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ECE 695 : Reliability Physics of Nano-Transistors

Lecture 14B: Voltage dependent HCI

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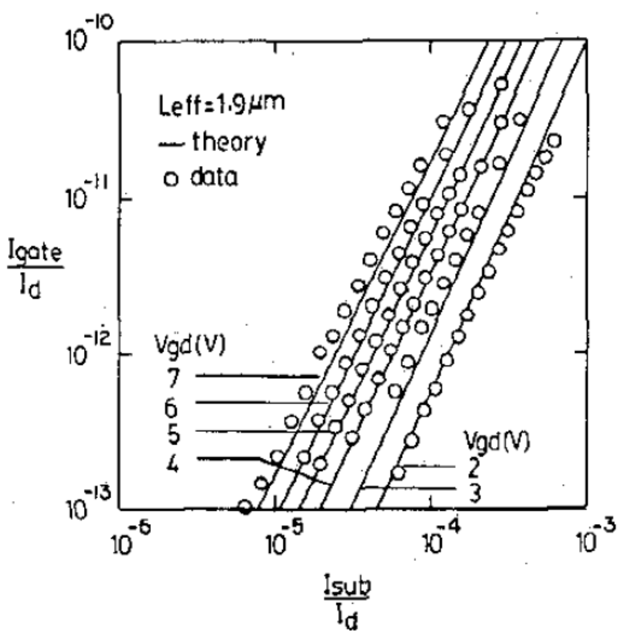
Substrate vs. gate current

$$\log\left(\frac{I_G}{I_D}\right) = \frac{\Phi_e}{q\mathcal{E}_m\lambda_e} + c.$$

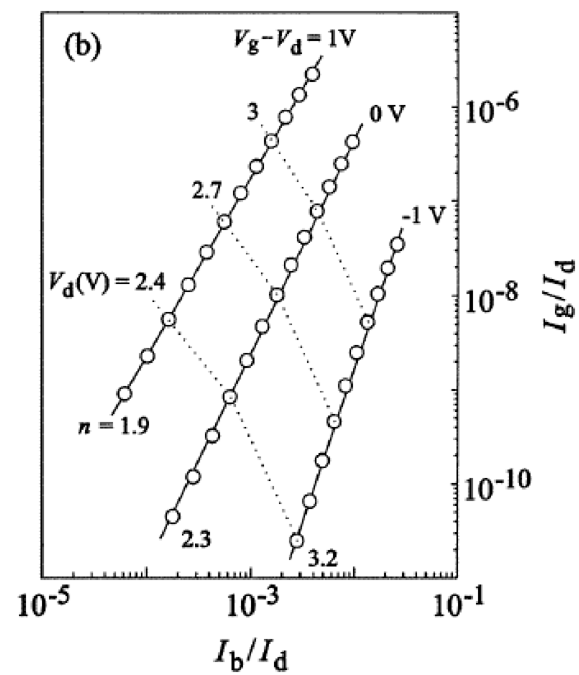
$$\log\left(\frac{I_{sub}}{I_D}\right) = \frac{\Phi_i}{q\mathcal{E}_m\lambda_e} + b$$

$$\frac{I_G}{I_D} = \left[e^{\frac{\Phi_i}{qE_m\lambda_e}}\right]^{\frac{\Phi_e}{\Phi_i}} = \left[\frac{I_{sub}}{I_D}\right]^{\frac{\Phi_e}{\Phi_i}}$$

$$\frac{I_g}{I_d} = 4\times10^{-4}\left[\frac{I_{sub}}{I_d}\right]^{\varphi_b/\varphi_i}$$



Hu, IEEE J. of Solid State Circuits, 1985.



Ang, EDL, 24(7), 469, 2003.

Voltage Scaling by Substrate Current

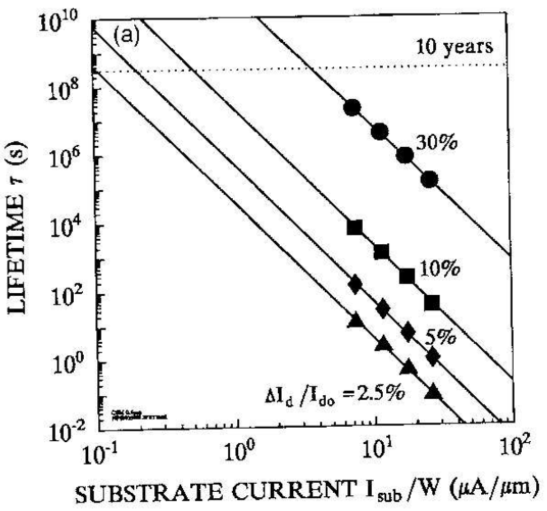
$$\log\left(\frac{I_G}{I_D}\right) = \frac{\Phi_e}{q\mathcal{E}_m\lambda_e} + c.$$

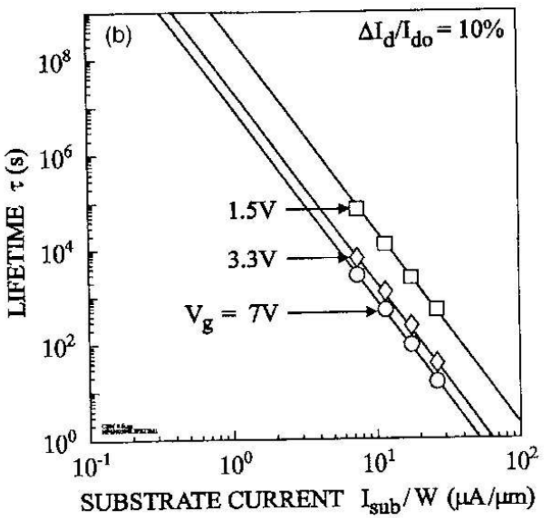
$$\log\left(\frac{I_{sub}}{I_D}\right) = \frac{\Phi_i}{q\mathcal{E}_m\lambda_e} + b$$

