi_B$$

Result: smaller W_{DM} higher V_T (than uniform doping)

stepwise constant doping (ii)

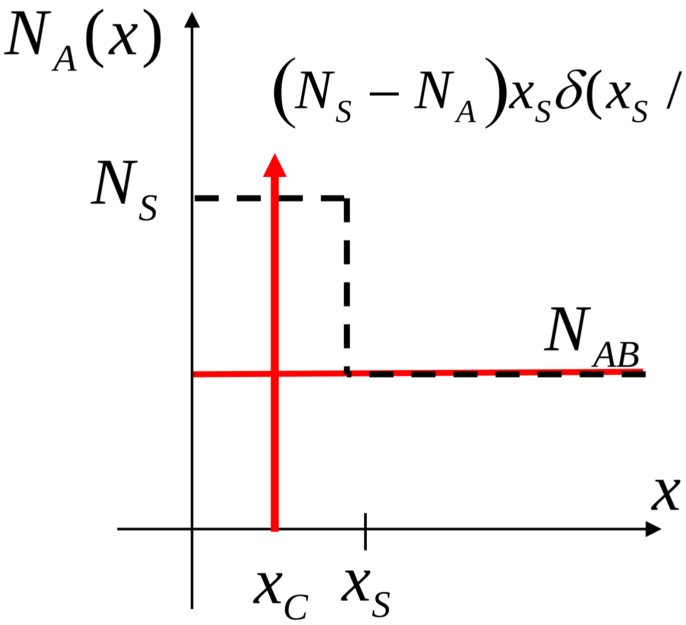


See Tau and Ning. pp. 178-181 for the solution to Poisson's equation for this profile.

Eqn. (4.28) for V_T

Eqn. (4.29) for W_{DM}

stepwise constant (mathematics)



