ECE695: Reliability Physics of Nano-Transistors
Lecture 16: Temperature dependence of HCl

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Outline

1. Empirical observations regarding HCl
2. Theory of bond dissociation: MVE vs. RRK
3. Hot carrier dissociation of SiH bonds
4. Hot carrier dissociation of SiO bonds
5. Conclusions
Empirical observations (1)

Less VT degradation at higher temperature

\( \Delta V_t ~ \text{Nit and Not confirms trap generation} \)

After dE correction, Nit could be larger at higher temperature

\( V_g = 3 \text{V}, \quad V_D = 7 \text{V} \)

Robust exponent, SiH dissociation?  

Variable exponent, SiO dissociation?
1. Empirical observations regarding HCl

2. Theory of bond dissociation: MVE vs. RRK

3. Hot carrier dissociation of SiH bonds

4. Hot carrier dissociation of SiO bonds

5. Conclusions
A model for HCl degradation
Carriers are no longer cold

(1) Electrons heated by field

SiH dissociation…

(2) Heating of electrons
Hot electrons break SiH bonds

SiO dissociation…

(3) Hot electron produces
Hot holes through II
Hot are trapped in oxide
Electron-hole recombination
breaks bonds
Dissociation by energy flow: What happened to activation of bond dissociation

Field induced

Charge State

Energy driven or e-h recombination

NBTI, TDDB

NBTI primarily

HCI, TDDB, etc.

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Dissociation of Si-H or Si-O bonds
Bond dissociation: RRK Theory

Recall from lecture 11 that

$$n_{\text{max}} \equiv \frac{E_F}{\Delta} = \frac{E_F}{\hbar \omega}$$

$$k_F^{\text{(NBTI)}} \approx (n_{\text{max}} + 1) \times \Gamma_A \left( \frac{\Gamma_A^{(0)}}{\Gamma_E^{(0)}} \right)^{n_{\text{max}}} \times \frac{E_F}{kT_L}$$

$$k_F^{\text{(HCI)}} \approx \left( f_{in} \frac{I_G(T_L)}{q} \right) \times \left( \frac{E_F - \Delta E_{IG}}{e kT_L} \frac{1}{\Gamma_E(T_L)} \right)$$

- Activation energy is considerably suppressed.
- Overall sign depends on current coupling

Weeks, Tully, Kimerling, PRB, 1975.
Bond dissociation at low voltages: 
**Coherent Multi-Vibrational Excitation**

Recall from **lecture 11** that in thermal equilibrium ...

Rates with injected current ...

\[ \Gamma_A = \Gamma_A^{(0)} + \left( \frac{I_G}{q} \right) f_{in} \quad \Gamma_E = \Gamma_E^{(0)} + \left( \frac{I_G}{q} \right) f_{in} \]

Dissociation rates of Si-H bonds ...

\[ F = (n_{\text{max}} + 1) \times \Gamma_A \left[ \frac{\Gamma_A^{(0)}/\Gamma_E^{(0)}}{\Gamma_E^{(0)}} \right]^{n_{\text{max}}} \]

\[ = (n_{\text{max}} + 1) \times \Gamma_A \left[ \frac{\Gamma_A^{(0)}}{\Gamma_E^{(0)}} + \left( \frac{I_{G,e}}{q} \right) f_{in} \right]^{n_{\text{max}}} \]

\[ F_{HCI} \left( \propto k_F \right) \approx (n_{\text{max}} + 1) \times \left( \frac{(I_G^{(e)}/q) f_{in}}{(\Gamma_E^{(0)})^{n_{\text{max}}}} \right) \]

\[ T.-C. Chen, Science, 1995. \]
1. Empirical observations regarding HCl
2. Theory of bond dissociation: MVE vs. RRK
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HCl T-Dependence: Si-H Dissociation

\[ N_{IT} = \left( \frac{\pi k_F N_O}{3 k_R} \right)^{1/2} \left( D_H t \right)^{1/2} \quad \text{... H model} \]

