On Reliability of Microelectronic Devices: An Introductory Lecture on Negative Bias Temperature Instability

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Reliability has always been Important!

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A 5000 year old example:

Stone vs. Copper tools

A modern example:

Honda vs. Yugo

“The car is named Yugo, because it doesn’t …”

Microelectronics reliability & viable technologies

- Pauli to his student Peierls, in 1932, on unreliability of Cu_2S, Ag_2S:

  “ *Do not work on semiconductors, it is a mess (eine schweinerei);*
  who knows if semiconductor exists at all …..”

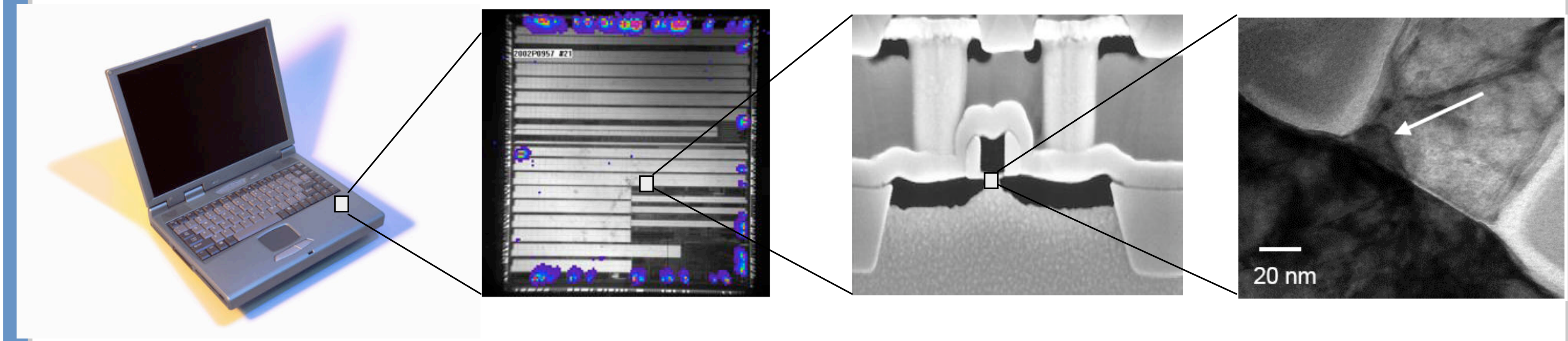
- Kelly (Bell Labs) to recently-hired Shockley in 1936:

  “Instead of mechanical devices, which has annoying maintenance problem, we should look for (reliable) solid state switch ….”

- Landauer on quantum computing (1992):

  “ *…. this proposal depends on speculative technology, does not in its current form account all possible sources of noise, unreliability, and manufacturing error, and probably will not work.”*

Warranty, Product Recall, and Other Facts of Life

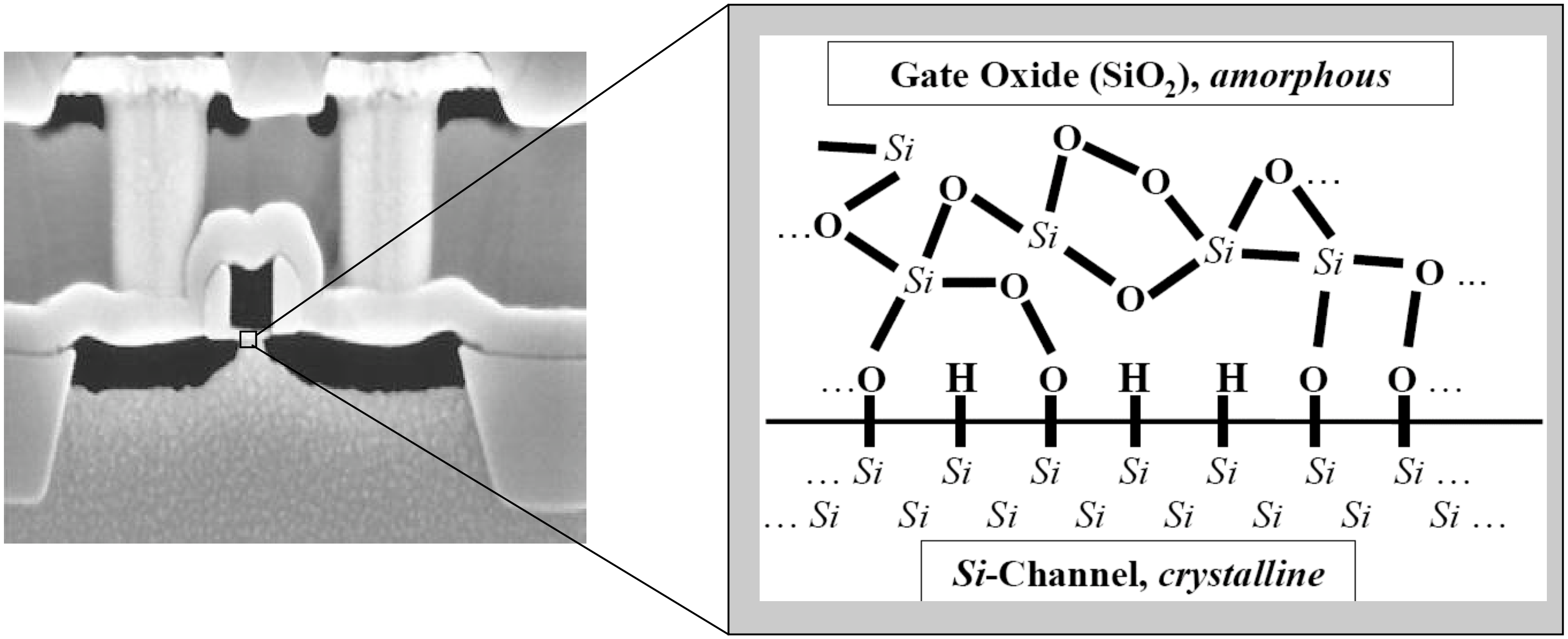


A manufacturer bets the company of the physics of reliability …..

… because the ICs operate in incredibly harsh conditions, turning on and off trillions of time during its lifetime ….

… because the lines could open, the source/drain can be shorted, the gate oxide can break ….

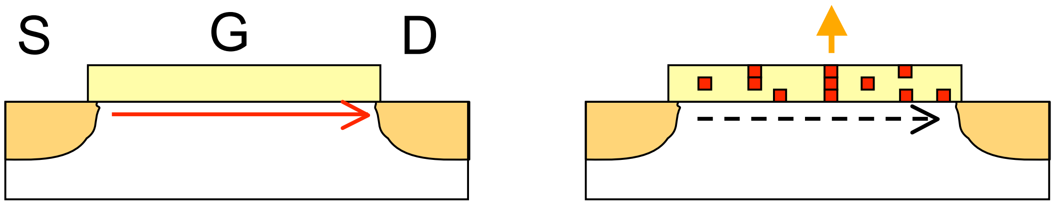
Si-H and SiO2 Bonds

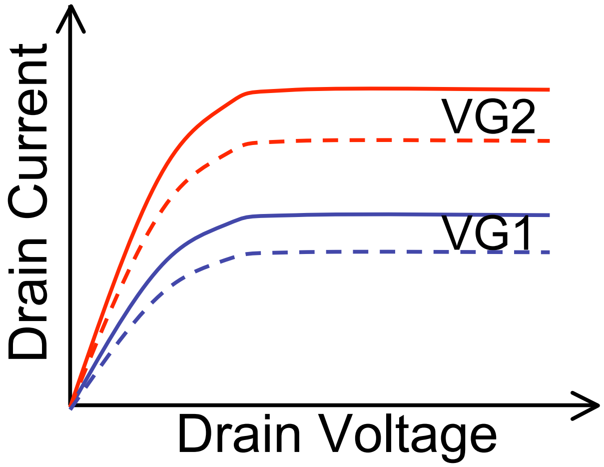


Reliability Issues in Modern Transistors

Initially ….

…. a few months later

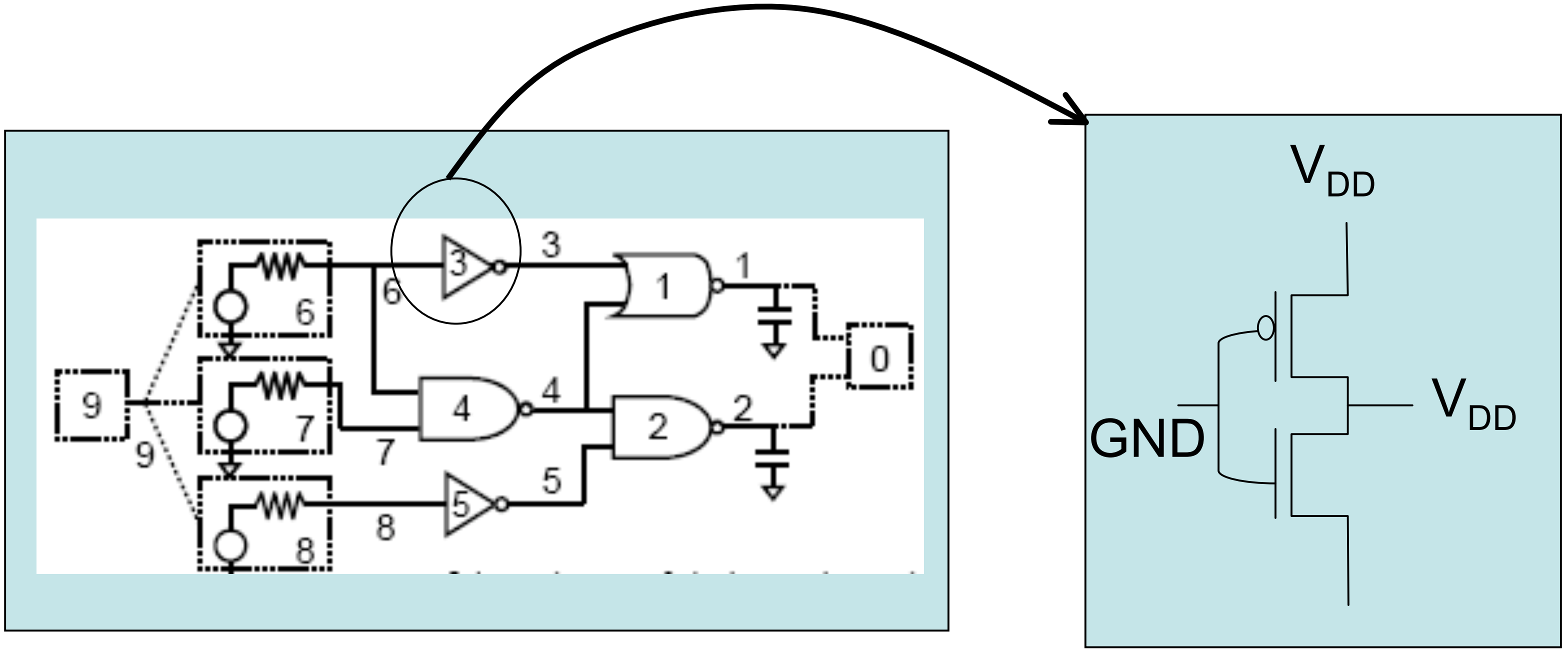




Broken Si-H bonds: Negative Bias Temperature Instability (NBTI)
Hot carrier degradation (HCI)

Broken Si-O bonds: Gate dielectric Breakdown (TDDB)

Introduction: NBTI defined



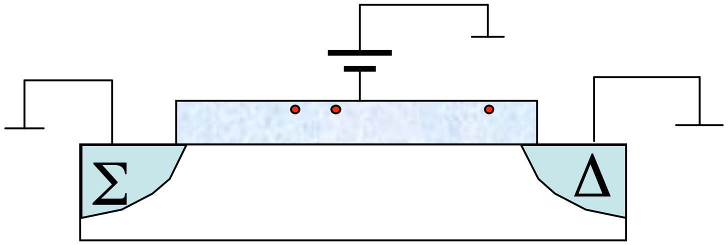
NBTI: Negative Bias Temperature Instability

