

# ECE695: Reliability Physics of Nano-Transistors

## Lecture 22: Voltage Dependence of Thin Dielectric Breakdown

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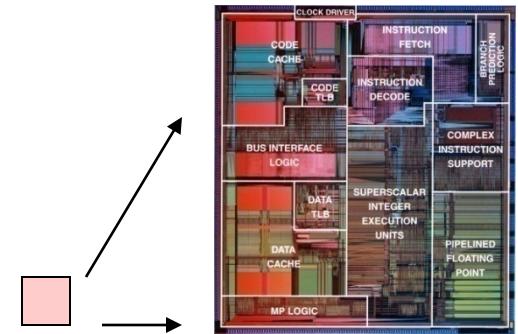
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# Outline

- I. Background: Voltage Acceleration for TDDB
2. Anode Hole Injection Model
3. Verification of Anode Hole Injection Model
4. Universality of Voltage Acceleration
5. Conclusions

# Dielectric Lifetime of an IC ...

$$T_{BD}^{50\%}(A_{IC}) = (A_{TEST} / A_{IC})^{1/\beta} T_{BD}^{50\%}(A_{TEST})$$

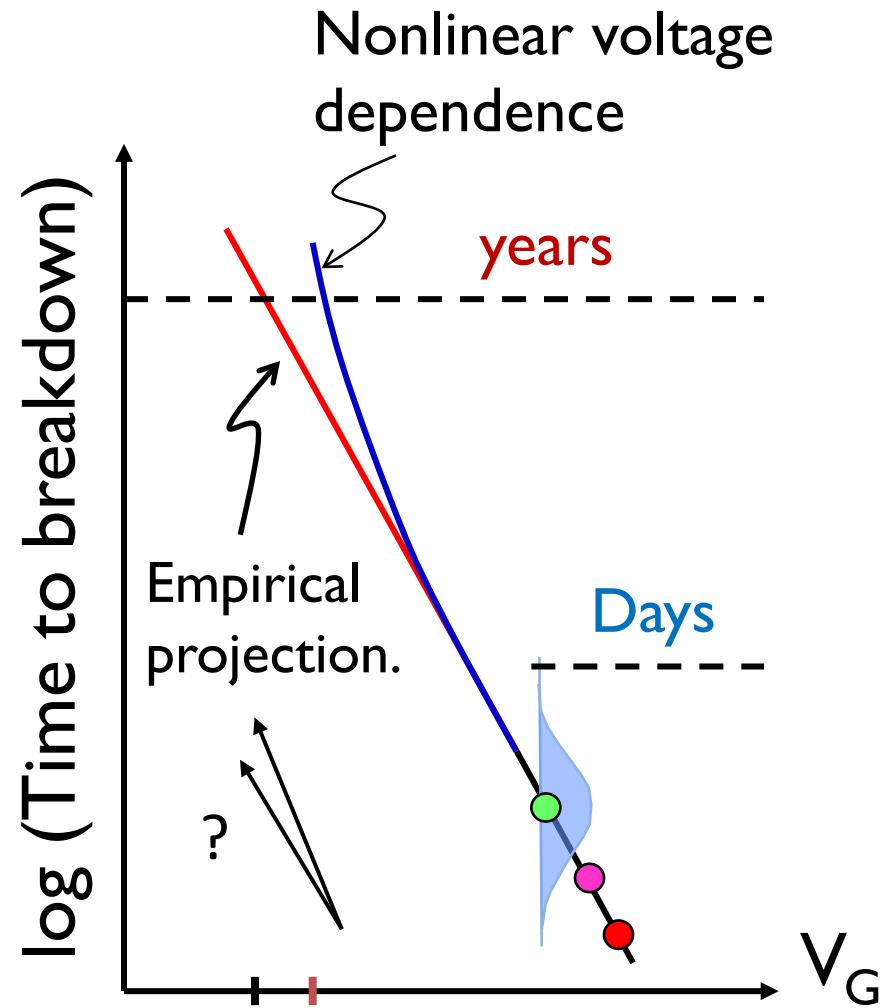
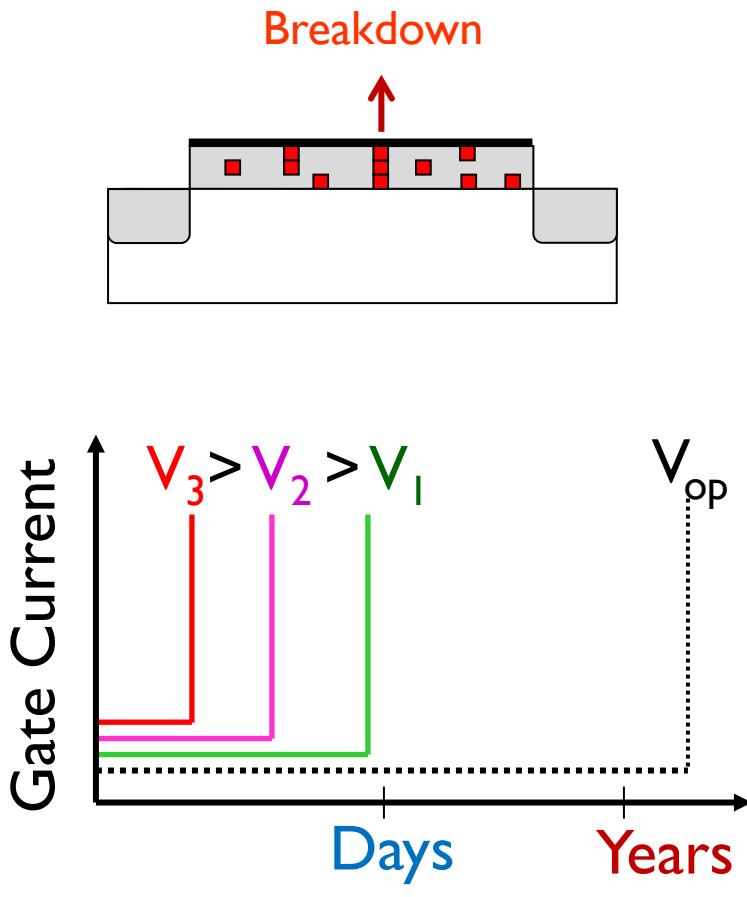


$$T_{BD}^{q\%}(A_{IC}) = \left[ \frac{\ln(1 - q/100)}{\ln(1 - 0.5)} \right]^{1/b} T_{BD}^{50\%}(A_{IC})$$

$$V_{safe} = V_{test} - \log \left[ \frac{10 \text{ yrs}}{T_{BD}^{q\%}} \right] / \gamma_{V,acc}$$

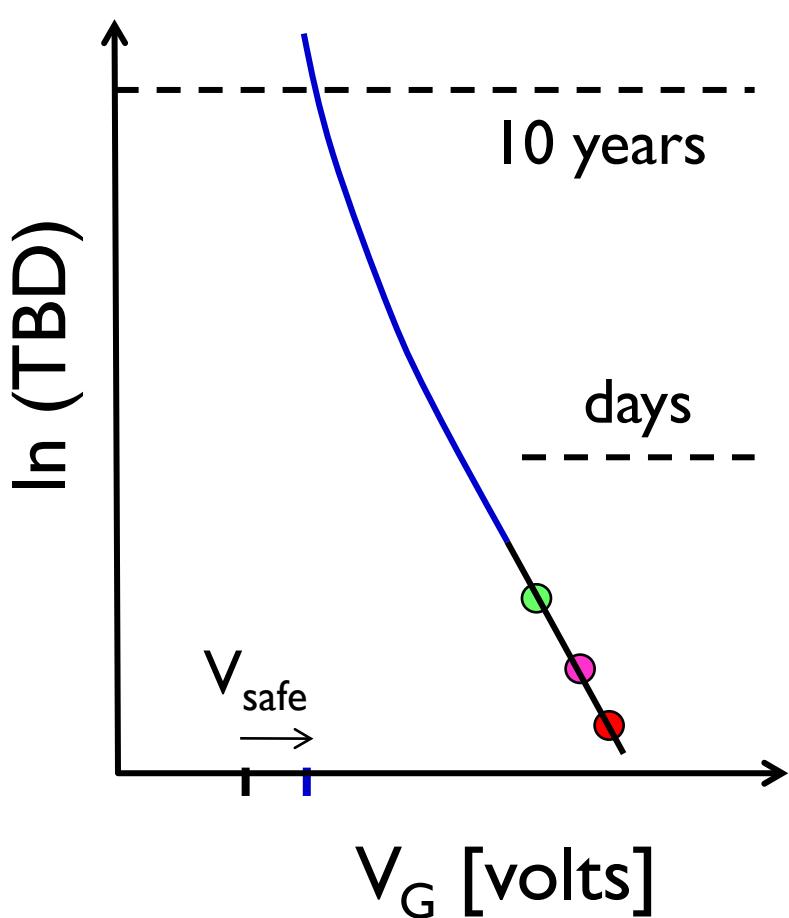
These three formula are sufficient for derive dielectric lifetime

# Basics of voltage acceleration

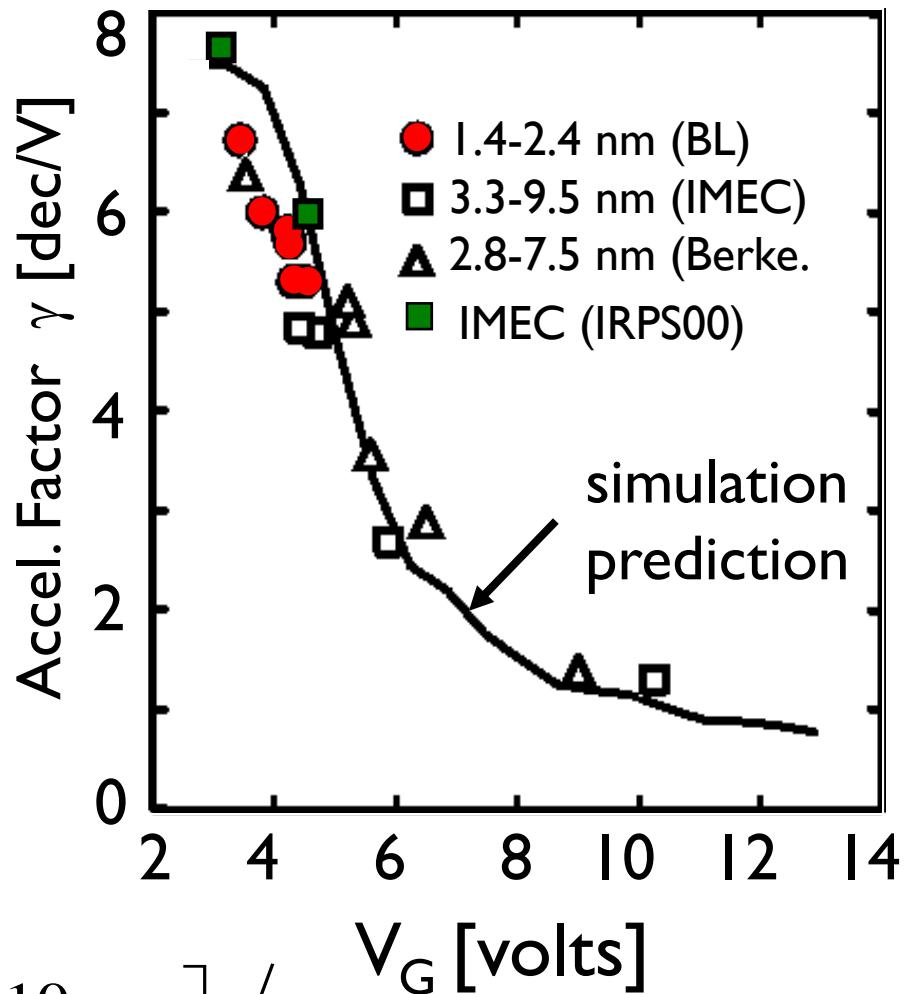


Highly accelerated voltage dependence

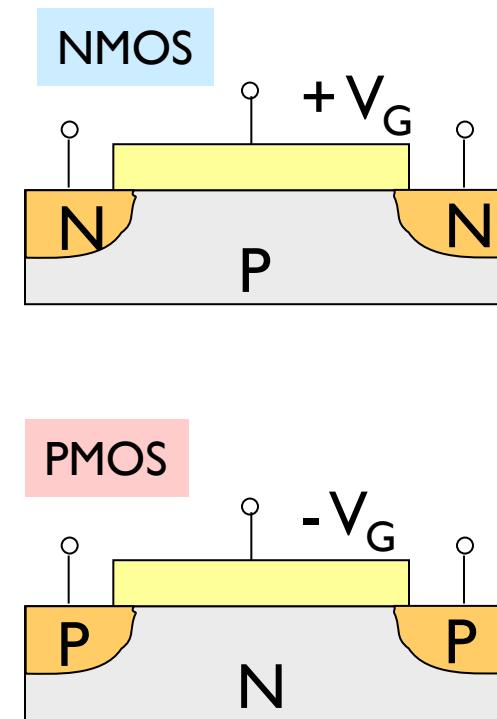
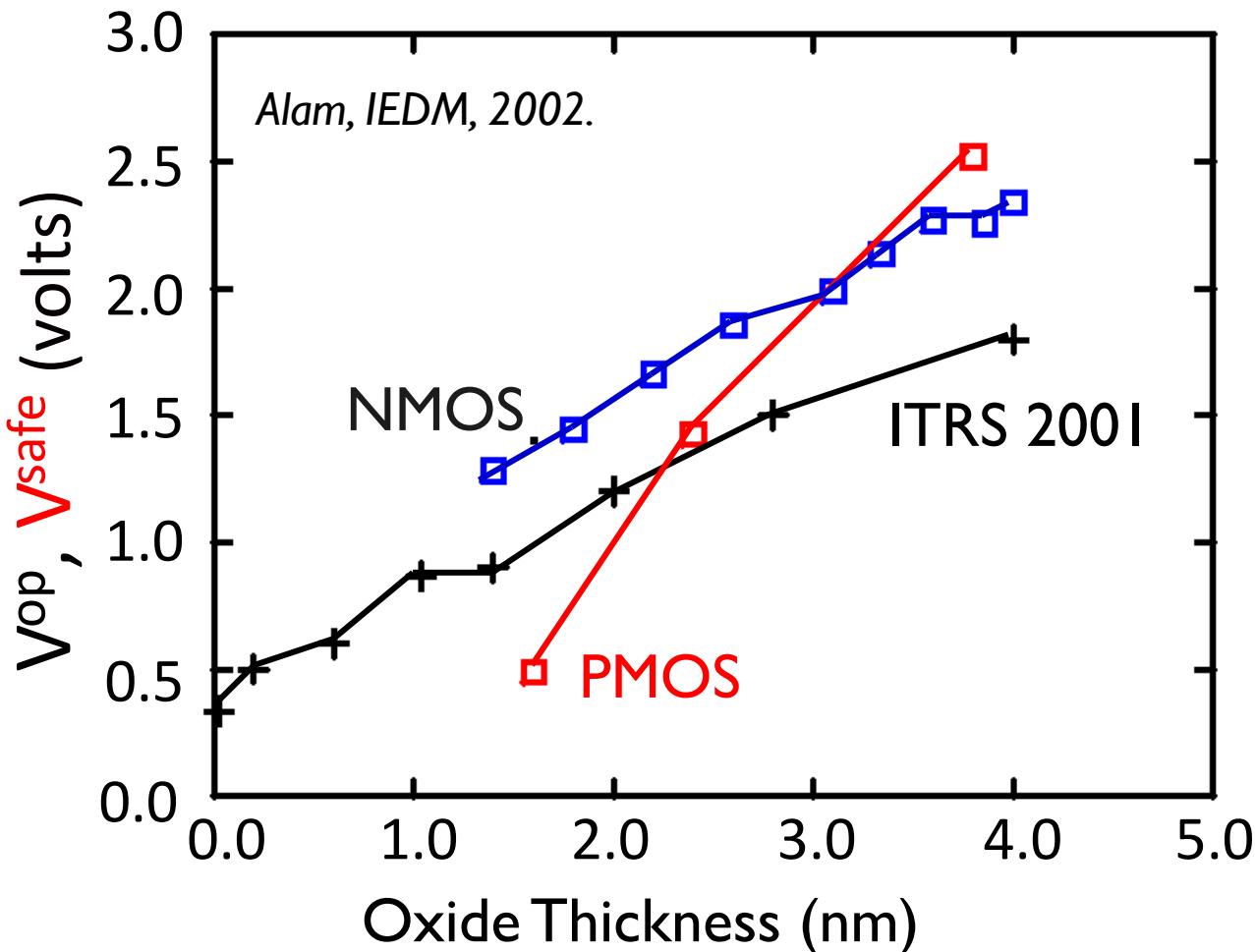
# Reduced Defect Generation at Low Voltage



$$V_{safe} = V_{test} - \log \left[ \frac{10 \text{ yrs}}{T_{BD}} \right] / \gamma_{V,acc}$$