\[ = \left( \frac{\pi k_F N_O}{6 k_R} \right)^{2/3} \left( D_{H_2} t \right)^{1/3} \quad \text{...H}_2 \text{ model} \]

\[ N_{IT}(..,T) \propto \left( \frac{k_F(T)}{k_R(T)} \right)^p \left[ D_X(T) \right]^q \]

\[ D_X(T) = D_0 e^{-E_D/kT} \quad k_R(T) = k_{R,0} e^{-E_R/kT} \]

\[ k_F = (I_G^{(e)}) \otimes g(E_F) \]
Recall: Field dependence of HCl

\[ I_G^{(e)} = \int_0^l q n_0 \left( \frac{k_B T_e(x)}{2 \pi m^*} \right)^{1/2} e^{-\Phi_e / \Phi} e^{k_B T_e(x)} dx. \]

\[ \approx \frac{I_D}{\nu_{sat}} \left[ l \sqrt{\frac{q \mathcal{E}_m \lambda_e}{m^*}} \frac{U_0 q \lambda_e}{\Phi_e} \right] e^{-\Phi_e / q \mathcal{E}_m \lambda_e} \]

\[ \propto \frac{I_D}{\nu_{sat}} e^{-\left( \Phi_e l / q \lambda_e \right) / (V_D - V_{dsat})} \]

with \( \lambda_e(T_L) = \left[ \frac{2 n_{ph}(T_{ref}) + 1}{2 n_{ph}(T_L) + 1} \right] \lambda_e(T_{ref}) \)

T-dependence of ID (through \( \mu \) and \( V_T \)) and \( v_{sat} \) (through \( m \)) are weak.

MFP decreases with lattice temperature, making injection difficult.
Dissociation of SiH bonds

\[ k_{F, MVE}^{(\text{HCl})} \approx \left( \frac{I_G (e)}{q} f_{in} \right)^{n_{\text{max}}} \left/ \left( \Gamma_E^{(0)} \right)^{n_{\text{max}}} \right. \]

\[ \left( \Gamma_E^{(0)} \right)^{-n_{\text{max}}} = Be \]

\[ k_{F, RKK}^{(\text{HCl})} \approx \left( f_{in} \frac{I_G (T_L)}{q} \right) \times \left( \frac{E_F - \Delta E_{IG}}{e kT_L} \right) \]

\[ \left( \Gamma_E^{(0)} \right) = Be^{-(DT)} \]

Dissociation rates decreases rapidly with increase in temperature

Foley, PRL, 80(6), 1336 1998

FIG. 1. A 400 Å × 400 Å image of a Si(100)-Q × 1)/H surface imaged at 11 K after threshold STM patterning of a series of parallel lines.
SiH T-Dependence: MVE Theory

\[ N_{IT} \propto \left( \frac{k_F N_O}{k_R} \right)^m (D_H t)^n \]
\[ \propto \left( I_G F_{HCl} \right)^m (D_H)^n \]

\[ I_G \propto \frac{I_D}{\nu_{sat}} e^{-\left( \Phi_e I / q \lambda_e (T_L) \right) / (V_D - V_{dsat})} \]

\[ F_{HCl} \propto \left( \Gamma_E^{(0)} \right)^{-n} = B e^{-\frac{DE_F}{h \omega_0} T_L} \]

\[ D_H \equiv D_0 e^{-E_A / k_B T_L} \]

Taken together, the SiH bond dissociation is weakly T-dependent
Outline

1. Empirical observations regarding HCl
2. Hot carrier dissociation of SiH bonds
3. Hot carrier dissociation of SiO bonds
4. Conclusions
Si-O bond dissociation

Degree of heating of the carriers

Dissociation of the bonds
(1) Electrons heated by field

SiH dissociation...
(2) Hot electrons break SiH bonds

SiO dissociation...
(3) Hot electron produces
   Hot holes through II
   Hot holes break SiO bonds