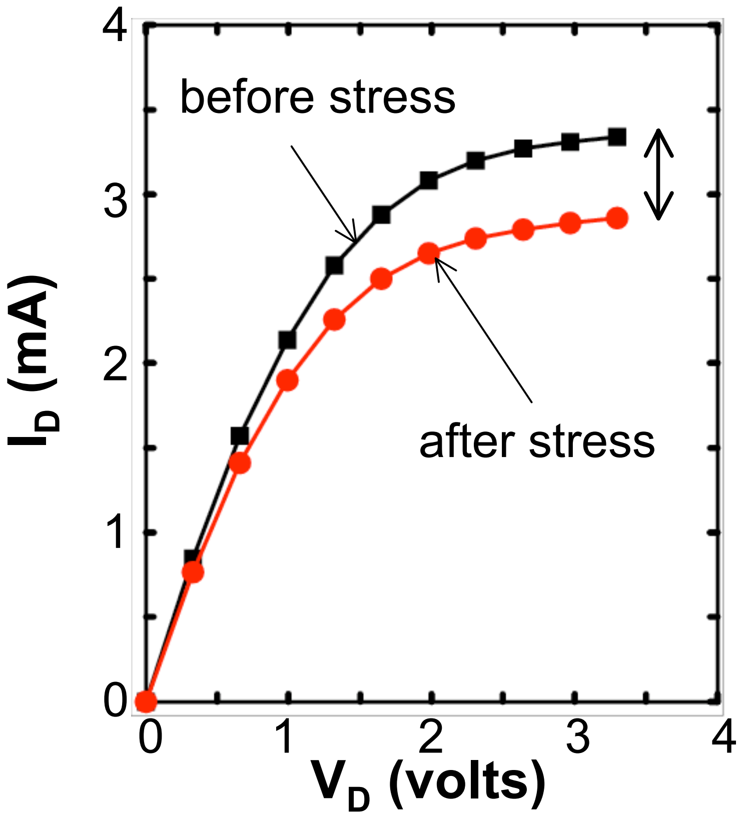
Gate: GND, **Drain**: VDD, **Source**: VDD

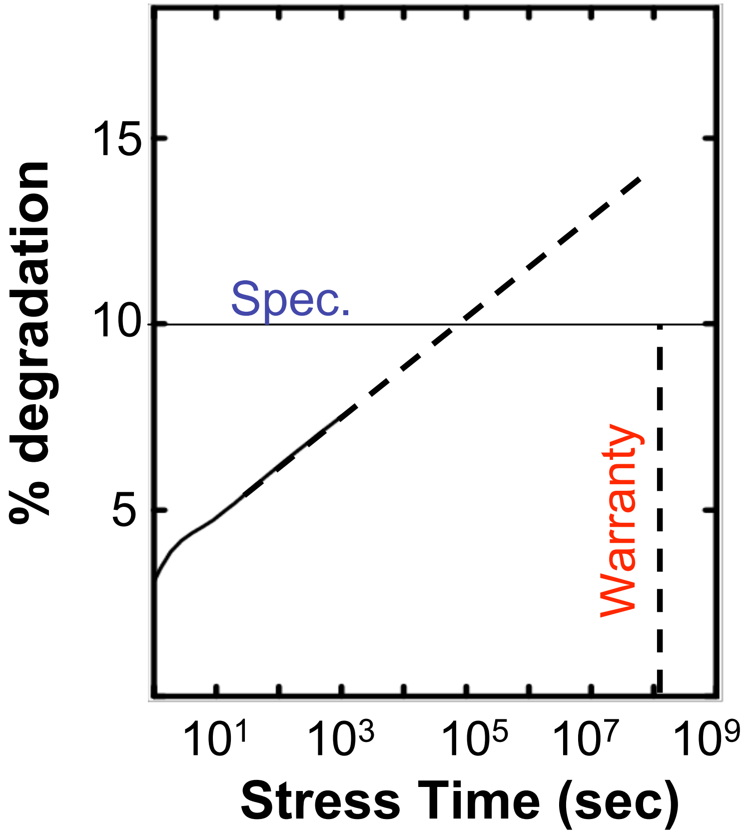
Gate negative with respect to S/D

Other degradation modes: TDDB, HCI, etc.

NBTI & Parametric Failure







A Brief History of NBTI

Experiments in late 1960s by Deal and Grove at Fairchild

- Role of Si-H bonds and BTI vs. NBTI story (J. Electrochem Soc. 1973;114:266)
- Came out naturally as PMOS was dominant
- Important in FAMOS and p-MNOS EEPROMS (Solid State Ckts 1971;6:301)

Theory in late 1970s by Jeppson (JAP, 1977;48:2004)

- Generalized Reaction-Diffusion Model
- Discusses the role of relaxation, bulk traps, …..
- Comprehensive study of available experiments

Early 1980s

- Issue disappears with NMOS technology and buried channel PMOS

Late 1980s and Early 1990s

- Begins to become an issue with dual poly gate, but HCI dominates device reliability

Late 1990s/Early 2000 (Kimizuka, IRPS97;282. Yamamoto, TED99;46:921. Mitani, IEDM02;509)

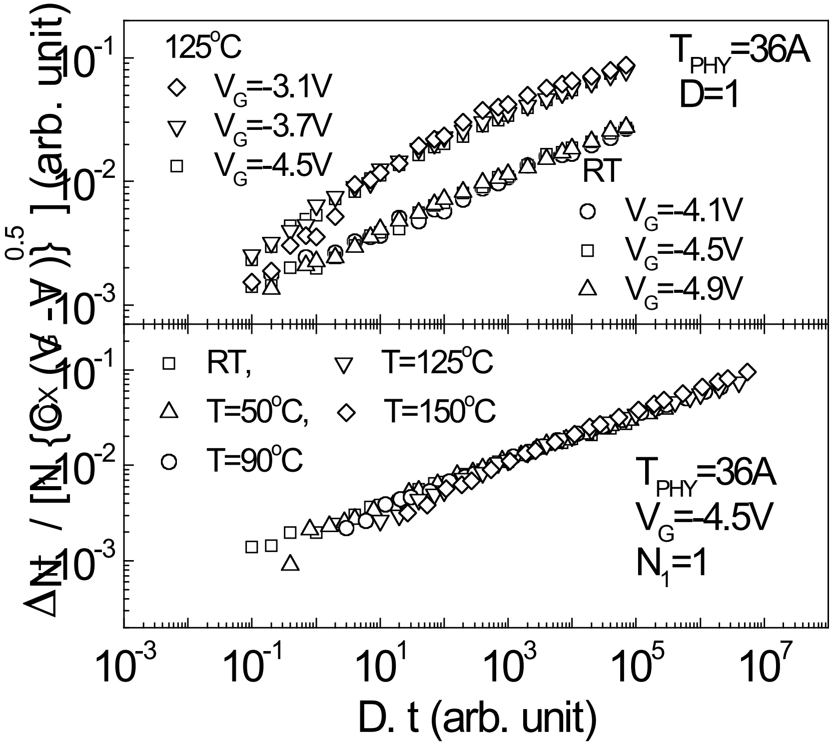
- Voltage scaling reduces HCI and TDDB, but increasing field & temperature reintroduce NBTI concerns for both analog and digital circuits
- Numerical solution is extensively used for theoretical modeling of NBTI.

Exponent and Activation

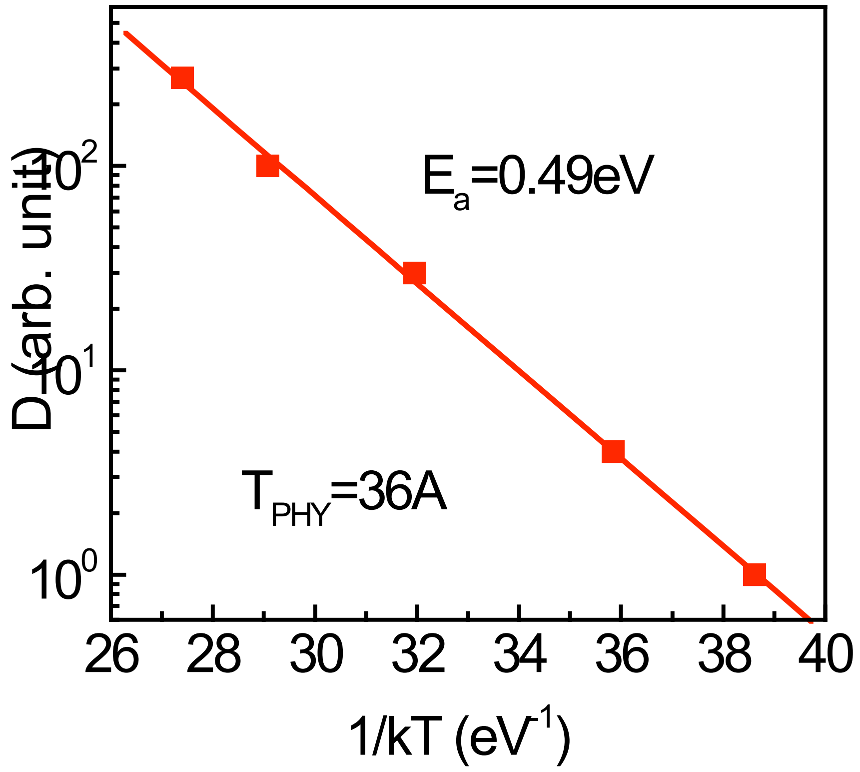
$$N_{IT}(t) = Ae^{-Ea/k_BT}\,t^n$$

$$\log(N_{IT}(t)) = n\log(t) + (\log(A) - Ea/k_BT)$$

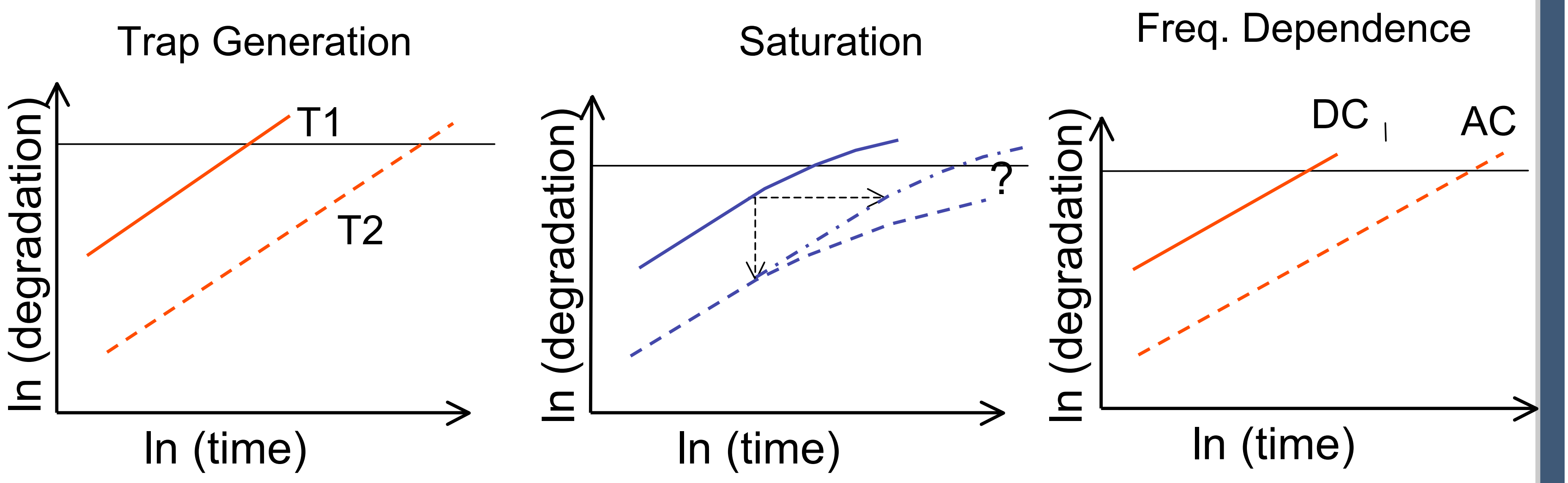
n ~ 0.25



Ea ~ 0.5



A 40-year-old Puzzle …


Trap Generation

Saturation

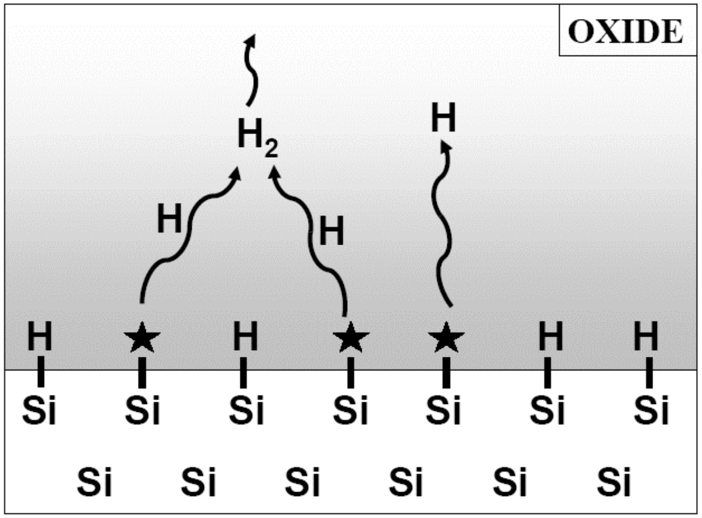
Freq. Dependence

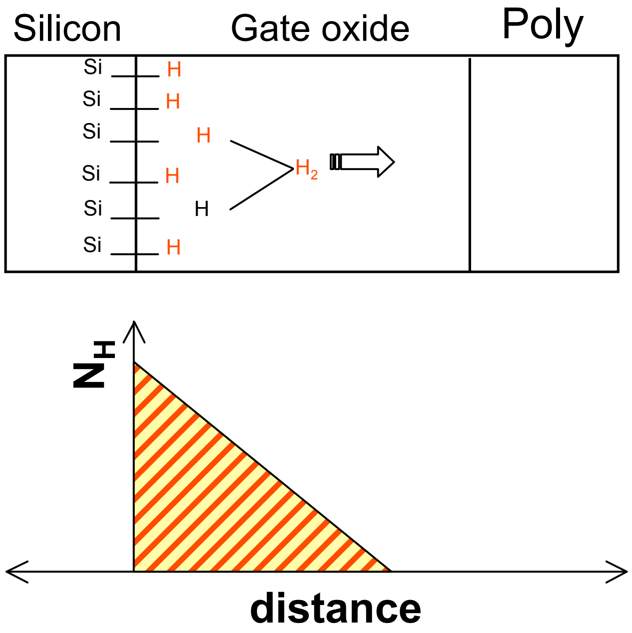
- n=0.25 (H diffusion ?)
- E_A=0.5 (H_2 diffusion ?)

