EE-612:
Lecture 19:
Device Variability

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NCN
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outline

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

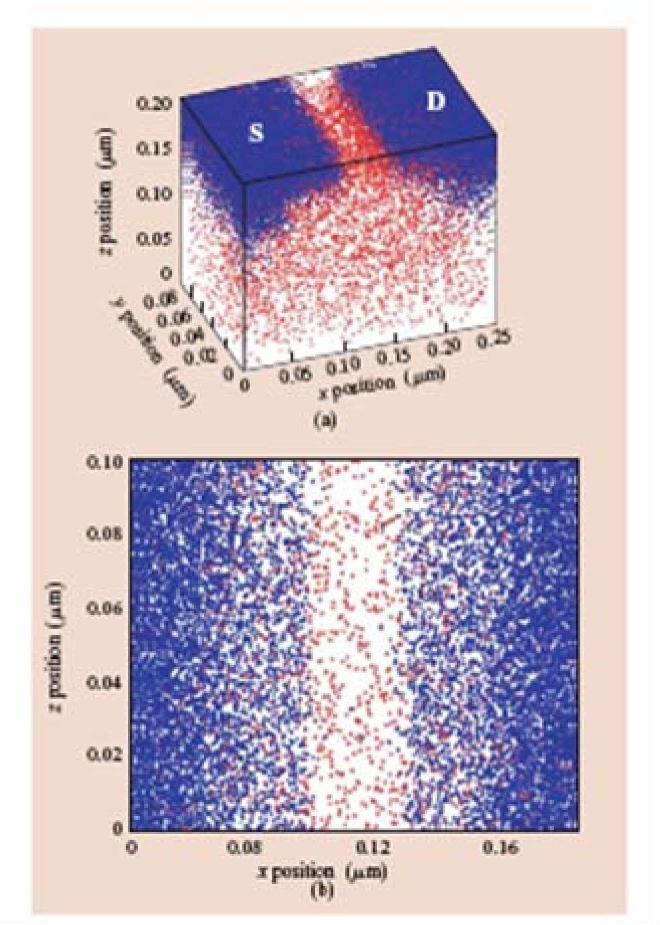
sources of variability

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)

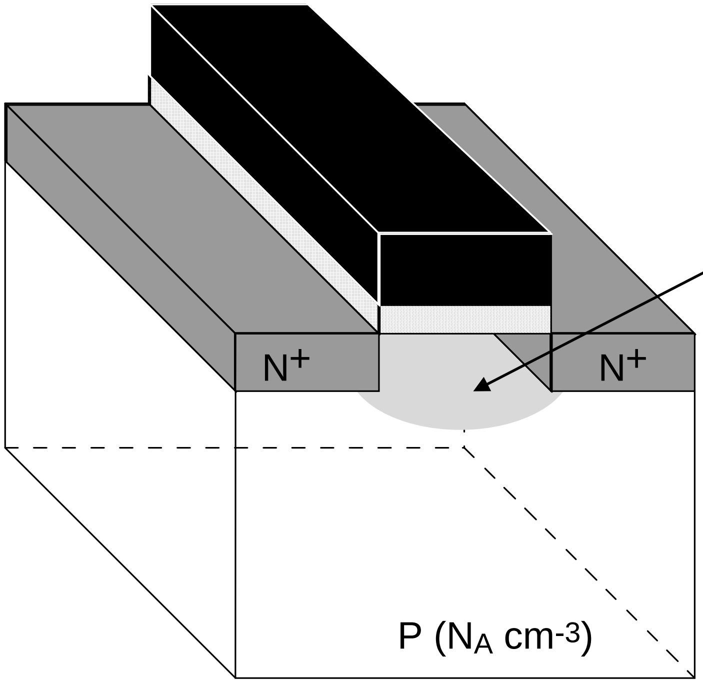
(b)

(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.

