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ECE695: Reliability Physics of Nano-Transistors
Lecture 24: Statistics of Oxide Breakdown: Cell percolation model

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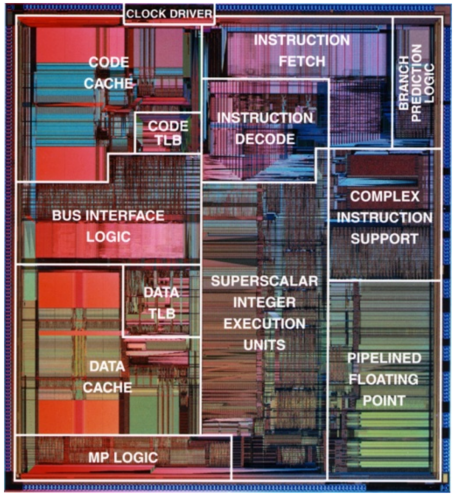
Outline

1. Observations: Failure times are statistically distributed
2. Models of Failure Distribution: Extrinsic vs. percolation
3. Percolation theory of multiple Breakdown
4. TDDB lifetime projection
5. Conclusions

A Fantastic Statistical Problem

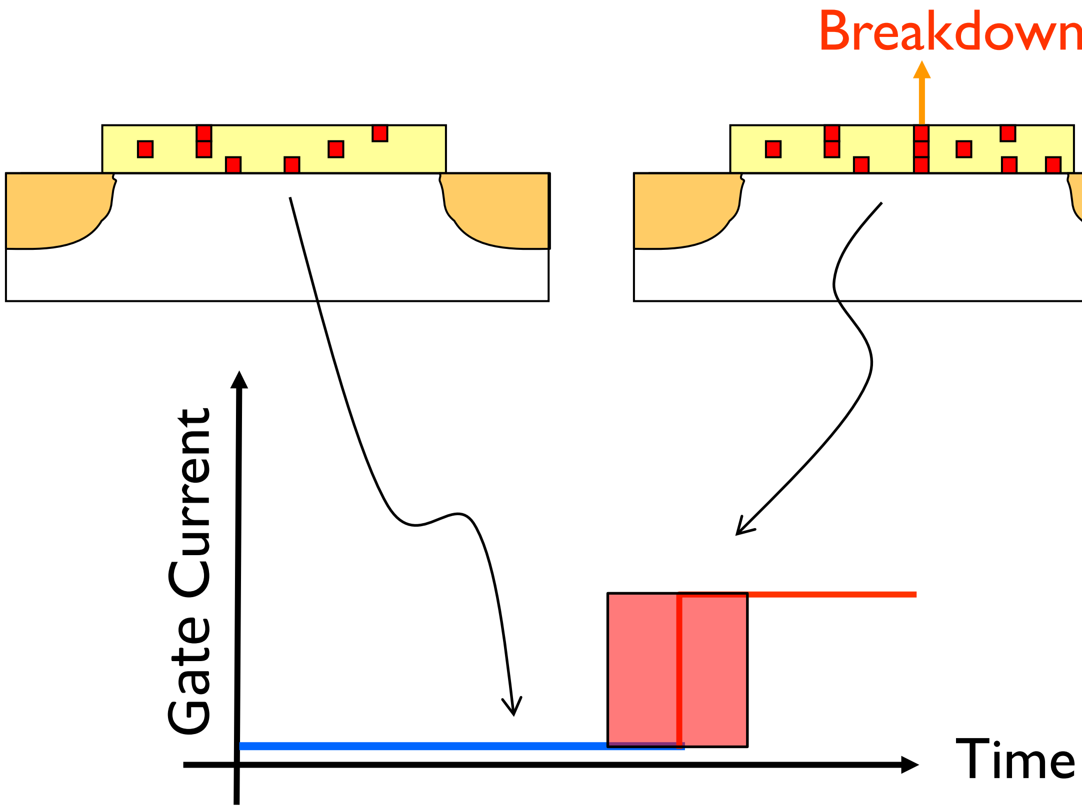
1 CPU ~ 10^8 -10^9 Transistors

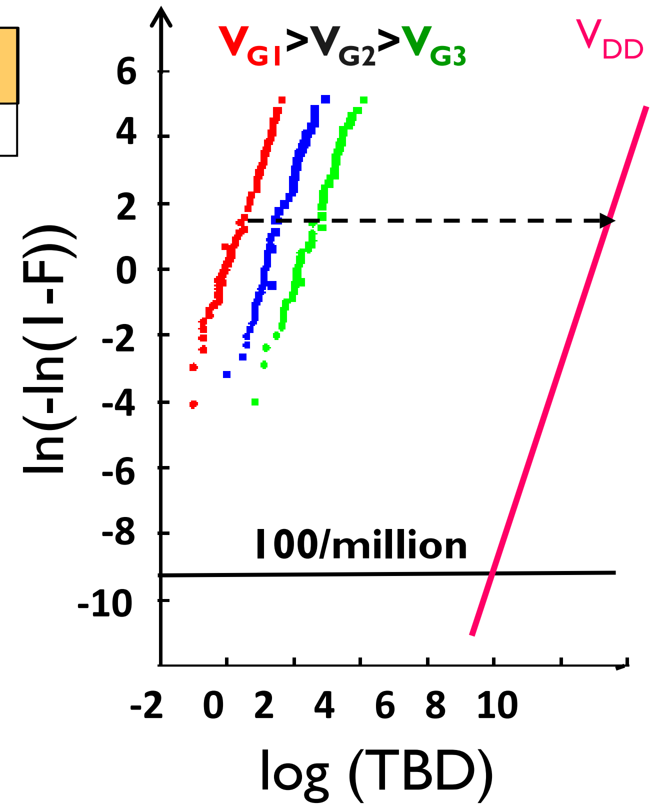


When one transistor fails, so does the IC. Industrial requirements demand no more one in 10000 ICs fail due to reliability. …. Ensure reliability @1e-13 levels!!

Statistics connects reliability and variability in a fundamental way …

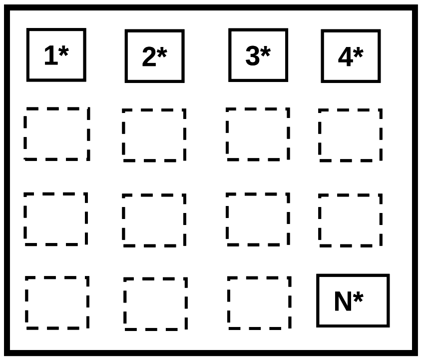
Average Failure Time vs. Failure Time Distribution

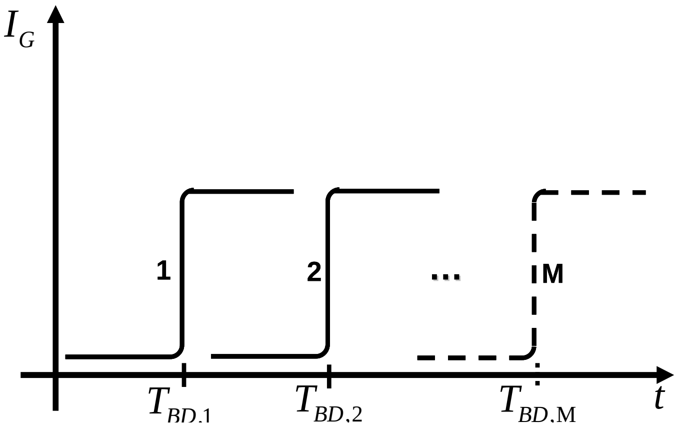


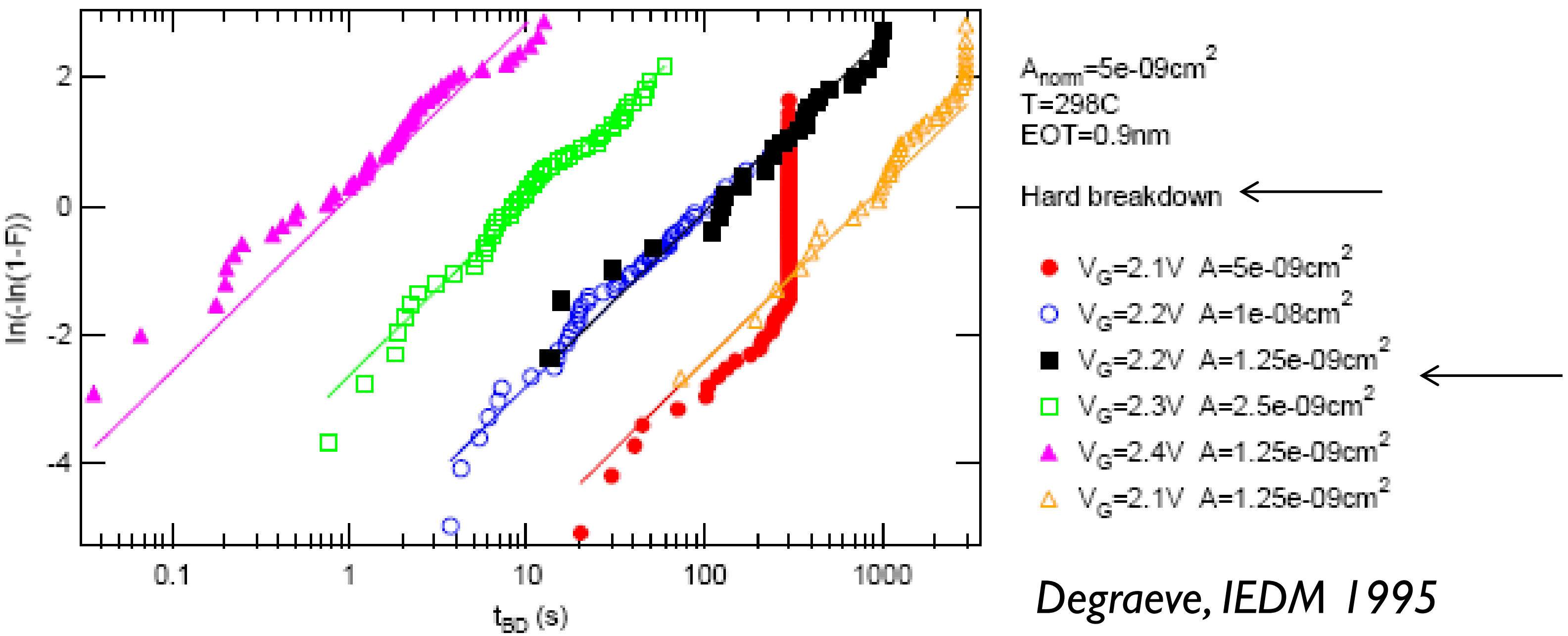


Average lifetime is not good enough ….

