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ECE695: Reliability Physics of Nano-Transistors

Lecture 13: Introductory Lecture on HCI Degradation

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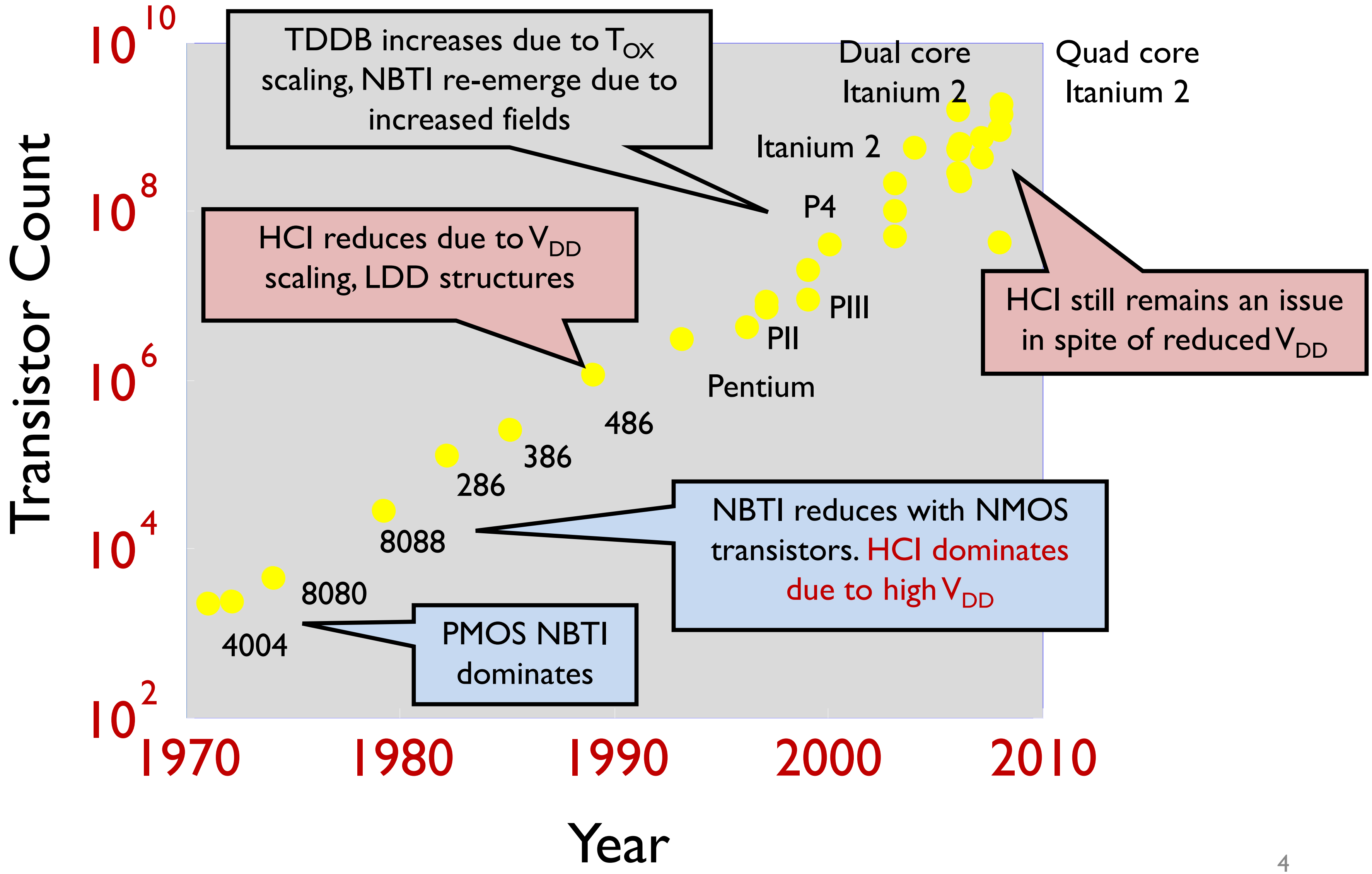
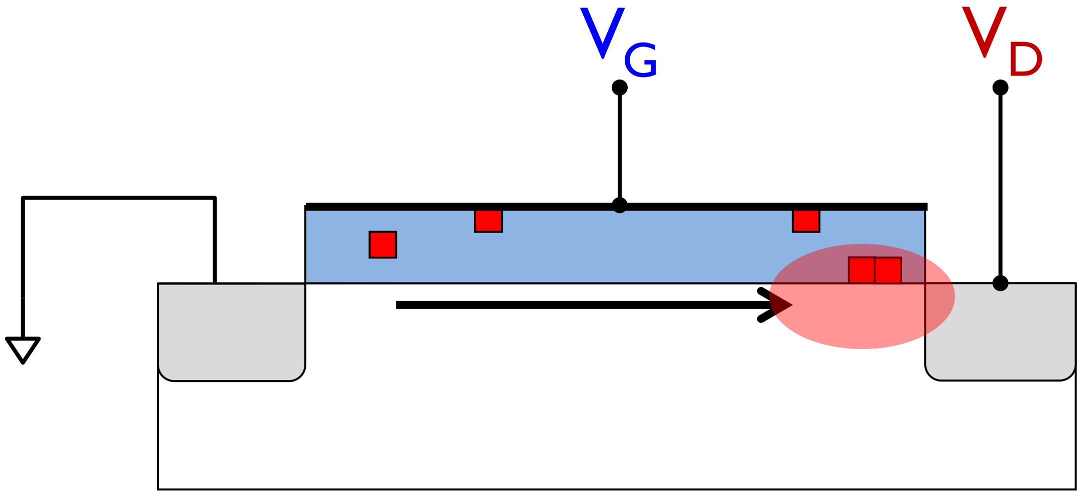
Outline of Lecture 13

1. Background and features of HCI Degradation
   1. Phenomenological observations
   2. Origin of Hot carriers
2. Theory of Si-H Bond Dissociation
3. Theory of Si-O Bond Dissociation
4. Conclusions

