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ECE695: Reliability Physics of Nano-Transistors
Lecture 12: Field dependence of NBTI

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Alam ECE-695

Outline

1. Background: Field dependent degradation
2. Components of field-dependent dissociation:
3. Interpreting experiments
4. Voltage acceleration factors
5. Conclusion

Importance of voltage acceleration

Degradation (I_{ON}, V_T, *etc.*)

Failure Criteria

Accelerated testing

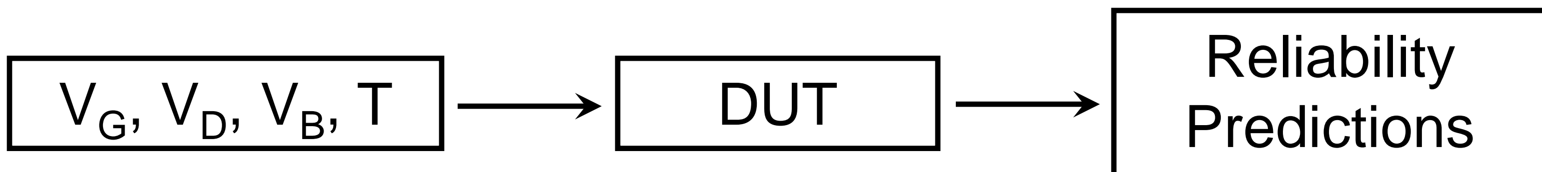
Operating conditions

Lifetime extrapolation TTF ~ 10 year

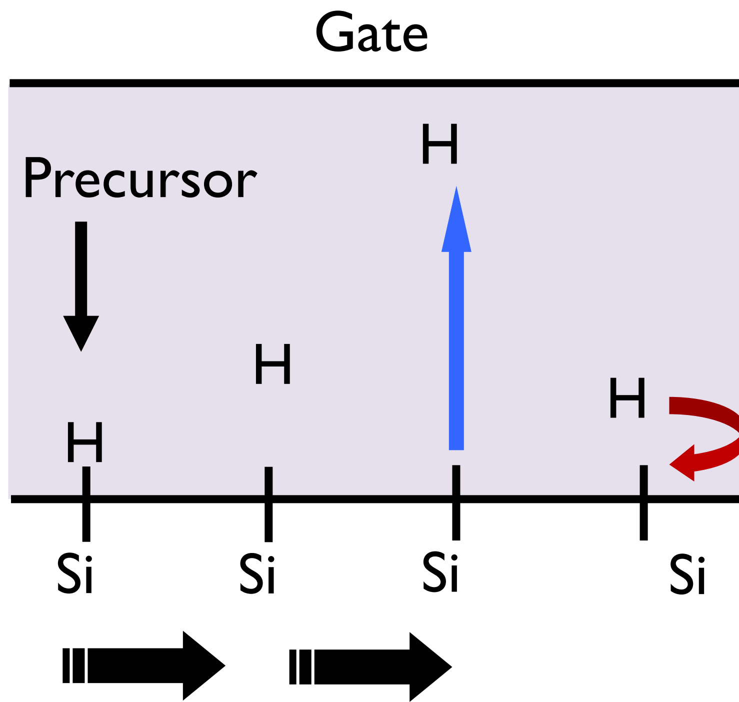
Statistical fluctuations $F_{FAIL} < 10^{-12}$

Time

Desired Lifetime



NBTI mechanism : interface-trap generation



S. Ogawa et. al., PRB, p.4298, 1995

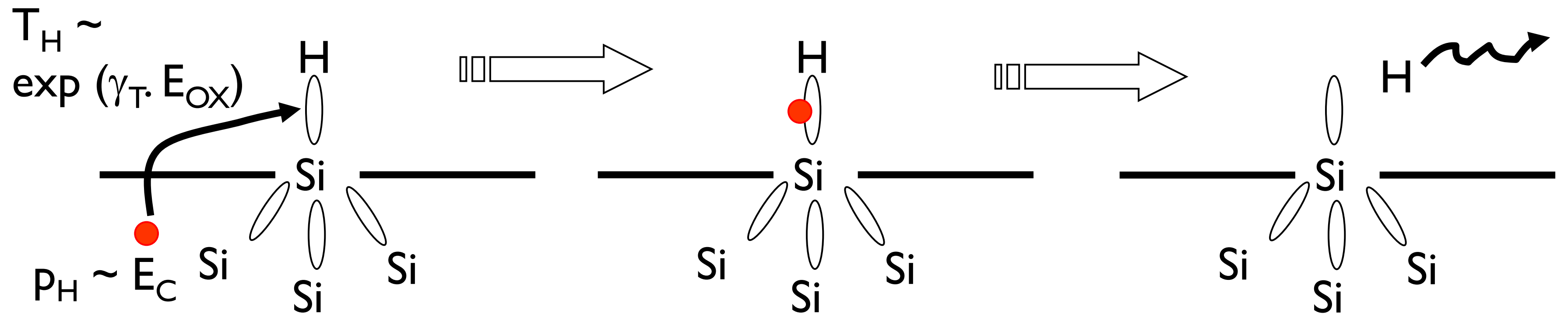
Dissociation of Si-H bonds create Si* and H