Background: Distribution shape independent of stress and area

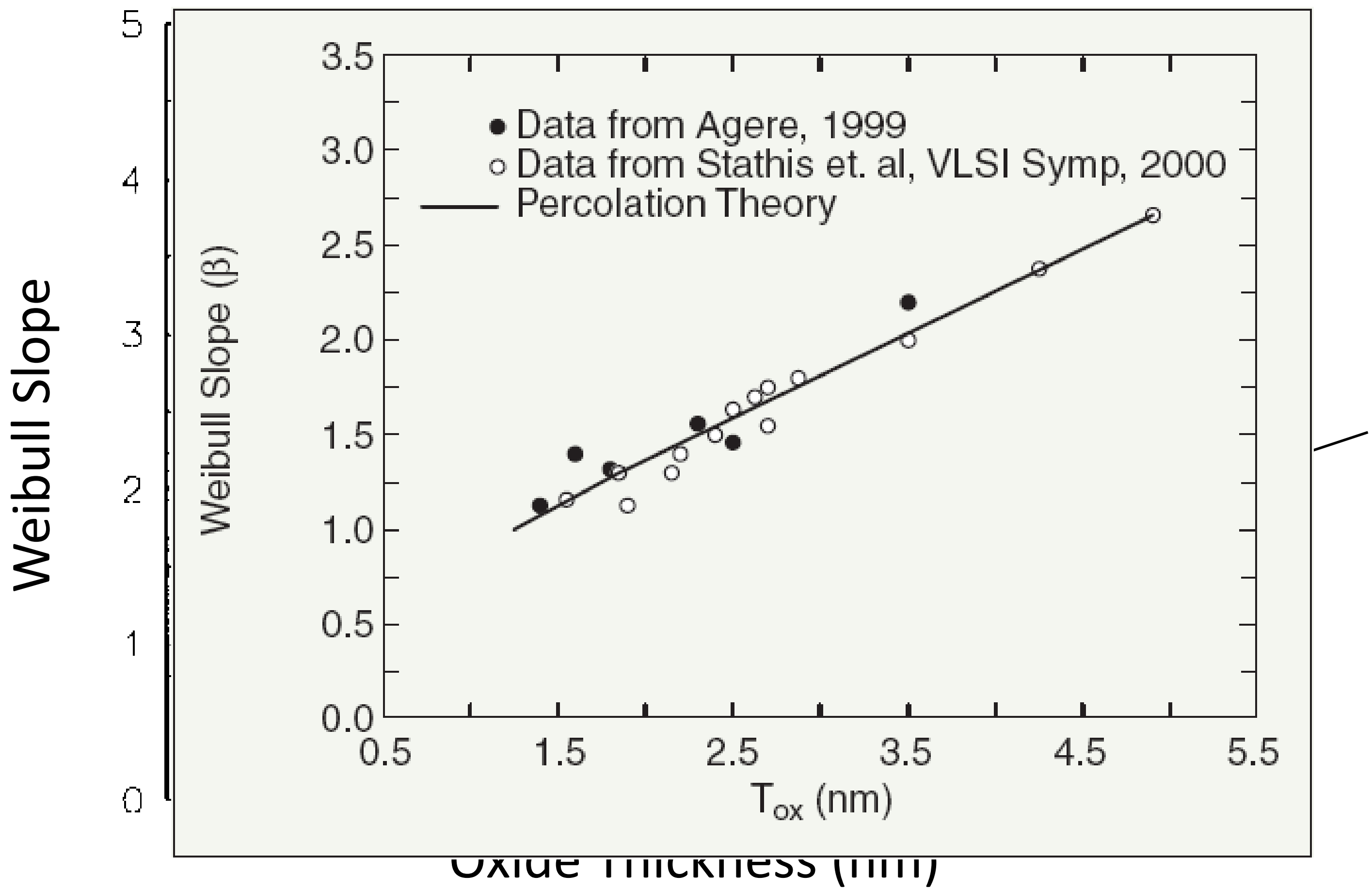






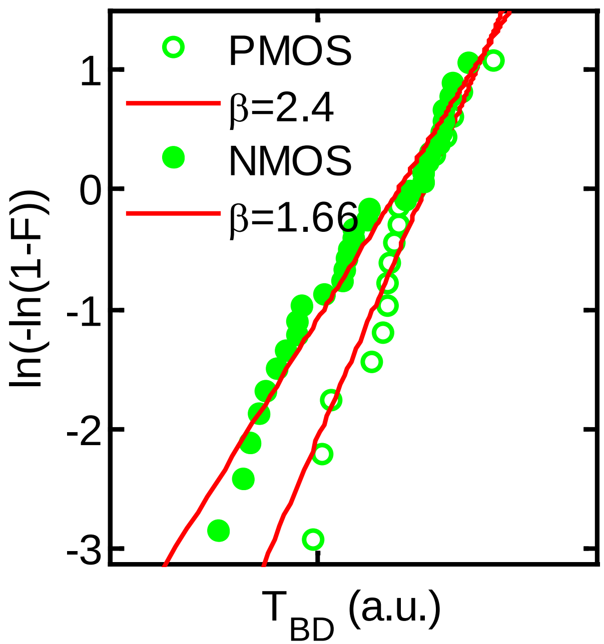
Degraeve, IEDM 1995

Background: Weibull slope scales linearly with oxide thickness

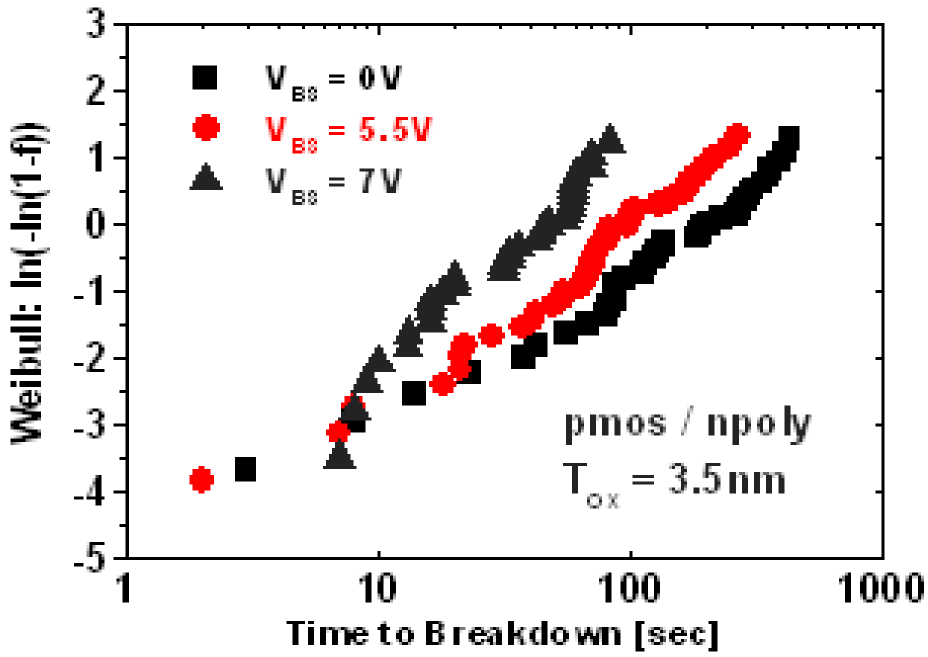


Thin oxide breaks much faster than thick oxide …

Background: Shape of Failure distribution for HCI vs. TDDB



NMOS and PMOS might have different shapes …



Distribution might depend on substrate (or backgate) bias…

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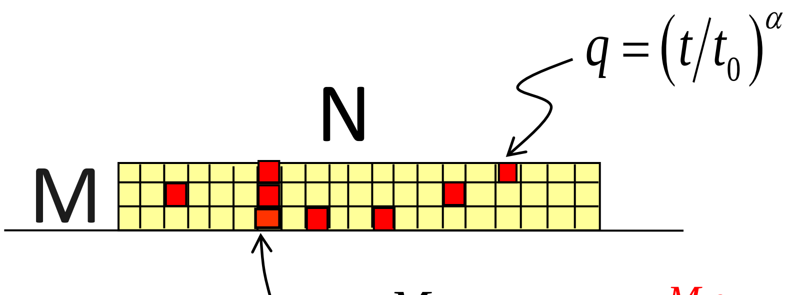
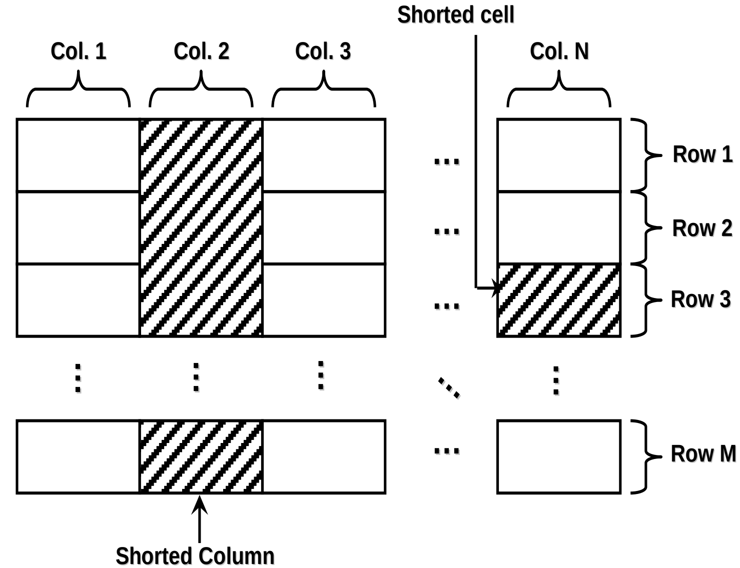
Intrinsic Percolation Model





$$p=q^{M}=\left(t/t_0\right)^{M\alpha}\equiv\left(t/t_0\right)^{\beta}$$

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

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

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

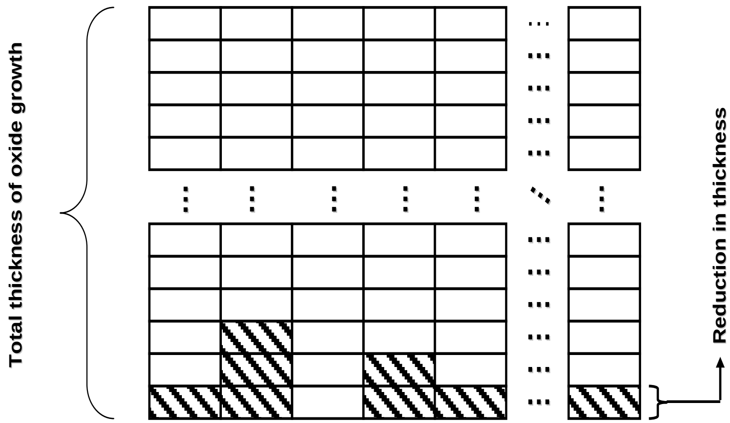
Comparison with Expt.

