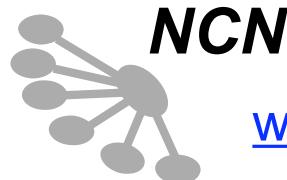


# **EE-612:**

# **Lecture 18:**

# **V<sub>T</sub> Engineering**

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Fall 2006



[www.nanohub.org](http://www.nanohub.org)

Lundstrom EE-612 F06

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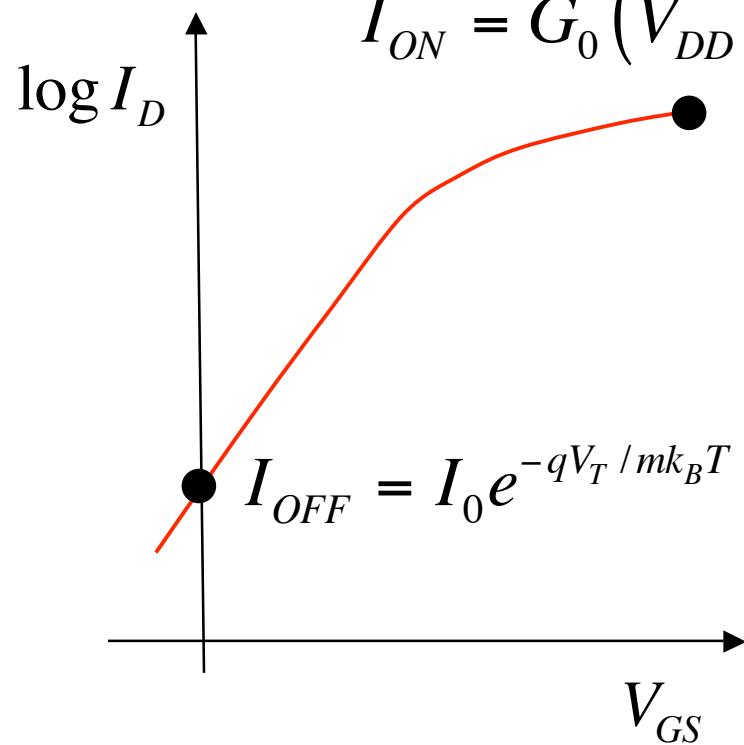
# outline

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- 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

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- 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 70 nm node (HP)

---

High-performance logic: 2006 (70nm node - bulk planar)

- i) physical gate length: 28 nm
- ii)  $EOT_{elec} = 1.84 \text{ nm}$
- iii)  $V_{DD} = 1.1V$
- iv)  $I_{OFF} = 0.15 \mu\text{A}/\mu\text{m}$
- v)  $I_{on} = 1130 \mu\text{A}/\mu\text{m}$
- vi)  $V_T(\text{sat}) = 0.168V$



ITRS 2005 edition  
[www.itrs.net](http://www.itrs.net)

$$V_T \approx 15\% V_{DD}$$

# ITRS 14 nm node (HP)

---

High-performance logic: 2020 (14nm node - DG)

- i) physical gate length: 5 nm (28)
- ii)  $EOT_{elec} = 0.9$  nm (1.84)
- iii)  $V_{DD} = 0.7V$  (1.1)
- iv)  $I_{OFF} = 0.11 \mu A/\mu m$  (0.15)
- v)  $I_{on} = 2981 \mu A/\mu m$  (1130)
- vi)  $V_T(\text{sat}) = 0.208V$  (0.168)

ITRS 2005 edition

# ITRS 70 nm node (LSP)

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low stand-by power logic: 2006 (70nm node - bulk planar)

- i) physical gate length: 28 nm
- ii)  $EOT_{elec} = 2.63 \text{ nm}$  (1.84)
- iii)  $V_{DD} = 1.2V$  (1.1V)
- iv)  $I_{OFF} = 10^{-5} \mu\text{A}/\mu\text{m}$  (0.15 )
- v)  $I_{on} = 500\mu\text{A}/\mu\text{m}$  (1130 )
- vi)  $V_T(\text{sat}) = 0.515V$  (0.268)

$$V_T \approx 40\% V_{DD}$$

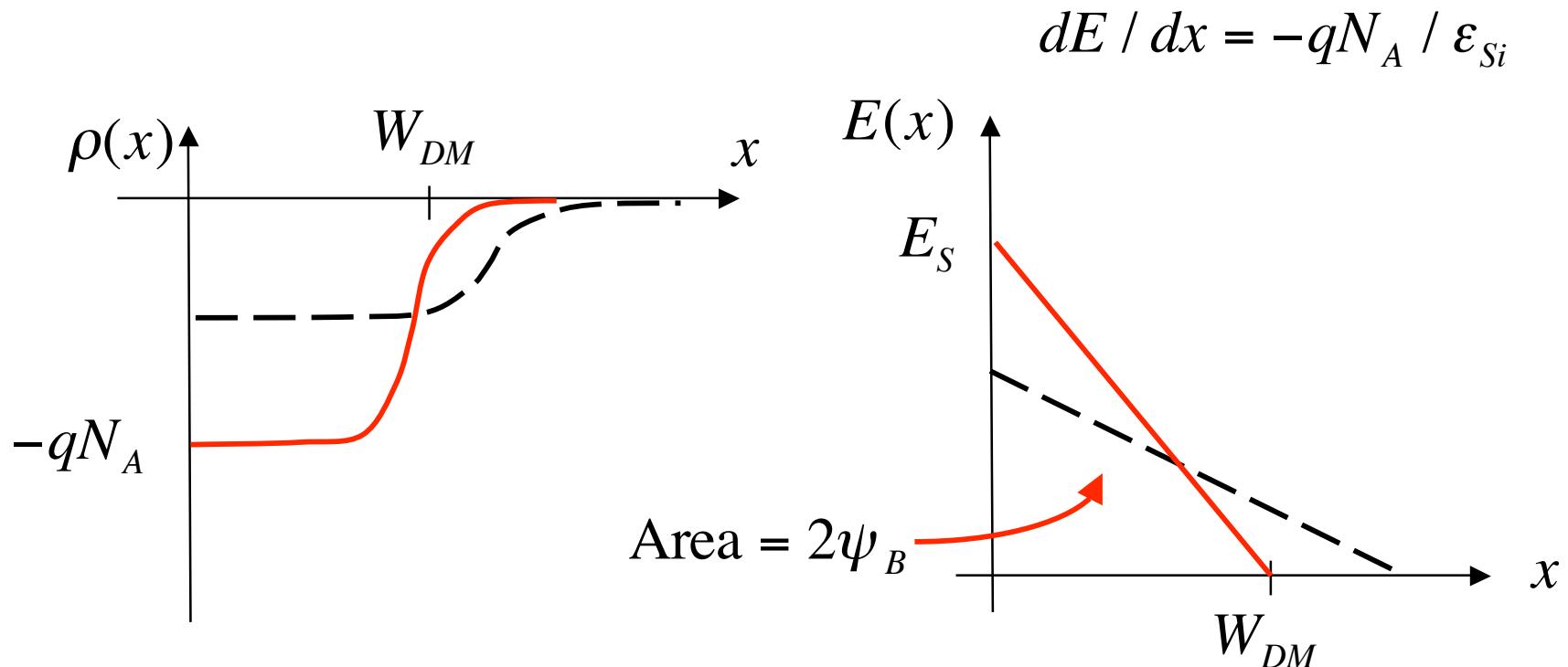
ITRS 2005 edition

# outline

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- 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