# NMOS vs. PMOS Reliability



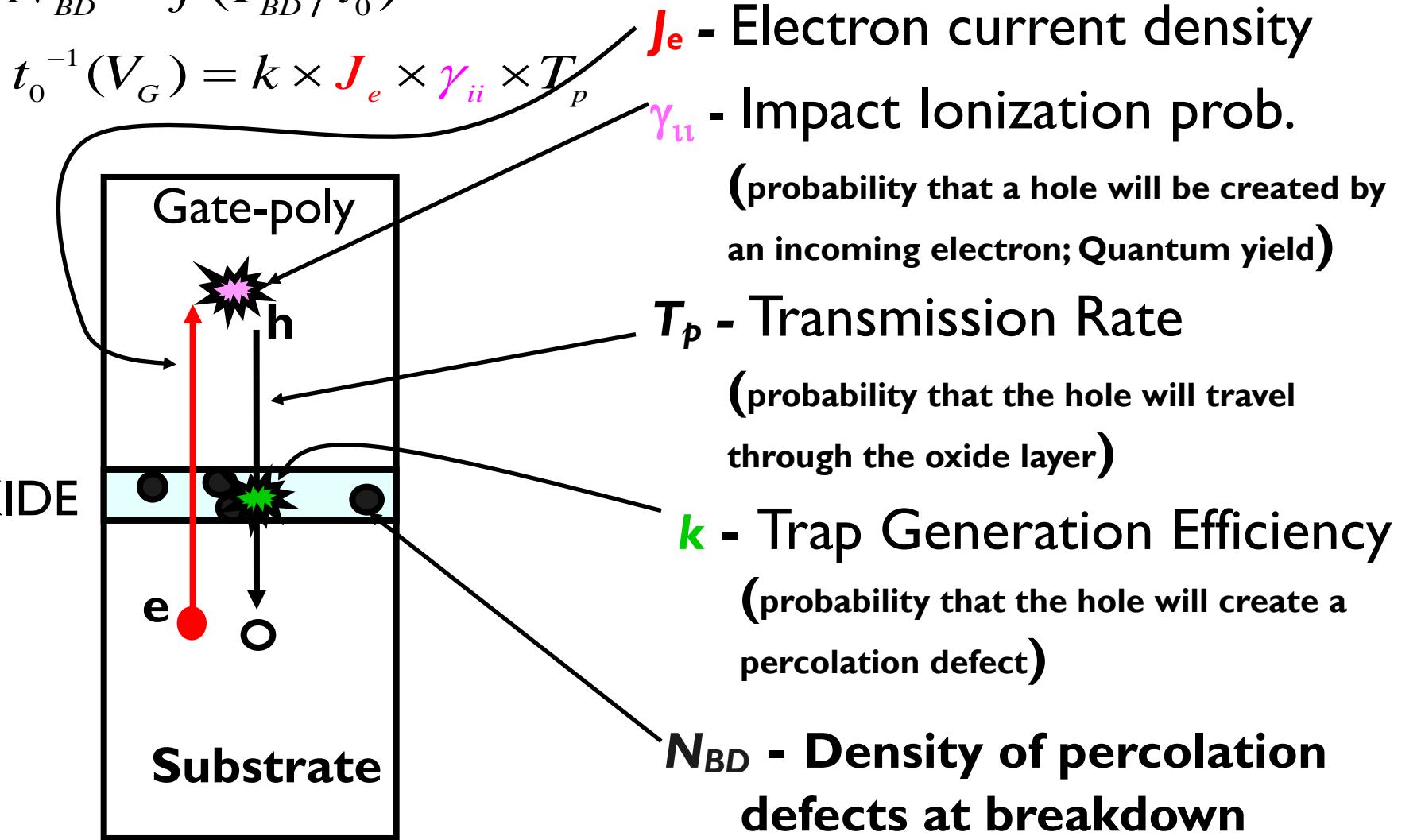
PMOS less reliable than NMOS, contacts defines everything !

# Outline

- I. Background: Voltage Acceleration for TDDB
2. Anode Hole Injection Model for SiO dissociation
3. Verification of Anode Hole Injection Model
4. Universality of Voltage Acceleration
5. Conclusions

# Theory of Anode Hole Injection

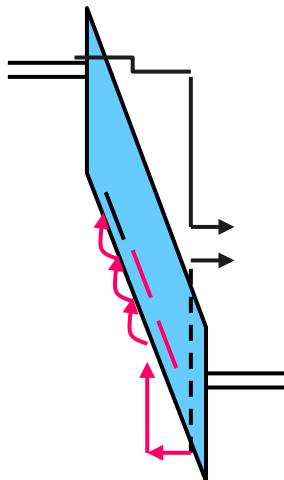
$$N_{BD} = f(T_{BD}/t_0)$$



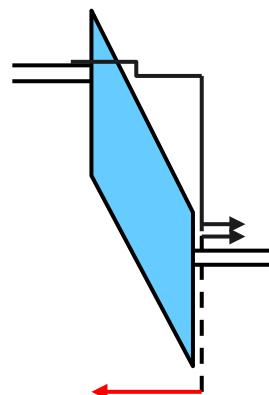
Ballistic transport and hot contacts ... in 1980s!

# Theory of TDDB: Three Regimes

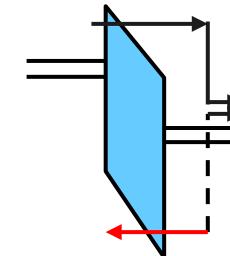
$$V_g > 13\text{ V}$$



$$13\text{ V} > V_g > 8\text{-}9\text{ V}$$



$$V_g < 8\text{-}9\text{ V}$$



## Oxide Ionization (Fischetti, 1984)

- origin of velocity saturation by acoustic phonons
- field dependence of impact ionization
- correlating holes to breakdown

## Plasmon Excitation (Fischetti 1985-1987)

- origin of holes in the oxide at this voltage
- 7.5 eV threshold ?
- metal gate

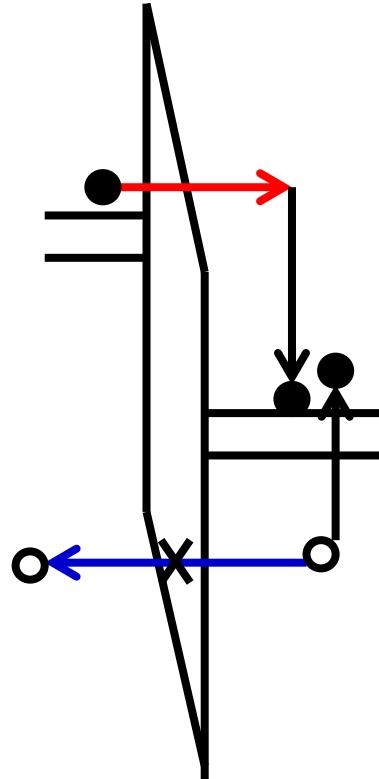
## Impact Ionization (1996 ..)

- polarity asymmetry
- connecting reliability to AHI

We will focus here

# Basic Anode Hole Injection Model

$$N_{BD} = f(T_{BD}/t_0) \quad t_0^{-1} \propto \mathbf{J}_e \times \gamma_{ii} \times \mathbf{T}_p$$



$$\mathbf{J}_e = A_1 \exp(-A_2/\mathcal{E})$$

$$\gamma_{ii} = B_1 \exp(-B_2/\mathcal{E}) \quad t_0^{-1} \propto \mathcal{E}$$

$$\mathbf{T}_p = C_1 \exp(-C_2/\mathcal{E})$$

$$T_{BD} = t_0 \times f^{-1}(N_{BD})$$

SUB OXIDE POLY

$$\ln(T_{BD}) = \ln(t_0) \propto 1/\mathcal{E}$$

# Constant field Impact Ionization

For thick oxide and HCl .....

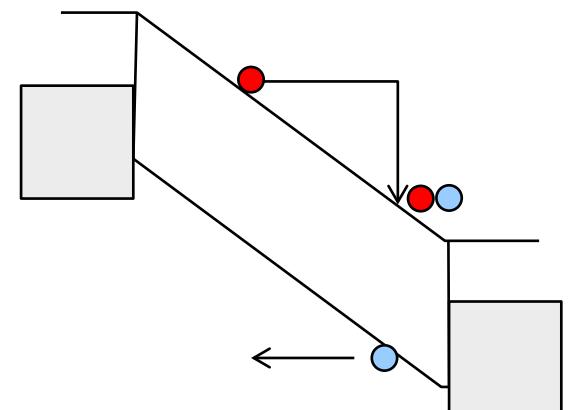
$$\frac{dI}{dz} = \alpha_{ii} I \quad \alpha_{ii} \equiv \int_{-\infty}^{\infty} dk W_{inp} f / \int_{-\infty}^{\infty} dk f$$

$$\alpha_{ii} \propto \gamma_{ii} \sim \exp(-\text{const.}/\mathcal{E}^k) \quad k \sim 1-2$$

$$q\mathcal{E}\nu_d = \frac{3}{2} \frac{k_B (\mathcal{T}_e - T_o)}{\tau_E} \sim \frac{k_B \mathcal{T}_e}{\tau_E}$$

$$k_B T_e = q\mathcal{E}\nu_d \tau_E \equiv q\mathcal{E} \times l_0$$

$$\alpha_{ii} \propto \gamma_{ii} = e^{-E_G/k_B \mathcal{T}_e} \sim e^{-B_2/\mathcal{E}}$$



Apparently the term Lucky electron model was coined by Shockley.

# ... vs. bulk impact ionization

For thin oxide TDDB

$$\alpha_{ii} = \int \frac{2\pi}{\hbar} |M|^2 \delta(E_f - E_i) dS_f$$

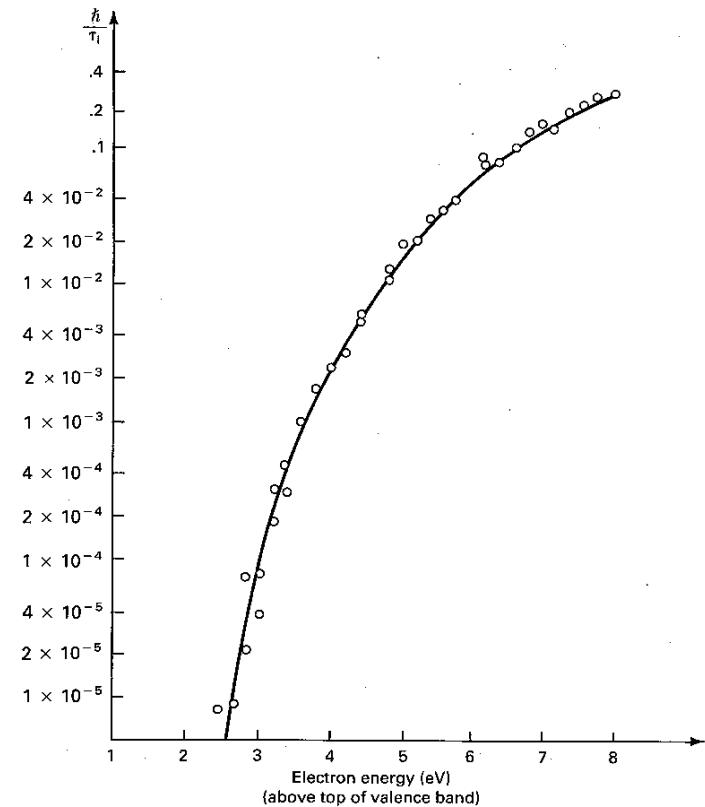
$$\sim 5 \times 10^{11} \left( \frac{E - E_{G,T}}{E_{G,T}} \right)^2$$

$$\frac{\alpha_{ii}}{1/\tau_{II}(E_T)} \propto \gamma_{ii} = B \left( \frac{E - E_{G,T}}{E_{G,T}} \right)^p$$

$1/\tau_{II}$  ≡ Energy, not momentum relaxation

$$\gamma_{ii} \sim 1-3 \quad (E > E_{g,th})$$

$$\sim \exp(DV) \quad (E < E_{g,th})$$

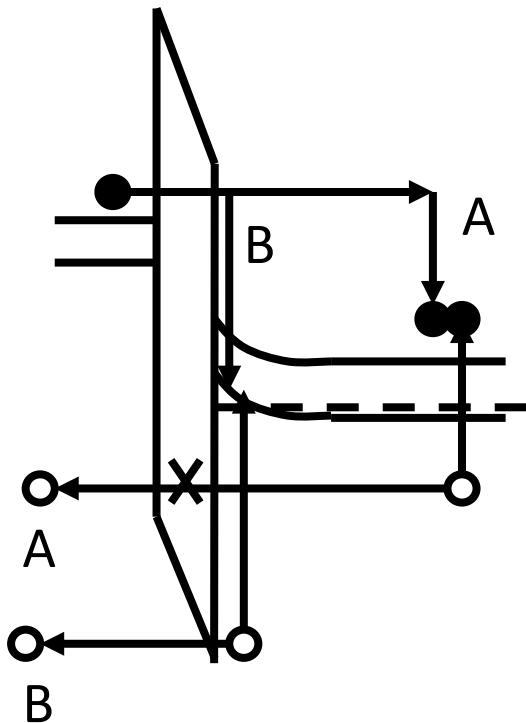


Ridley, *Quantum Processes*,  
p. 276-278.  
Hess, p. 190, Ch. 13 – Fig. 13.17..

