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ECE695A: Reliability Physics of Nano-Transistors
Lecture 26-1: Statistics of soft breakdown via methods of Markov chains

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Outline

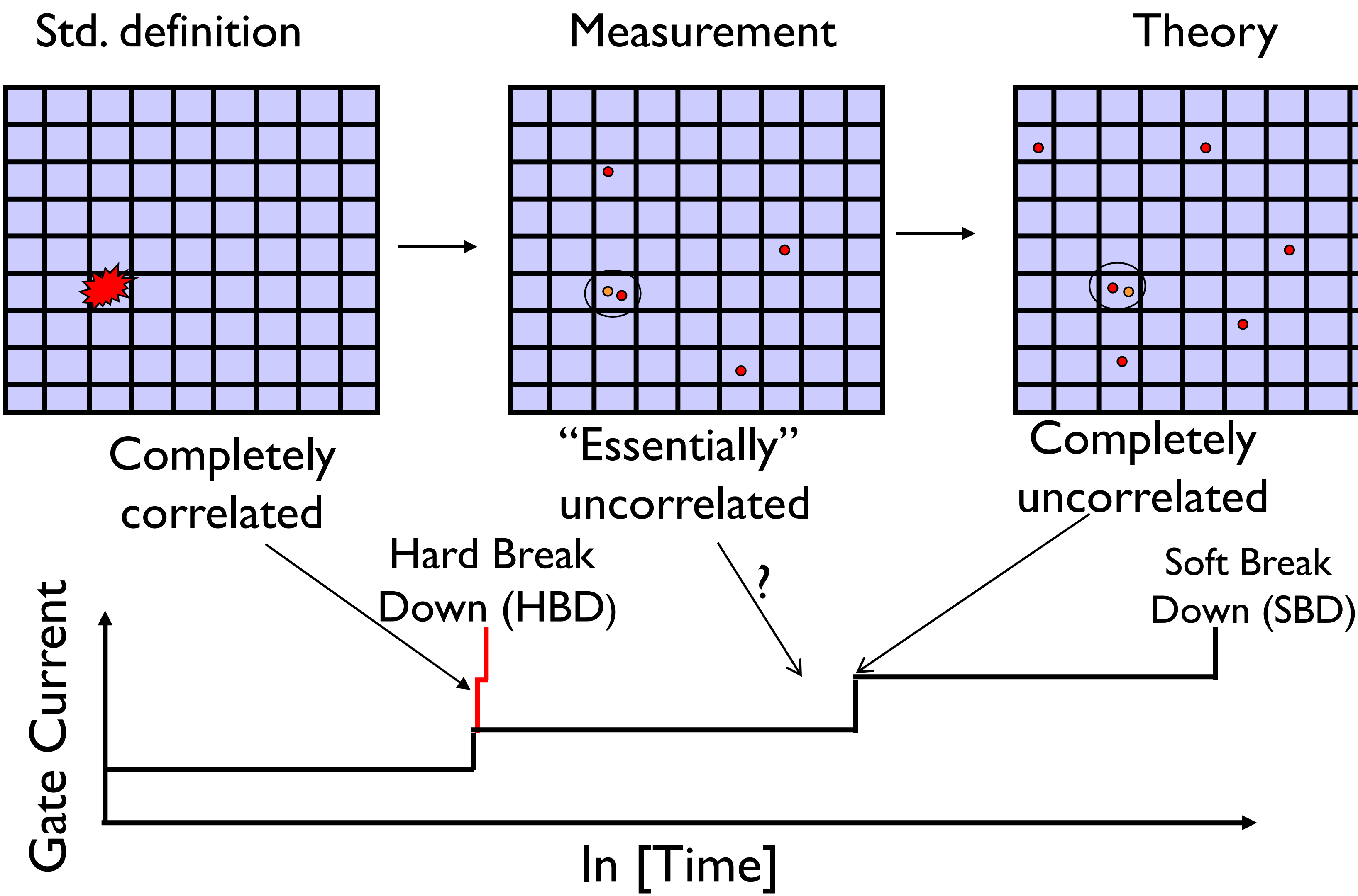
1. Spatial vs. Temporal correlation

2. Theory of correlated Dielectric Breakdown

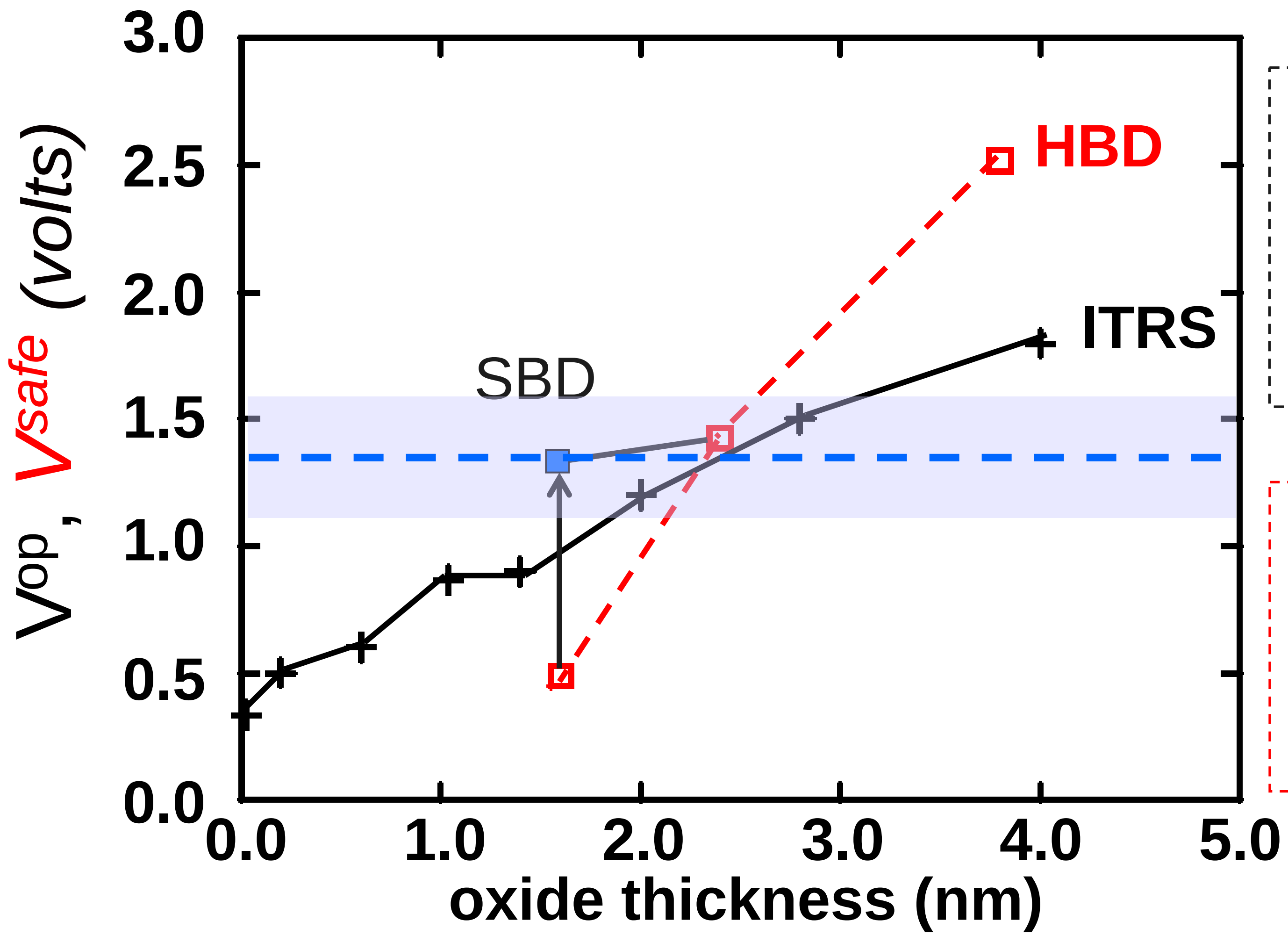
3. Excess leakage as a signature of correlated BD

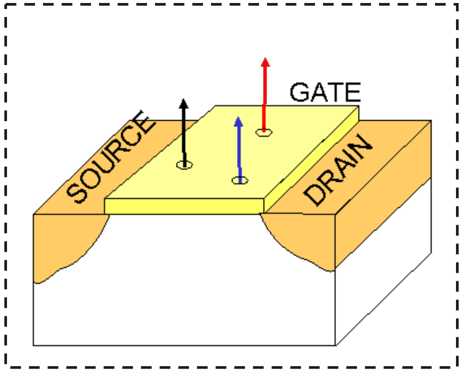
4. Conclusions

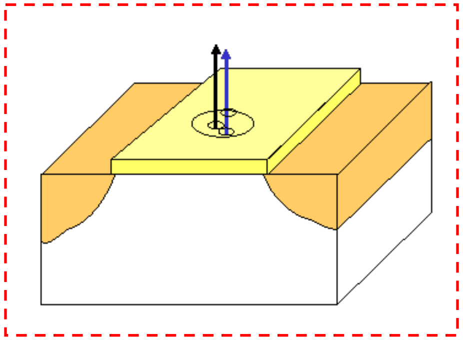
Soft BD improves dielectric lifetime



PMOS reliability limits







Oxide reliability impossible without SBD
Correlation determines the improvement

Standard theory is insufficient …

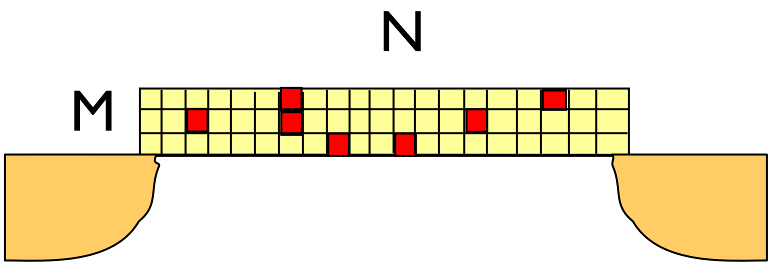
Prob. of filled cell: $q = \left(\alpha t^{\alpha} / NM\right)$

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

N: number of cells along row

M: number of cells along column

α: constant?



Probability of 1-SBD:

$$P_1 = Np\left(1 - p\right)^{N-1}$$

Probability of 2-SBD:

$$P_2 = C_2^N \left[p^2\right]\left[\left(1 - p\right)^{N-2}\right]$$

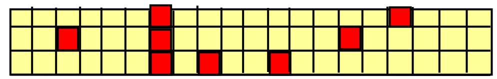
For large N

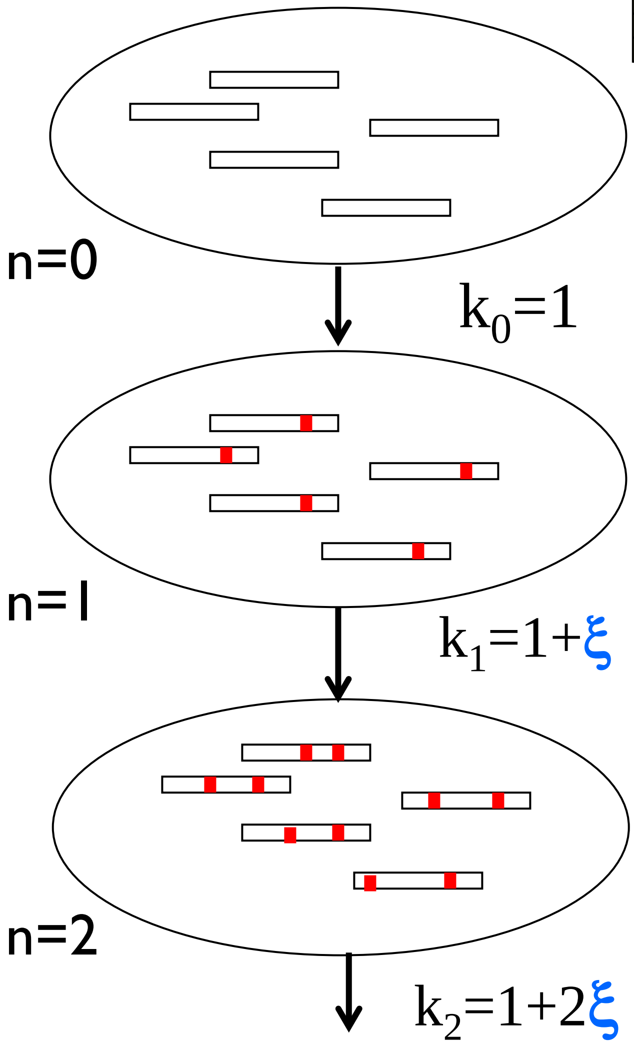
$$P_n = \left(\chi^n / n!\right) exp\left(-\chi\right)$$

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

Assumption: trap generation probability does not change after SBD

Computing Number of Devices with n-SBD





ξ: correlation factor

$$\frac{dP_0}{d\chi} = -k_0 P_0$$

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

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

$$P_0 = exp\left(-\chi\right)$$

$$P_n = f\left(\xi\right)\left(\frac{\chi^n e^{-\chi}}{n!}\right)$$

$$f\left(\xi\right) = \prod_{m=0}^{n-1}\left(1+m\xi\right)\left(\frac{1-exp\left(-\xi\chi\right)}{\xi\chi}\right)^n$$

For SBD, correlation is weak, i.e. ξ ▯ 0

$$P_0 = exp(-\chi)$$

$$P_n = f(\xi) \times \left(\frac{\chi^n e^{-\chi}}{n!} \right)$$

$$f(\xi) = \prod_{m=0}^{n-1} (1 + m\xi) \left(\frac{1 - exp(-\xi\chi)}{\xi\chi} \right)^n$$

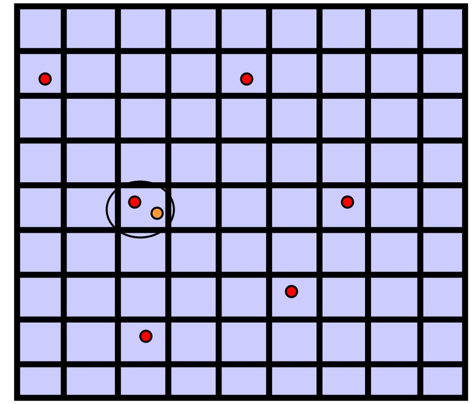
If $\xi \to 0,\ f(\xi) \to 1$, so that

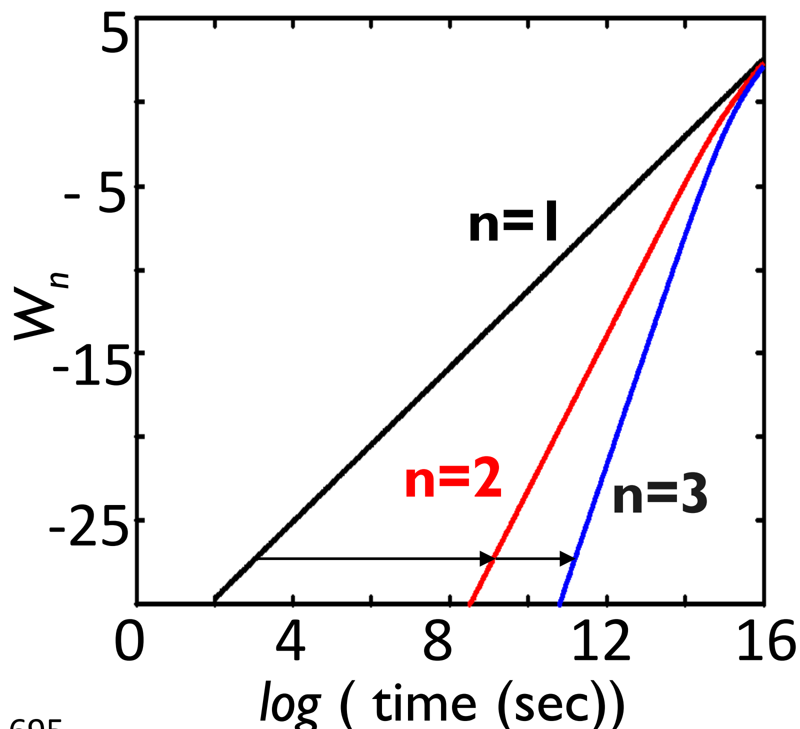
$$P_n \to \left(\frac{\chi^n e^{-\chi}}{n!} \right),$$