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

## uniform doping (ii)

---

$W_{DM}$  controls short channel effects

need  $L / mW_{DM} > 2$

$E_S$  controls threshold voltage

$$\begin{aligned} V_T &= V_{FB} + 2\psi_B - Q_{DM} / C_{OX} \\ &= V_{FB} + 2\psi_B + \varepsilon_{Si} E_S / C_{OX} \end{aligned}$$

*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.

Would like to control  $W_{DM}$  and  $V_T$  independently.

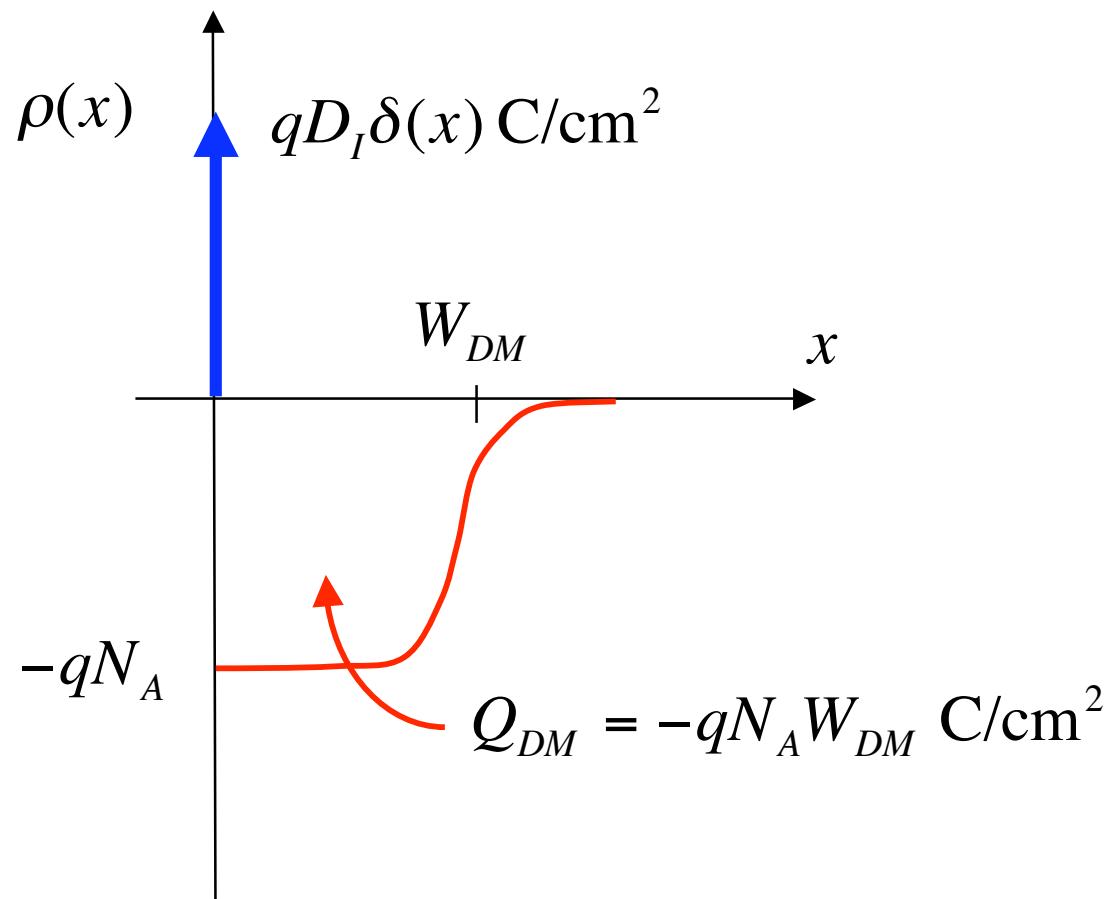
Solution: non-uniform doping.

# outline

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- 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

