Lecture 8
On the Mechanics of Defect Generation and Gate Dielectric Breakdown

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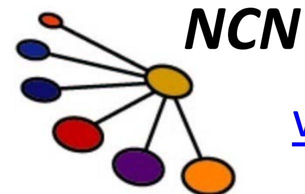

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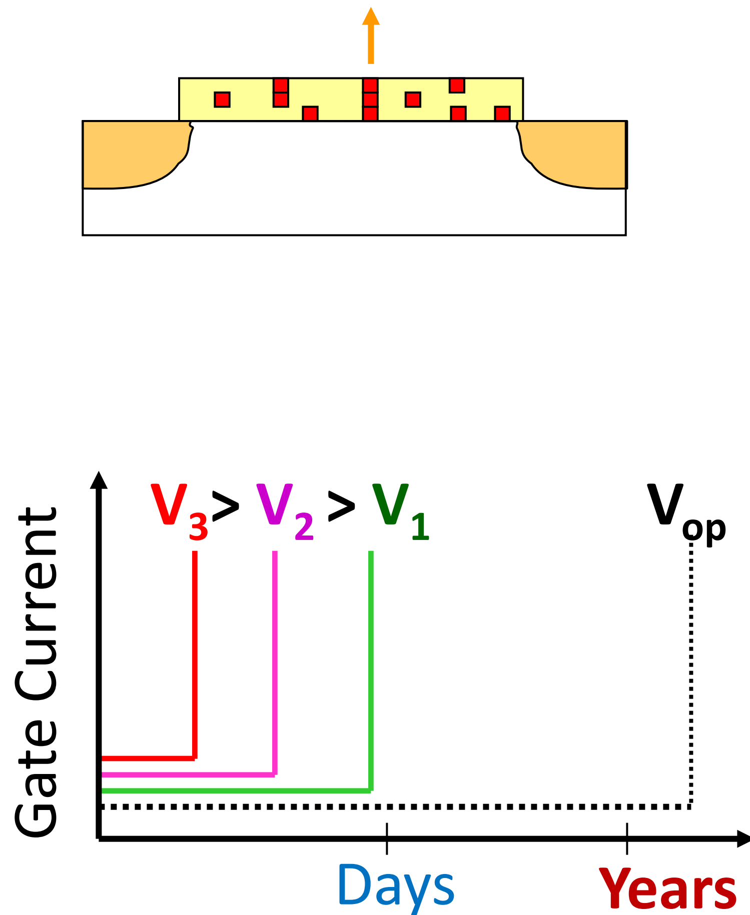
outline of lecture 8

1) **Theory of oxide breakdown**
2) Statistics of Failure Distribution
3) Soft vs. Hard Breakdown
4) Correlated vs. Uncorrelated Breakdown
5) Conclusions

how to determine gate oxide reliability



Nonlinear projection for processes with threshold

years

Std.

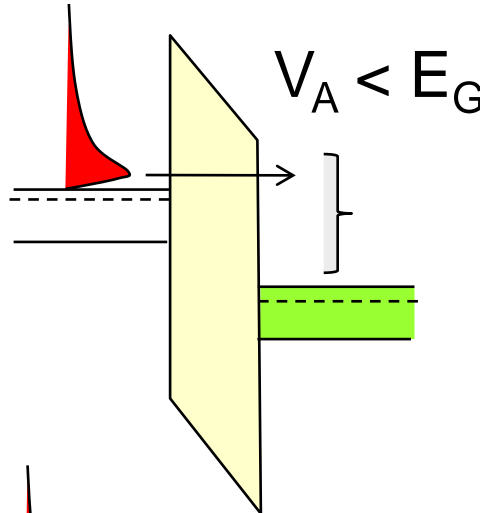
Days

ln (TBD)

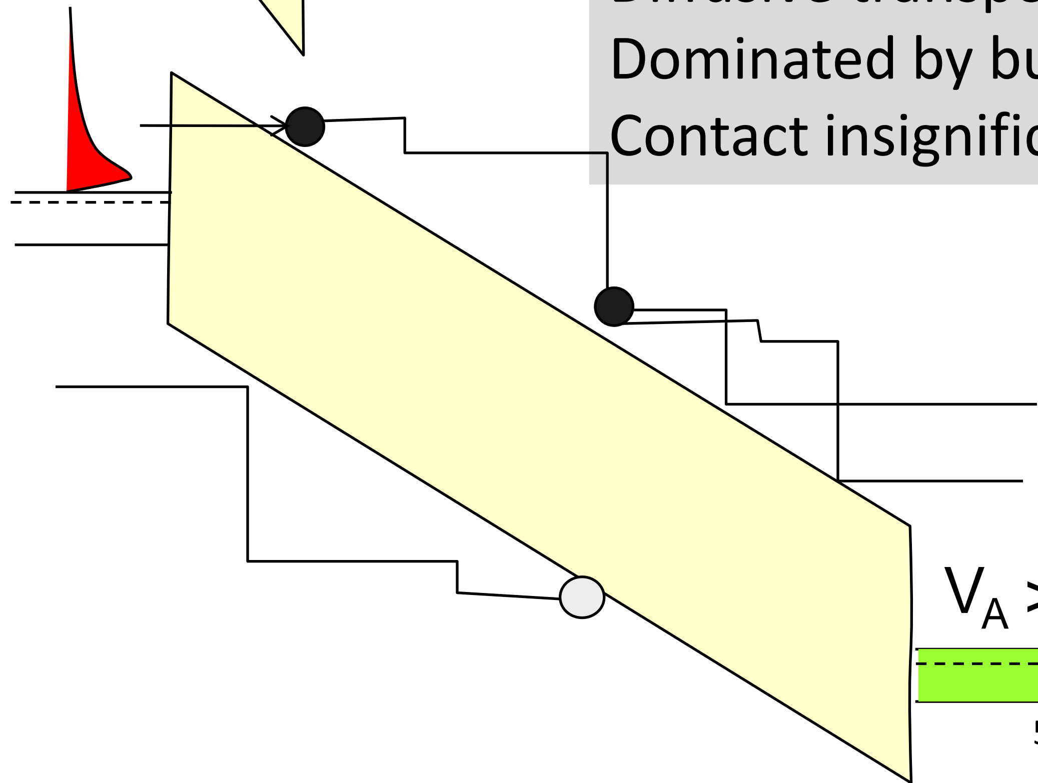
V_G

Empirical projection is very difficult, if not impossible …

breakdown in thick vs. thin oxides



Ballistic transport
Hot contact
Contact dictates BD

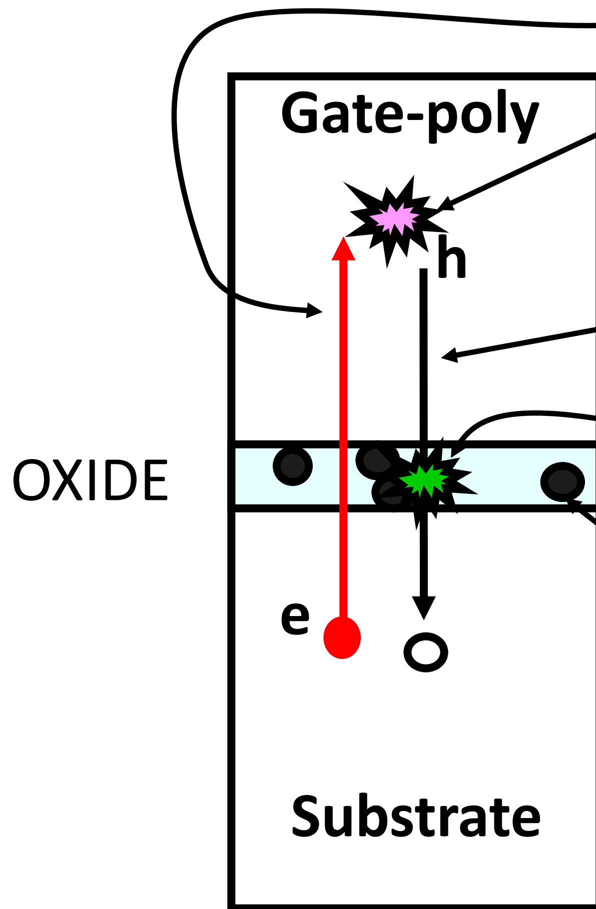


Diffusive transport
Dominated by bulk
Contact insignificant

$$\frac{dE}{dx} = q\mathcal{E}_{OX} - \frac{E}{\lambda}$$

theory of anode hole injection

$$T_{BD} = \left(\frac{N_{BD}}{k} \right)^n \frac{1}{J_e \alpha T_p}$$



J_e - Electron current density

α - Impact Ionization Rate

(probability that a hole will be created by an incoming electron)

T_p - **Transmission Rate**

(probability that the hole will travel through the oxide layer)

k - Trap Generation Efficiency

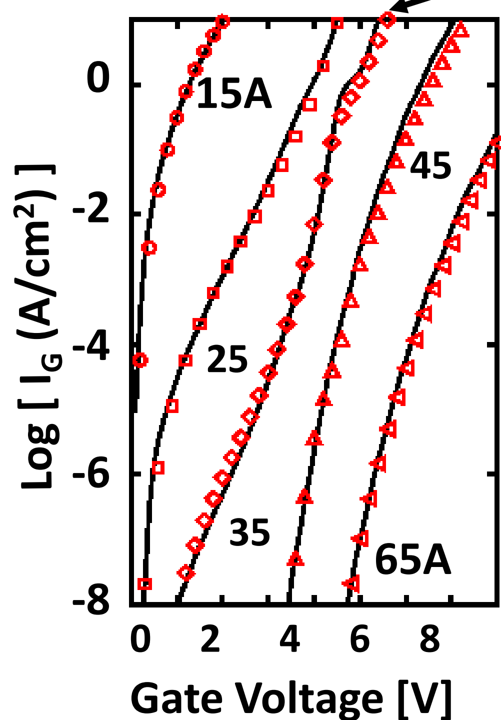
(probability that the hole will create a percolation defect)

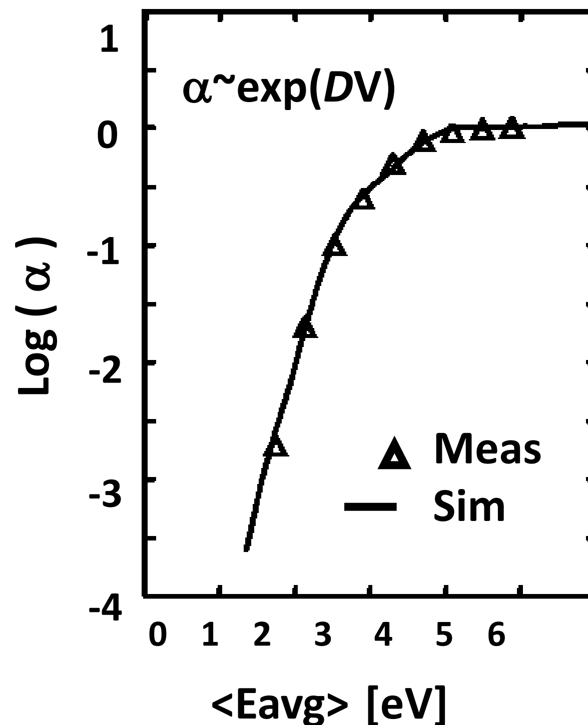
N_{BD} - **Density of percolation defects at breakdown**

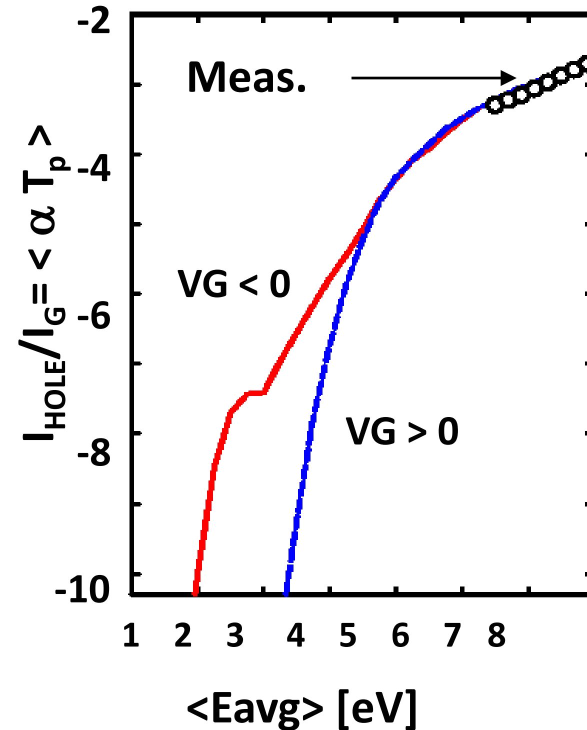
Ballistic transport and hot contacts … in 1980s!