(1) Straight line in a Weibull plot …

yes $$W \equiv \beta \ \ln(t) - M\alpha \ \ln(t_0) + \ln(N)$$

(2) Area scaling holds…

yes $$W_2 - W_1 = \ln\left(N_2/N_1\right) = \ln\left(A_2/A_1\right)$$



Lee, 1988.

(3) Weibull slope independent of voltage…

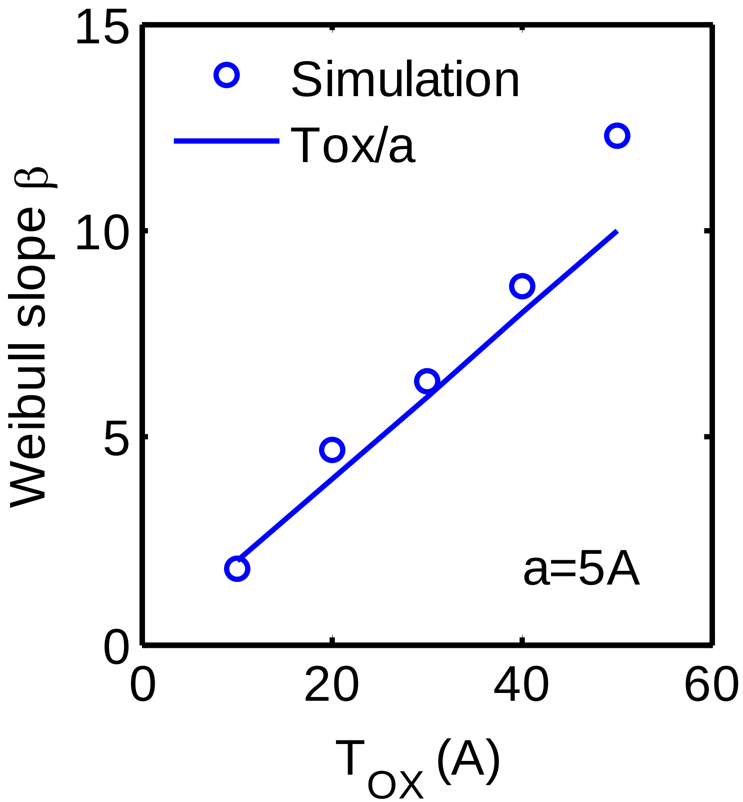
yes $$\beta_{\text{def}} = T_{\text{ox}}/a_0$$

(4) Weibull slope scales linearly with thickness…

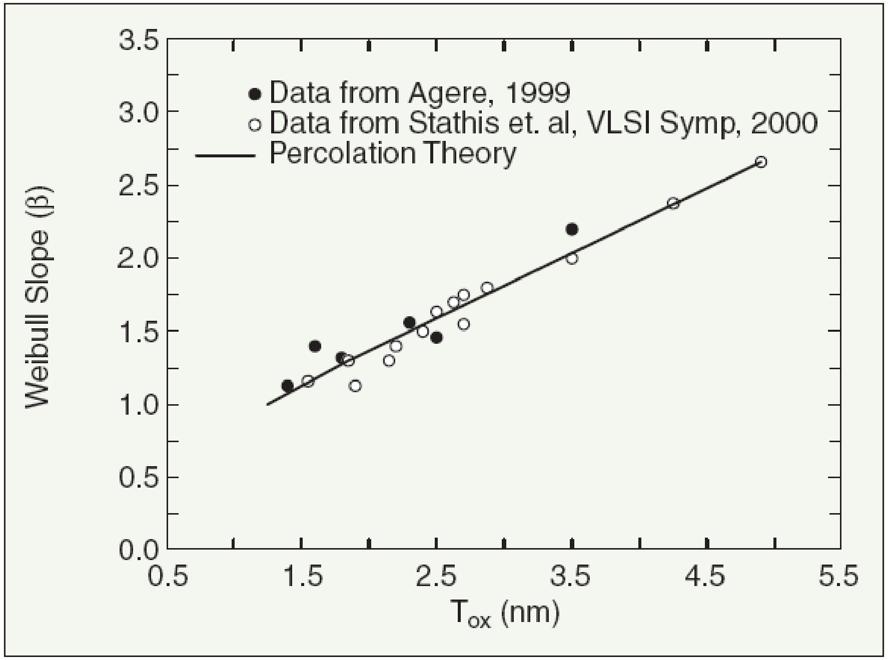
yes $$\beta_{\text{def}} = T_{\text{ox}}/a_0$$

Bottom-up Prediction for Oxide Scaling

Theory



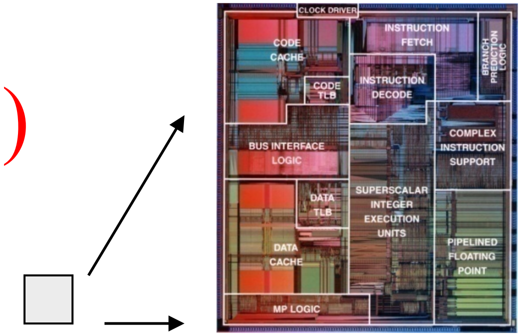
Measurement



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

Homework: Derive the Projection Rules…

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

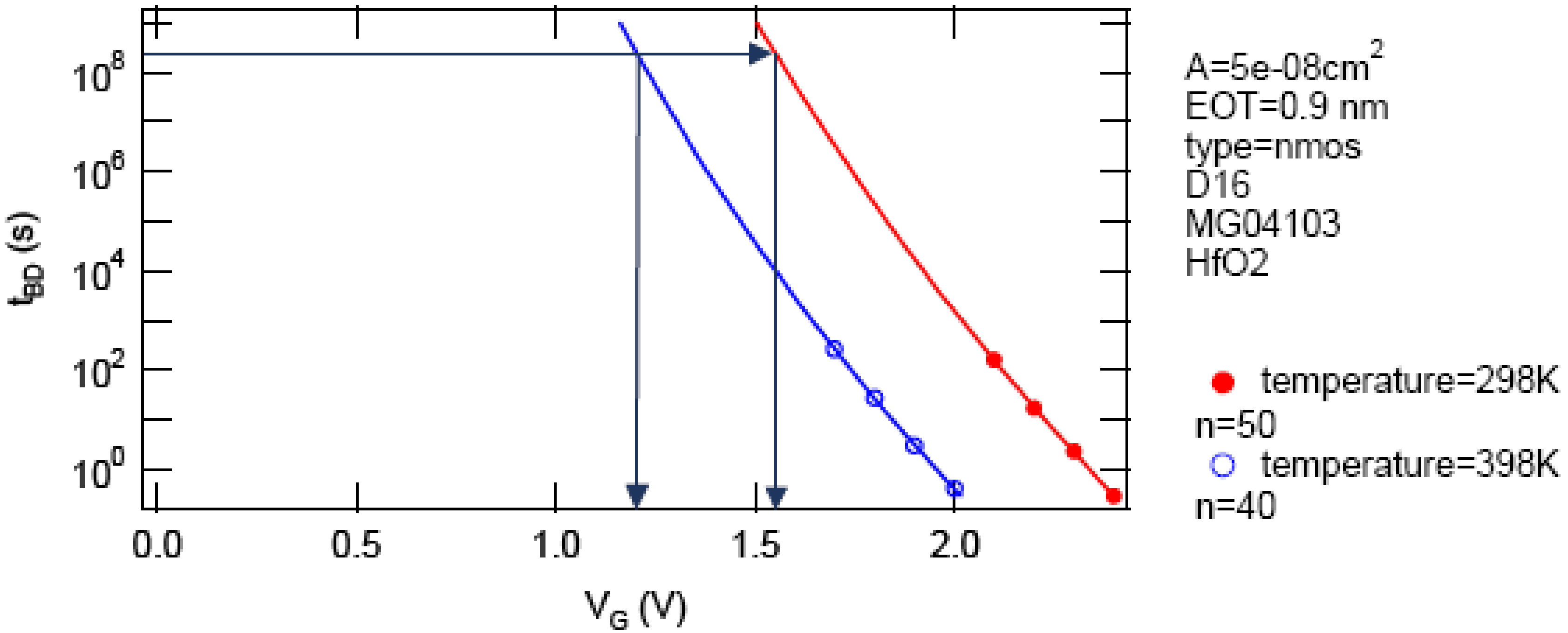


$$T_{BD}^{q\%}(A_{IC}) = \left[\frac{\ln(1-q/100)}{\ln(1-0.5)}\right]^{1/\beta} T_{BD}^{50\%}(A_{IC})$$