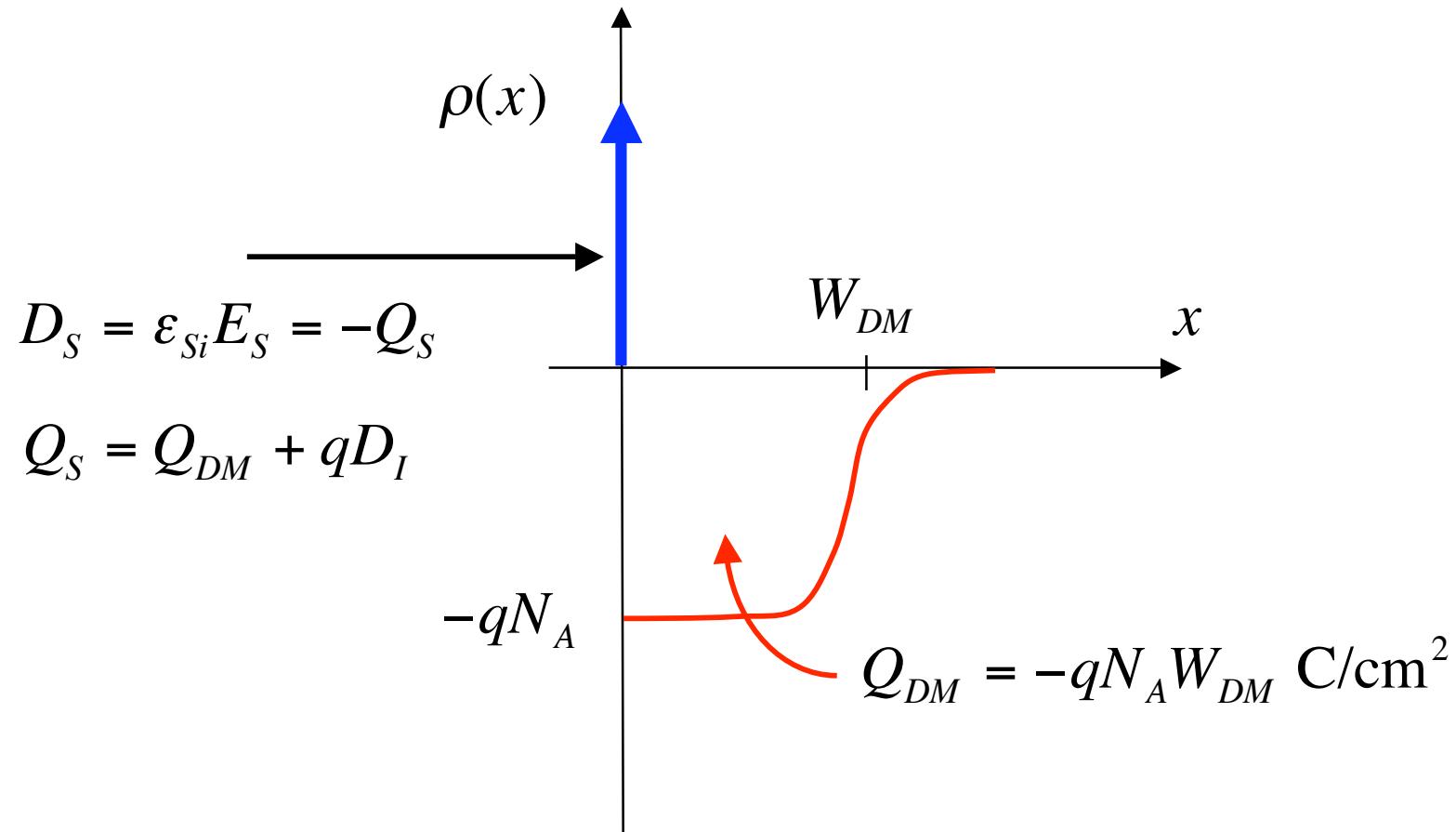
# delta function at the surface



$D_I$ : dose ( $\text{cm}^{-2}$ )  
 $>0$  ( $\text{As}^+$ ,  $\text{P}^+$ )  
 $<0$  ( $\text{B}^-$ )

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

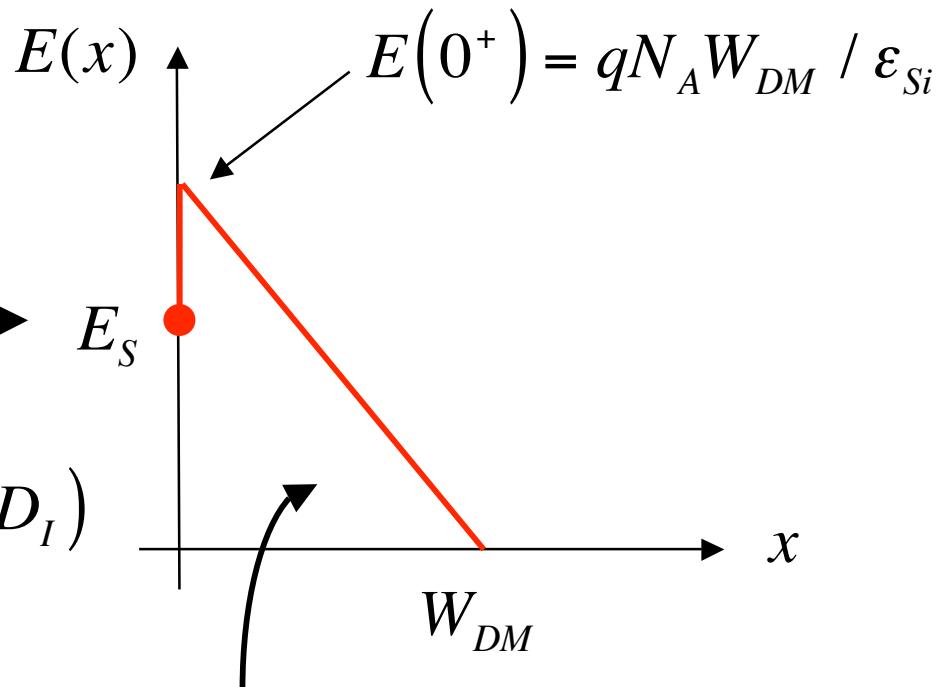
# electrostatics



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

## electrostatics (ii)

$$\begin{aligned}\varepsilon_{Si} E_S &= -Q_S \\ &= (qN_A W_{DM} - qD_I)\end{aligned}$$