AHI model: numerical calculation

$$J_h = J_e \alpha T_p$$





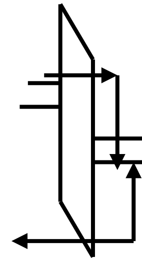


Ghetti, INFOS99
Lo, APL97

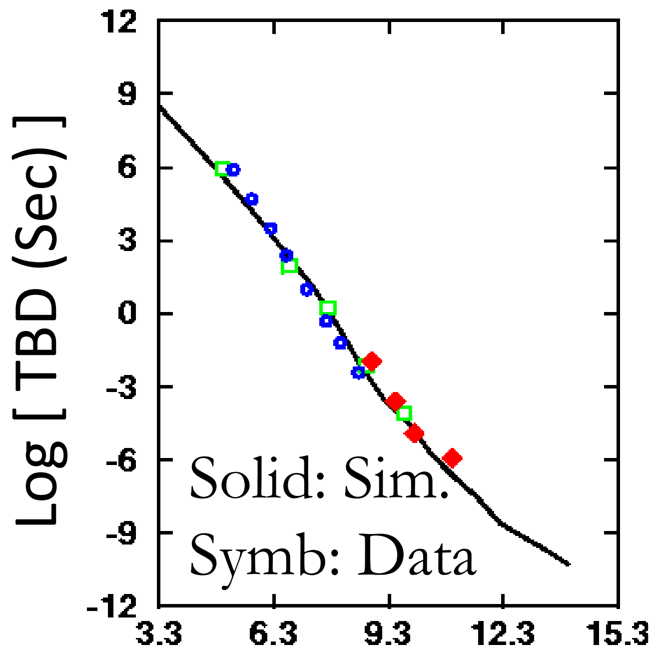
Bude (IEDM98)
Ezaki (SISC00)
Kamakura(IEDM99,JAP00))
Palestri(SISC00)

Bude(IEDM98)
Alam(IRPS00)
Palestri(SISC00)

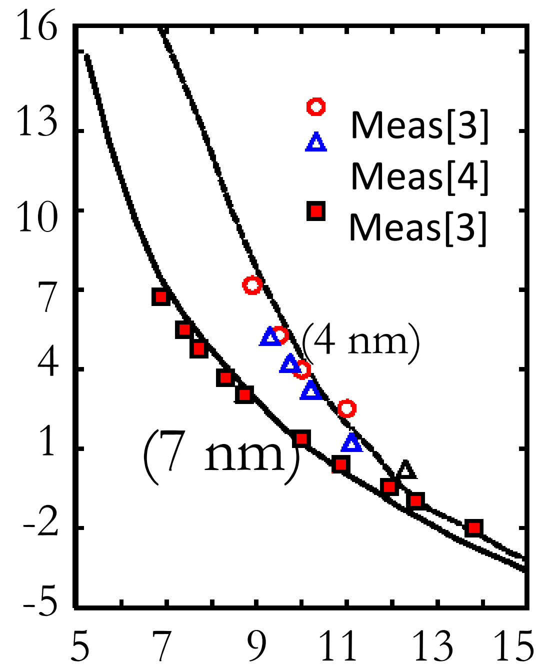
AHI model verified



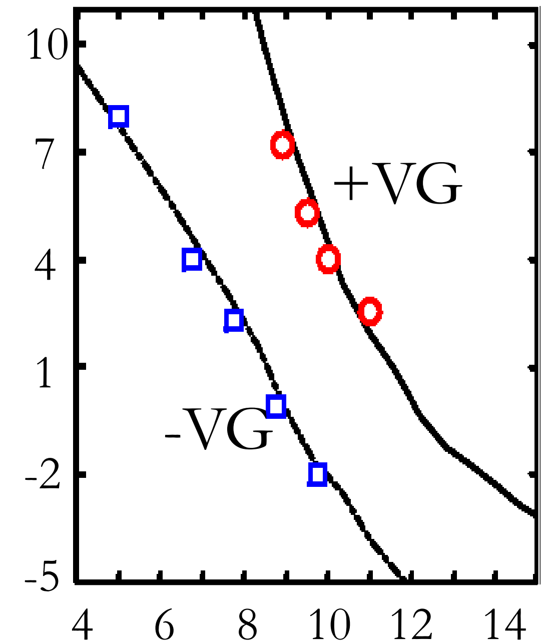
Field Dependence



Tox Dependence.



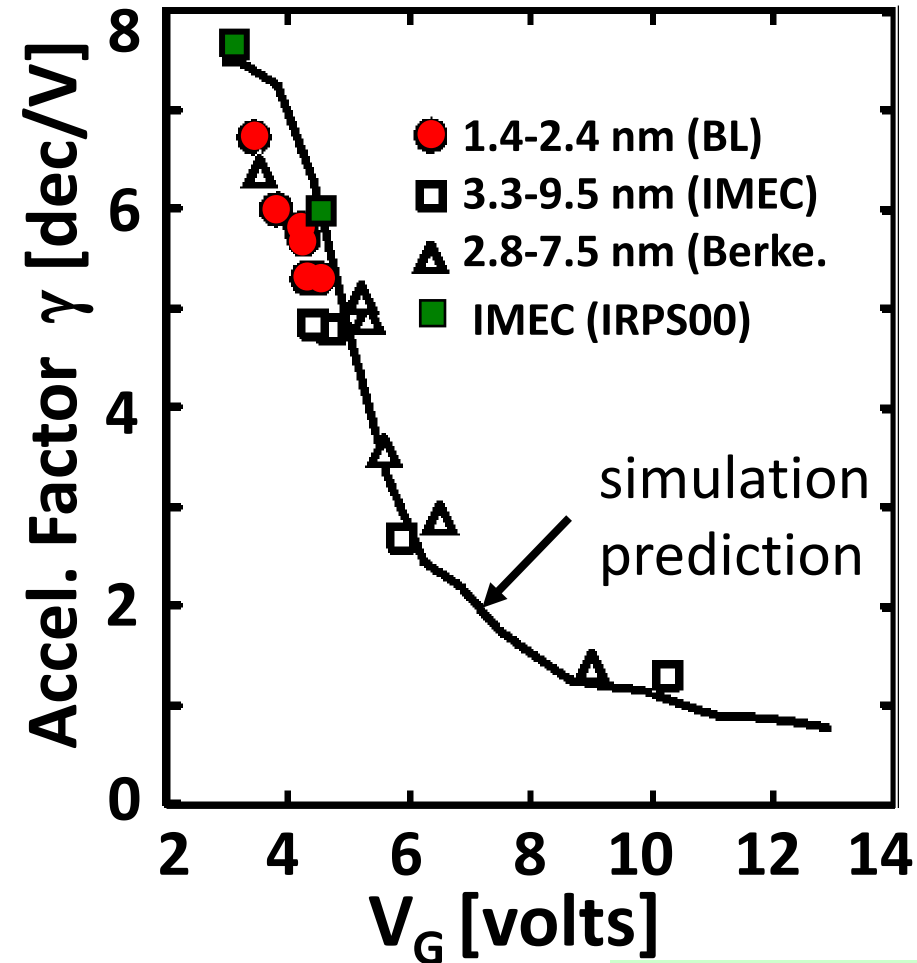
Polarity Dependence

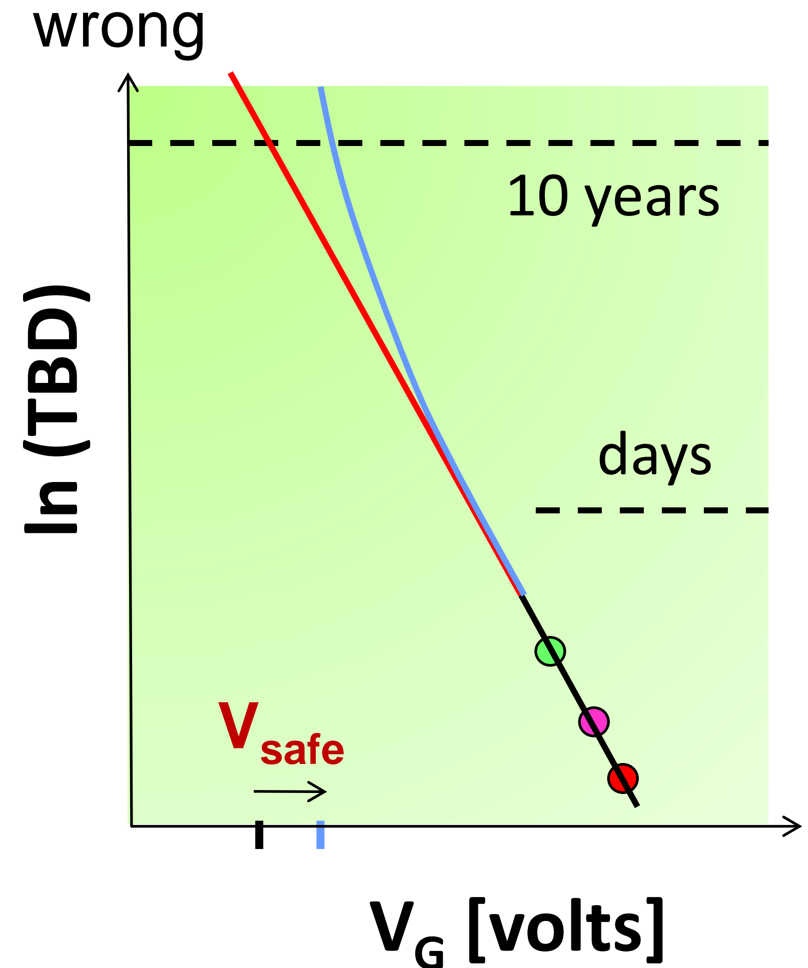


Electric Field (MV/cm)

[1] Teramoto, IRPS, 99, [2] Yassine, APL, 99. [3] T. Nigam, JAP, 97

reduced defect generation at low voltage

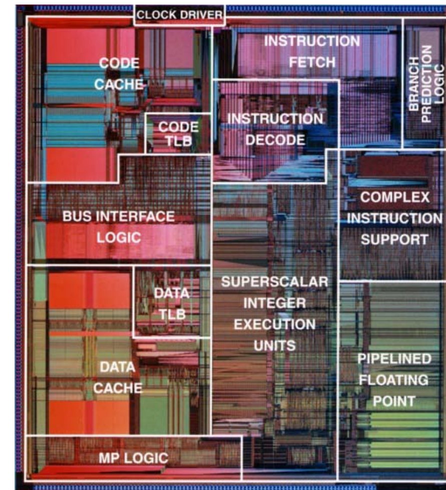




$$V_{safe} = V_{test} - \log\left[\frac{10\ \text{yr}}{T_{BD,Test}}\right] \Big/ \gamma$$

…. but this is a statistical problem

1 CPU ~ 10^8 -10^9 Transistors



When one transistor fails, so does the IC

Statistics connects reliability and variability in a fundamental way …

outline of lecture 8

1) Theory of oxide breakdown
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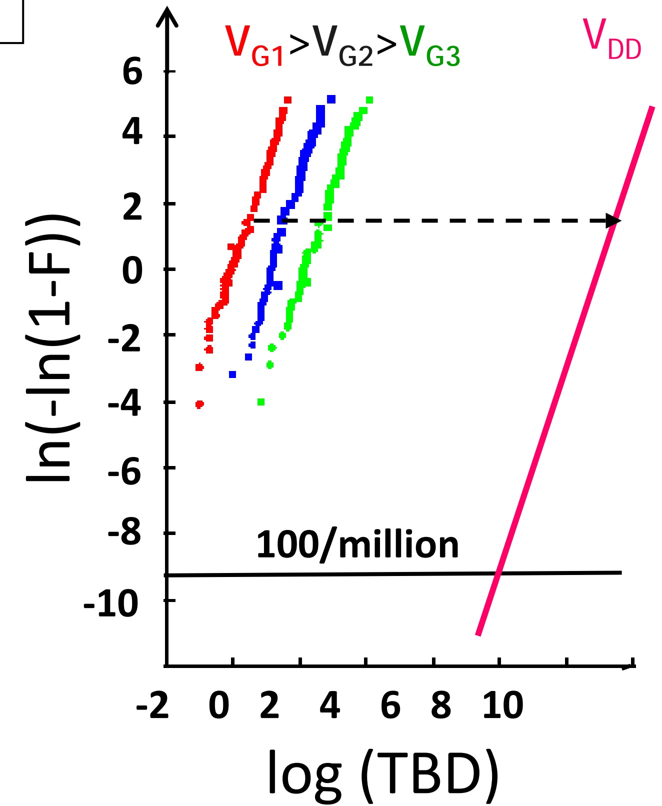
5) Conclusions

mean failure time vs. failure time distribution

Breakdown

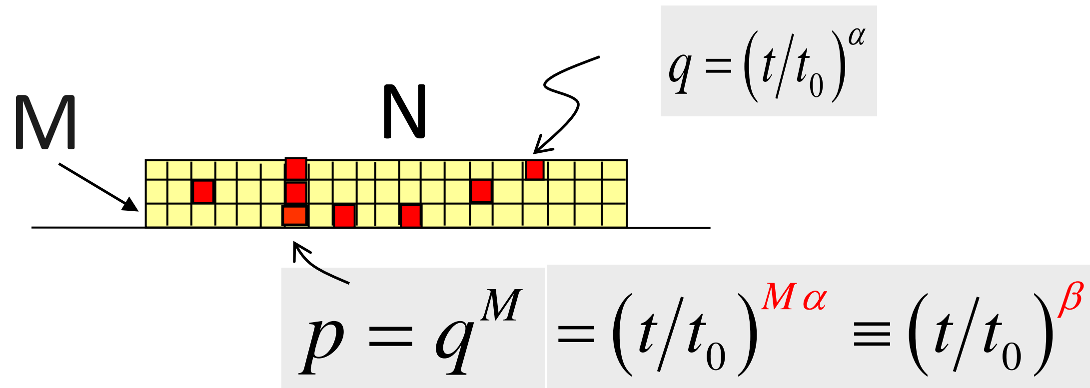
Gate Current

Time



Average lifetime is not good enough ....