Hot Carrier Degradation: Emerging Issue

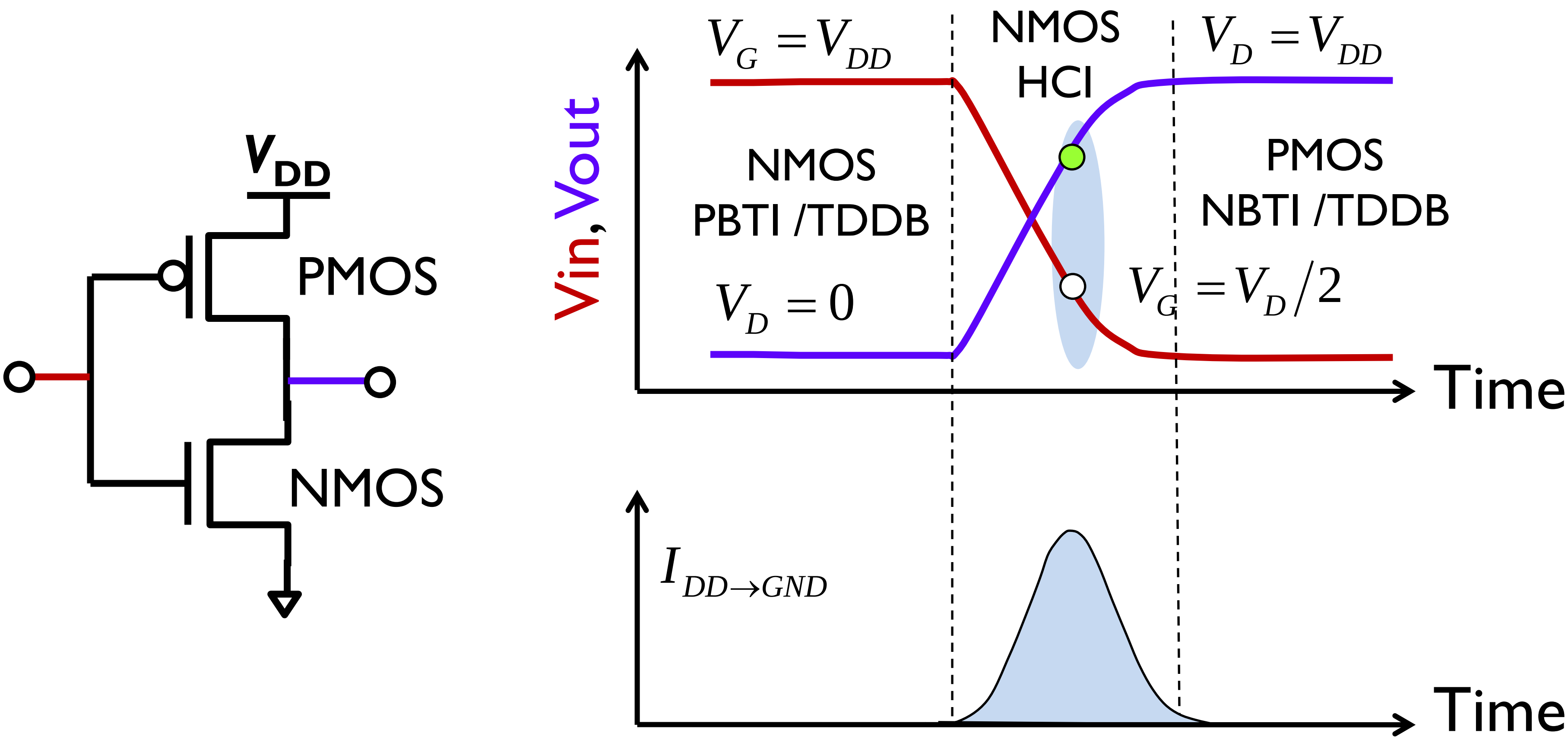


Hot carrier degradation



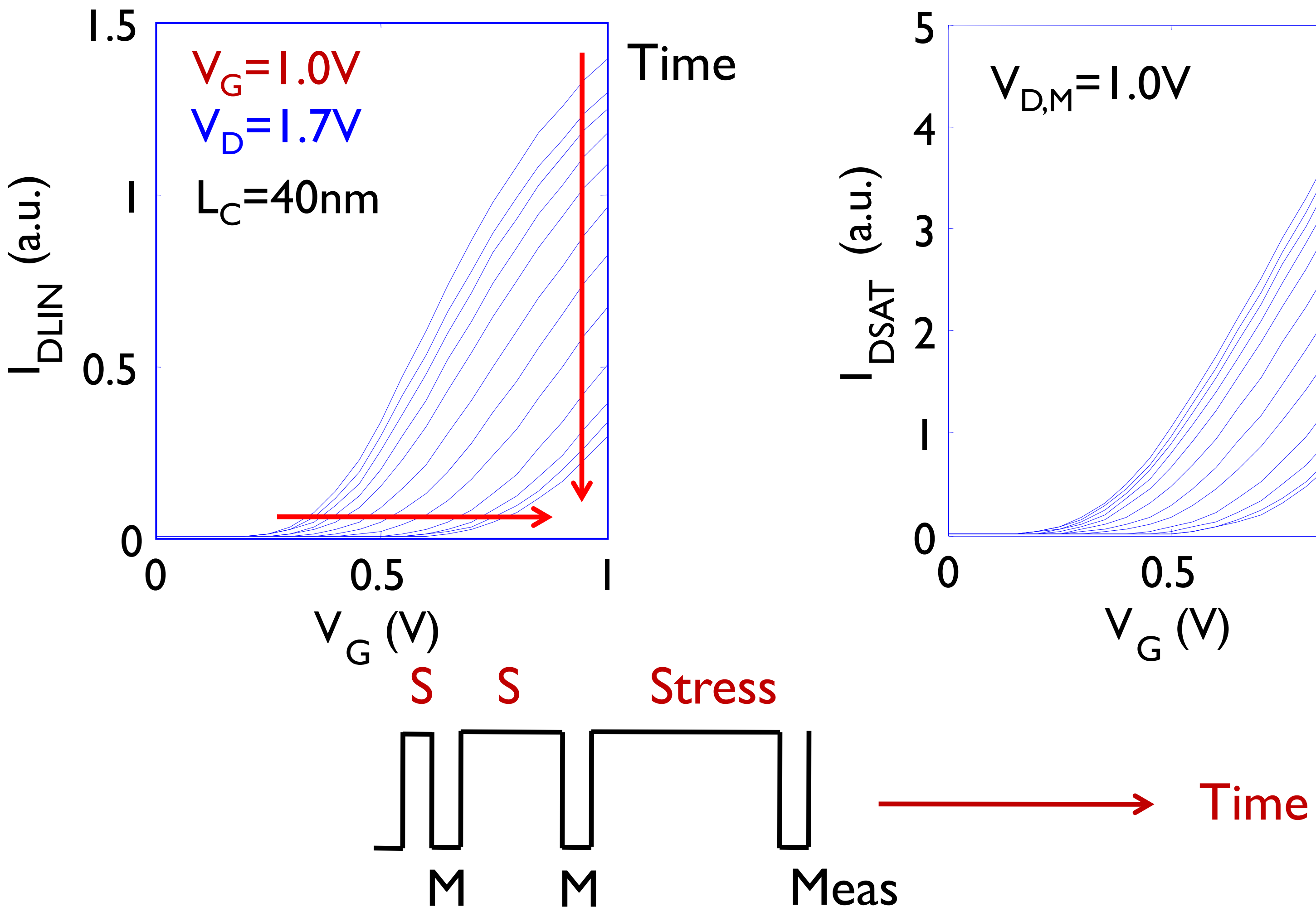
HCI occurs during the on-state ($V_G > V_T$) , at $V_D > V_G$

Classical HCI … only ON state?!