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

Area =  $2\psi_B$   
did not change

## electrostatics (iii)

---

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

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

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

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

ii) select  $D_I$  for desired  $V_T$

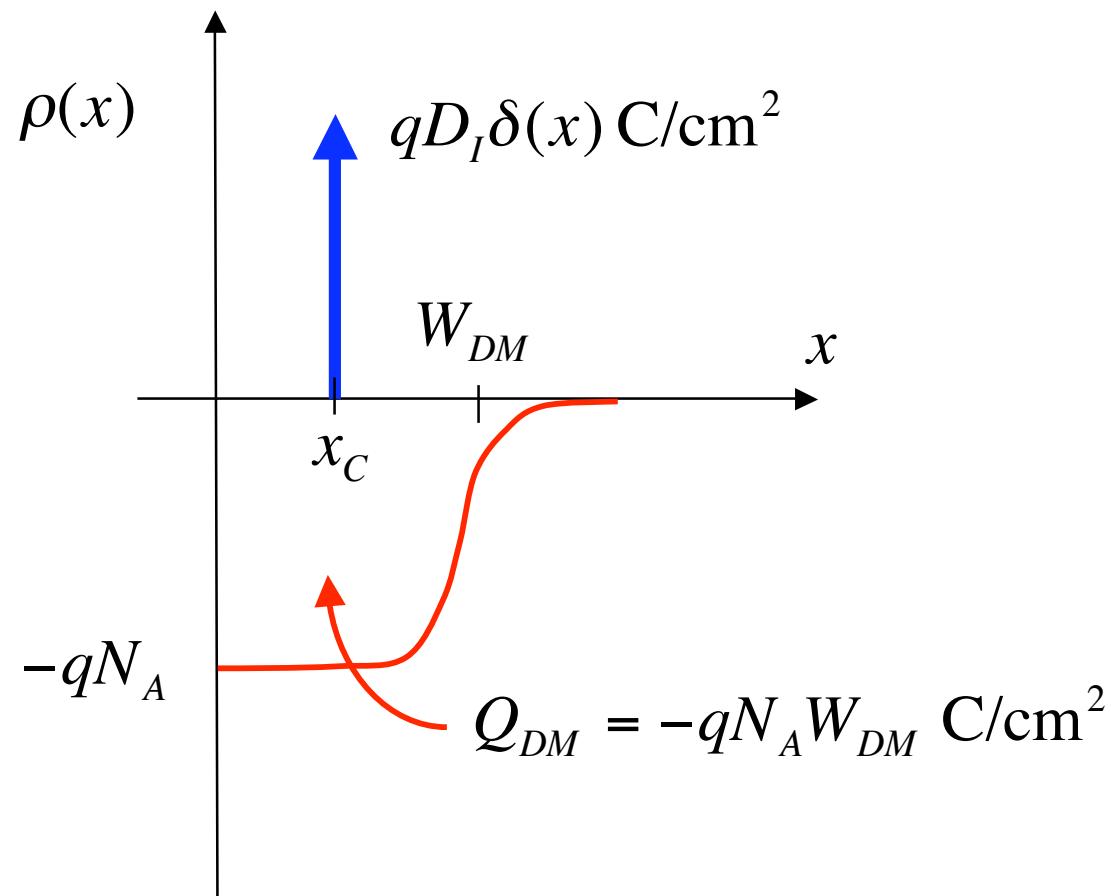
# outline

---

- 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

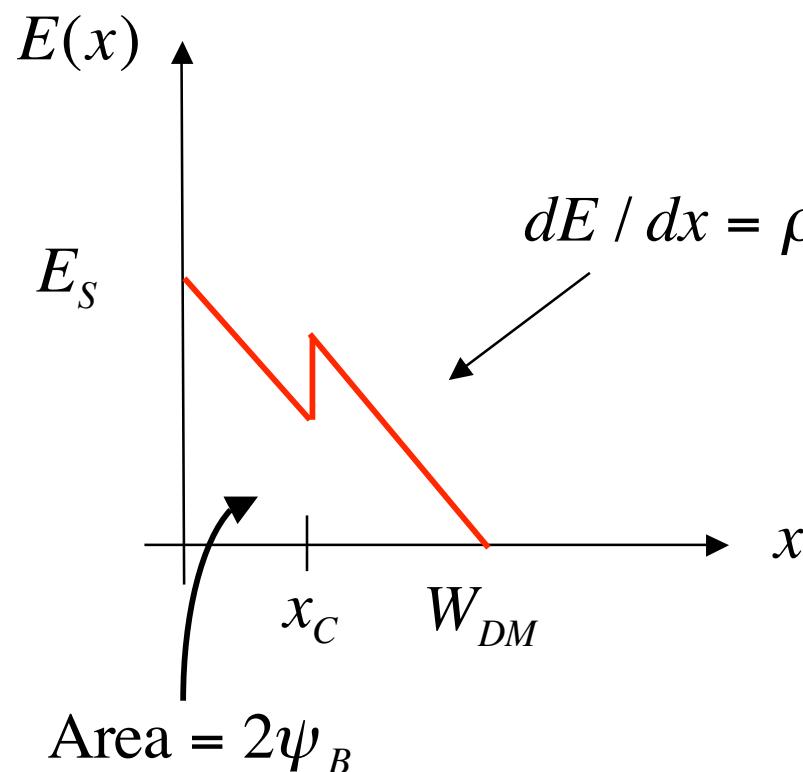
delta function at  $x = x_C$

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

# electrostatics

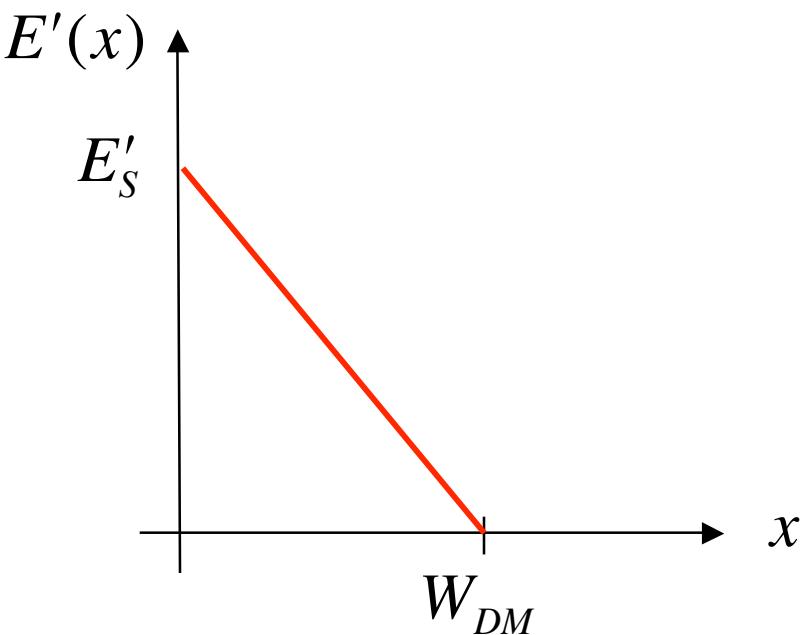
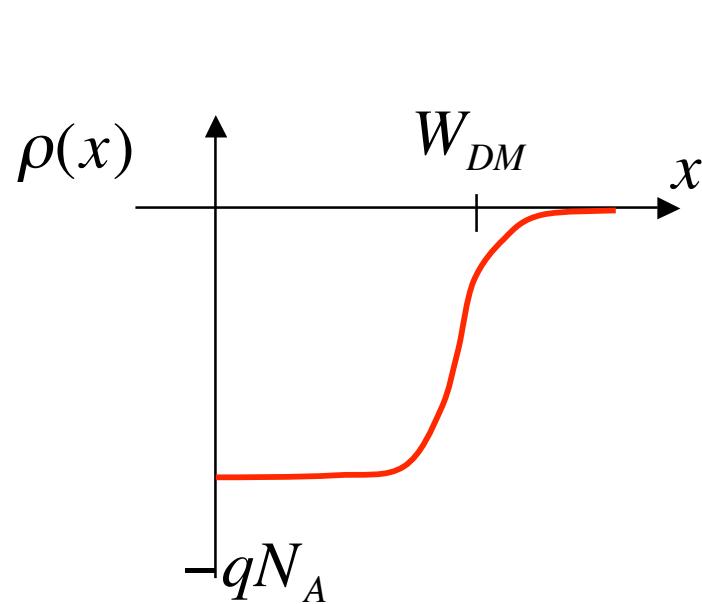


$$E(x) \longrightarrow E(x) = \int_x^{\infty} -\rho(x)dx / \epsilon_{Si}$$

$E_S$  decreased  
 $V_T$  decreased  
How is  $W_{DM}$  affected?