(simple) theory of statistical breakdown



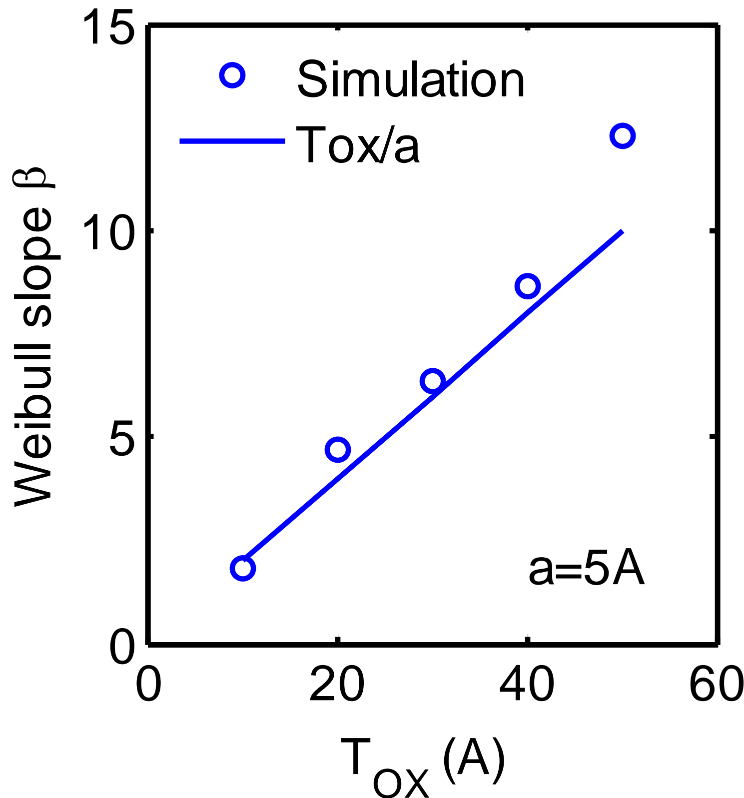
$$P_0=(1-p)^N=(1-Np/N)^N=\exp(-Np)$$

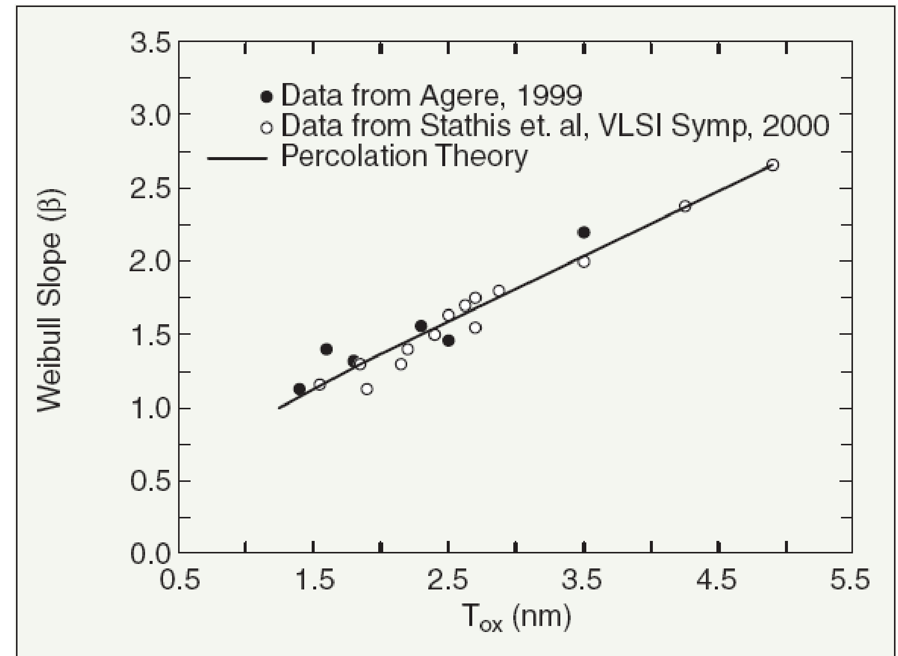
$$1-F(p)=P_0=\exp(-Np)$$

$$W\equiv\ln(-\ln(1-F))=\beta\ \ln(t)-M\alpha\ \ln(t_0)+\ln(N)$$

Straight-line in a Weibull plot, slope proportional to thickness

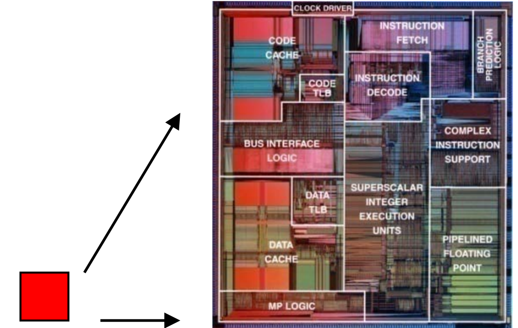
bottom-up prediction for oxide scaling





Thin oxide breaks much faster than thick oxide due to percolation, process-improvement cannot solve this problem

lifetime projection …



$$T_{BD}^{50\%}(A_{IC}) = (A_{TEST} / A_{IC})^{1/\beta} \; T_{BD}^{50\%}(A_{TEST})$$

$$T_{BD}^{q\%}(A_{IC}) = \left[\frac{\ln(1 - q/100)}{\ln(1 - 0.5)} \right]^{1/b} T_{BD}^{50\%}(A_{IC})$$

$$V_{safe} = V_{test} - \log\left[\frac{10\ yrs}{T_{BD}^{q\%}} \right] \Big/ \gamma_{V,acc}$$

HW: Derive this equations based on the last 5 slides …..

NMOS vs. PMOS reliability

Alam, IEDM2002

NMOS

PMOS

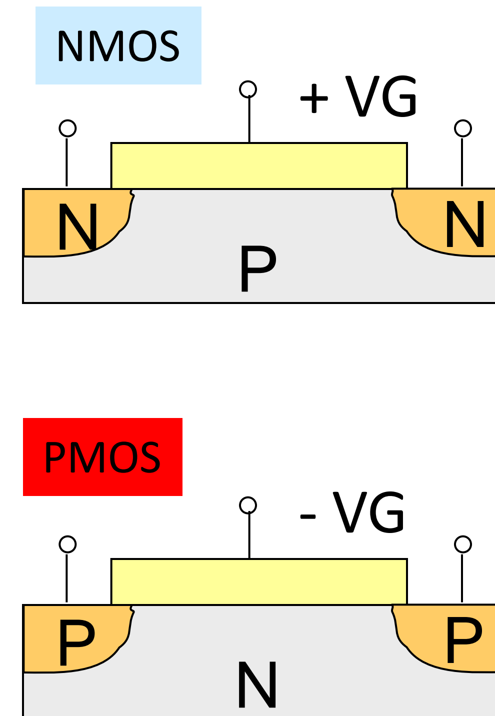
ITRS 2001

V_{op}, V_{safe}

3.0 2.5 2.0 1.5 1.0 0.5 0.0

0.0 1.0 2.0 3.0 4.0 5.0

Oxide Thickness (nm)

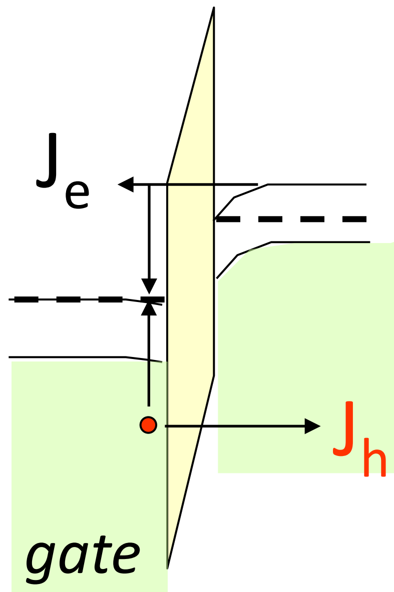


PMOS less reliable than NMOS, contacts defines everything !

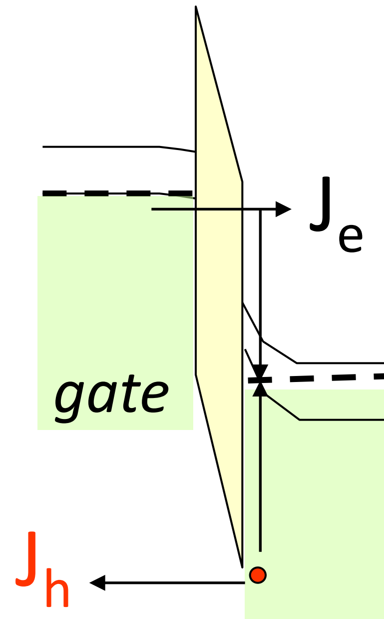
PMOS less reliable than NMOS below 2 nm

$T_{BD} \sim 1/J_h$ with $J_h = J_e \langle \alpha T_h \rangle$

NMOS



PMOS



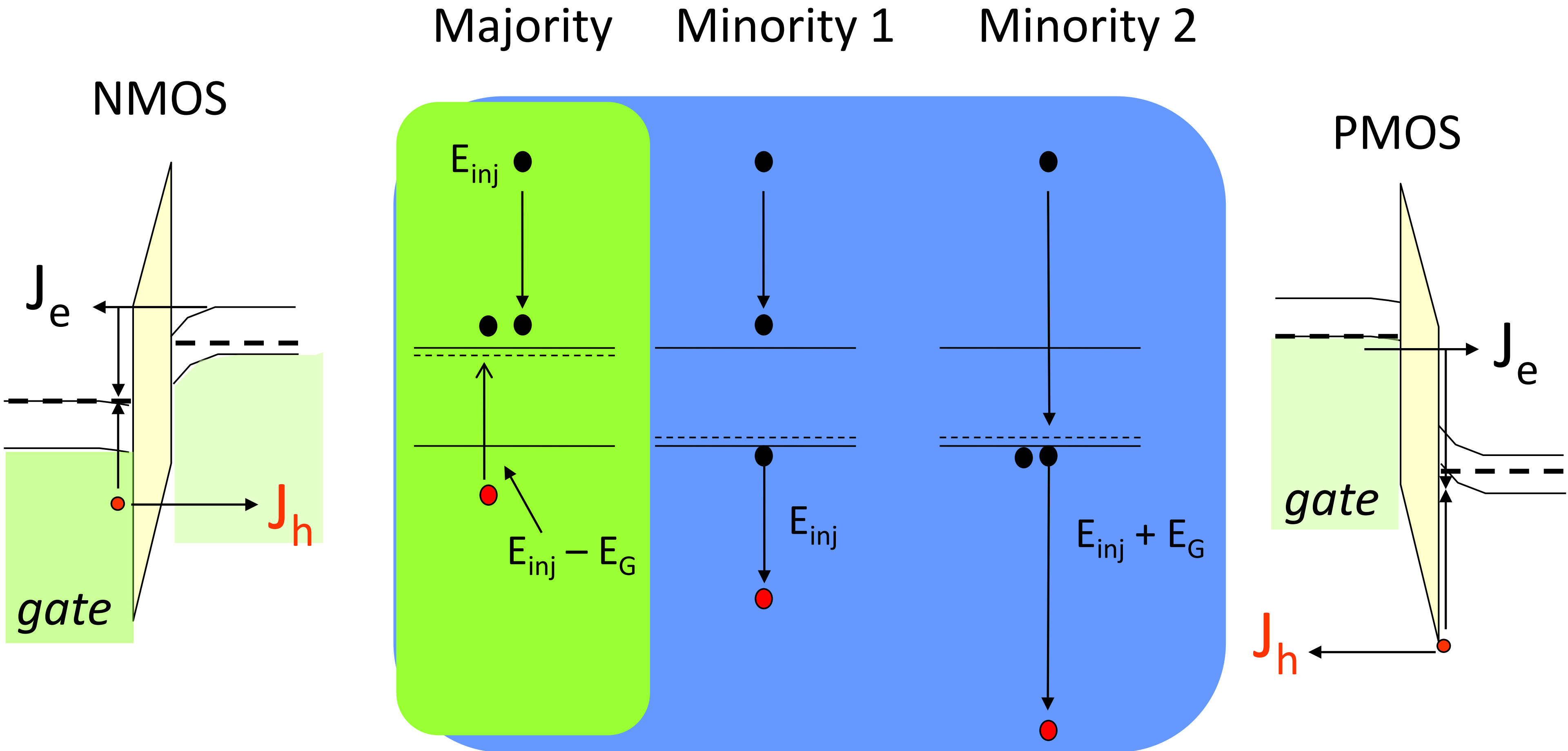
For oxide < 2 nm:

$J_h^{PMOS} > J_h^{NMOS}$, so

$T_{BD}^{PMOS} < T_{BD}^{NMOS}$

Bude, IEDM98
Alam, IRPS00
Weir, ECS02

majority vs. minority ionization … role of hot contacts



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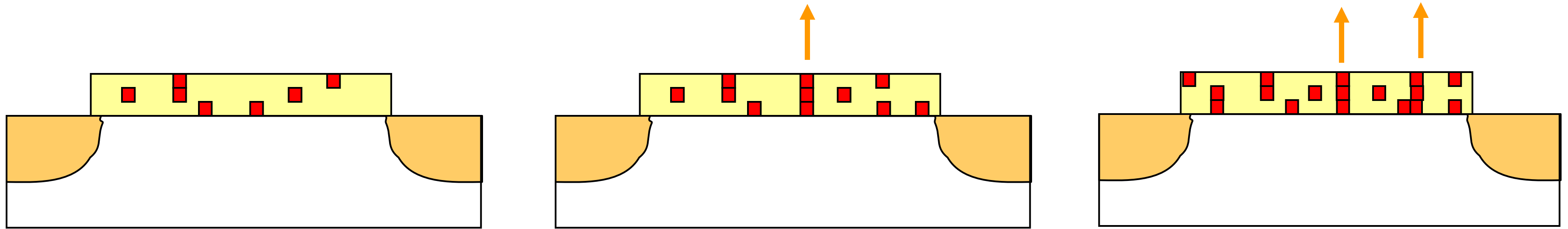
soft breakdown for PMOS



SBD

Gate Current

Gate Current (mA)

0.6
0.4
0.2
0.0

3rd SBD

2nd SBD

1st SBD

0 1 2 3 4

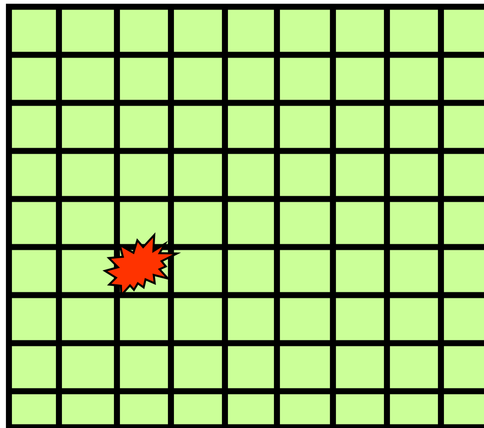
log (Time)

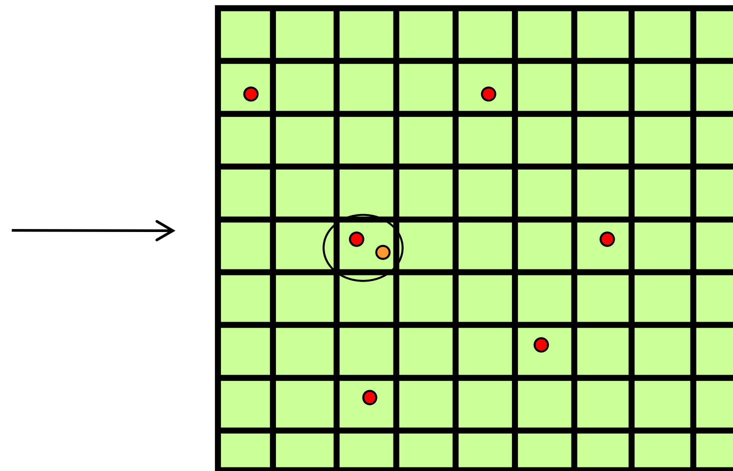
Weir, *IE* … *D*, 2004.