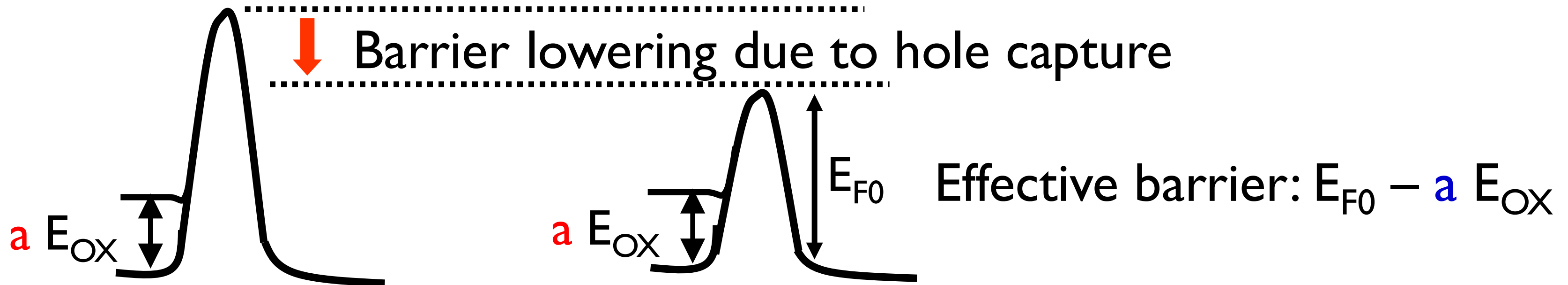
H diffuses away and leave Si* (N_{IT} generation)

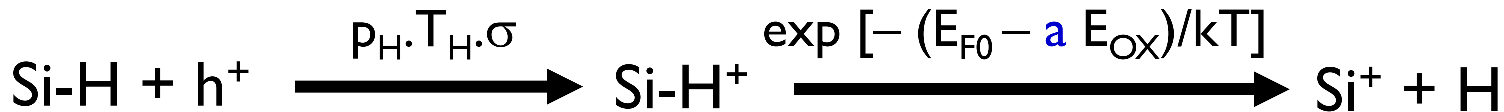
H reacts back and form Si-H (N_{IT} anneal)

N_{IT} generation depends on H removal from surface

Field-dependent bond dissociation





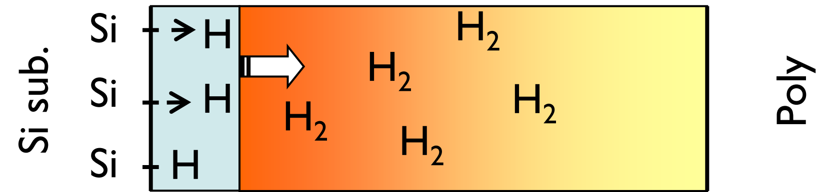


$k_F \sim E_C \exp(\gamma E_{OX}) \exp(- E_{F0}/kT)$

$\gamma = \gamma_T + a/kT$ γ_T=0.16-0.18,

a=0.6-1.2

Interface traps with H_2 diffusion



Generation of traps

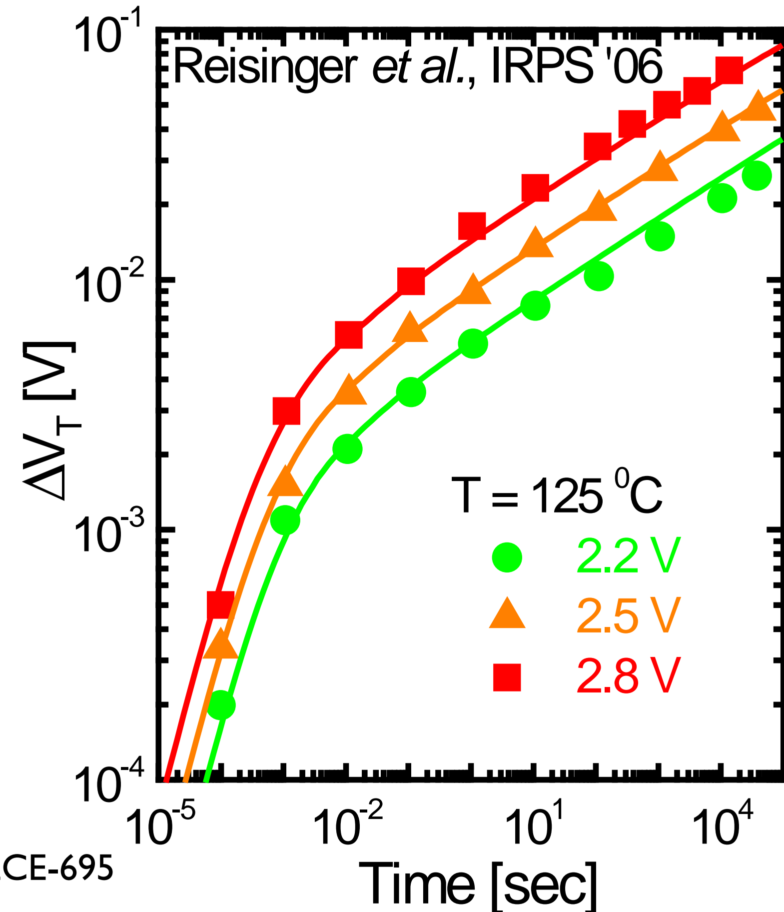
$$N_{IT}(t) \propto \left(\frac{k_F N_0}{2k_R} \right)^{2/3} (D_{H_2} t)^{1/6}$$