- The exponent is soft (n_{sat} = 0.16) !
- NBTI depends on frequency.

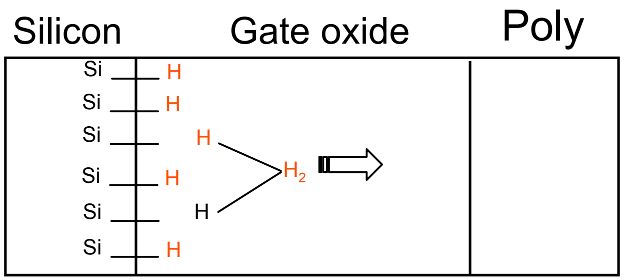
Before 1980 | | After 2000

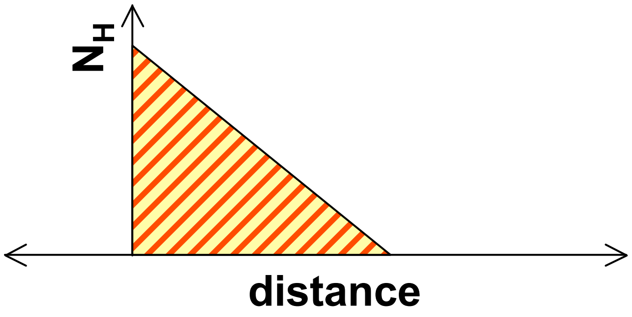
A Word about Drawings

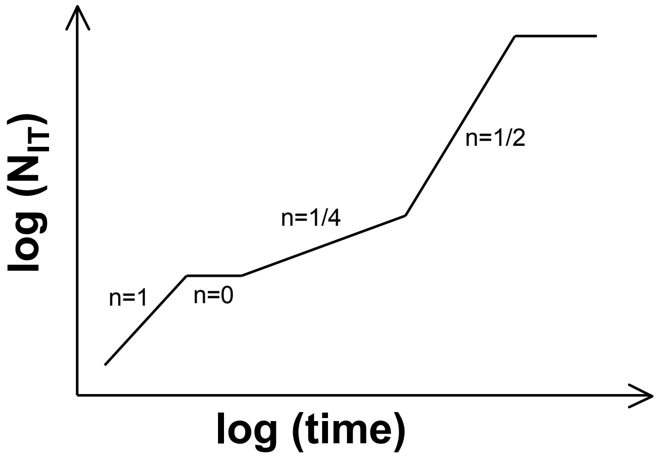




The Reaction-Diffusion Model







$$\frac{dN_{IT}}{dt} = k_F(N_0 - N_{IT}) - k_R N_H(0) N_{IT}$$

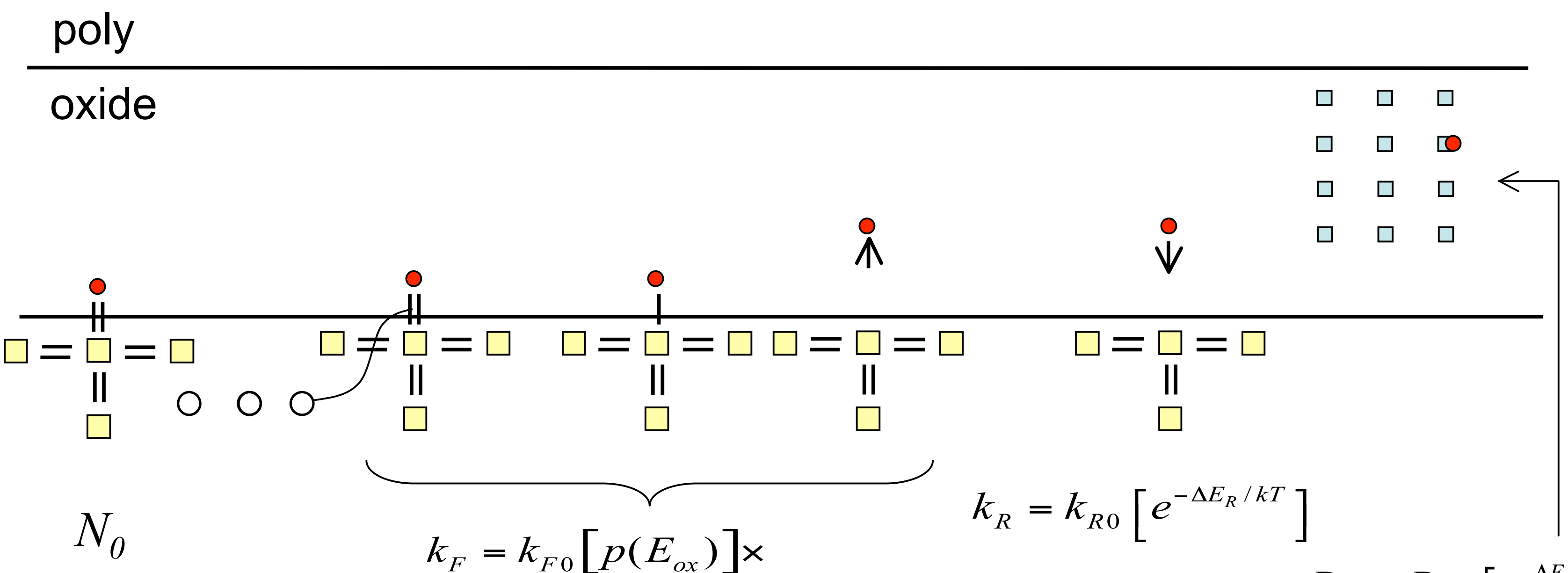
k_F: Si-H dissociation rate const.
Creates broken-bond N_{IT}
k_R : Rate of reverse annealing of Si-H
N_0: Total number of Si-H bonds

$$\frac{dN_H}{dt} = D_H \frac{d^2 N_H}{dt^2} + N_H \mu_H E + \frac{\delta}{2}\frac{dN_{IT}}{dt}$$

N_H: Hydrogen density
D_H: Hydrogen diffusion coefficient
μ_H: Hydrogen mobility

Meaning of the Parameters

$$SiH + h^{+} \quad \overset{k_F}{\underset{k_R}{}} \quad Si^{+} + H$$

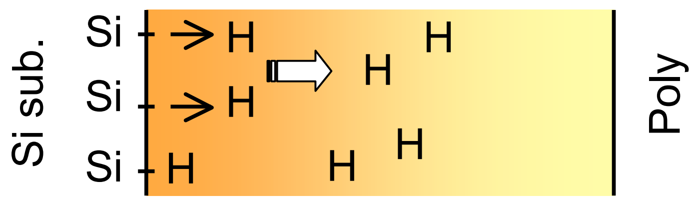


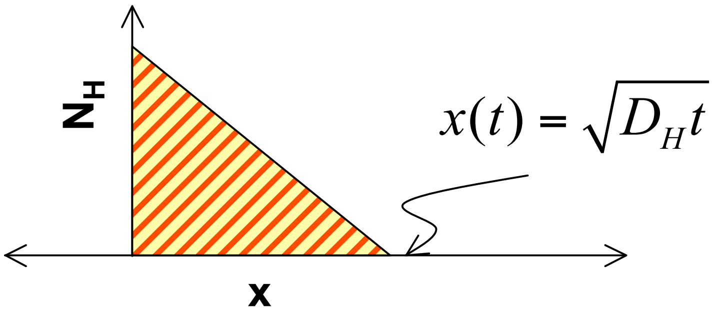
$$k_F = k_{F0}\left[p(E_{ox})\right] \times \left[\sigma e^{-E_{ox}/E_0}\right] \times \left[e^{-\Delta E_F/kT}\right]$$

$$k_R = k_{R0}\left[e^{-\Delta E_R/kT}\right]$$

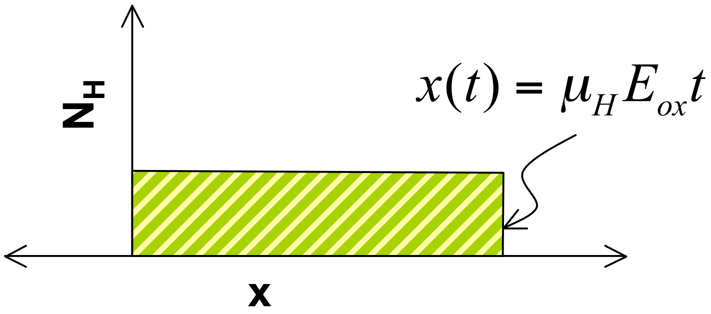
$$D_H = D_{H0}\left[e^{-\Delta E_H/kT}\right]$$

A Reformulation of R-D Model





$$x(t) = \sqrt{D_H t}$$



$$x(t) = \mu_H E_{ox} t$$

$$\cancel{\frac{dN_{IT}}{dt}} = k_F(N_0 - N_{IT}) - k_R N_H(0) N_{IT}$$

If trap generation rate is small, and if N_{IT} much smaller than N_0, then

$$\left(\frac{k_F N_0}{k_R}\right) \approx N_H(0) N_{IT}$$

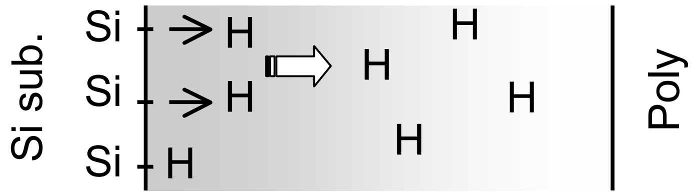
$$\frac{dN_{IT}}{dt} = D_H \frac{d^2 N_H}{dx^2} + N_H \mu_H E + \frac{\delta}{2}\frac{dN_H}{dt}$$

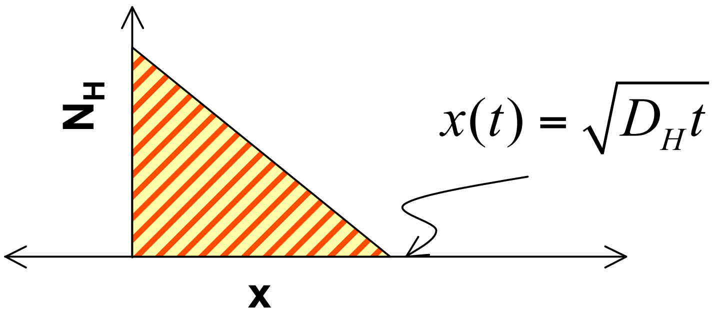
$$N_{IT}(t) = \int_{x=0}^{x(t)=f(D_H,\mu_H,t)} N_H(x,t)\,dx$$

$$N_{IT}(t) = \int_0^{\sqrt{D_H t}} N_H(x,t)\,dx \quad \text{(Neutral)}$$

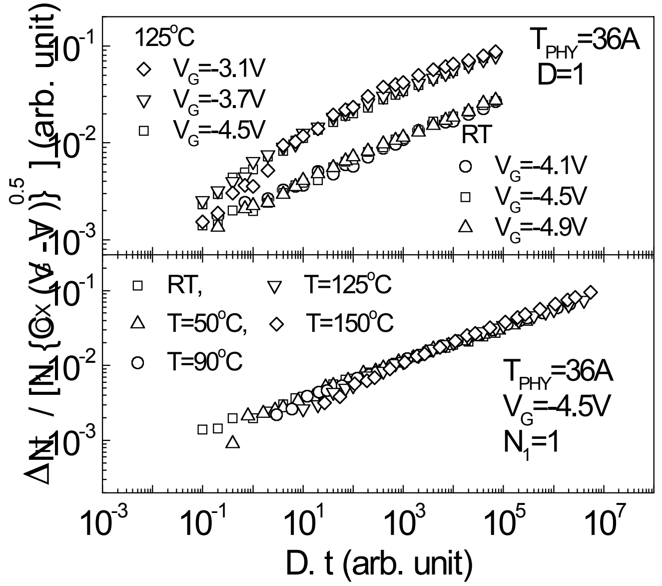
$$N_{IT}(t) = \int_0^{\mu_H E_{ox} t} N_H(x,t)\,dx \quad \text{(Charged)}$$

NIT with Neutral H Diffusion





$$x(t) = \sqrt{D_H t}$$



$$\left(\frac{k_F N_0}{k_R}\right) \approx N_H(0)N_{IT}$$

$$N_{IT}(t) = \int_0^{\sqrt{D_H t}} N_H(x,t)\,dx$$

$$= \frac{1}{2} N_H(0)\sqrt{D_H t}$$

Combining these two, we get

$$N_{IT}(t) = \sqrt{\frac{k_F N_0}{2k_R}}\,(D_H t)^{1/4}$$

n=1/4 even with two sided diffusion

n ~ 1/4 is a possible signature of neutral H diffusion

Reproduces results of Jeppson, JAP, 1977.