$$\frac{I_G}{I_D} = \left[e^{\frac{\Phi_i}{q\mathcal{E}_m\lambda_e}}\right]^{\frac{\Phi_e}{\Phi_i}} = \left[\frac{I_{sub}}{I_D}\right]^{\frac{\Phi_e}{\Phi_i}}$$

$$t_0(V_G,V_D) = \frac{A}{I_G} = \frac{A}{I_D}\left[\frac{I_D}{I_{sub}}\right]^{\frac{\Phi_e}{\Phi_i}}$$

$$t_0(V_G,V_D) = \frac{A}{I_G} = \frac{A}{I_D}\frac{\upsilon_{sat}}{e^{-\mathcal{B}/(V_D-V_{D,sat})}}$$





Ang, Microelectronics Reliability, 39, 1311, 1999.

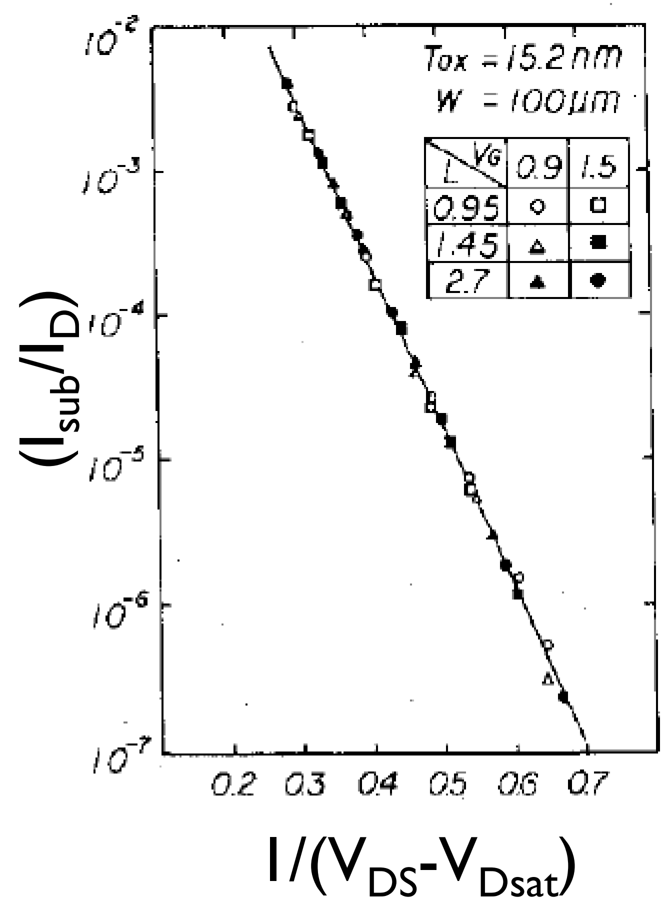
Isub-VD Correlation

$$\frac{I_G}{I_D} = \left[e^{-\frac{\Phi_i}{qE_m\lambda_e}} \right]^{\frac{\Phi_e}{\Phi_i}} = \left[\frac{I_{sub}}{I_D} \right]^{\left(\frac{\Phi_e}{\Phi_i}\right)}$$

$$t_0(V_G, V_D) = \frac{A}{I_G} = \frac{A}{I_D}\left[\frac{I_D}{I_{sub}} \right]^{\frac{\Phi_e}{\Phi_i}}$$

$$t_0(V_G, V_D) = \frac{A}{I_G} = \frac{A}{I_D}\frac{\upsilon_{sat}}{e^{-\mathcal{B}/(V_D - V_{D,sat})}}$$

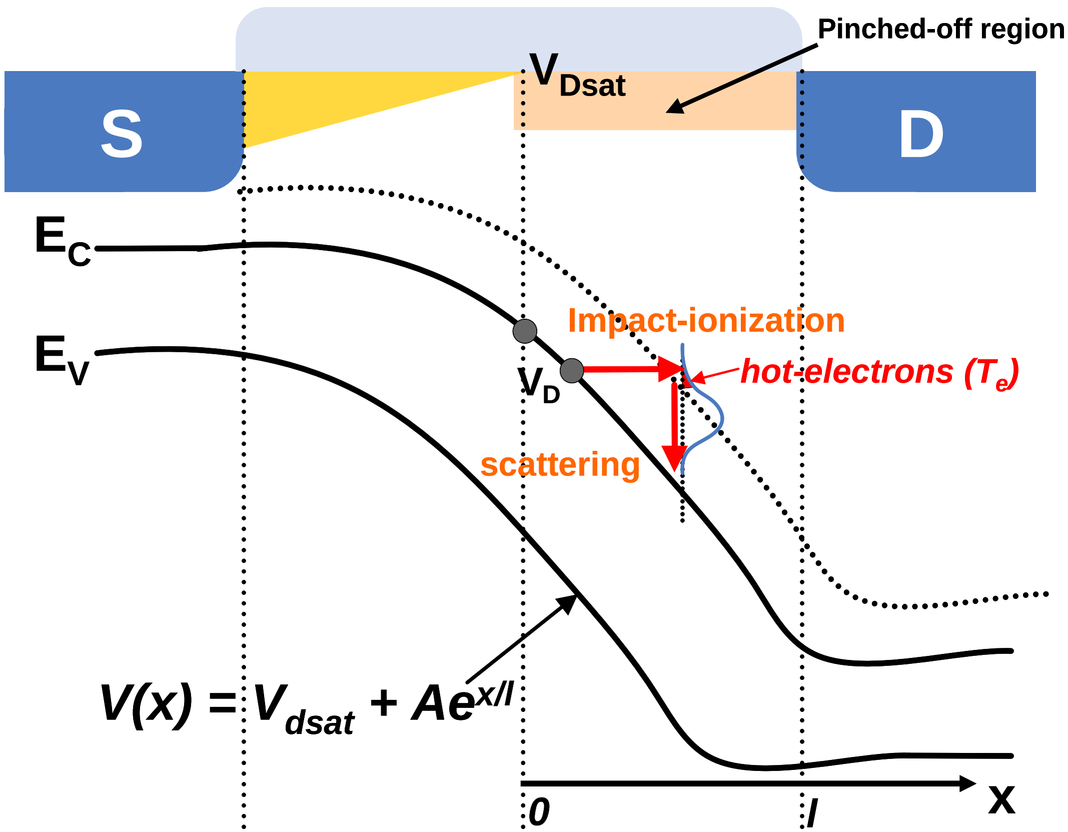
$$\Rightarrow \left[\frac{I_D}{I_{sub}} \right]^{\frac{\Phi_e}{\Phi_i}} = \frac{\upsilon_{sat}}{e^{-\mathcal{B}/(V_D - V_{D,sat})}}$$