$$k_F = k_0 p_h T \sigma e^{-(E_{F0} - a\mathcal{E}_{ox})/k_B T}$$

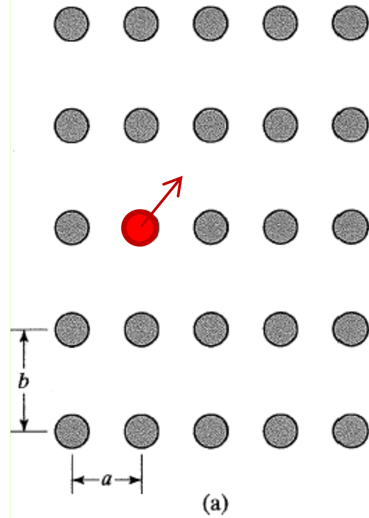
k_R....field independent

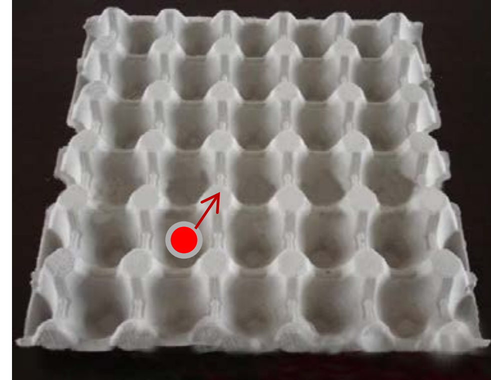
D_{H_2}....field independent

Focus on forward dissociation

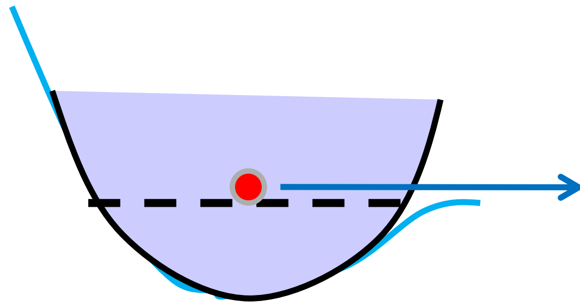


Aside: Three types of bond dissociation



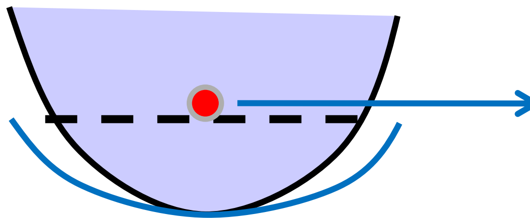


Field induced



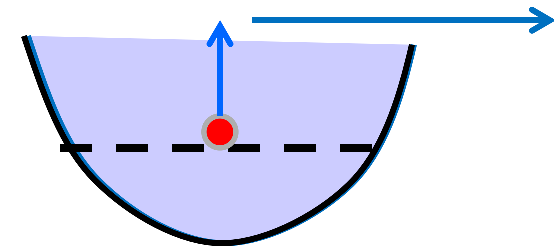
NBTI, HCI, TDDB
(partly ... Small)

Charge State



NBTI primarily

Radiation or e-h recombination



HCI, TDDB, etc.

Outline

1. Background: Field dependent degradation

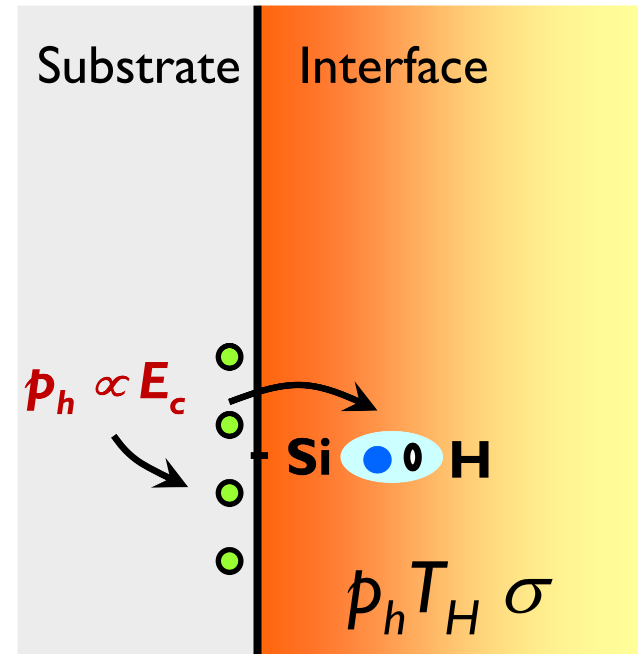
2. Components of field-dependent dissociation:
   - Tunneling
   - Hole density
   - Bond polarization factor