NIT with Neutral H_2 Diffusion

$$\left(\frac{k_F N_0}{k_R}\right) \approx N_H(0) N_{IT}$$

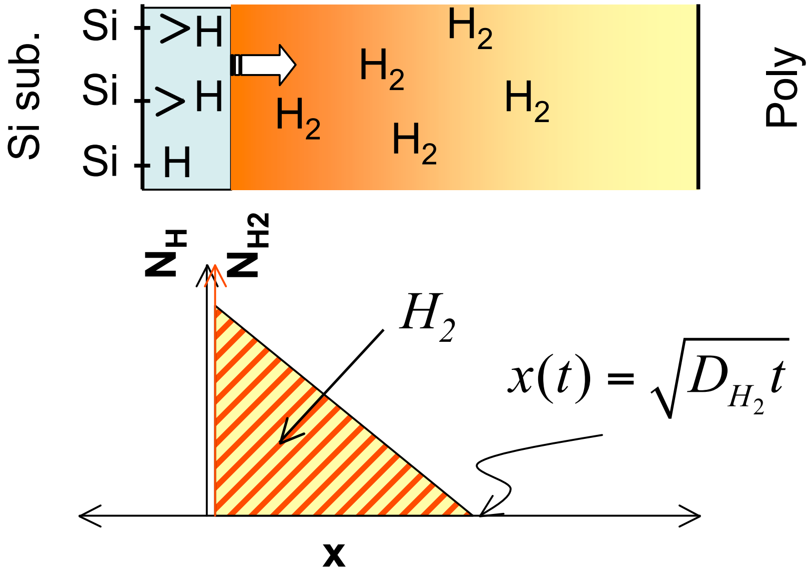
$$N_{IT}(t) = \int_0^{\sqrt{D_{H_2} t}} N_H(x,t)\,dx$$

$$= \frac{1}{2} N_{H_2}(0)\sqrt{D_{H_2} t}$$

$$const. = \frac{N_H(0)^2}{N_{H_2}(0)} \quad (2H \qquad H_2)$$

Combining these two, we get

$$N_{IT}(t) \propto \sqrt{\frac{k_F N_0}{2k_R}} (D_{H_2} t)^{1/6}$$



- ❍ $n \sim 1/6$ is a possible signature of neutral H_2 diffusion
- ❍ Small exponent because generation is more difficult.

Reproduces results of Chakravarthi, IRPS, 2003.

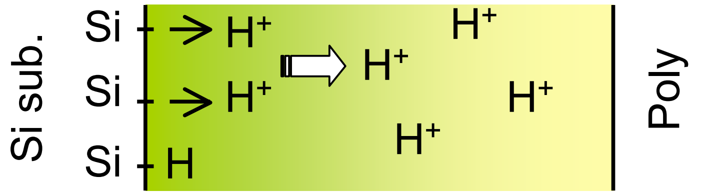
NIT with charged H^+ Drift

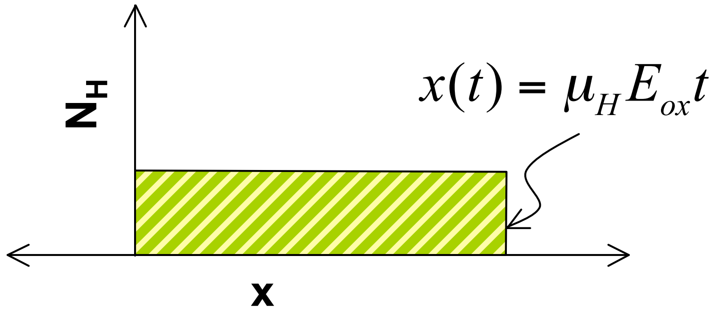
$$\left(\frac{k_F N_0}{k_R}\right) \approx N_H(0) N_{IT}$$

$$N_{IT}(t) = \int_0^{\mu_H E_{ox} t} N_H(x,t)dx$$
$$= \frac{1}{2} N_H(0) \mu_H E_{ox} t$$

Combining these two, we get

$$N_{IT}(t) = \sqrt{\frac{k_F N_0}{2k_R}} (\mu_H E_{ox} t)^{1/2}$$





- $n \sim 1/2$ is a possible signature of charged H diffusion
- Rapid removal of H^+ by E_{ox} field increase N_{IT} gen. rate.

Reproduces results of Ogawa, PRB, 1995.

NIT with charge H_2^+ Drift

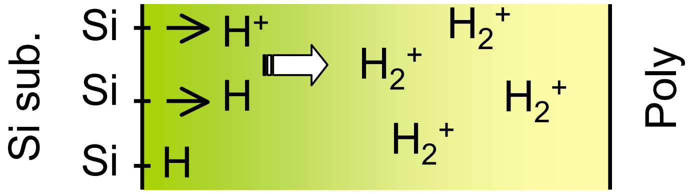
$$\left(\frac{k_F N_0}{k_R}\right) \approx N_H(0) N_{IT}$$

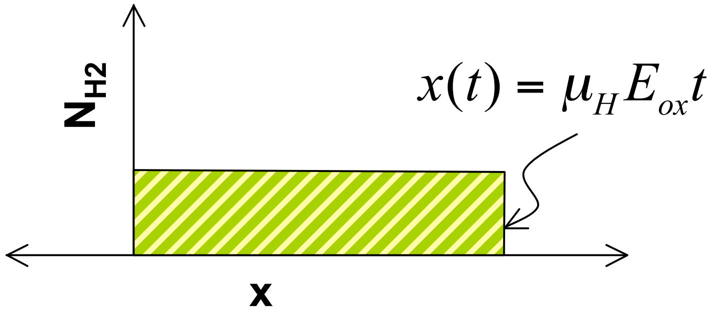
$$N_{IT}(t) = \int_0^{\mu_H E_{ox} t} N_{H2}(x,t)\,dx$$
$$= \frac{1}{2} N_{H2}(0) \mu_H E_{ox} t$$

$$const. = \frac{N_H(0)^2}{N_{H_2}(0)} \quad \left(H + H^+ \qquad H_2^+\right)$$

Combining these two, we get

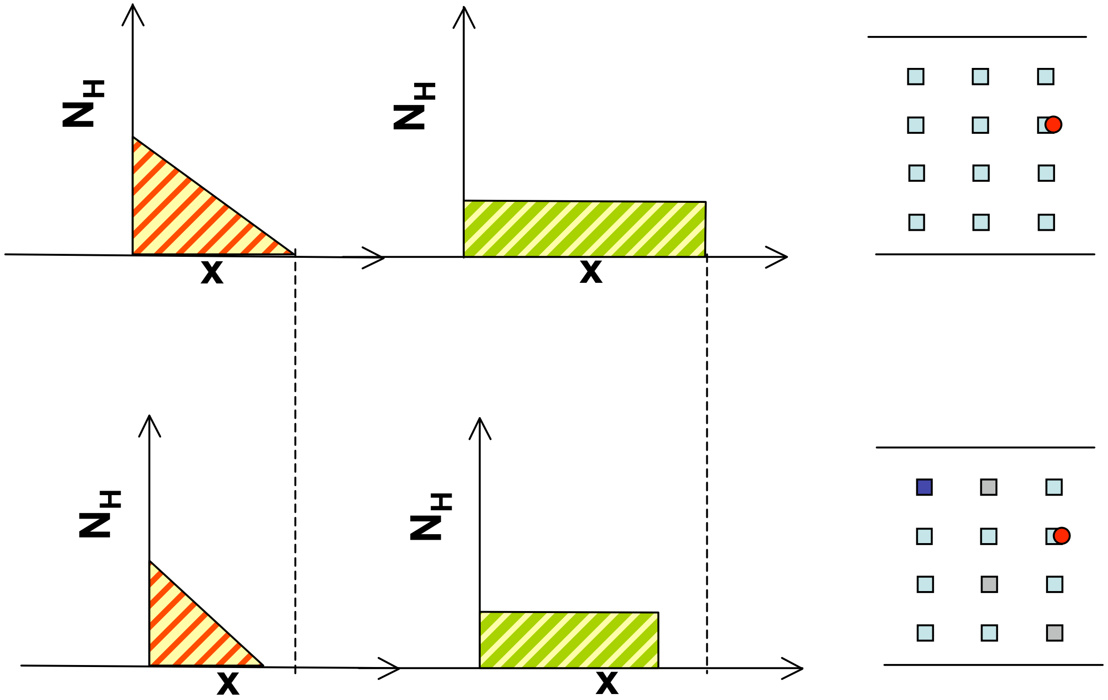
$$N_{IT}(t) \propto \sqrt{\frac{k_F N_0}{2k_R}} \left(\mu_H E_{ox} t\right)^{1/3}$$





- $n \sim 1/3$ is a possible signature of charged H_2^+ diffusion
- Exponents above 1/3 seldom seen in charge-pumping expt. (uncorrelated to SILC).

Dispersive Diffusion & non-rational *n*



$$N_{IT}(t) \propto \sqrt{\frac{k_F N_0}{2k_R}}(D_{H_*}t)^n$$

$$D_H = D_0(\omega_0 t)^{-p}$$

Shkrob, PRB, 1996; 54:15073

$$N_{IT}(t) \propto \sqrt{\frac{k_F N_0}{2k_R}}\left(\frac{D_0}{w^p}\right)^n t^{n(1-p)}$$

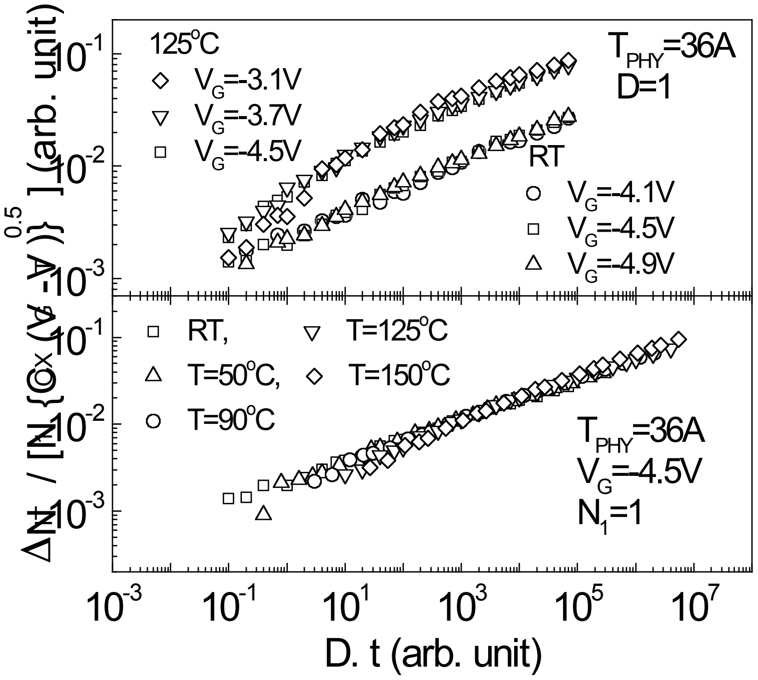
- R-D model predicts n=0.30-0.12
- More amorphous oxides for better NBTI
- For finite oxides, at very long time all n must be rational (no problem > 10 yrs)

	n_{ideal}	n_{dis}
H	0.25	0.20-0.25
H2	0.16	0.128-0.144
H2+	0.33	0.264-0.297

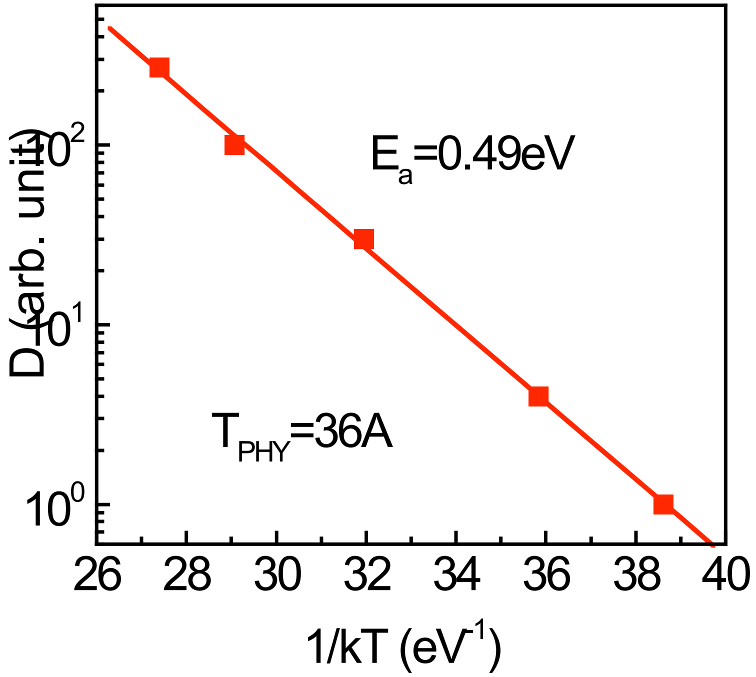
Puzzle: H or H_2 or H_2^+ ?