# AHI Model: At High and Low Voltages

$$J_h = J_e \gamma_{ii} T_p$$

Schrödinger-Poisson Eq.  
Full Band Monte Carlo



If  $V_g$  is relatively high ...

$$J_e = A_1 \exp(-A_2/\mathcal{E})$$

$$\alpha_{ii} = 1 - 2 \quad T_p \sim \text{const.}$$

$$\ln(T_{BD}) \sim (J_e \gamma_{ii} T_p)^{-1} \sim 1/\mathcal{E}$$

If  $V_g$  is relatively low ...

$$J_e = f(\mathcal{E})$$

$$\langle \gamma_{ii} T_p \rangle = M \exp(DV_G)$$

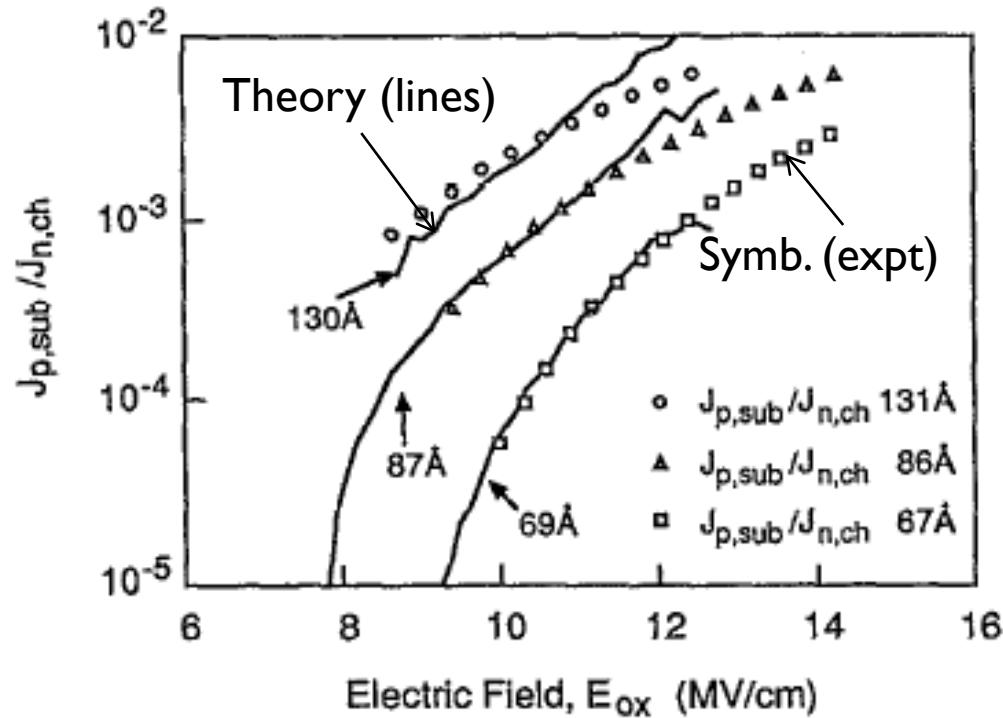
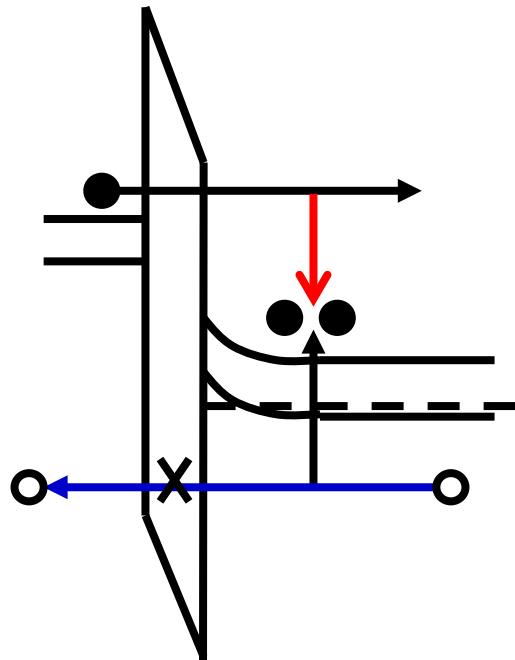
$$\ln(T_{BD}) \sim -\ln(J_e \gamma_{ii} T_p) = -\gamma_V V_G$$

# AHI – Analytical theory at moderate voltage

$$J_{p,sub} = AJ_e \times \gamma_{ii} \times \left( \frac{C(W_{eg} - E_{g,th})}{2\pi m_h^*} \right)^{1/2} \times \exp \left( -\frac{q\Phi_b - \beta \mathcal{E}_{ox}^{1/2}}{C(W_{eg} - E_{g,th})} \right)$$

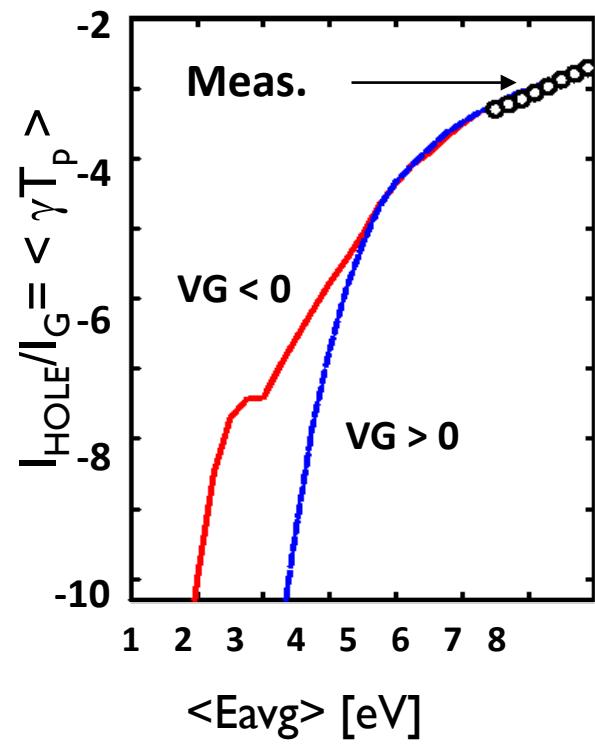
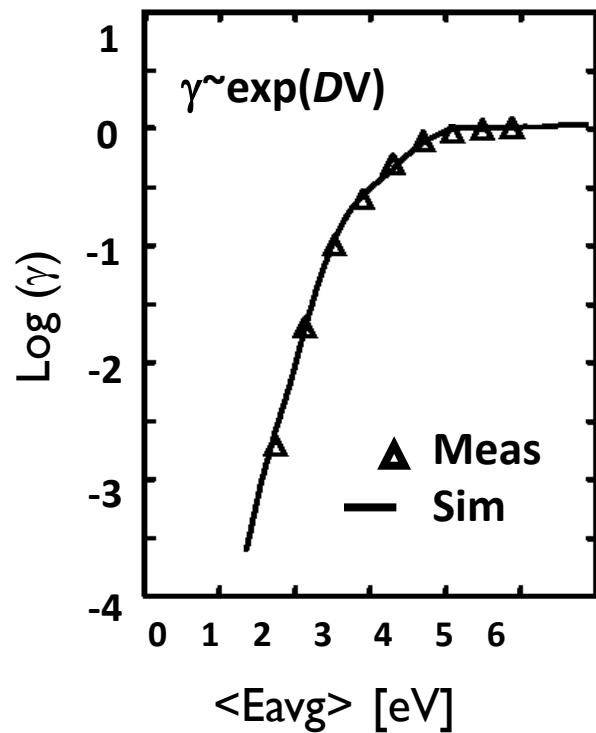
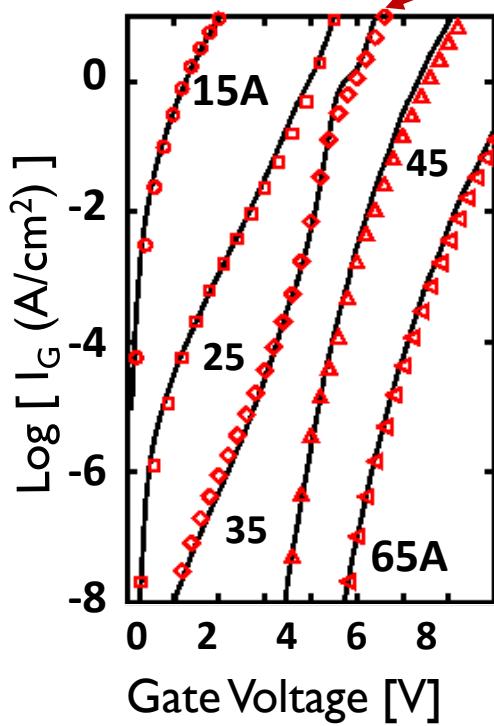
$$\mathcal{E}_{ox} = V_{ox} / T_{ox}$$

$$A = 0.0018 \text{ s/m}, C = 0.055$$



# AHI Model at low voltage: Numerical Calculation

$$J_h = J_e \times p_{ii} \times T_p$$

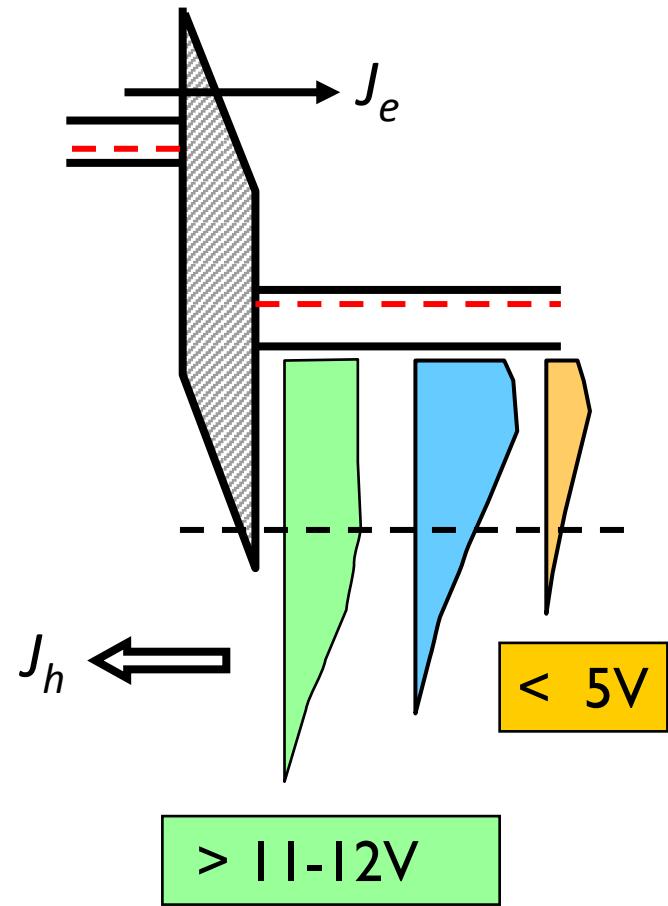
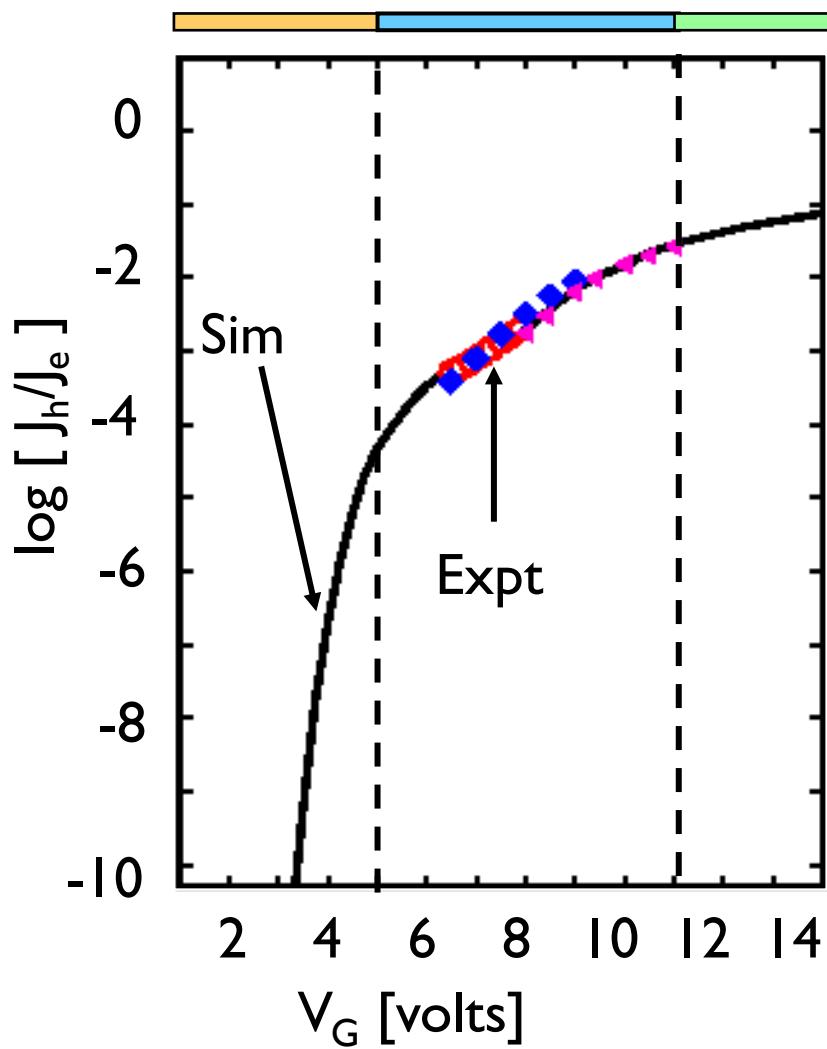


Ghetti, INFOS, 99.  
Lo, APL, 97.

Bude, IEDM, 98.  
Ezaki, SISC, 00.  
Kamakura, IEDM, 99, JAP, 00.  
Palestri, SISC, 00.

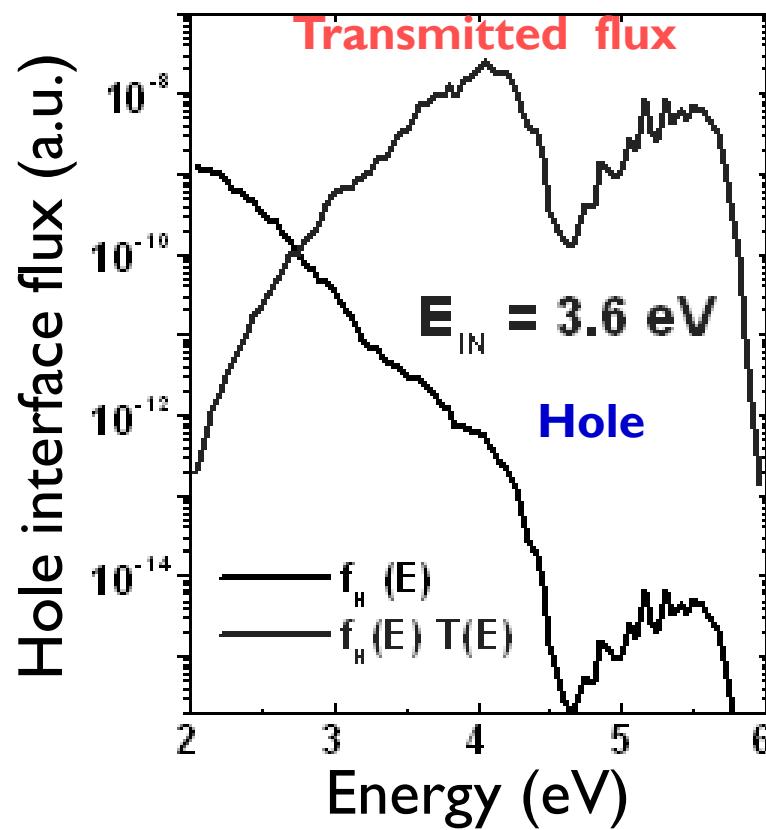
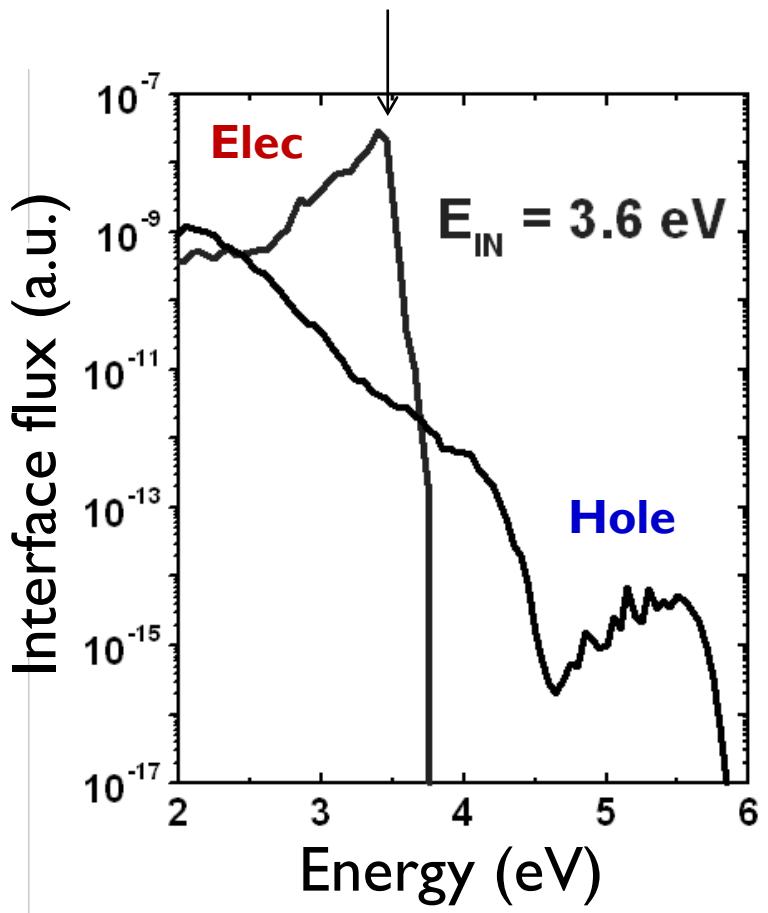
Bude, IEDM, 98.  
Alam, IRPS, 00.  
Palestri, SISC, 00.