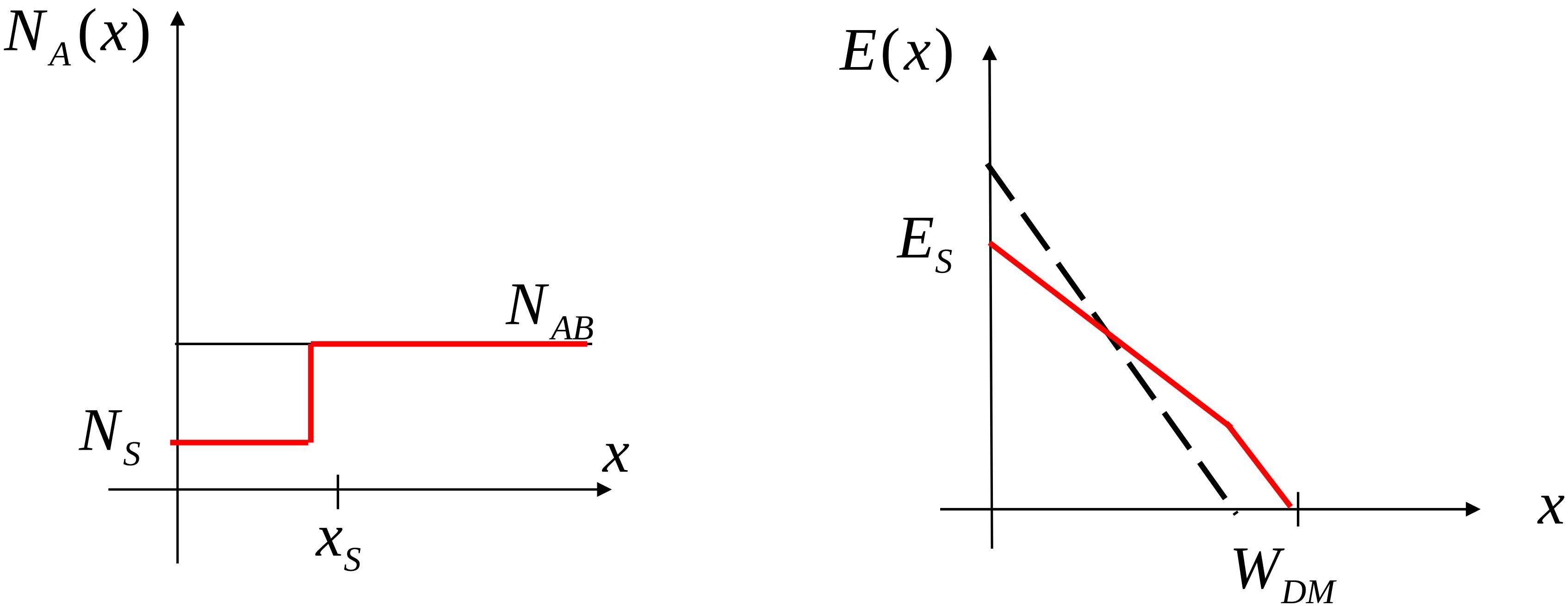
$$qD_I = -q(N_S - N_{AB})x_S$$

$$x_C = x_S/2$$

Use delta function results for W_{DM} and V_T

"retrograde" doping

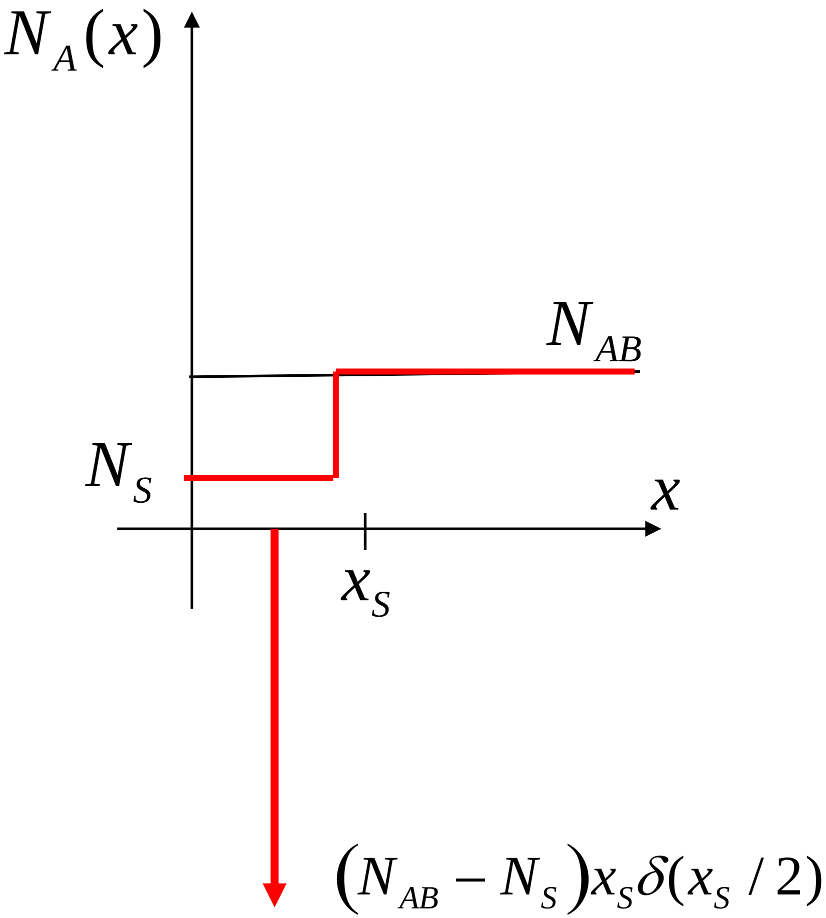
$$dE / dx = -qN_A / \varepsilon_{Si}$$



$$\text{Area} \approx 2\psi_B$$

Result: larger W_{DM} lower V_T (than uniform doping)

