2009 NCN@Purdue-Intel Summer School

Notes on Percolation and Reliability Theory

Lecture 10
Interface Damage and Negative Bias Temperature Instability

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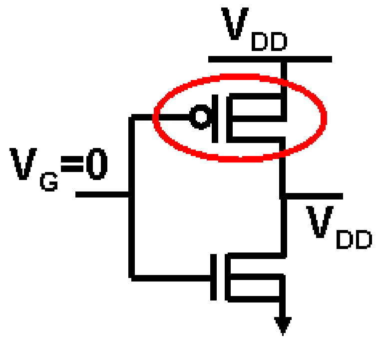
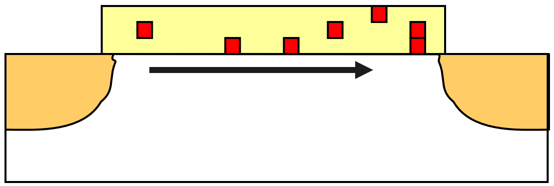
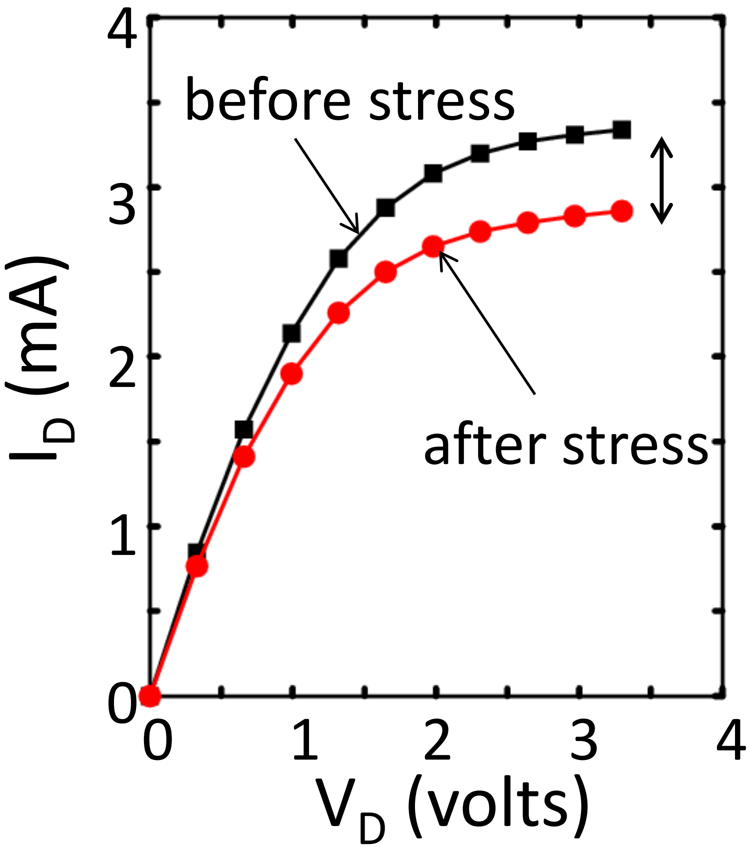
Outline of Lecture 10

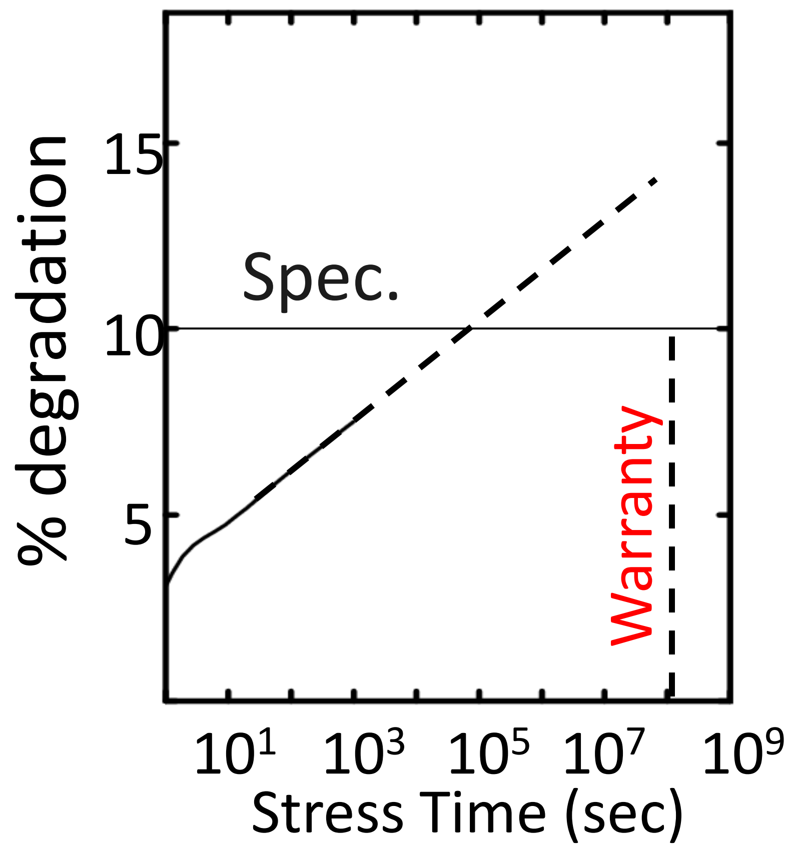
1) Background information
2) NBTI interpreted by R-D model
3) The act of measurement and observed quantity
4) NBTI vs. Light-induced Degradation
5) Possibility of Degradation-free Transistors
6) Conclusions

Negative Bias Temperature Instability









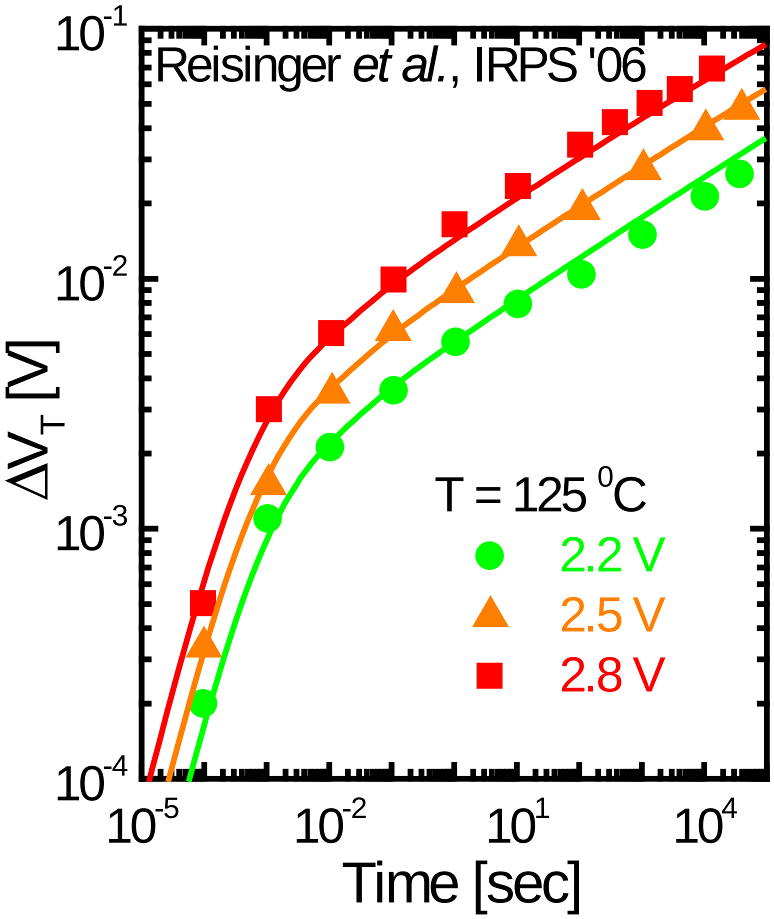
Characteristics of NBTI Degradation

$$I_D(t) \propto \mu \times \left[V_G - V_T(t) \right]$$

$$V_T(t) = V_T(t=0) + \Delta V_T(t)$$

$$\Delta V_T = A e^{-Ea/k_B T} t^n$$

- n ~ 0.16
- Ea ~ 0.5 eV
- A depends on E_{ox}



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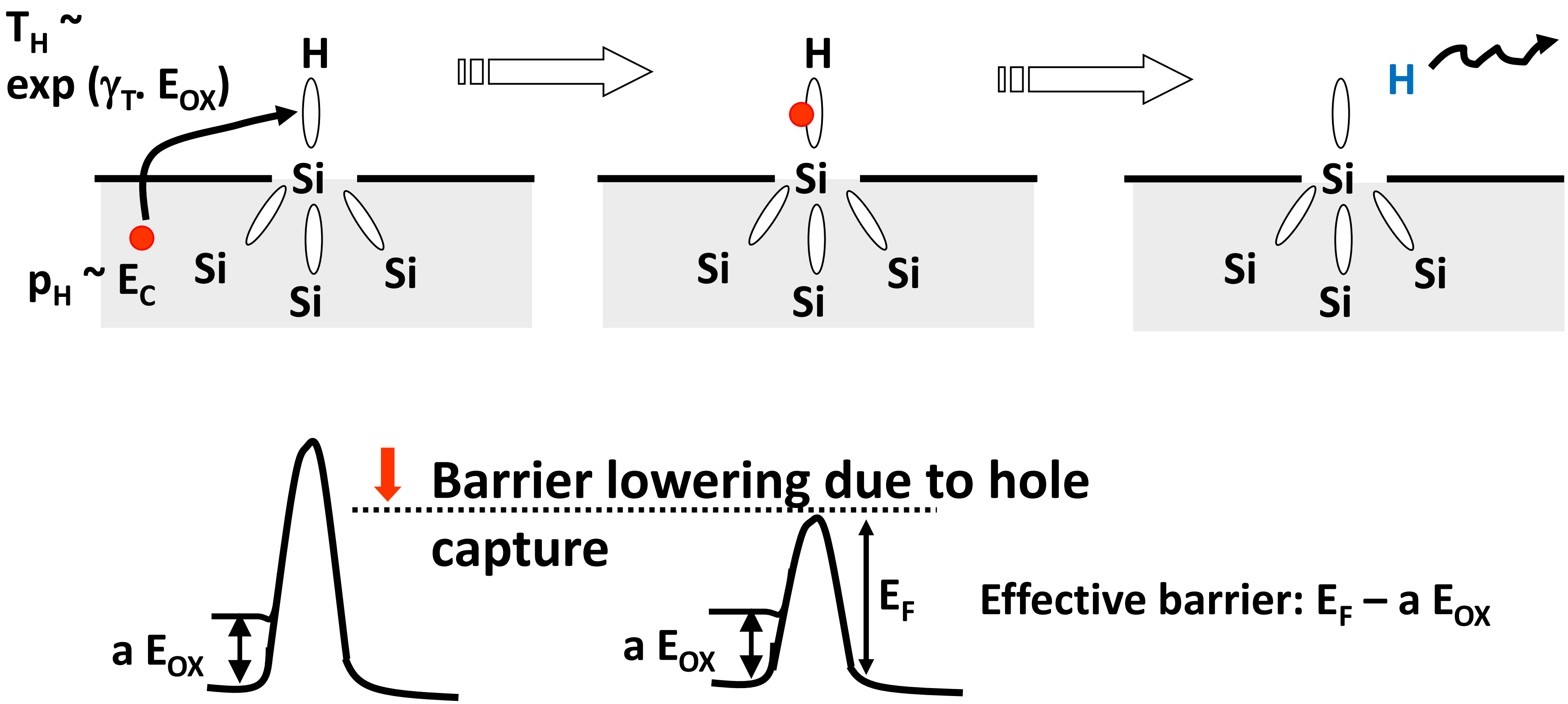
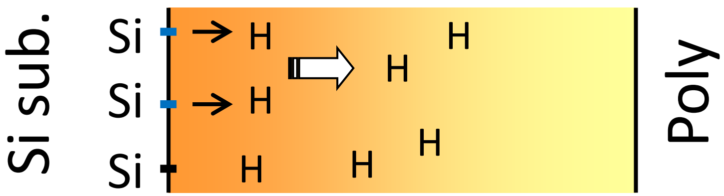
Basics of NBTI Model