Outline

1. Background and empirical scaling
2. Theory of hot carriers: Hydrodynamic model
3. Theory of hot carriers: Monte Carlo model
4. Theory of hot carriers: Universal Scaling
5. Conclusion
6. Appendices

V- dependence at low-voltages: Monte Carlo



Monte Carlo

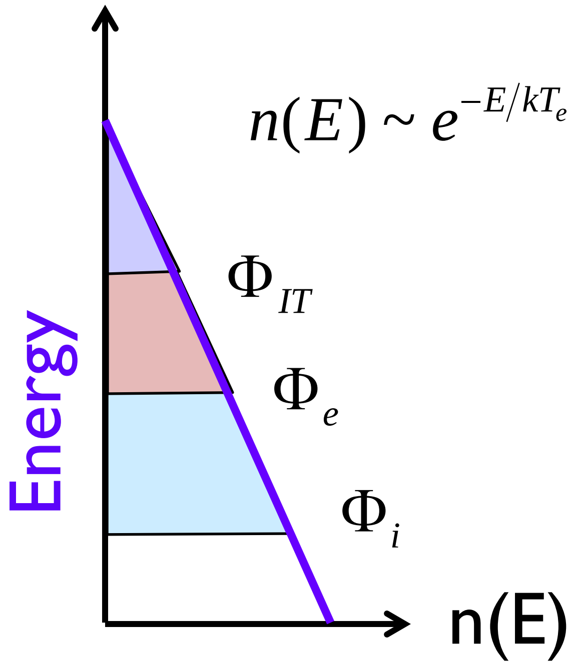
Hydrodynamic

Drift-Diffusion

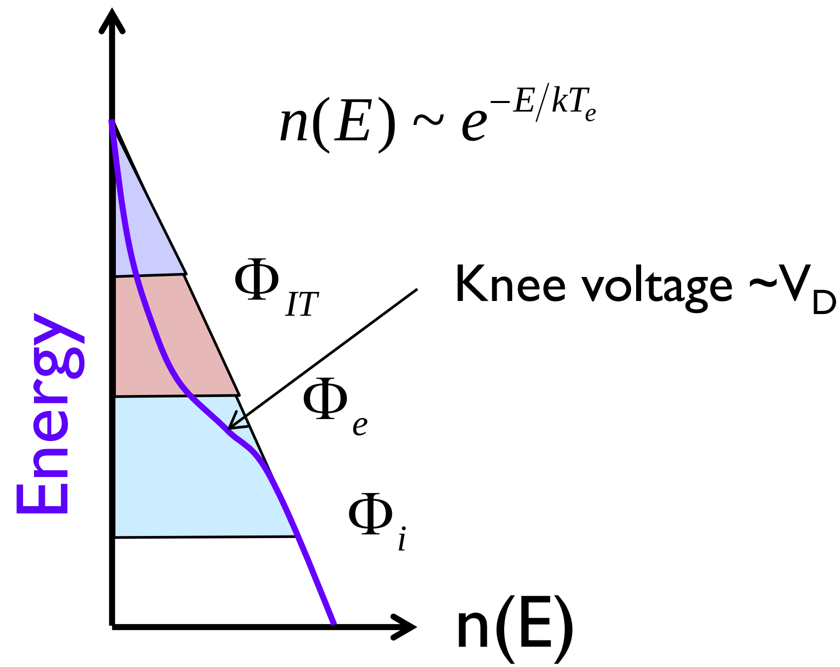
(see Prof. Lundstrom's EE656 Notes at Nanohub)

What is the problem?

Classical MOSFET



Modern MOFET

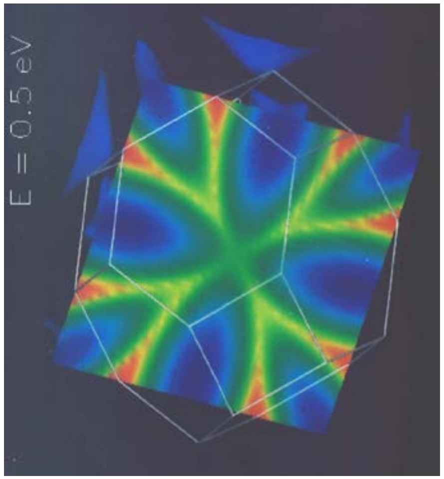


$$t_0^{-1}(V_G, V_D) = I_G \propto \frac{I_D}{W_{eff}}\left[\frac{I_{sub}}{I_D}\right]^{\frac{\Phi_e}{\Phi i}}$$