$$1 - F_n = P_0 + P_1 + \cdots + P_{n-1}$$

$$W_n = ln(-ln(1 - F_n))$$
$$= (n\beta) ln(t) + const.$$

W:Weibull distribution



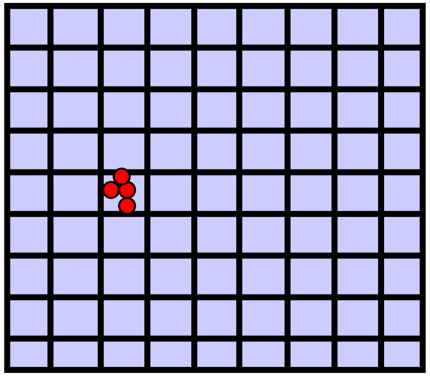


For HBD, correlation is strong, i.e. $\xi \rightarrow \infty$

$$P_0 = exp(-\chi)$$

$$P_n = f(\xi) \times \boxed{\left(\frac{\chi^n e^{-\chi}}{n!} \right)}$$

$$f(\xi) = \prod_{m=0}^{n-1} (1 + m\xi) \left(\frac{1 - exp(-\xi\chi)}{\xi\chi} \right)^n$$

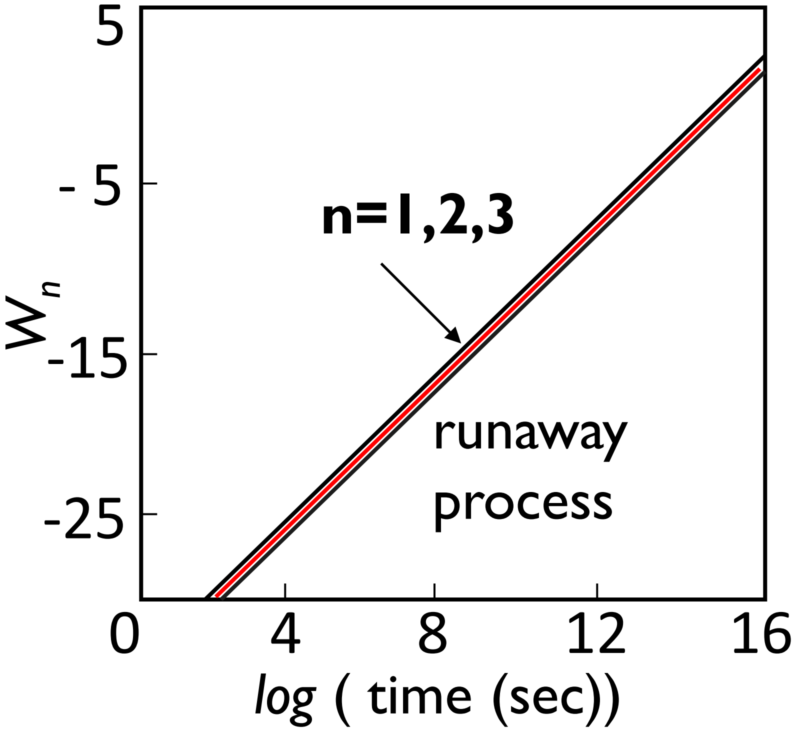


If $\xi \rightarrow \infty$, $f(\xi) \rightarrow 0$, so that

$P_{n\geq 0} \rightarrow 0$, and

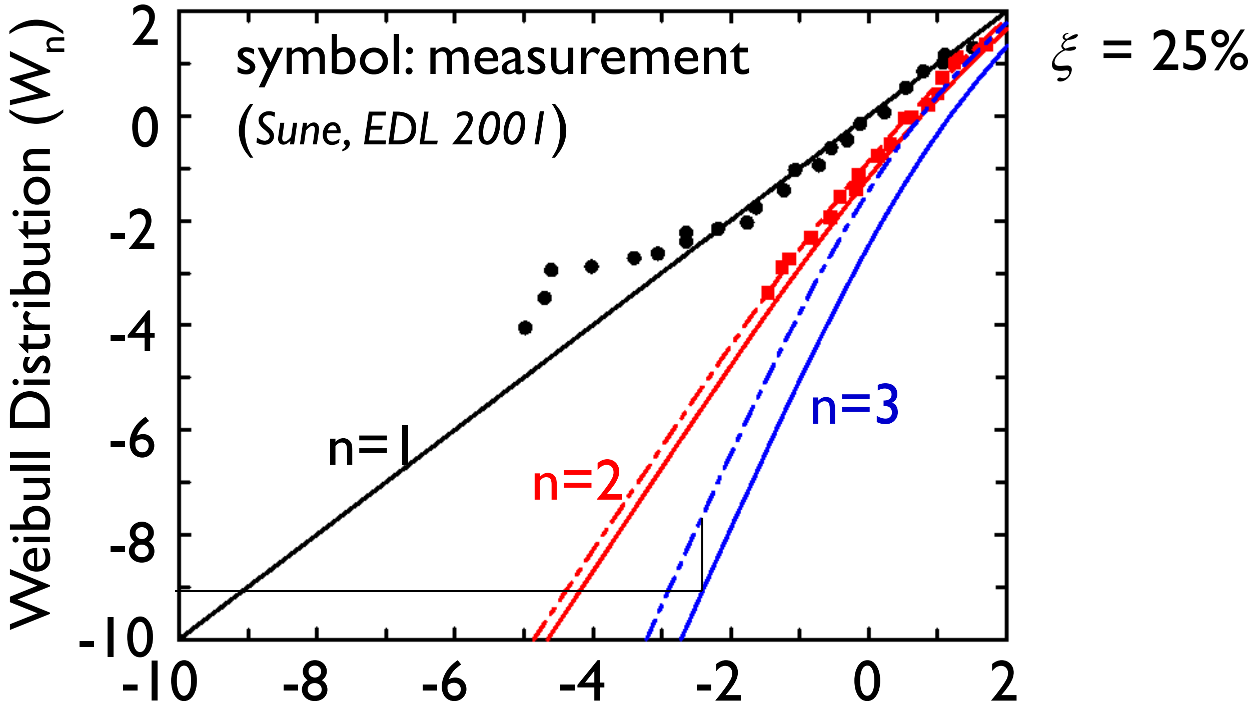
$$1 - F_n = P_0 + P_1 + \cdots + P_{n-1}$$
$$= 1 - F_1$$
$$W_n = ln(-ln(1 - F_1))$$
$$= \beta \times ln(t)$$