Si-H + h^+ → Si-H^+ → Si^+ + H

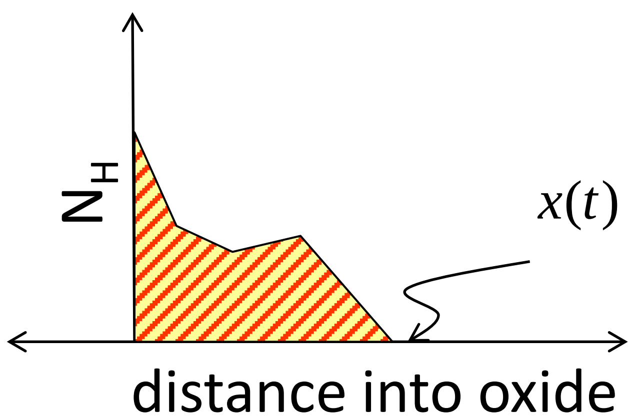
The Reaction-Diffusion Model



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

If dN$_{it}$/dt is small, & $N_{IT} < N_0$,

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



$$\frac{dN_{IT}}{dt} = D_H \frac{d^2 N_H}{dx^2}$$

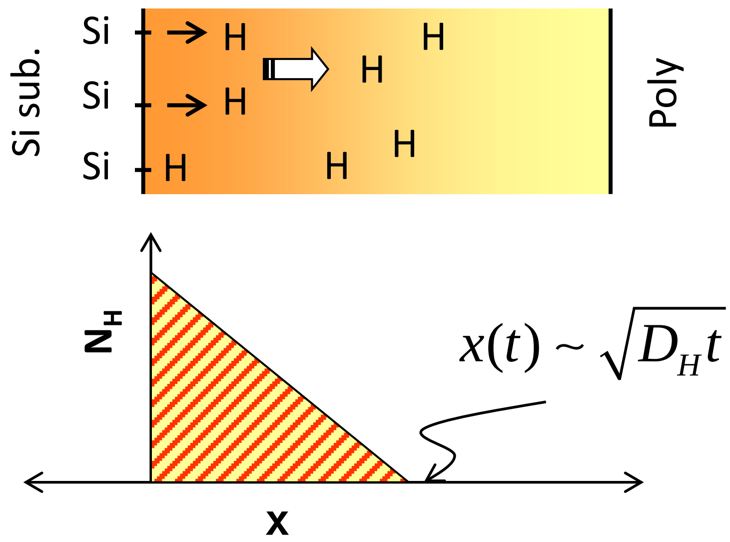
$$N_{IT}(t) = \int_{x=0}^{x(t)=f(D_H,\mu_H,t)} N_H(x,t)dx$$

Interface traps with diffusion of atomic H

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

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

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



Combining these two, we get

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

Jeppson, JAP, 1977.

simple differential equation gives rise to power-law !

Interface traps with H_2 diffusion

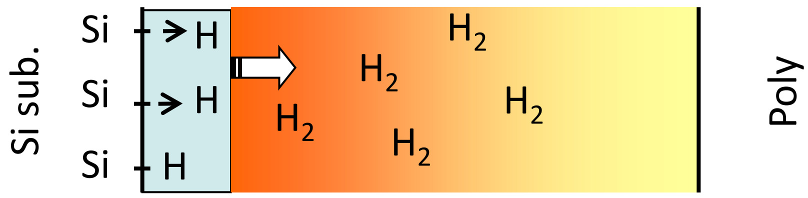
$$\left(\frac{k_F N_0}{k_R}\right) \approx N_H(0) N_{IT}$$

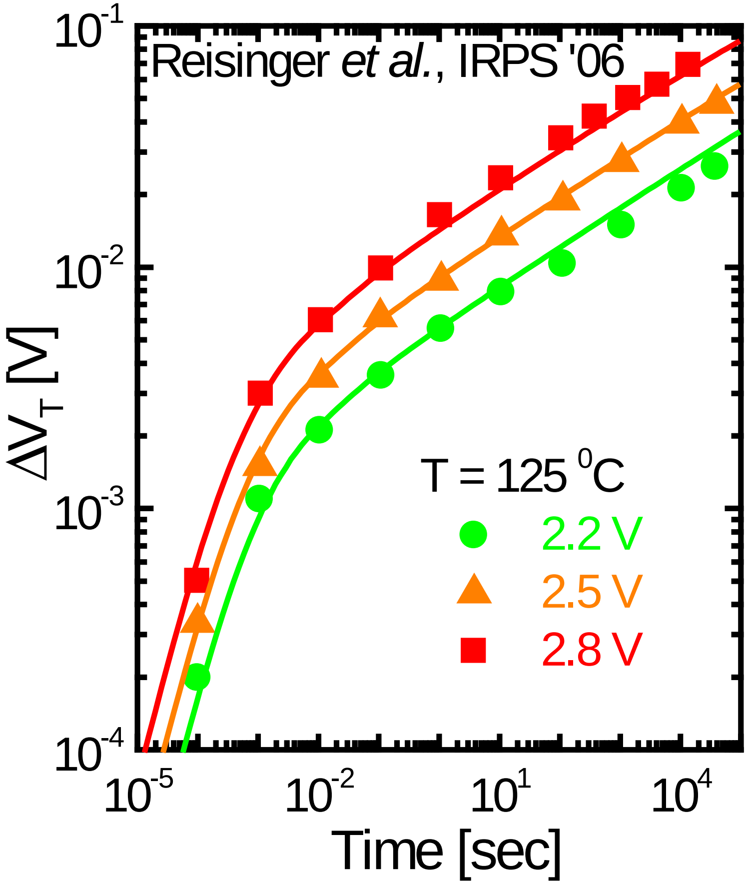
$$N_{IT}(t) = \frac{1}{2} N_{H_2}(0)\sqrt{D_{H_2} t}$$

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

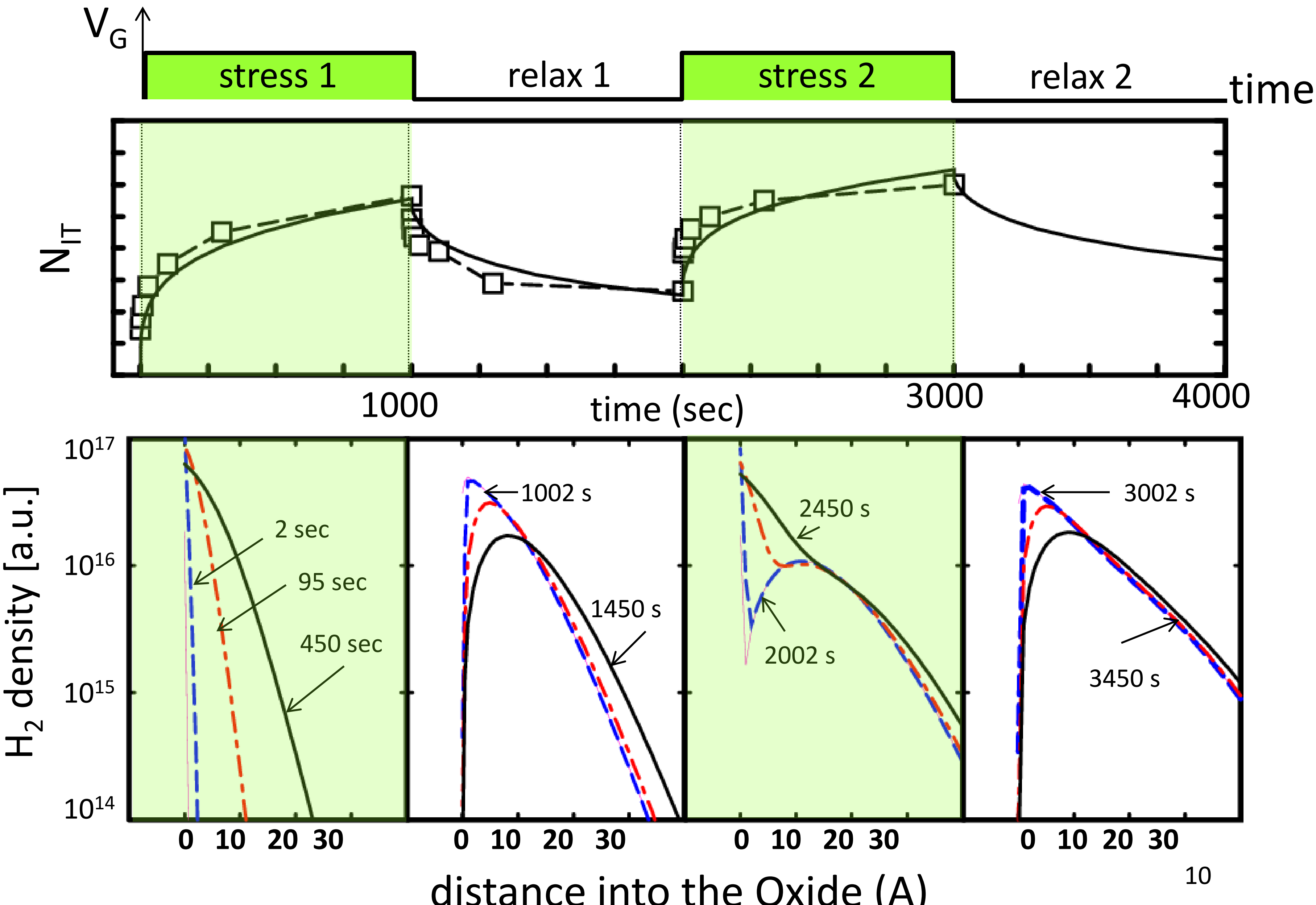
Combining the three, we get

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





Self-healing at AC stress

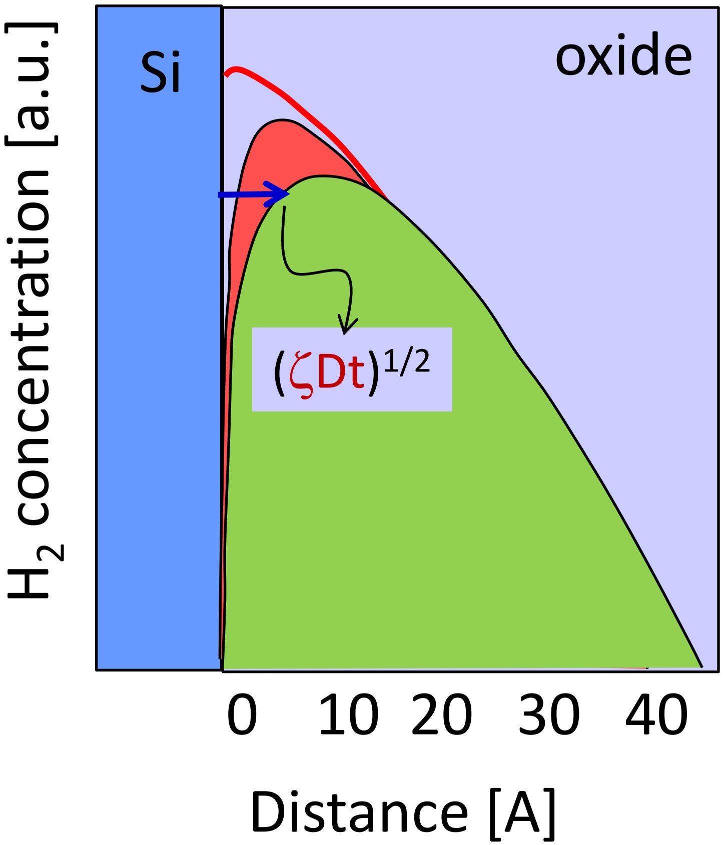


Alam, IEDM 2003

NBTI relaxation

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

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



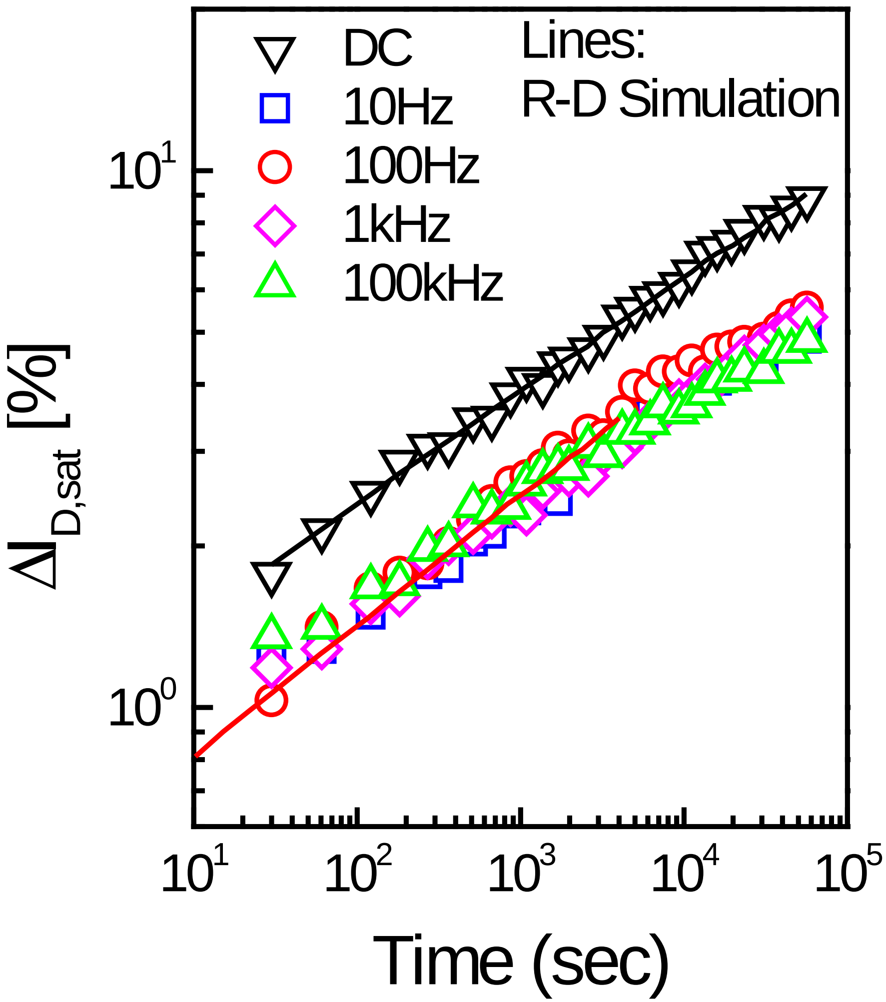
$$\frac{dN_{IT}}{dt} = k_F (N_0 - N_{IT}) - k_R N_H(0) N_{IT}$$