physical reasons for improved reliability

Standard reliability

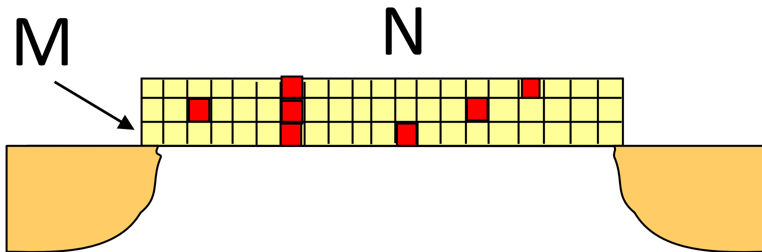
reliability with soft breakdown





Many BD in IC before 2nd BD in the same transistor

statistics of soft breakdown



Prob. of a filled column: $p = q^M$

Prob. of filled cell: $q=(at^{\alpha}/NM)$

Prob. of exactly n-SBD

$$P_n = {}^{N}C_n\, [p^n]\, [(1-p)^{(N-n)}]$$

$$P_n = (\chi^n/n!)\exp(-\chi)$$

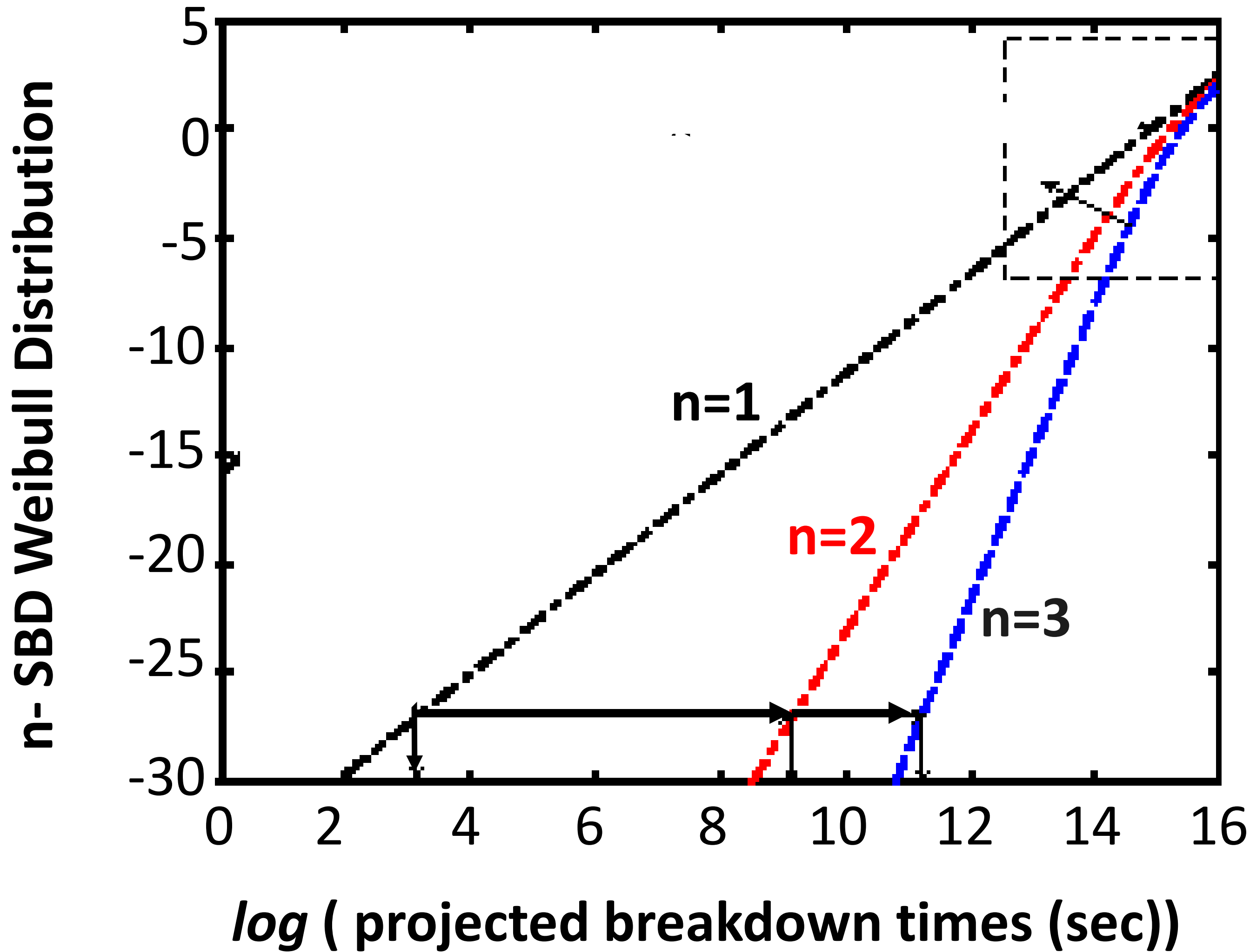
with $\chi=(t/\eta)^{\beta}$ and $\beta=M\alpha$

Prob. of >= n SBD

$$F_n(\chi) = 1 - \sum_{k=0}^{n-1} P_k(\chi)$$

Measured data: $W_n = \ln[-\ln(1-F_n)]$

lifetime improvement

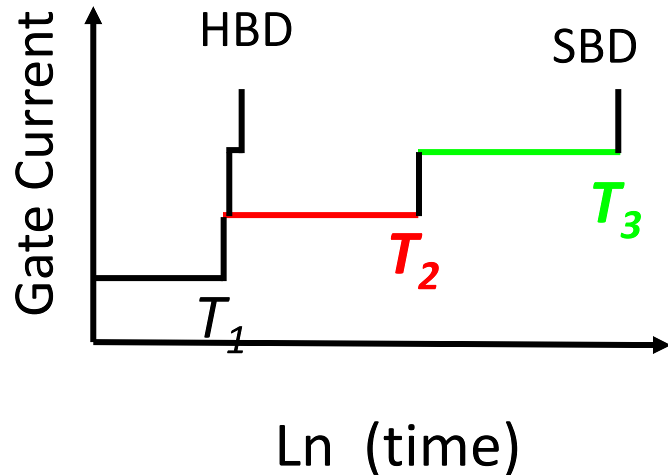


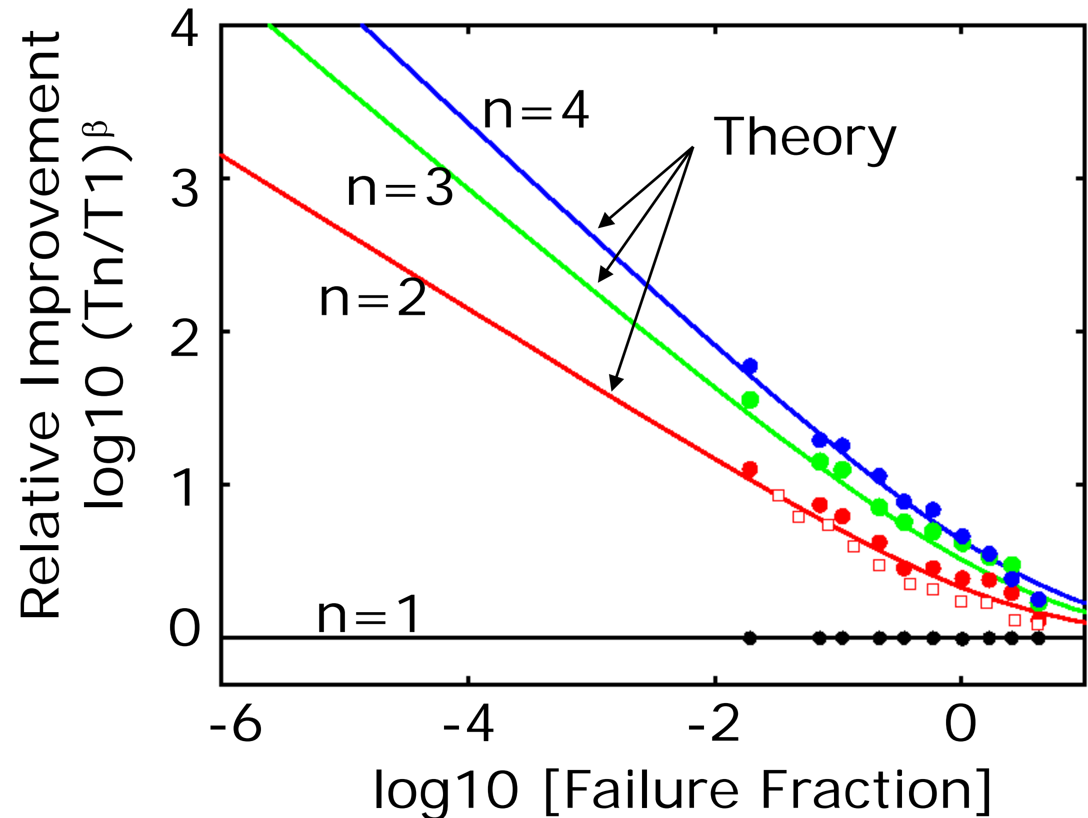
100 million Transistors

1 part per 10^4 failure

SBD improves lifetime geometrically …

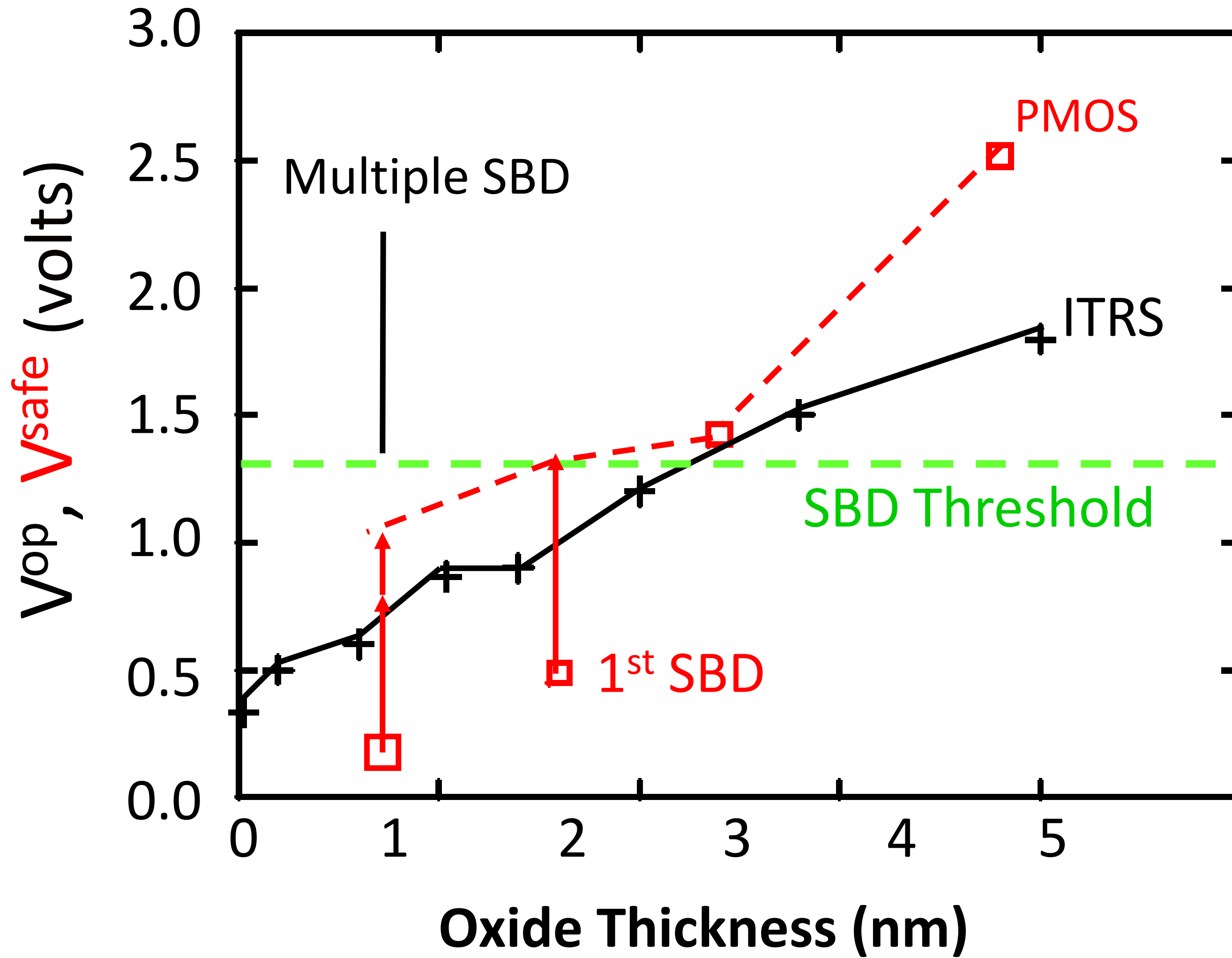
$$(T_n / T_1)^{\beta} = (n/e)(2\pi n)^{1/2n} / F_n^{(1-1/n)}$$





