EE-612: Lecture 19: Device Variability

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outline

1) Sources of variability
2) Random dopant fluctuations (RDF)
3) Line edge roughness (LER)
4) Impact on design
sources of variability

1) Intrinsic device variability
   - random dopant fluctuations (RDF)
   - line-edge roughness (LER)
   - oxide thickness fluctuations

2) Extrinsic process variability
   - lot to lot
   - wafer to wafer
   - across wafer
   - across chip

3) Reliability
   - negative bias temperature instability (NBTI)
   - hot electron injection
   - electromigration
50 nm MOSFET

(a) Randomly placed dopants in a 50-nm channel-length MOSFET. Blue dots are donors creating the source and drain. Red dots are acceptors, primarily in the channel. The gate is not shown, but would cover the channel region between source (S) and drain (D).

(b) Top view.

discrete doping effects

\[ V = W \times L \times W_{DM} \]

example:
\[ L = 50 \text{ nm} \]
\[ W = 100 \text{ nm} \]
\[ W_{DM} = 50 \text{ nm} \]
\[ N_A = 10^{18} \text{ cm}^{-3} \]
\[ N_{TOT} = 250 \]

Number of dopants in the critical volume is a statistical quantity
discrete doping trends

Figure 1. Random dopant fluctuations.

V_T variation

number of dopants in the channel depletion region:

\[ N_{TOT} = N_A W L W_{DM} \]

standard deviation:

\[ \sigma_{N_{TOT}} = \sqrt{N_A W L W_{DM}} \]

threshold voltage:

\[ \sigma_{V_T} = \frac{q}{C_{ox}} \sqrt{\frac{N_A W_{DM}}{3WL}} \quad \text{eqn. (4.64) Yuan and Taur} \]
discrete doping effects (ii)

Effects:
1) $\sigma_{V_T}$ (10’s of mV)
2) lower avg. $V_T$ (10’s of mV)
3) asymmetry in $I_D$
4) increased off-current

(see Wong and Taur, IEDM, 1993, p. 705)
variation in $V_T$

90 nm NMOS

$$\sigma_{V_T} \propto \frac{1}{\sqrt{WL}}$$

effect on off-current

\[ \rho(V_T) = \frac{1}{\sqrt{2\pi}\sigma_{V_T}} e^{-\frac{(V_T - V_{T0})^2}{2\sigma_{V_T}^2}} \]

\[ \langle I_{OFF} \rangle = \int_{-\infty}^{+\infty} \rho(V_T)I_{OFF}(V_T) dV_T \]

\[ \langle I_{OFF} \rangle = I_{OFF,nom} \exp \left[ \frac{\sigma_{V_T}^2}{2(mk_B T)^2} \right] > I_{OFF,nom} \]

solutions

1) retrograde doping profiles
2) undoped SOI
3) circuit design
4) new doping technologies

Takahiro Shinada, et al., *Nature*, 437, 1128, 2005
LER

Line edge roughness

A 22 nm MOSFET
In production 2008

From

From A. Asenov, Univ. of Glasgow

Discrete dopants
LER

1) second most significant contributor to variability

2) arises from statistical variations in lithography (photons) absorption, chemical reactivity, molecular structure of resist

3) Leads to variation of $L_{\text{eff}}$ along the width

variability is becoming a major issue

G. Declerck, Keynote talk, VLSI Technol. Symp. 2005
sources of variability

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