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

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

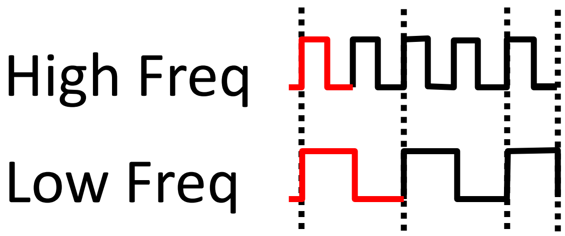
$$N_{IT} = N_{IT}^{(0)} \left(1 - \sqrt{\frac{\xi t / \tau_0}{1 + t/\tau_0}} \right)$$

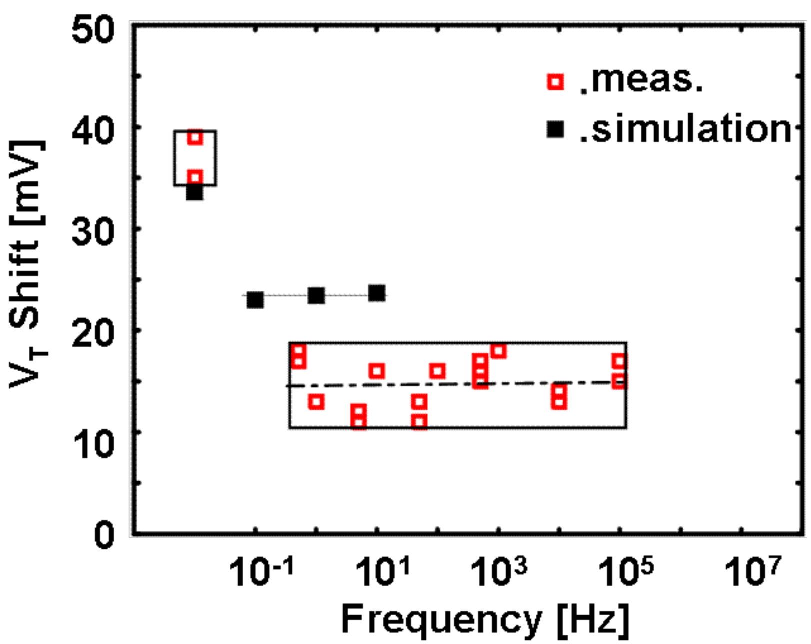
Frequency independent degradation

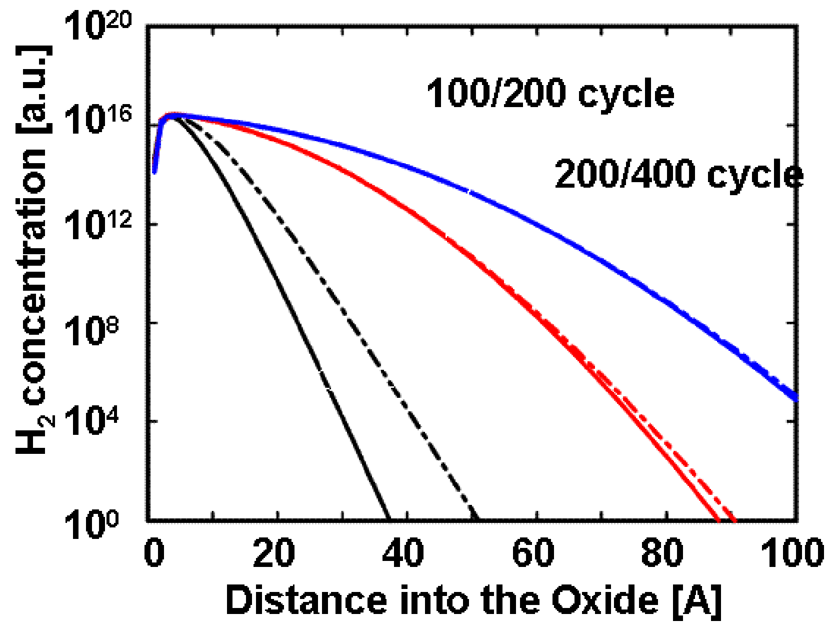


- Both AC and DC NBTI degradation show same time characteristics.
- Experiments show that frequency independence holds till at least 2 GHz

NBTI model for frequency independence







Smaller duty cycle reduces V_T shift …

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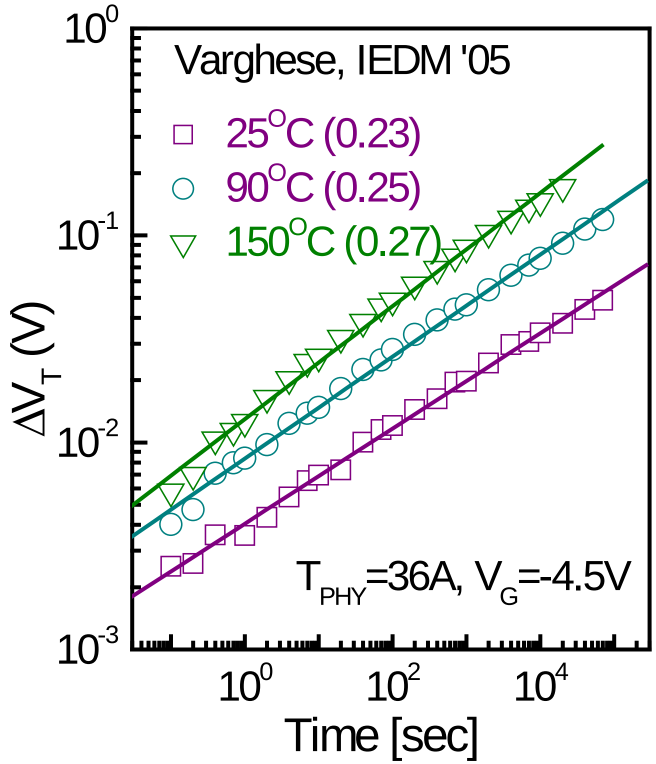
An enduring puzzle

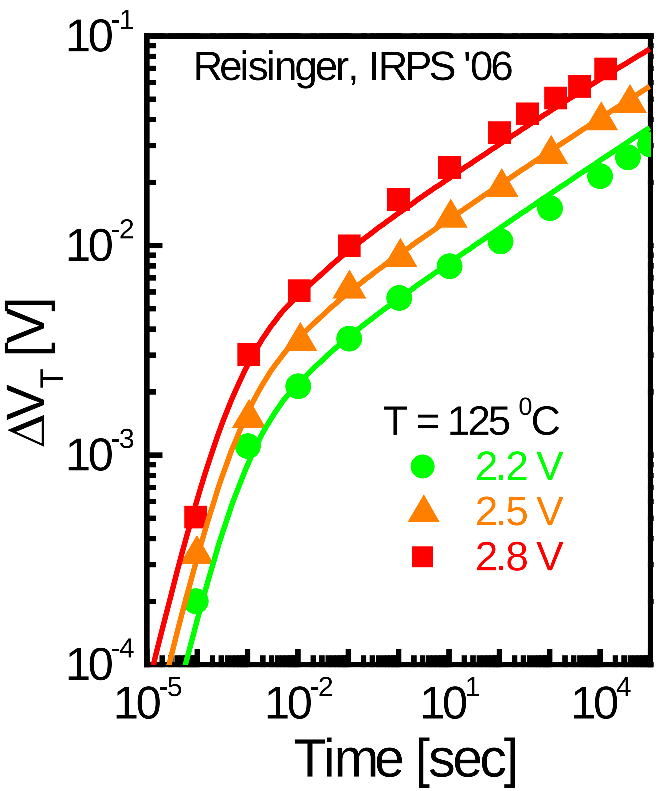
Classical measurement

$$\Delta V_T = A_1 t^{1/4}$$



Modern On-the-fly meas.

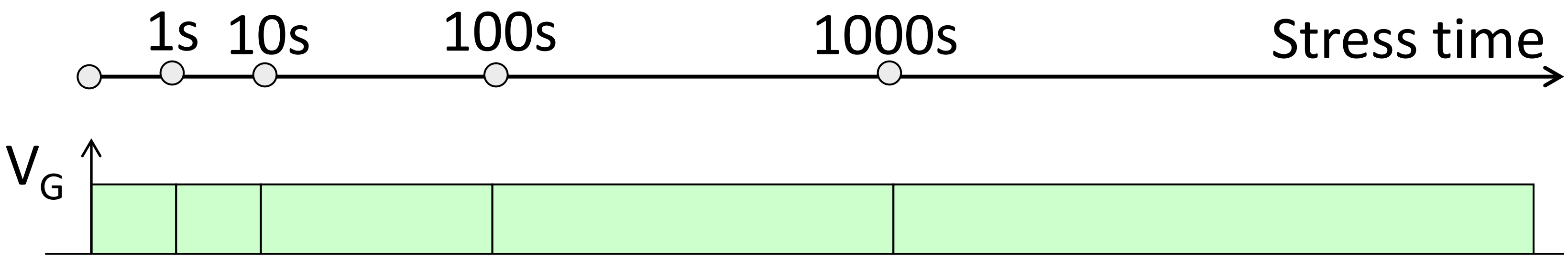
$$\Delta V_T = A_2 t^{1/6}$$



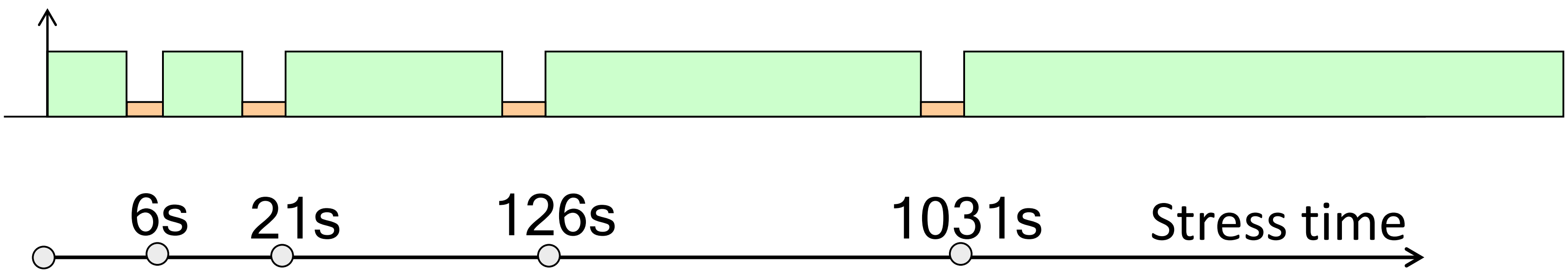
Two different ways of measurement give two different results !