Explore the T-dependencies of both
Recall: Heating of Electrons

Impact Ionization by the hot electrons generate hot holes

Hot hole
E > 4.7eV

Hot Electron
E > 3.1eV
Temp dependence of impact ionization

\[ I_{\text{sub}} = \int_0^1 I_e(x) \times S_{ii} \, dx . \]

\[ = \int_0^1 \, dx \int_0^\infty \, dE \times qn_0 \left( \frac{k_BT_e(x)}{2\pi m^*} \right)^{1/2} e^{-\frac{E}{k_BT_e(x)}} \times S_{ii} \left( E > E_T \right) \]

\[ = \int_0^1 \, dx qn_0 \left( \frac{k_BT_e(x)}{2\pi m^*} \right)^{1/2} \int_0^\infty \, dE \frac{-E}{\mathcal{E}_{m}\lambda_e} \times S_{ii} \left( E > E_T \right) \]

‘Hot’ electrons cooler at higher lattice temperature, because mean-free path is smaller.

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Recall: Rate of impact ionization

For $E > \Phi_{ii}$

$$S_{ii} \approx C_{ii} \left[ \left( \frac{E}{\Phi_{ii}} \right) - 1 \right]^{\gamma}$$

$$\Phi_{ii} \approx E_G(T_L) \left( 1 + \frac{m_e}{m_e + m_h} \right)$$

$\Phi_{ii} = 1.75 \text{ eV},$

$C_{ii} = 10^{12} \text{ s}^{-1},$

$\gamma = 1$

$m = 0.5m_0$
Impact ionization suppressed at higher $T$, so is the hot hole population.
T-Dependent SiO dissociation: RRK Theory

\[ N_{IT,\text{SiO}} = \sum_E g(E) \left[ 1 + e^{-k_F(V_G, V_D)t} \right] dE \]

\[ k_F \propto I_h \times e^{-\Phi_h/\mathcal{E}_m \lambda_h} \times F_{\text{siO}} \]

\[ I_h(T_L) = I_h(T_{L,\text{ref}}) e^{\frac{-\Phi_{ii}}{\mathcal{E}_m} \left[ \frac{1}{\lambda_e(T_L)} - \frac{1}{\lambda_e(T_{L,\text{ref}})} \right]} \]

\[ k_F^{(\text{HCl})} \propto \left( \frac{e^{-E_F - \Delta E_L}}{kT_L} \right) \Gamma_E(T_L) \]

SiO barrier larger, could be fully compensated
If compensated, what about VT shift?

\[ V_g = 3V, \quad V_D = 7V \]


Less degradation at higher temperature
\( \Delta I_{cp} \sim N_{it} \) and Not confirms trap generation
After \( \Delta E \) correction, \( N_{it} \) could be larger at higher temperature
The puzzle of VT shift

\[ V_G = \frac{V_D}{2} \]

Relative barrier height is larger at smaller temperature

Conclusions

1) HCI temperature dependence is pronounced for VT at lower temperature. The defect generation – as reflected in CP signal – is essentially temperature independent.

2) In general, it is more difficult to meet VT-based HCI lifetime requirement at lower temperature.

3) Two different theories could explain the temperature dependence of HCI – MVE and RRK theories.

4) HCI measurement allows a unique probe to the status of carriers within the devices and have often been used as a calibration tool for device modeling.

5) HCI based writing is the key to all Flash memories.


The electron-holes recombination theory is due to L.C. Kimberly discussed in “Recombination enhanced defect reactions”, Solid State Electronics, 21(11), 1978.

Negative temperature activation is discussed in Lifetimes of Hydrogen and Deuterium Related Vibrational Modes in Silicon M. Budde, PRL, 87(14), 2001.