$$N_{IT}(t) = \sqrt{\frac{k_F N_0}{2k_R}}(D_o e^{-Ea/k_B T} t)^n$$

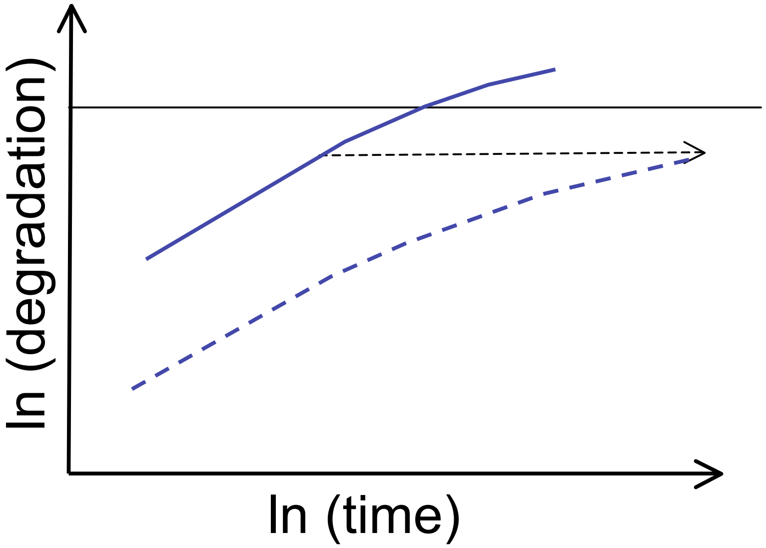
n ~ 0.25 (H or H_2^+ diffusion?)



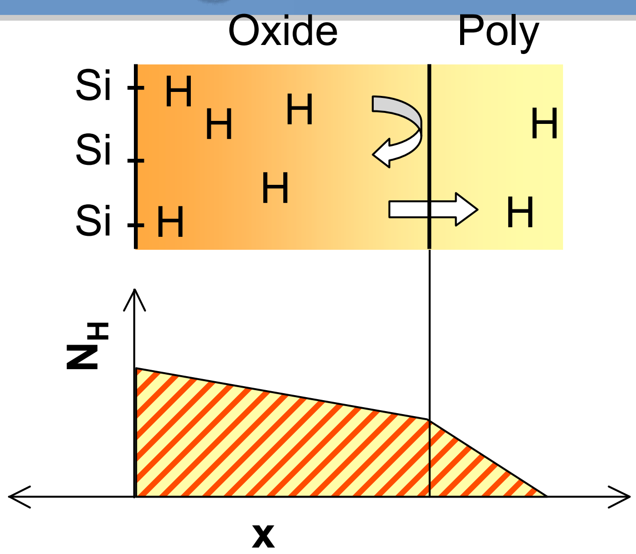
Ea ~ 0.5 (H_2 diffusion ?)

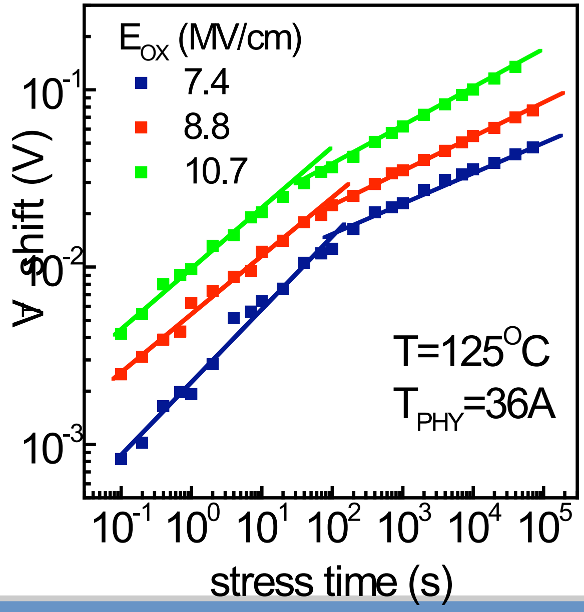


Clue 1: NBTI Saturation



Saturation by Poly Reflection





(1) $$\left(\frac{k_F N_0}{k_R}\right) \approx N_H(0) N_{IT}$$

(2) $$N_{IT}(t) = \frac{1}{2} N_H(T_{ox})\sqrt{D_H t} + \frac{W}{2}\left\{N_H(W) + N_H(0)\right\}$$

(3) $$D_H^{(poly)} \frac{N_H(W)}{\sqrt{D_H^{(poly)} t}} = D_H^{(ox)}\left(\frac{N_H(0) - N_H(W)}{W}\right)$$

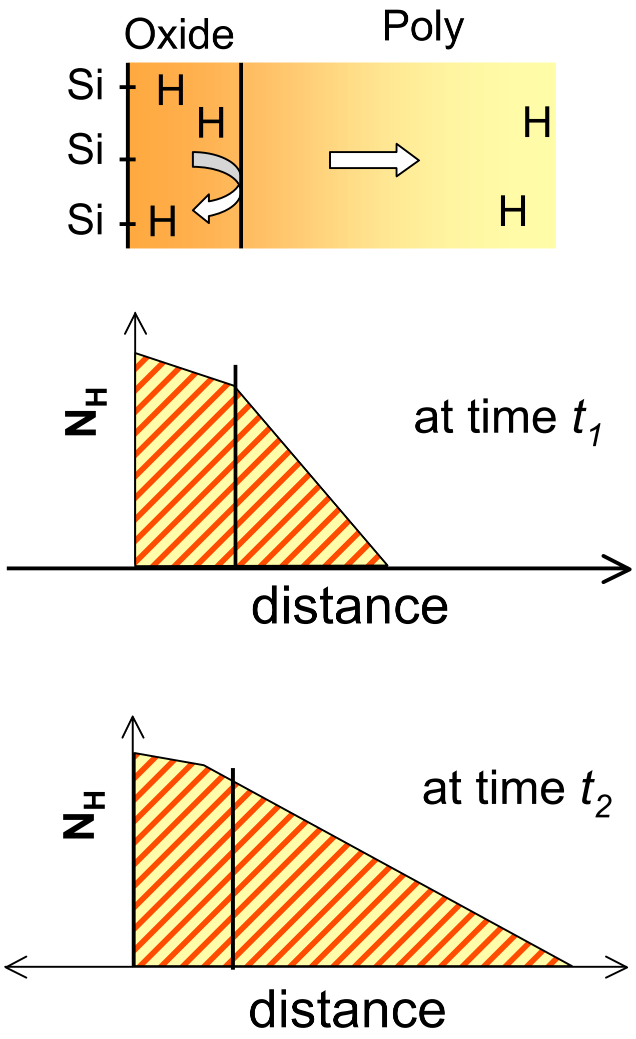
Combining, at short time, we get

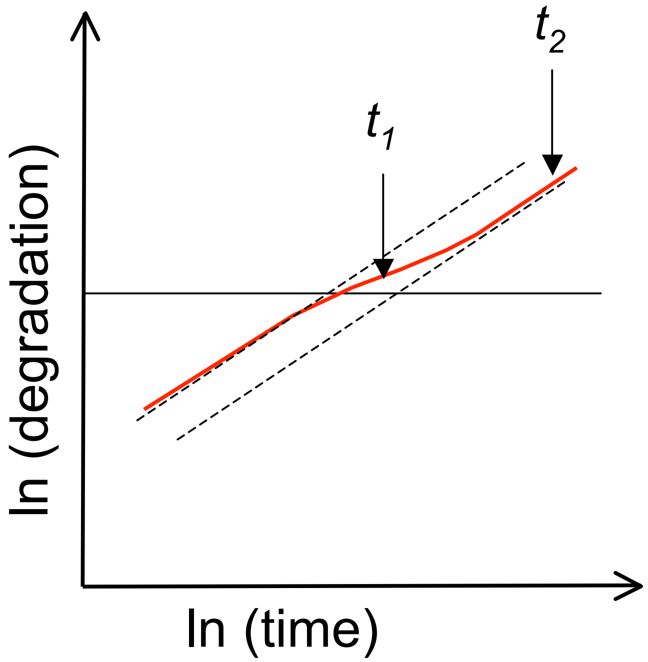
$$N_{IT}(t) \propto \sqrt{\frac{k_F N_0}{2k_R}}\left(\sqrt{D^{(poly)} t} + 2T_{ox} + \frac{T_{ox}^2}{D^{(ox)}}\sqrt{\frac{D_H^{(poly)}}{t}}\right)^{1/2}$$

… but alas, at long time ….

$$N_{IT}(t) \approx \sqrt{\frac{k_F N_0}{2k_R}}\left\{D_H^{(poly)} t\right\}^{\bigcirc\!\!\!\!\!\!1/4}$$