Measurement changes the NBTI degradation

What we **think** we do during measurement …



What we **actually** do during measurement …

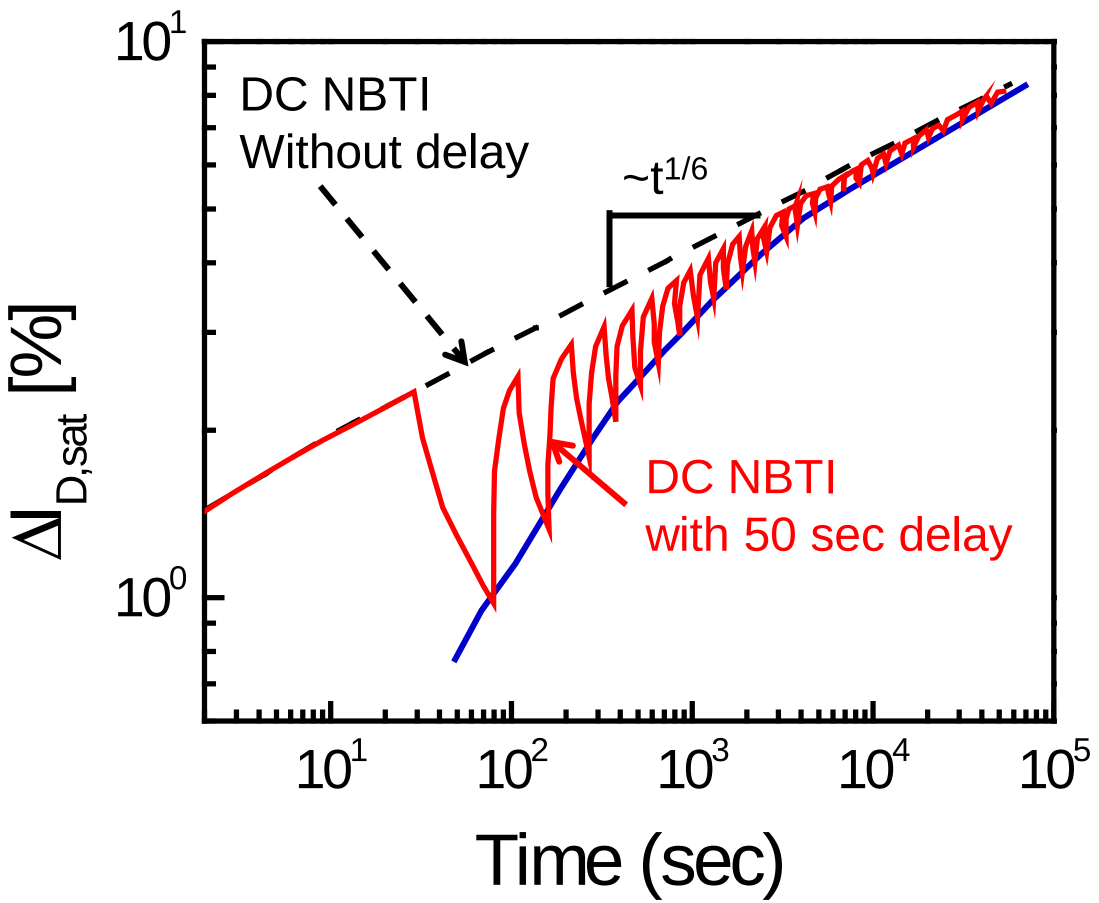


* 5 sec. measurement window (for example).

S. Rangan, Intel, IEDM 2003.

Measurement is like a variable frequency AC stress ….

More measurement & less (!) accuracy



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 !

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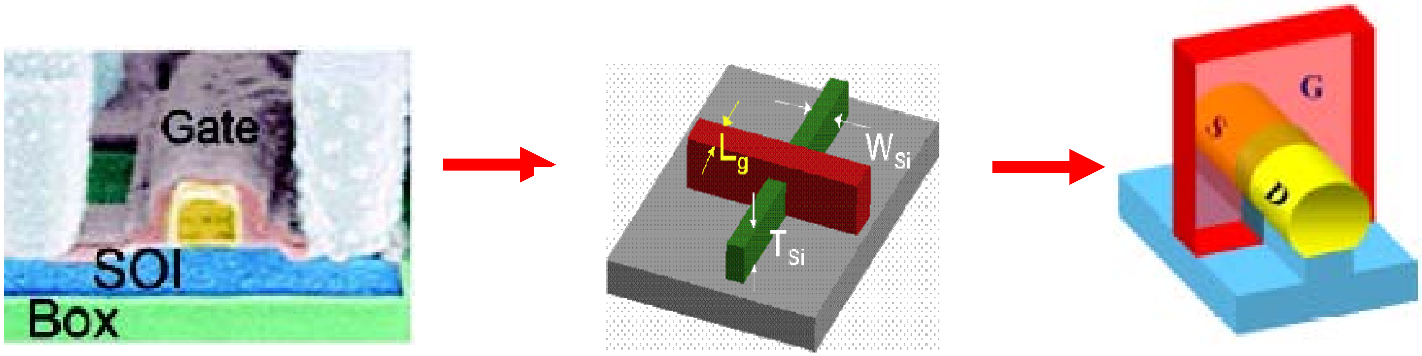
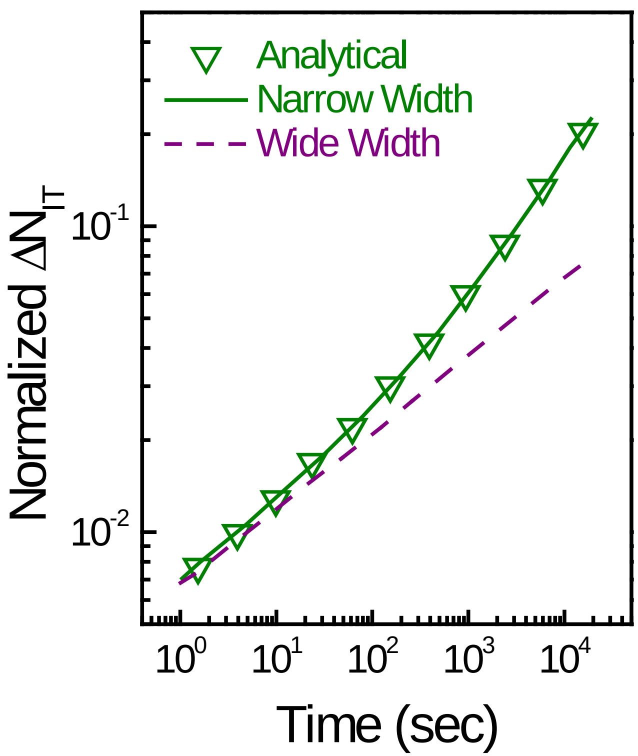
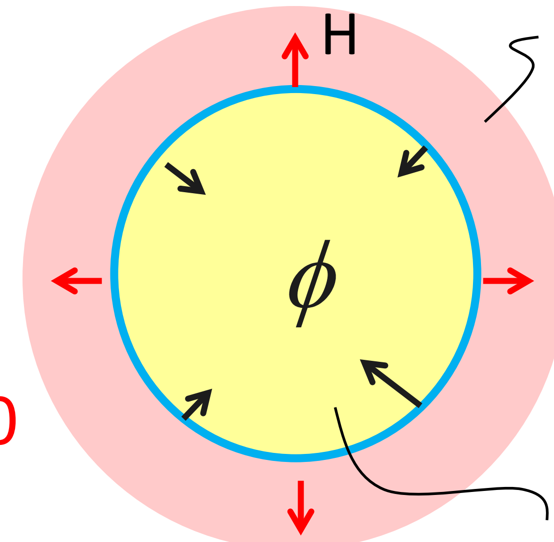
Non planar devices





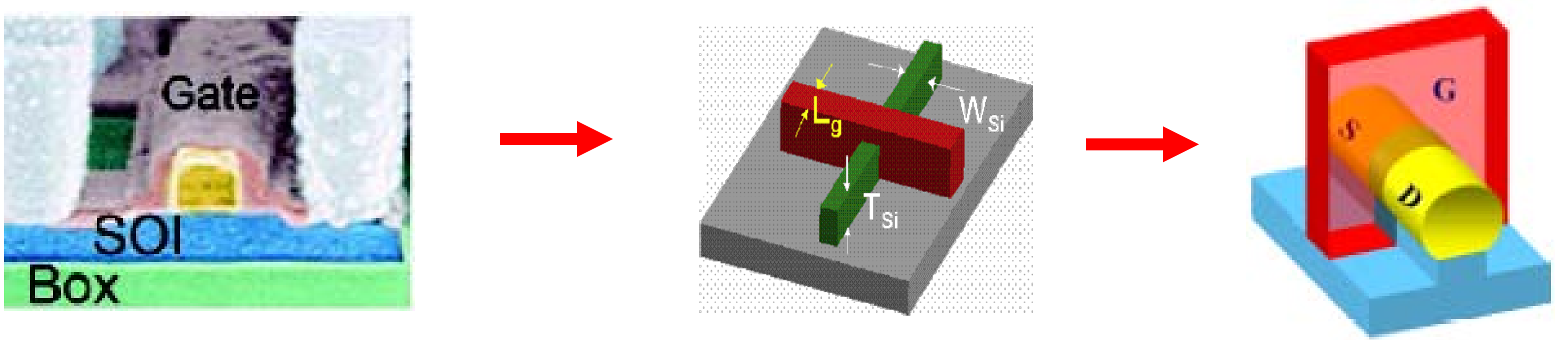
$$\varepsilon \nabla^2 \phi = 0$$

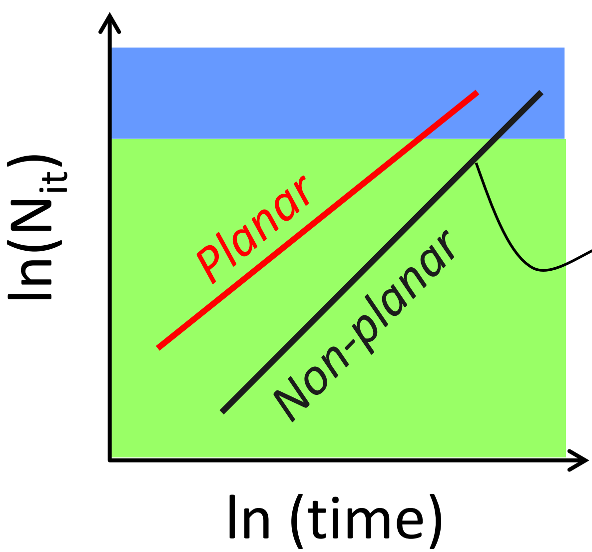
$$D_H \nabla^2 N_H = 0$$



Reliability theory anticipates performance-degradation trade-off.

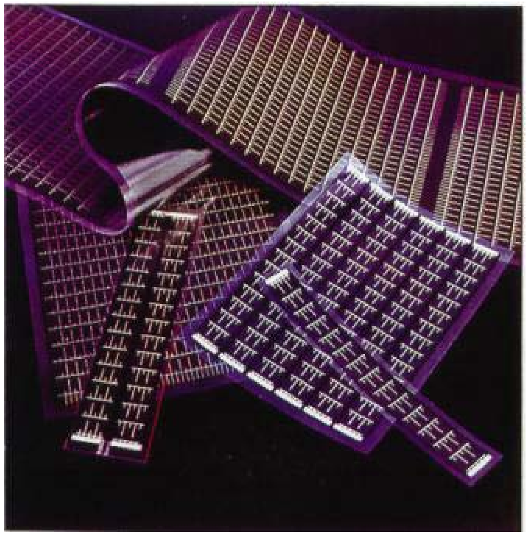
Performance and reliability

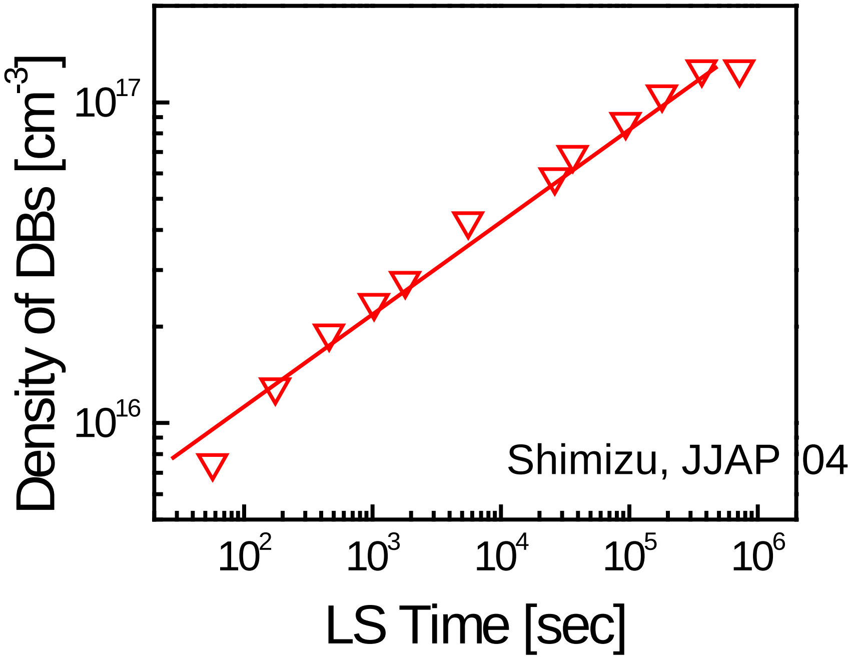




Higher slope, but lower degradation at lower operating voltage

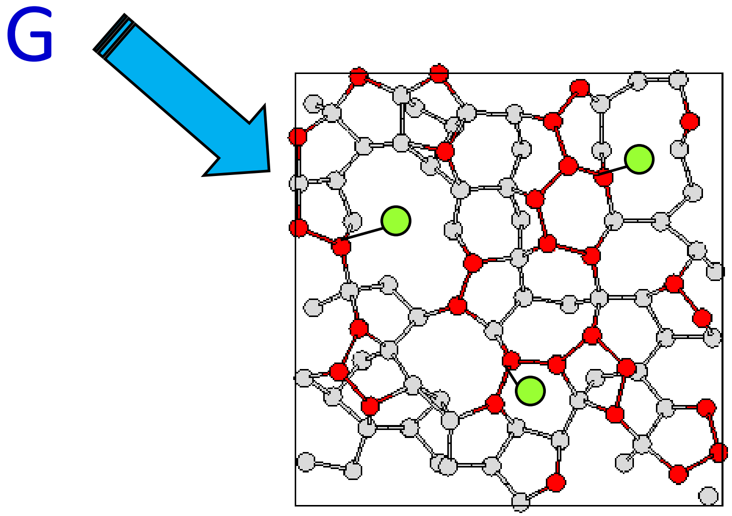
Light-induced degradation in solar cells