True only for logic transistor, at relatively low operating voltage

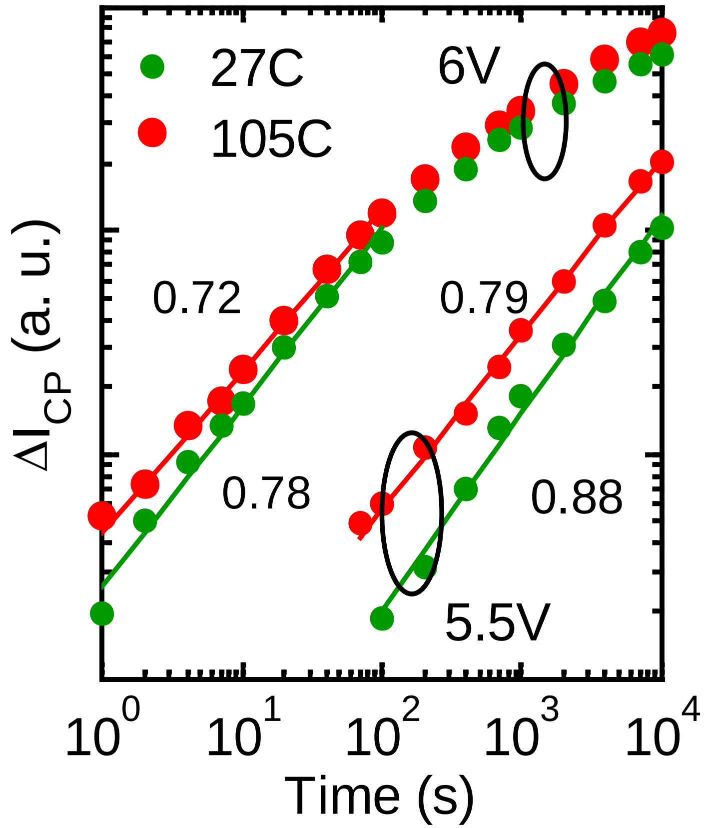
Impact on Device Performance

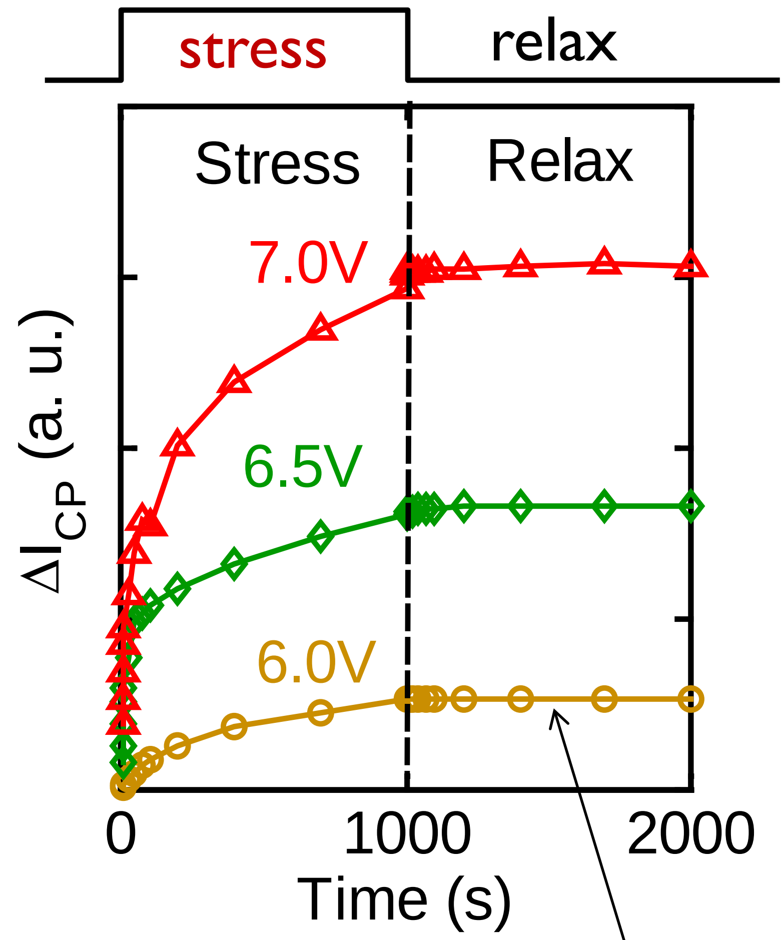


- Degradation of I_{DLIN} ,V_T and I_{DSAT} occur during hot carrier stress

Observation 1: Time exponents and recovery

$$\Delta I_{CP} \propto N_T = A \times t^n$$



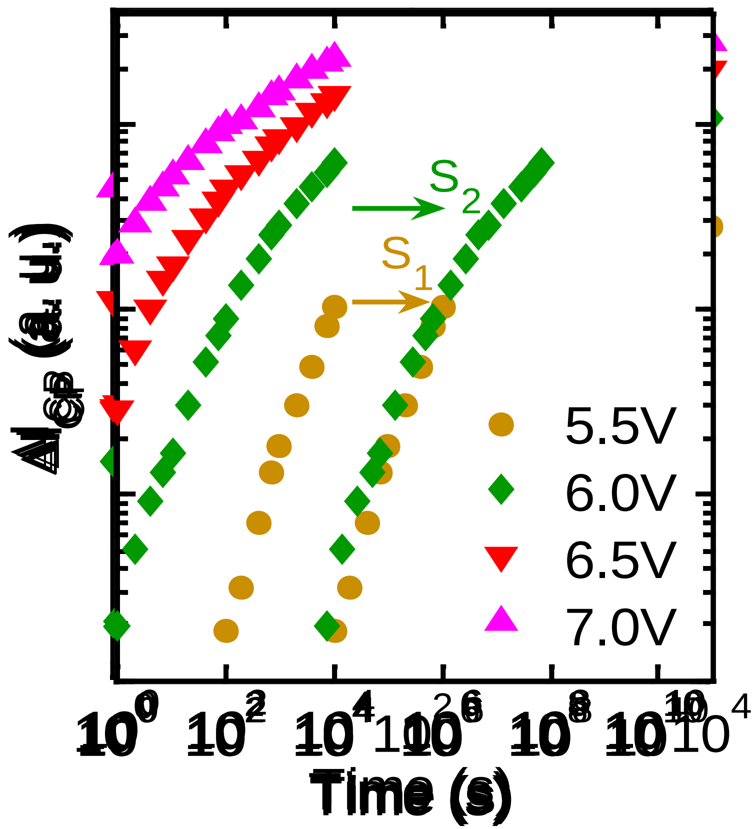


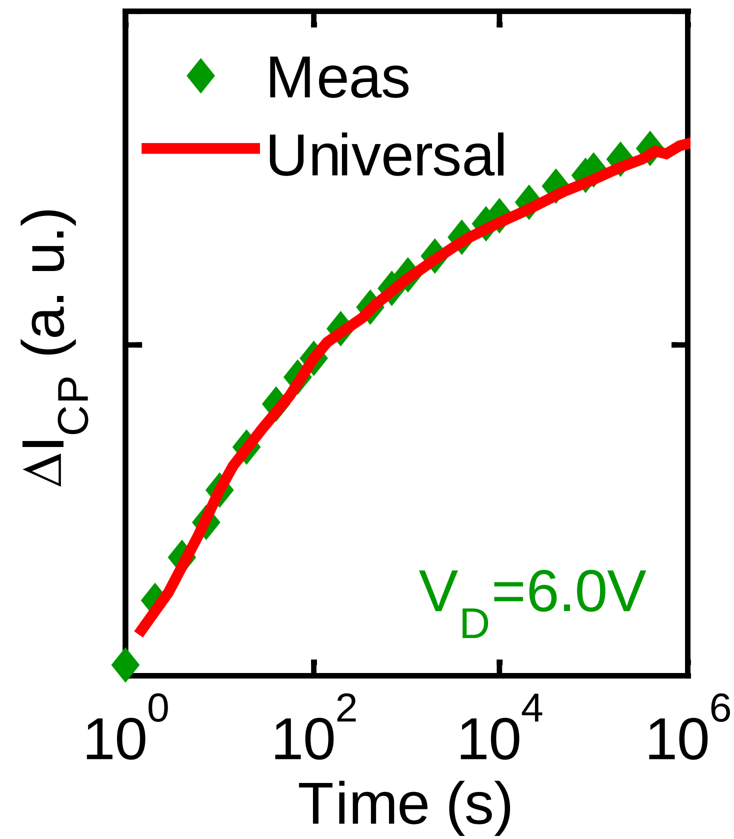
No recovery

Time exponent, n > 0.3

n depends on stress time

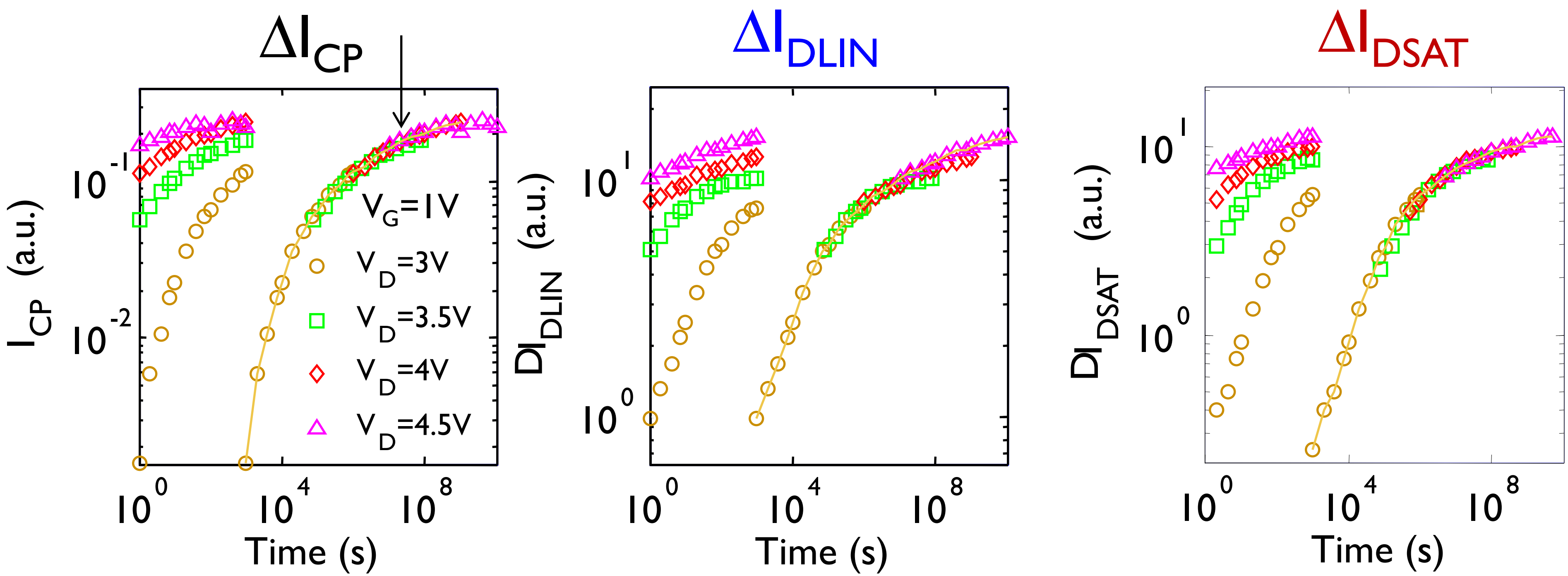
Observation 2: HCI Degradation is Universal





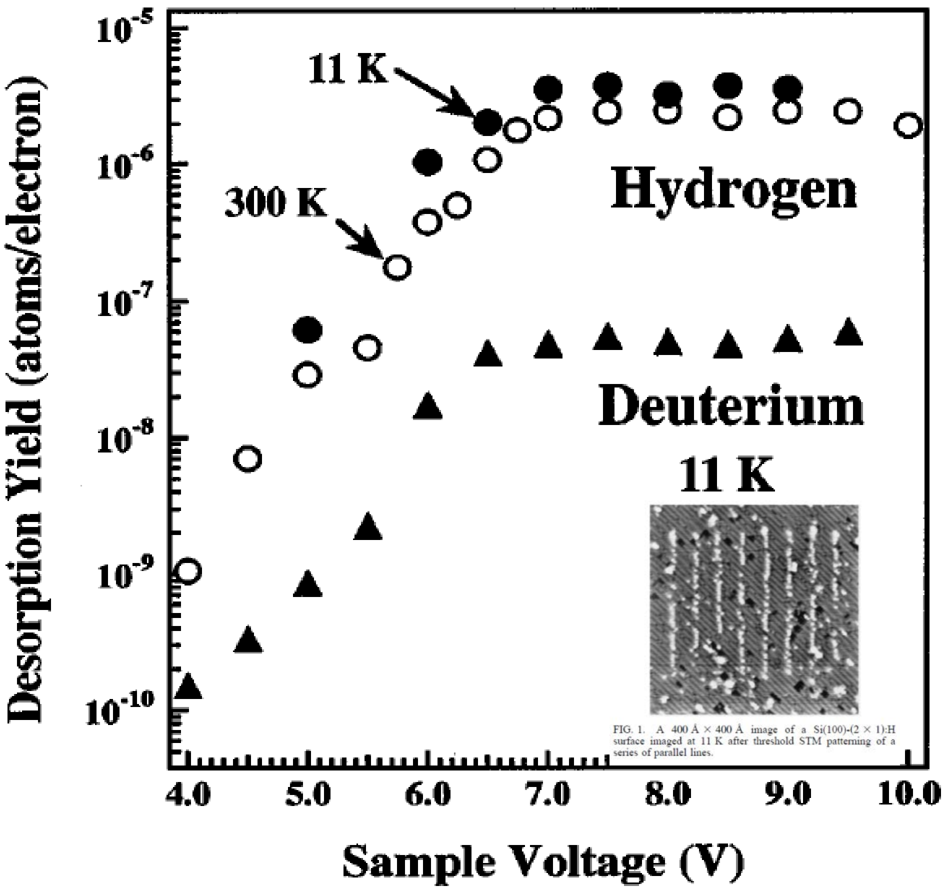
$$\Delta I_{CP} \propto N_T = f\left(\frac{t}{\tau(V_D)}\right)$$

ON-State Logic: Universality of various metrics

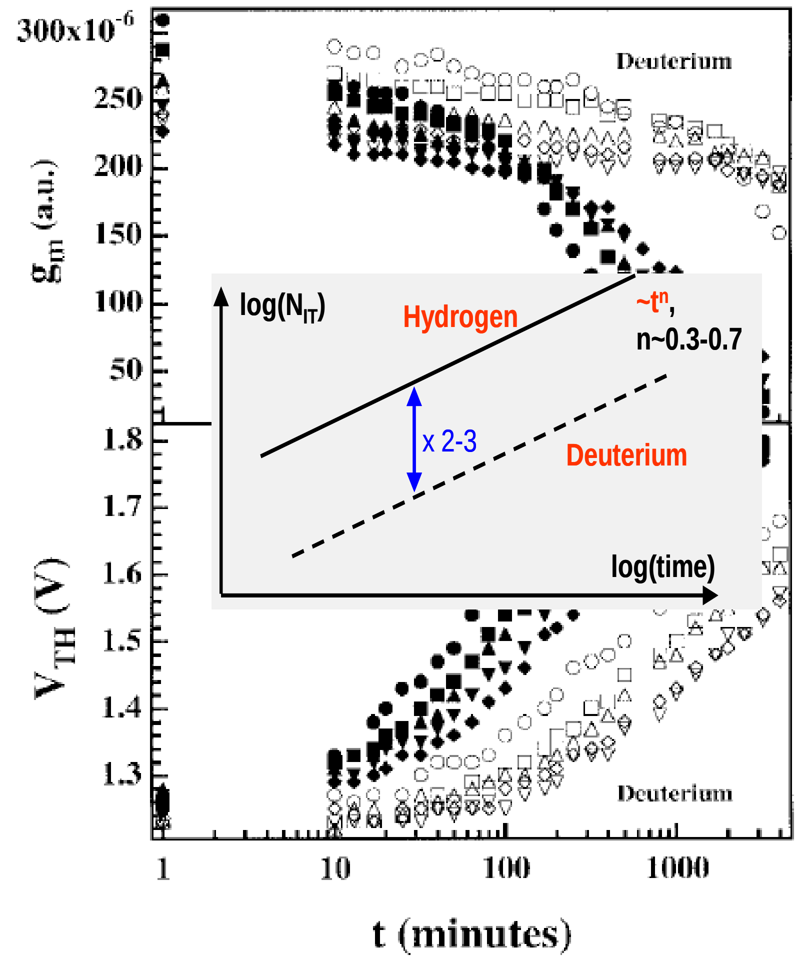


- ON-state degradation (V_G= 1V & 2V) in logic transistors (L_{CH} = 0.16μm & 0.7μm) also show universal behavior

Observation 3: Hydrogen vs. deuterium



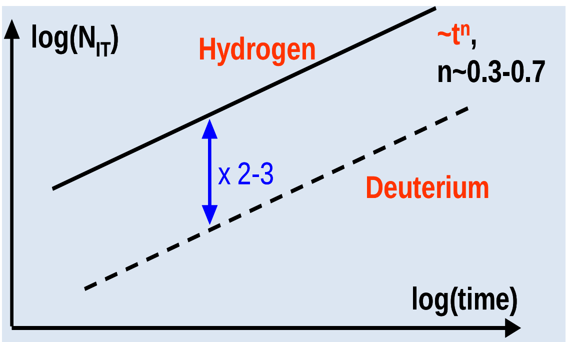
Foley, PRL, 80(6), 1336, 1998.



Hess, TED, 45(2), 406, 1998.

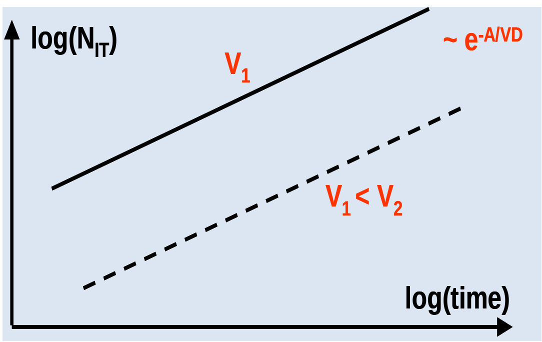
Summary: Empirical Observations

Time exponent



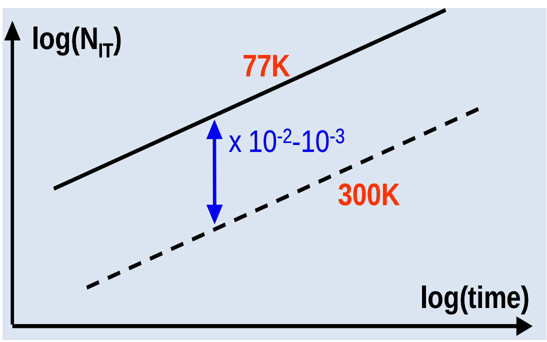
Significant difference between H and D!