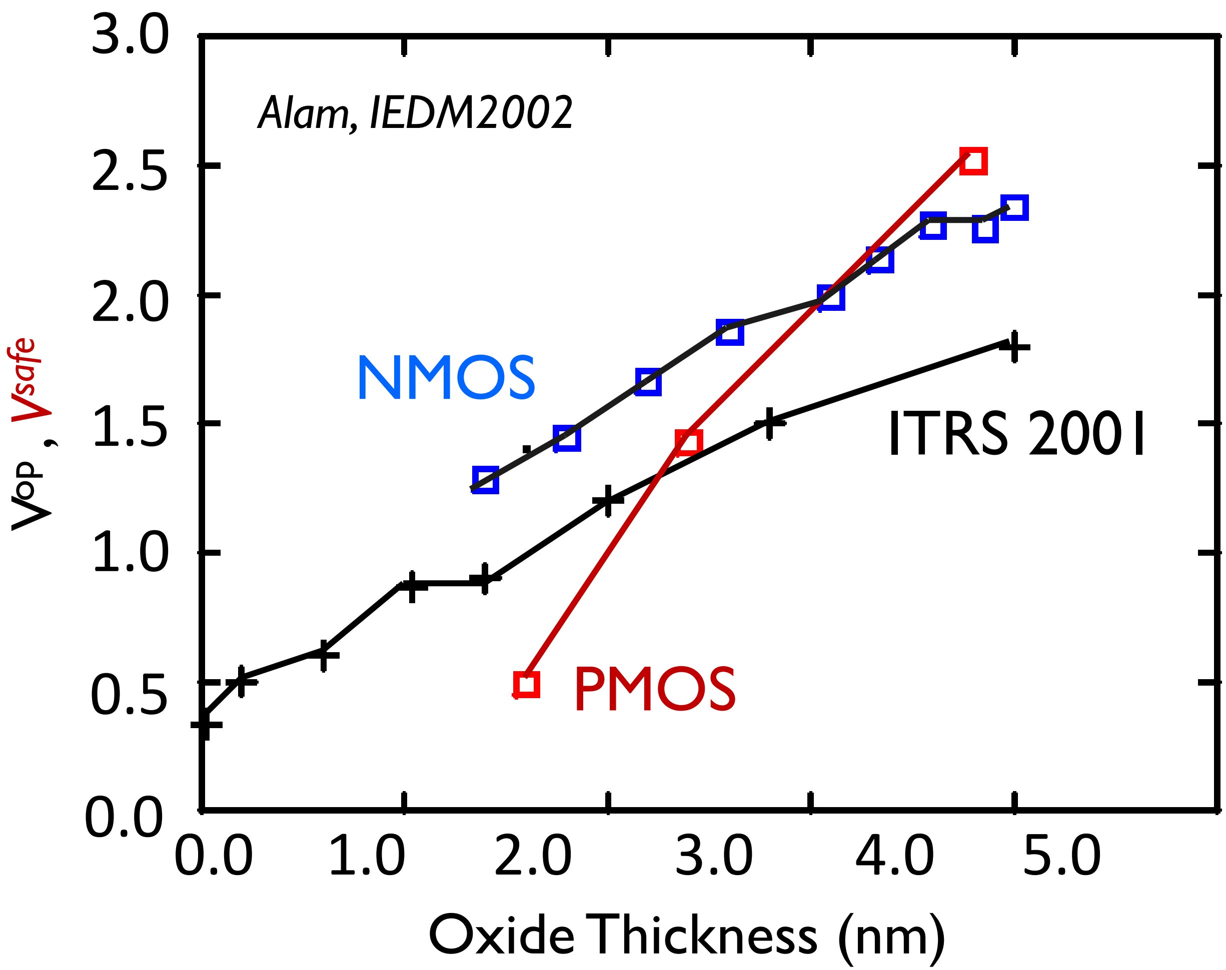
$$V_{safe} = V_{test} - \log\left[\frac{10\ yrs}{T_{BD}^{q\%}}\right] \Big/ \gamma_{V,acc}$$

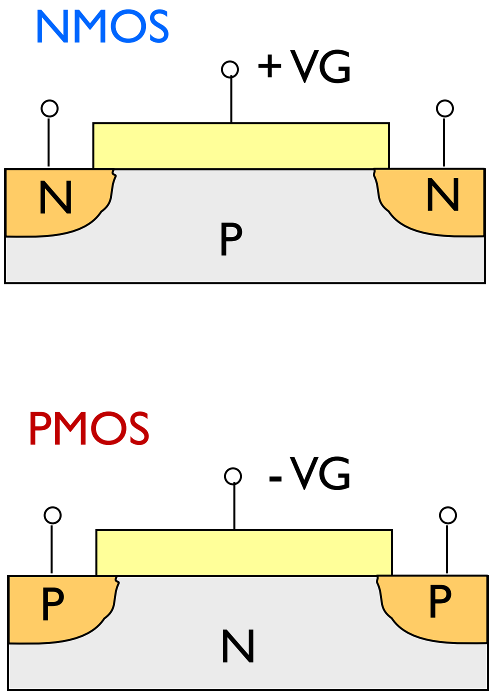
Lifetime projection

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



NMOS vs. PMOS Reliability





PMOS less reliable than NMOS, contacts defines everything !

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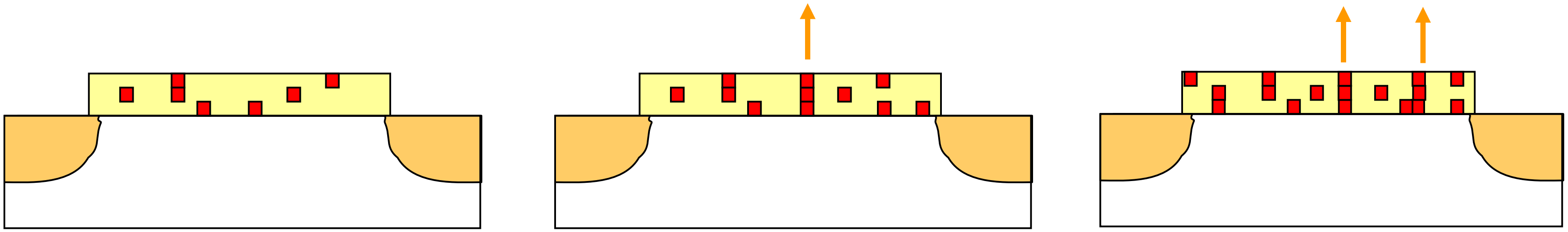
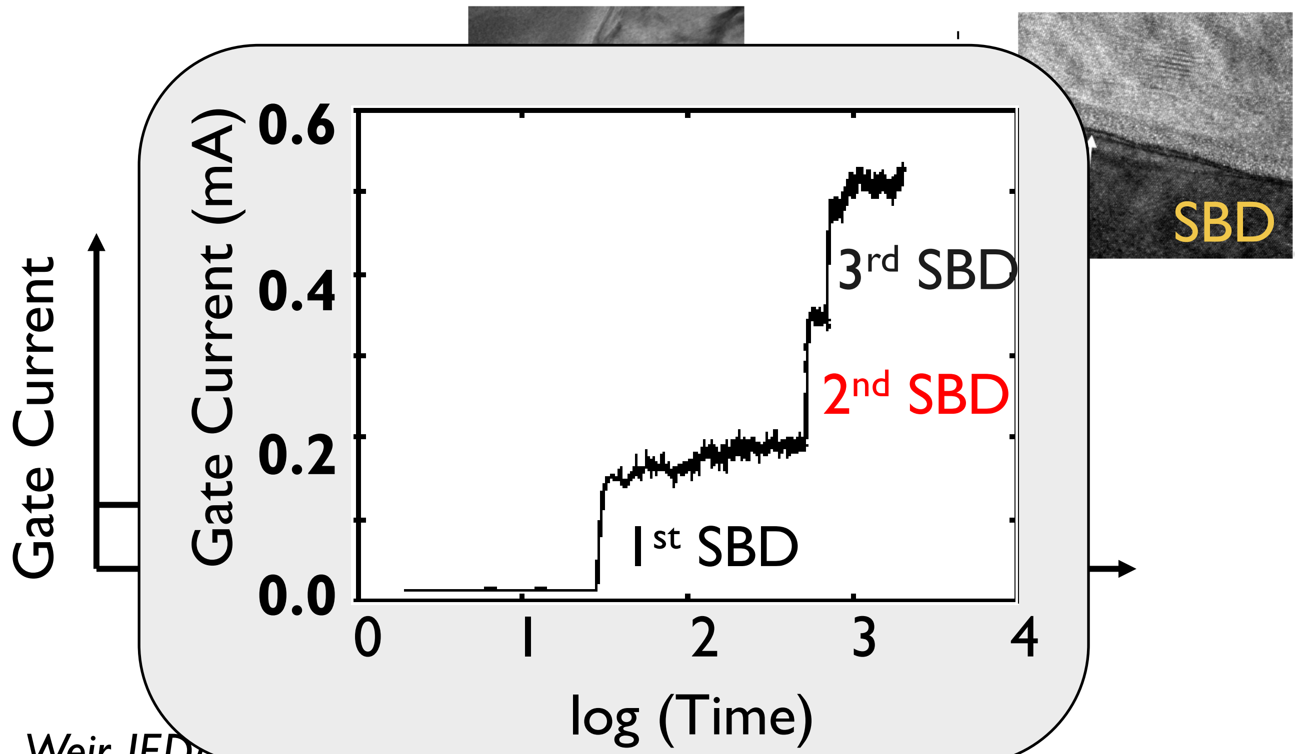
Soft breakdown for PMOS