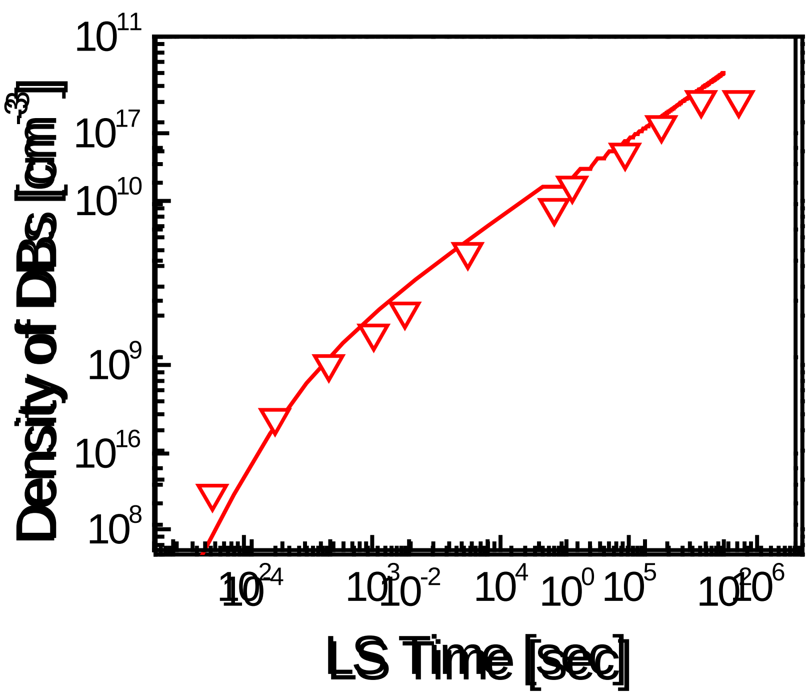


Light induced degradation has a time exponent of n=1/3

Reaction-diffusion model for LID



3-fold coordinated
Surface atoms of a-Si.
Green – H
Red – surface Si
White -- Bulk



Reaction:

$$\frac{dN_{DB}}{dt} = k_F N_0 G - k_R N_{DB} N_H \quad \sim 0$$

Free H Generation:

$$\frac{dN_H}{dt} = \frac{dN_{DB}}{dt} - k_H N_H^2$$

$$N_{DB} \propto (3k_H)^{1/3} \left(\frac{k_f N_0 G}{k_r} \right)^{2/3} t^{1/3}$$

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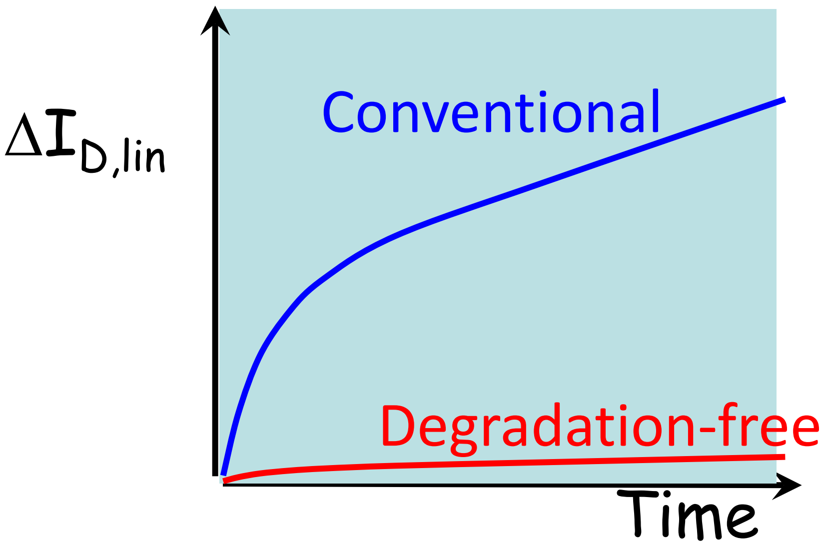
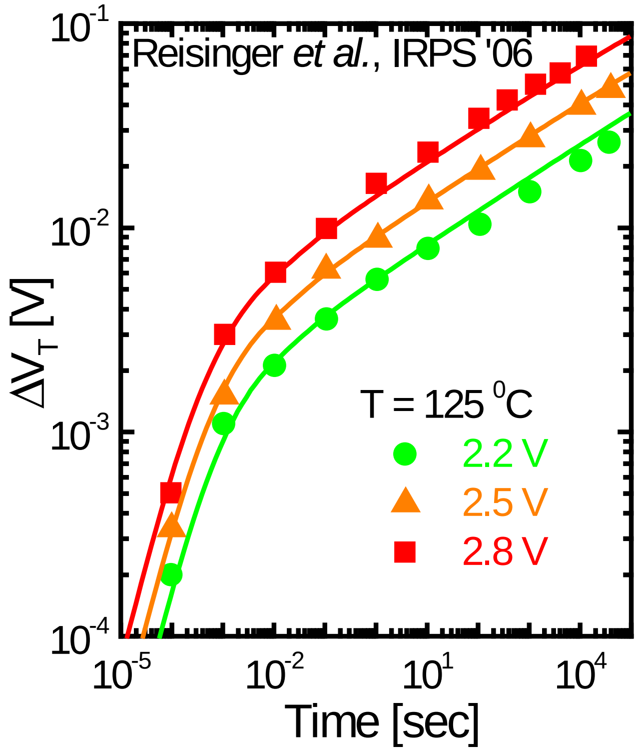
NBTI-aware logic and degradation-free transistors (A. E. Islam)

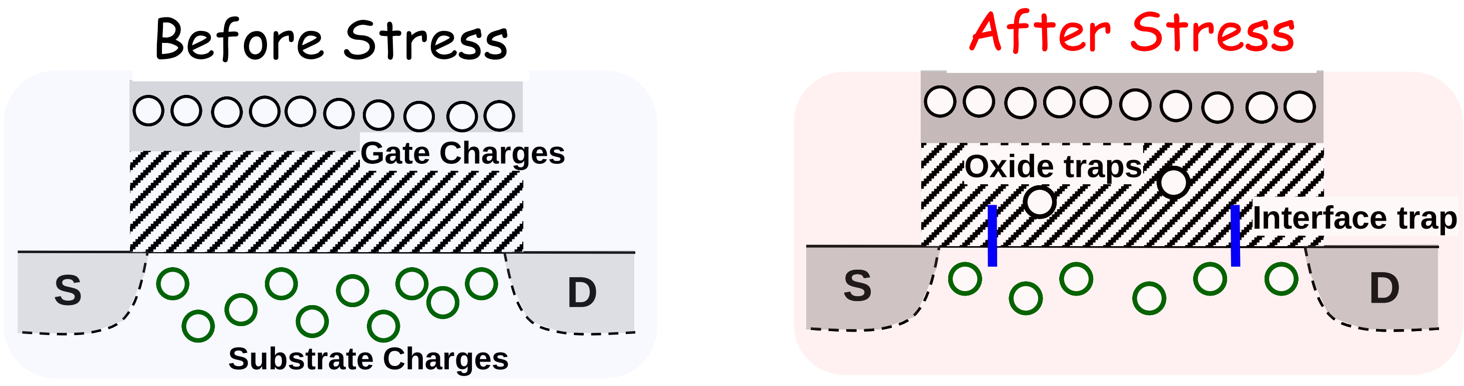
$$-\frac{\Delta I_D}{I_{D0}} = \frac{\Delta \mu_{eff}}{\mu_{eff0}} - \frac{\Delta V_T}{V_G - V_{T0}} \qquad I_D = A\,\mu_{eff}\left(V_G - V_T\right)$$

If we could make $\Delta\mu$ positive …

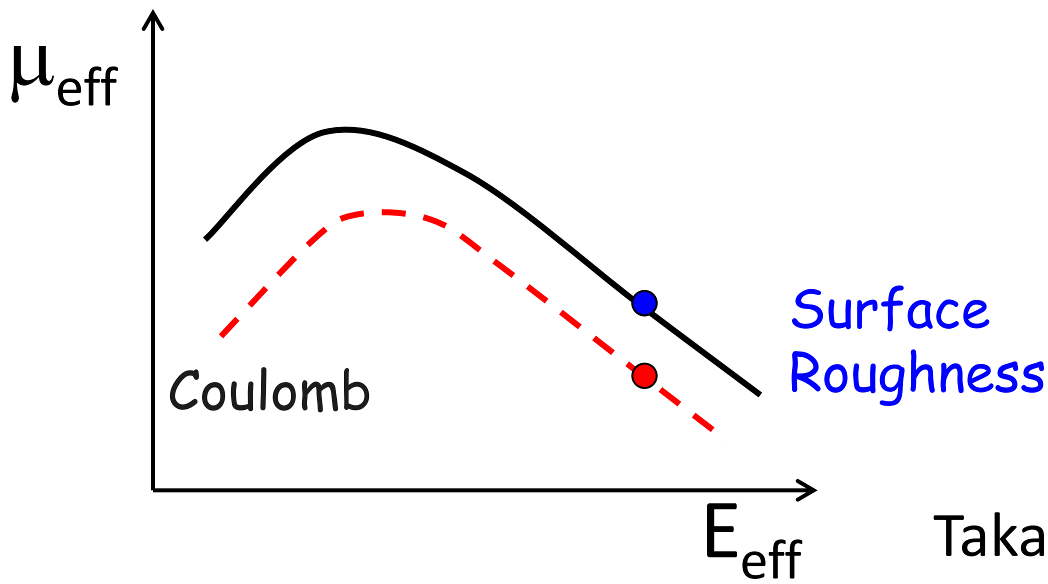




Mobility and VT-shift



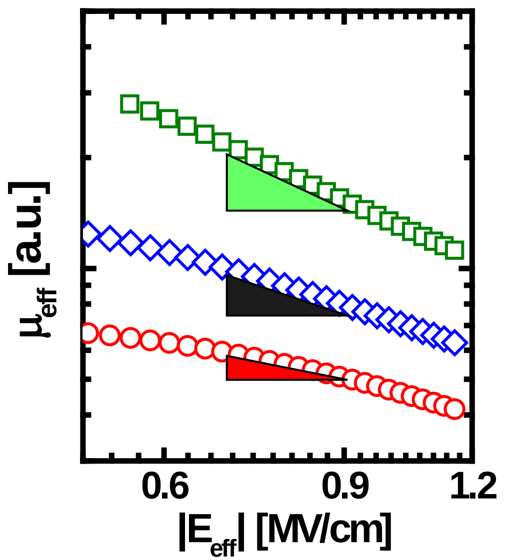
$$E_{eff} = Q_{dep} + \eta Q_{inv} \sim (V_G - V_T)$$