3. Interpreting experiments & voltage acceleration

4. Conclusion

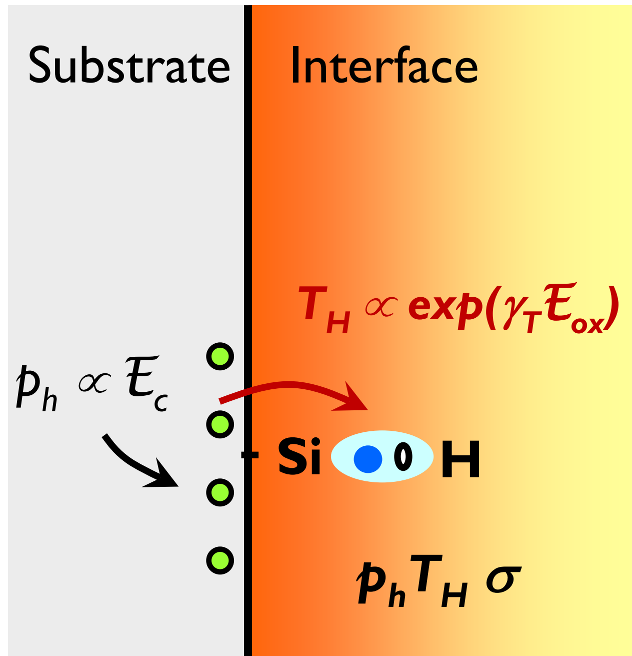
Inversion charges in the channel

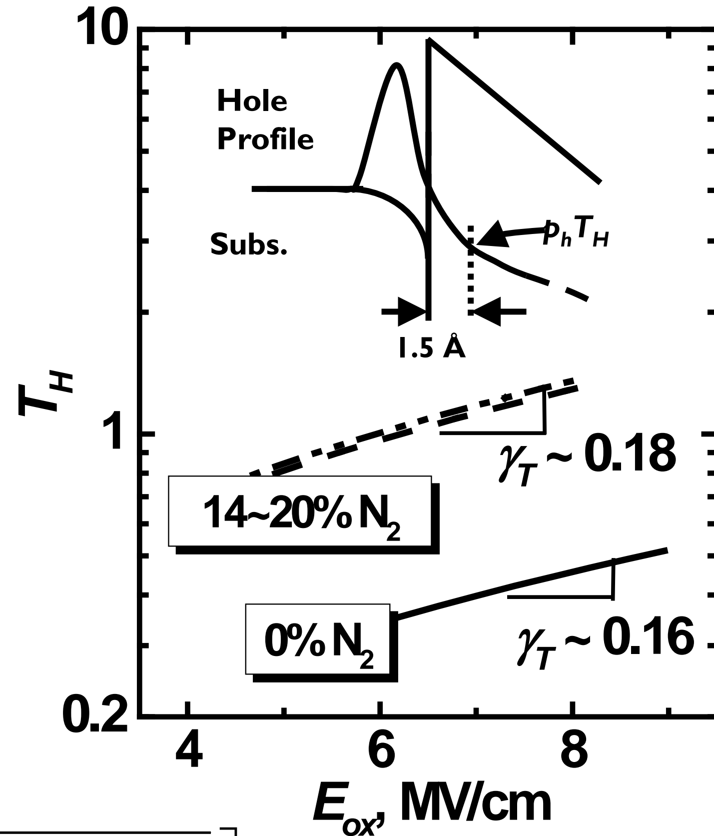
$$Q_{inv} = qp_h$$
$$= C_{ox}\left(V_G - V_T\right) \propto \mathcal{E}_c$$



A rather simple form inversion charges, appropriate for the phenomenological description

Inversion and capture into the bonds





$$Q_{inv} = qp_h = C_{ox}\left(V_G - V_{th}\right) \propto \mathcal{E}_c$$

$$T_H \sim \exp\left[-2\int_0^{t_{int}} dx \frac{\sqrt{2qm_{ox}\left(\Phi_B - x\mathcal{E}_{ox}\right)}}{\hbar}\right]$$

γ_T reduces with Φ_B

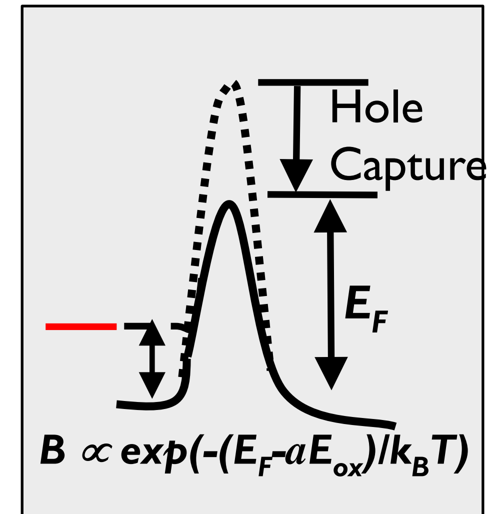
$$\ln T_H \sim -\frac{2\sqrt{2qm_{ox}\Phi_B}}{\hbar}t_{int} + \left[\sqrt{\frac{m_{ox}}{2q\Phi_B}}\frac{qt_{int}^{\ 2}}{\hbar}\right]\mathcal{E}_{ox} - \dots\dots\dots,$$

Polarization of free atoms: calculate *a*

$$k_F = k_0 p_h T \sigma e^{-(E_{F0} - aE_{ox})/k_B T}$$

$$p = -q \int r \times n(r) \mathrm{dr}$$

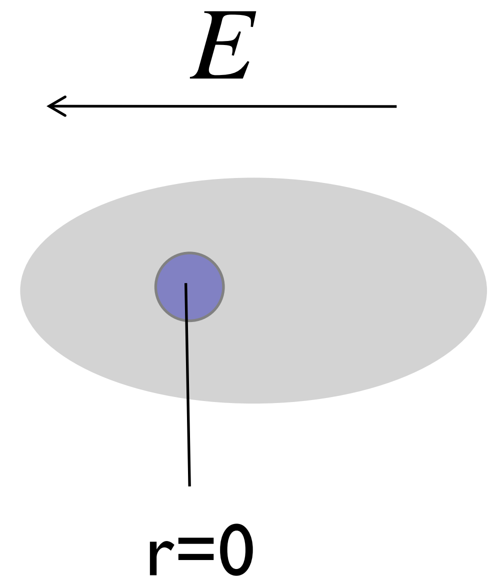
Finite contribution because the electron charge is not symmetric