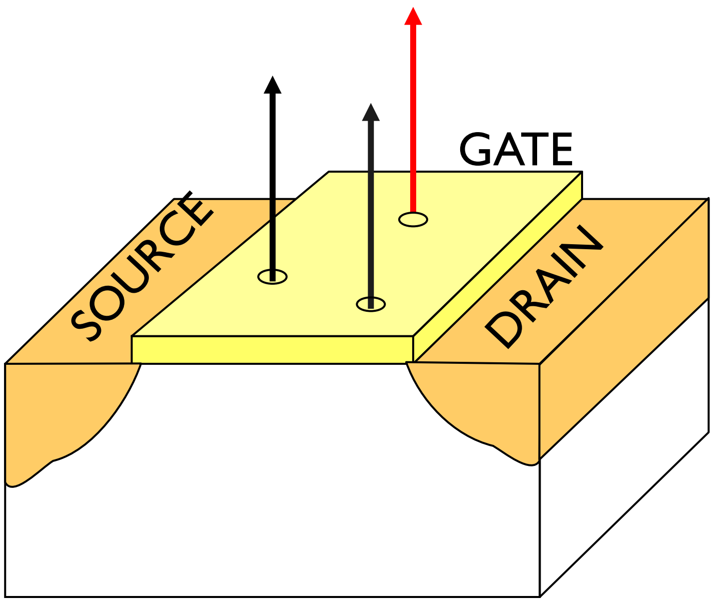




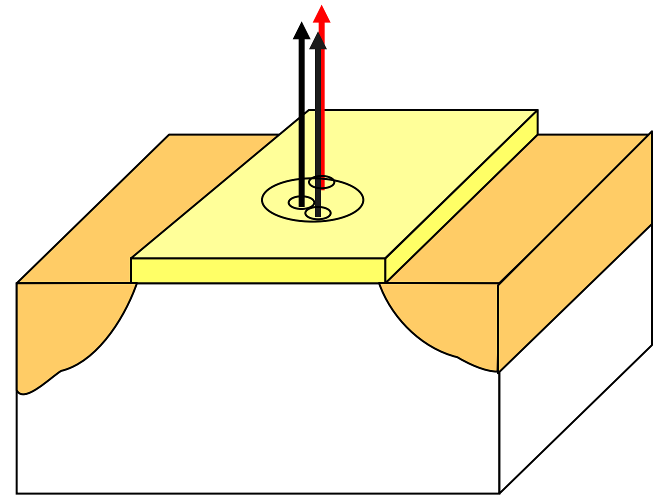
Weir, IEDM,

Correlated vs. uncorrelated breakdown

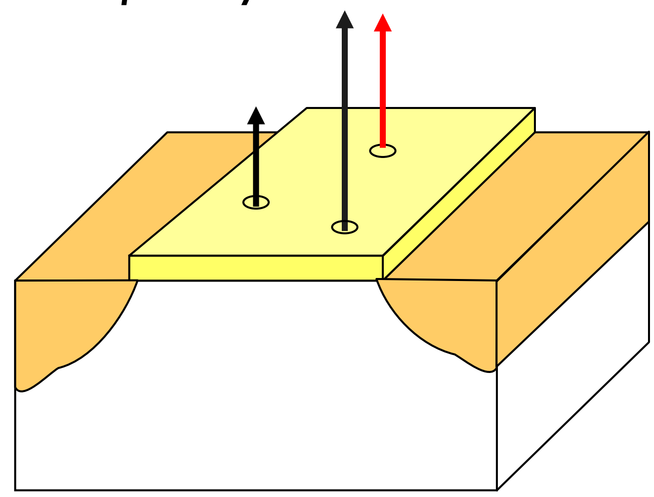
Spatially and Temporally uncorrelated



Spatially *correlated*

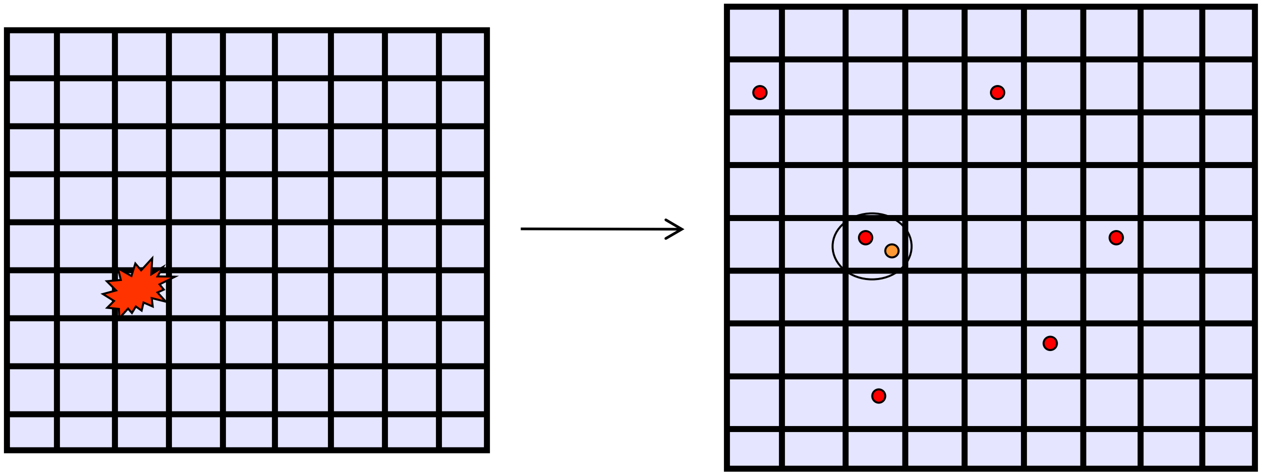


Temporally *correlated*



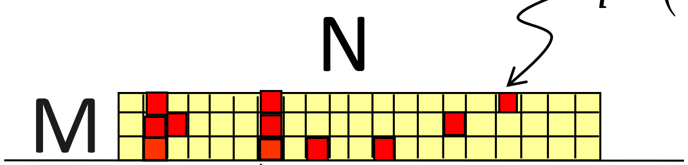
Physical reasons for improved reliability

Standard reliability　　Reliability with soft BD



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

Statistics of multiple breakdown



$$q = \left(t/t_0\right)^{\alpha}$$

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

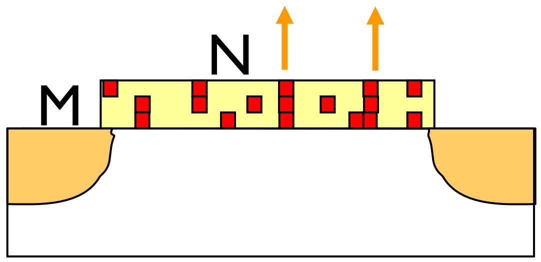
$$p = q^M = \left(t/t_0\right)^{M\alpha} \equiv \left(t/t_0\right)^{\beta}$$

$$P_n = {}^N C_n \times p^n \times (1-p)^{N-n} = \frac{N!}{(N-n)!n!} \times p^n \times \left(1 - \frac{Np}{N}\right)^{N-n}$$

$$= \frac{1}{n!} N(N-1)\ldots(N-n+1) \times p^n \times \left(1 - \frac{Np}{N}\right)^{N-n}$$

$$\approx \frac{\left(Np\right)^n}{n!} \times \left(1 - \frac{Np}{N}\right)^{N} \approx \frac{\left(Np\right)^n}{n!} \times e^{-Np} = \frac{\chi^n}{n!} \times e^{-\chi}$$

Statistics of Soft Breakdown



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

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

Prob. of exactly n-SBD

$$P_n = {}^N C_n \times p^n \times (1-p)^{N-n}$$

$$P_n = \frac{\chi^n}{n!} e^{-\chi} \qquad \chi \equiv \left(\frac{t}{\eta}\right)^{\beta}, \beta \equiv M\alpha$$