Alam, Nature, 2003

PMOS reliability with SBD



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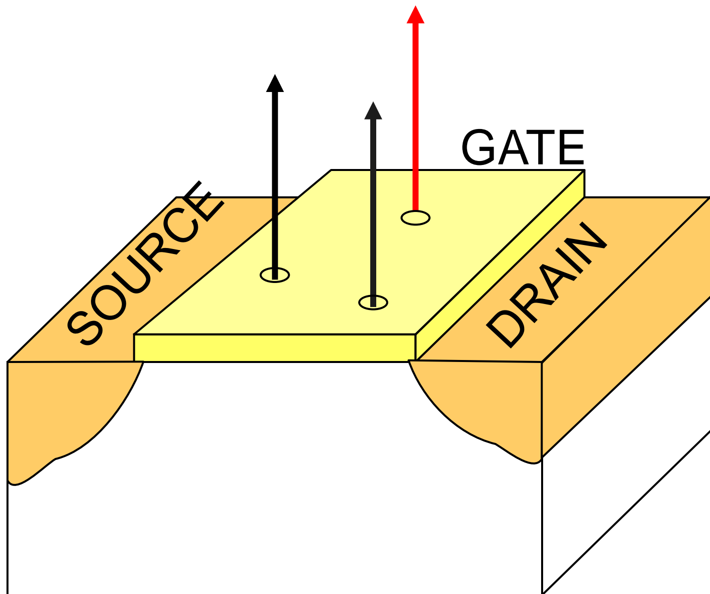
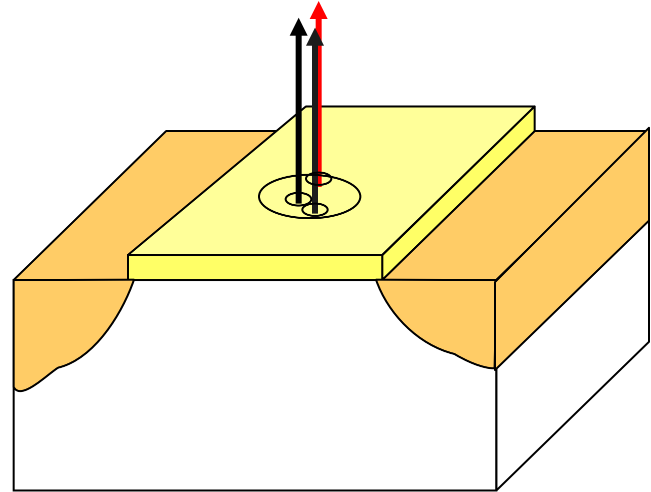
partially correlated breakdown

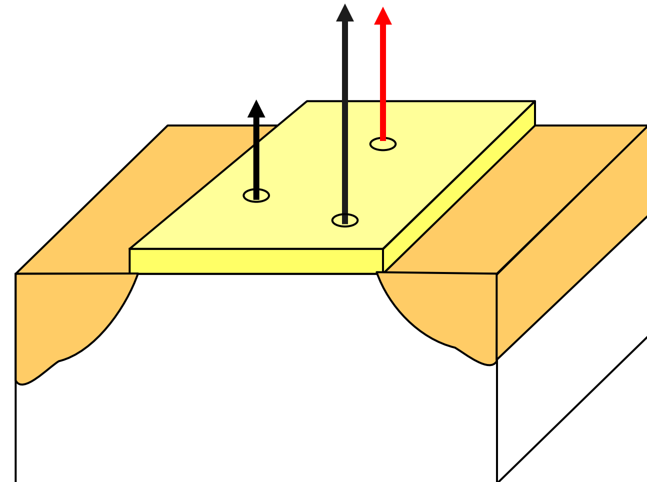
Spatially and Temporally
uncorrelated



Spatially *correlated*

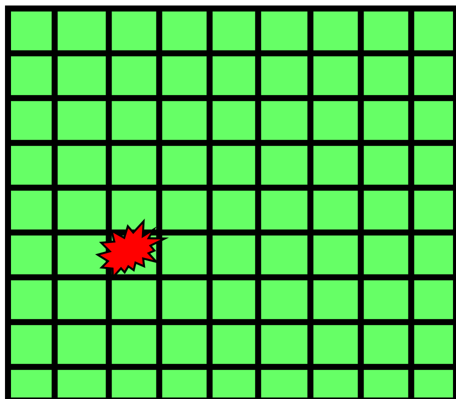


Temporally *correlated*

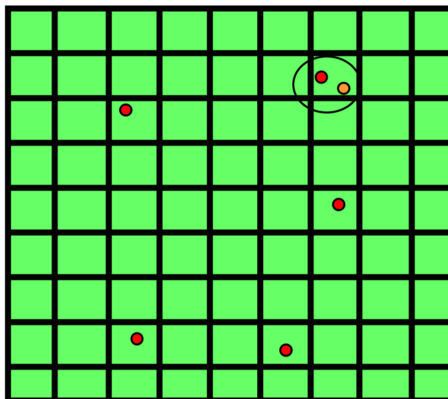


soft BD improves dielectric lifetime

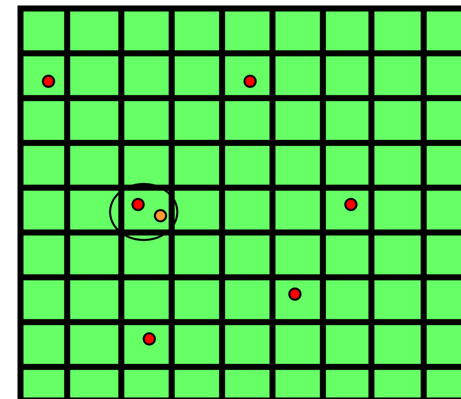
Std. definition



Measurement



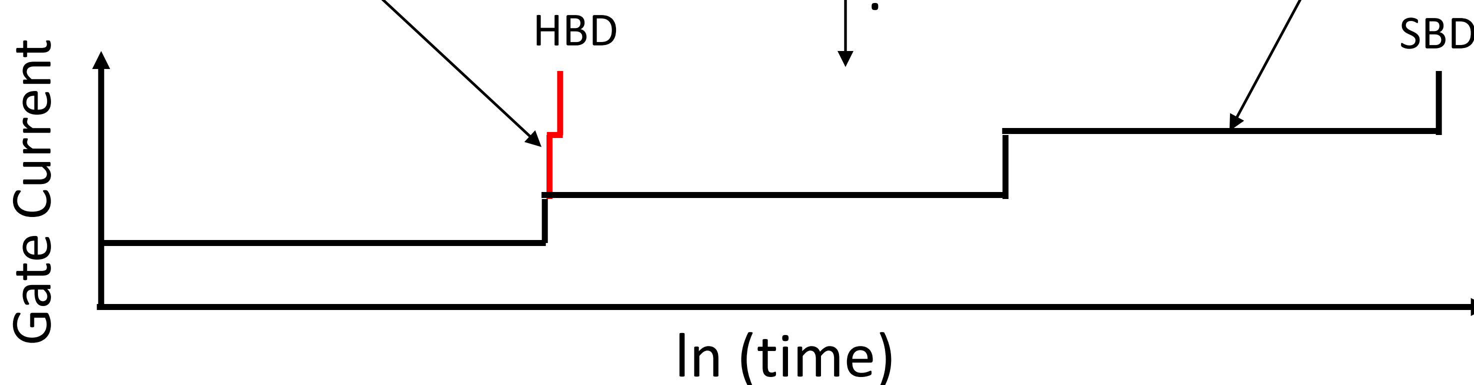
Theory



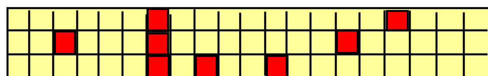
Completely correlated

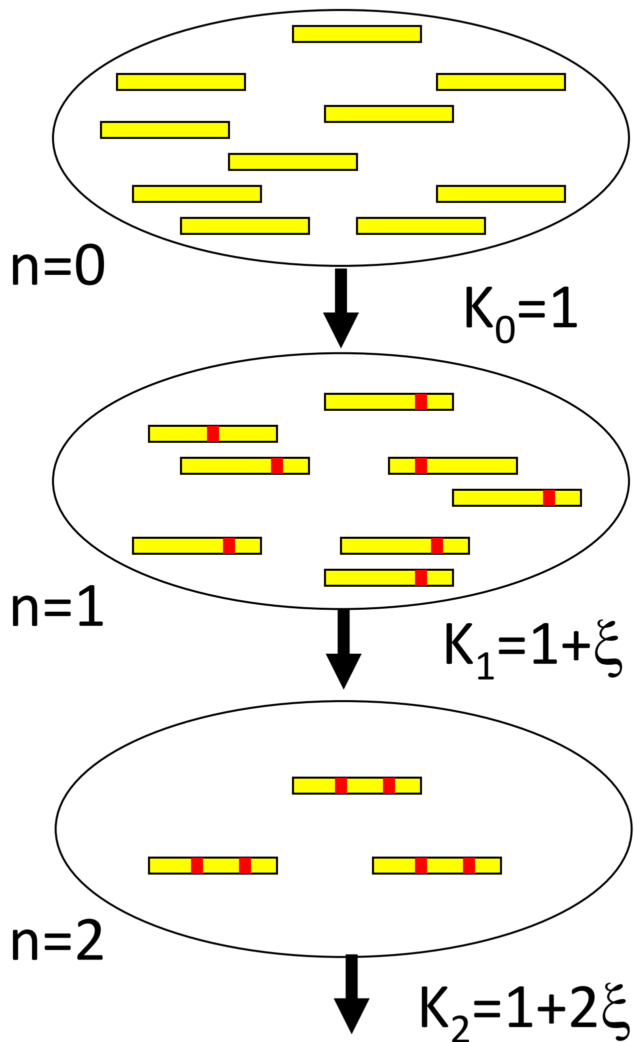
"Essentially" uncorrelated

Completely uncorrelated



computing number of devices with n-SBD





$$\frac{dP_o}{d\chi} = -k_o P_o \qquad \chi=(t/\eta)^{\beta}$$

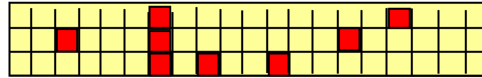
$$\frac{dP_n}{d\chi} = k_{n-1} P_{n-1} - k_n P_n$$

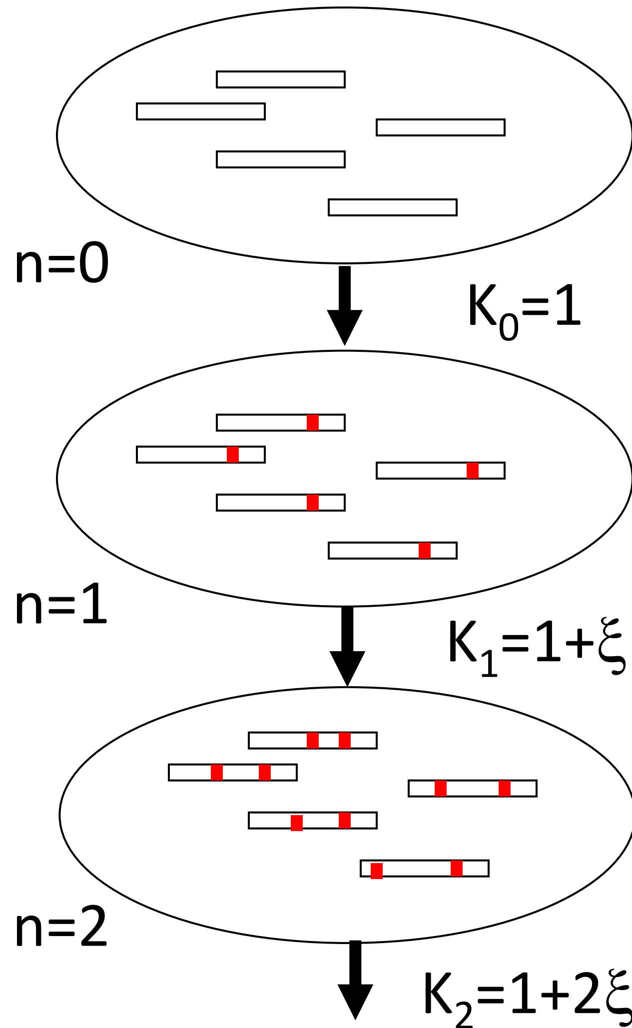
$$P_o = \exp(-\chi)$$

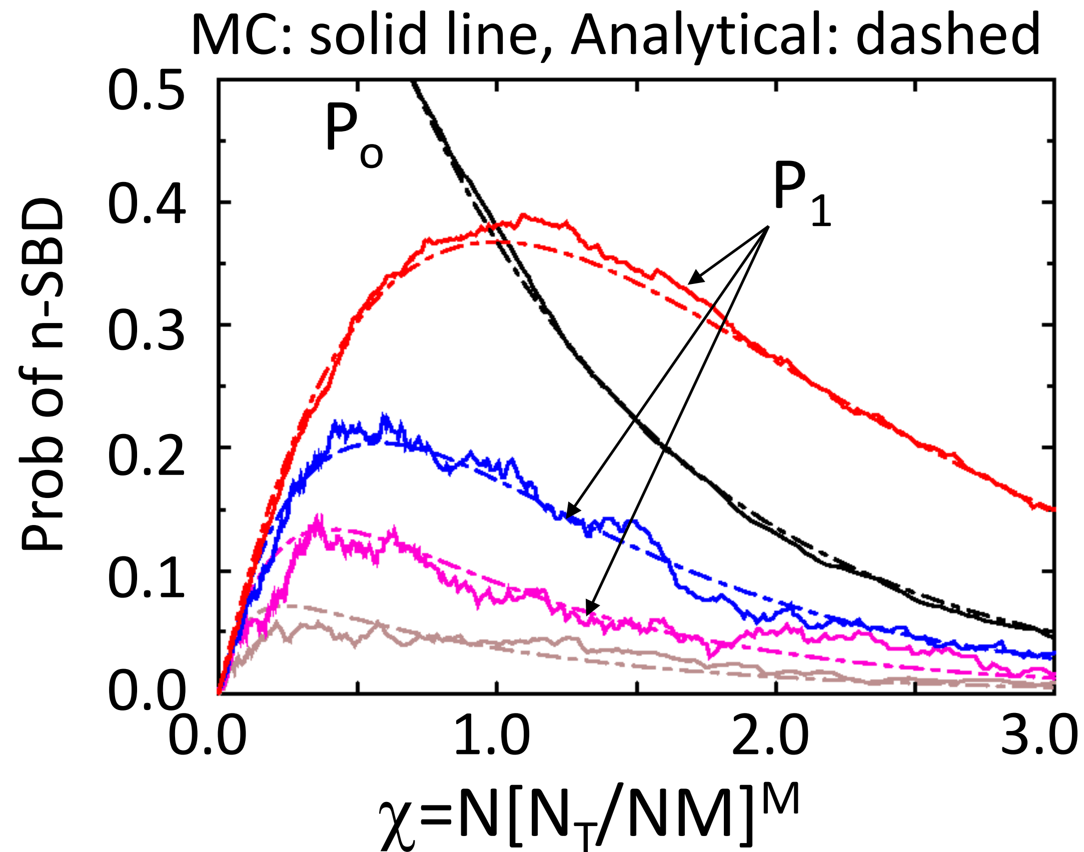
$$P_n = f(\xi)\,(\chi^n/n!)\,\exp(-\chi)$$