Voltage Scaling



Scales with respect to drain voltage!

Temp. Scaling



Negative temp. coefficient!

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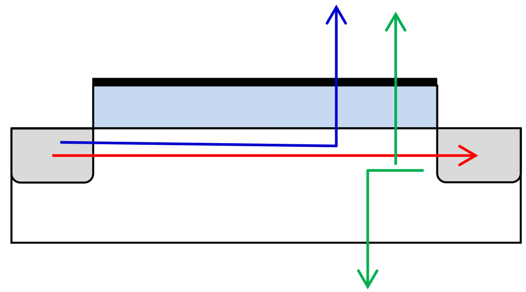
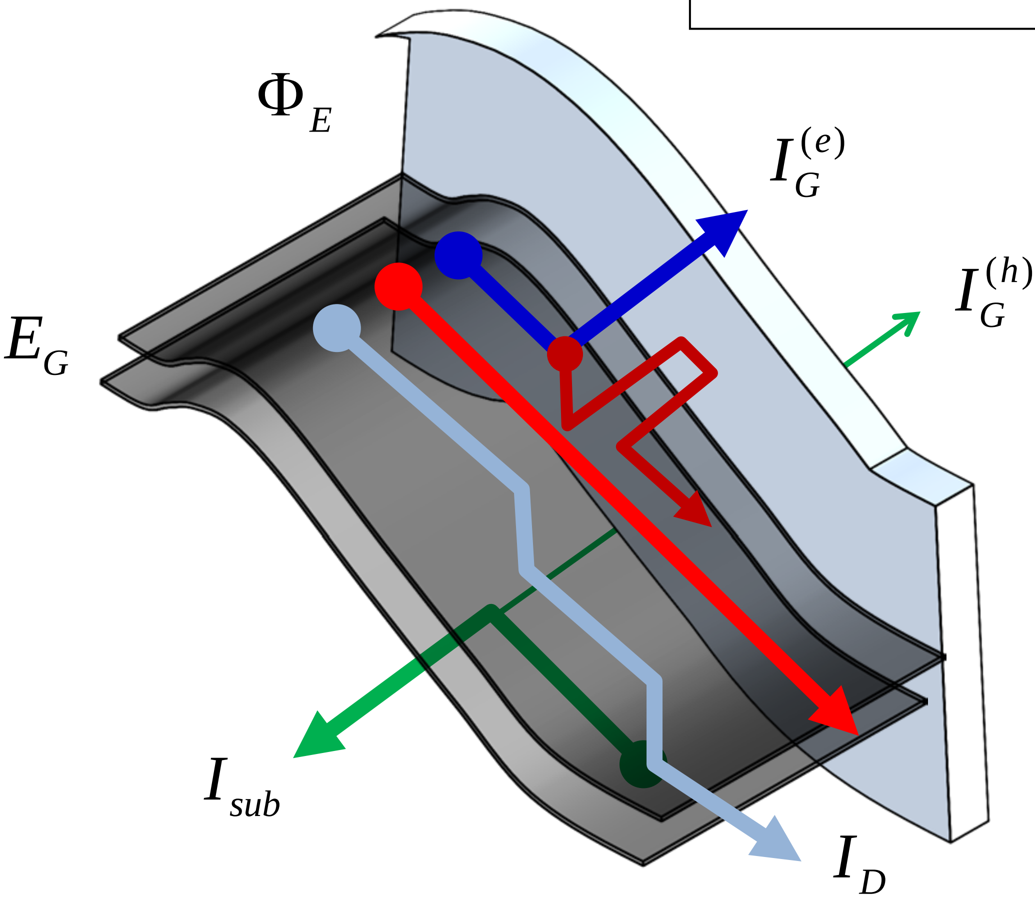
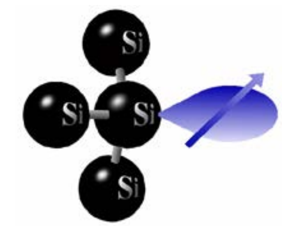
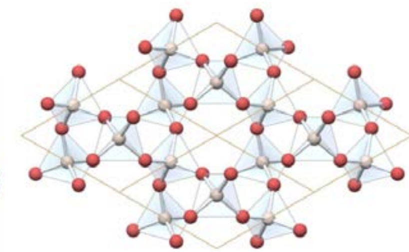
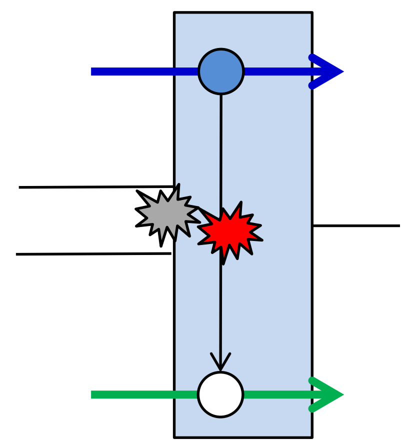
Different types of dangling bonds