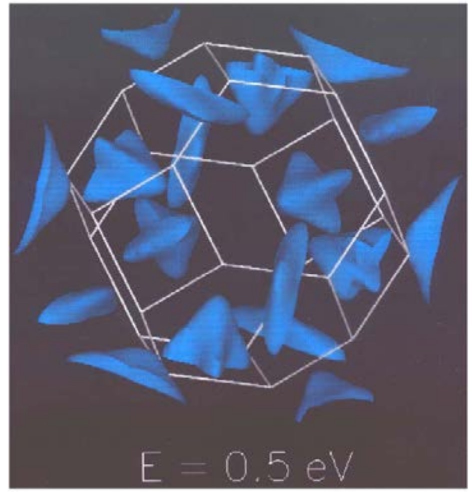
$$t_0^{-1}(V_G, V_D) = I_G = \frac{r_{ii}^{\ m} I_D}{k_1 W} + \frac{r_{ii}^{\ m} I_D^{\ 2}}{k_2 W^2} + \frac{V_d^{\ \gamma}}{k_3}\frac{I_D^{\ \alpha}}{W^{\alpha}}$$

HCI by Monte Carlo Simulation

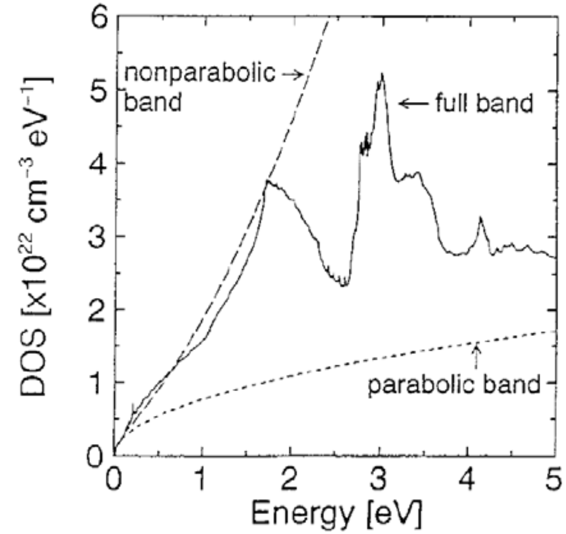
Conduction band …



Valence band …

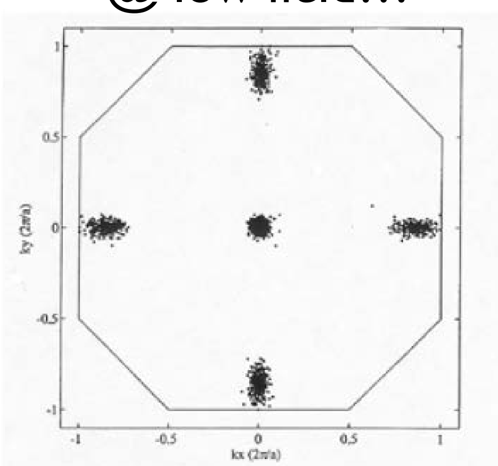


Density of states …



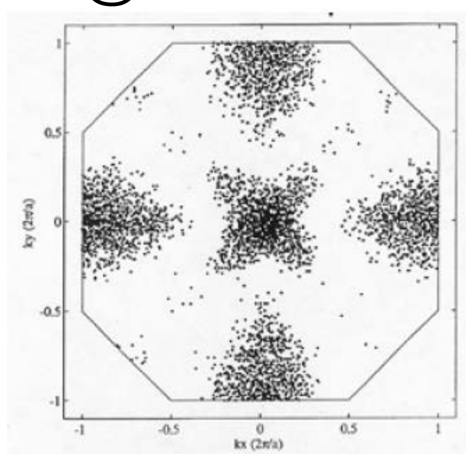
Carrier distribution …

@ low field…



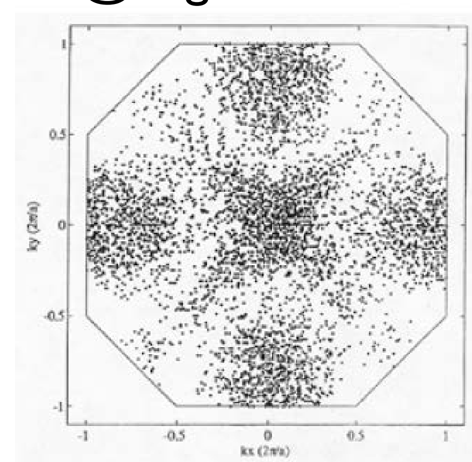
1 kV/cm
Si <100>

@ medium field…



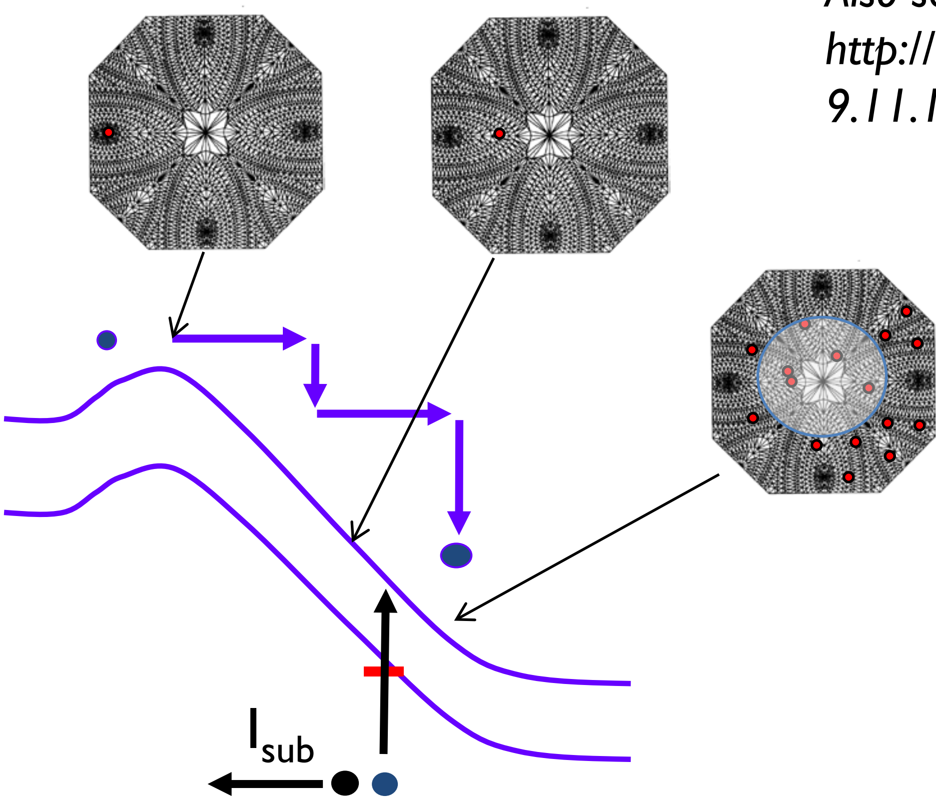
100 kV/cm

@ high field…