# Understanding the Hole Fluxes



# Hole Oxide Flux Distributions

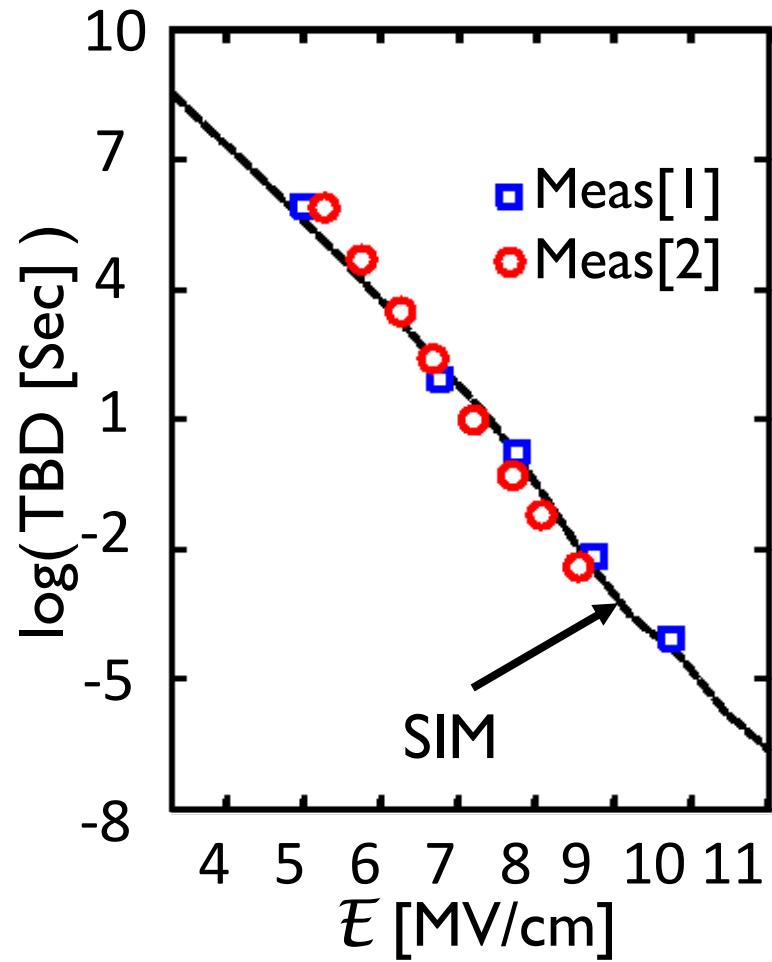
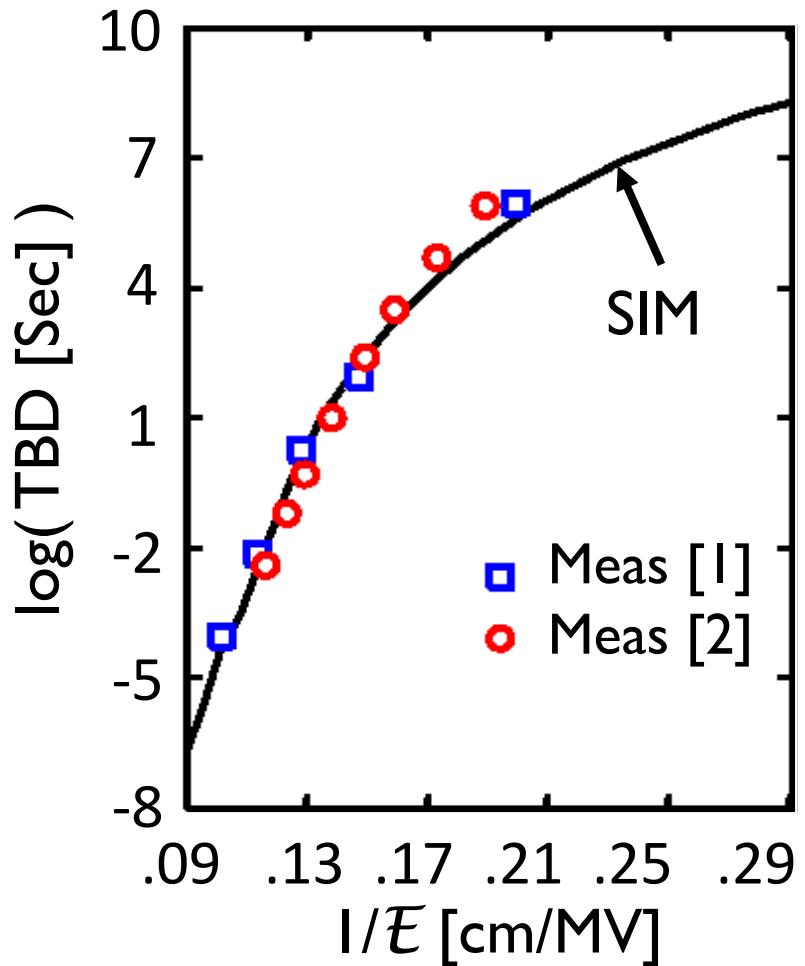
Given flux generation rate,  $G_H$ , first solve for interface flux,  $f_H(E)$ , and then calculate the transmitted flux =  $f_H(E) T(E)$



# Outline

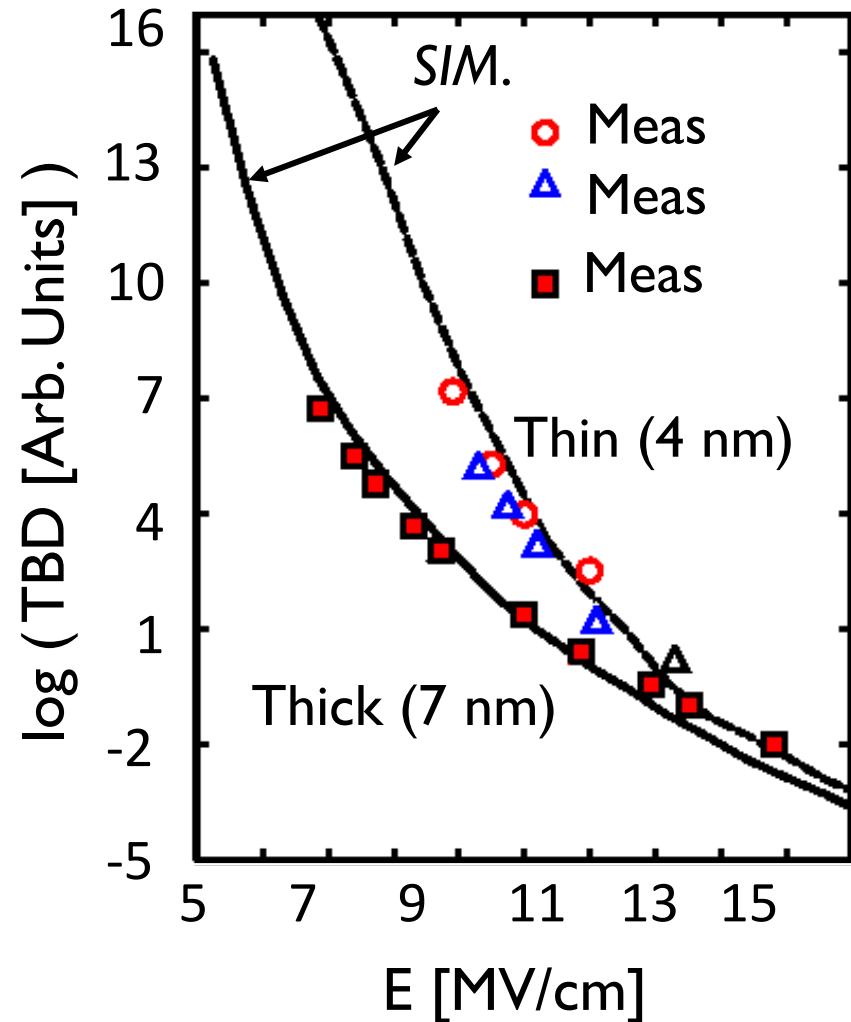
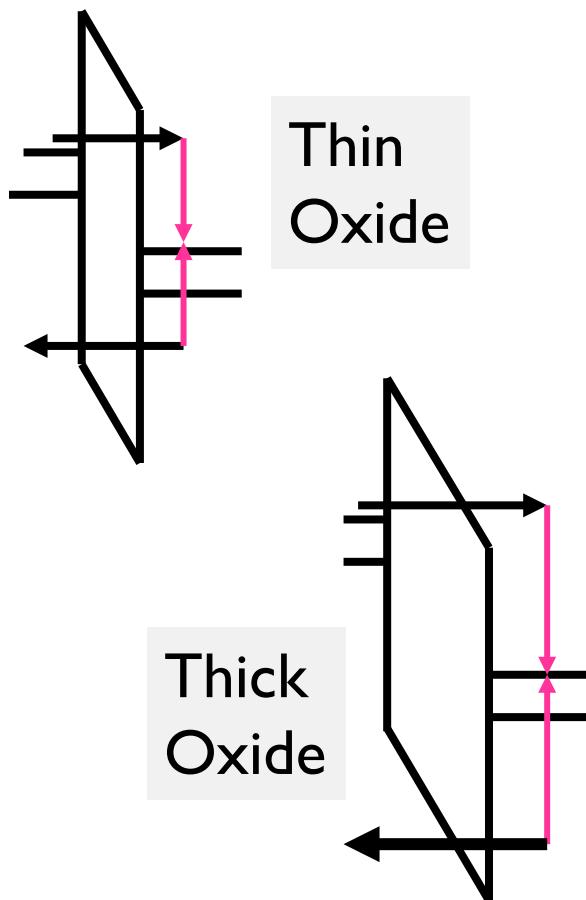
- I. Background: Voltage Acceleration for TDDB
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# Verification: Field Dependence



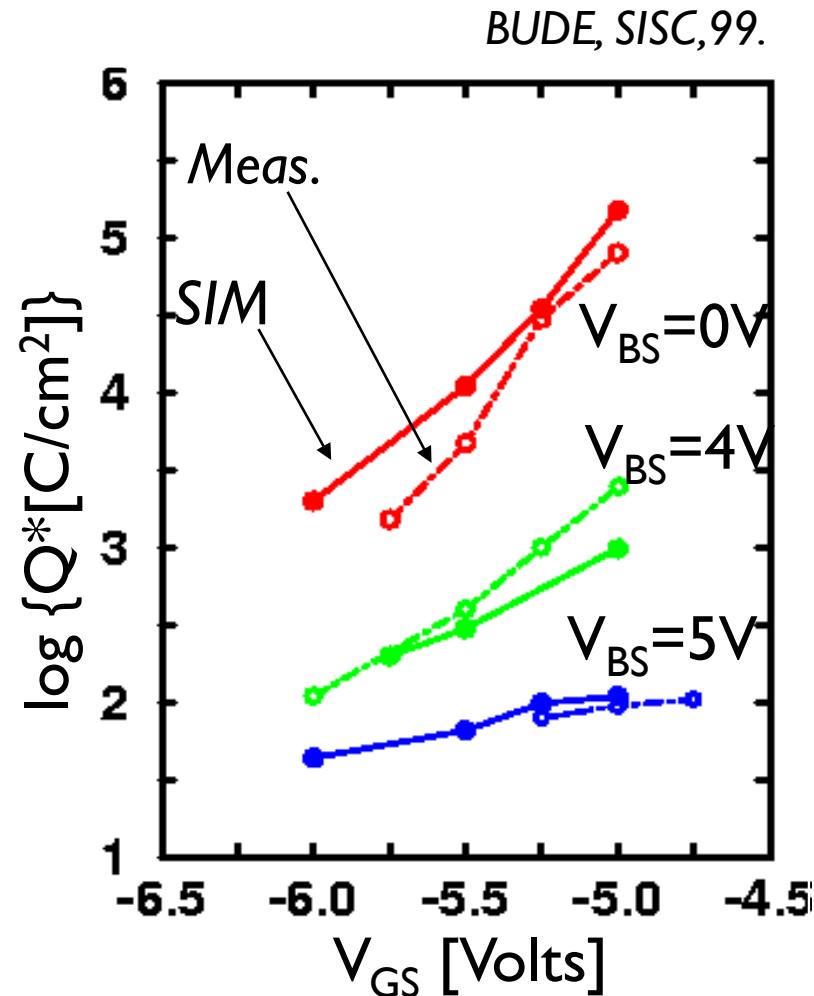
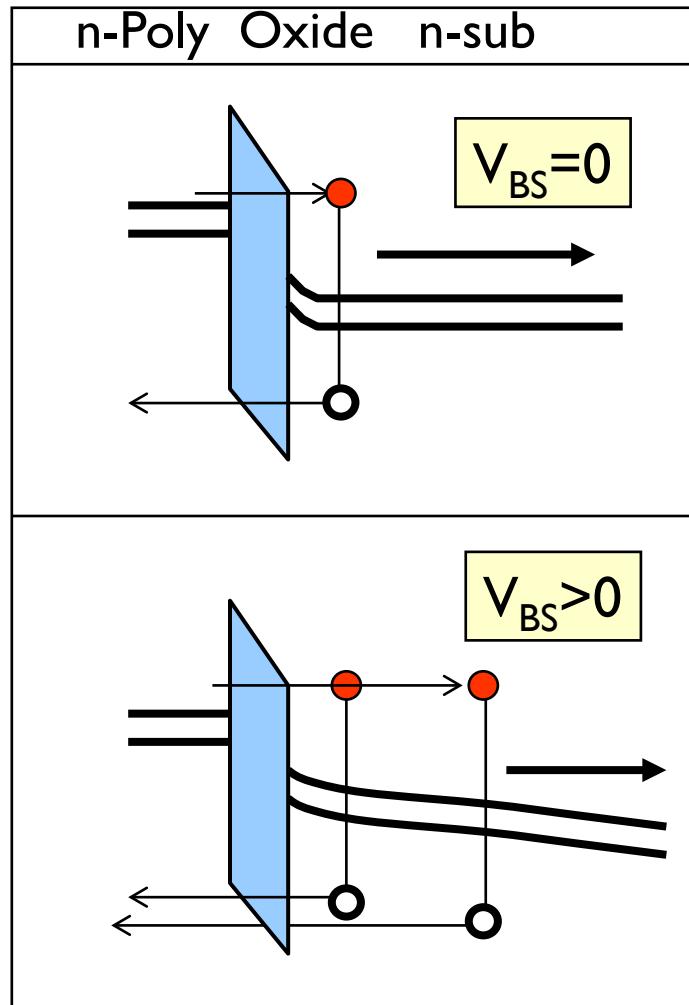
[1] Teramoto, IRPS, 99; [2] Yassine, APL, 99.