W_n is independent of *n*



Correlated distributions for multiple SBD

$$P_n = f(\xi)\left(\frac{\chi^n e^{-\chi}}{n!}\right)$$



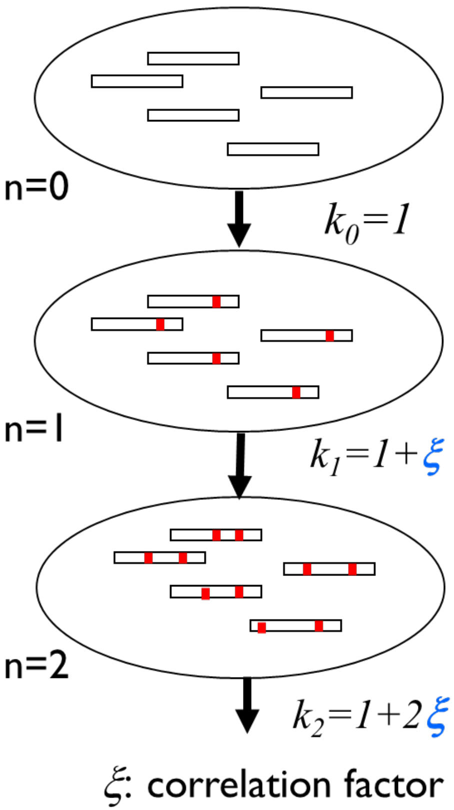
$$\chi = (t/\eta)^{\beta}$$

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

Outline

1. Theory of correlated Dielectric Breakdown
2. Excess leakage as a signature of correlated BD
3. How to determine the position of the BD Spot
4. Why is localization so weak?
5. Conclusions

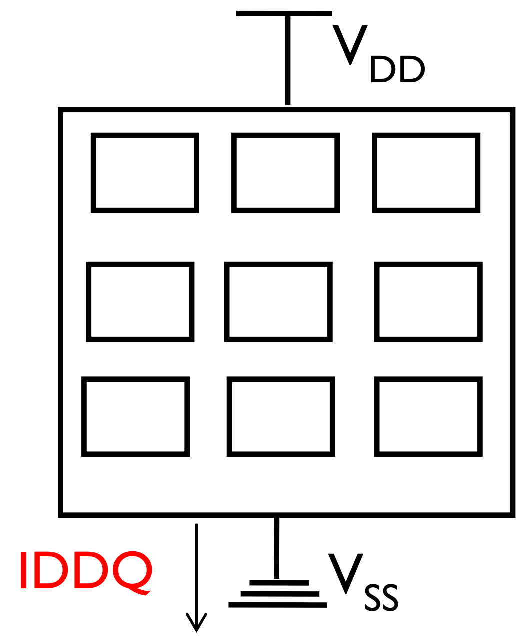
Post Silicon I_{DDQ} Leakage Current



R_0 (0 short)

R_1 (1 short)

R_2 (2 shorts)



$$\sum_{n=0}^{\infty} N_n(t) = N_0(t=0)$$

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

$$\frac{I_{DDQ}}{N_T I_0} = \sum_{m=1}^{\infty} m \times P_m = L(say)$$

Post silicon I_{DDQ} measurement

$$\sum_{n=1}^{\infty}\frac{d(nP_n)}{d\chi}=\sum_{n=1}^{\infty}nP_{n-1}-\sum_{n=1}^{\infty}nP_n$$

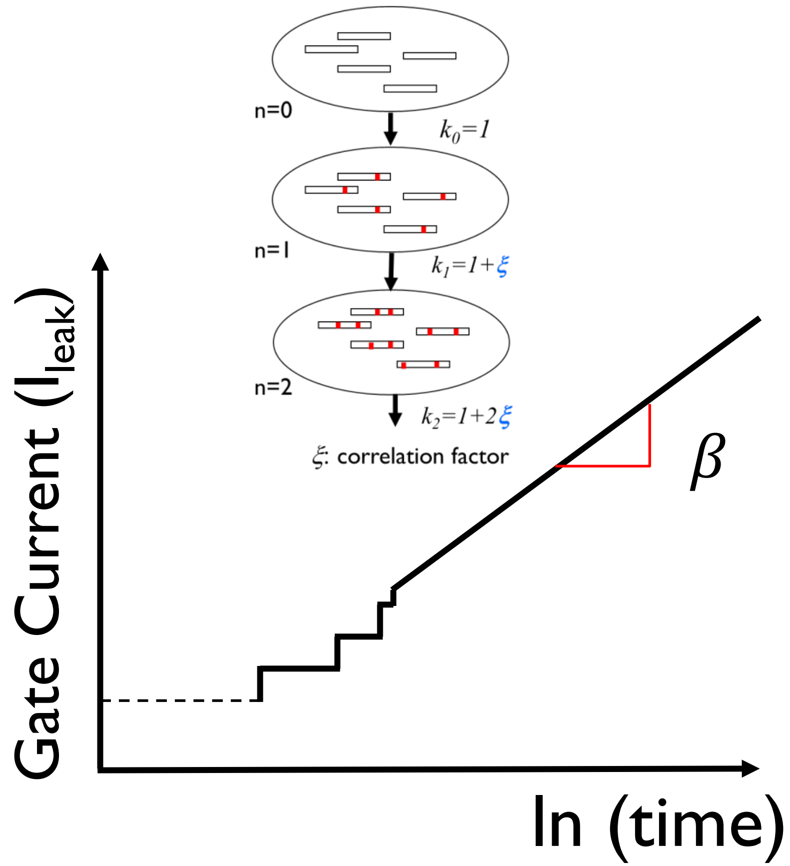
$$\frac{d}{d\chi}\sum_{n=1}^{\infty}nP_n=\sum_{n=1}^{\infty}nP_{n-1}-\sum_{n=1}^{\infty}nP_n$$