IEEE TRANSACTIONS ON ELECTRON DEVICES. VOL. 37. NO 4. APRIL 1990, p. 980. Temperature dependence of the channel hot-carrier degradation of n-channel mosfet’s, PAUL HEREMANS, GEERT VAN DEN BOSCH, RUDI BELLENS, GUIDO GROESENEKEN.
Self Test Review questions

1. What is the difference between hot atom dissociation vs. cold atom dissociation?

2. Many experiments are reported at 77K and 295K. Why these temperatures?

3. Why is there such a big difference between VT degradation and NIT degradation?

4. Impact ionization threshold is significantly larger than Eg. What role does it have for HCl degradation? Explain.

5. Will there by no HCl degradation if VD reduced below impact ionization threshold? What theory would you use to calculate the defect generation rate.
ECE695: Reliability Physics of Nano-Transistors
Lecture 16: Appendices
Temperature dependence of HCl

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1. Equilibrium theory of forward and reverse dissociation

2. Rice-Ramsperger-Kassel Theory of bond dissociation

3. Multi-vibration Coherent Excitation Theory of Bond dissociation

4. Conclusion
Appendix 1: T-dependence of $k_F$ and $k_R$

Derive ... 

$$k_F = k_{F0} \times e^{\frac{-E_F}{k_BT}} \propto (n_{\text{max}} +1) \times e^{\frac{-E_F}{k_BT}}$$

$$F = \Gamma_0 \left( n_{\text{max}} +1 \right) \times \left[ \frac{\Gamma_{\text{ext}}}{\Gamma_{\text{ext}} + \Gamma_0} \right]^{n_{\text{max}} +1}$$

$$n_{\text{max}} \equiv \frac{E_F}{\hbar \omega_0} = \frac{E_F}{\Delta}$$

Consider an harmonic oscillator with equally spaced levels ...
Transition rates due to phonons

In a harmonic oscillator ...

\[ A u_n = \sqrt{n} u_{n-1} \]

\[ \langle n-1 | A | n \rangle = \sqrt{n} \hbar \]

Therefore the transition rate is ...

\[ M_{n-1,n} = \frac{2\pi}{\hbar} \left| \langle n-1 | A | n \rangle \right|^2 = n \hbar \]

\[ F_{(n-1) \rightarrow n} \equiv n\hbar \times \Gamma_A \times P_{n-1} \]

Absorbing/Emitting phonons in Equilibrium

Probability of a Si-H bond at the i-th vibration mode ...

\[ i \Gamma_A P_{i-1} + (i + 1) \Gamma_E P_{i+1} - (i + 1) \Gamma_A P_i - i \Gamma_E P_i = 0 \]

\[ \Gamma_A = \Gamma_0 \left( 1 - \frac{\delta}{2} \right) \quad \Gamma_E = \Gamma_o \left( 1 + \frac{\delta}{2} \right) \quad \frac{i + 1}{i} \to 1 \]

\[ \left. \frac{d^2 P}{d \varepsilon^2} \right|_i = \frac{P_{i-1} - 2P_i + P_{i+1}}{\Delta^2} = -\frac{\delta}{\Delta} \frac{2P_{i+1} - P_{i-1}}{2\Delta} \]

\[ \frac{d^2 P}{d \varepsilon^2} + \frac{\delta}{\Delta} \frac{dP}{d \varepsilon} = 0 \quad \Rightarrow P(\varepsilon) = C \times e^{-\delta \times \varepsilon / \Delta} \]
Absorbing/Emitting phonons in Equilibrium

\[ P(\varepsilon) = C \times e^{-\frac{\Delta \varepsilon}{\Delta}} \]

Detailed balance …

\[ \frac{\Gamma_A}{\Gamma_E} = e^{-\frac{\Delta}{k_B T}} \approx 1 - \frac{\Delta}{k_B T} \]

\[ \frac{\Gamma_A}{\Gamma_E} = \frac{\Gamma_0 (1 - \delta/2)}{\Gamma_0 (1 + \delta/2)} = 1 - \delta \]

\[ \delta = \frac{\Delta}{k_B T} \]

\[ P(\varepsilon_i) = C \times e^{-\frac{\varepsilon_i}{k_B T}} \]

and \( C \) by normalization

\[ \sum_i p(\varepsilon_i) = 1 \]