K. Bernstein, et al, *IBM J. Res. and Dev*., **50**, p. 433, 2006

discrete doping effects



$$V = W \times L \times W_{DM}$$

example:

L = 50 nm

W = 100 nm

W_{DM} = 50 nm

N_A = 10^{18} cm^{-3}

N_{TOT} = 250

Number of dopants in the critical volume is a **statistical quantity**

discrete doping trends

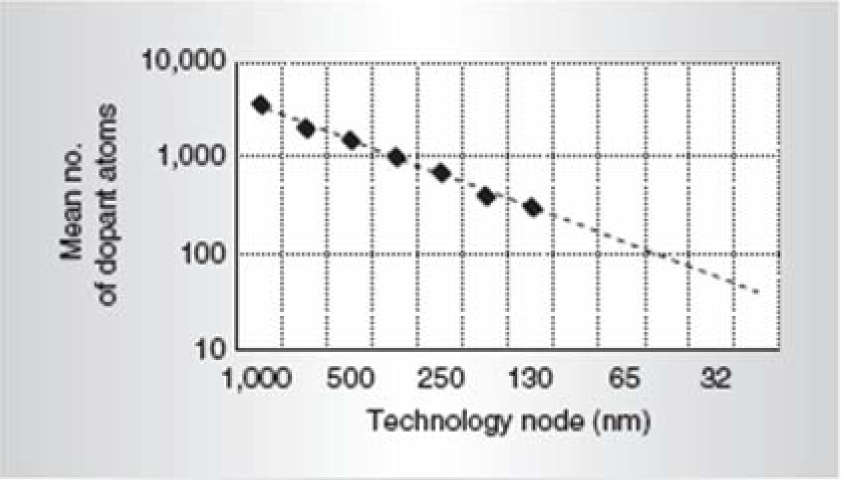


Figure 1. Random dopant fluctuations.

S. Borkar, *IEEE Explore*, p. 10, Nov./Dec. 2005

V_T variation

number of dopants in the channel depletion region:

$$N_{TOT} = N_A W L W_{DM}$$

standard deviation:

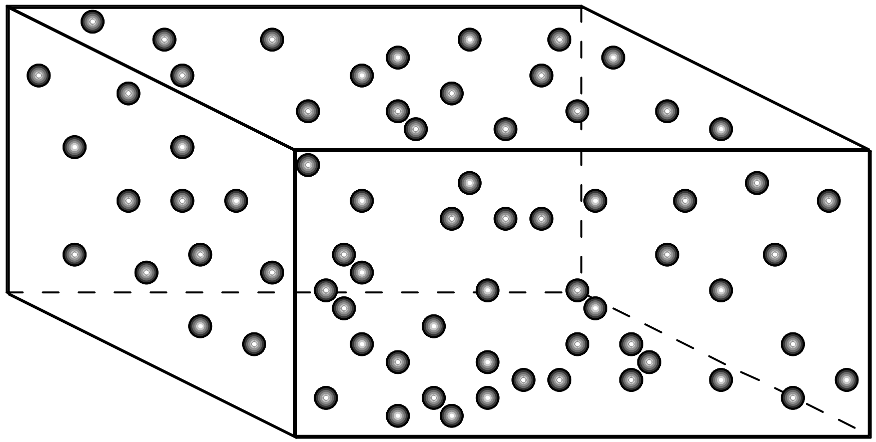
$$\sigma_{N_{TOT}} = \sqrt{N_A W L W_{DM}}$$

threshold voltage:

$$\sigma_{V_T} = \frac{q}{C_{ox}} \sqrt{\frac{N_A W_{DM}}{3WL}}$$

eqn. (4.64) Yuan and Taur

discrete doping effects (ii)



Effects:

1) σ_{VT} (10's of mV)

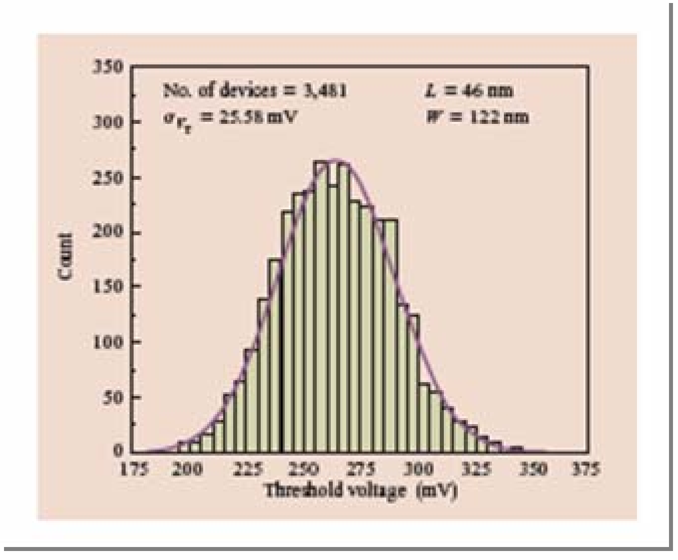
2) lower avg. V_T (10's of mV)

