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

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) $V_{DD} = 1.0$V
iv) $I_{OFF} = 0.71 \mu A/\mu m$
v) $I_{on} = 1513 \mu A/\mu m$
vi) $V_T(sat) = 0.094$V

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

ITRS 2007 edition
Table PIDS 2a
www.itrs.net
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) $I_{OFF} = 3.3 \times 10^{-5} \mu A/\mu m$

v) $I_{on} = 569 \mu A/\mu m$

vi) $V_{T(sat)} = 0.567V$

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

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

\[ \frac{dE}{dx} = -\frac{qN_A}{\varepsilon_{Si}} \]

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

Lundstrom EE-612 F08 8
uniform doping (ii)

$W_{DM}$ controls short channel effects

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

\[ \rho(x) = qD_1 \delta(x) \text{ C/cm}^2 \]

\[ W_{DM} \]

\[ Q_{DM} = -qN_A W_{DM} \text{ C/cm}^2 \]

\( D_1: \) dose (cm\(^{-2}\))

>0 \ (\text{As}^+, \text{P}^+)

<0 \ (\text{B}^-)

(assume net p-type doping (\(Q_S < 0\)))
electrostatics

\[ D_S = \varepsilon_{Si} E_S = -Q_S \]

\[ Q_S = Q_{DM} + qD_I \]

\[ -qN_A \]

\[ Q_{DM} = -qN_A W_{DM} \text{ C/cm}^2 \]

(assume net p-type doping \((Q_S < 0)\)
electrostatics (ii)

\[ \varepsilon_{Si} E_S = -Q_S \]
\[ = \left( qN_A W_{DM} - qD_I \right) \]
\[ E_S = E\left(0^+\right) - \frac{qD_I}{\varepsilon_{Si}} \]

\[ E\left(0^+\right) = \frac{qN_A W_{DM}}{\varepsilon_{Si}} \]

Area = 2\(\psi_B\)
did not change
electrostatics (iii)

\[ W_{DM} = \sqrt{\frac{4 \varepsilon_{Si} \psi_B}{qN_A}} \]
does not depend on \( D_I \)

\[ V_T = V_{FB} + 2\psi_B - \frac{(Q_{DM} + qD_I)}{C_{ox}} \]

\[ \Delta V_T = -\frac{qD_I}{C_{ox}} \]

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

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
The diagram illustrates a delta function at $x = x_C$.

The delta function is given by

$$\delta(x)$$

The relation between $\delta(x)$ and $\rho(x)$ is

$$\rho(x) = qD_1 \delta(x) \text{ C/cm}^2$$

The quantities $W_{DM}$ and $Q_{DM}$ are defined as

$$W_{DM} = -qN_A$$

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

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

\[ E(x) = \frac{1}{\varepsilon_{Si}} \int_{x}^{\infty} -\rho(x)dx \]

\[ \frac{dE}{dx} = \frac{\rho}{\varepsilon_{Si}} \]

Area = 2\(\psi_B\)

ES decreased
VT decreased
How is \(W_{DM}\) affected?
electrostatics (ii)

\[ \frac{dE}{dx} = \frac{\rho}{\varepsilon_{Si}} \quad \text{solve by superposition} \]

\[ \rho(x) \quad W_{DM} \quad x \]

\[ -qN_A \]

\[ E'(x) \quad E'_S \]

\[ W_{DM} \]

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

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

\[ \varepsilon_{Si} E'' = -qD_I \]
electrostatics (iv)

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

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

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

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

\[ \frac{dE}{dx} = -\frac{qN_A}{\varepsilon_{Si}} \]

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 $W_{DM}$
Use delta function results for $W_{DM}$ and $V_T$
“retrograde” doping

\[ \frac{dE}{dx} = -\frac{qN_A}{\varepsilon_{Si}} \]

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

Area \( \approx 2\psi_B \)
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

\[ \frac{dE}{dx} = -qN_A / \varepsilon_{Si} \]
ideal ground plane doping

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

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

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

$E_S W_{DM} = 2\psi_B$

$\frac{1}{2} E_S W_{DM} = 2\psi_B$  
(uniform)
delta doping

\[ 2\psi_B = E_S x_S \]

\[ \varepsilon_{Si} E_S \leq qN_A^+ \Delta x \]

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

\[\psi_S = - \int_0^{W_D} E(x) \, dx\]

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

\[\int u \, dv = uv - \int v \, du\]

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

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

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

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

\[ 2\psi_B = \frac{qN_{AB}}{2\varepsilon_{Si}} W_{DM}^2 \quad \frac{q}{\varepsilon_{Si}} \int_0^{W_{DM}} x\delta N'(x)dx \quad \int_0^{W_{DM}} \delta N'(x)dx \]

\[ -D_I \]

\[ x_C \]
integral solution (v)

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

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

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

just like the result we got for:

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

\[ x_C = \frac{\int_0^{W_{DM}} x\delta N_A'(x)dx}{\int_0^{W_{DM}} \delta N_A'(x)dx} \]
integral solution (vi)

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

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

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

\[ VT = ? \]

\[ W_{DM} = ? \]
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
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

\[ E_{VAC} \]

\[ \Phi_M \]

\[ \chi_S \]

\[ \Phi_S \]

\[ E_F \]

\[ E_C \]

\[ E_V \]

\[ n\text{-channel} \]

\[ p\text{-channel} \]