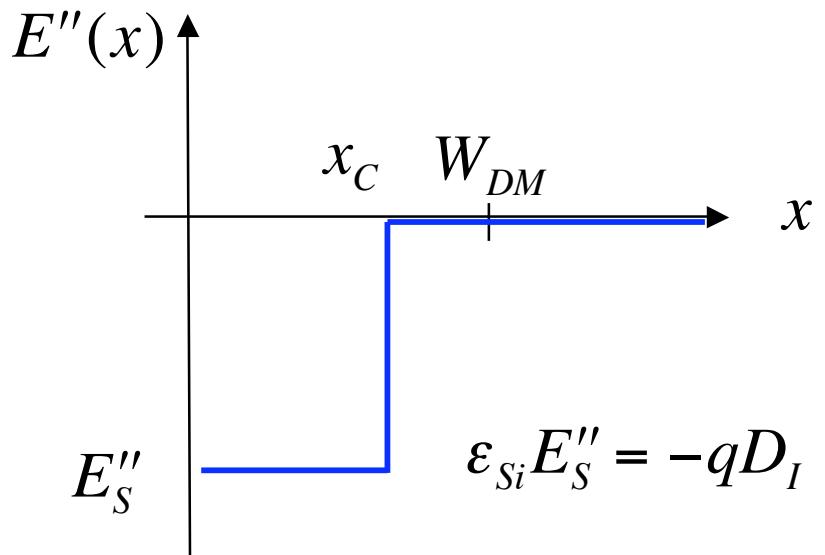
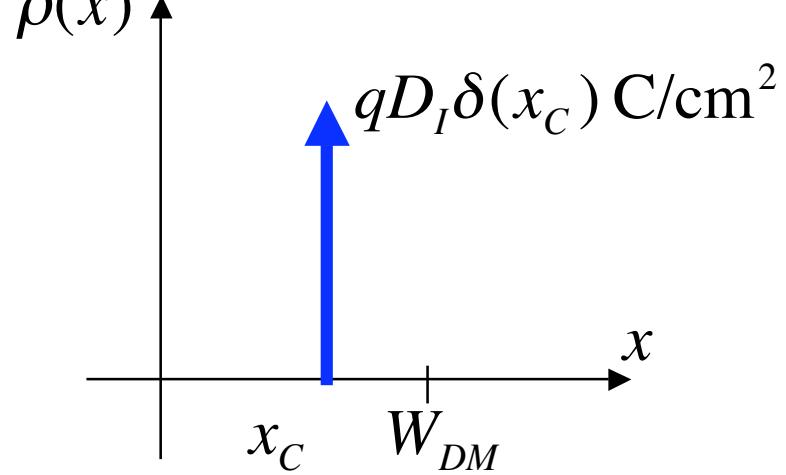
## electrostatics (ii)

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



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

# electrostatics (iii)



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

## electrostatics (iv)

---

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

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

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

## electrostatics (v)

---

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

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

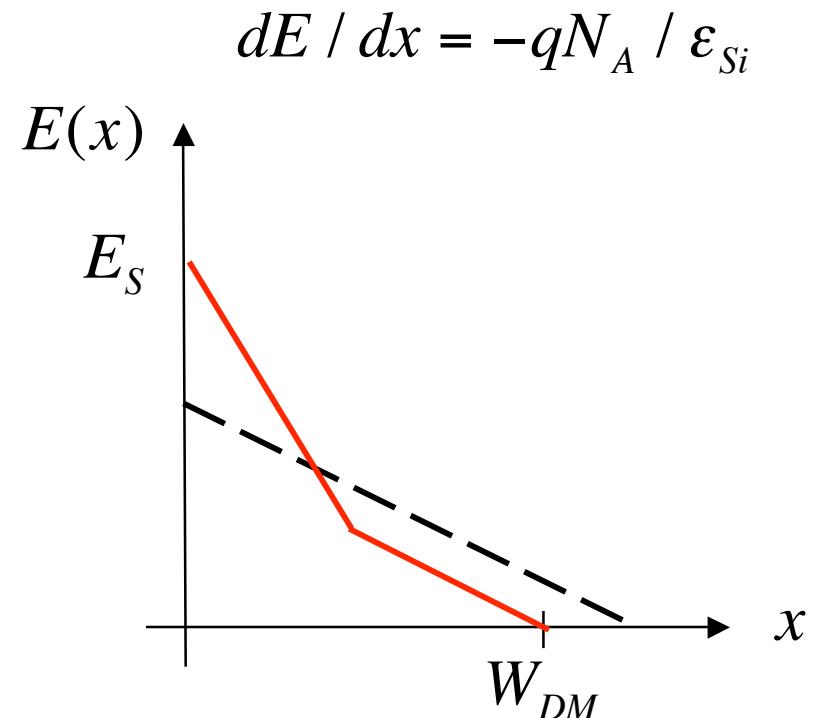
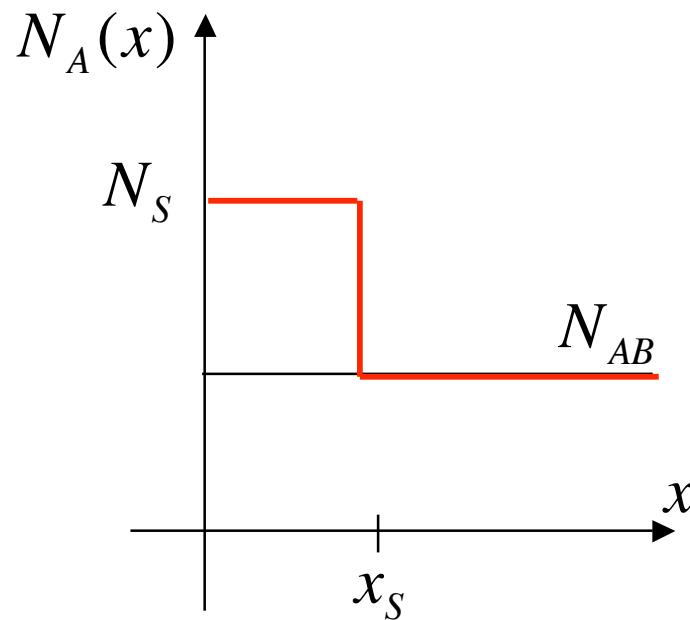
When  $x_C > 0$ , both  $W_{DM}$  and  $V_T$  are affected, but when  $x_C$  is close to 0, we get a large change in  $V_T$  and a small change in  $W_{DM}$

# outline

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- 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