$$f(\xi) = \prod_{m=0}^{n-1}(1+m\xi)[1-\exp(-\xi\chi)]/\xi\chi]^n$$

computing number of devices with n-SBD



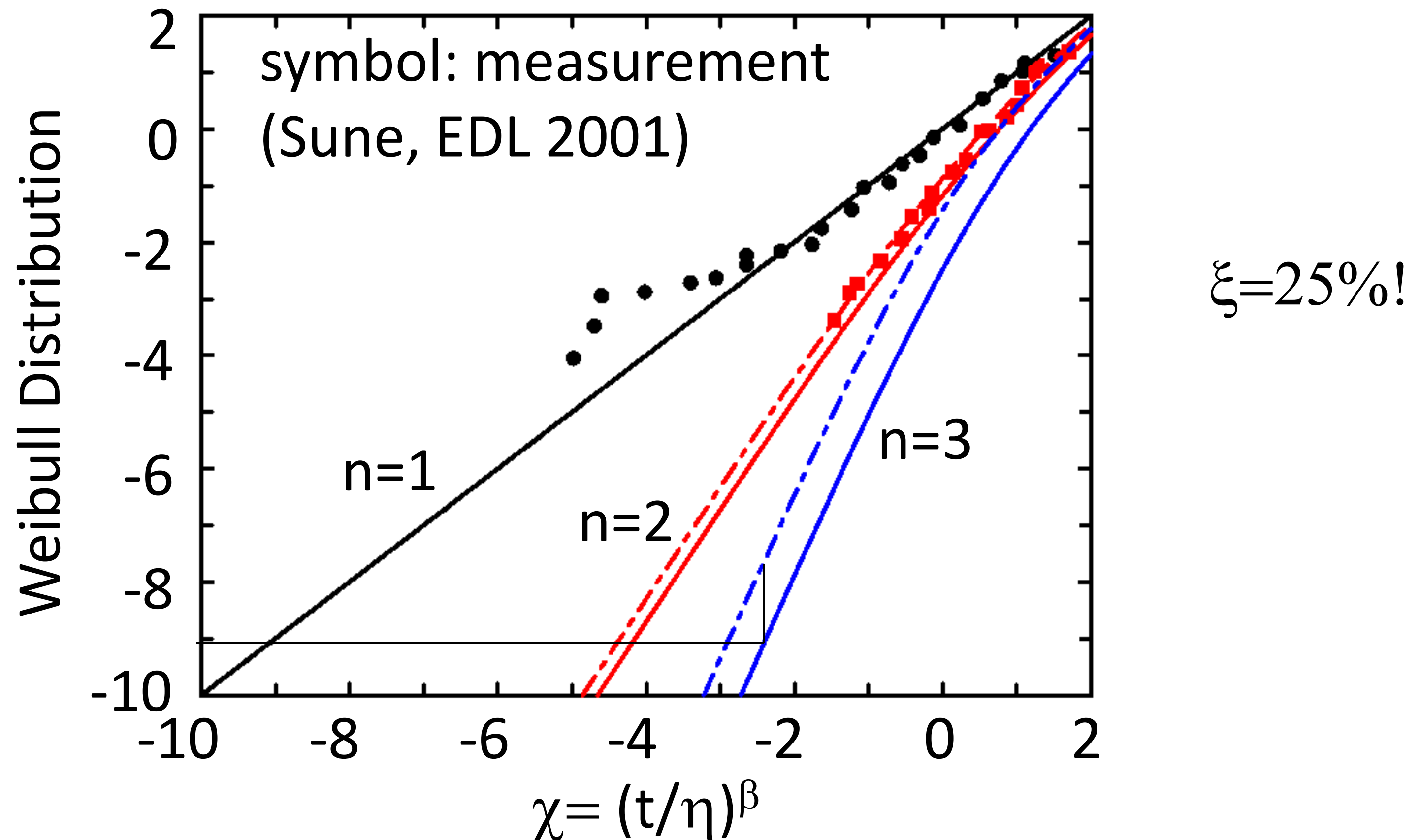




Recall: Island-size distribution …

correlated distributions for multiple SBD

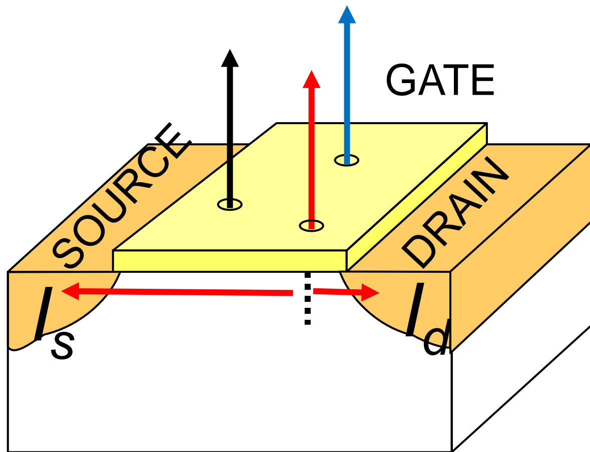
$$P_n = f(\xi)\ (\chi^n/n!)\ \exp(-\chi)$$

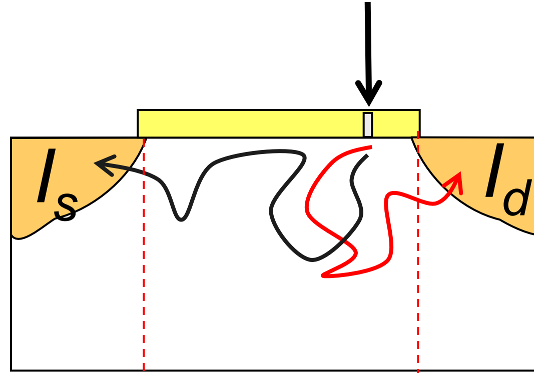


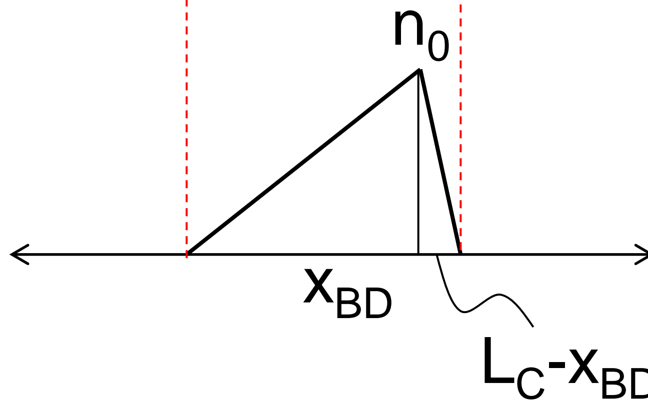
ξ=25%!

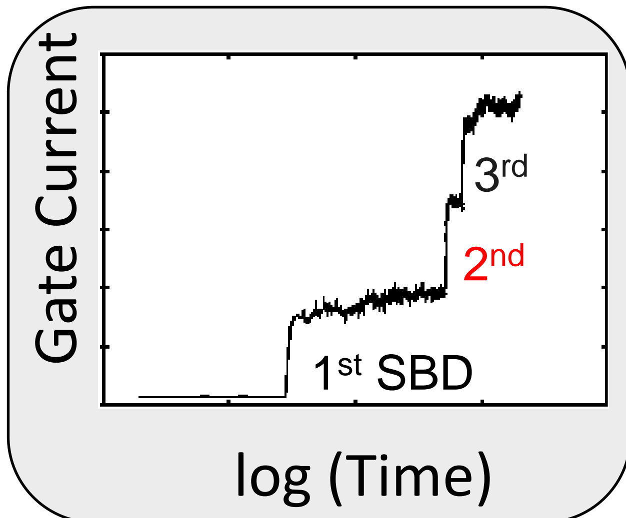
By measuring first and second SBD distributions, we determine ξ; which allows computation of all other distributions

current ratio technique









$$J = qD\frac{dn}{dx} + n\mu E$$

(the $n\mu E$ term is crossed out with a red X)

$$\nabla \bullet J = 0$$

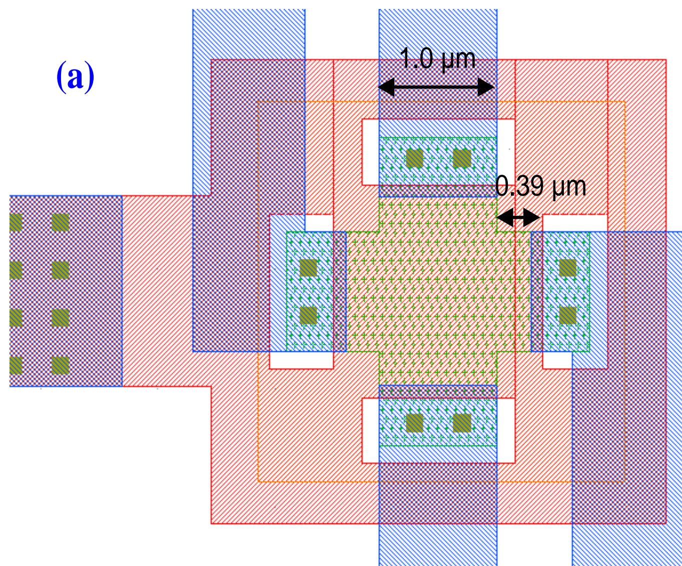
$$D\frac{d^2 n}{dx^2} = 0$$

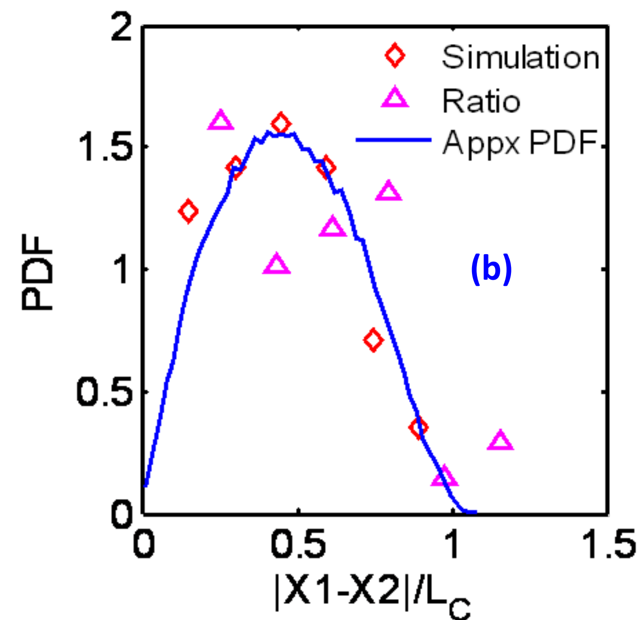
$$n = Ax + B$$

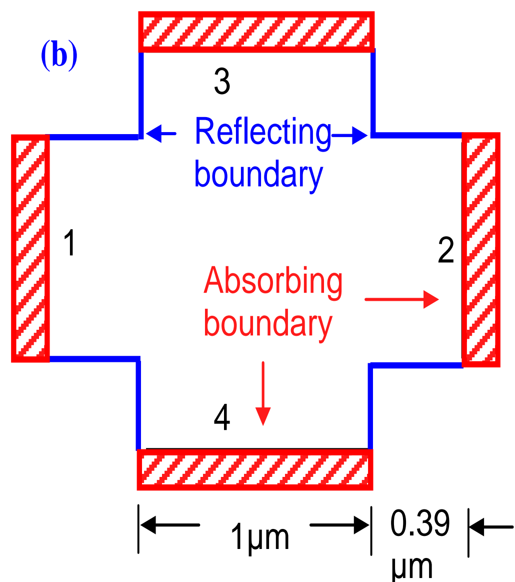
$$J_s = qD\frac{n_0}{x_{BD}}$$

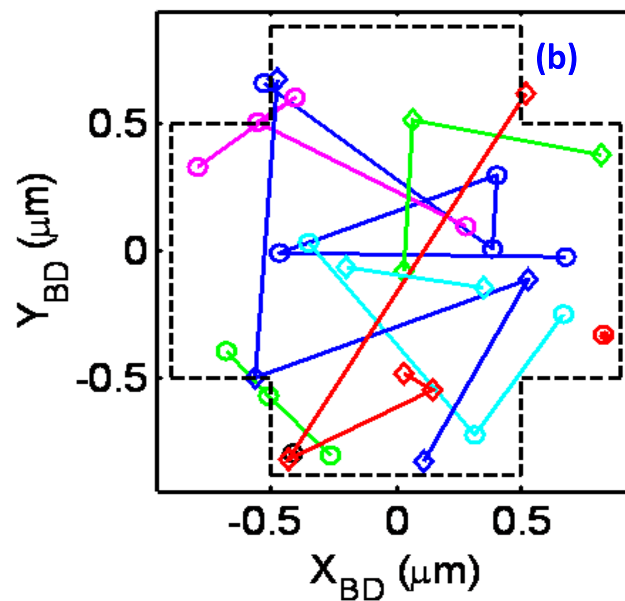
$$\frac{J_d}{J_s + J_d} = \frac{x_{BD}}{L_C}$$

spatially uncorrelated breakdown









conclusions

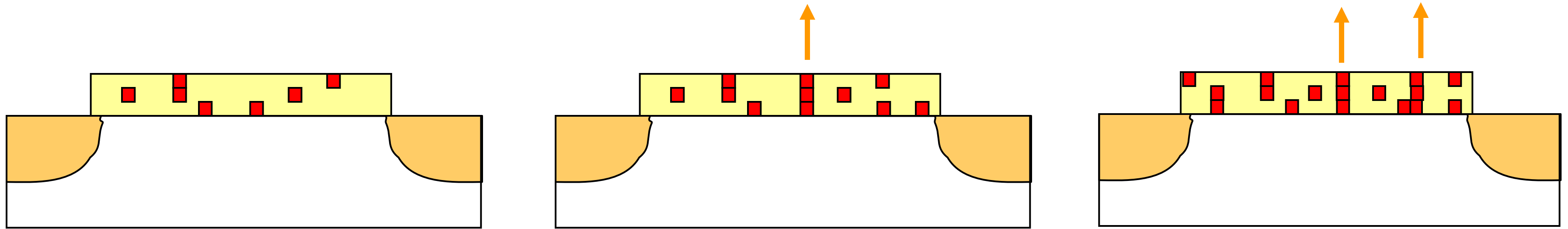
- The reliability of modern ultrathin oxides involve delicate interplay between reduced defect generation at low voltages, statistics of failure distribution, and uncorrelated generation of breakdown paths.