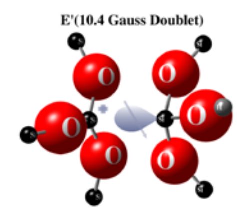




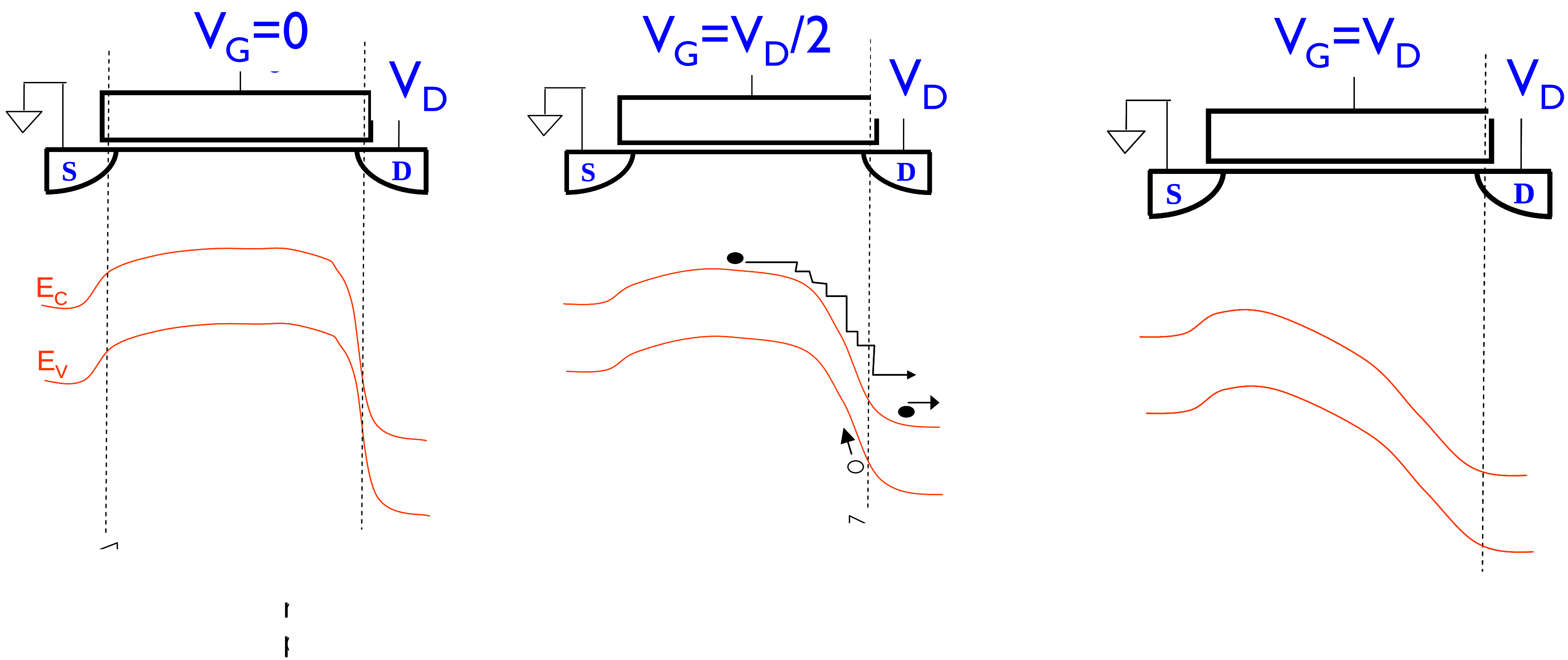








Bias condition for hot carriers

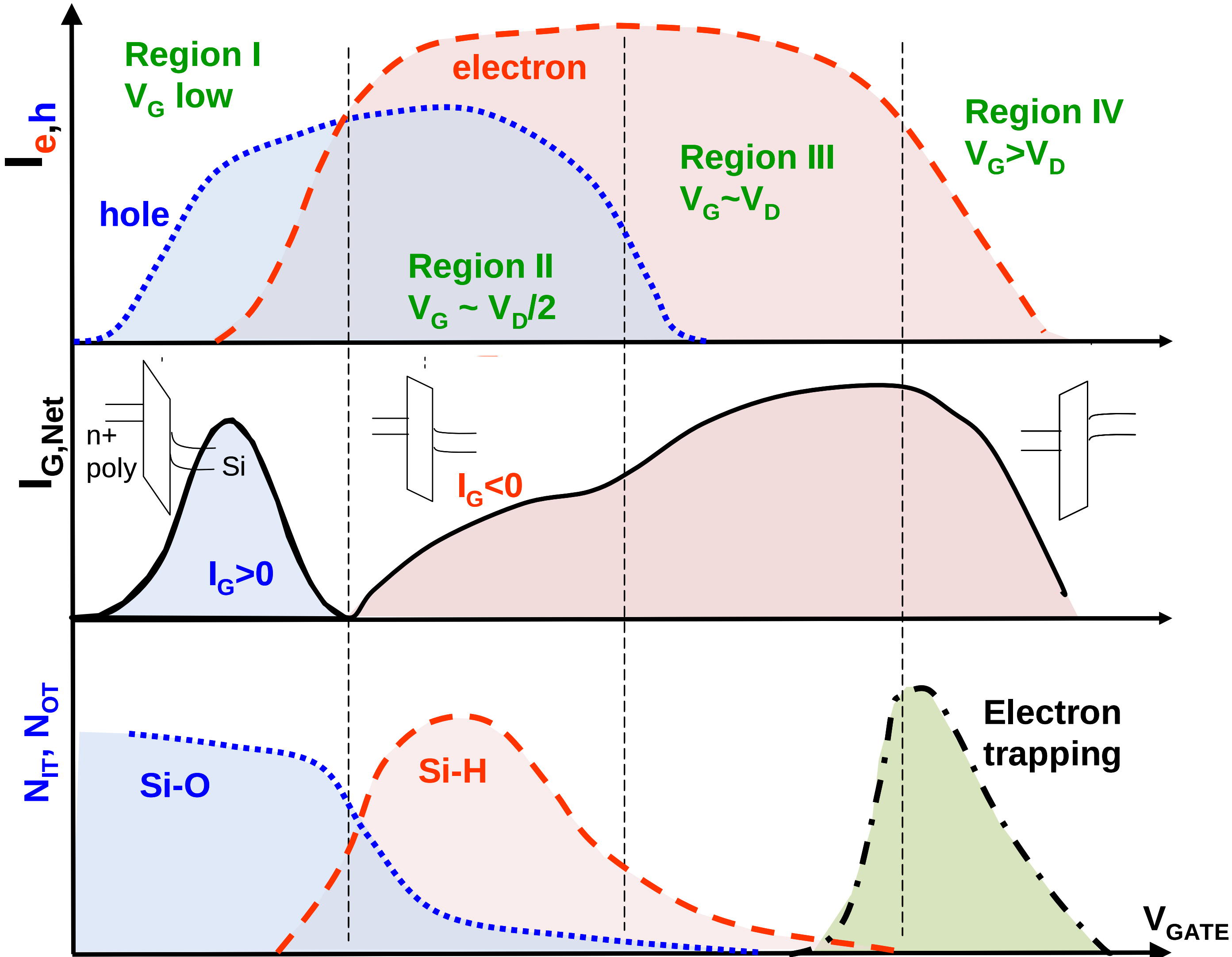


Transistors off, very few carriers

Transistors on, Maximum damage

Transistor ON, but relax over channel

Contributions of SiO, SiH, and trapped Charges



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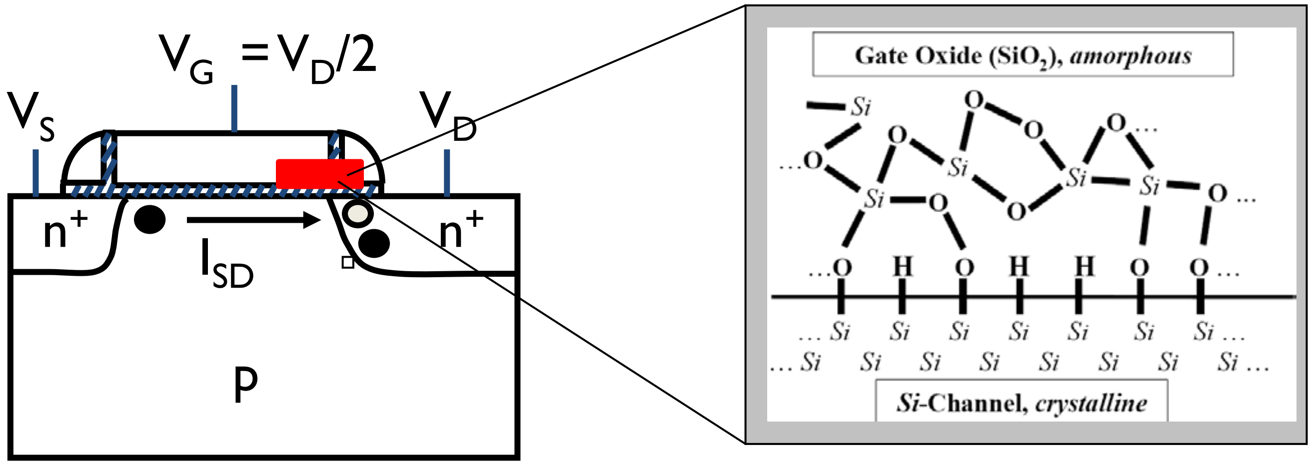
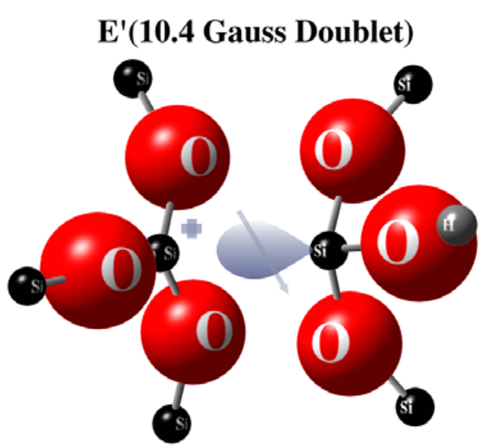
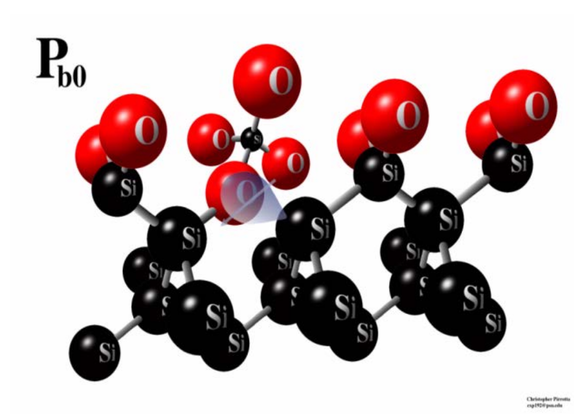
Dissociation of SiH and SiO bonds



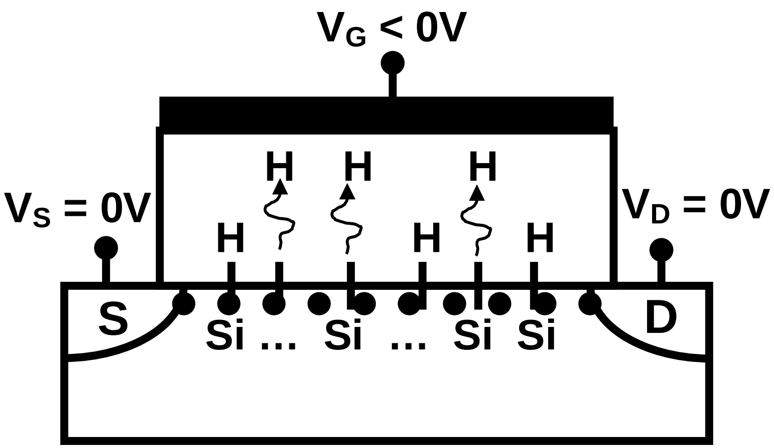


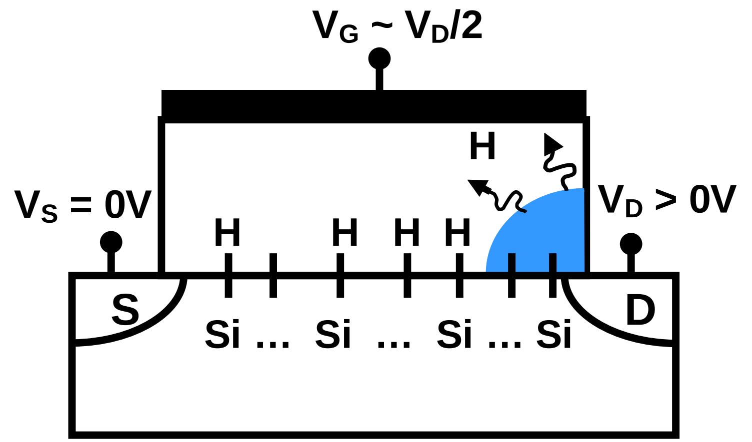


HW: SiH contribution
a factor of 3 larger …

[100] surface
Pb_0 along [111]

NBTI & HCI degradation compared





NBTI(PMOS)

Cold holes

Traps uniform in channel

SiH bonds

HCI (NMOS)

Hot carriers

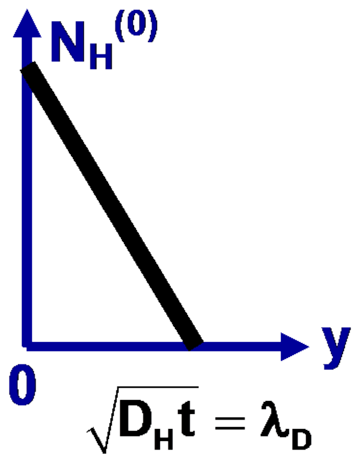
Localized damage

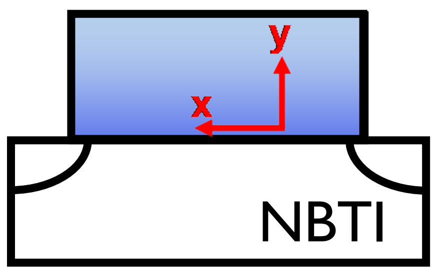
SiH and SiO bonds

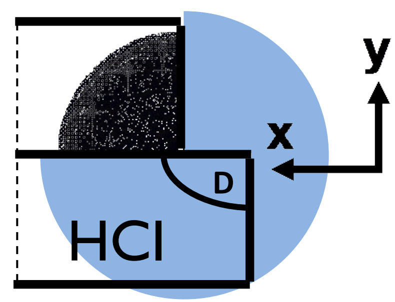
Time Exponent of Si-H dissociation

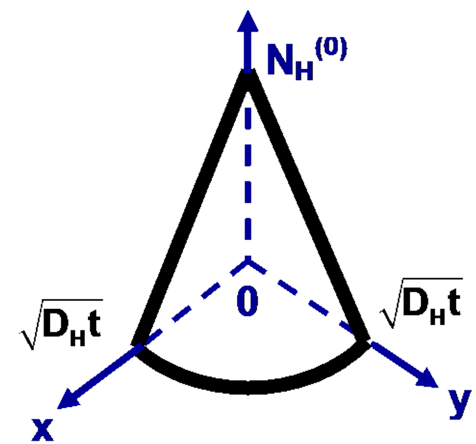
$$\frac{dN_{IT}}{dt} = k_f\left[N_0 - N_{IT}\right] - k_r N_{IT} N_H(0) \qquad \Rightarrow k_F N_0 / k_R = N_{IT} N_H(0)$$

$$N_{IT}(t) \propto \int N_H(r,t)\, dV$$









$$N_{IT}^{NBTI}(t) = N_H^{(0)} \times \sqrt{D_H t}$$

$$N_{IT}^{HCI}(t) = \left(\frac{\pi}{12}\right) N_H^{(0)} \times \left(\sqrt{D_H t}\right)^2$$

$$N_{IT}(t) = \sqrt{\frac{k_f N_0}{k_r}}\left(D_H t\right)^{1/4}$$

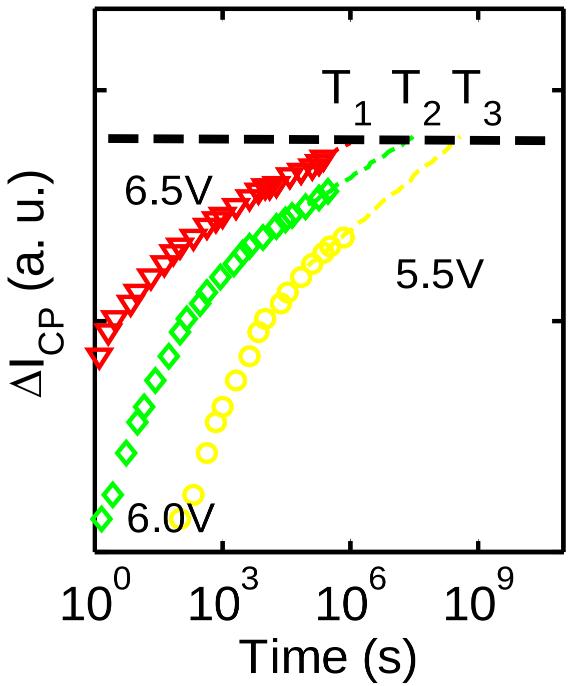
$$N_{IT}(t) = \sqrt{\frac{k_f N_0}{k_r}}\left(D_H t\right)^{1/2}$$