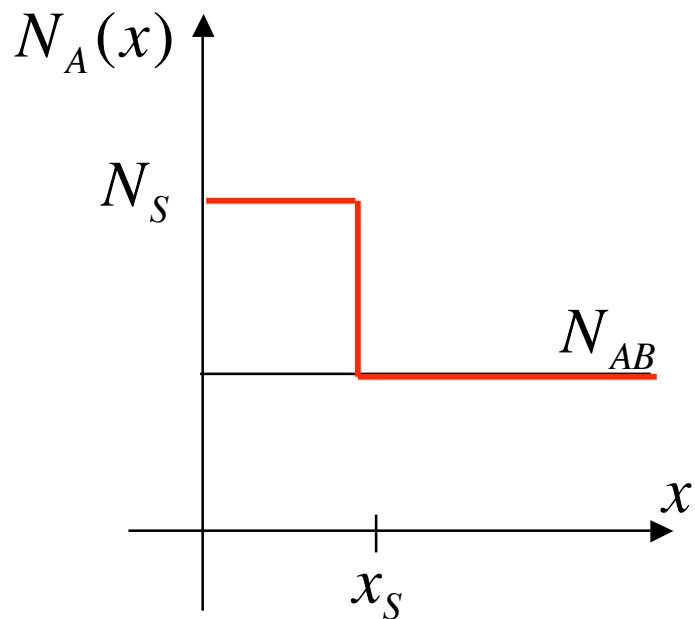
$$dE / dx = -qN_A / \epsilon_{Si}$$

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

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

## stepwise constant doping (ii)

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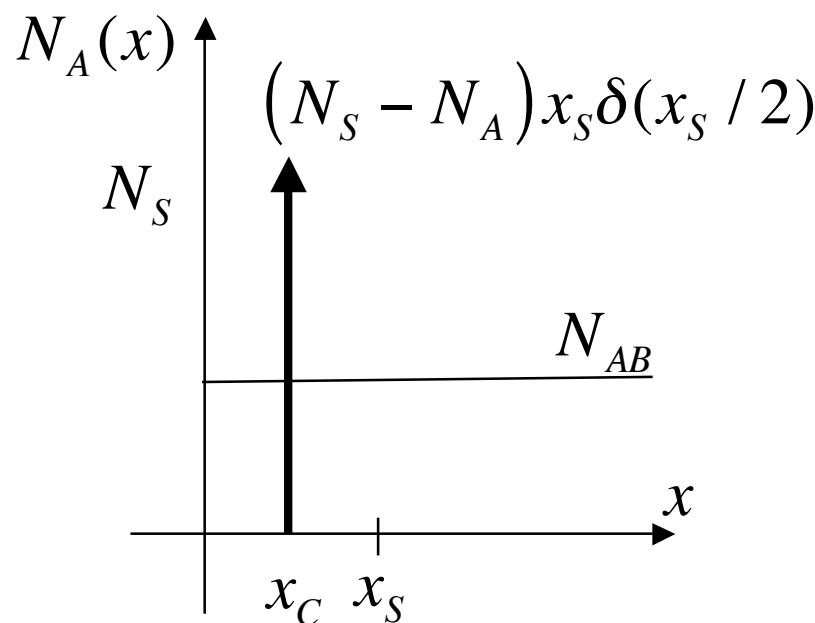


See Tau and Ning. pp. 178-181 for the solution to Poisson's equation for this profile.

Eqn. (4.28) for  $V_T$

Eqn. (4.29) for  $W_{DM}$

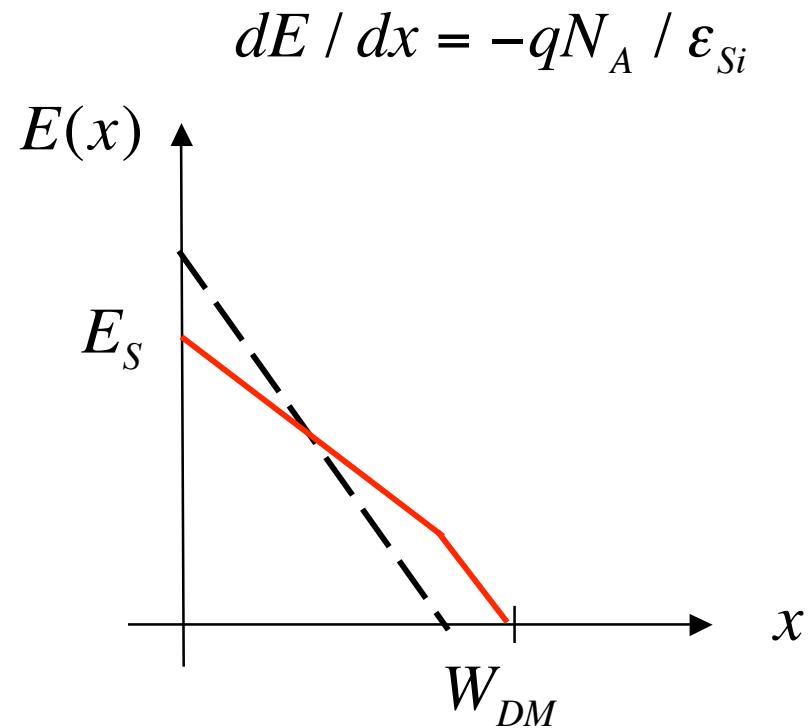
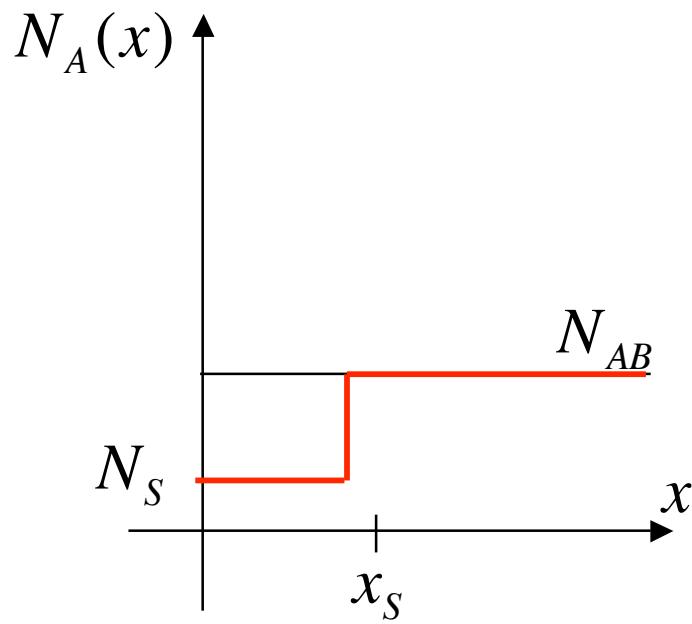
# stepwise constant (mathematics)