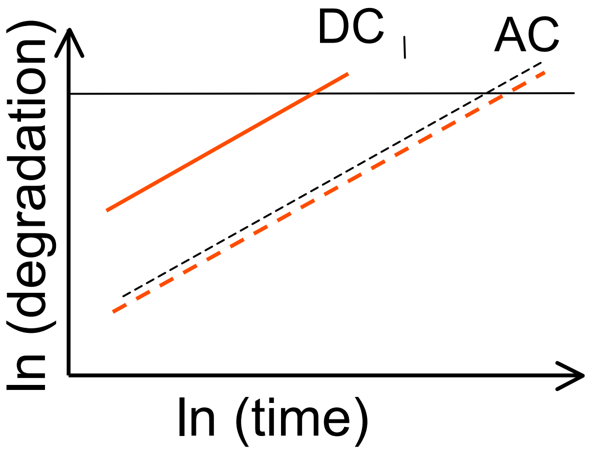
… but the explanation is wrong

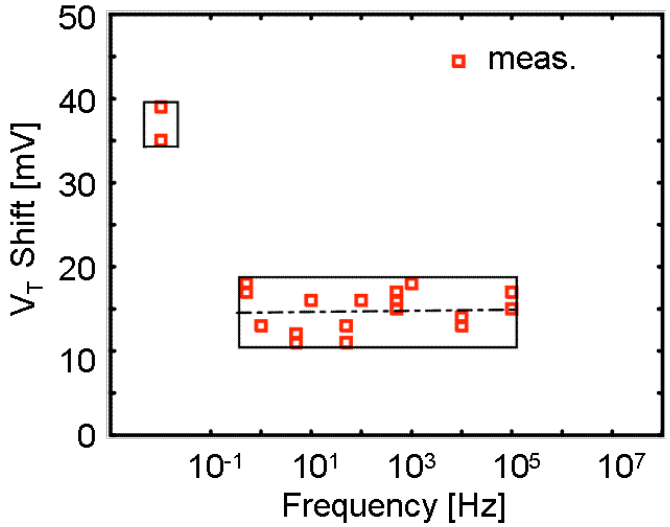




Kufluoglu, unpublished results

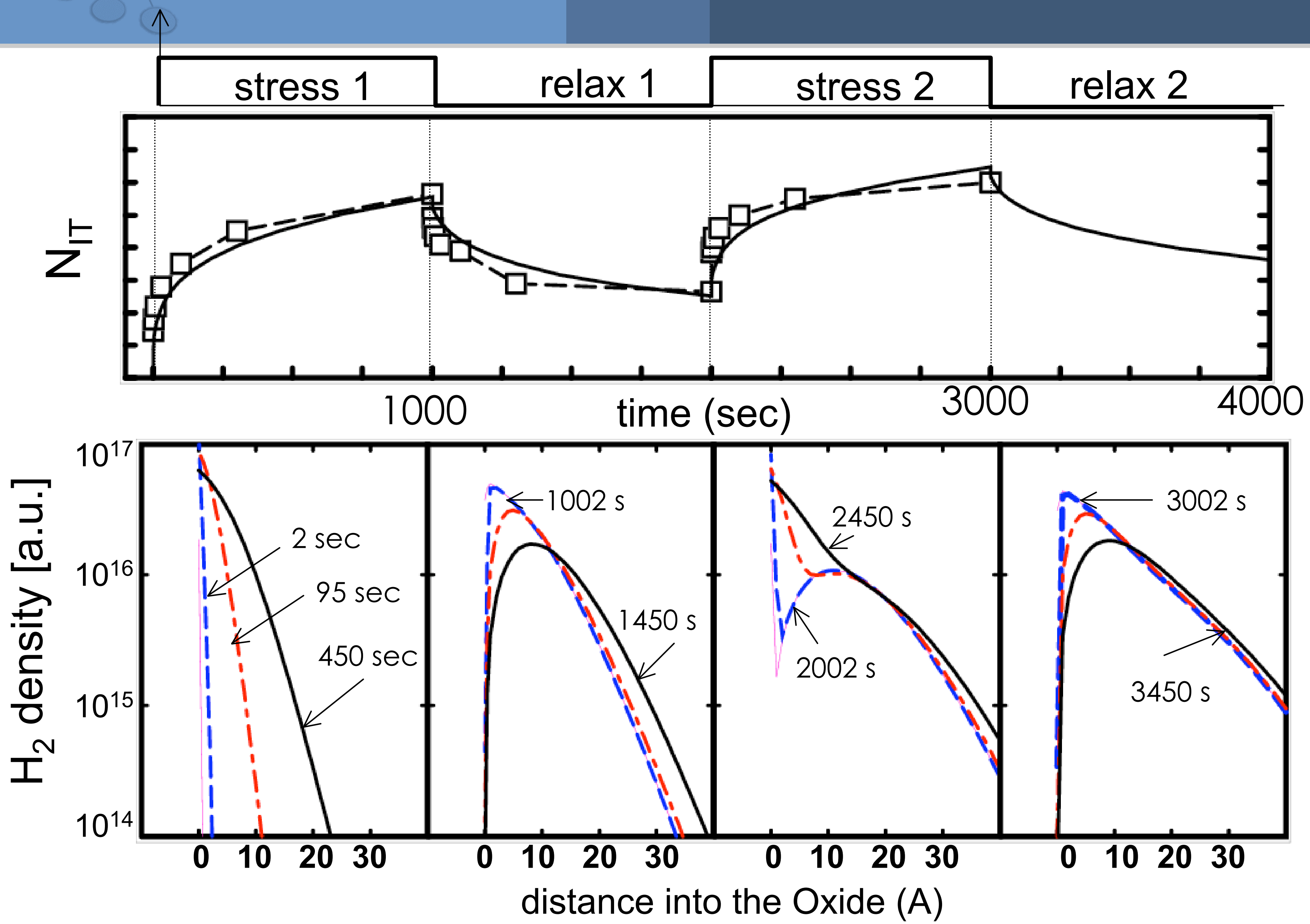
Clue 2: Frequency Dependence



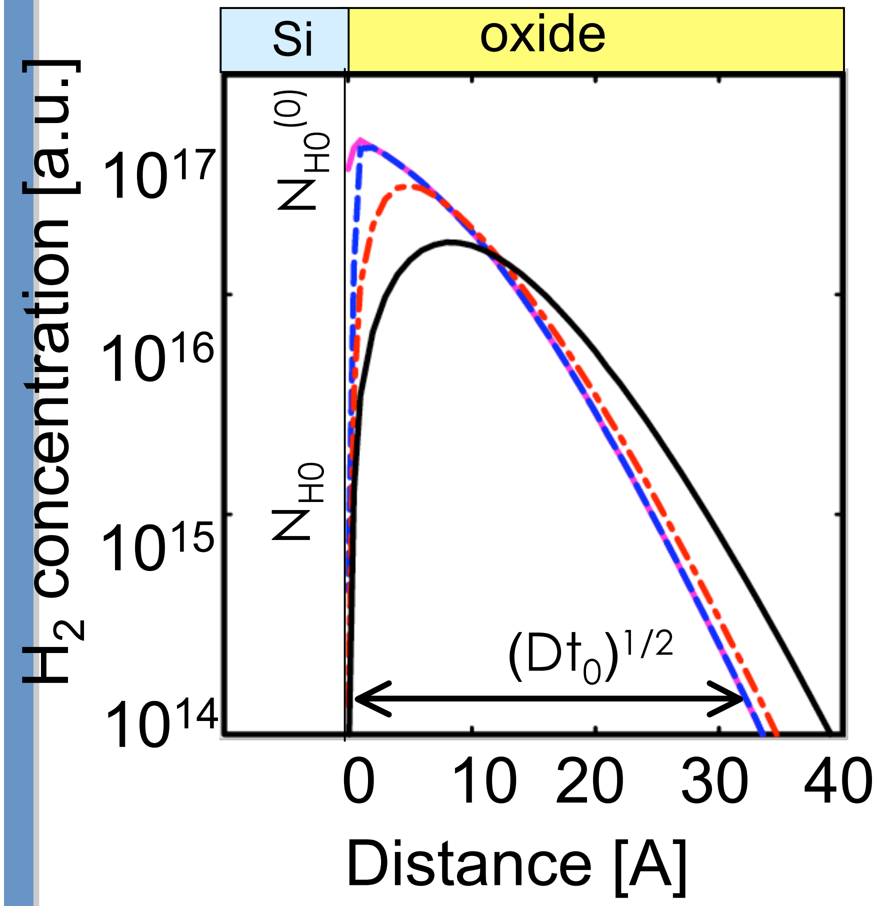


Ming-Fu Li, National University of Singapore, EDL, 2002.

R-D Model at Low Frequencies



Analytical Model: Relaxation Phase



$$N_{IT}^{(0)} = \frac{1}{2} N_H(0)\sqrt{D_H \tau_0}$$

$$N_{IT}^{(*)} = \frac{1}{2} N_H(0)\sqrt{\xi D_H t}$$

$$\frac{dN_{IT}}{dt} = \cancel{k_F}(N_0 - N_{IT}) - k_R N_H(0) N_{IT}$$

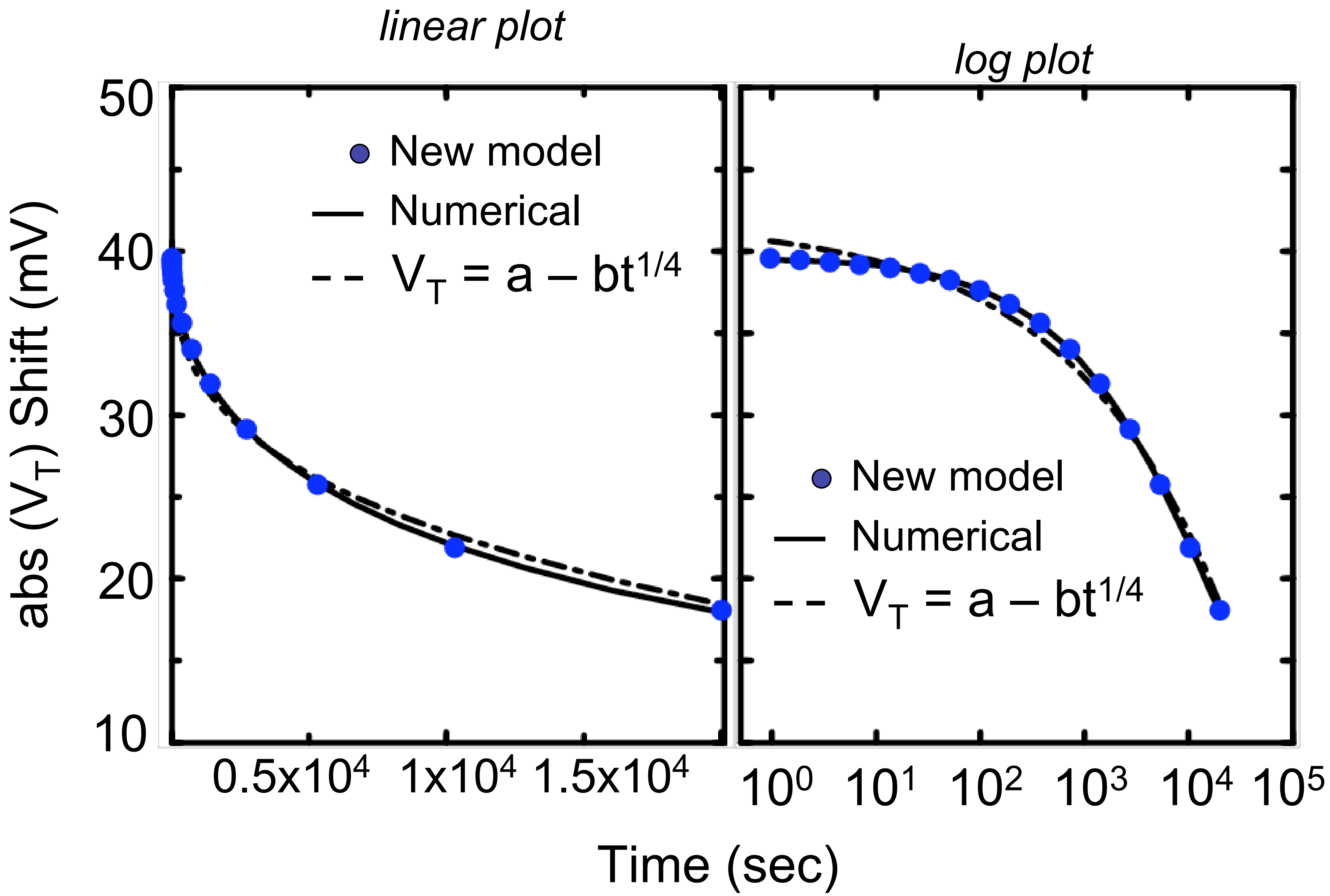
$$N_{H0} = N_{H0}^{(0)} - N_H^{(*)}$$

$$N_{IT} = N_{IT}^{(0)} - N_{IT}^{(*)}$$

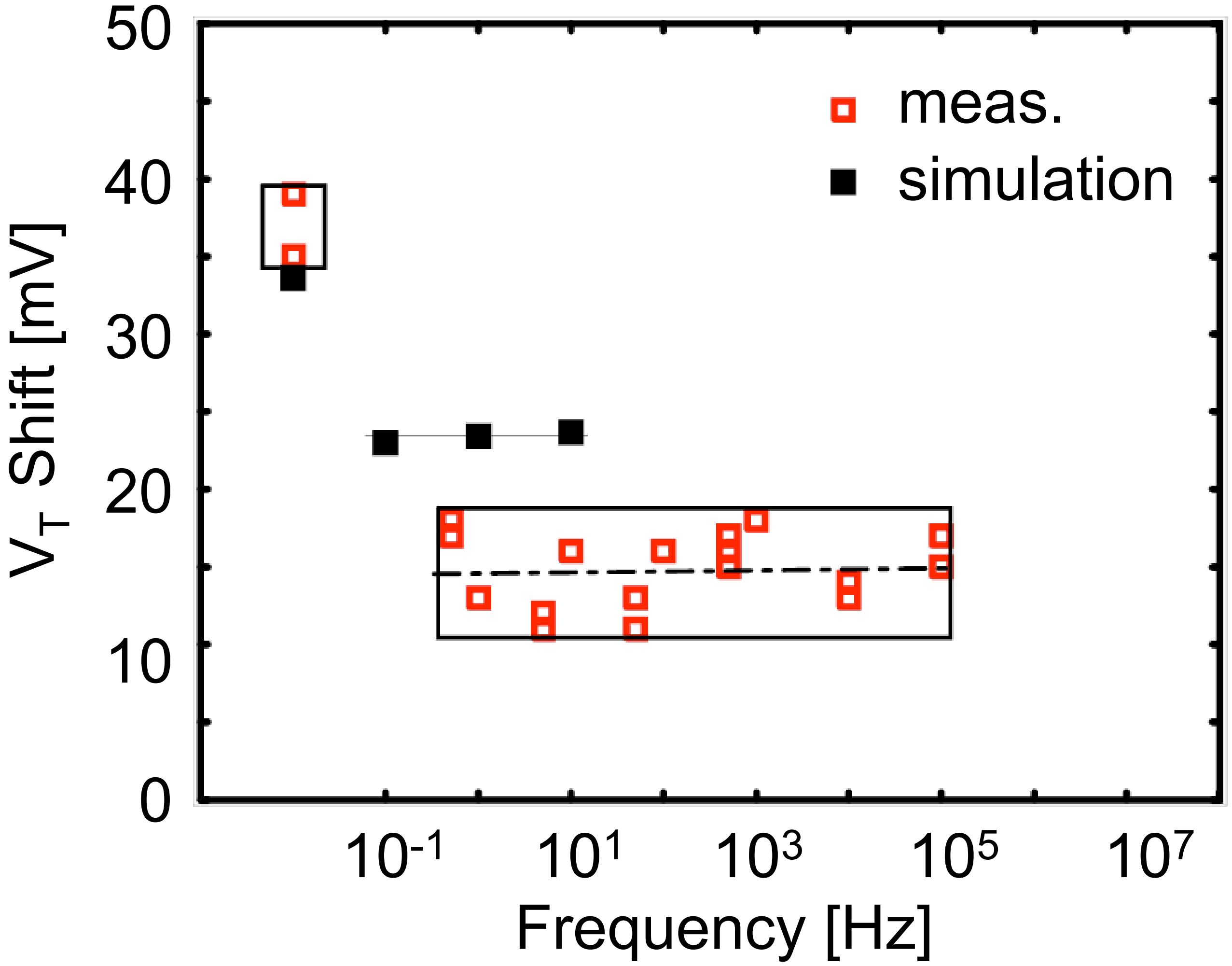
$$A N_{H0}^{2} + B N_{H0} + C = 0$$

$$N_{IT} = N_{IT}^{(0)}\left(1 - \sqrt{\frac{\xi x}{1+x}}\right) \qquad x \equiv \left(\frac{t}{\tau_0}\right)$$