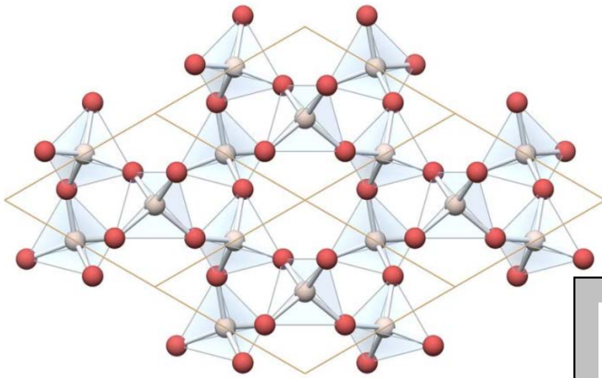
$$p = \alpha \mathcal{E}_{loc} + \beta \mathcal{E}_{loc}^2$$

Polarizability

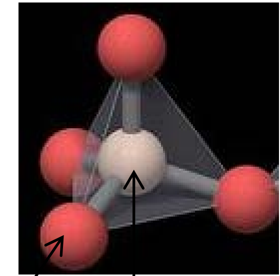
Hyper-Polarizability

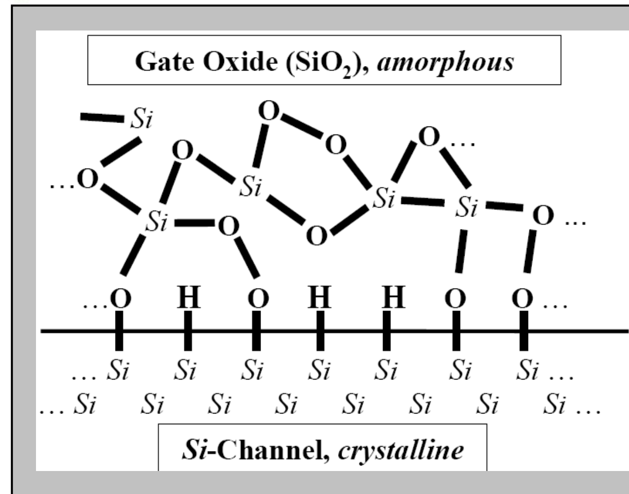


Aside: Polarity of SiO_2 and SiH bonds

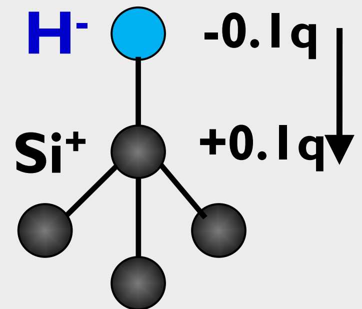


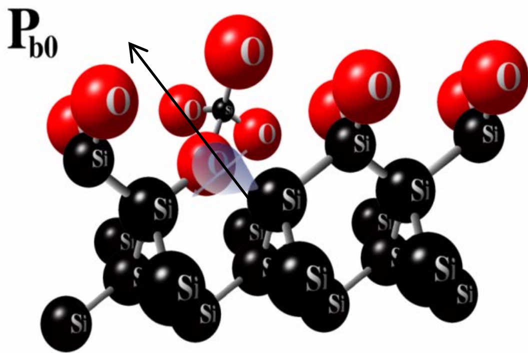
Polar bonds individually **randomized** in bulk





Q*=0.1q





Polar bonds individually **aligned** at interface

Dipole moments in a polar material

Force balance for charges

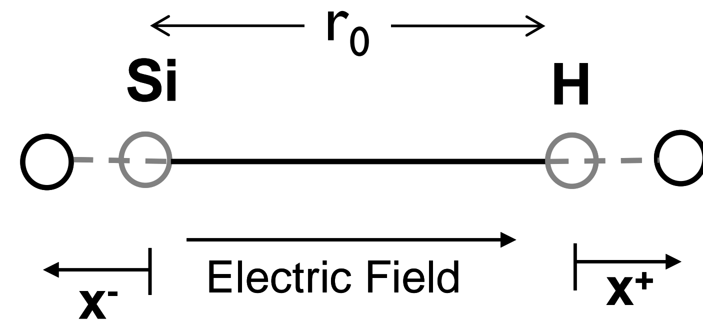
equilibrium

$$F_{Q^*} = -F_{-Q^*} = Q^* \times \mathcal{E}_{loc} - \gamma \times \left(x^+ - x^- \right) = 0$$

electrostatic Spring term

Additional displacement …

$$\left(x^+ - x^- \right) = Q^* \times \mathcal{E}_{loc} / \gamma$$

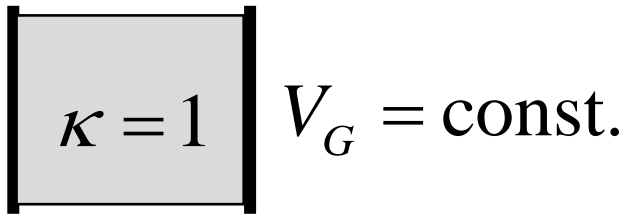


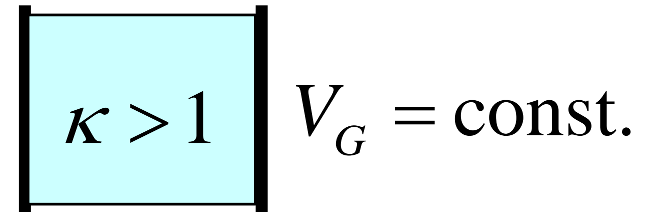
$$p = Q^* r = Q^* \left\{ r_0 + (x^+ - x^-) \right\} = \left[Q^* \times r_o \right] + \left[\left(Q^{*2} / \gamma \right) \times \mathcal{E}_{loc} \right]$$