300kV/cm

Monte Carlo Simulation in a MOSFET



Also see:
http://nanohub.org/resources/7919/download/2009.11.13-ECE656-L31.pdf

$$k(t) = k_0 - \int_0^t \frac{q\mathcal{E}(x(t'))}{\hbar} dt'$$

$$x(t) = x_0 + \int_0^t \upsilon(x(t'))dt$$

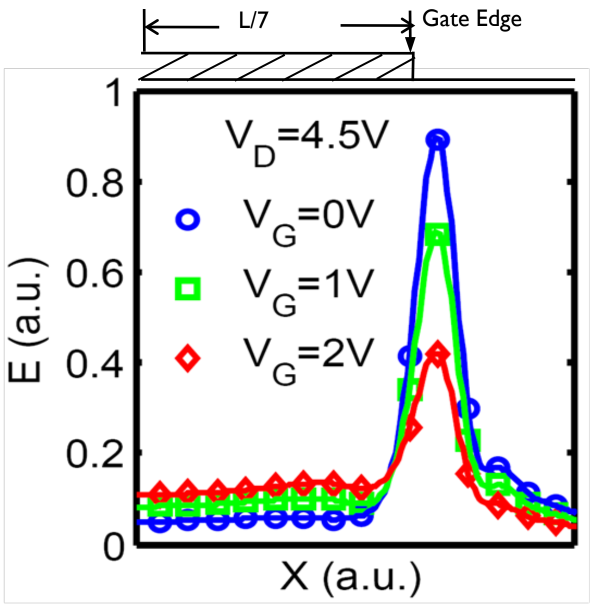
MC on nanohub
bulkmc (Arizona)
demons (Purdue)
SMC (Bell Labs)

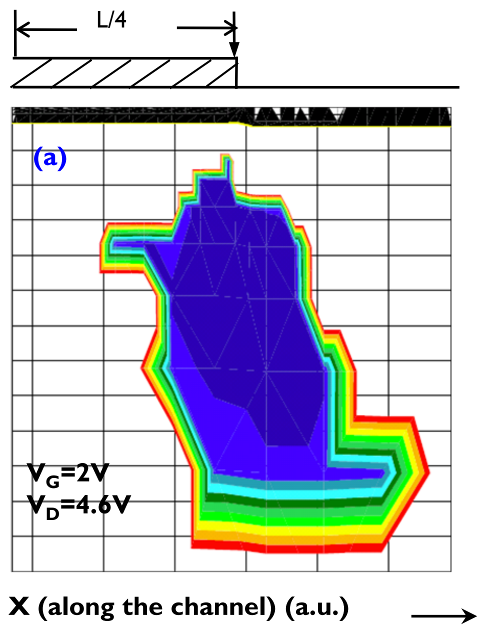
Why is the electron off-center?

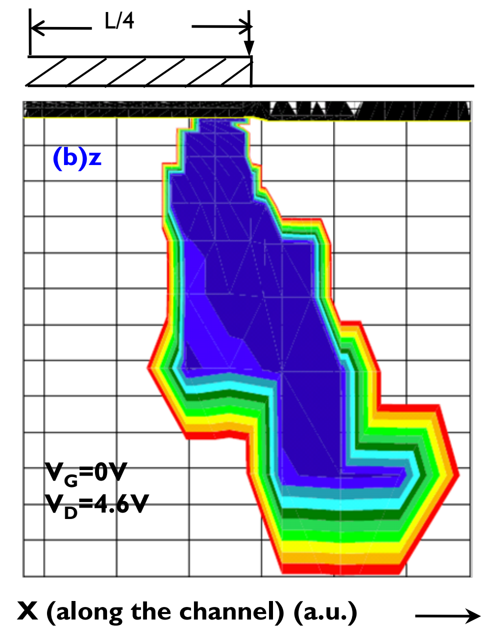
Is the notion of threshold energy clear?

Device/Monte-Carlo Simulation

Simulated with special Monte Carlo Simulator from Bell Labs.