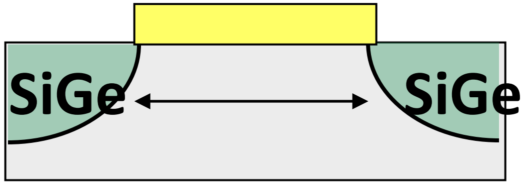


Takagi, T-ED '94

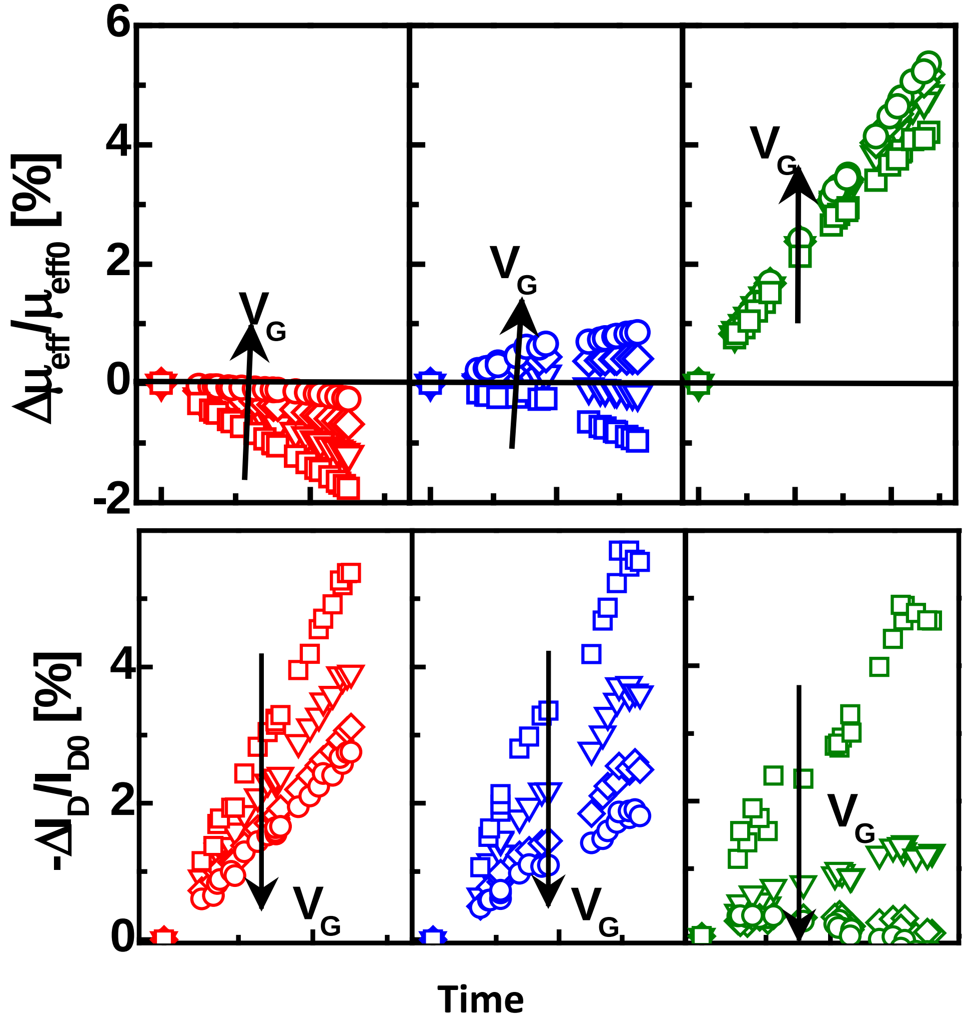
Degradation-free logic transistors ...

$$-\frac{\Delta I_D}{I_{D0}} = \frac{\Delta \mu_{eff}}{\mu_{eff0}} - \frac{\Delta V_T}{V_G - V_{T0}}$$



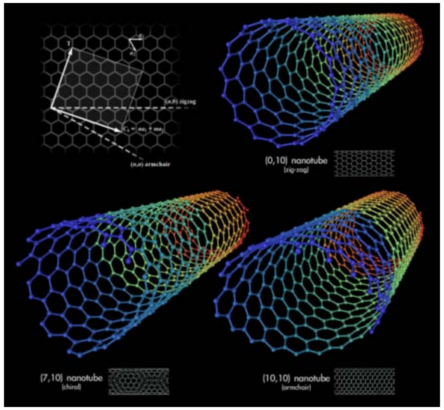


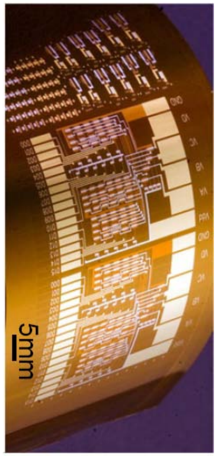
By strain engineering!

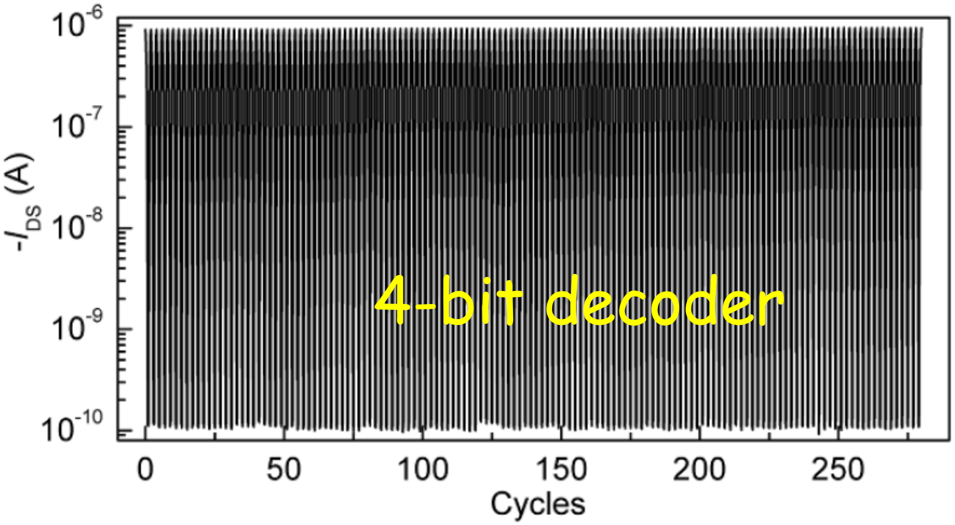


Steep μ_{eff} vs. E_{eff} → Negligible ΔI_D

Implications for CNT-based TFT reliability







Hydrogen-free interfaces may have no interface traps …

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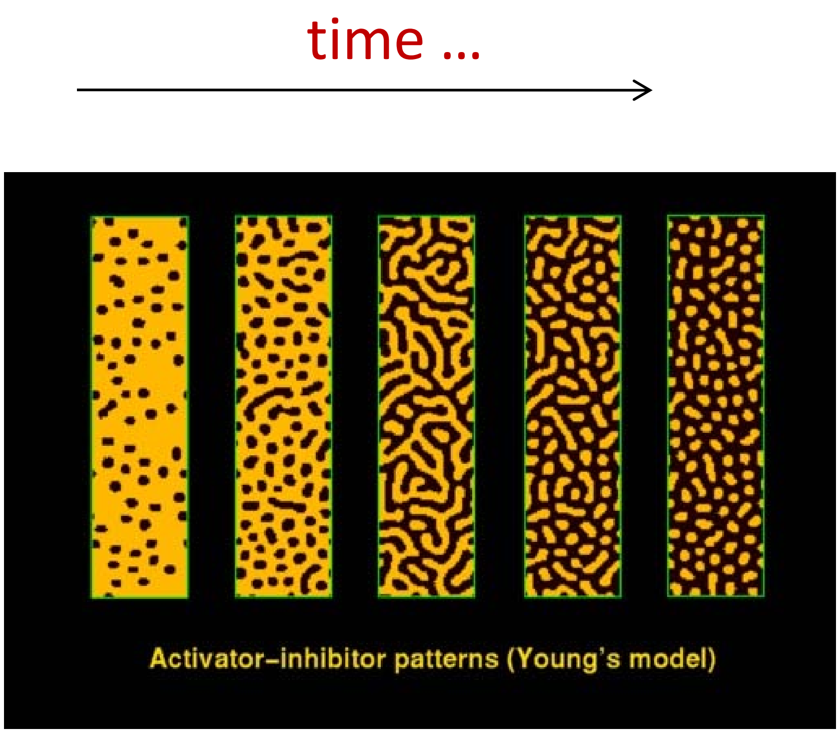
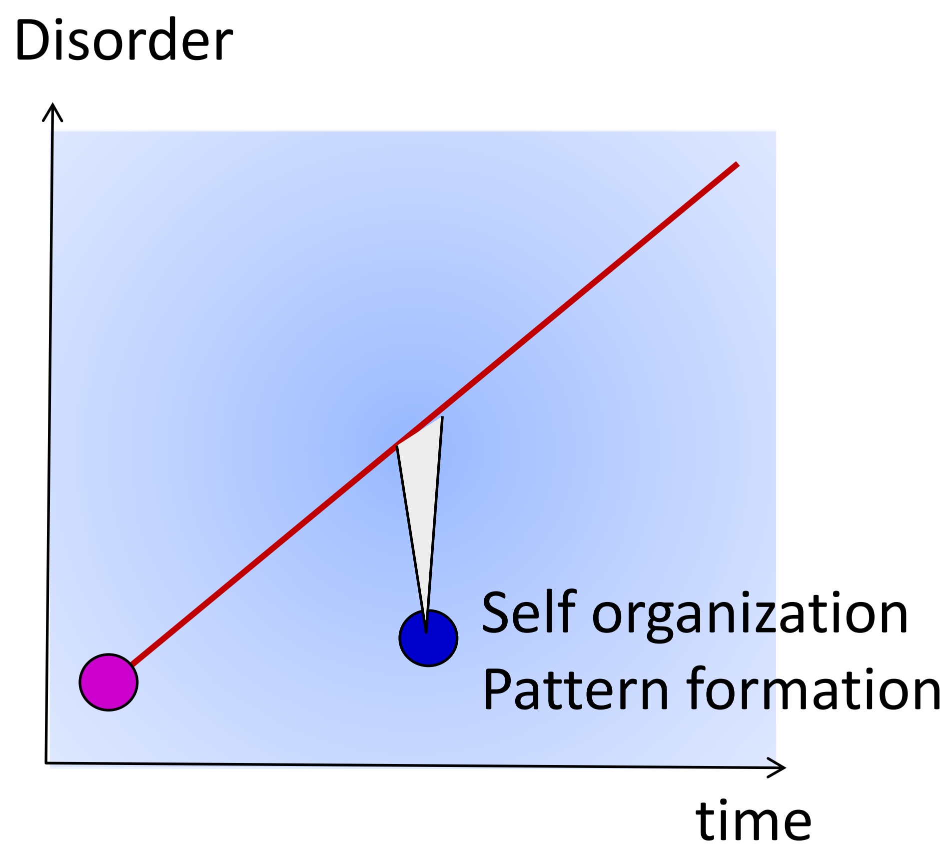
The power of reaction-diffusion model



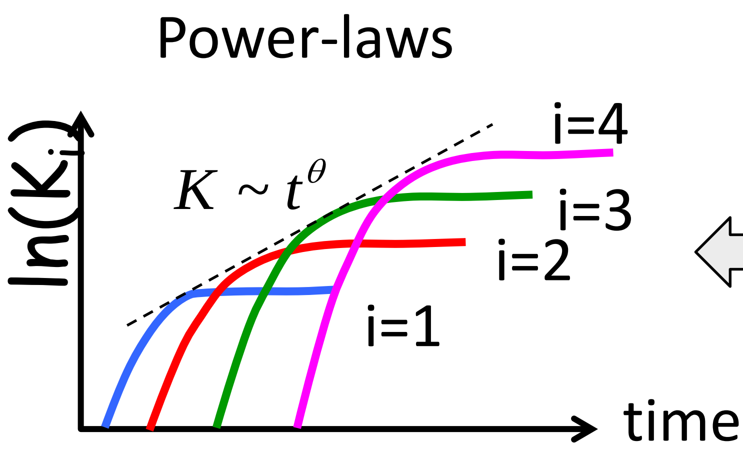
Turing's model of Morphogenesis, 1953.

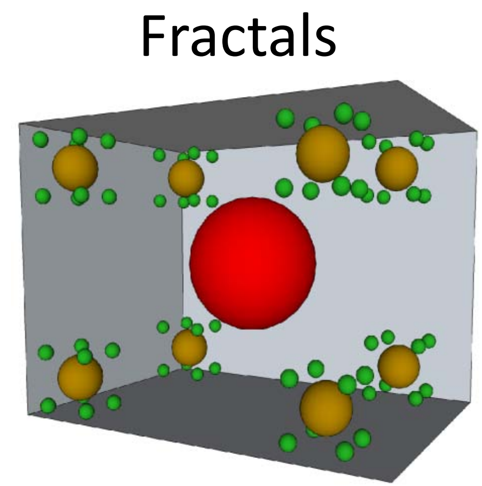


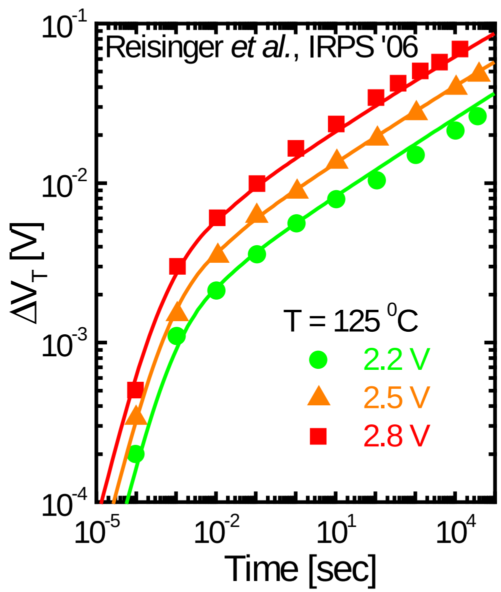
Prigogine, "From being to becoming", 1980.