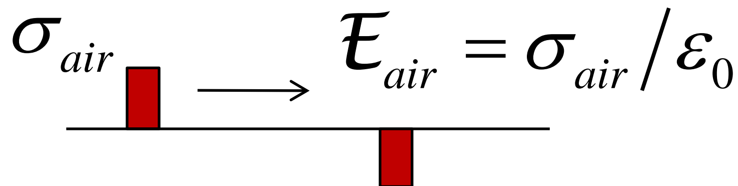
Permanent dipole Induced dipole

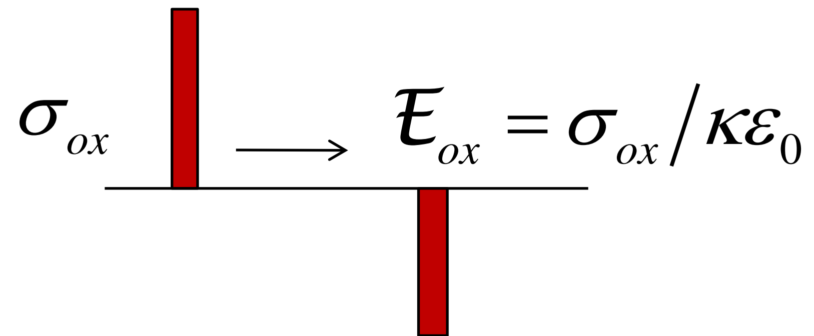
Aside: Calculation of E_{loc} from E_{ox} ....

$\mathcal{E}_{ox} = V_G / T_{ox}$ for any dielectric ...



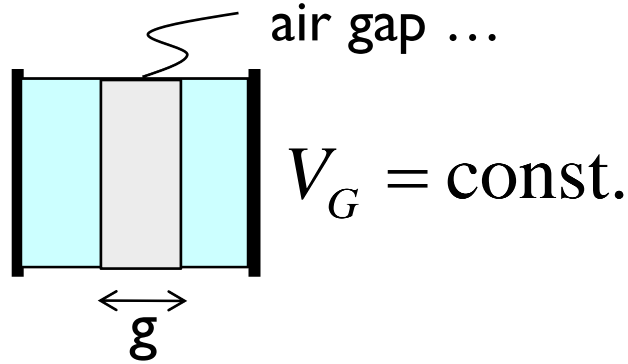


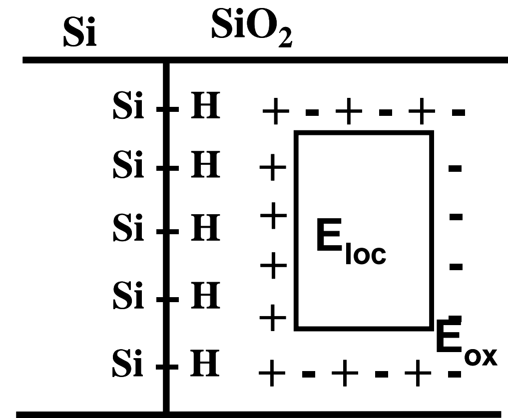




$$\mathcal{E}_{air} = \mathcal{E}_{ox} \Rightarrow \sigma_{ox} = \kappa\sigma_{air}$$

E_{loc} vs. E_{ox}: Field enhancement in gaps ….





$$\sigma^*_{ox} \quad \mathcal{E}^*_{ox} = \sigma^*_{ox} / \kappa_{ox}\varepsilon_0$$

$$\sigma^*_{ox} \quad \mathcal{E}_{air} = \sigma^*_{ox} / \varepsilon_0$$

$$\mathcal{E}_{loc} \equiv \mathcal{E}_{air} = \kappa_{ox}\mathcal{E}^*_{ox} \cong \kappa_{ox}\mathcal{E}_{ox}$$

$$\because \; \mathcal{E}_{loc}\, g + \mathcal{E}^*_{ox}\left(T_{ox} - g\right) = V_G$$

$$\mathcal{E}^*_{ox} = \frac{V_G}{T_{ox} + \left(\kappa_{ox} - 1\right) g} \xrightarrow{g\sim 0} \mathcal{E}_{ox}$$

Strong enhancement of local field for an isolated bond in a gap

Calculation of E_{loc} from E_{ox} ....

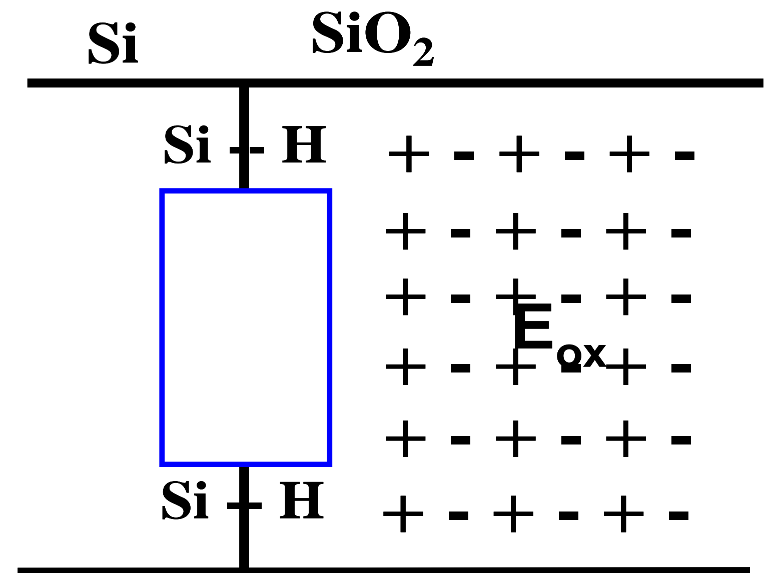
$$\Delta U_{Si-H} \approx \left[Q^* \times r_o \times \mathcal{E}_{loc} \right] \equiv a\mathcal{E}_{ox}$$