$$qD_I = -q(N_S - N_{AB})x_S$$
$$x_C = x_S / 2$$

Use delta function results for  $W_{DM}$  and  $V_T$

# retrograde doping



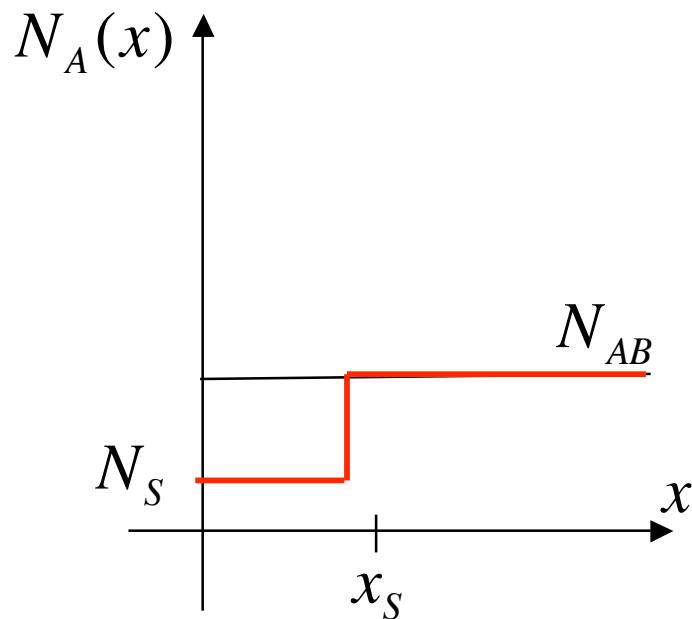
$$dE / dx = -qN_A / \epsilon_{Si}$$

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

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

# retrograde doping

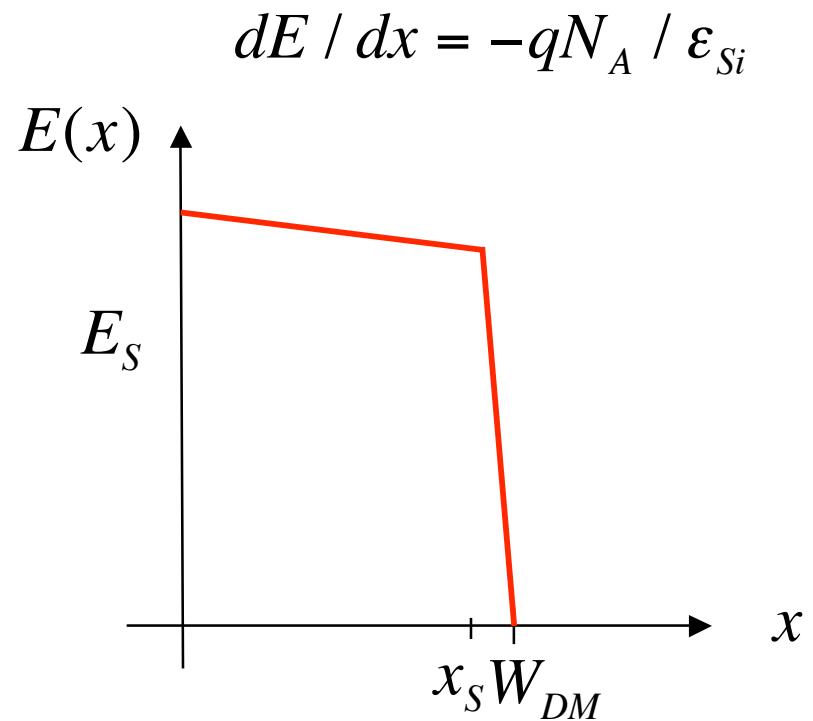
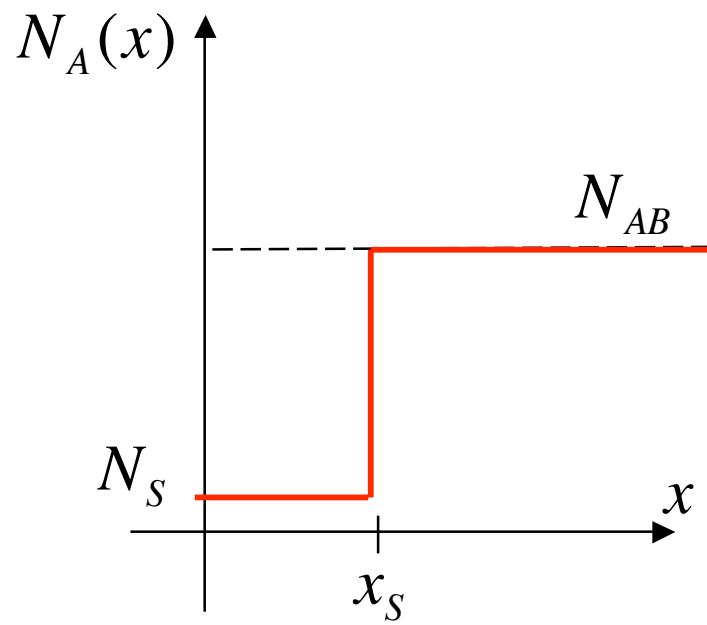
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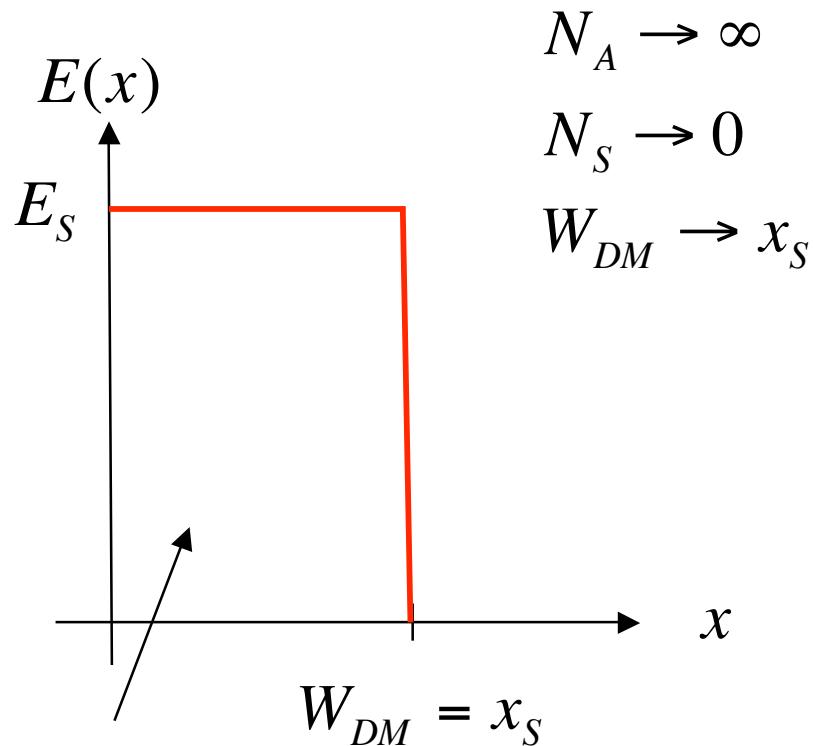
‘equivalent’ to a delta-function  
of positive charge at  $x_C/2$