Approximate Bose-Einstein distribution
Net flux in Equilibrium

\[ F = (i + 1) \Gamma_A P_i - i \Gamma_E P_{i+1} \]

\[ = (i + 1) \Gamma_A P_i \left( 1 - \frac{\Gamma_E}{\Gamma_A} \frac{P_{i+1}}{P_i} \right) \]

\[ = (i+1) \times \Gamma_A P_i \left( 1 - e^{\frac{\Delta}{k_B T}} e^{\frac{-\Delta \times (i+1)}{k_B T}} e^{\frac{-\Delta \times (i)}{k_B T}} \right) = 0 \]

\[ \Gamma_A \quad P_i \quad \Gamma_E \]

... as expected.
Meaning of the distribution ...
Probability that a Si-H climbs the barrier

... that it finally absorbs a phonon to break the bond

\[ F = \left( n_{\text{max}} + 1 \right) \times \Gamma_A \times e^{-\frac{E_F}{k_B T}} \]

\[ \equiv k_{F0} \times e^{-\frac{E_{F0}}{k_B T}} \]
Appendix 2: Hot carrier induced dissociation by MVE (Coherent)

In thermal equilibrium ...
\[ \Gamma_A^{(0)} = \Gamma_E^{(0)} \times e^{\frac{-\hbar \omega_0}{k_B T}} \]

Rates with injected current ...
\[ \Gamma_A = \Gamma_A^{(0)} + (I/q)f_{in} \quad \Gamma_E = \Gamma_E^{(0)} + (I/q)f_{in} \]

Dissociation rates of Si-H bonds ...
\[ F = (n_{\text{max}} + 1) \times \Gamma_A \left[ \frac{\Gamma_A}{\Gamma_E} \right]^{n_{\text{max}}} \]
\[ n_{\text{max}} = \frac{E_F}{\Delta} = \frac{E_F}{\hbar \omega} \]
\[ = (n_{\text{max}} + 1) \times \Gamma_A \left[ \frac{\Gamma_A^{(0)} + (I/q)f_{in}}{\Gamma_E^{(0)} + (I/q)f_{in}} \right]^{n_{\text{max}}} \]
\[ \approx (n_{\text{max}} + 1) \times \Gamma_A \left[ \frac{\Delta}{\Gamma_E^{(0)} e^{\frac{-\hbar \omega}{k_B T}} + (I/q)f_{in}} \right]^{n_{\text{max}}} \]
\[ \approx (n_{\text{max}} + 1) \times \left[ \frac{(I/q)f_{in}}{\left( \Gamma_E^{(0)} \right)^n} \right]^{n_{\text{max}} + 1} \]

Salam, PRB, 1994.
Hot carrier induced dissociation

In thermal equilibrium …

\[ \Gamma_A^{(0)} = \Gamma_E^{(0)} \times e^{-\frac{\hbar \omega_0}{k_B T}} \]

Rates with injected current …

\[ \Gamma_A = \Gamma_A^{(0)} + \left( \frac{I}{q} \right) f_{in} \quad \Gamma_E = \Gamma_E^{(0)} + \left( \frac{I}{q} \right) f_{in} \]