$$\therefore\frac{dL}{d\chi}=\left[\sum_{i=0}^{\infty}iP_i+\sum_{i=0}^{\infty}P_i\right]-\sum_{n=1}^{\infty}nP_n$$

$$\therefore\frac{dL}{d\chi}=L+1-L$$

$$\therefore\frac{dL}{d\chi}=1$$

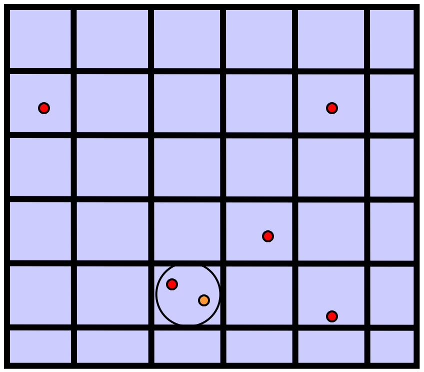
$$L=\chi=\left(\frac{t}{\eta}\right)^{\beta}$$

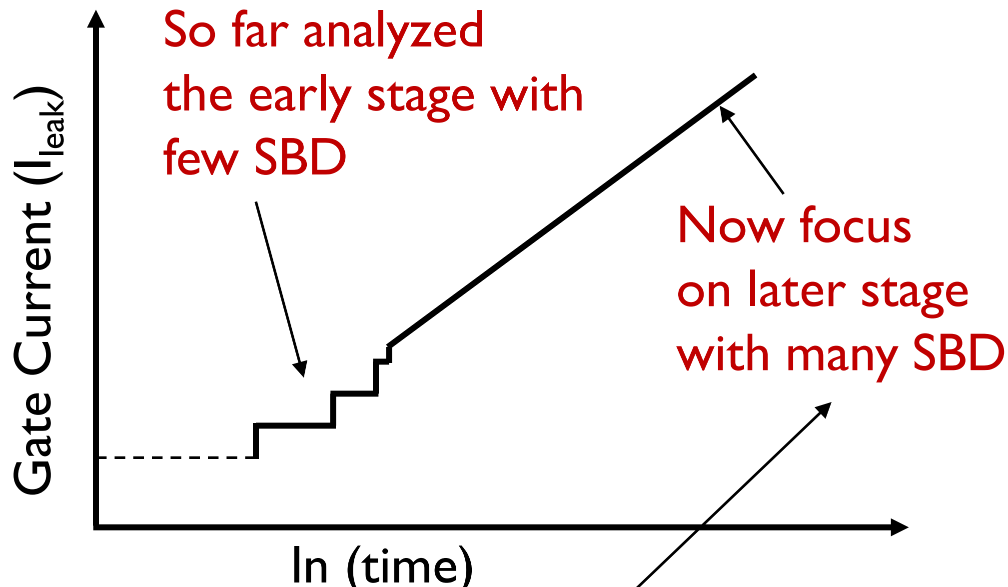


$$\ln(L)=\beta\ln(t)-\beta\ln(\eta)$$

$$\eta=\eta_0 e^{\gamma_V(V-V_0)}$$

Homework: SBD and leakage current





I_o = current per SBD
N_T = # of transistors