retrograde doping

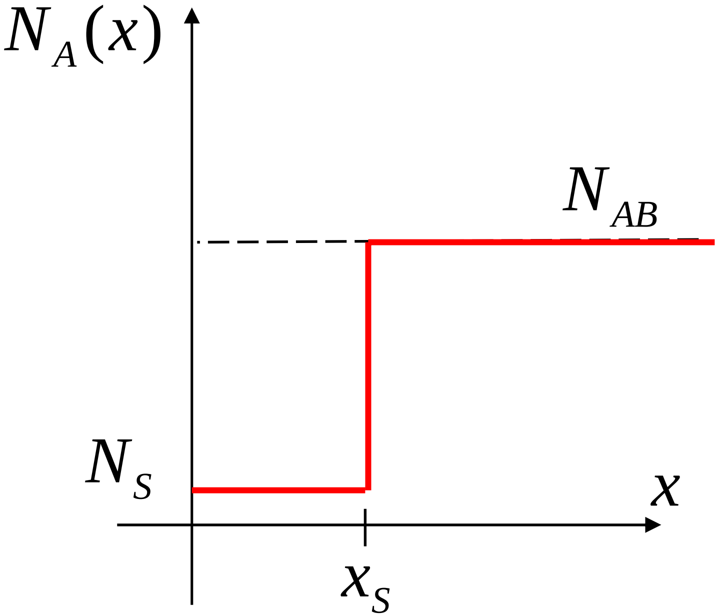


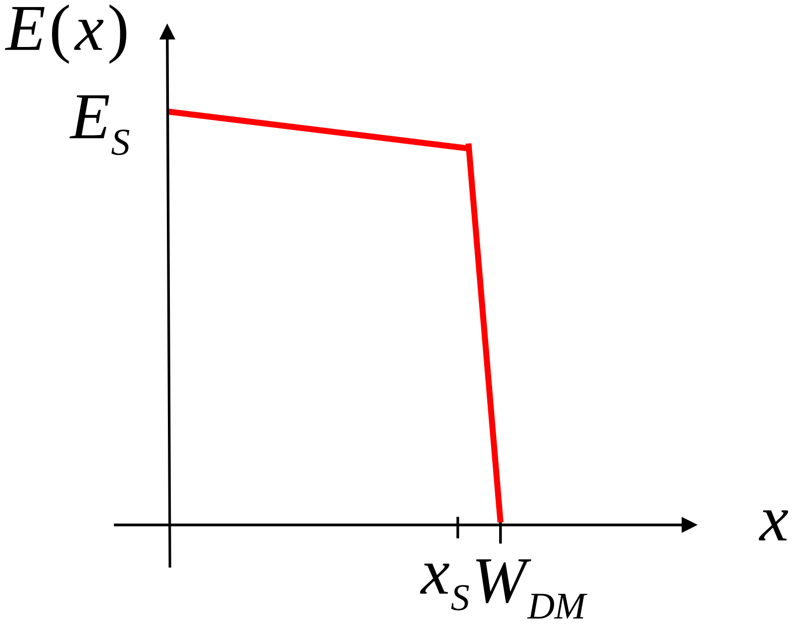
'equivalent' to a delta-function of positive charge at $x_C/2$