Dissociation rates of Si-H bonds …

\[ F = (n_{\text{max}} + 1) \times \Gamma_A^{1} \left[ \frac{\Gamma_A^{(0)} + (I/q)f_{in}}{\Gamma_E^{(0)} + (I/q)f_{in}} \right]^{n_{\text{max}}} \]

\[ = (n_{\text{max}} + 1) \times \Gamma_A^{1} \left[ \frac{\Gamma_A^{(0)} + (I/q)f_{in}}{\Gamma_E^{(0)} + (I/q)f_{in}} \right]^{n_{\text{max}}} \]

\[ \approx (n_{\text{max}} + 1) \times \Gamma_A^{1} \left[ \frac{\Delta}{\Gamma_E^{(0)} e^{-\frac{\hbar \omega_0}{k_B T}} + (I/q)f_{in}} \right]^{n_{\text{max}}} \]

\[ \approx (n_{\text{max}} + 1) \times \frac{\left[ (I/q)f_{in} \right]^{n_{\text{max}} + 1}}{\left( \Gamma_E^{(0)} \right)^n} \]

Salam, PRB, 1994.
Appendix 3: Derivation of the RRK Model

Show that the occupation of level $i$ for a molecule with $s$-degrees of freedom in equilibrium is given by …

$$P_{i,0} \sim \frac{1}{(s-1)!} \left( \frac{E}{kT} \right)^{s-1} \frac{e^{-E_i/k_B T}}{kT}$$

And that any one of the atom within the molecule will get energy more than $E^*$ is given by the DOS

$$D(E) = \left( E - E^* / E \right)^{s-1}$$

So that the enhanced dissociation is given by

$$F_{IG} \propto \frac{m(I_G f_i / q) \left( E^* - E_{IG} \right)^{s-1}}{\left( \Gamma_A + \Gamma_E \right)} \times e^{-(E^* - E_{IG} / kT)}$$

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Dissociation with an energy kick

Probability of a Si-H bond at the i-th vibration mode with kick ...

\[ i\Gamma_A P_{i-1} + (i+1)\Gamma_E P_{i+1} - (i+1)\Gamma_A P_i - i\Gamma_E P_i + (I_G f_i / q)P_{i-k} = 0 \]

Solve for i-th state..

\[ P_i = \frac{i}{(\Gamma_A + \Gamma_E)}(\Gamma_E P_{i+1} + \Gamma_A P_{i-1}) + \frac{iP_{i-k}}{(\Gamma_A + \Gamma_E)}(I_G f_i / q) \]

For \( s=1 \), \( P_{i,0} = \frac{e^{-E_i / k_B T}}{kT} \) (See L11)

For \( s>1 \) \( P_{i,0} \sim \frac{1}{(s-1)!} \left( \frac{E}{kT} \right)^{s-1} e^{-i\Delta / k_B T} \frac{e^{-i\Delta / k_B T}}{kT} \)

Will now be shown ....
Distribution function with internal degree of freedom (e.g. two atoms, $S=1$)

For $s>1$ $P_{i,0} \sim \frac{1}{(s-1)!}\left(\frac{E}{kT}\right)^{s-1} e^{-\frac{i\Delta}{k_BT}}$

$$f(E) = \frac{e^{-E/k_BT}}{kT} dE$$

$$f(E = E_1 + E_2) = f(E_1)f(E_2) = \left(\frac{1}{kT}\right)^2 e^{-E/k_BT} dE_1 dE_2$$

$$f(E_A \leq E \leq E_B) = f(0 \leq E \leq E_B) - f(0 \leq E \leq E_A)$$

$$f(0 \leq E \leq E_A) = \left(\frac{1}{kT}\right)^2 e^{-E/k_BT} \int_{0}^{E_A} dE_1 \int_{0}^{E_A-E_1} dE_2$$

$$= \left(\frac{1}{kT}\right)^2 e^{-E/k_BT} \frac{E_A^2}{2!}$$
Dissociation with an energy kick