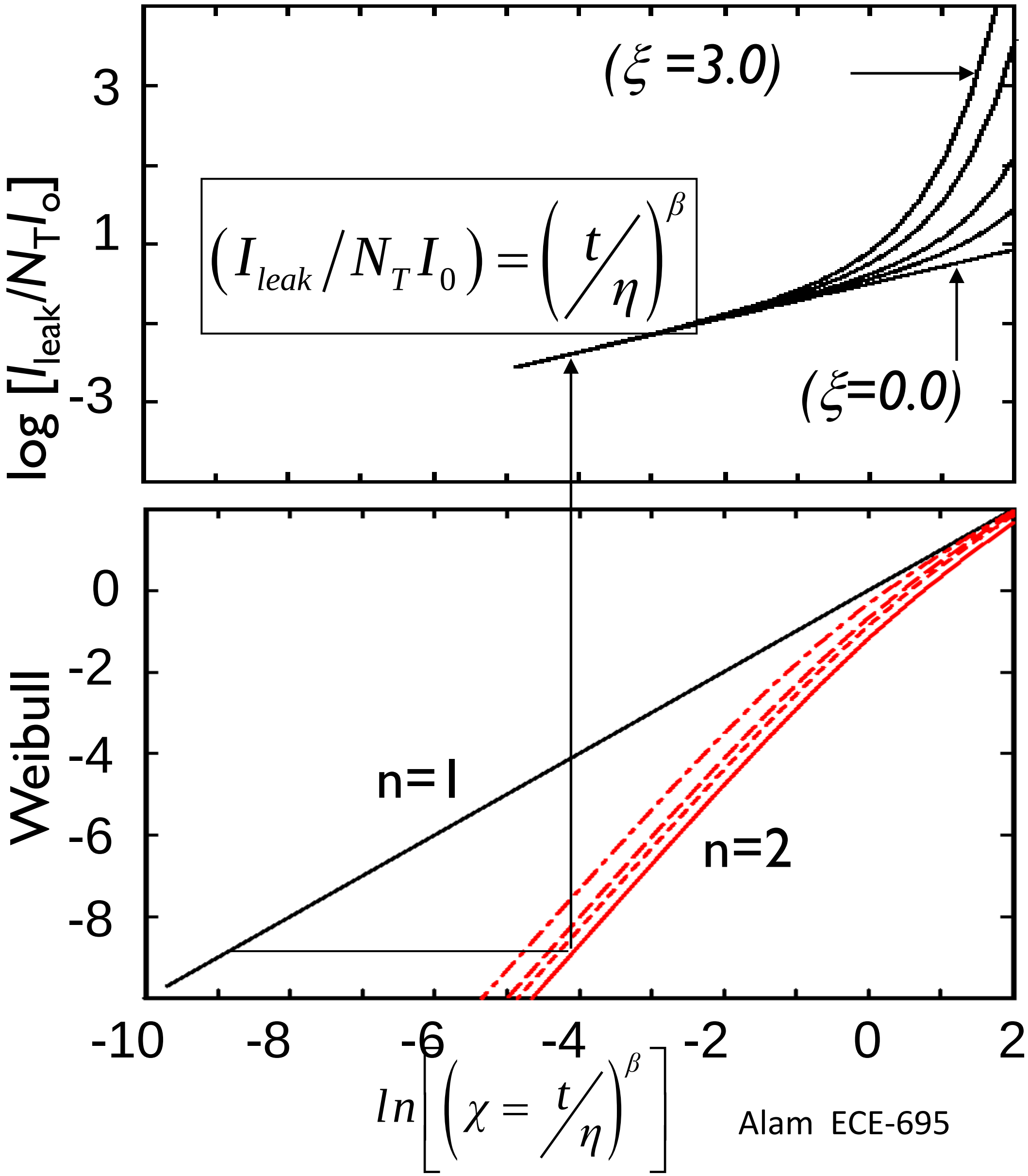
Theory

Meas.

$$\left(I_{leak}/N_T I_0\right) = \sum nP_n = \sum n f(\xi)\left(\frac{\chi^n e^{-\chi}}{n!}\right)$$

$$= \frac{exp(\xi\chi)-1}{\xi}$$

Correlation parameter from leakage



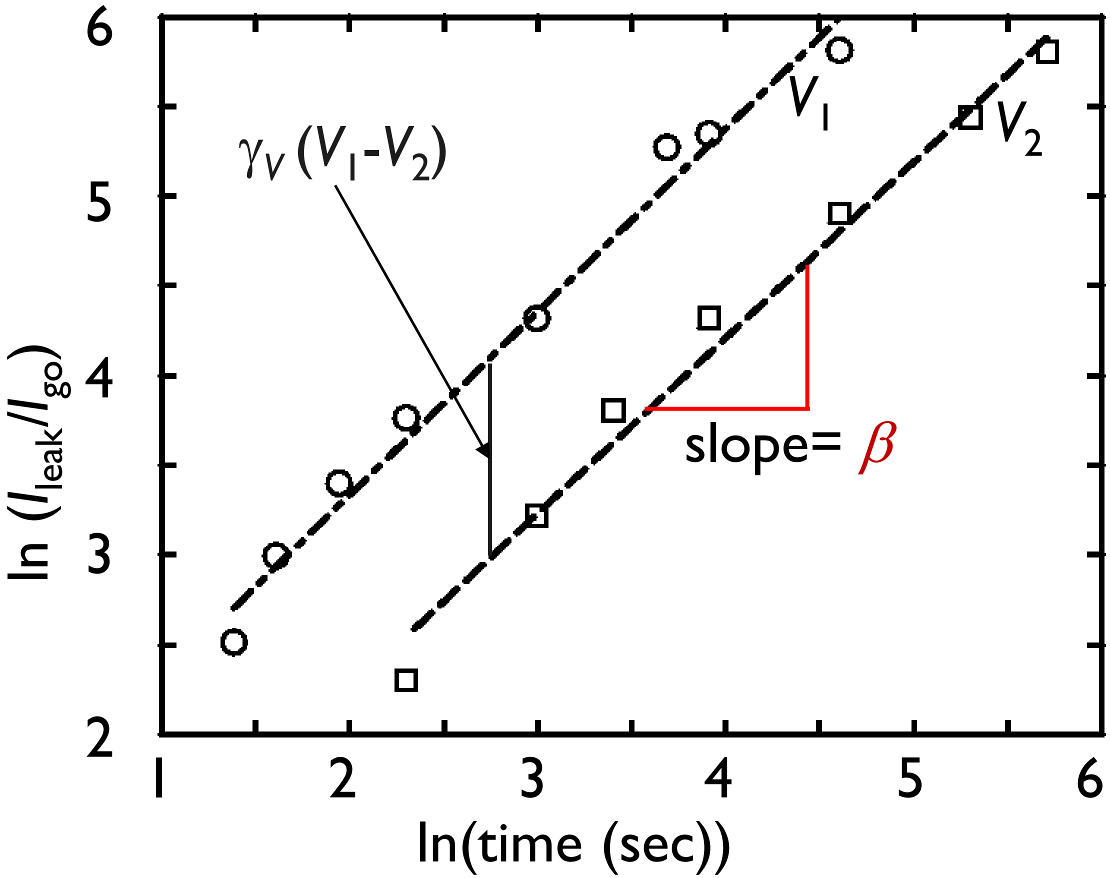
$$\left(I_{leak}/N_T I_0\right) = \frac{exp(\xi\chi)-1}{\xi}$$

Even with significant increase in post-SBD trap generation, the $\xi \rightarrow 0$ limit should describe the measured leakage data well.