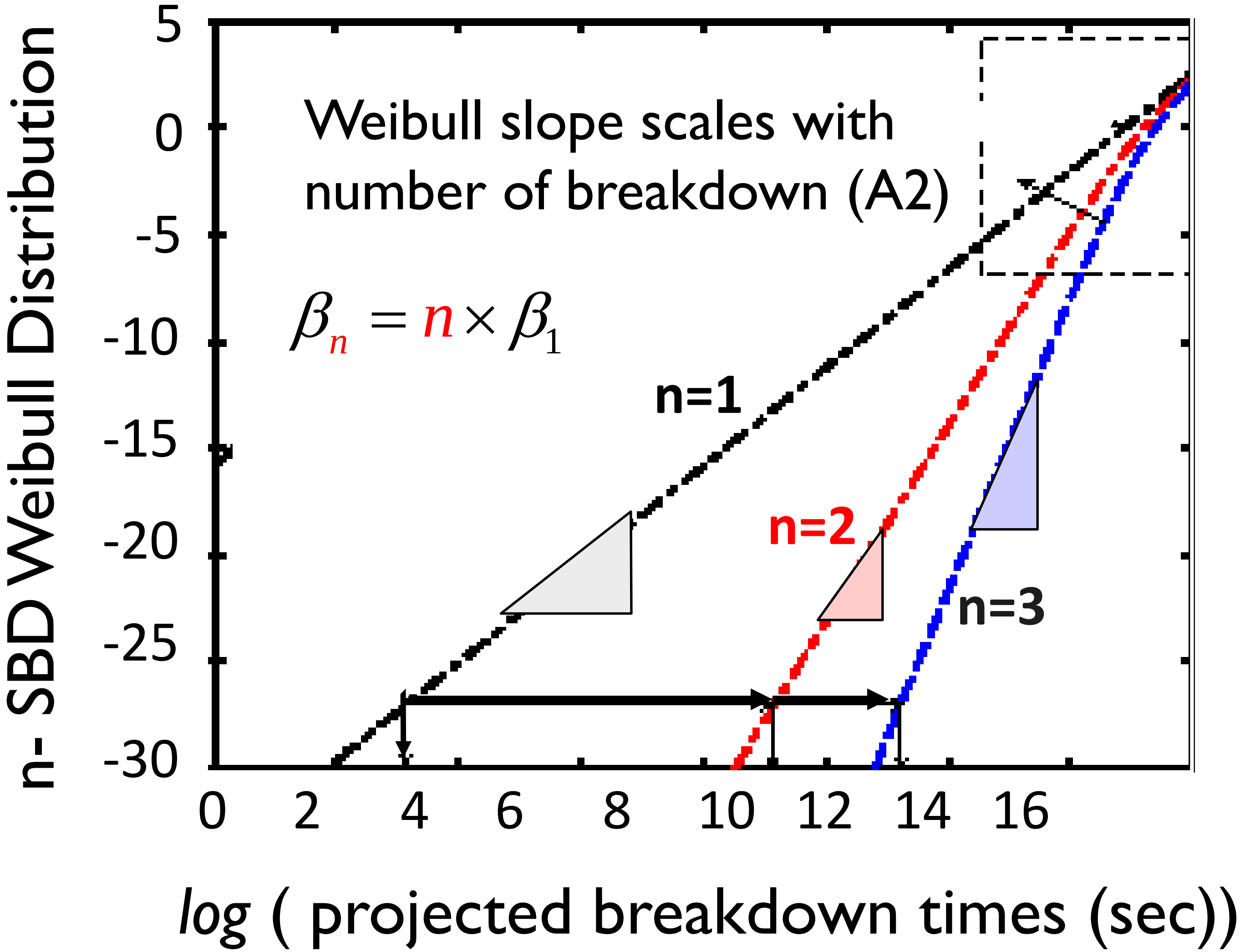
Prob. of $\geq$ n SBD

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

$$1 - F_n(\chi) \sim \chi^n / n!$$

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

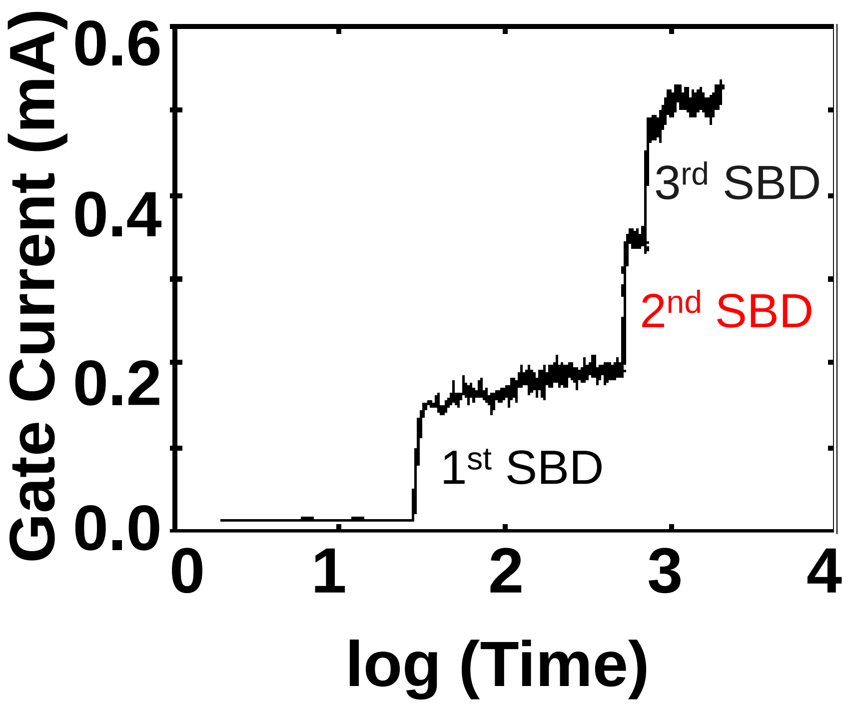
Lifetime improvement due to n-SBD

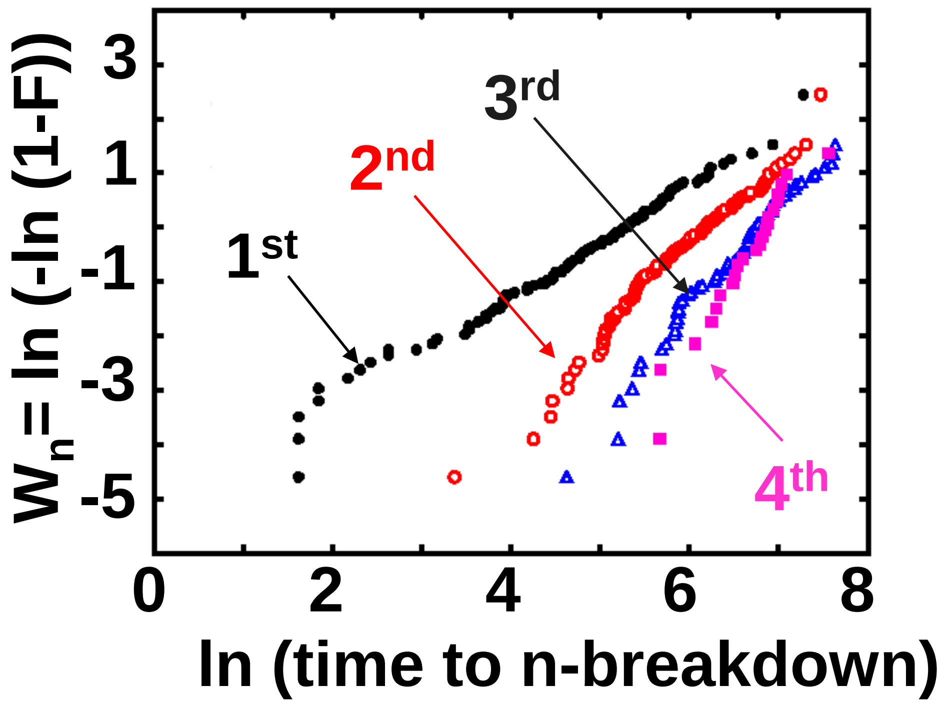


100 million Transistors

1 part per 10^4 failure

Temporal Correlation: Times to n-SBD

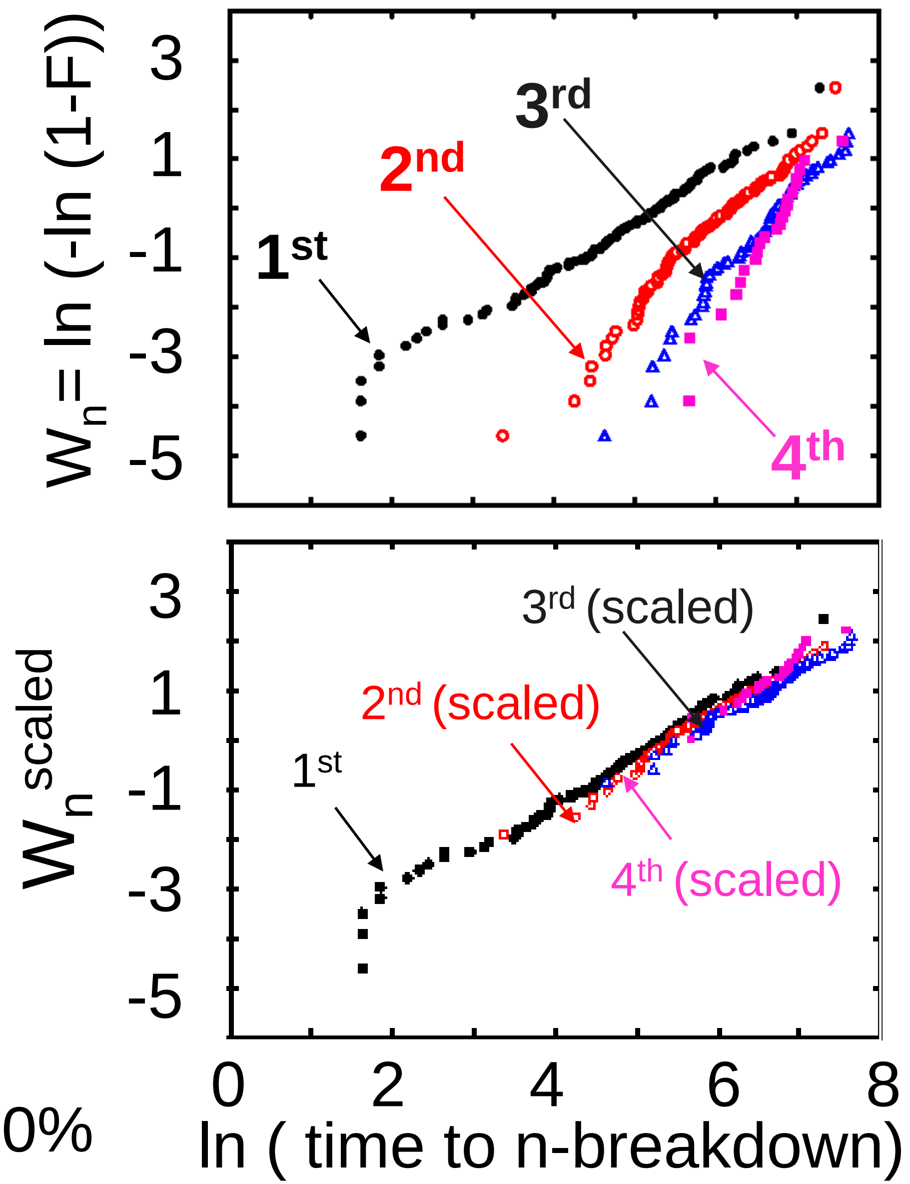




Temporal Independence Confirmed

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