$$D_I = \left(N_{AB} - N_S\right)x_S\delta\left(x_S/2\right)$$

ground plane doping

$$dE / dx = -qN_A / \varepsilon_{Si}$$



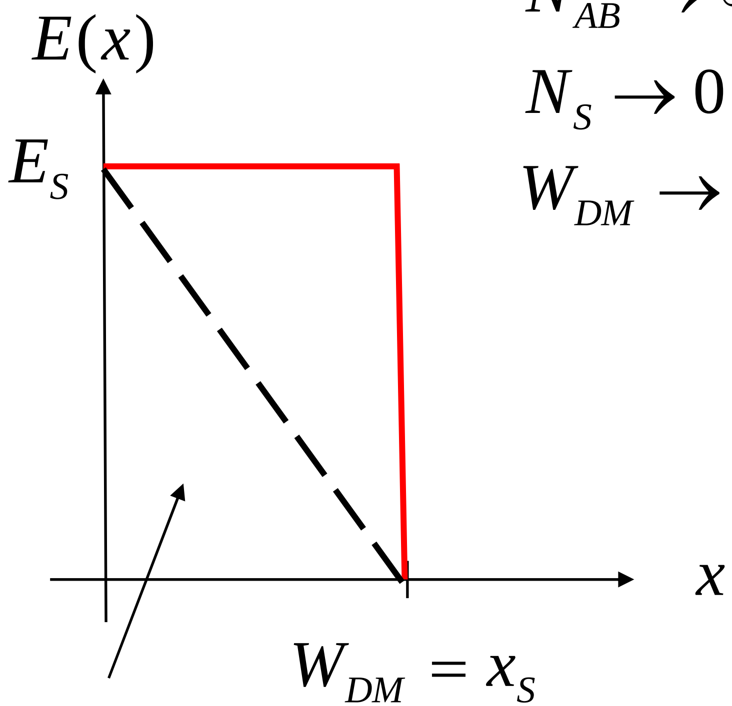


ideal ground plane doping

$$N_{AB} \to \infty$$

$$N_S \to 0$$

$$W_{DM} \to x_S$$



$$E_S W_{DM} = 2\psi_B$$

$$\frac{1}{2} E_S W_{DM} = 2\psi_B \quad \text{(uniform)}$$

$$E_S = 2\psi_B / W_{DM}$$

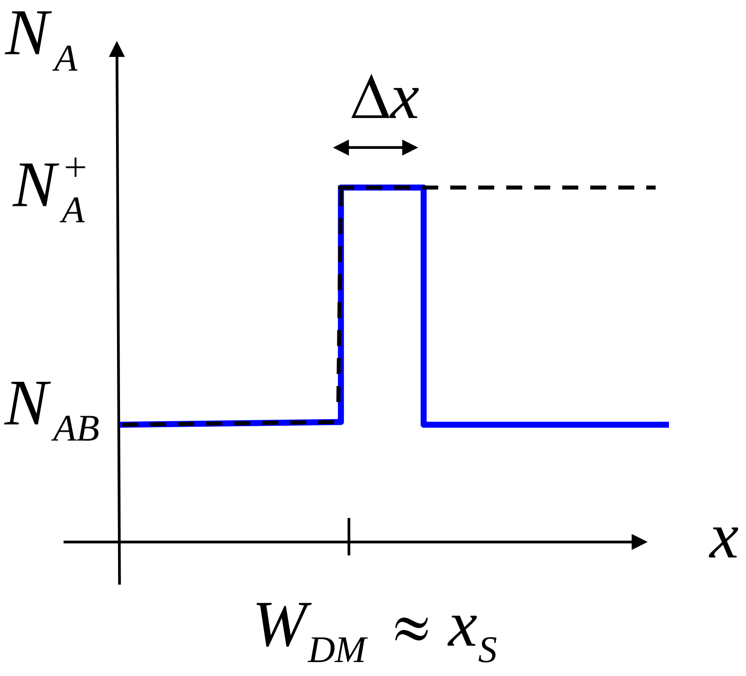
(ground plane)

$$E_S = 4\psi_B / W_{DM}$$

(uniform)

For the same W_{DM}, we get half the electric field at the surface and, therefore, a lower V_T.

delta doping

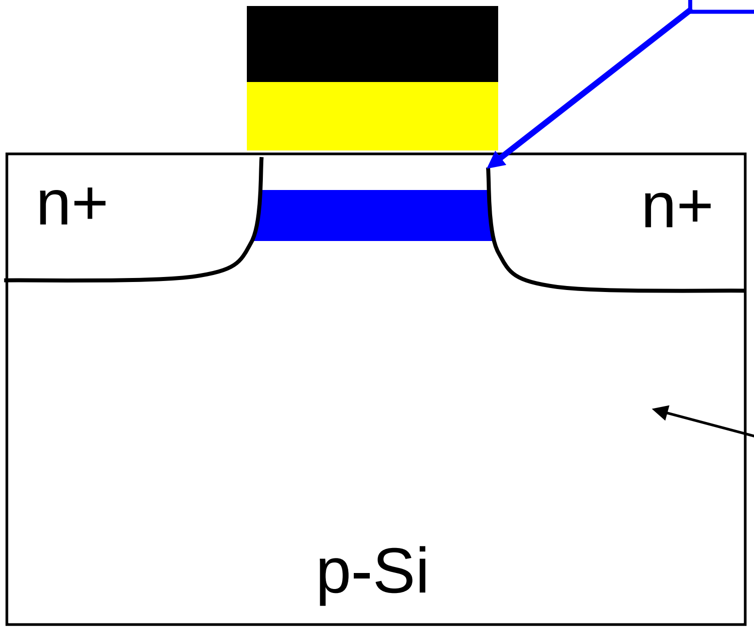


$$2\psi_B = E_S x_S$$

$$\varepsilon_{Si} E_S \leq q N_A^+ \Delta x$$

$$N_A^+ \Delta x \geq \frac{\varepsilon_{Si} 2\psi_B}{q x_S}$$

delta doping (iii)



delta doping to set W_{DM} and V_T

light doping for low C_J and junction low leakage

outline

1) V_T Specification

2) Uniform Doping

3) Delta-function doping, $x_C = 0$

4) Delta-function doping, $x_C > 0$

5) Stepwise uniform

6) Integral solution

integral solution to Poisson's equation

$$dE / dx = -qN_A(x) / \varepsilon_{Si}$$

$$\int_{E(x)}^{0} dE = -\frac{q}{\varepsilon_{Si}} \int_{x}^{W_D} N_A(x)dx$$

$$-E(x) = -\frac{q}{\varepsilon_{Si}} \int_{x}^{W_D} N_A(x)dx$$

$$E(x) = \frac{q}{\varepsilon_{Si}} \int_{x}^{W_D} N_A(x)dx$$

integral solution (ii)