Alam, IEDM02
Nafria, JAP1993

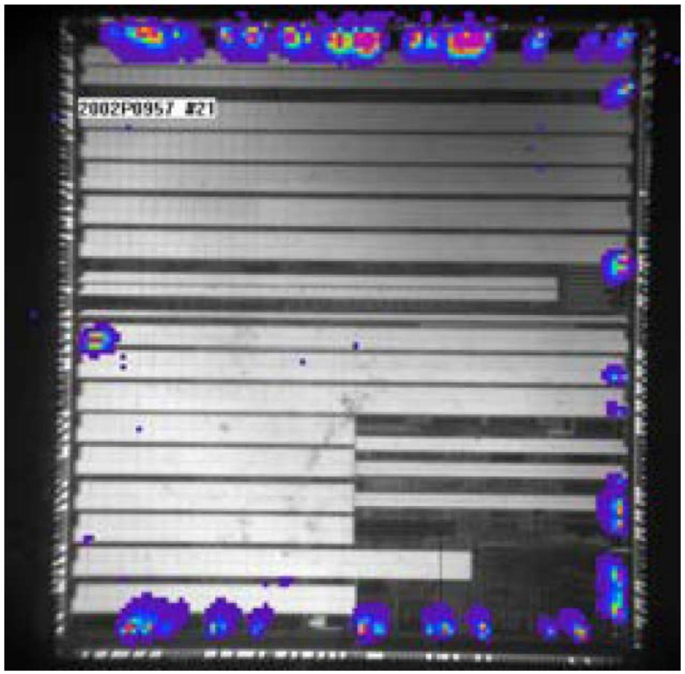
A new measurement for Weibull slope and voltage acceleration

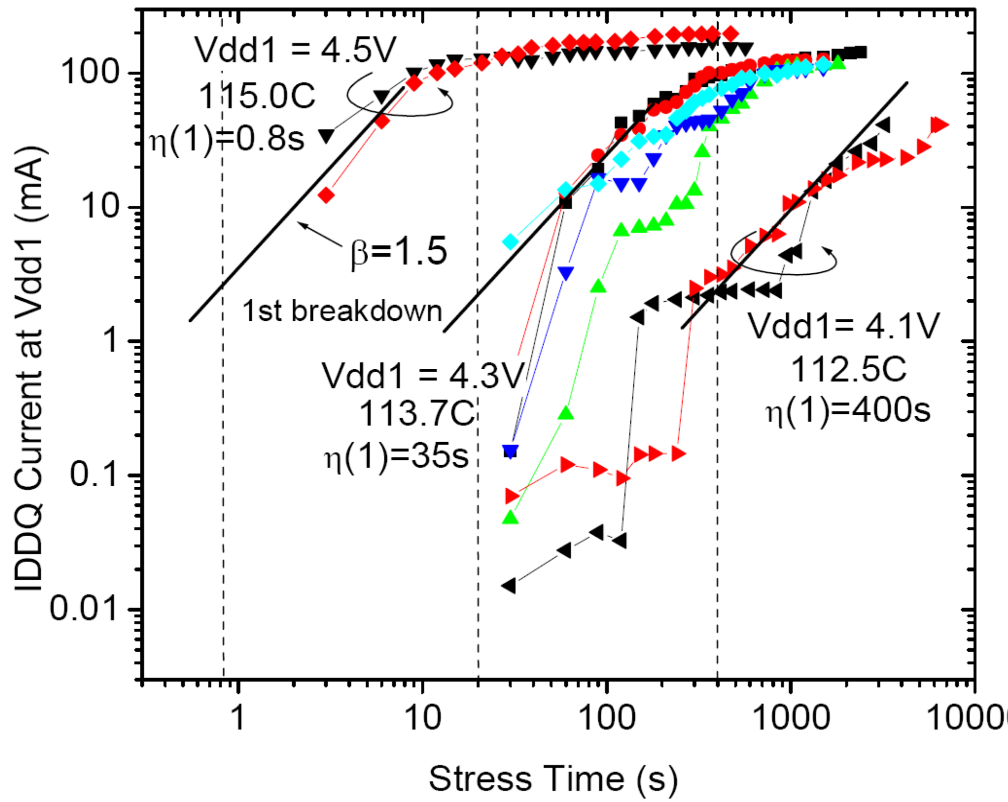
$$\ln\left(I_{leak}\right)=\beta\left[\ln\left(t\right)+\gamma_V\left(V-V_0\right)-\ln\left(\eta_0\right)+const.\right]$$



Only a few large area devices needed! (We can predict rest of the results from single voltage curve)

Soft gate dielectric breakdown (TDDB)





Note the quantized jumps and asymptotic slopes

Conclusions

- An algorithm of determining both in time correlation is discussed. We find that in classical MOSFET, the correlation is weak.
- IDDQ Leakage current due to dielectric breakdown increases with time as a power-law.
- IDDQ measurement helps determine Weibull factor, voltage acceleration factor (γ_V), and correlation factor (ξ) just by using few devices at very low voltages. No need for hundreds of devices tested for long period of time.