$$\mathcal{E}_{loc} \cong \kappa \mathcal{E}_{ox}$$

$$\Delta U_{Si-H} \approx \left[Q^* \times r_o \times \kappa \mathcal{E}_{ox} \right]$$

$$a = Q^* \times r_o \times \kappa \approx Q^* \times r_o \times \left(\frac{\kappa_{ox} + \kappa_{si}}{2} \right)$$

$$a = 0.15 * (4 + 12) / 2 = 0.9$$



$$N_{IT}(t) \propto \left(\frac{k_F N_0}{2k_R} \right)^{2/3} (D_{H_2} t)^{1/6}$$

$$k_F = k_0 p_h T \sigma e^{-(E_{F0} - aE_{ox})/k_B T}$$

$$\propto (p_h)^{2/3} e^{\frac{2\gamma_T E_{ox}}{3}} e^{-\frac{2(E_{F0} - aE_{ox})}{3k_B T}} e^{-\frac{E_A}{6k_B T}}$$

Putting back the pieces: Non-Arrhenius activation

$$N_{IT}(t) \propto \left(\frac{k_F N_0}{2k_R}\right)^{2/3} (D_{H_2} t)^{1/6}$$

$$k_F = k_0 p_h(\mathcal{E}_c) T(\mathcal{E}_{ox}) \sigma e^{-(E_{F0} - aE_{ox})/k_B T}$$

$$\Delta V_{IT} = \frac{q(\alpha \Delta N_{IT})}{C_{ox}}$$

$$k_R = k_{R0} e^{-(E_{R0})/k_B T}$$

$$N_{IT}(\mathcal{E}_{ox}, T, t) \propto (\mathcal{E}_c)^{2/3} e^{\frac{2}{3}\gamma_T E_{ox}} e^{-\frac{2(E_{F0} - aE_{ox} - E_{R0})}{3k_B T}} e^{-\frac{E_A}{6k_B T}} t^{1/6}$$

$$(\text{for fixed T}) \propto (\mathcal{E}_c)^{2/3} e^{\frac{2}{3}\gamma \mathcal{E}_{ox}} t^{1/6}$$

$$\gamma \equiv \left(\gamma_T + \frac{a}{k_B T}\right)$$

$$(\text{for fixed field}) \propto e^{-\frac{E_A^*}{6k_B T}} t^{1/6}$$

$$E_A^* = 4(E_{F0} - aE_{ox} - E_{R0}) + E_A$$

Outline

1. Background: Field dependent degradation

2. Components of field-dependent dissociation:
   Tunneling
   Hole density
   Bond polarization factor

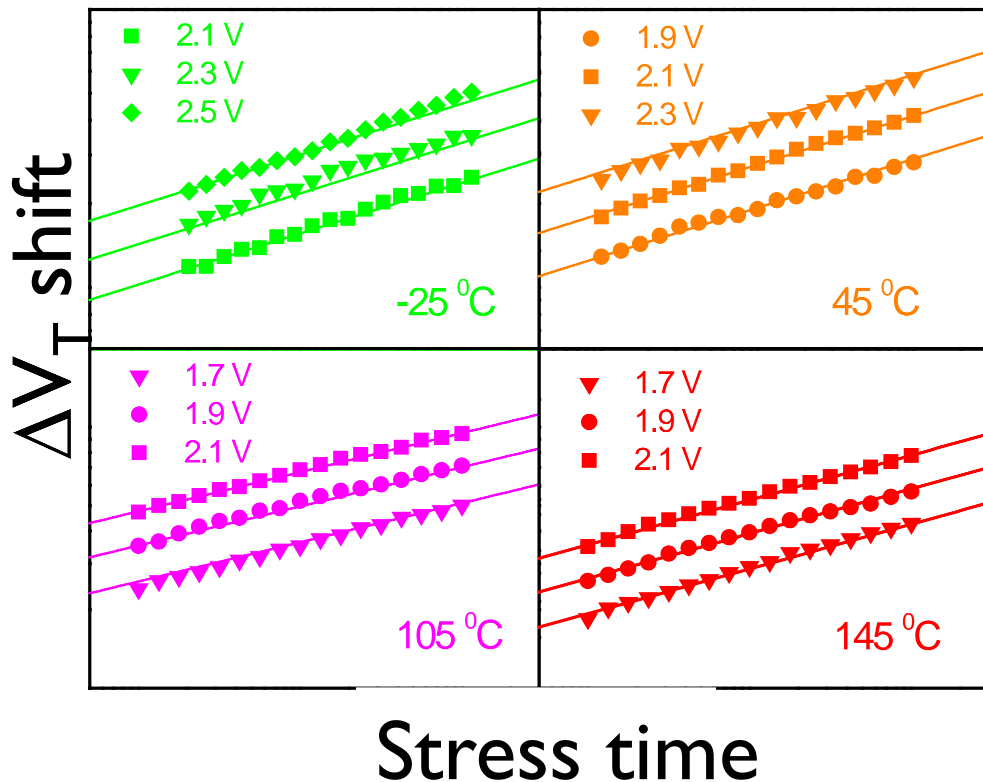
3. Interpreting experiments & voltage acceleration