$$\psi_S = -\int_0^{W_D} E(x)dx$$

$$E(x) = \frac{q}{\varepsilon_{Si}} \int_x^{W_D} N_A(x)dx$$

$$\psi_S = -\int_0^{W_D} \left[\int_x^{W_D} \frac{q}{\varepsilon_{Si}} N_A(x')dx' \right] dx$$

$$\underbrace{\left[\int_x^{W_D} \frac{q}{\varepsilon_{Si}} N_A(x')dx' \right]}_{u} \underbrace{dx}_{dv}$$

$$\int u dv = uv - \int v du$$

$$\psi_S = \frac{q}{\varepsilon_{Si}} \int_0^{W_D} xN(x)dx$$

integral solution (iii)

$$E_S = \frac{q}{\varepsilon_{Si}} \int_0^{W_{DM}} N_A(x)dx$$

integral of doping controls V_T

$$2\psi_B = \frac{q}{\varepsilon_{Si}} \int_0^{W_{DM}} xN(x)dx$$

first moment of doping controls W_{DM}

see Taur and Ning, p. 177

integral solution (iv)

$$2\psi_B = \frac{q}{\varepsilon_{Si}} \int_0^{W_{DM}} x N(x) dx \qquad N_A(x) = N_{AB} + \delta N_A'(x)$$

$$2\psi_B = \frac{q N_{AB}}{\varepsilon_{Si}} \frac{W_{DM}^2}{2} + \frac{q}{\varepsilon_{Si}} \int_0^{W_{DM}} x \delta N_A'(x) dx$$

$$2\psi_B = \frac{q N_{AB}}{2\varepsilon_{Si}} W_{DM}^2 + \frac{\frac{q}{\varepsilon_{Si}} \int_0^{W_{DM}} x \delta N_A'(x) dx}{\int_0^{W_{DM}} \delta N_A'(x) dx} \int_0^{W_{DM}} \delta N_A'(x) dx$$

x_C

$-D_I$

integral solution (v)

$$2\psi_B = \frac{q}{\varepsilon_{Si}} \int_0^{W_{DM}} xN(x)dx$$

$$N_A(x) = N_{AB} + \delta N_A'(x)$$

$$2\psi_B = \frac{qN_{AB}}{2\varepsilon_{Si}} W_{DM}^2 + -qD_I x_C$$

$$D_I = -\int_0^{W_{DM}} \delta N_A'(x)dx$$

$$x_C = \frac{\int_0^{W_{DM}} x\delta N_A'(x)dx}{\int_0^{W_{DM}} \delta N_A'(x)dx}$$

just like the result we got for:

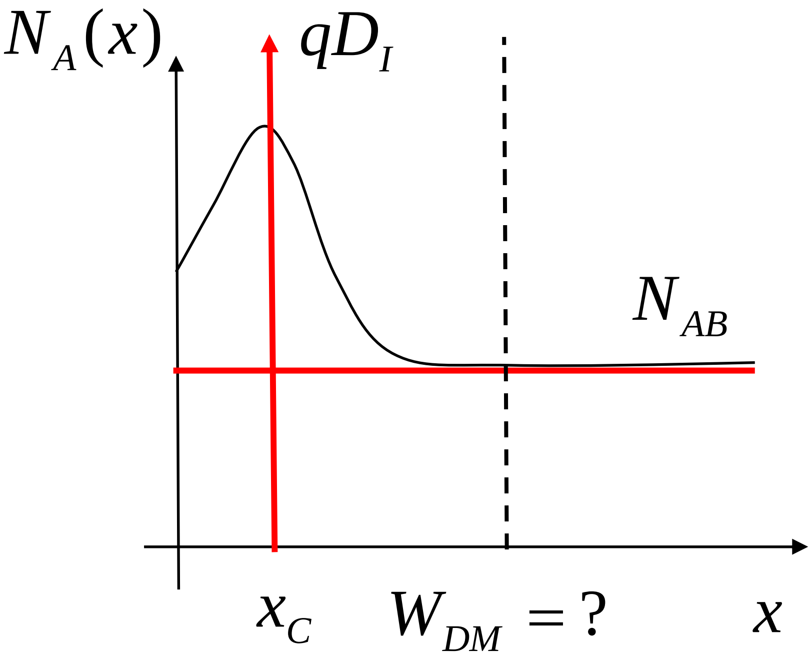
$$N_A(x) = N_{AB} - qD_I \delta(x_C)$$

integral solution (vi)

$$W_{DM} = \sqrt{\frac{2\varepsilon_{Si}}{qN_A}\left(2\psi_B + qD_I x_C / \varepsilon_{Si}\right)}$$