Universal Scaling for SiH Bonds

$$N_{IT}^{\text{SiH}} = \left(\frac{k_F \left(V_G, V_D \right) N_0}{k_R} \right)^{\alpha} \times t^n$$

$$\equiv \left(\frac{t}{t_0} \right)^n = f_{\text{SiH}} \left(\frac{t}{t_0} \right)$$

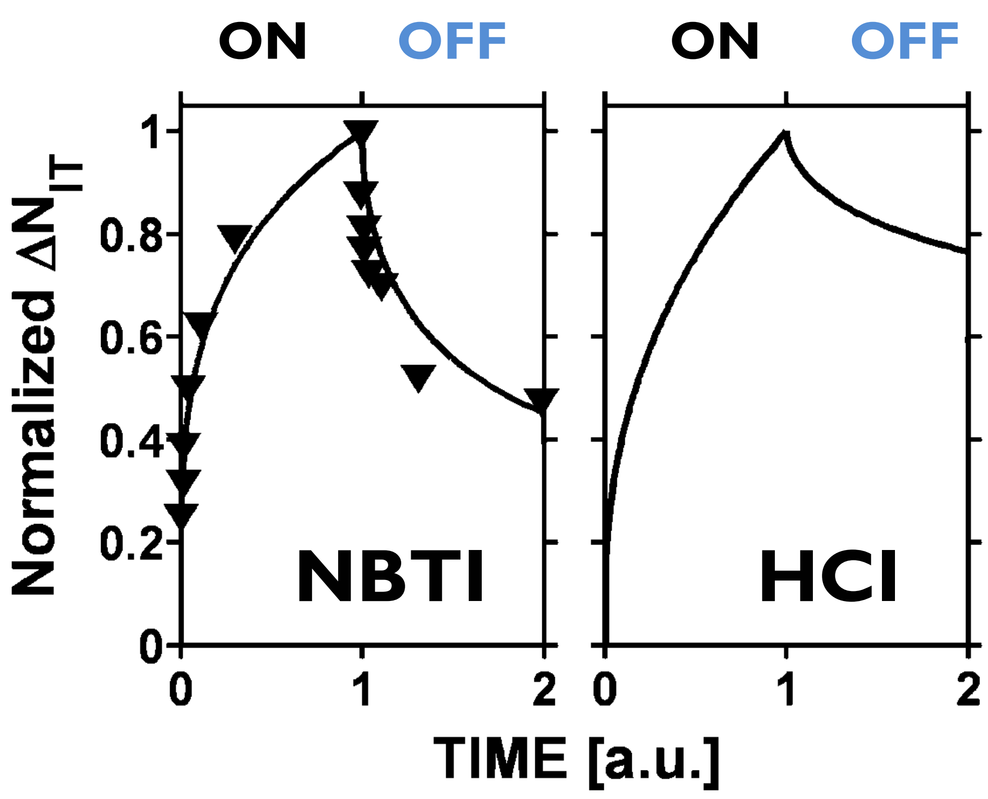
with $\quad t_0 \left(V_G, V_D \right) = g\left(k_F, k_R, N_0 \right)$

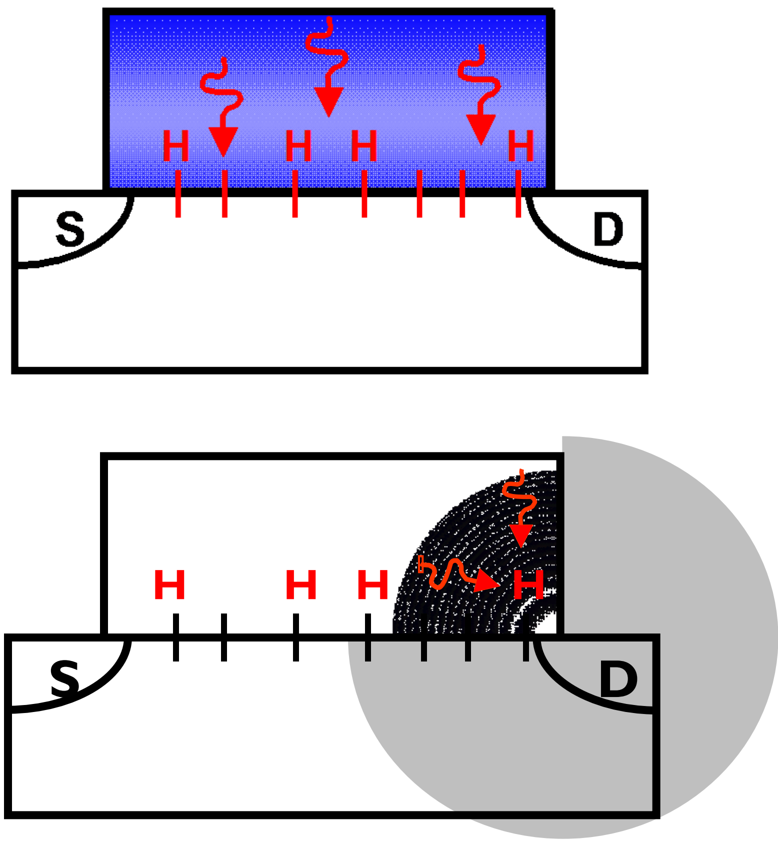


All curves scaled by a factor form a universal curve.

What about Relaxation?

Experiments show very little relaxation!



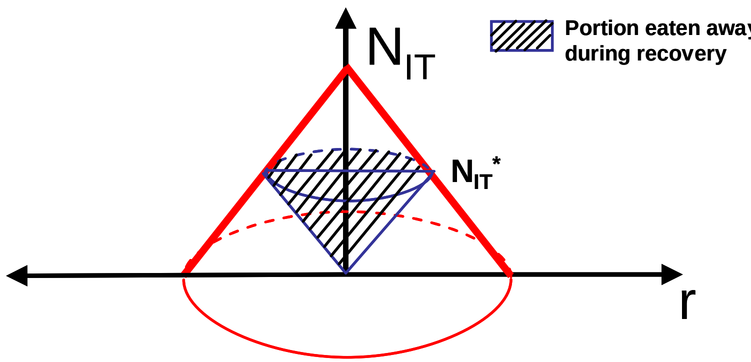


NBTI Data: Chen et al., IRPS Proc. P.196, 2003, M.A. Alam, IEDM Tech. Dig. p.345, 2003

Very Small Relaxation for HCI

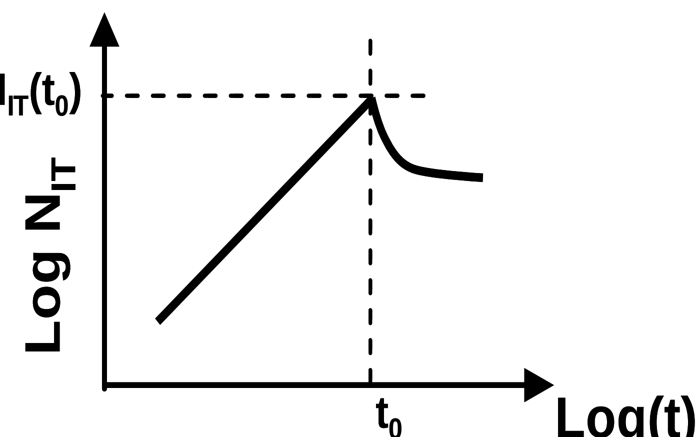
With n=1/2 for atomic H diffusion …

$$\left.\frac{N_{IT}^{HCI}(2t_0)}{N_{IT}^{HCI}(t_0)}\right]_H = \frac{1}{1+\dfrac{\frac{1}{2}t_0}{(t_0+t_0)}} = \frac{4}{5}$$



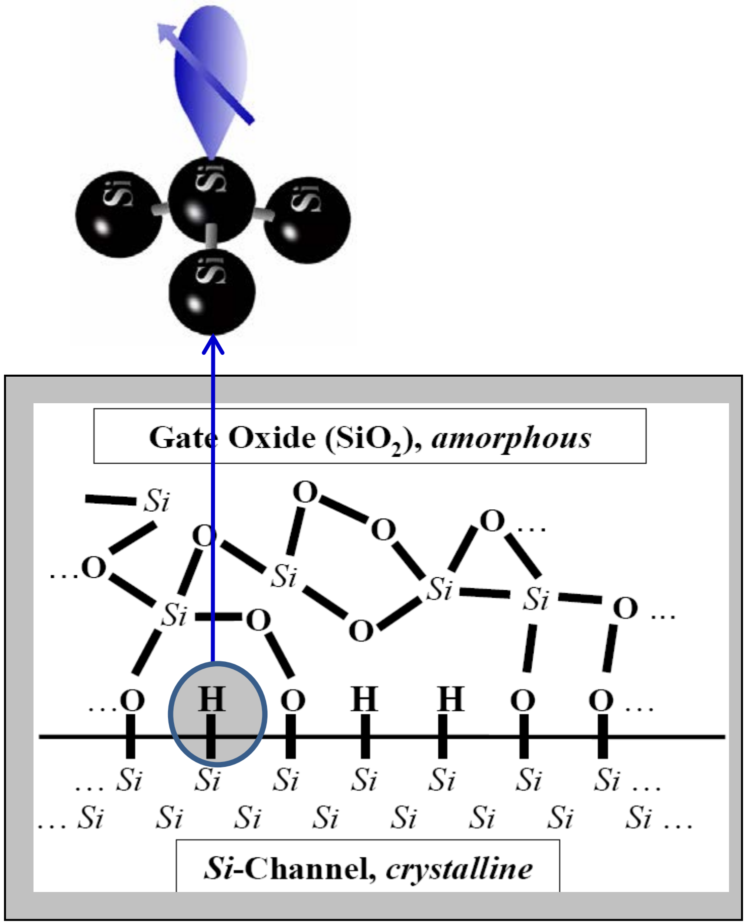
With n=1/3 for H2 diffusion …

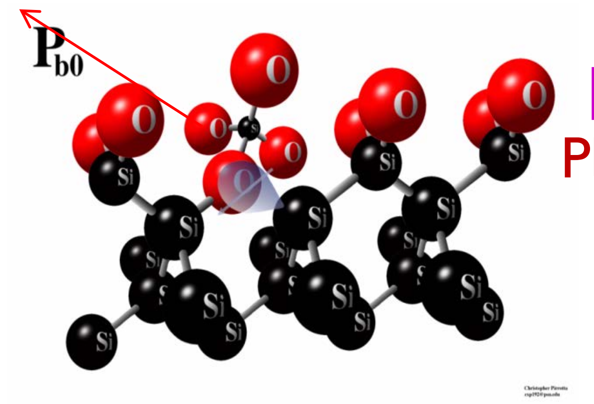
$$\frac{N_{IT}^{HCI}(2t_0)}{N_{IT}^{HCI}(t_0)} = \frac{1}{1+\dfrac{\frac{1}{3}t_0}{(t_0+t_0)}} = \frac{6}{7}$$