Continuing after the previous page …

\[ f(E_A \leq E \leq E_B) = f(0 \leq E \leq E_B) - f(0 \leq E \leq E_A) \]

\[ = \left( \frac{1}{kT} \right)^2 e^{-E/k_B T} \left( \frac{E_B^2 - E_A^2}{2!} \right) \]

\[ = \left( \frac{1}{kT} \right)^2 e^{-E/k_B T} \left( \frac{(E_A + dE)^2}{2!} - \frac{E_A^2}{2!} \right) \]

\[ = \left( \frac{1}{kT} \right)^1 e^{-E/k_B T} \frac{E_A^1}{1!} \frac{dE}{kT} = \left( \frac{E_A}{kT} \right)^{s-1} e^{-E_A/k_B T} \frac{1}{(s-1)!} \frac{dE}{kT} \]
Dissociation with an energy kick

\[ P_i = \frac{i}{(\Gamma_A + \Gamma_E)}(\Gamma_E P_{i+1} + \Gamma_A P_{i-1}) + \frac{iP_{i-k}}{(\Gamma_A + \Gamma_E)}(I_G f_i / q) \]

Insert \( P_{i,0} \sim \frac{1}{(s-1)!}(\frac{E}{kT})^{S-1} e^{-i\Delta/k_BT} + \frac{e^{-E_i/k_BT}}{kT} \) (if \( S=1 \), See L11)

\[ F \equiv F_{\text{thermal}} + F_{IG} = \sum_{i=m-k}^{\infty} P_S P_i \text{ where } P_S = (E - E^*/E)^{S-1} \]

\[ F_{IG} \propto \int_{E^*}^{\infty} dE (E - E^*/E)^{S-1} \frac{1}{(s-1)!}(\frac{E - E_{IG}}{kT})^{S-1} e^{-(E-E_{IG})/k_BT} \]

\[ = \frac{m(I_G f_i / q)}{\Gamma_A + \Gamma_E} \left( \frac{E^* - E_{IG}}{E^*} \right)^{S-1} e^{-(E^* - E_{IG})/kT} \times e^{-(E^* - E_{IG})/kT} \]

\[ \sim \frac{(I_G f_i / q)}{\Gamma_E} \times e^{-(E^* - E_{IG})/kT} \text{ (for } S=1) \]
Appendix 4: Si-H vs. Si-D bond dissociation

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

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Hydrogen vs. Deuterium Experiments
(wrong interpretation through bound levels)

\[ F_{IG} \sim \frac{(I_G f_i / q)}{\Gamma_E} \times e^{-(E^* - E_{IG} / kT)} \quad \text{for } S=1 \]

This is wrong

\[ F_{IG}^{SiD} \sim \frac{(I_G f_i / q)}{\Gamma_{E,D}} \times e^{-(E_D^* - E_{IG}/kT)} \]

\[ F_{IG}^{SiH} \sim \frac{(I_G f_i / q)}{\Gamma_{E,H}} \times e^{-(E_H^* - E_{IG}/kT)} \]

\[ \frac{F_{IG}^{SiH}}{F_{IG}^{SiD}} \sim \frac{\Gamma_{E,D}}{\Gamma_{E,H}} \times e^{+(E_D^* - E_H^*)/kT} \]

Mass effect dominant (incorrect)

Phonon coupling to substrate can be neglected (incorrect)
Hydrogen vs. Deuterium Experiments (correct interpretation with phonon coupling)

\[
F_{IG} \sim \frac{(I_G f_i / q)}{\Gamma_E} \times e^{-\left(\frac{E^* - E_{IG}}{kT}\right)} \quad \text{(for } S=1) \\
\]

\[
F_{IG}^{SiD} \sim \frac{(I_G f_i / q)}{\Gamma_{E,D}} \times e^{-\left(\frac{E^* - E_{IG}}{kT}\right)} \\
\]

\[
F_{IG}^{SiH} \sim \frac{(I_G f_i / q)}{\Gamma_{E,H}} \times e^{-\left(\frac{E^* - E_{IG}}{kT}\right)} \\
\]

\[
\frac{F_{IG}^{SiH}}{F_{IG}^{SiD}} \sim \frac{\Gamma_{E,D}}{\Gamma_{E,H}} \\
\]

Phonon coupling to substrate is the dominant cause. SiD better coupled to substrate, so has larger gamma for relaxation.