# Verification: Thickness Dependence



Voltage ( $V$ ), not the electric field ( $E$ ), controls TBD

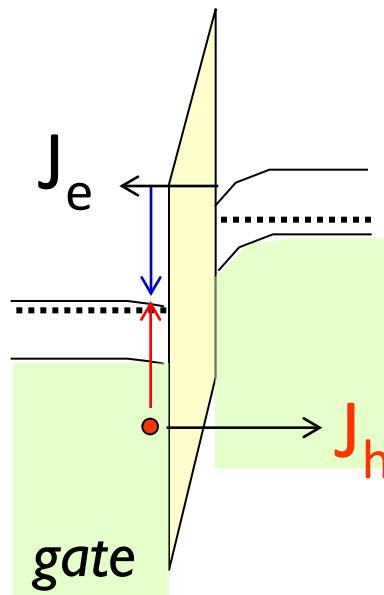
# Verification: Substrate Bias Experiments



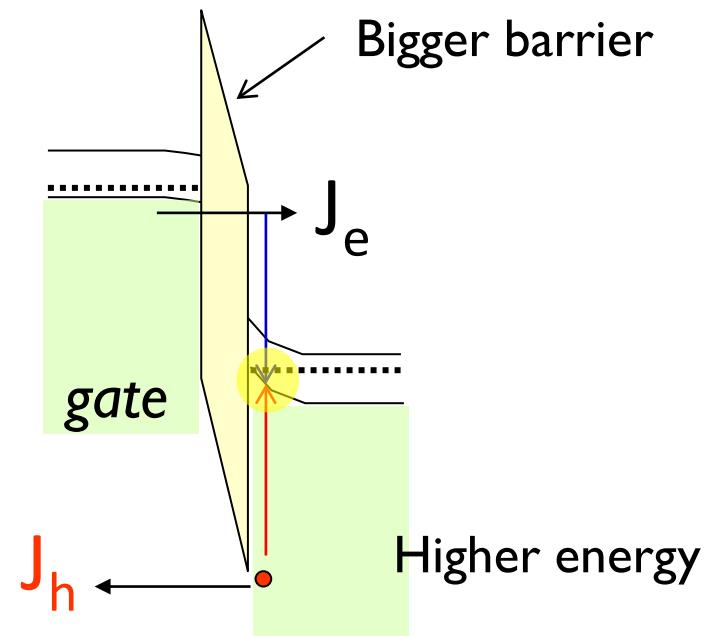
# Verification: Majority vs. Minority Ionization

$$T_{BD} \sim J_h^{-1} \quad J_h = J_e \times p_{ii} \times T_p$$

NMOS



PMOS



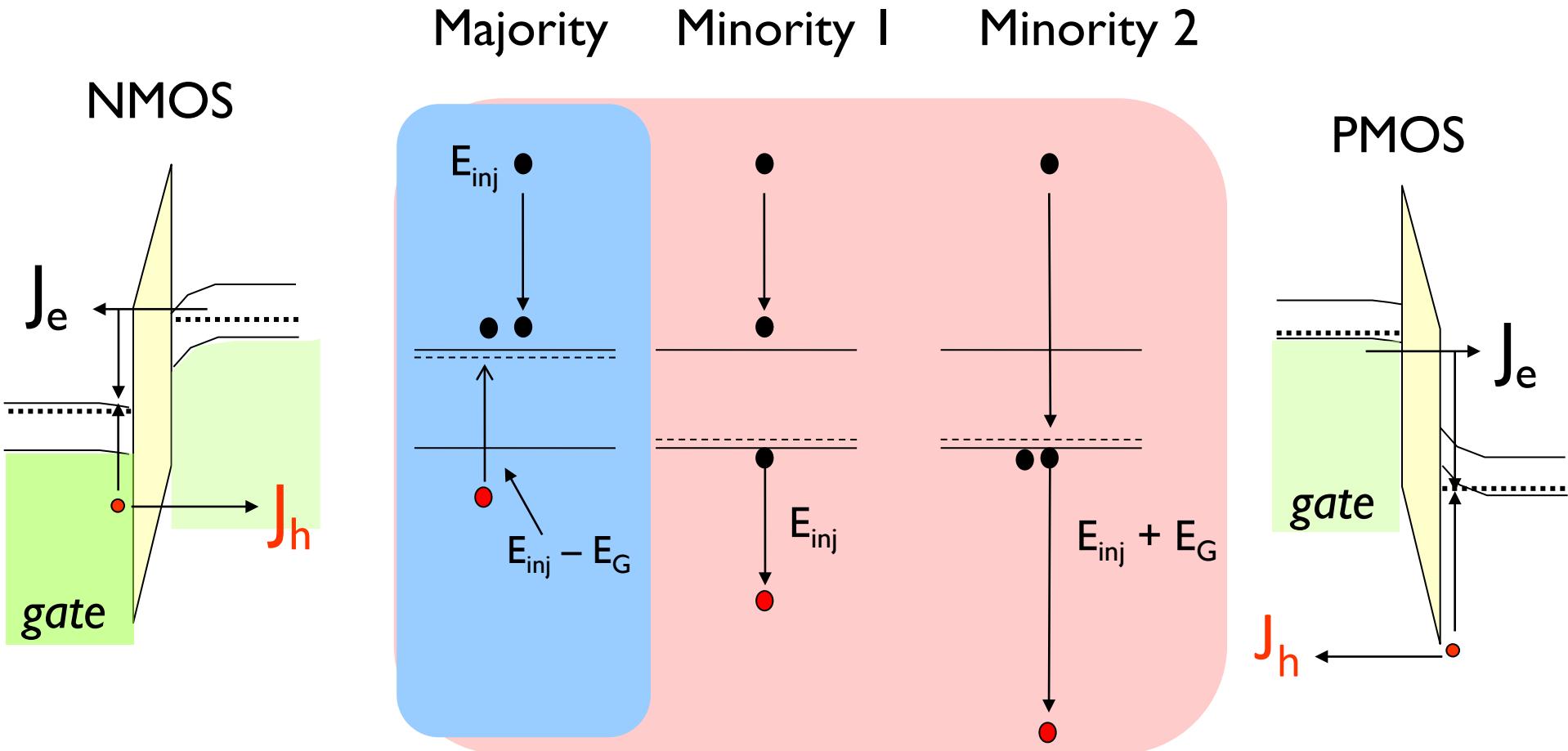
For oxide  $< 2$  nm:

$J_h^{\text{PMOS}} > J_h^{\text{NMOS}}$ , so

$T_{BD}^{\text{PMOS}} < T_{BD}^{\text{NMOS}}$

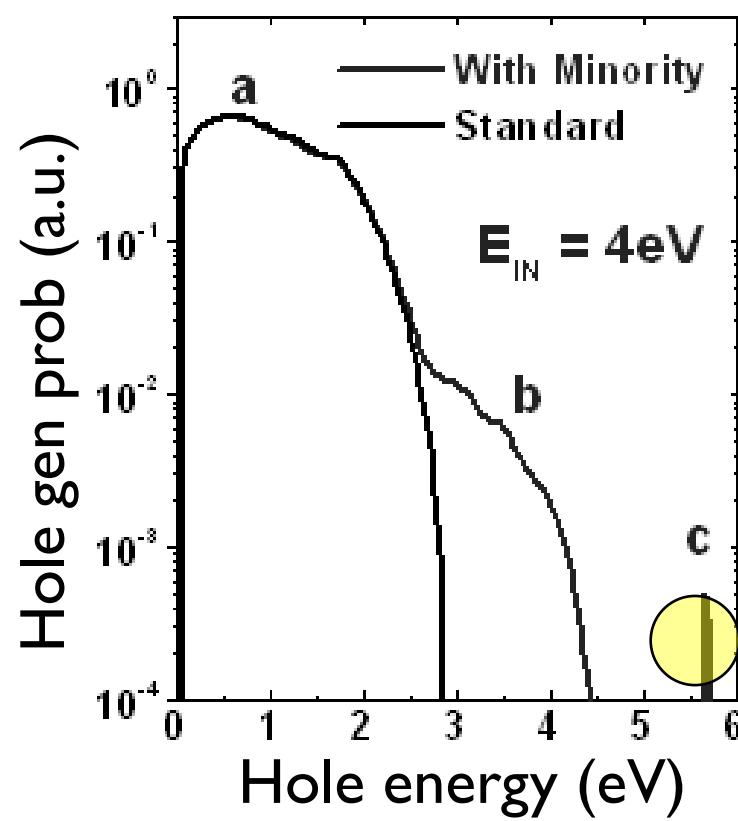
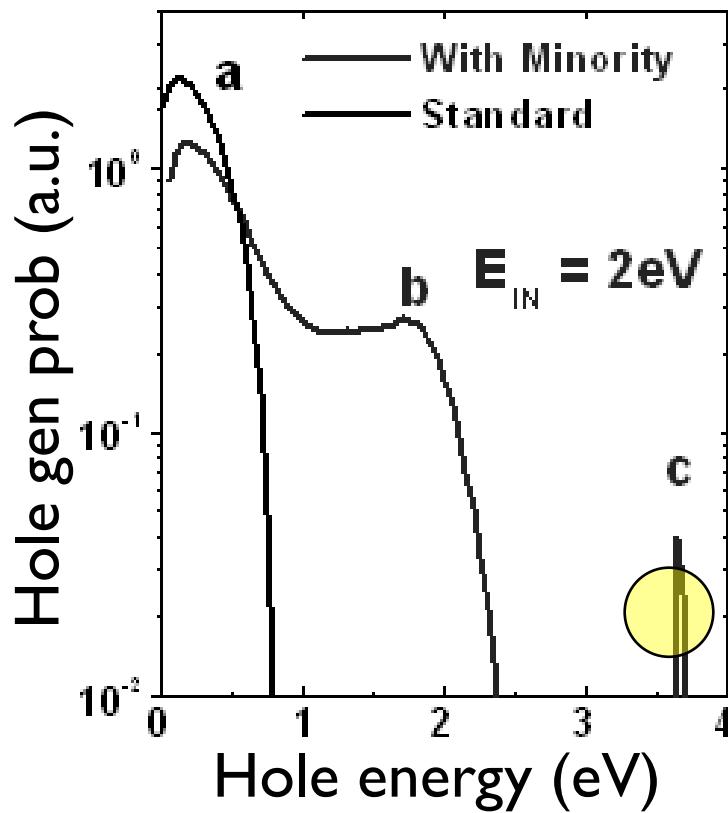
# Majority vs. Minority Ionization ...

## Role of Hot Contacts

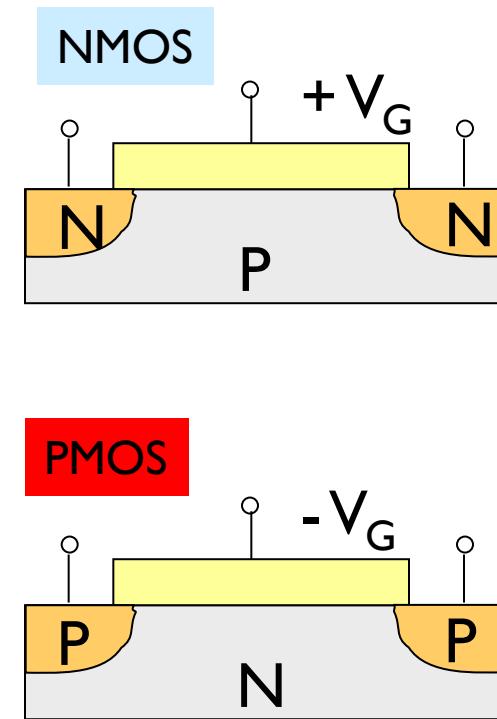
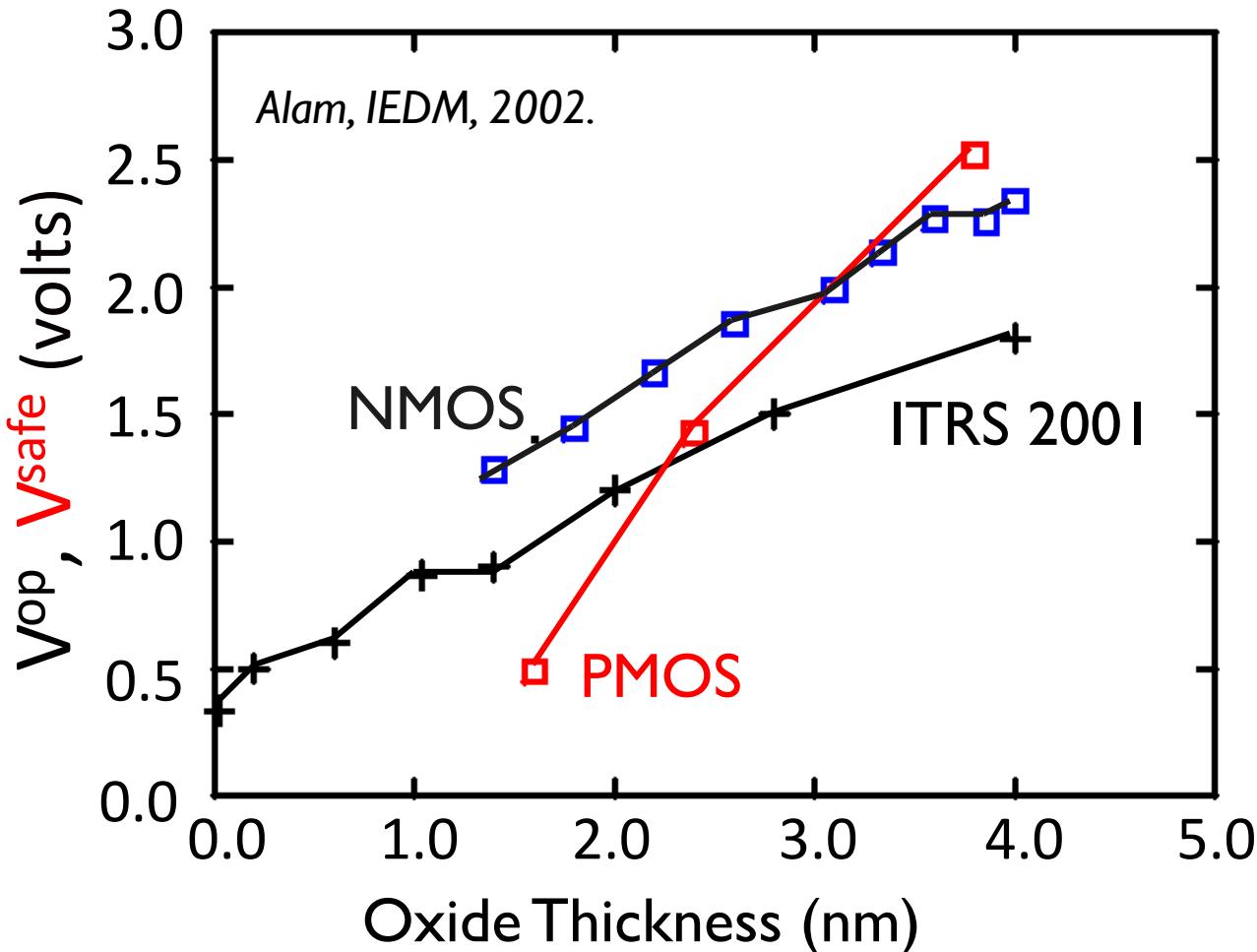