3) asymmetry in I_D

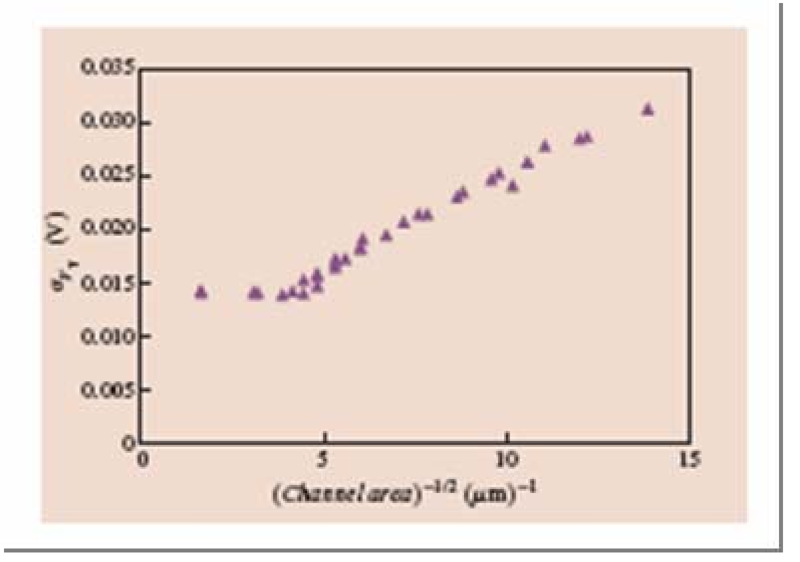
4) increased off-current

(see Wong and Taur, IEDM, 1993, p. 705)

variation in V_T



90 nm NMOS



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

K. Bernstein, et al, *IBM J. Res. and Dev*., **50**, p. 433, 2006

effect on off-current

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

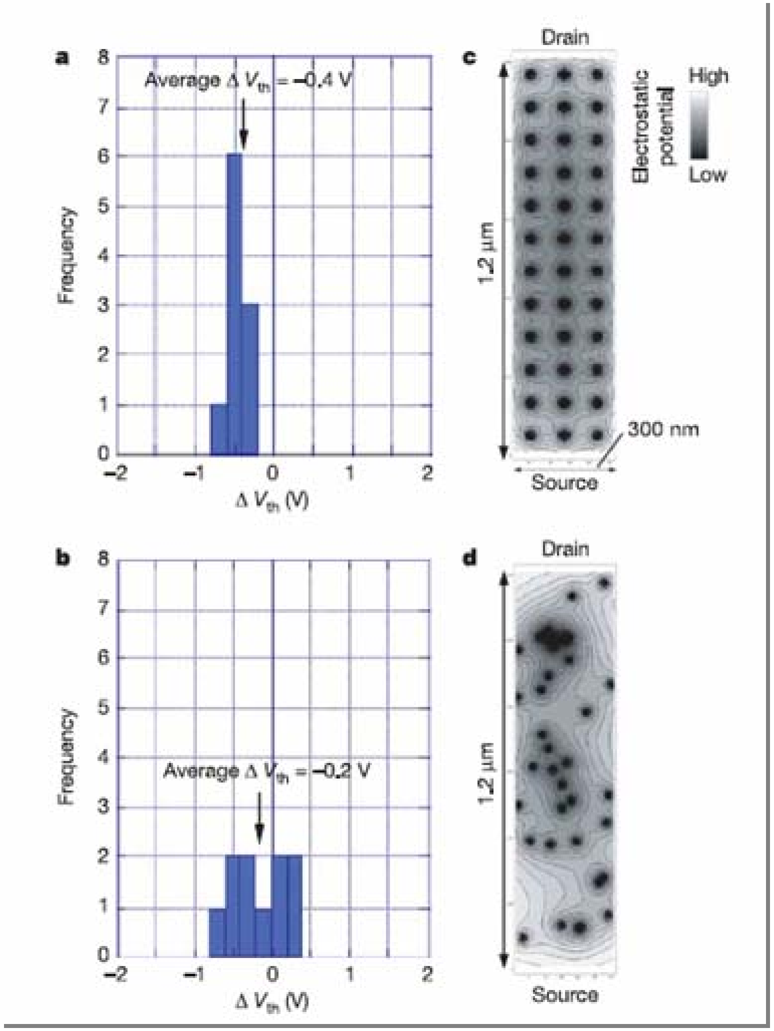
$$\langle I_{OFF} \rangle = \int_{-\infty}^{+\infty} \rho(V_T) I_{OFF}(V_T) dV_T$$