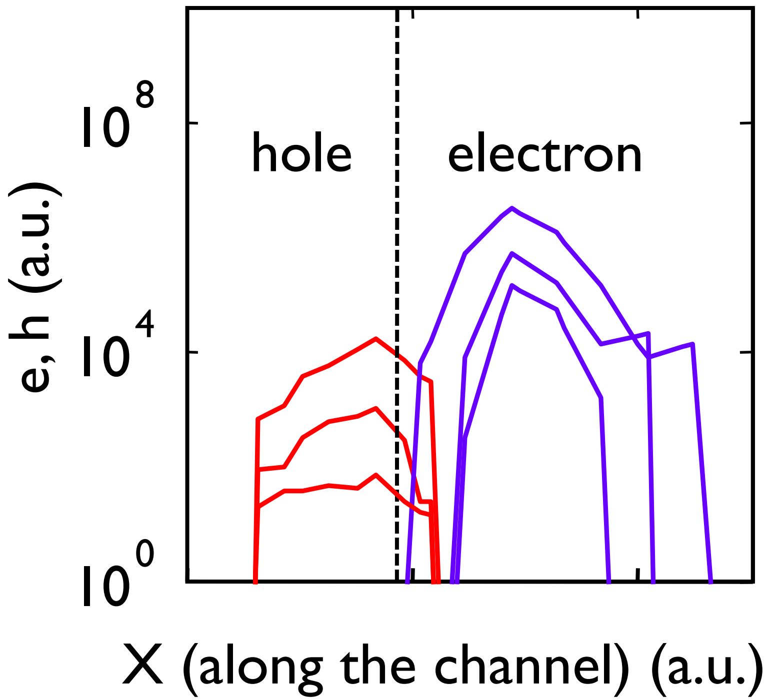


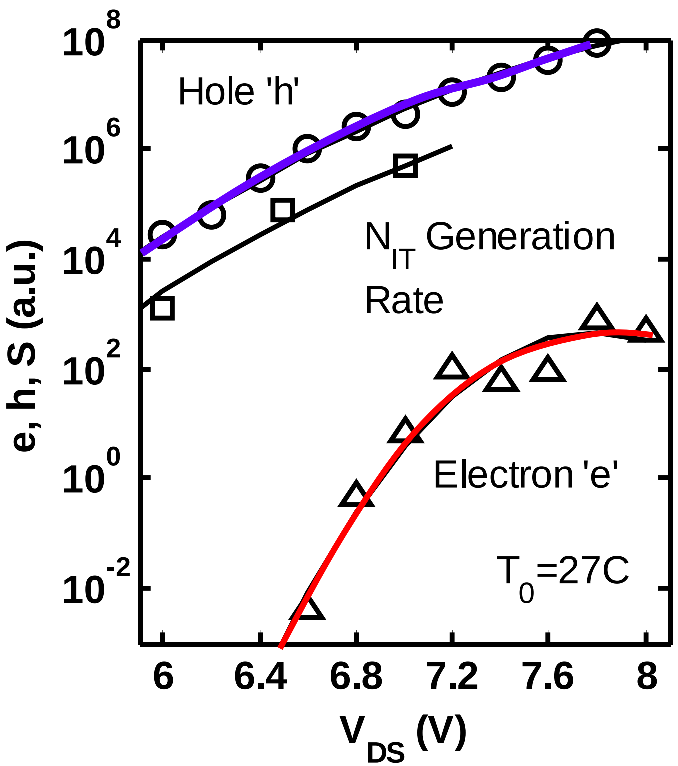
Hot carrier distribution can be calculated accurately from Monte Carlo simulation. It is a very difficult calculation however.

N_{IT} correlation with hot holes

Monte Carlo simulation

D.Varghese, EDL, Vol. 26, p. 572, 2006





Damage primarily due to broken Si-O bonds

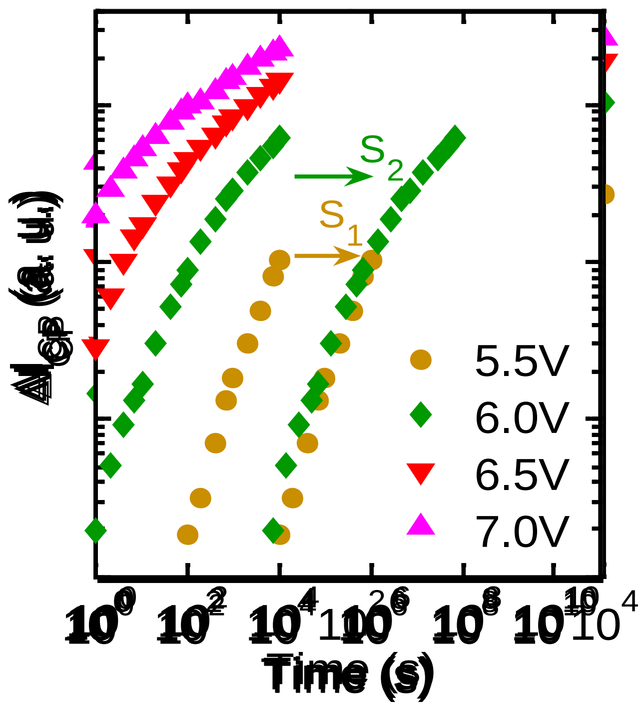
Outline

Recall: Voltage Dependent Constant t_0

$$N_{IT}^{SiH} = \left(\frac{k_F(V_G, V_D) N_0}{k_R} \right)^{\alpha} t^n \equiv \left(\frac{t}{t_0} \right)^n = f_1\left(\frac{t}{t_0} \right)$$