# Hole Generation Probabilities

Hole generation,  $G_H$ , 10 Å from oxide interface in a hole inversion layer

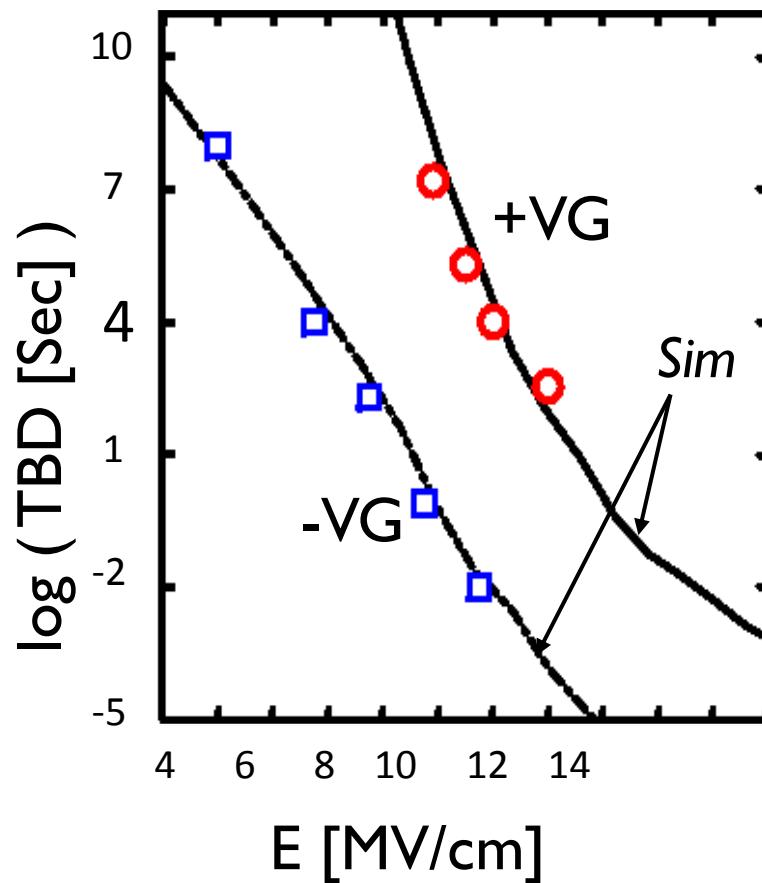
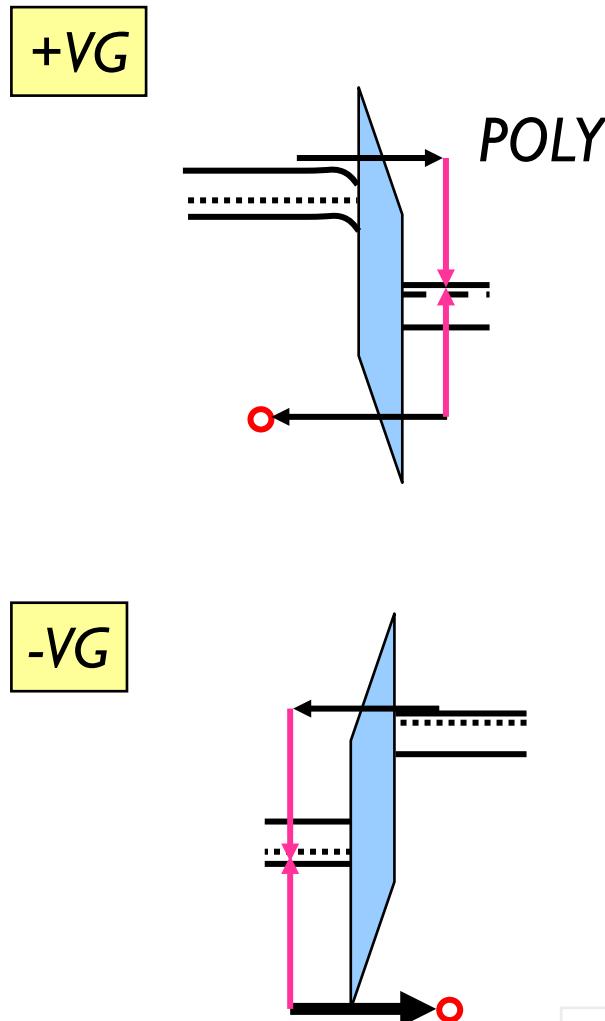


# NMOS vs. PMOS Reliability



PMOS less reliable than NMOS, contacts defines everything !

# Verification: Polarity dependence

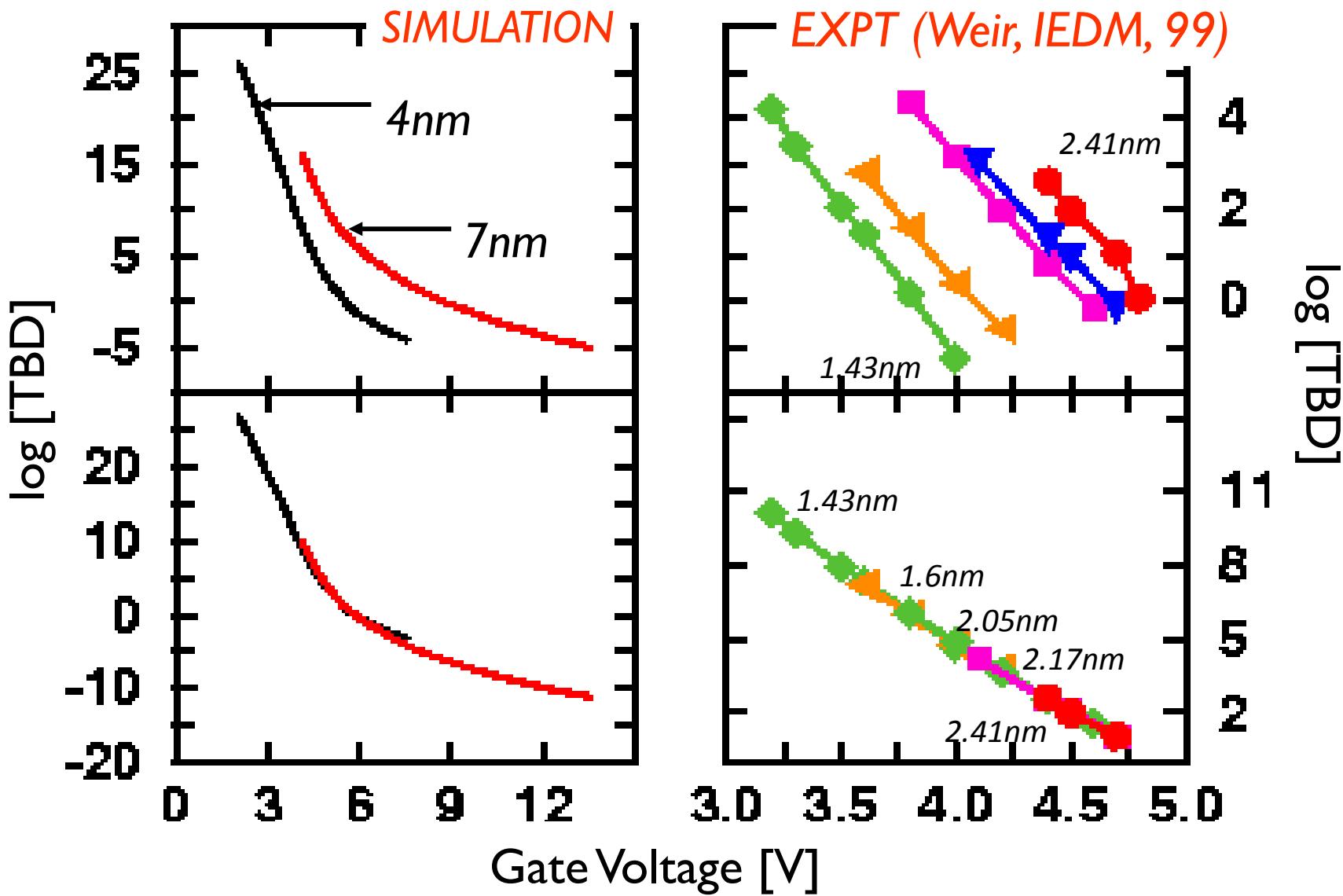


$\langle \gamma T_h \rangle$  changes with polarity

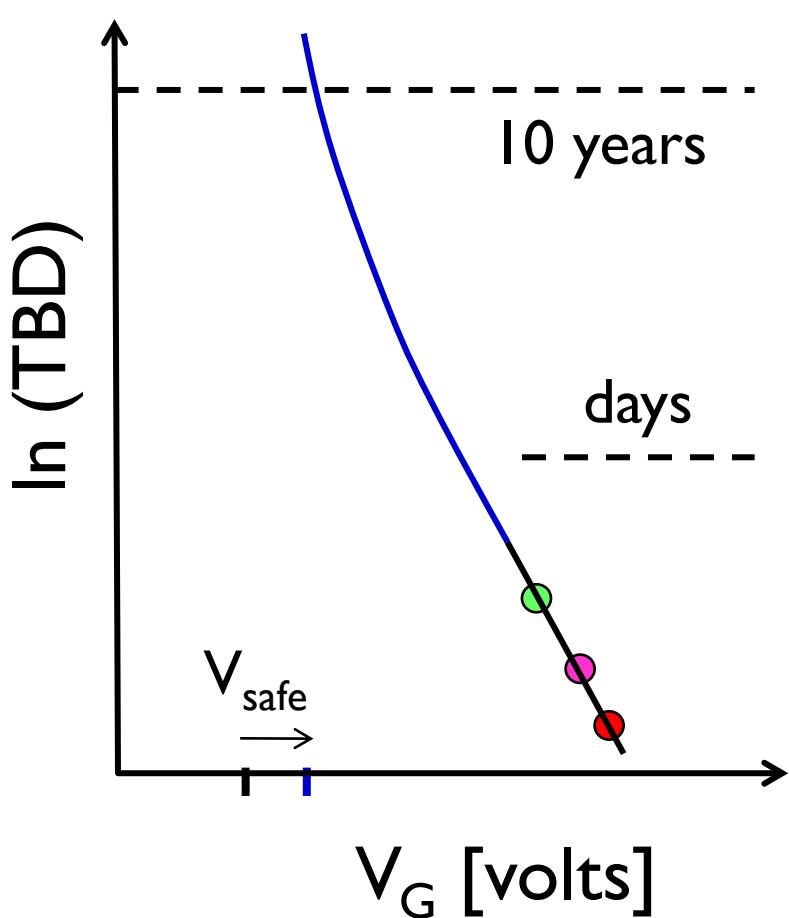
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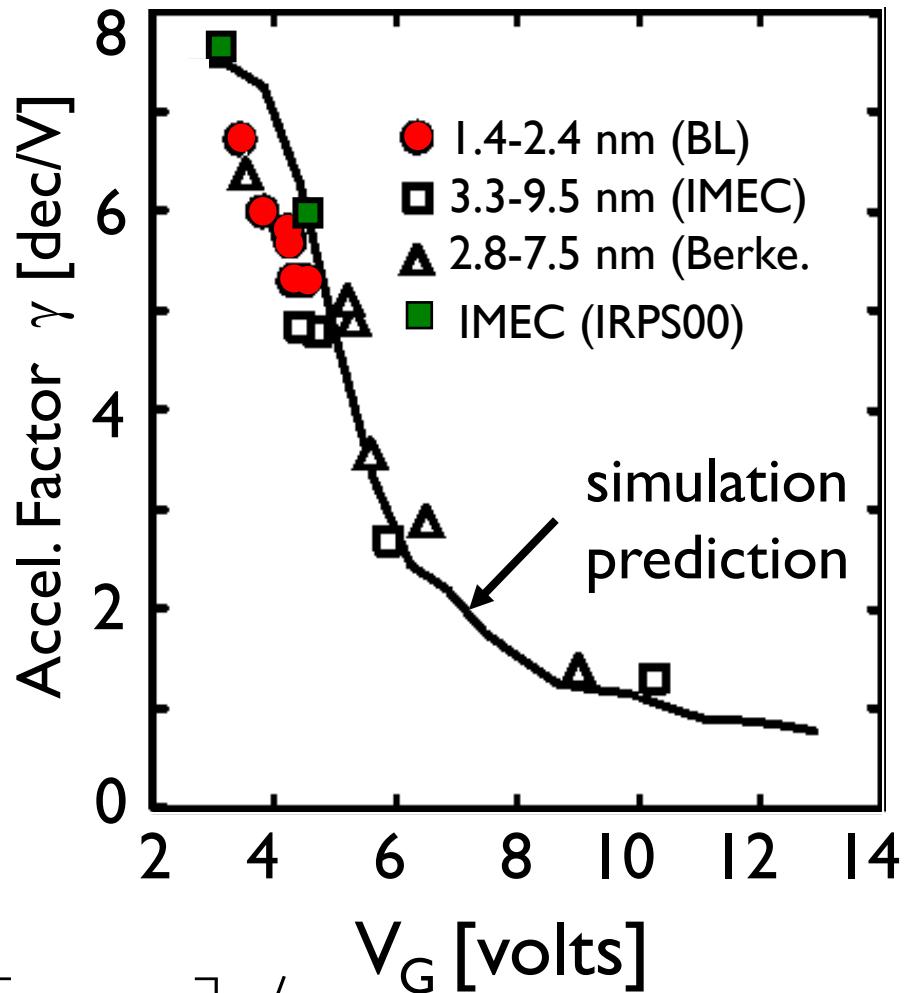
# Universal $V_G$ -dependent TBD



# Reduced Defect Generation at Low Voltage



$$V_{safe} = V_{test} - \log \left[ \frac{10 \text{ yrs}}{T_{BD}} \right] / \gamma_{V,acc}$$



# Conclusions

- ❑ Anode hole injection provides a model of defect generation (hot hole capture, followed by electron-hole recombination).
- ❑ Establishing the defect generation mechanism through wide variety of supplementary experiment is very important, because it is impossible to probe the lifetime at operating voltages.
- ❑ Voltage acceleration is voltage-dependent and this nonlinearity is universal. Note that this universality is different from the universality we discussed during HCI, NBTI, and TDDB breakdown.

# References

There have been considerable amount of work on gate dielectric breakdown. Here I refer to some of the work I have done – additional references can be found in the papers.

- You could get started by reading “A Future of Function or Failure?” M. A. Alam, Bonnie E. Weir, and P. Silverman, IEEE Circuits and Devices - The Electronics and Photonics Magazine 18(2), pp. 42-48, 2002.

Reviews can be found in ....

- “Gate Dielectric Breakdown in the Time-Scale of ESD Breakdown,” B. Weir, C. Leung, P. Silverman, and M. Alam, Microelectronics Reliability, 45, pp. 427-436, 2005.

Modern theory of dielectric breakdown is discussed in ... “Gate dielectric breakdown: a focus on ESD protection,” B. E. Weir, C.-C. Leung, P. J. Silverman, and M. Alam, Proc. of IRPS, pp. 399-404, 2004.

- “Can an Accurate Anode Hole Injection Model Resolve the E vs. I/E controversy ?” M. A. Alam, Jeff Bude, and A. Ghetti, Proceedings of International Reliability Physics Symposium, pp. 21-26, (2000).
- “Anode Hole Generation Mechanisms,” A. Ghetti, M. A. Alam, and J. Bude, Microelectronics Reliability, 41(9), pp. 1347-1354, 2001.

Theory of soft and hard breakdown are discussed in ...

“Uncorrelated Breakdown of Silicon Integrated Circuits,” M. A. Alam, R. K. Smith, B. E. Weir, and P. J. Silverman, Nature, 6914, p. 378, 2002.