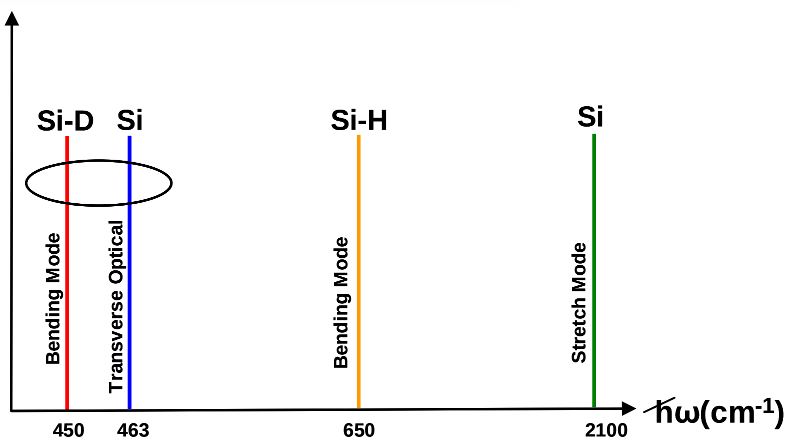


25% of bonds broken is SiH, so the relaxation <5%.

Origin of Si-H and Si-D bond dissociation







Of Pa, Pb, Pc -- only Pb survives
Related to NBTI degradation

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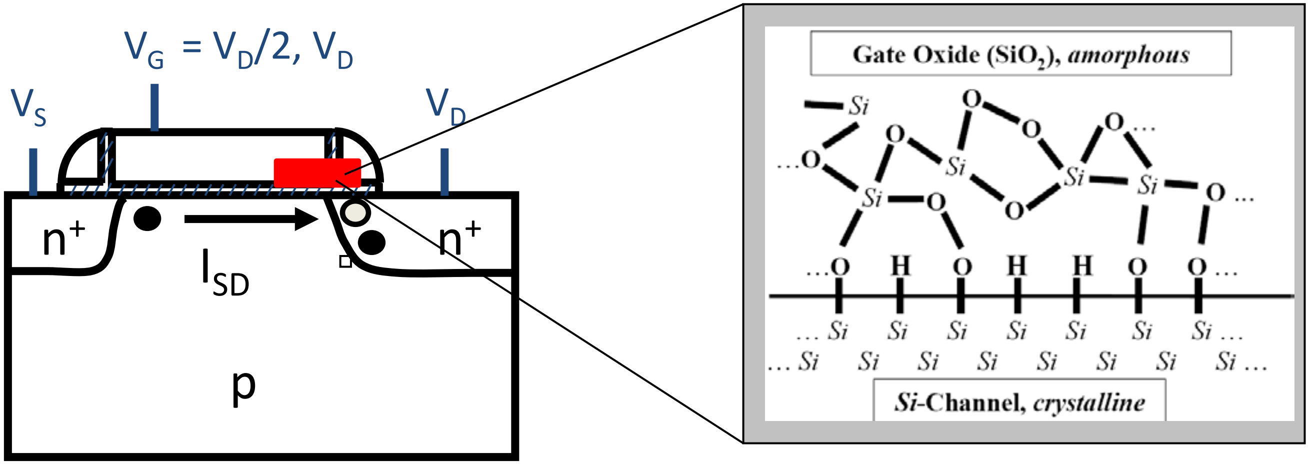
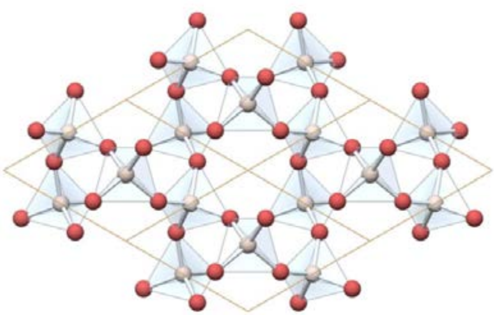
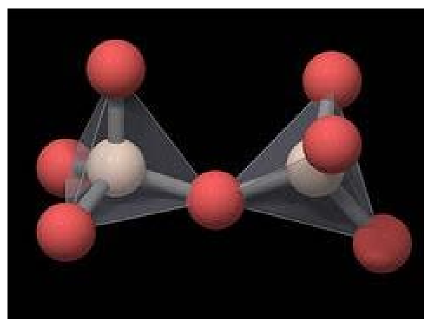
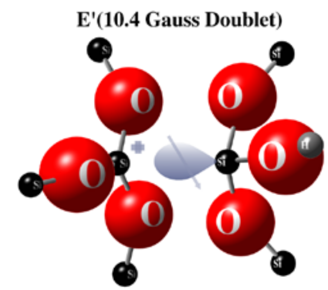
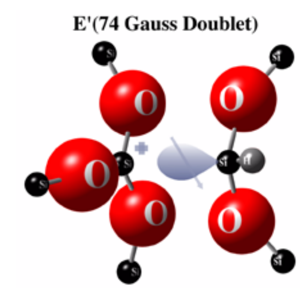
Dissociation of SiO Bonds