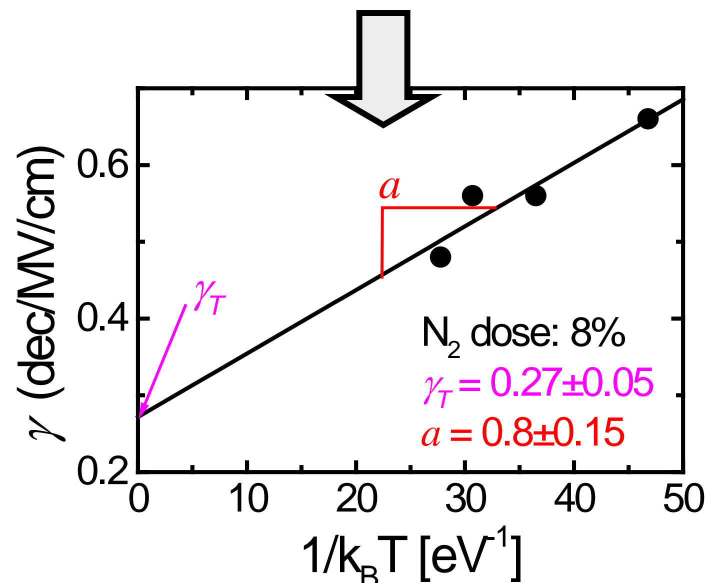
4. Conclusions

Experiments for γ_T and a

$\Delta V_T \sim |E_c|^{2/3} exp(2\gamma E_{ox}/3)\ t^n$

where, $\gamma = \gamma_T + a/k_B T$





From polarization
a = 0.6~1.2

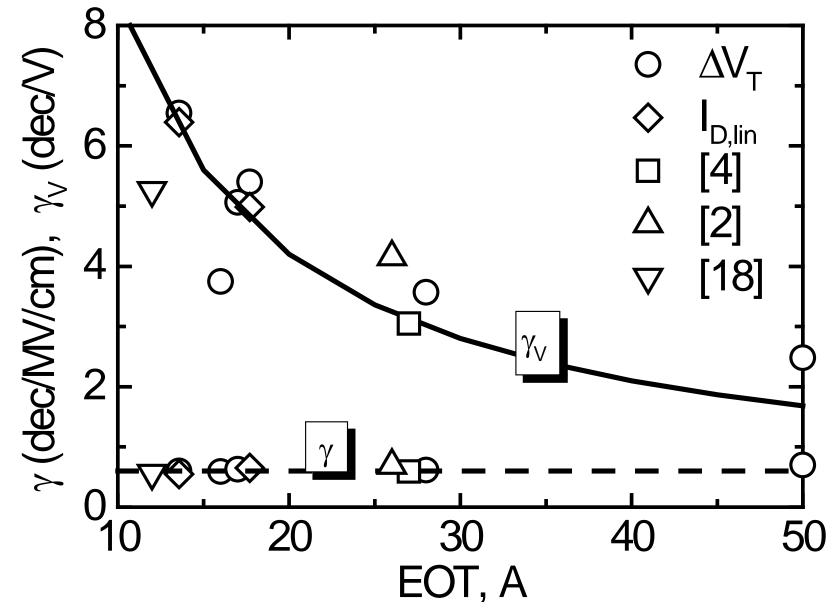
Voltage acceleration factors

To generate same number of defects at two different fields

$$E_1^{2/3}\exp\left(2\gamma E_1/3\right)t_1^{\,n}=E_2^{2/3}\exp\left(2\gamma E_2/3\right)t_2^{\,n}$$

$$\left(\frac{V_1}{V_2}\right)^{2/3}\exp\left[\frac{2\gamma\left(V_1-V_2\right)}{3\left(EOT\right)}\right]=\left(\frac{t_2}{t_1}\right)^{n}$$

$$\gamma_V\,(\text{in dec/V})\approx\frac{\log_{10}\left(t_1/t_2\right)}{\left(V_2-V_1\right)}=\frac{4\gamma}{2.3\left(EOT\right)}$$



Same voltage acceleration for all thicknesses ....

Conclusions

- We have discussed a simple theory of SiH bond dissociation based on the dielectric polarization. The theory appears consistent with experiments.
- NBTI phenomena has temperature-dependent voltage-acceleration and field-dependent temperature acceleration. Need careful analysis for determination of these important numbers.

Summary and Recommendation

1. Begin with a series of temperature, voltage, and duty cycle dependent experiments. Do not oversample, use on-the-fly or fast measurements (To be discussed in L17-20).
2. Decompose the contributions from interface defects and trapping. (See HW and Lectures 8-11)
3. Determine the time-exponents of individual components and compare with theoretical prediction.
4. Determine temperature activation energy by lateral scaling. Consider Arrhenius assumption carefully.
5. Determine polarization parameter **a** for field acceleration.
6. Now you have a complete model for NBTI degradation. Make projection and validate against long term data.

Self-Test Questions

1) Explain the difference between local field and global field within an oxide.
2) Explain physically why electric field decreases bond strength.
3) How does the dissociation process becomes non-Arrhenius?
4) Do you think the diffusion and repassivation will also become non-Arrhenius when field is applied? Why or why not?
5) Would field acceleration become smaller or larger for high-k dielectric for the same level of inversion charge?
6) Is NBTI a field-driven or voltage-driven phenomenon?
7) Can NBTI be described by classical voltage-independent voltage acceleration factors?