- The reliability of ultra-thin gate dielectric is primarily dictated by ‘hot’ contacts – hence the difference between PMOS and NMOS reliability. The uncorrelated breakdown.

- The physics of statistical distribution of failure times and that of length scaling in very short channel transistors are the same, because they are based on similar physical principles.

reference

soft breakdown for PMOS



Gate Current

0.6
0.4
0.2
0.0

Gate Current (mA)

0 1 2 3 4

log (Time)

1st SBD

2nd SBD

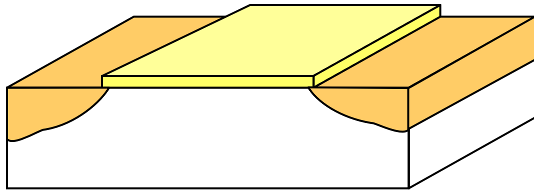
3rd SBD

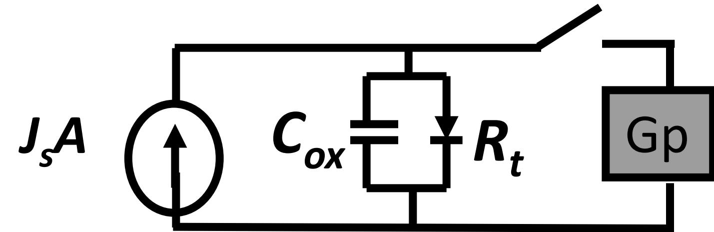
SBD

Weir, *IE*... *D*, 2004.

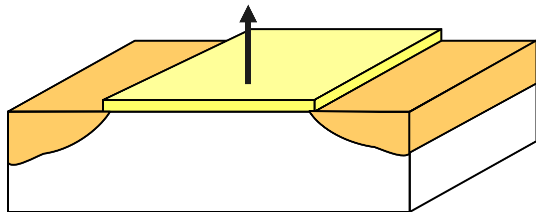
simple model for soft/hard breakdown

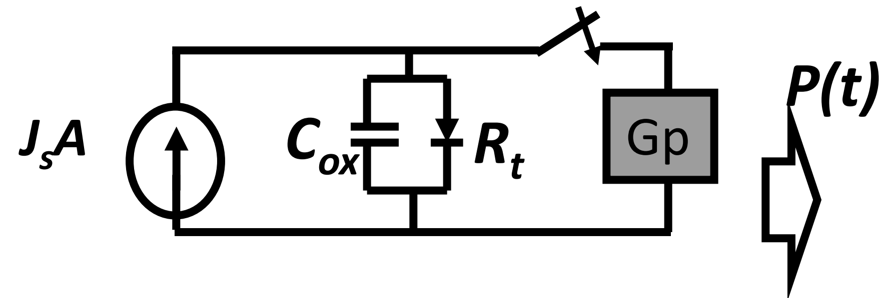
(a) t < TBD, only tunneling



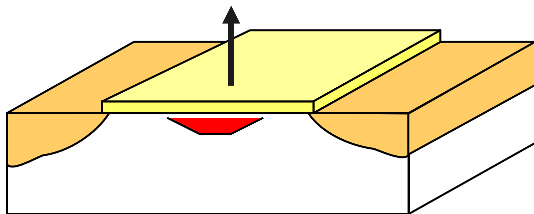


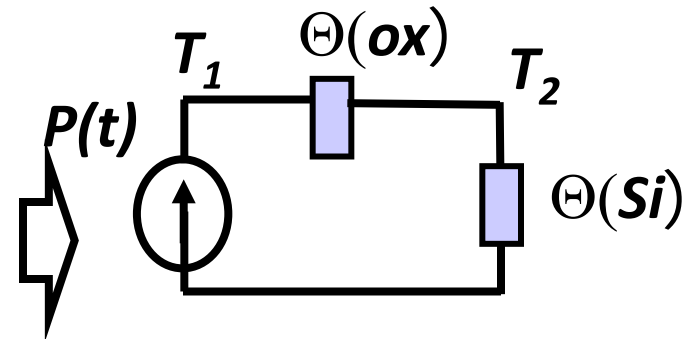
(b) t = TBD, BD current initiates





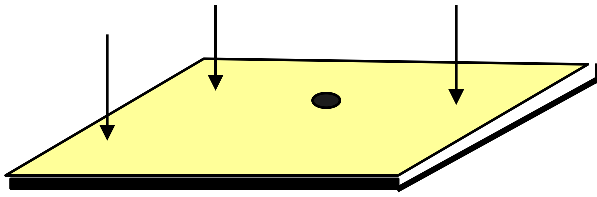
(c) t > TBD, transient heating

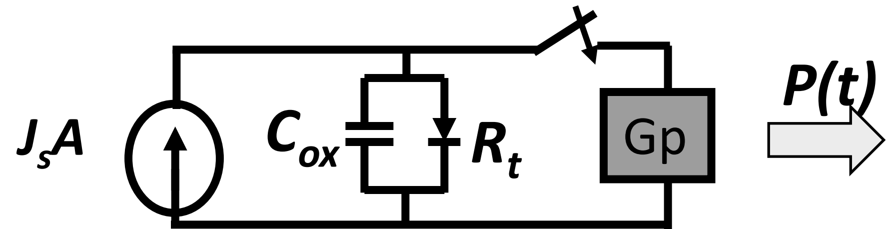




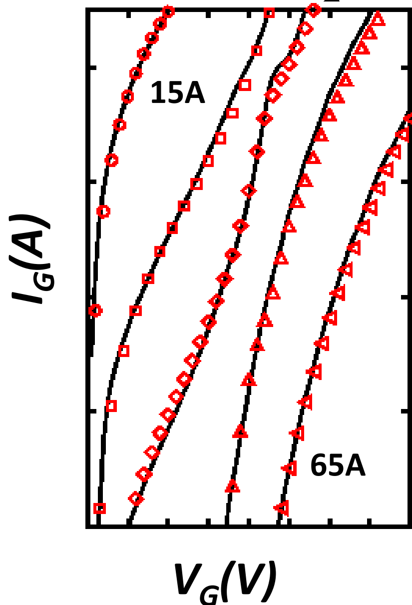
If P(t) below certain threshold, breakdown will be soft

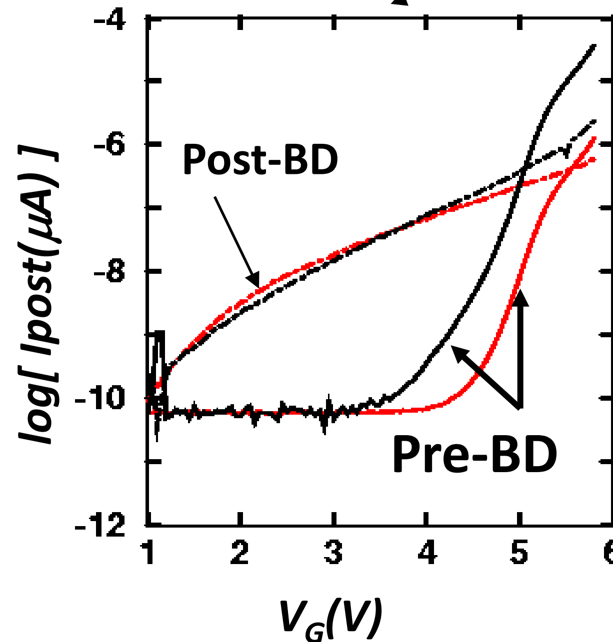
a simple model for SBD and HBD

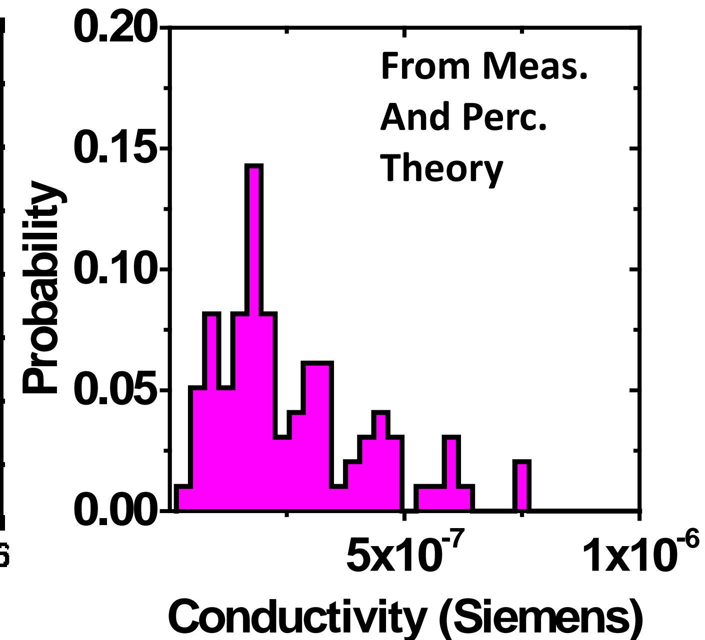




$$AC_{ox}(\,dV/dt\,) + A\alpha \;\; \exp(-\beta/V) + \{g_0\}V^{\delta} = AJ$$







Alam, ITED 2002, p. 232

statistical distribution of perc. resistance

Probability

0.4
0.2
0.0

$3a_0$
$2.2a_0$
$2a_0$

Sim.
(arb. units)

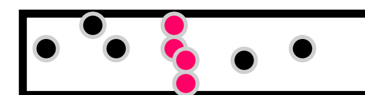
0.4
0.2
0.0

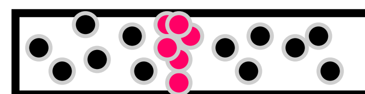
2 nm
1.7 nm
1.5 nm

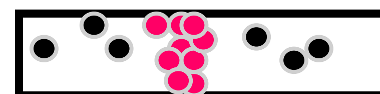
Meas

5×10^{-7} 1×10^{-6}

Conductivity (Siemens)

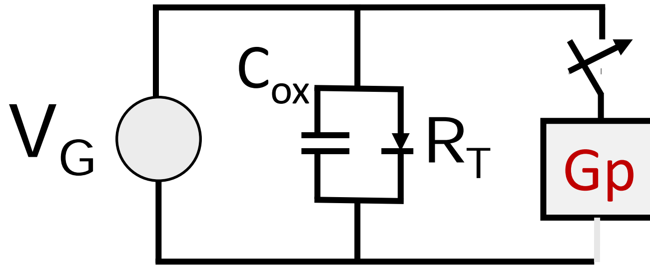

Sample 1


Sample 2


Sample n

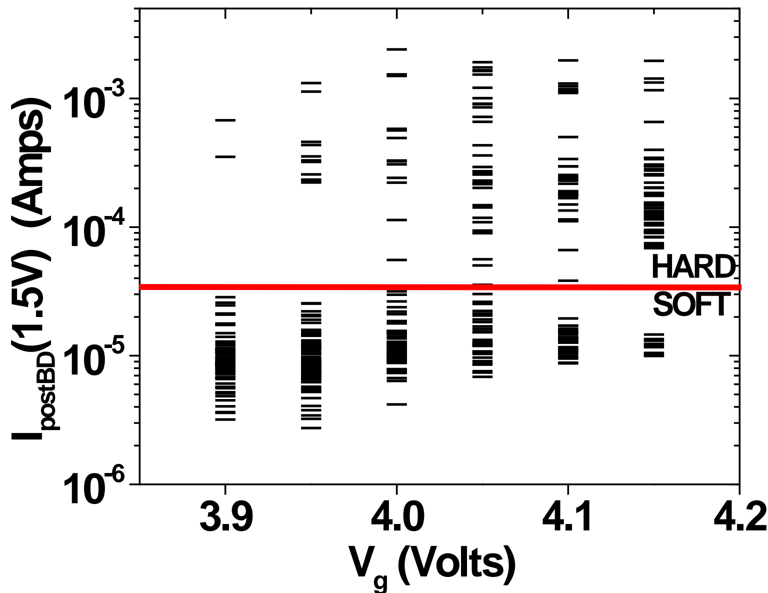
- Weakly thickness dependent
- G_{max}/G_{min} = 5 -10

soft breakdown at reduced voltage

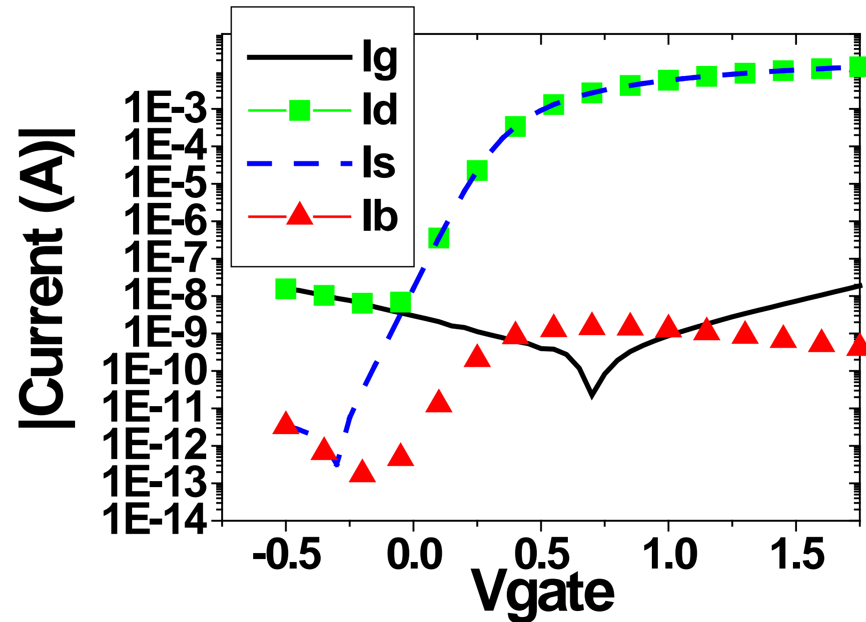


$$P = G_p V_G^2$$

Softer BD ←

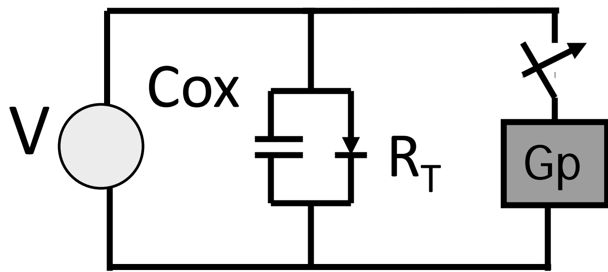


Expt. Evidence of SBD @ low VG



Performance unaffected by SBD

G_p is known, how to determine P_{THER} ?