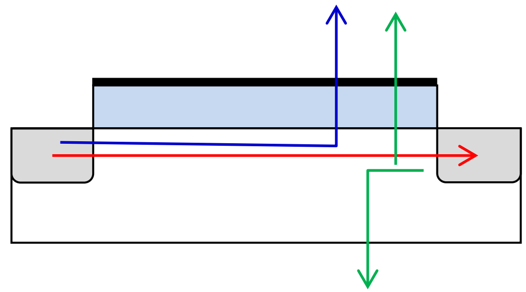


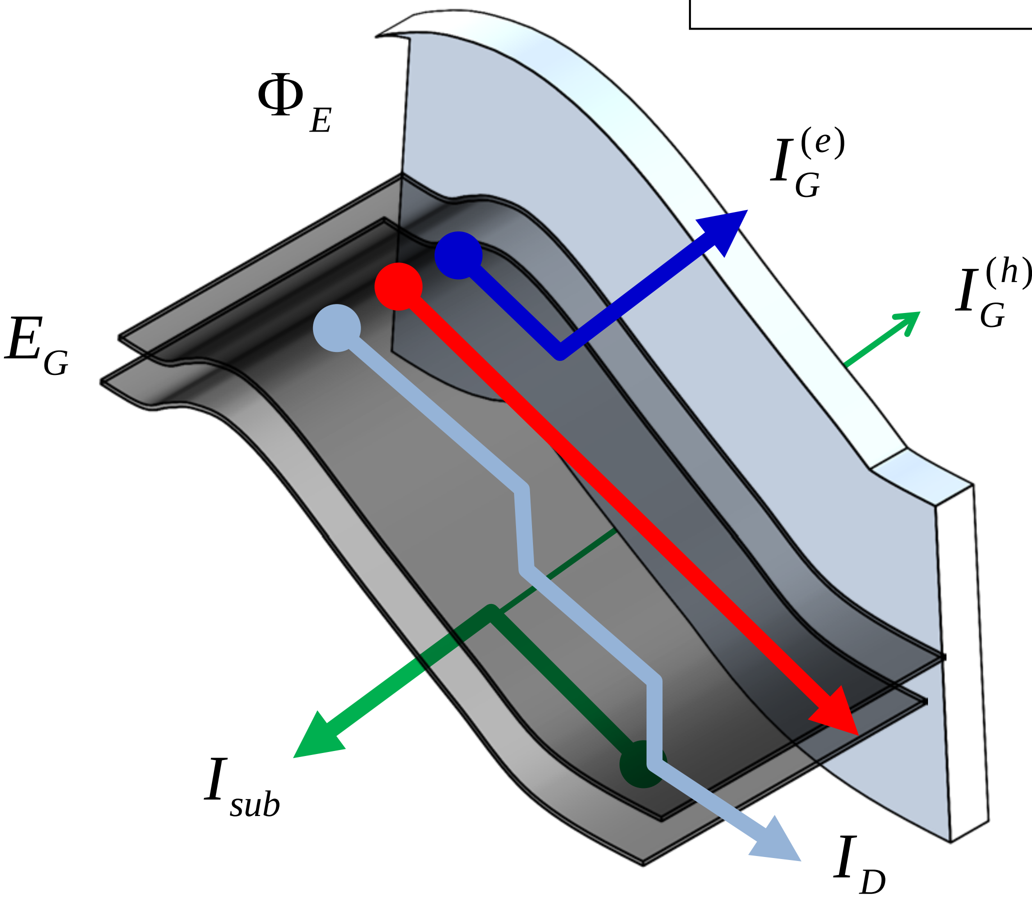


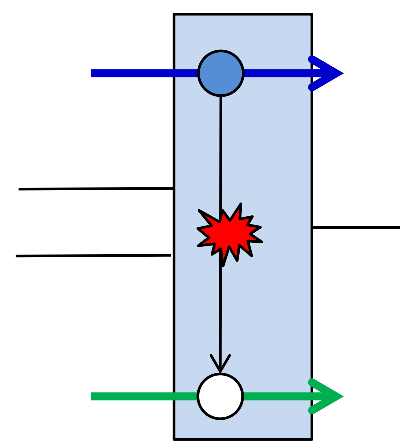


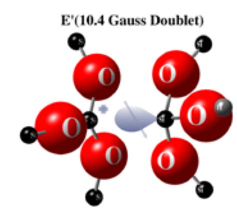


Different types of dangling bonds

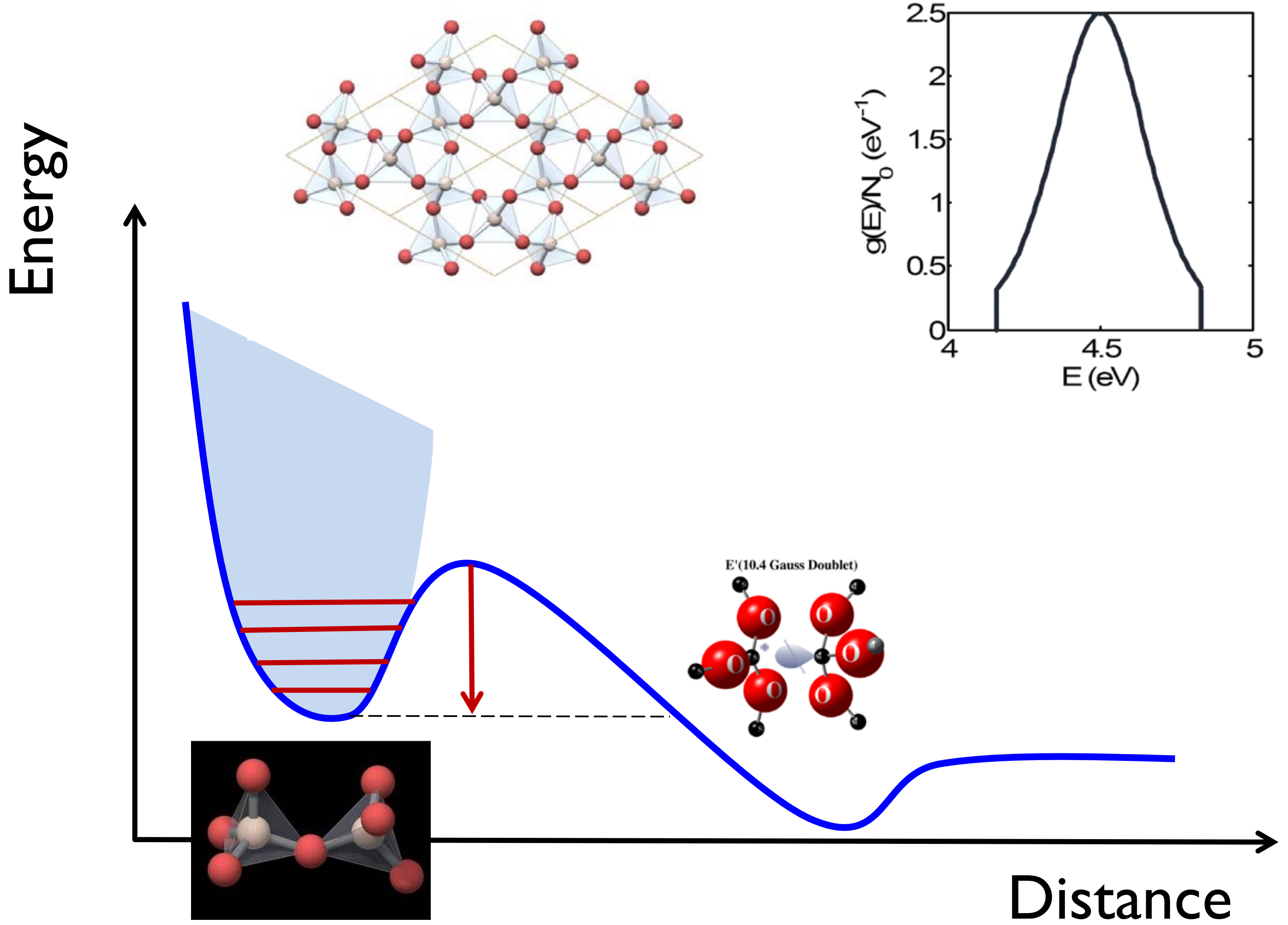








Dissociation barriers and their distribution

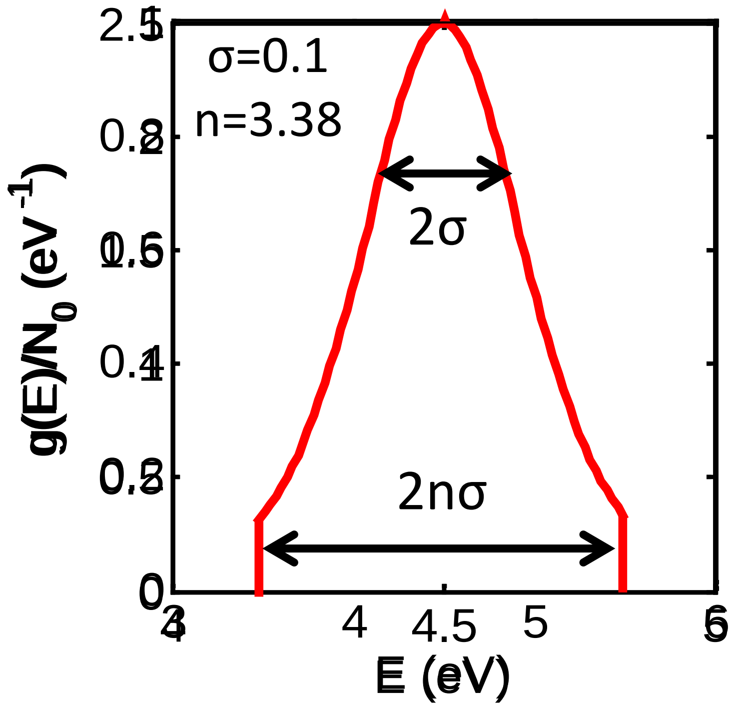


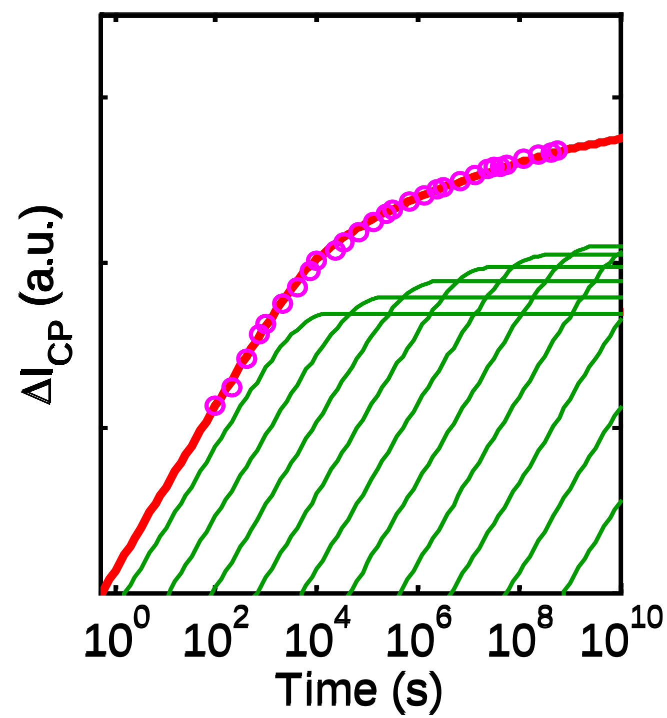
SiO bond dispersion model

$$\frac{dN_{IT}(t)}{dt} = k_f\left(N_0 - N_{IT}(t)\right)$$

$$\frac{dN_{IT}(t)}{dt} = \int_{E_0-n\sigma}^{E_0+n\sigma} k_f(E)\left(g(E) - f(E,t)\right)dE$$

K. Hess et al., IEDM, 5.1.1, 2000; Hess, Ckt & Dev. 2001.





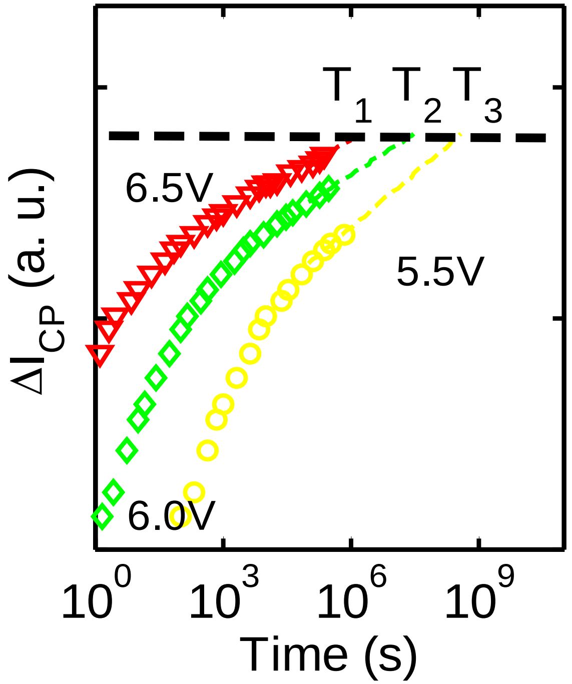
Universal scaling function for SiO bonds

$$N_{IT}^{SiO} = \sum_{E} g(E, E_A)\left[1 + e^{-k_F(E, V_G, V_D)t}\right] dE \equiv f_2\left(\frac{t}{t_0(V_G, V_D)}\right)$$

Will discuss the exact form of t_0 later …

$$t_0^{-1}(V_G, V_D) = I_G = k\frac{I_D}{W_{eff}}\left[\frac{I_{sub}}{I_d}\right]^{\frac{\Phi_e}{\Phi i}}$$

$$t_0^{-1}(V_G, V_D) = I_G = \frac{r_{ii}^{\,m} I_D}{k_1 W} + \frac{r_{ii}^{\,m} I_D^{\,2}}{k_2 W^2} + \frac{V_d^{\,\gamma}}{k_3}\frac{I_D^{\,\alpha}}{W^{\alpha}}$$



Conclusions

- Hot carrier degradation became important soon after NMOS and PMOS technologies were introduced. Insistence on keeping the VD unchanged contributed to the issue.

- Hot carriers break both SiH as well as SiO bonds. And the hot electron/hole trapping also contributes. Taken together there could be a significant shift in voltages.

- One can treat the kinetics of SiH and SiO bond dissociation separately. Both follow universal scaling laws.

Self-Test Questions

1. Both SiH and SiO are involved in HCI degradation. Give two evidences.
2. Why doesn't HCI occur during NBTI stress condition?
3. I suggested that HCI curve can shifted horizontally to form a universal curve, do you believe that I can do a corresponding vertical shift to form the universal curve.
4. What is the physical origin of distribution of bond-strengths for SiO bonds?
5. Why is it that SiH bonds are easily repassivated, while SiO bond are not. What can you do to repassivate these bonds?
6. HCI is a bigger problem for NMOS compared to PMOS – what could be the reason.
7. Why did people expect HCI to disappear below 1V?