$$F_n(\chi) \rightarrow F_1(\chi)$$



Temporal Correlation $\xi < 10\%$

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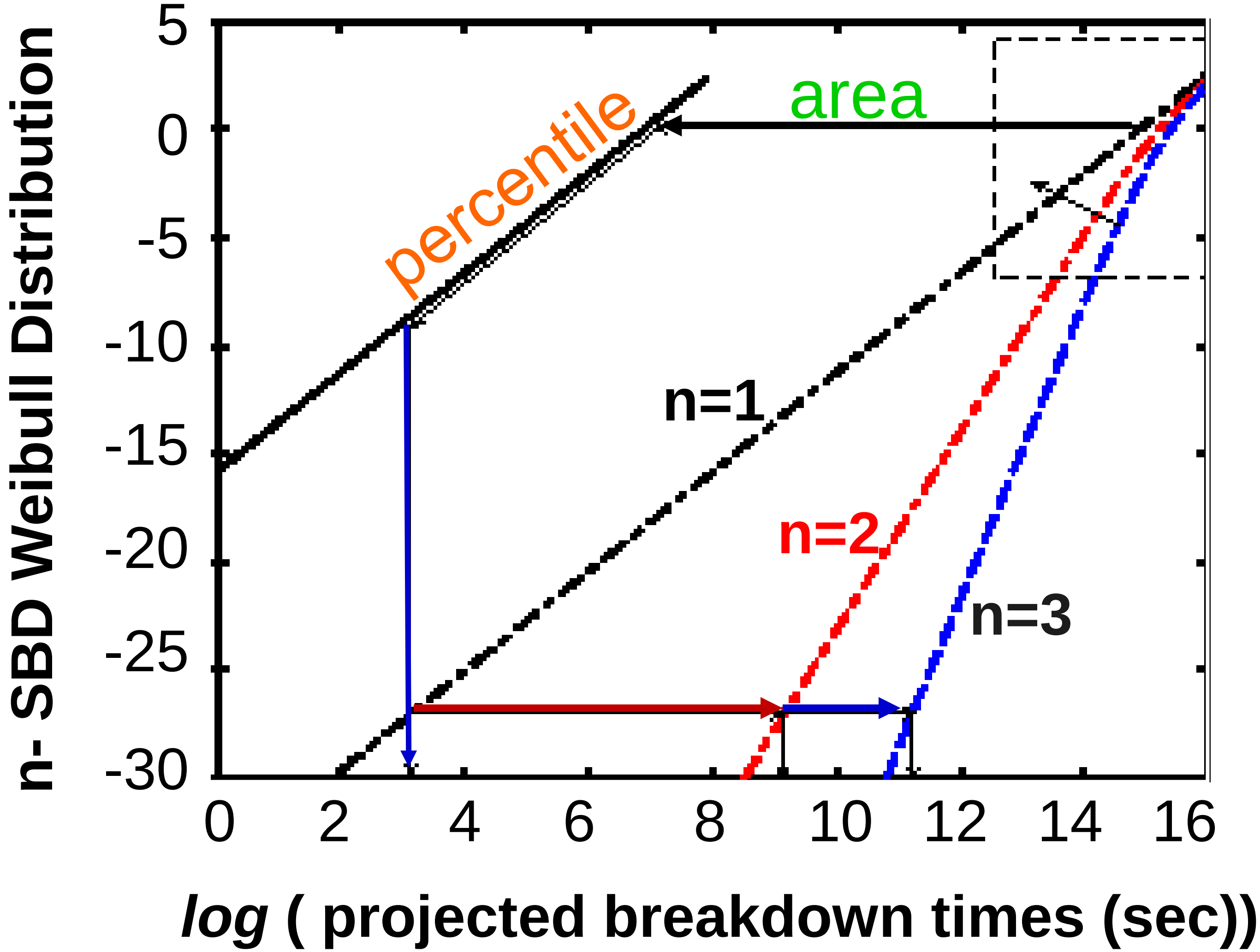
Lifetime Improvement

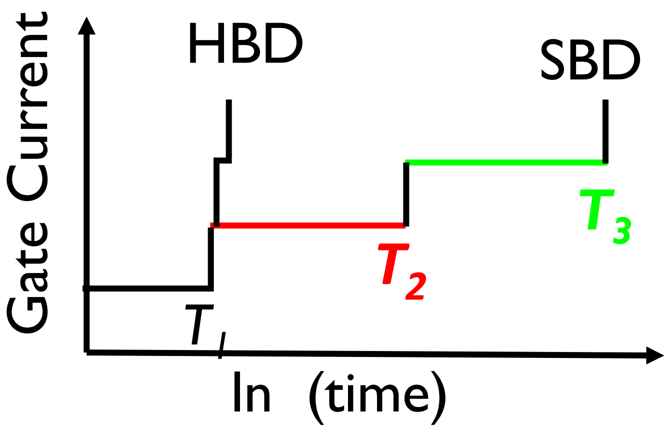


100 million transistors/IC

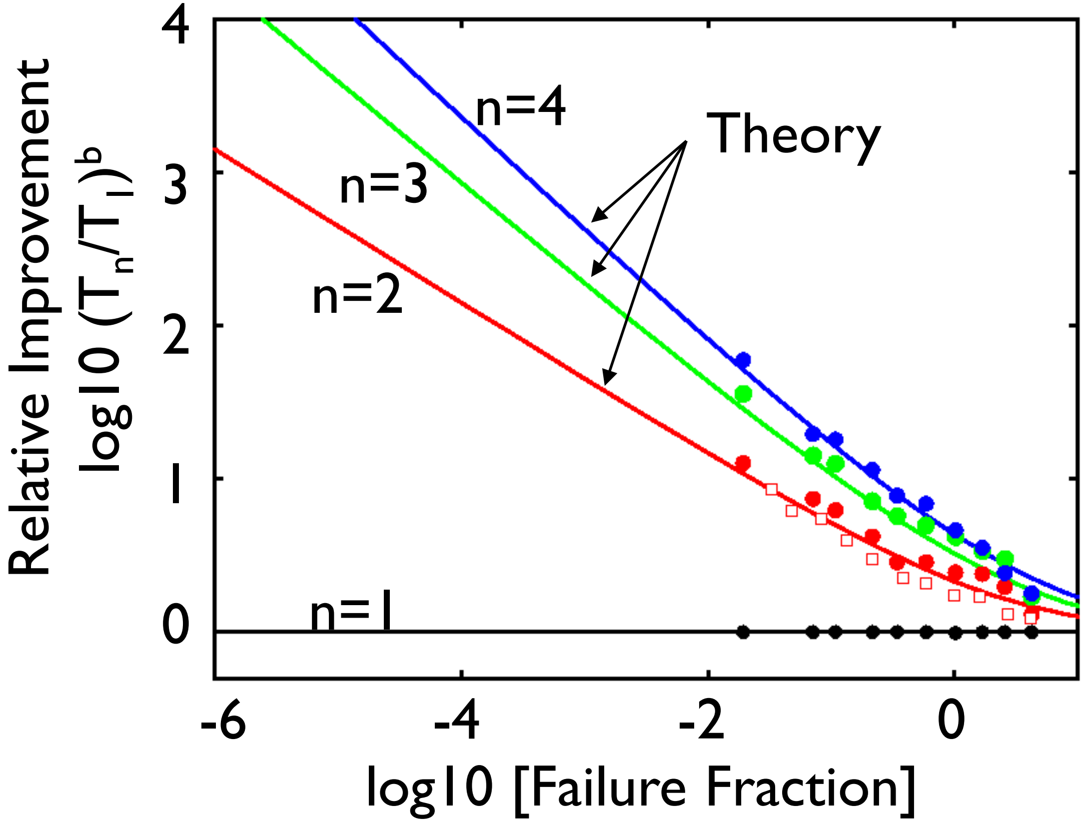
1 part per 10^4 failure

SBD improves Lifetime Geometrically

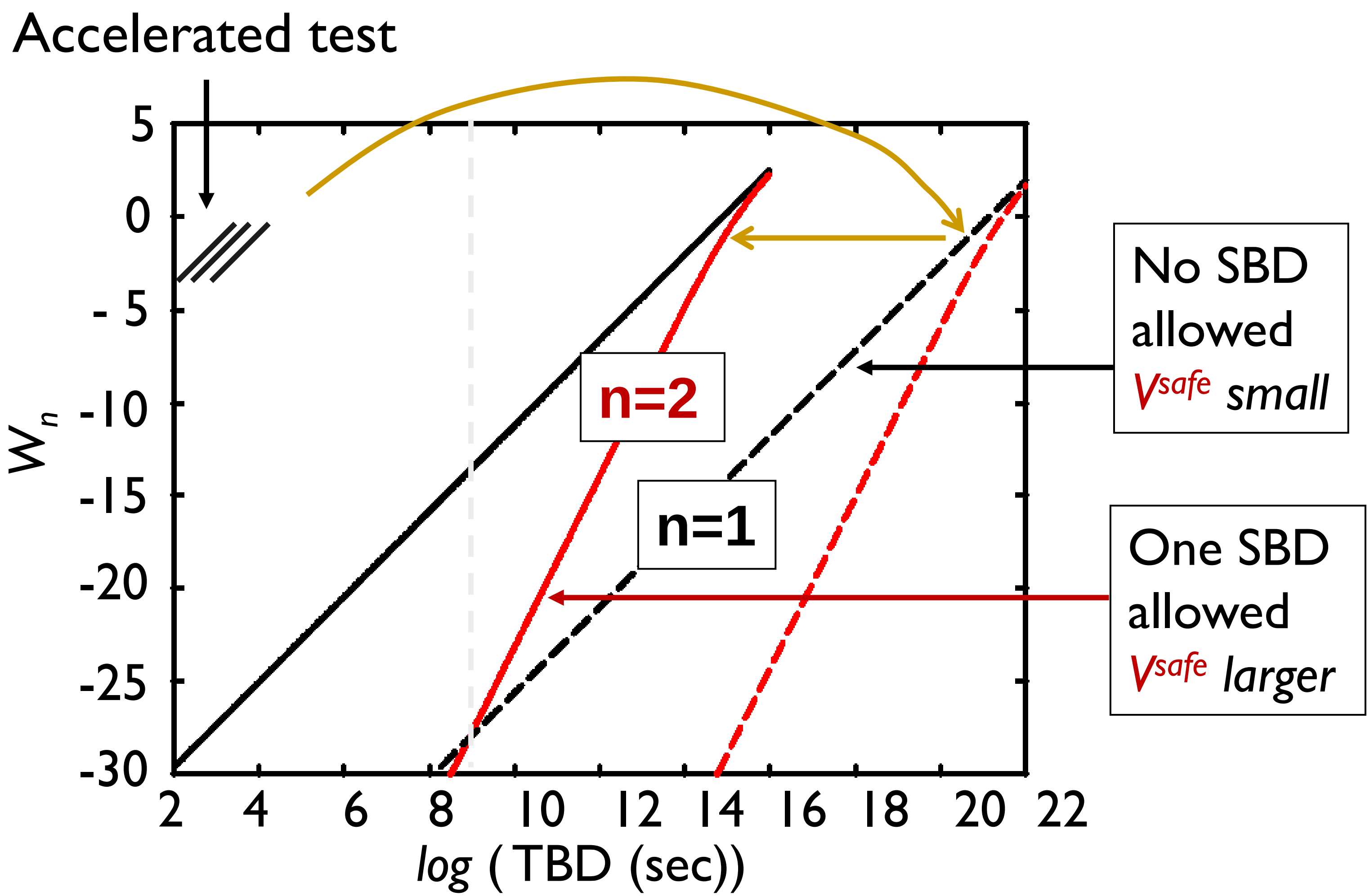
$$\left(\frac{t_{\mathrm{n}}}{t_1}\right)^{\beta} = \left(\frac{n}{e}\right)\left(\frac{1}{2\pi n}\right)^{1/2n} \frac{\left(F_{\mathrm{n}}^{*}\right)^{1/n}}{F_1^{*}}$$