Approximate Analytical Models

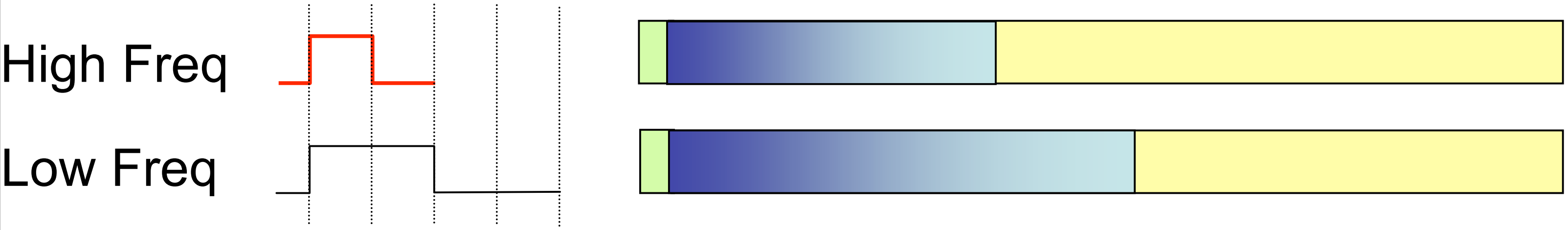


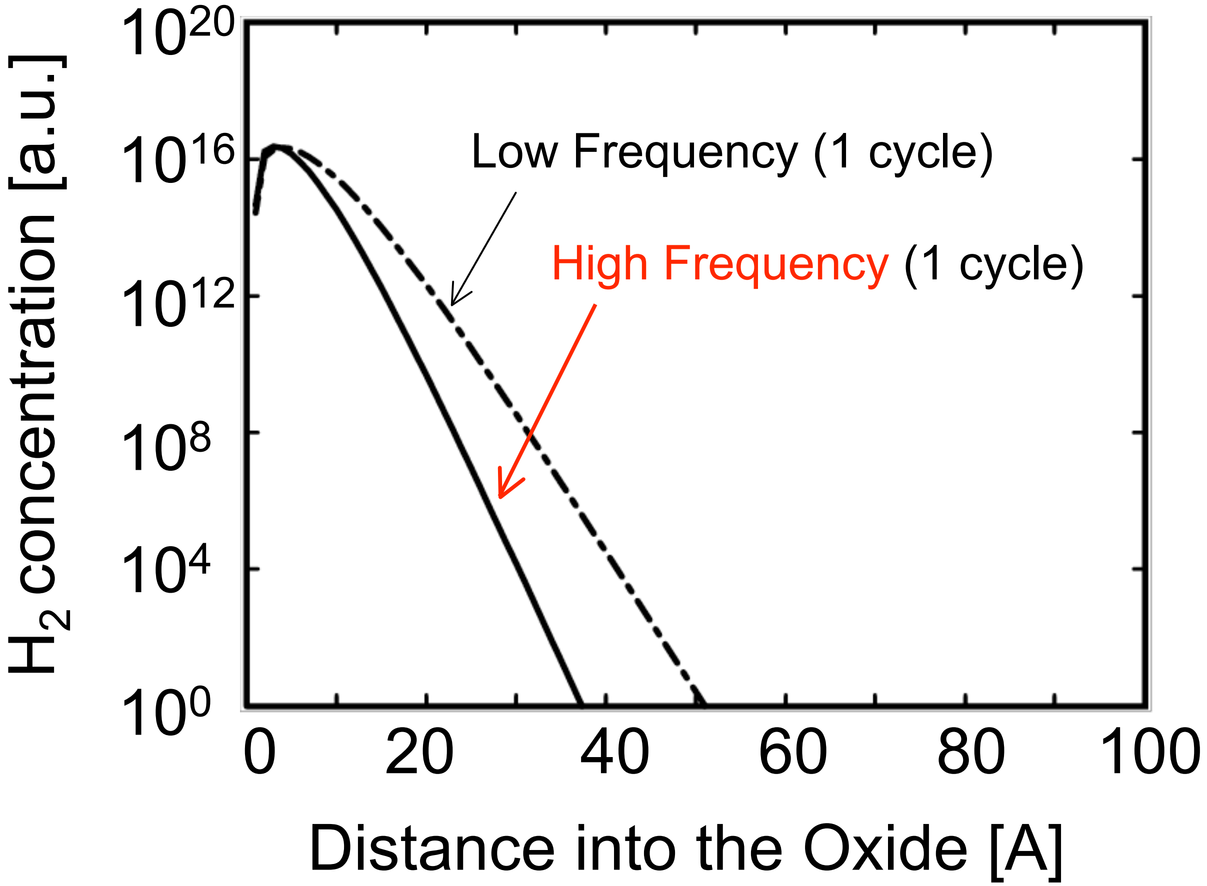
Frequency Dependence Interpreted



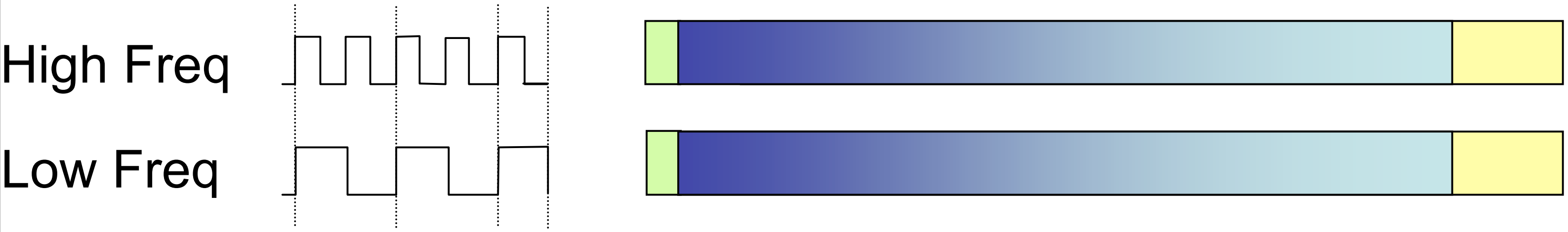
Symmetry in R-D model requires frequency-independent degradation

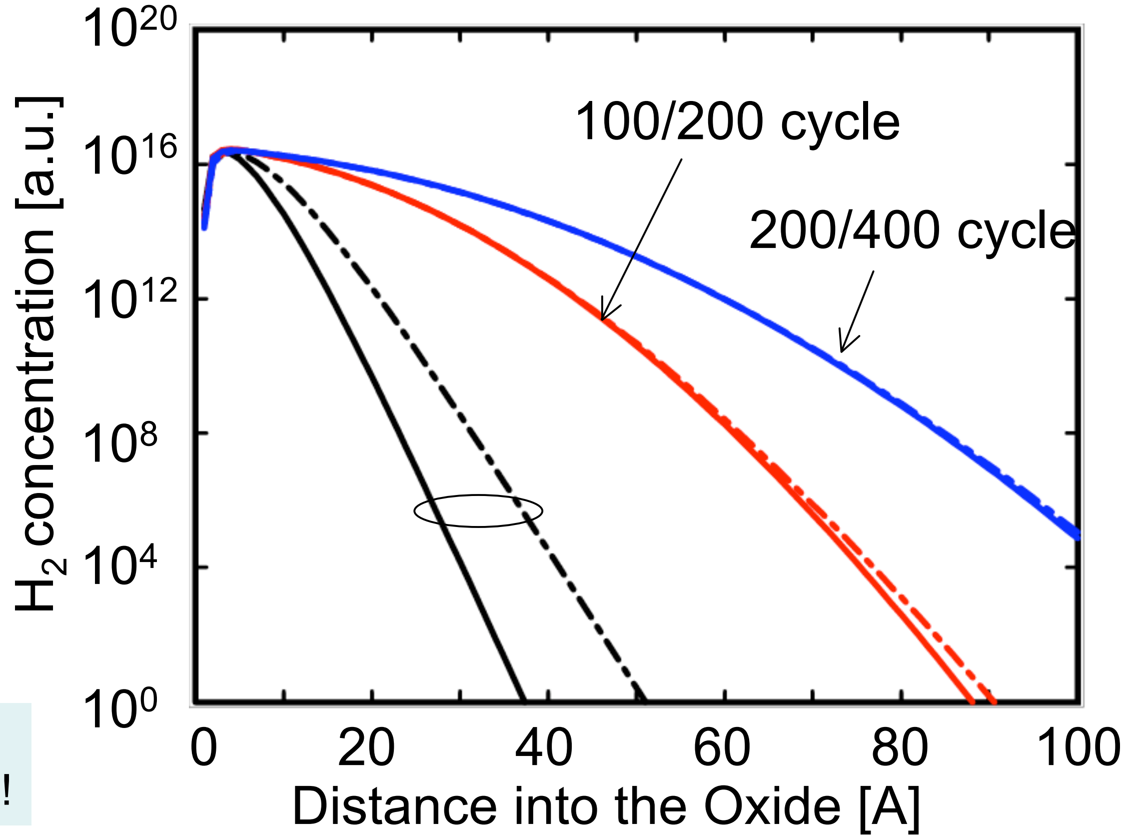
Frequency Independence Interpreted





Frequency Independence Interpreted

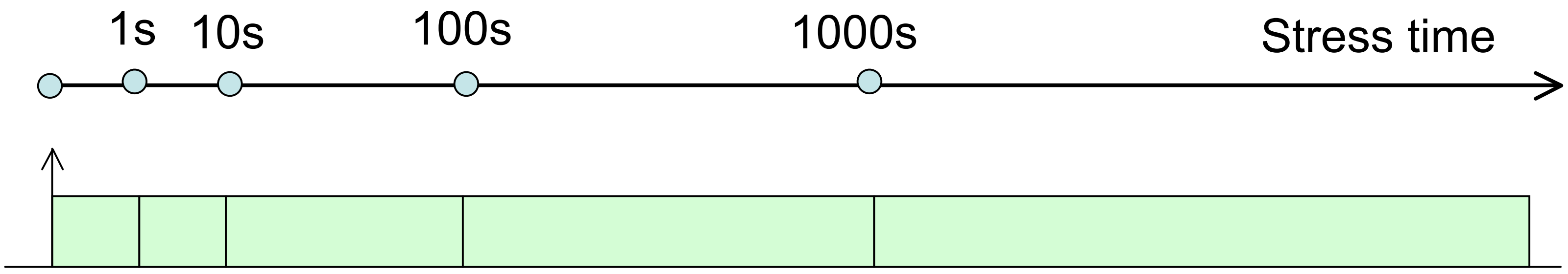




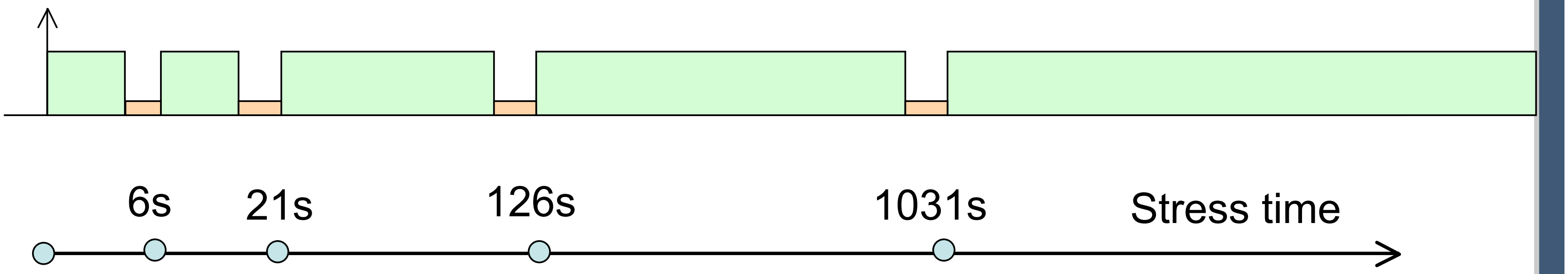
R-D model anticipates
Frequency Independence!