- “Uncorrelated Breakdown of Silicon Integrated Circuits,” M. A. Alam, R. K. Smith, B. E. Weir, and P. J. Silverman, Nature, 6914, p. 378, 2002. A Phenomenological Theory of Correlated Multiple Soft Breakdown Events in Ultrathin Gate Dielectrics ”, M. Alam and R. K. Smith, Proc. of International Reliability Physics Symposium, pp. 406-411, 2003.
- “A Study of Soft and Hard Breakdown : The Statistical Model,” M. A. Alam, B. E. Weir, and P. J. Silverman, IEEE Transaction on Electron Devices, 49 (2), pp. 232-238, 2002. Also, see part 2 in TED, 49 (2), pp. 239-246, 2002. ”

The temperature dependence is discussed in

- B. Weir, Semiconductor Science and Technology, 15, 455-461, 2000. Also, see B. Kaczer et al. Microelectronics Engineering, 48, 47, 1999. And J. Suehle, IRPS Proc. 2000.

Measurements theories are discussed in

- “SILC as a Measure of Trap Generation and Predictor of TBD in Ultrathin Oxides”, M. A. Alam, IEEE Transaction on Electron Devices, 49 (2), pp. 226-231, 2002.
- “Theory of Current-Ratio Method for Oxide Reliability: Proposal and Validation of a New Class of Two-Dimensional Breakdown-Spot Characterization Techniques,” M. Alam, D. Monroe, B. Weir, and P. Silverman, Proceedings of International Electron Device Meeting, 2005.

# Review Questions

1. What is the difference between constant-field impact ionization and constant-energy impact ionization? Where should we use the respective theories?
2. What is the difference between majority and minority ionization? Which one is dominant in NMOS TDDB?
3. What does the backgate (or substrate) experiments prove?
4. Is TDDB a voltage dependent or a field-dependent phenomenon?
5. What measurement techniques are used explore time-dependent defect generation?
6. What is the origin of nonlinear voltage acceleration for TDDB? Is this a good thing or a bad thing?
7. What was the consequence of ignoring nonlinearity in voltage acceleration for the semiconductor industry?

# Appendices

- I. A semiclassical derivation of impact ionization rate
2. Impact ionization and hole flux ( $E > E_{g, th}$ )
3. Temperature dependence of TDDB
4. Verification: Dielectric breakdown at ESD timescale
5. Additional Verification of anode hole injection theory

# 1. A simple derivation of Impact ionization

$$E_T = q^2 / 4\pi\epsilon_0 r_{eff} \quad r_{eff} = 2r_0$$

$$E = \frac{1}{2}mv^2 \quad E_T = \frac{1}{2}mv_T^2$$

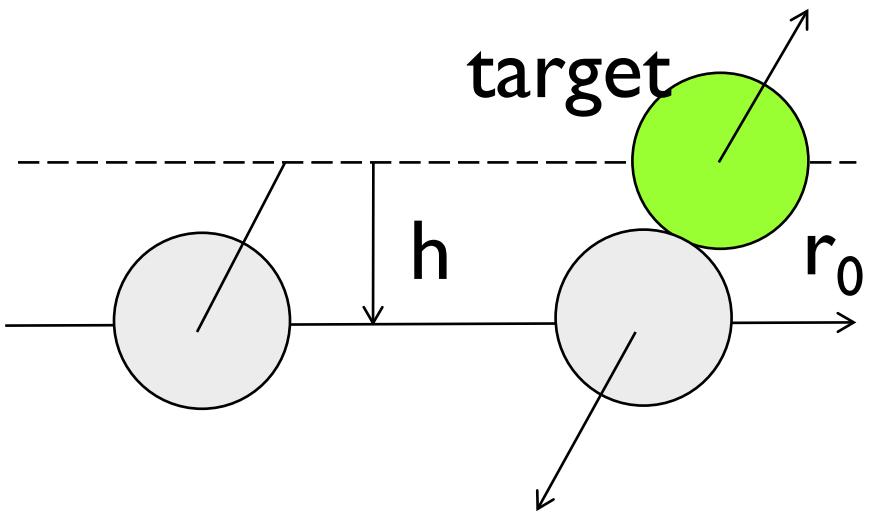
$$\sin \theta = \frac{h}{2r}$$

$$v_T = v \cos(\theta) > \sqrt{\frac{2E_T}{m}}$$

$$\rightarrow \left(1 - \frac{h^2}{4r^2}\right) > \frac{E_T}{E}$$

$$S = \pi h^2 = 4\pi r^2 \left(1 - \frac{E_T}{E}\right)$$

$$\tau^{-1} = v/\lambda = 8\pi r_0^2 \frac{NE_T}{\sqrt{2mE}} \left(\frac{E}{E_T} - 1\right)$$



Woods, APL, 52(1), 1988; TED, 49(2), 2002.

## 2. An analytical model for AHI

Voltage drop across the oxide  $V_{ox} = V_G - V_{FB} - 2\phi_F \leftarrow$  Band-bending at threshold

$$E_{ox} = V_{ox}/T_{ox}$$

For HCl, this was  $kT_h$ .  
Here, energy is constant

P-Si subs. SiO<sub>2</sub>      Gate elect.

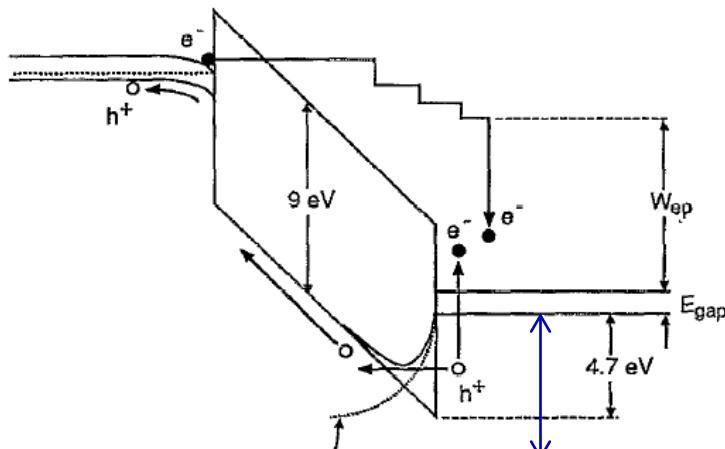


Image potential

$$W_{hg} = C(W_{eg} - E_{g,th})$$

$$J_h = qn_s \left( \frac{W_{hg}}{2\pi m_h^*} \right)^{1/2} \exp \left( -\frac{q\Phi_h}{W_{hg}} \right)$$

$$q\Phi_h = q\Phi_b - \beta \mathcal{E}_{ex}^{1/2}$$

$$\beta = \left( q^3 / 4\pi\epsilon_0\epsilon_{ox} \right)^{1/2}$$

Kobayashi, JAP, 77(7), 1995; Alig, PRB, 22, 1980.

# ... now calculate excess hole concentration

QY and hole gen.

Relaxation by phonons.

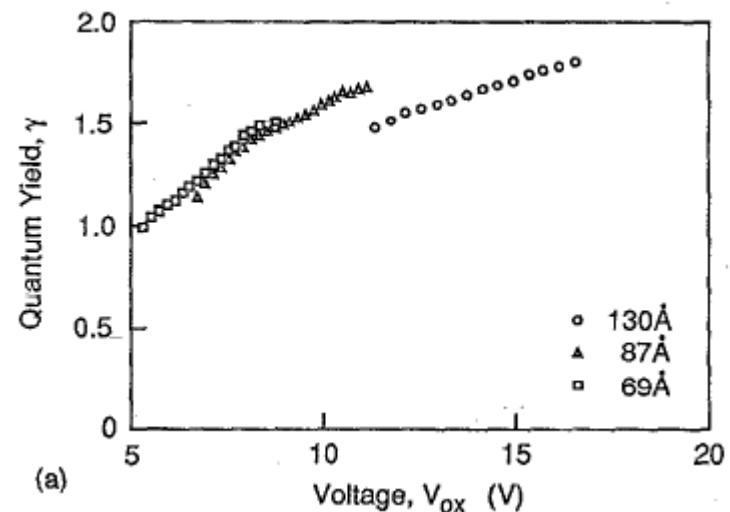
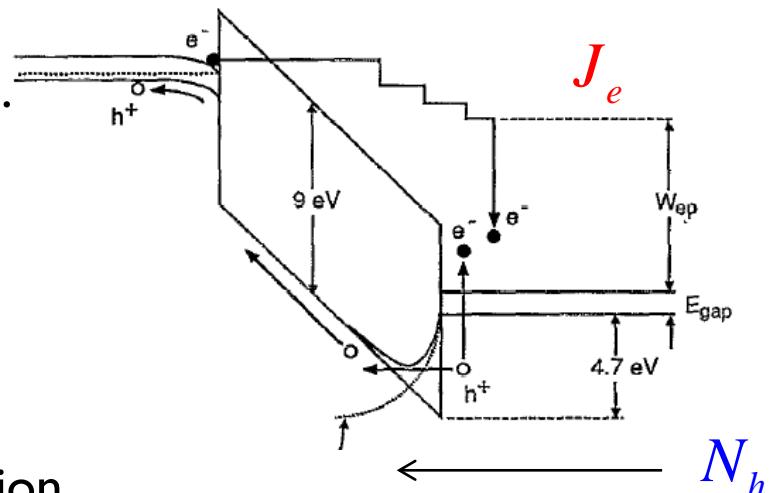
$$\frac{dN_h}{dt} = \frac{\gamma J_e}{q} - \frac{N_h - N_{h0}}{\tau_p}$$

$$N_h - N_{h0} = \frac{\tau_p \gamma J_e}{q} \quad \text{Steady state population.}$$

Spatial distribution of holes ...

$$\frac{\partial p_n}{\partial t} = 0 = -\frac{p_n - p_{n0}}{\tau_p} + D_p \frac{\partial^2 p_n}{\partial x^2}$$

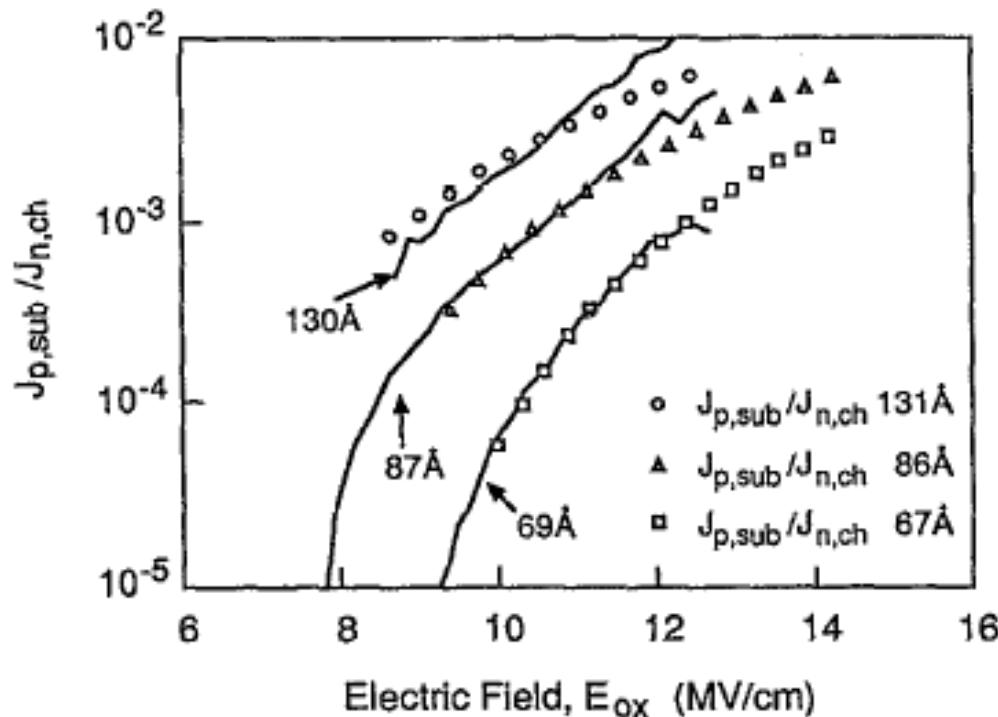
$$n_s = p_n(0) - p_{n0} = \frac{\tau_p \gamma J_e}{qL_p} \frac{1}{1 - \exp(-d/L_p)}$$



# ... putting things back together

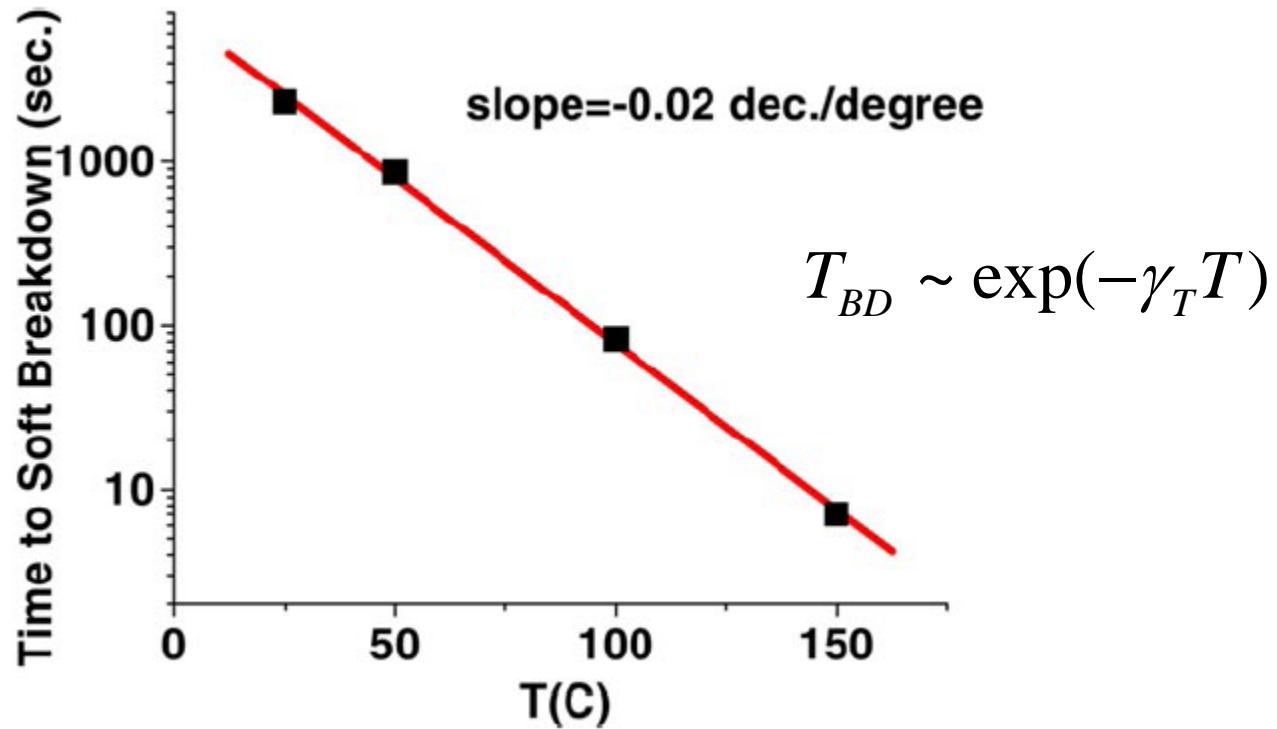
$$J_{p,sub} = AJ_e \times \gamma \times \left( \frac{C(W_{ep} - E_{gap})}{2\pi m_h^*} \right)^{1/2} \times \exp \left( -\frac{q\Phi_b - \beta E_{OX}^{1/2}}{C(W_{ep} - E_{gap})} \right)$$

$$A = 0.0018 \text{ s/m}, C = 0.055$$



### 3. TDDB Temperature dependence

Temperature dependence is weak and non-activated



### 3. T-Dependence of TDDB

T-dependence is weak/non-activated because just like HCl (see Lecture 16), the process involves three steps of different temperature activation. First, tunneling is (essentially independent of temperature); second, impact ionization has counter-acting temperature dependence, and finally, bond dissociation through RRK mechanism has weak temperature dependence.