$P = G_p V^2$

$Gpcrit = P_{THER}/V^2$

Based on ratio of soft to hard- BDs at V_1 and V_2, determine P_{THER}.
Use it can determine Vsafe.

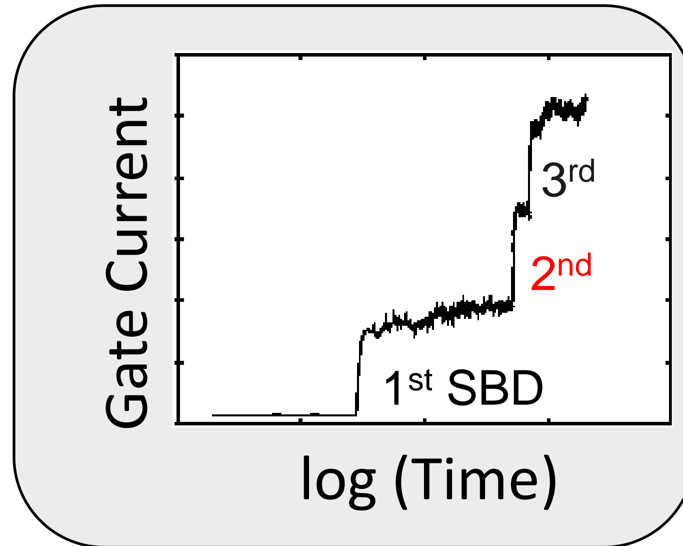
PDF
Gp,crit (*V1*)
SBD
HBD

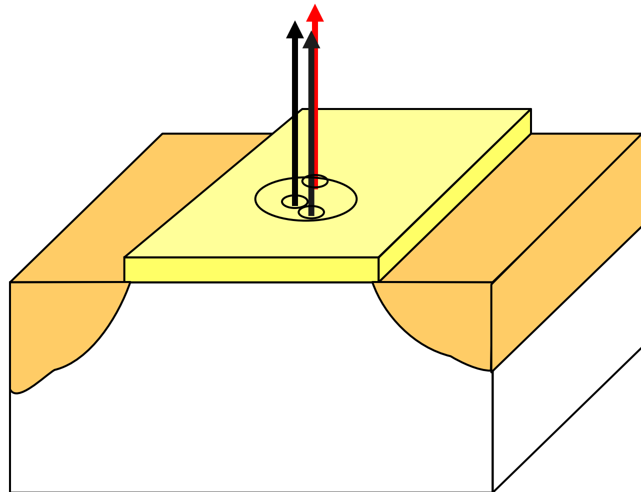
PDF
Gp,crit (*V2*)
SBD
HBD

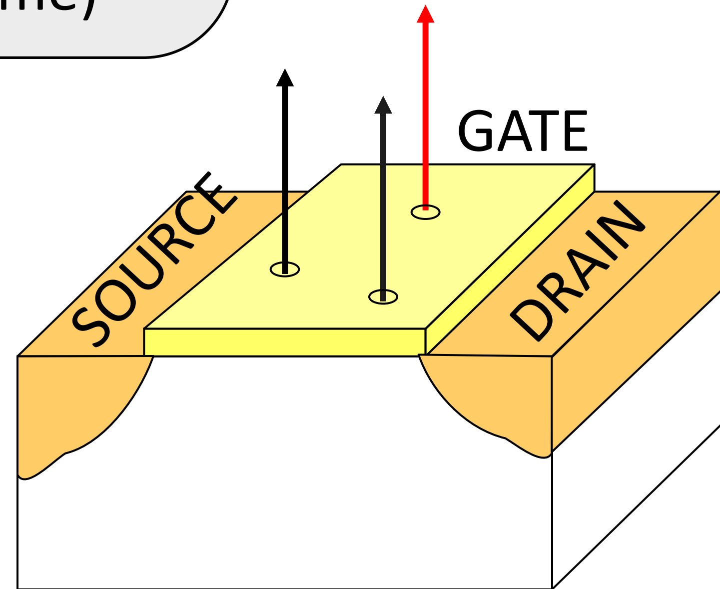
PDF
Gp,crit (Vsafe)
SBD
HBD

G_p

features of hard and soft breakdown

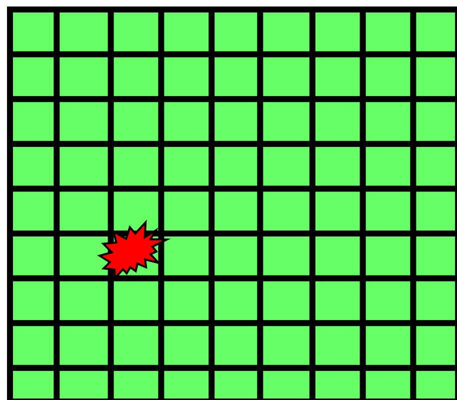




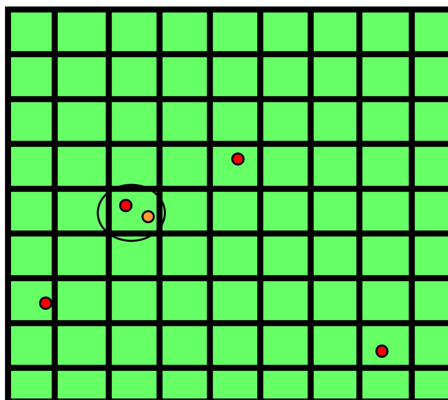


theory of correlated soft breakdown

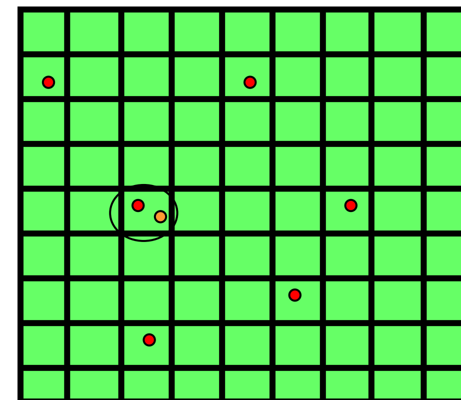
Std. definition



Measurement



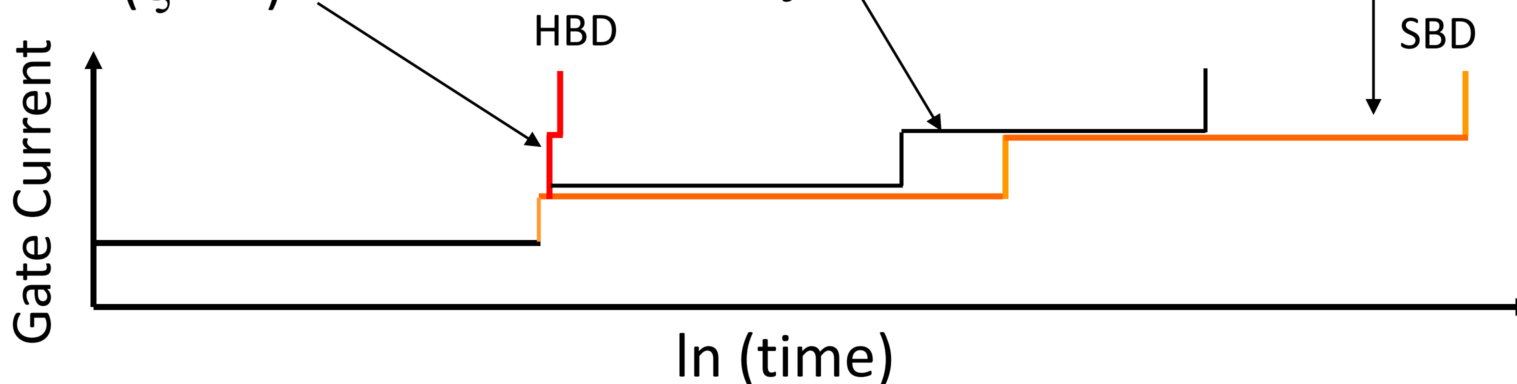
Theory



Completely correlated ($\xi = \propto$)

"Essentially" uncorrelated ($\propto < \xi < 0$)

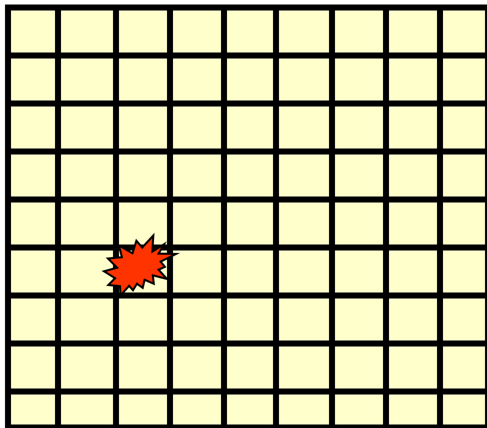
Completely uncorrelated ($\xi = 0$)

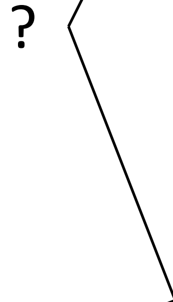


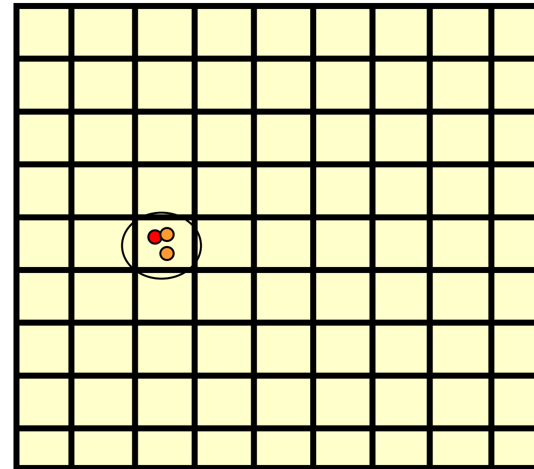
physical reasons for improved reliability

new reliability definition

Std. reliability definition

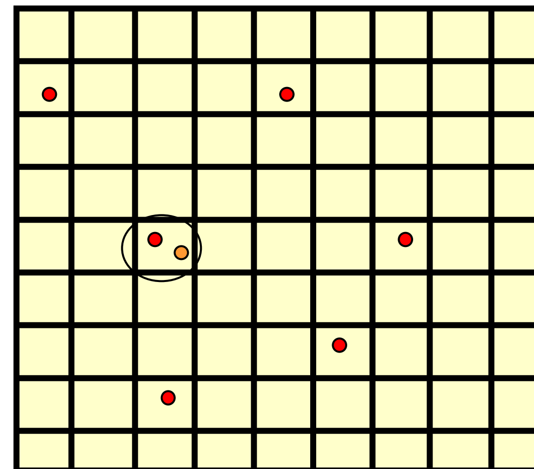






Correlated

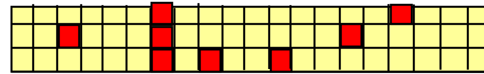
Few BD in IC before 2nd BD in the same transistor

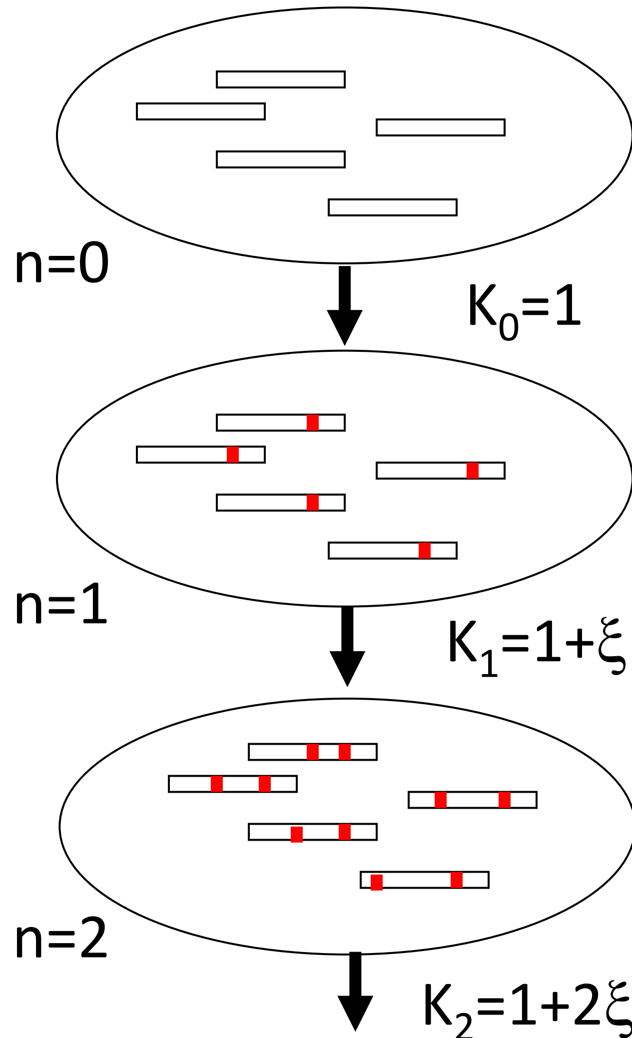


Uncorrelated

Many BD in IC before 2nd BD in the same transistor

computing number of devices with n-SBD





$$\frac{dP_o}{d\chi} = -k_o P_o$$

$$\chi=(t/\eta)^{\beta}$$

$$\frac{dP_n}{d\chi} = k_{n-1}P_{n-1} - k_n P_n$$

$$P_o=\exp(-\chi)$$

$$P_n = f(\xi) \quad (\chi^n/n!)\exp(-\chi)$$

$$f(\xi)=\prod_{m=0}^{n-1}(1+m\xi)[1-\exp(-\xi\chi)]/\xi\chi]^n$$