Alam, Nature, 2003

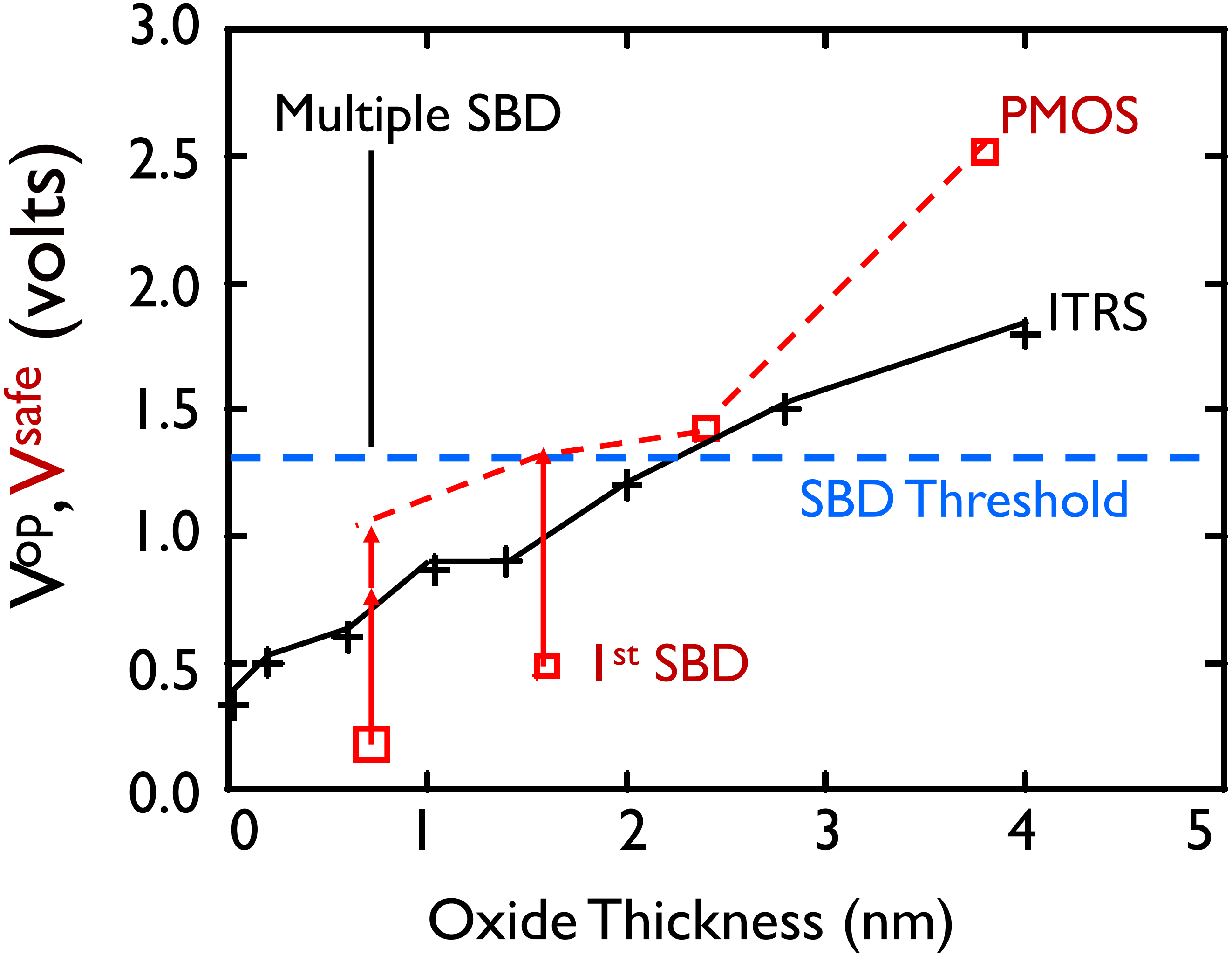


Uncorrelated Breakdown & TDDB Lifetime



Enhanced lifetime can be traded for higher speed !

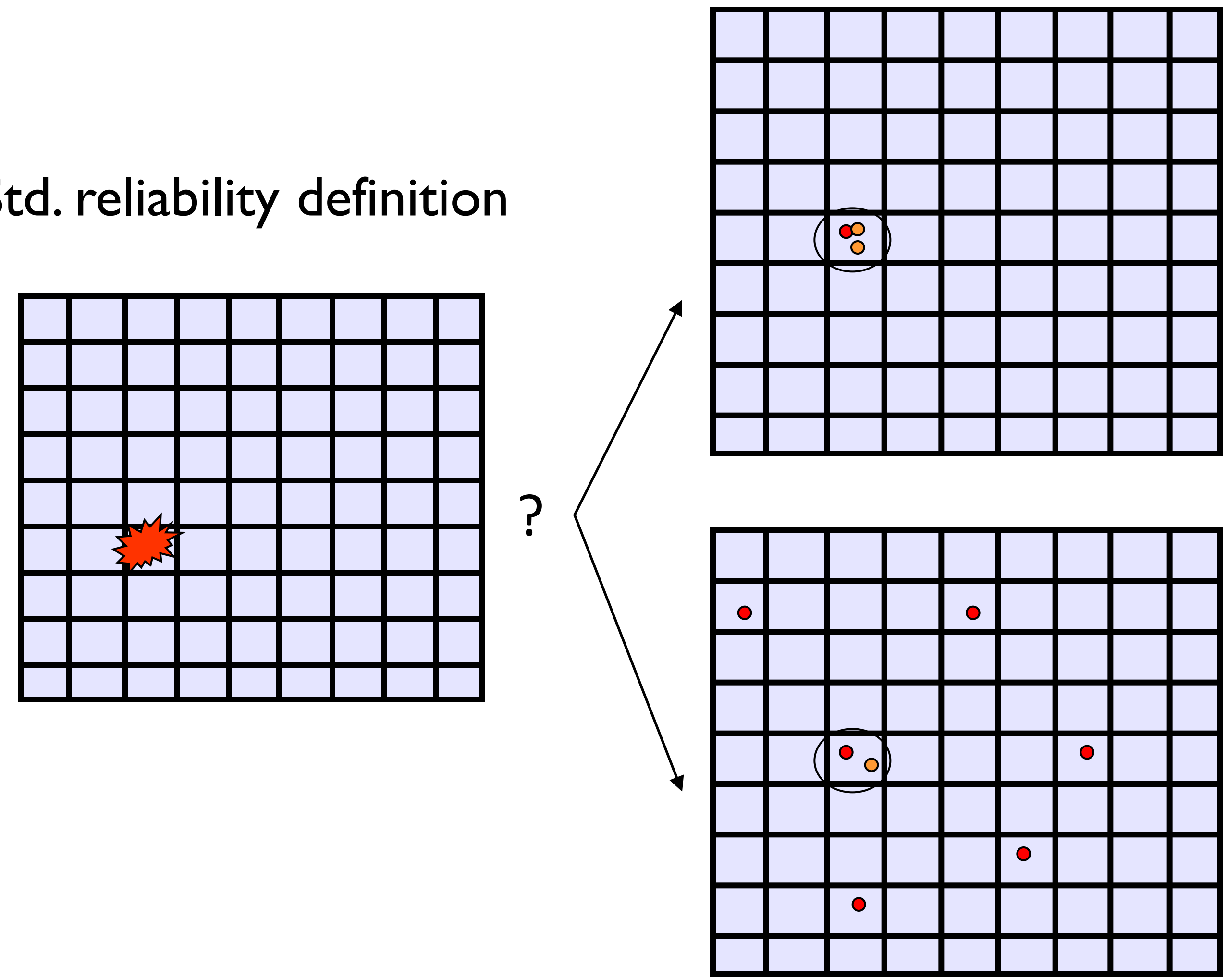
PMOS Reliability with SBD



Physical Reasons for Improved Reliability

Std. reliability definition

New 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

Conclusions

Failure distribution is an intrinsic property of thin oxides that can be understood in terms of simple application of percolation theory.

When statistics (negative) and voltage acceleration (positive) are both accounted for, CMOS lifetime is marginally balanced.

If breakdown is soft, it allows remarkable enhancement of lifetime. This enhancement has been key to PMOS TDDB qualification.

If defect generation is correlated (back-gate bias or HCI induced TDDB), the failure distribution changes dramatically.

References

[1] J. Lee*, et al.*, "Statistical modeling of silicon dioxide reliability," in *Reliability Physics Symposium 1988. 26th Annual Proceedings., International*, 1988, pp. 131-138.

[2] R. Degreave*, et al.*, "A new analytic model for the description of the intrinsic oxide breakdown statistics of ultra-thin oxides," in *Reliability of Electron Devices, Failure Physics and Analysis, 1996. Proceedings of the 7th European Symposium on*, 1996, pp. 1639-1642.

[3] Y. W. Ernest and et al., "Ultra-thin oxide reliability for ULSI applications," *Semiconductor Science and Technology,* vol. 15, p. 425, 2000.

[4] M. A. Alam*, et al.*, "Statistically independent soft breakdowns redefine oxide reliability specifications," in *Electron Devices Meeting, 2002. IEDM '02. Digest. International*, 2002, pp. 151-154.

[5] M. A. Alam*, et al.*, "Thin dielectric films: Uncorrelated breakdown of integrated circuits," *Nature,* vol. 420, pp. 378-378, 2002.

Review Questions

1) What is difference between intrinsic and extrinsic breakdown?
2) What is difference between correlated and uncorrelated BD?
3) Can you use the box percolation theory for thick oxides as well?
4) How does Weibull slope related to oxide thickness? Is low Weibull slope good?
5) Does Weibull slope depend on voltage? What about defect size?
6) Can you estimate the defect-size for SiO_2 from Weibull slope?
7) Why is it that people did not notice the distribution until recently?
8) I often say that 'distribution is physical'. Do you understand what it means in TDDB context?