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

# ground plane doping



# ideal ground plane doping



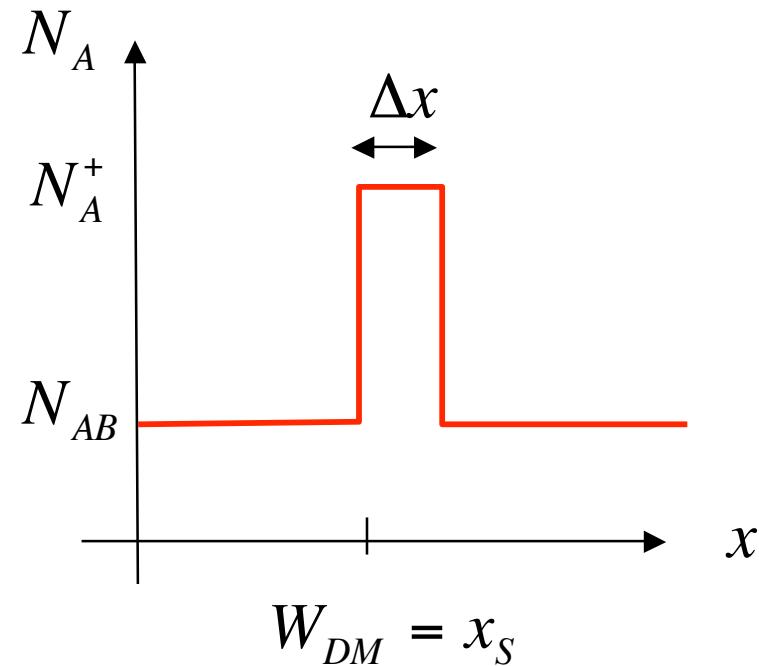
$E_S = 2\psi_B / W_{DM}$   
(ground plane)

$E_S = 4\psi_B / W_{DM}$   
(uniform)

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

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

# delta doping



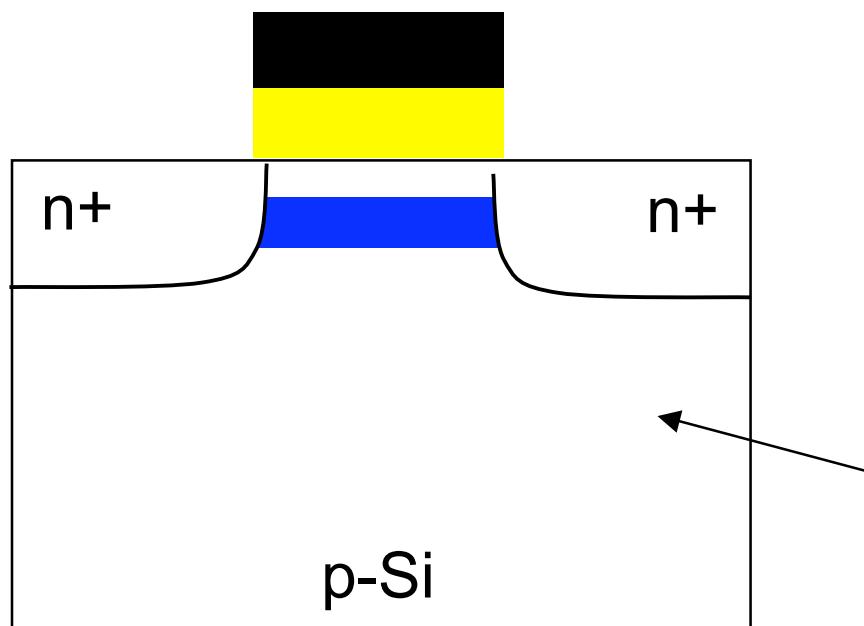
$$2\psi_B = E_S x_S$$

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

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

## delta doping (iii)

---



light doping for low  $C_J$   
and junction low  
leakage

# outline

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- 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**

# 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)

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

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

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

A blue bracket labeled 'u' is placed under the first term of the inner integral, and a blue bracket labeled 'dv' is placed under the second term.

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

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

## 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)

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

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

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

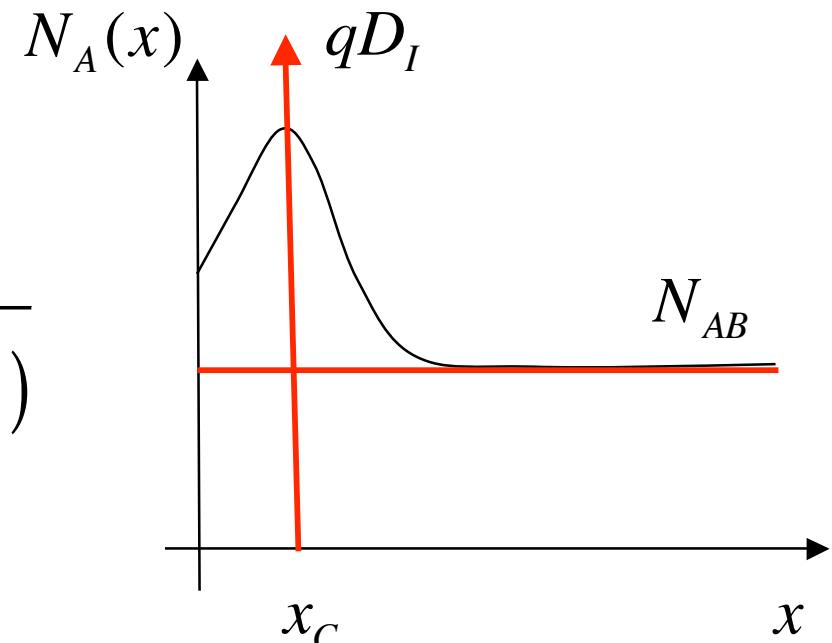
# integral solution (v)

---

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

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

identical to previous results



# outline

---

- 1)  $V_T$  Specification
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- 5) Stepwise uniform
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## integral solution (iii)

---

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

integral of doping controls  $V_T$

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

first moment of doping  
controls  $W_{DM}$

see Taur and Ning, p. 177

## integral solution (iv)

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

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

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

# integral solution (v)

---

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

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

identical to previous results