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

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



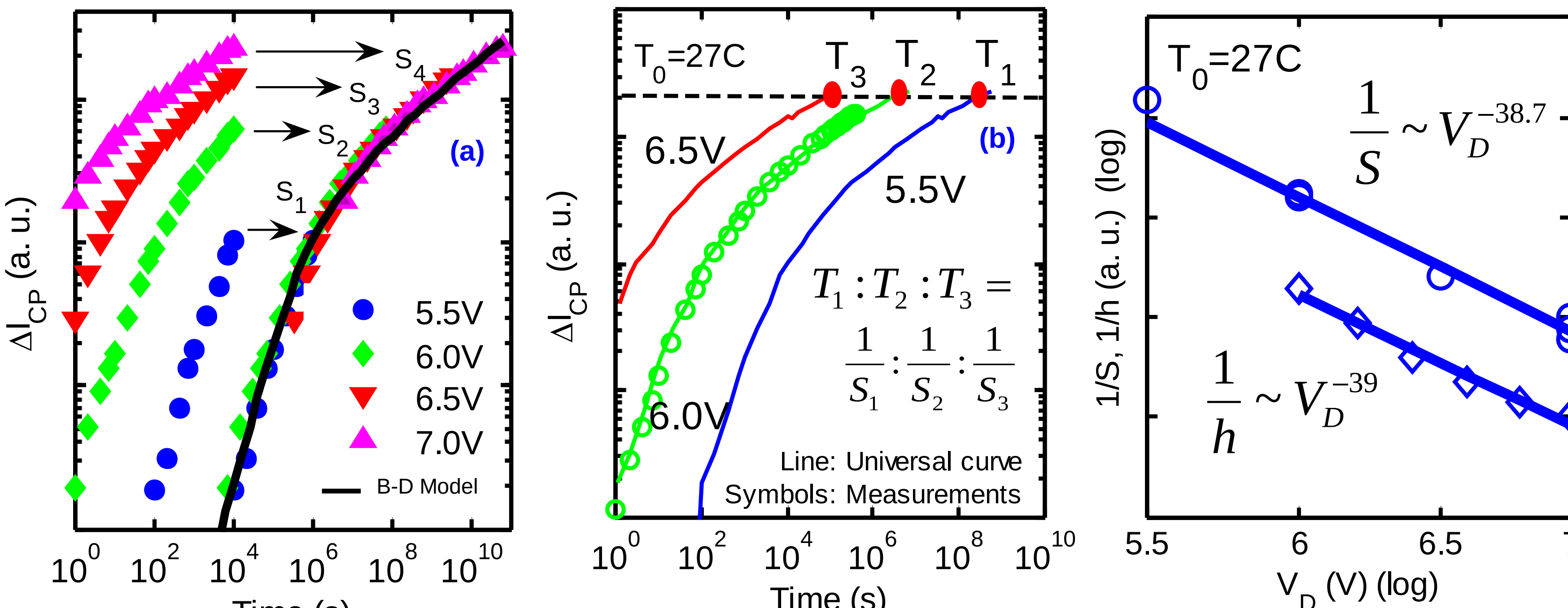
How to determine t_0 …

$$t^* / t_0(V_G, V_D) = f^{-1}(N_{it}^*) = \text{const.}$$

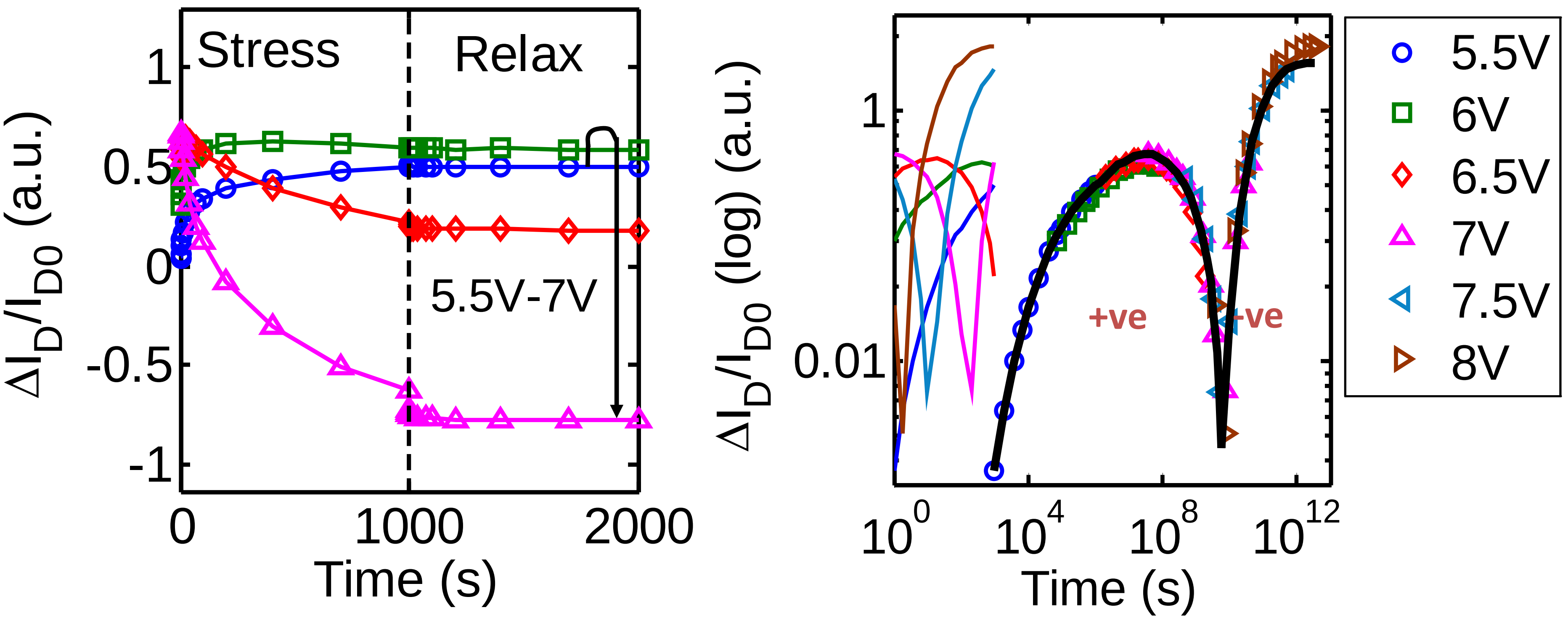
$$t_0(V_G, V_D) \propto t^*(V_G, V_D)$$

Universality of Degradation (NMOS)

Varghese, IRPS, 2008.