Measurement: A variable-*frequency* AC Stress!

What we thought we were doing …



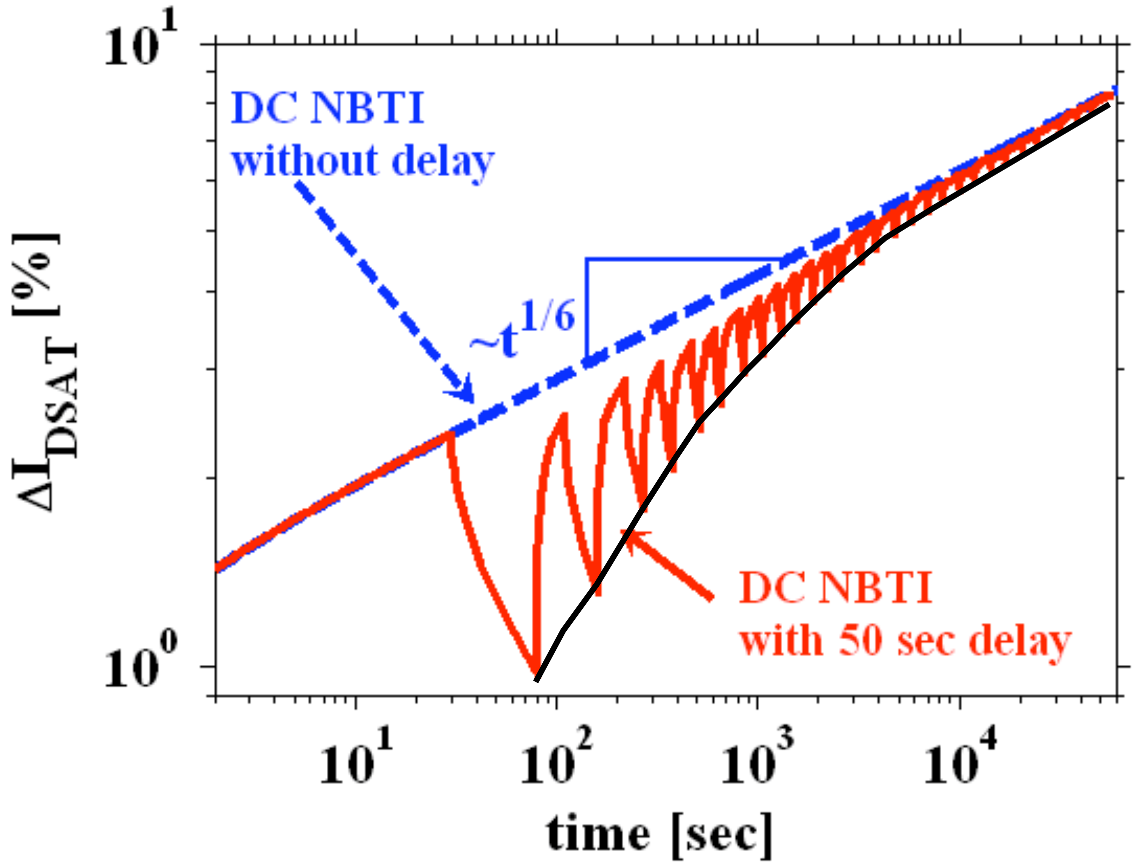
What we were actually doing …



* 5 sec. measurement window (for example).

S. Rangan, Intel, IEDM 2003.

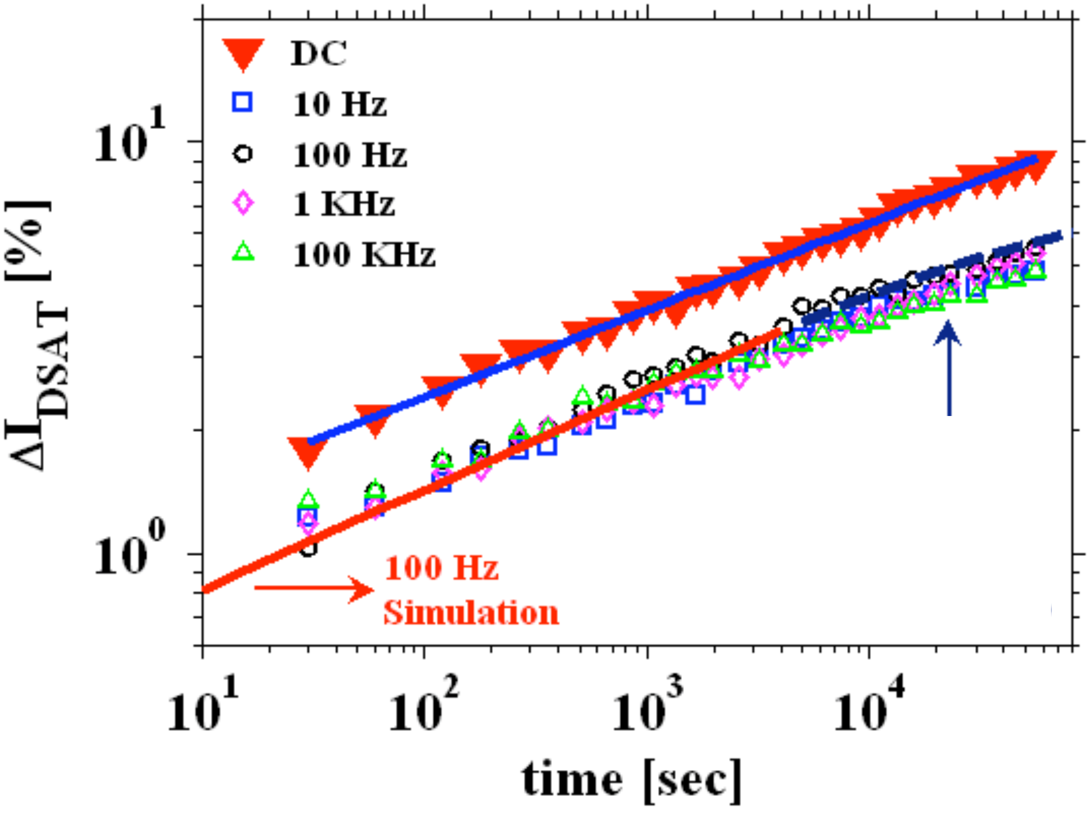
R-D Simulations for DC NBTI



H. Kuflouglu,
unpublished
results

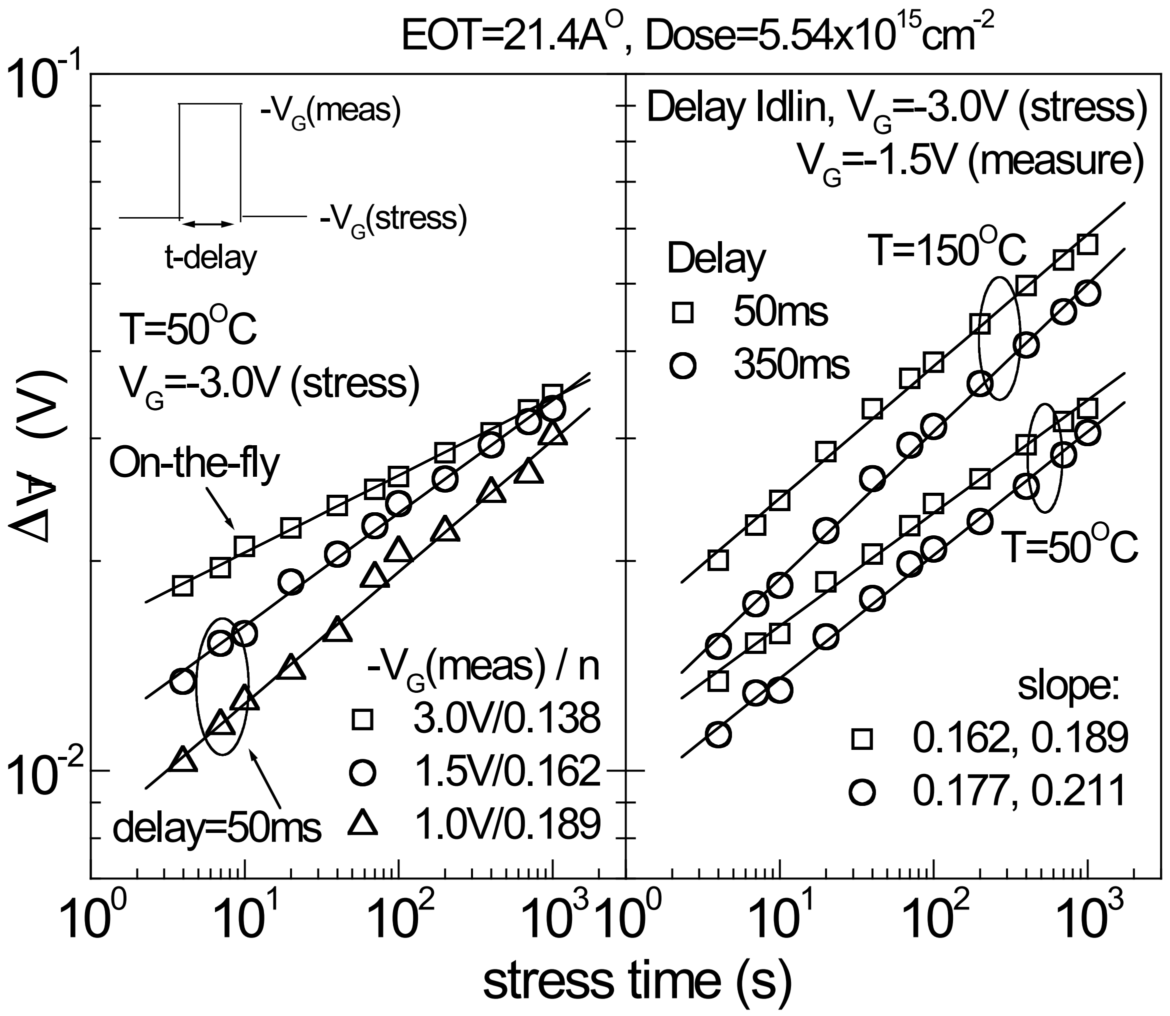
Actually, n=0.16 at all times (H2 diffusion), measurement delay makes it appear n=0.25 at short times. A 40 year old puzzle finally resolved!

AC NBTI: Sim. & Measurement



- Only DC simulations are fit to experimental data (V_G=2.1V).
- AC simulations are inherently related to DC results
- Delay of 6.3 sec is used

Conclusive Confirmation



D. Varghese,
IEDM 2005

Conclusions

- Reliability is, has been, and will be a key consideration for a viable technology.
- Over the last fifteen years, reliability engineering (a collection of pragmatic, empirical rules) have gradually evolved into reliability physics (grounded in sound understanding of underlying physics).
- In this talk we considered NBTI, similar physical models exist for Hot carrier degradation and Time dependent dielectric breakdown.
- The NBTI model provides proper prescription of extrapolating device lifetime. We will consider these extrapolation methods in a separate talk.
- Finally, do not underestimate the power of simple models. What we did in 4/5 lines of algebra, is actually equivalent to tens of PRB, JAP, TED, EDL papers over last 30 years.

Collaboration and References

Experiments: S. Mahapatra, S. Kumar, D. Saha, D. Varghese, IIT

[1] Mahapatra and Alam, IEDM 2002, p. 505.
[2] Mahapatra, Kumar, & Alam, IEDM 2003, p. 337.
[3] Mahapatra et al. IEDM 2004, p. 105.

Theory: M. Alam, H. Kufluoglu, Purdue University

[1] Alam, Weir, & Silverman, IWGI 2001, p. 10.
[2] Alam, IEDM 2003, p. 346.
[3] Kufluoglu & Alam, IEDM 2004, p. 113.

- For convenience, most of the figures of this talk are taken from these references. I will use other figures to illustrate difference in opinions or to generalize results.

Questions & Answers