Reaction-diffusion model produces complex structures out of homogenous systems

Power laws, fractals, SPICE models







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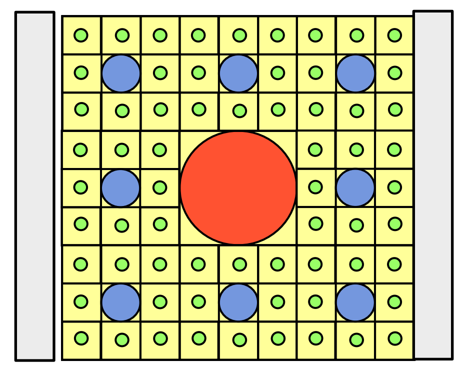


$$I_T = f(V_D, V_G) \times \xi\left(\frac{L_C}{L_S}, D_C {L_S}^2\right)$$

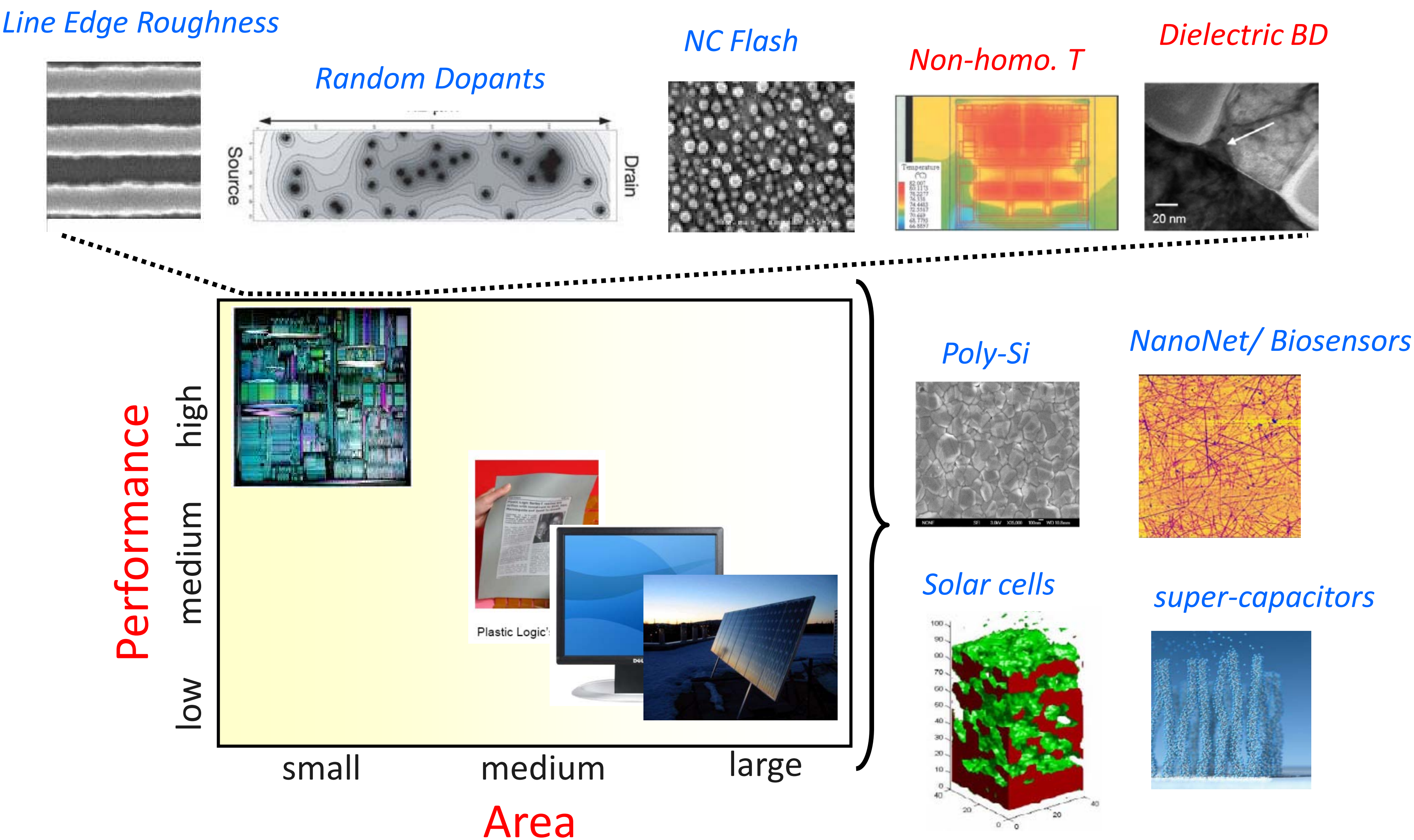
A classical device may become fractal over a period of time …

Conclusions

- NBTI has been one of the most important reliability challenge since the very inception of CMOS.
- The very strange properties of NBTI involving power-law time exponent, relaxation, frequency independence arise from the peculiar properties of reaction-diffusion models.
- Initially presumed different, NBTI in PMOS transistors and LID in a-Si solar cells appear to arise from the same physical phenomena.
- It is possible to design a degradation free transistors. Degradation-free does not mean defect-free devices.
- Finally, reaction-diffusion model appears to self-organize ordered surfaces. If this is also true for NBTI, the entire literature of NBTI spice model will have to be revisited.

epilogue

Disorder and Ohm's law



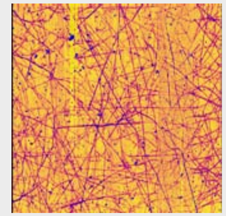
$$G \propto \frac{\tau}{m^*} \frac{1}{L}$$

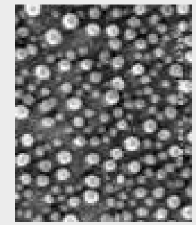
Does not mean what it used to ...

Theory and Application

Nonlinear

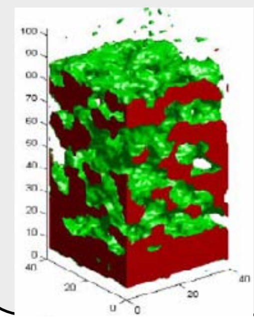
Percolation

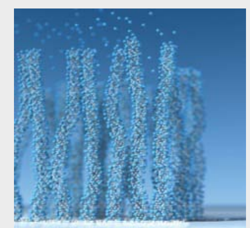




Finite

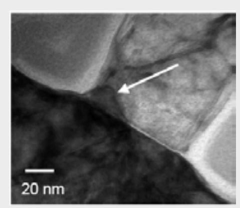
Fractals





Correlated

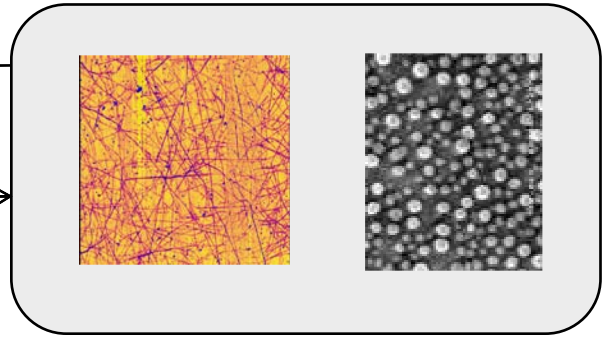
Temporal Percolation

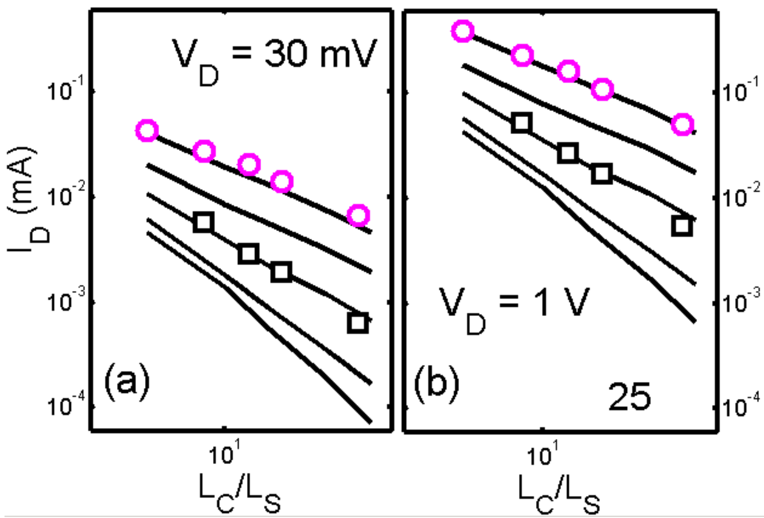


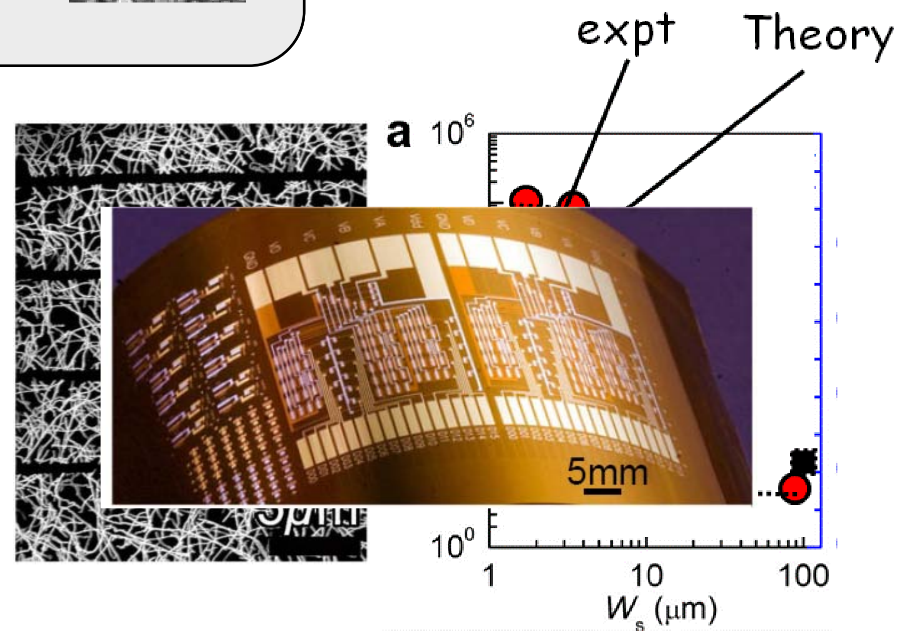
Nonlinear Stick Percolation for Electronic Devices

Nonlinear

Percolation







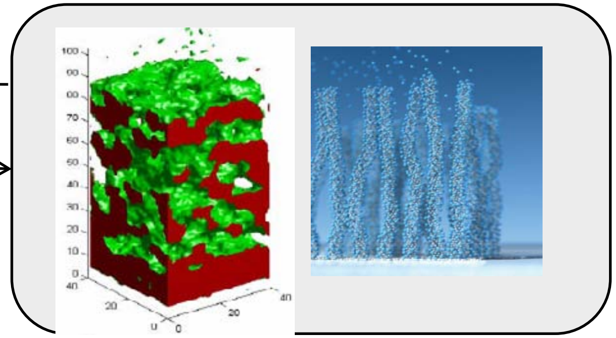
$$I_D = f(V_D, V_G) \times \xi\left(\frac{L_C}{L_S}, D_C L_S^{\,2}\right)$$