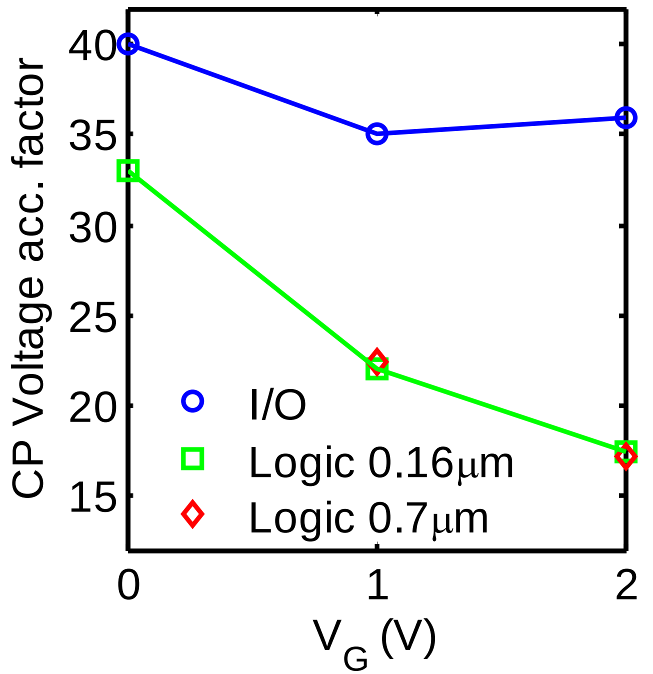


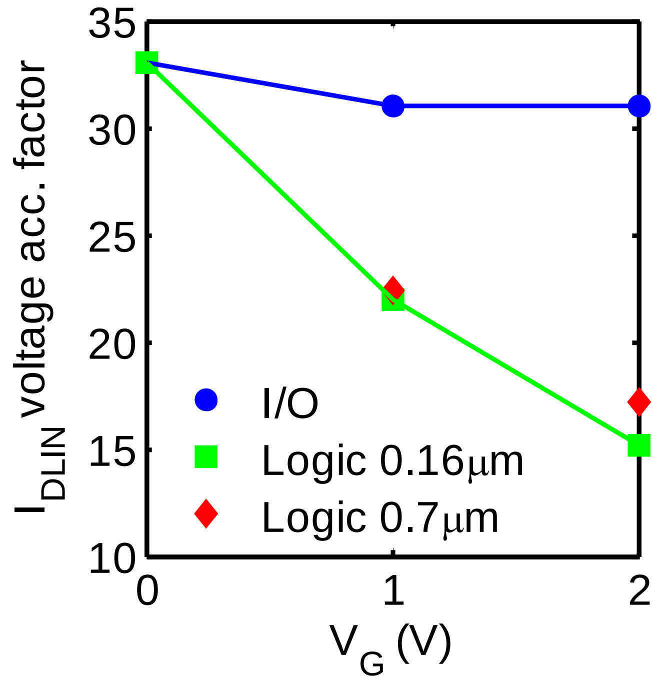
Universality of degradation (PMOS)



DePMOS show sign reversal in ΔI_{DLIN}, reflecting change from acceptor-like to donor-like traps

Discussion: Voltage Acceleration





Voltage acceleration factor reduces at higher gate biases

Voltage dependence of hot carrier profile from Monte Carlo simulation is required to understand the trends in acceleration factors

Conclusions

- Theory of HCI has been developed over many years – first by C. Hu via Hydrodynamic solution of BTE and later by Hess/Bude via Monte Carlo solution of BTE. Both provide reasonable explanation of voltage acceleration factors for HCI degradation for relatively long channel transistors. And both demonstrate universal scaling.

- For shorter channel transistors at low voltages, solution of BTE is difficult (MC has too few yield, while hydrodynamic model is inappropriate). Varghese's Universal scaling theory provides an excellent alternative.

Review Questions

1. Why is Isub called a thermometer of hot electron distribution? Why can you not simply measure hot electrons by looking at the drain current?
2. What are the three methods of HCI voltage acceleration?
3. If theory of universal scaling is so good, why not use it all the time? (Hint: Think about measurement time)
4. How many devices and how long do you need for HCI testing based on hydrodynamic theory? What about Universal scaling theory? What about direct lifetime projection?
5. If Monte Carlo simulation is so good, why does not everyone use Monte Carlo simulator to do lifetime testing?
6. We assumed $t0 \sim 1/IG \sim 1/kF$, what theory of SiH bond dissociation did we use?
7. Explain the origin of power-exponent of 2 in the Keldysh theory.
8. What is the impact ionization threshold for GaAs?

References

- The theory of HCI voltage acceleration is primarily due to C. Hu. In a series of paper in 1980s, he clarified the role of various factors. See Hu, J Solid-State Circuits, 20(1), p. 295, 1985. Also, see Grosenekan, Semi. Science/Tech, 10, 1208, 1995.
- Modern theory of hot-electron distribution is developed by M. Fischetti, J. Bude (EDL, 16,10, p 439,1995), and K. Hess The phenomelogical models are due to Guerin, TDMR, 7(2), p. 225, 2007 and Rauch, TDMR, 5(4), p. 701, 2005.
- The scaling theory of acceleration is due to Varghese and Alam, see D. Varghese, Ph.D. Thesis, 2009. Precursor of the Scaling theory can be found in Liang, EDL, 13(11), 569, 1992. D. S. Ang, TED, 45(1), p 149, 1998.
- The theory of Impact ionization and Keldysh formulation are discussed in many textbooks, see for example, K. Hess book on semiconductor devices, Chapter 13. Or, Ridley's book on Quantum Processes, p. 27 . Also, see C. Jungemann, SSE 39(7), p. 1079, 1996) ,