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

$$k_F \propto J_h \times F_{sio}$$

$$J_h = q n_s \left( \frac{W_{hg}}{2\pi m_h^*} \right)^{1/2} \exp \left( -\frac{q\Phi_h}{W_{hg}} \right)$$

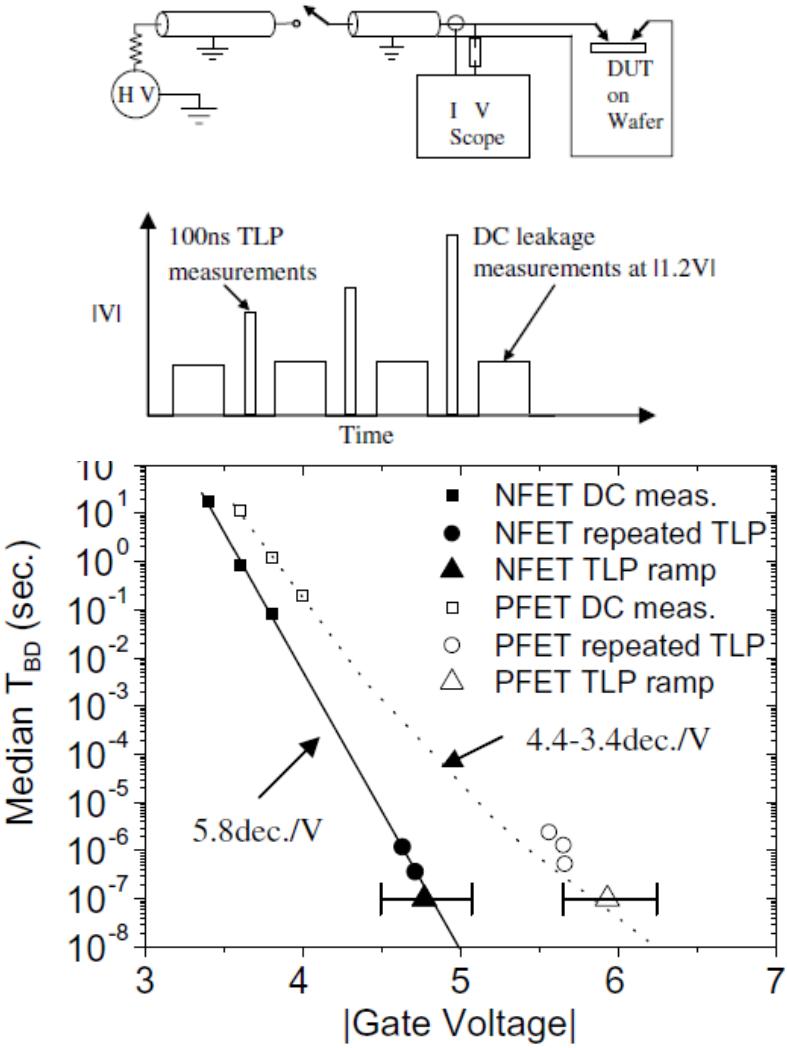
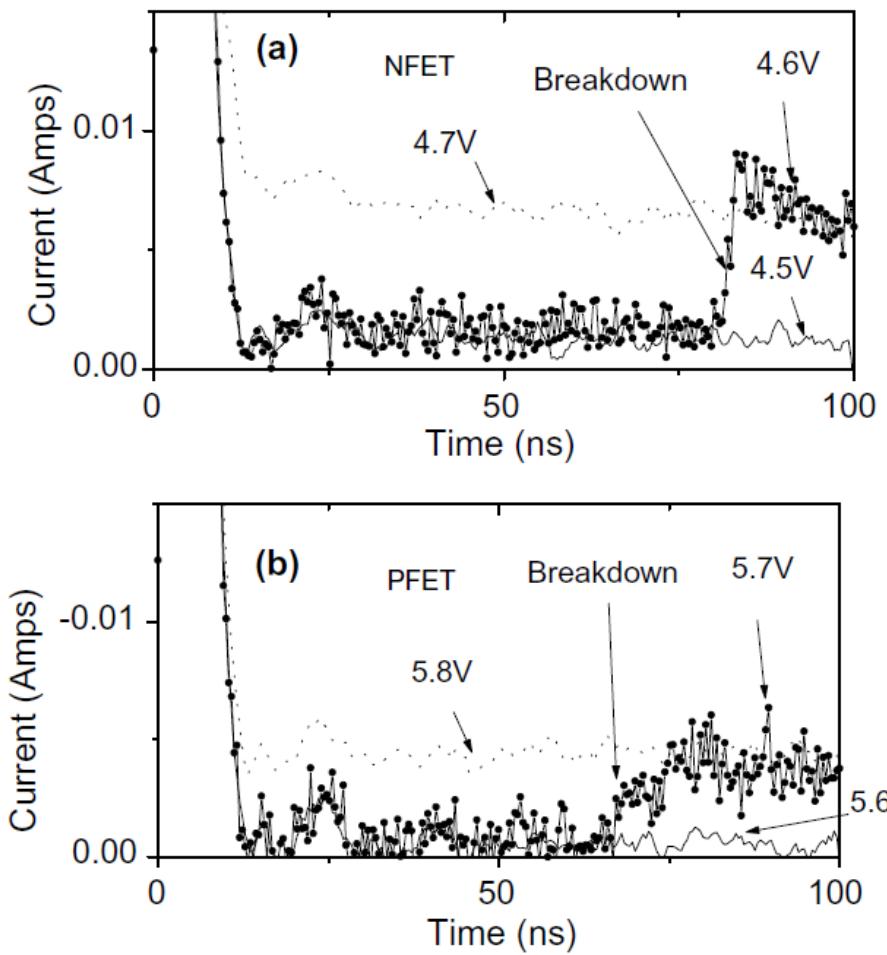
$$n_s = \frac{\tau_p \gamma J_e}{qL_p} \frac{1}{1 - \exp(-d/L_p)}$$

$$F_{sio} \propto \left( \frac{e^{-\frac{(E_F - \Delta E_{Ih})}{kT_L}}}{\Gamma_E(T_L)} \right)^{\uparrow}$$

$$\left( \Gamma_E^{(0)} \right) = B e^{DT_L}$$

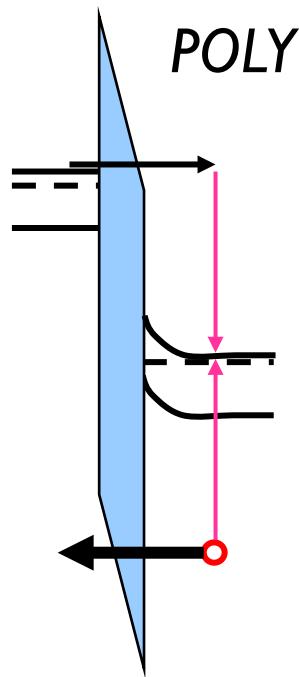
## 4. Dielectric breakdown at very short timescale

Weir, MR, 2004

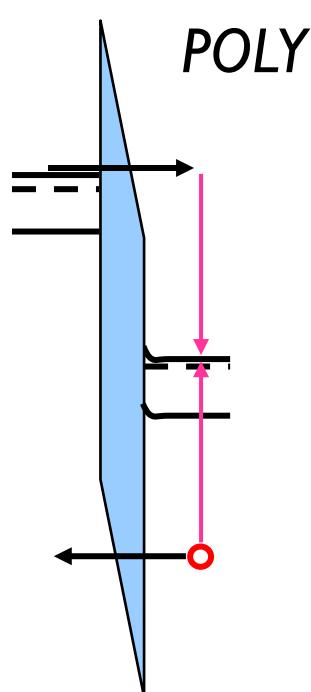


## 5. Verification: Poly doping dependence

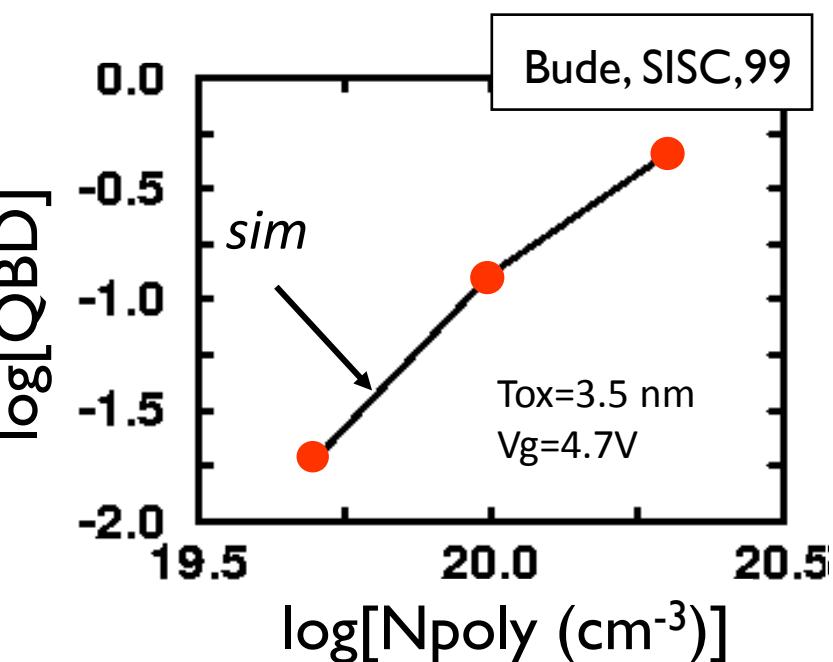
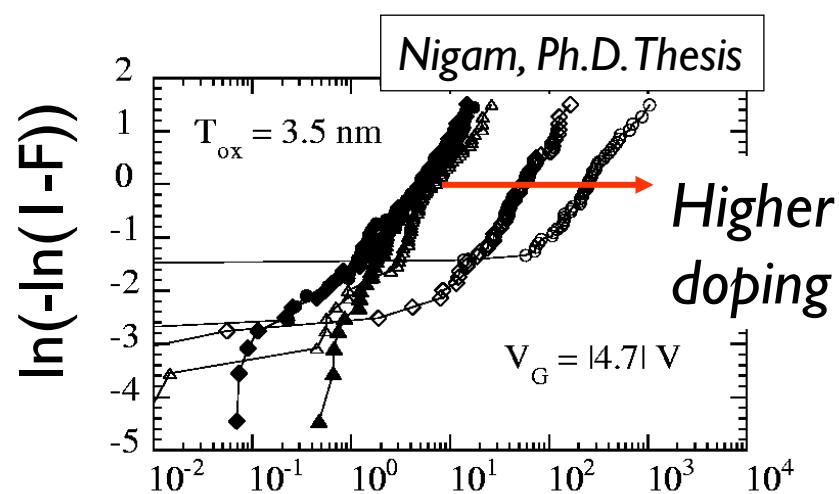
Low  $N_{\text{poly}}$



High  $N_{\text{poly}}$

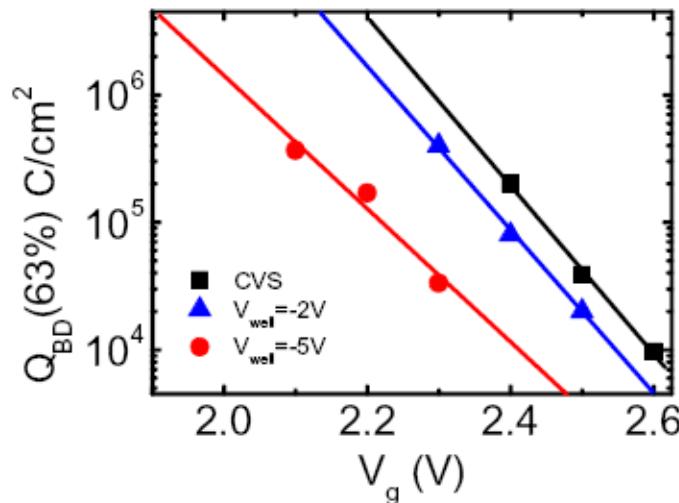
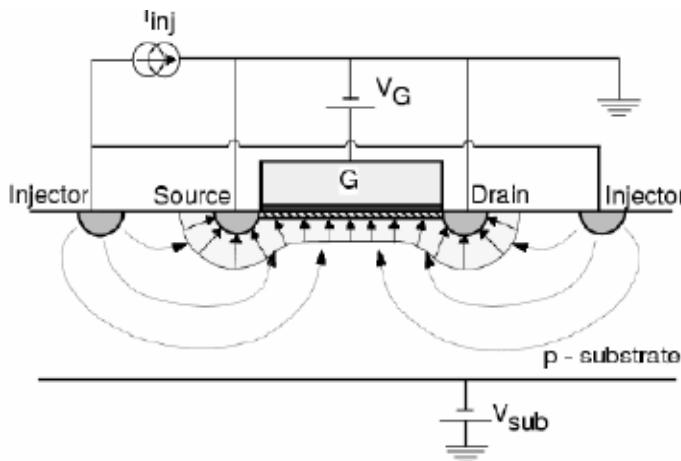
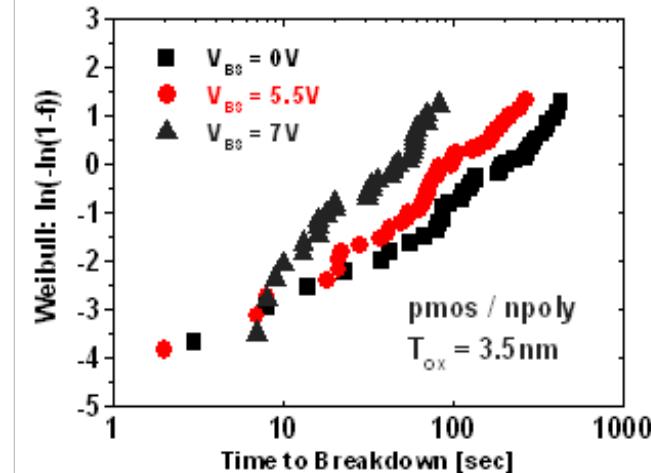
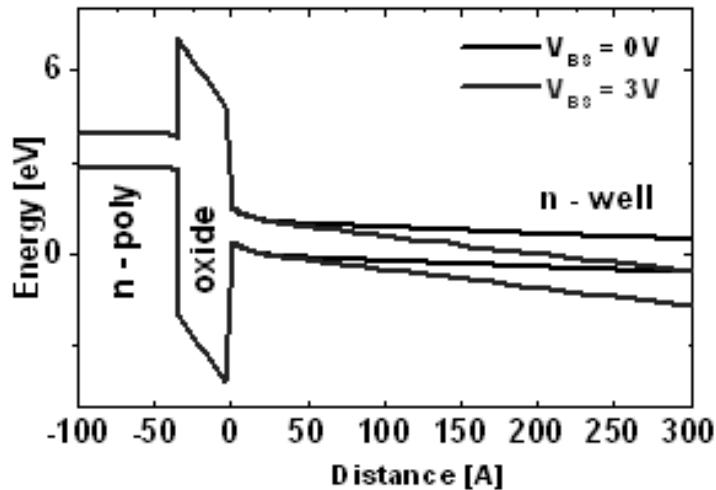


Depletion field in low  $N_{\text{poly}}$  devices increases  $\langle T_h \rangle$  and  $J_h$



## 5. Verification: Breakdown with an N-well Bias

$T_{BD}$  reduces with  $V_{BS} > 0$ , because hot holes gain excess energy



# Origin of Universality

Larger voltage acceleration at lower voltages for  
 $T_{BD}$ ,  $Q_{BD}$