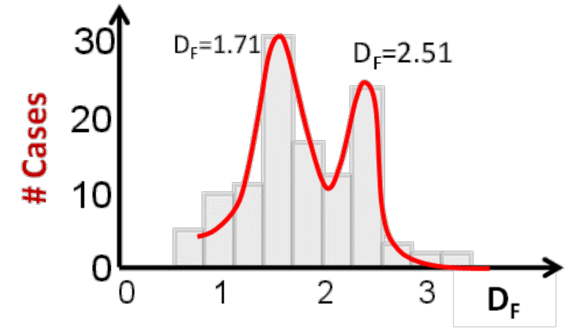
Width dependent
On/Off ratio …

Response of Fractal Surfaces

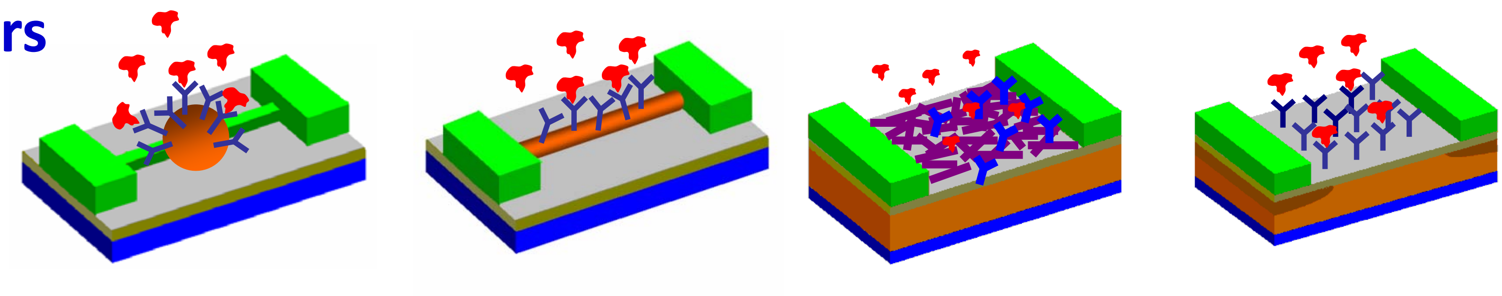
Finite

Fractals



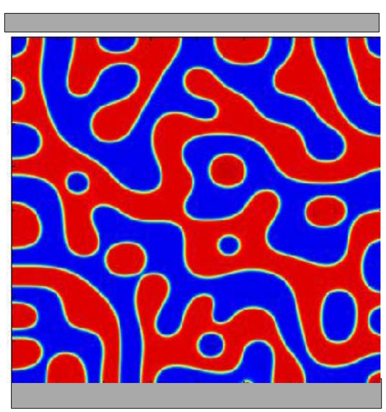


Sensors

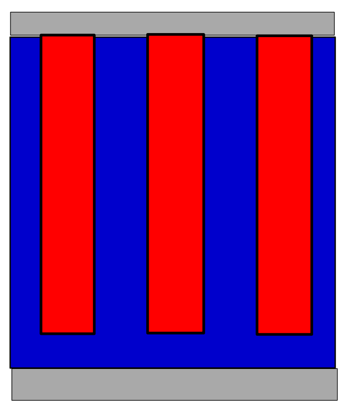


Solar Cells

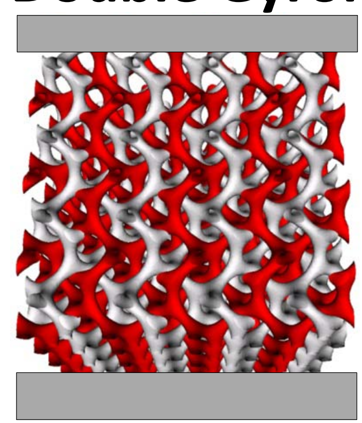
Spinodal



Ordered



Double Gyroid

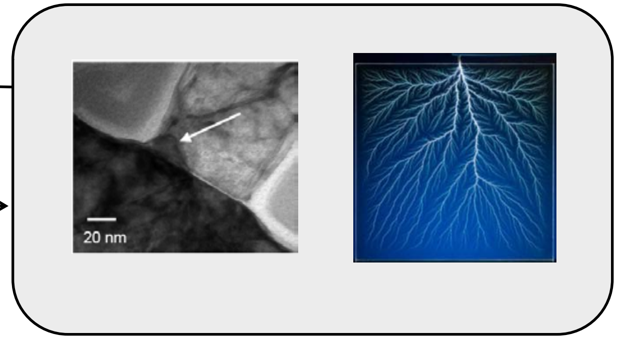


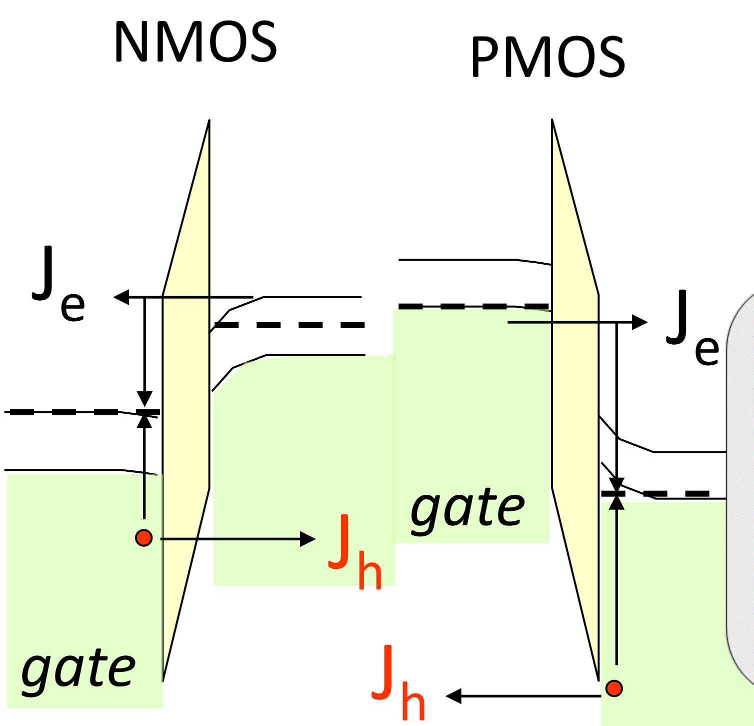
Reliability and Dielectric Breakdown

Correlated

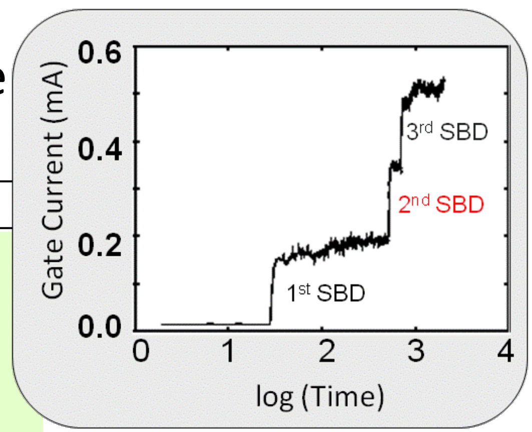
Temporal

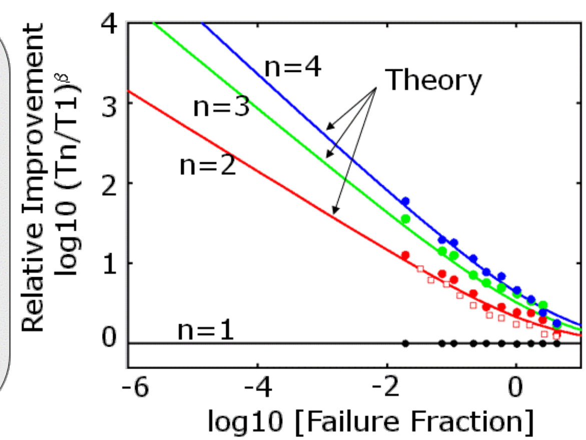
Percolation





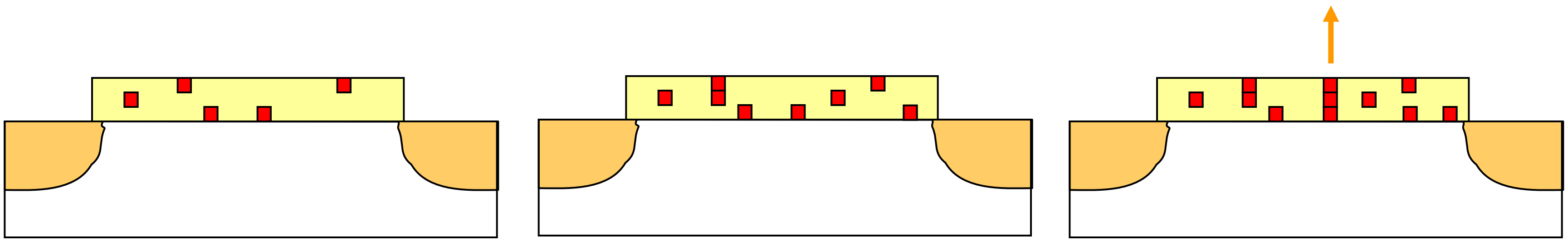
$$\left(\frac{T_n}{T_1}\right)^{\beta} = \frac{n}{e}\frac{\left(2\pi n\right)^{1/2n}}{F_n^{(1-1/n)}}$$

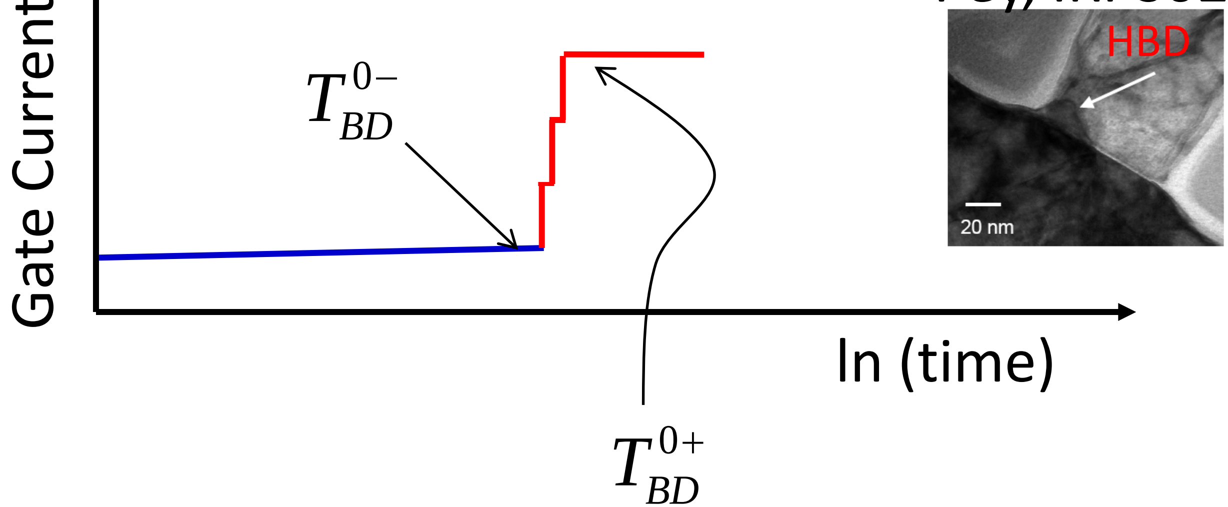




Why is reliability predictable?

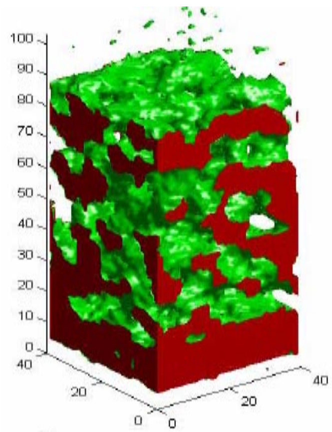
distinction between $T_{BD}(0^+)$ vs. $T_{BD}(0^-)$

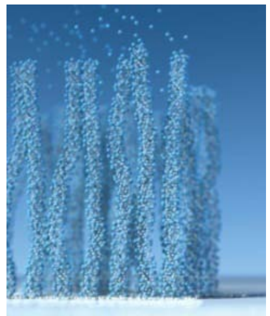


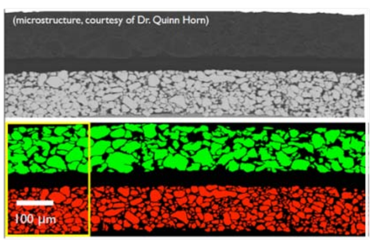


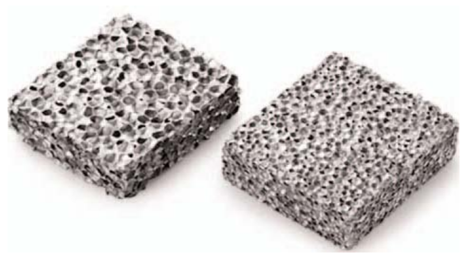
Pey, IRPS02

On random materials and biomimetic design









Life at the edge of equilibrium thermodynamics uses geometry in remarkable ways … description of that geometry is essential in understanding the function of biomimetic materials and devices