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

D.J. Frank, et al., *Proc. IEEE*, **89**, 259, 2001

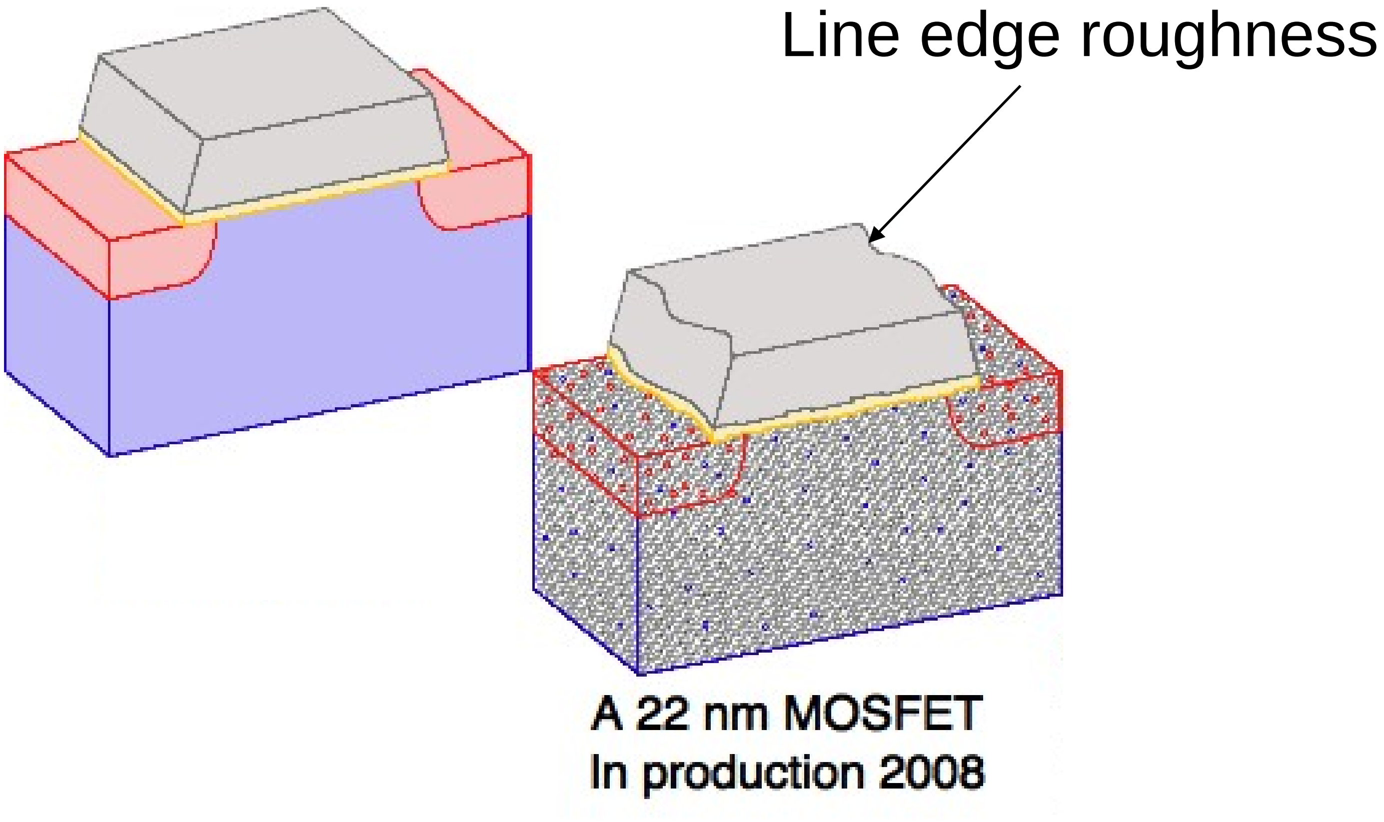
solutions

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



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

LER



From

LER

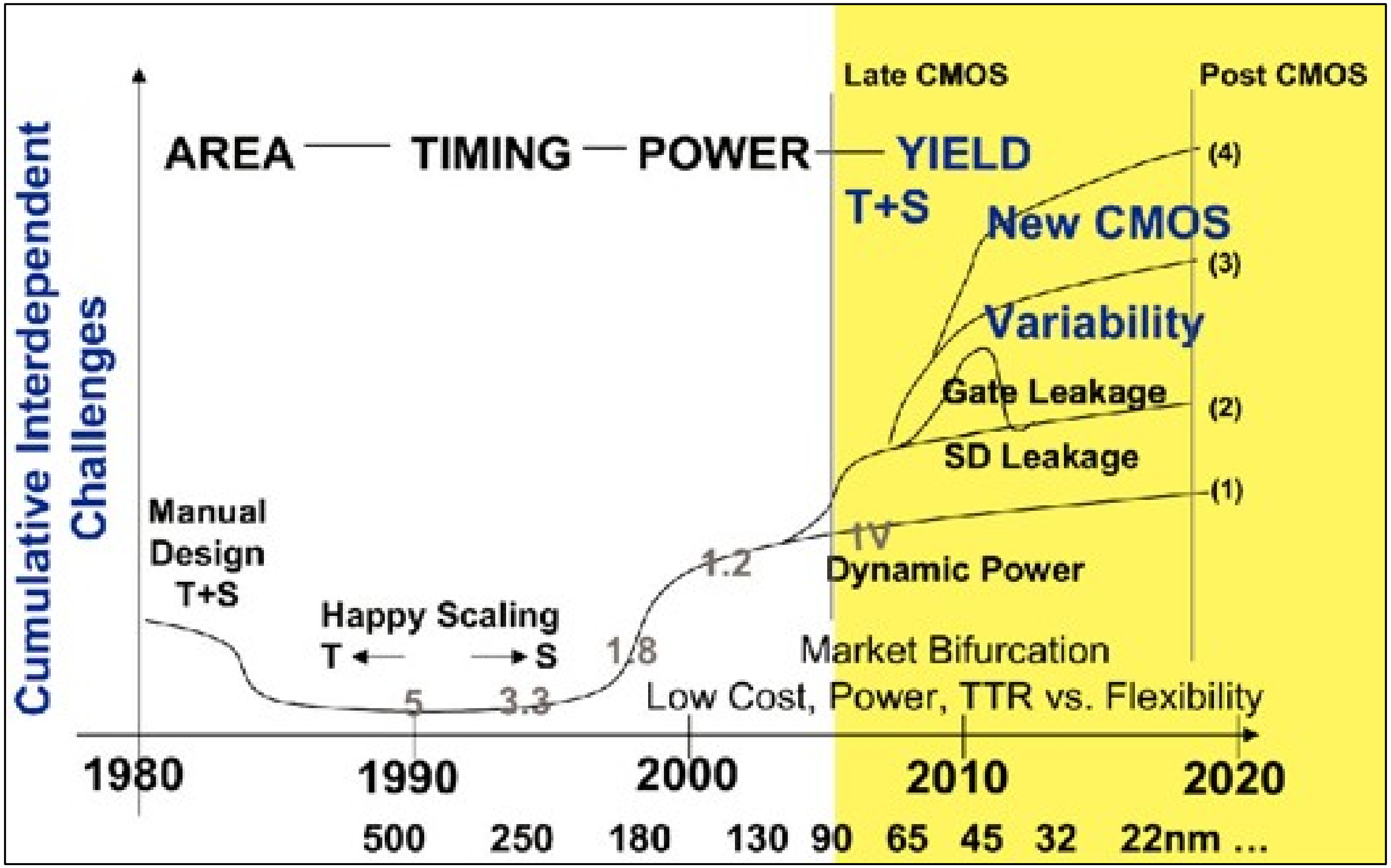
1) second most significant contributor to variability

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

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

Source: K. Bernstein, et al, *IBM J. Res. and Dev.*, **50**, p. 433, 2006

variability is becoming a major issue



G. Declerck, Keynote talk, VLSI Technol. Symp. 2005

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