$$V_T = V_{FB} + 2\psi_B - Q_S / C_{ox}$$

$$Q_S = -q \int_0^{W_{DM}} N_A(x)dx$$



$$V_T = ?$$

outline

1) V_T Specification
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3) Delta-function doping, $x_C = 0$
4) Delta-function doping, $x_C > 0$
5) Stepwise uniform
6) Integral solution
7) Summary

summary

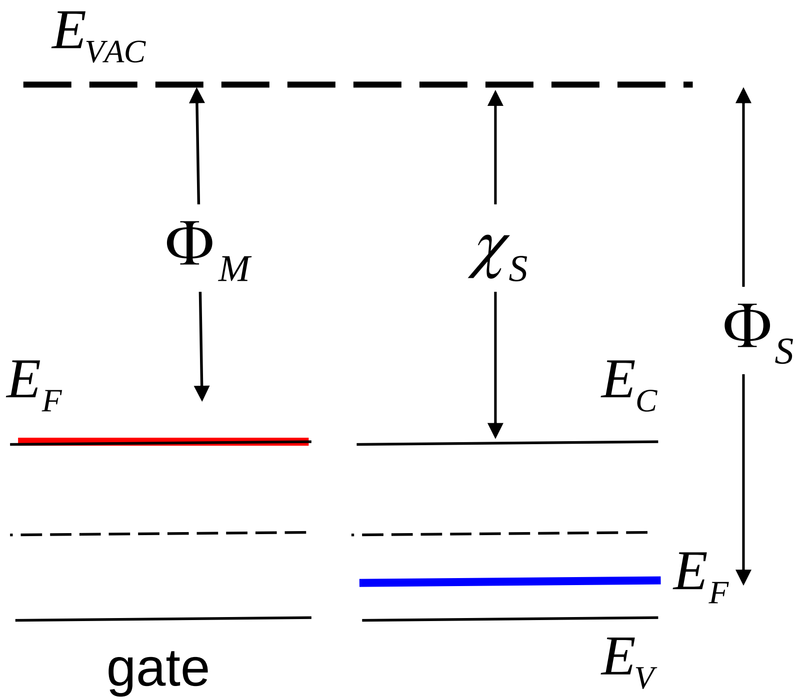
1) V_T engineering involves setting V_T, W_{DM}, and considerations such as junctions capacitance and body effect.

2) Uniform doping sets both V_T and W_{DM}

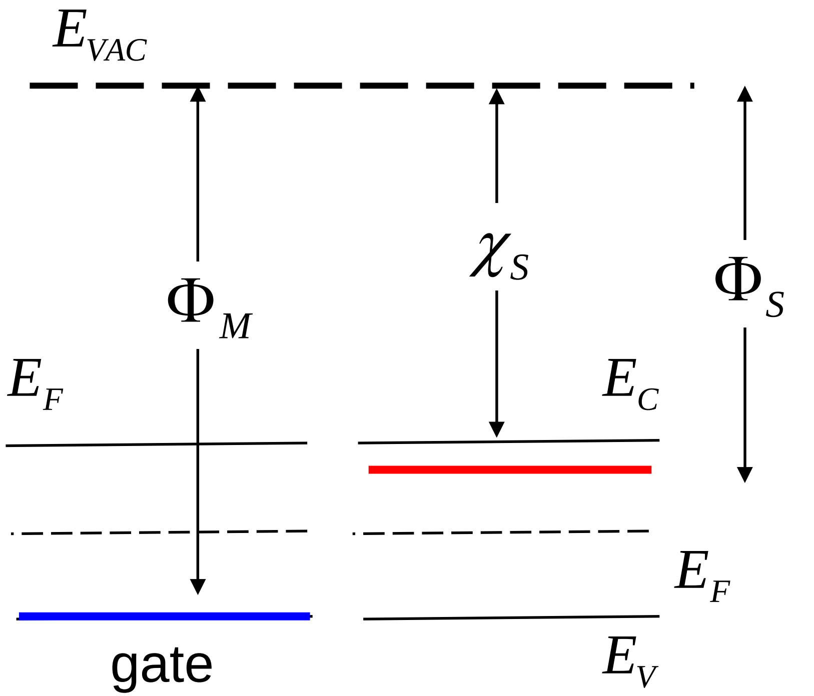
3) Nonuniform doping profiles can be used to achieve a thin W_{DM} without an unacceptably high V_T.

4) For metal gates, V_T engineering also involves “workfunction engineering.”

workfunctions



n-channel



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