

ECE 695 : Reliability Physics of Nano-Transistors

Lecture 14A: Voltage dependent HCI

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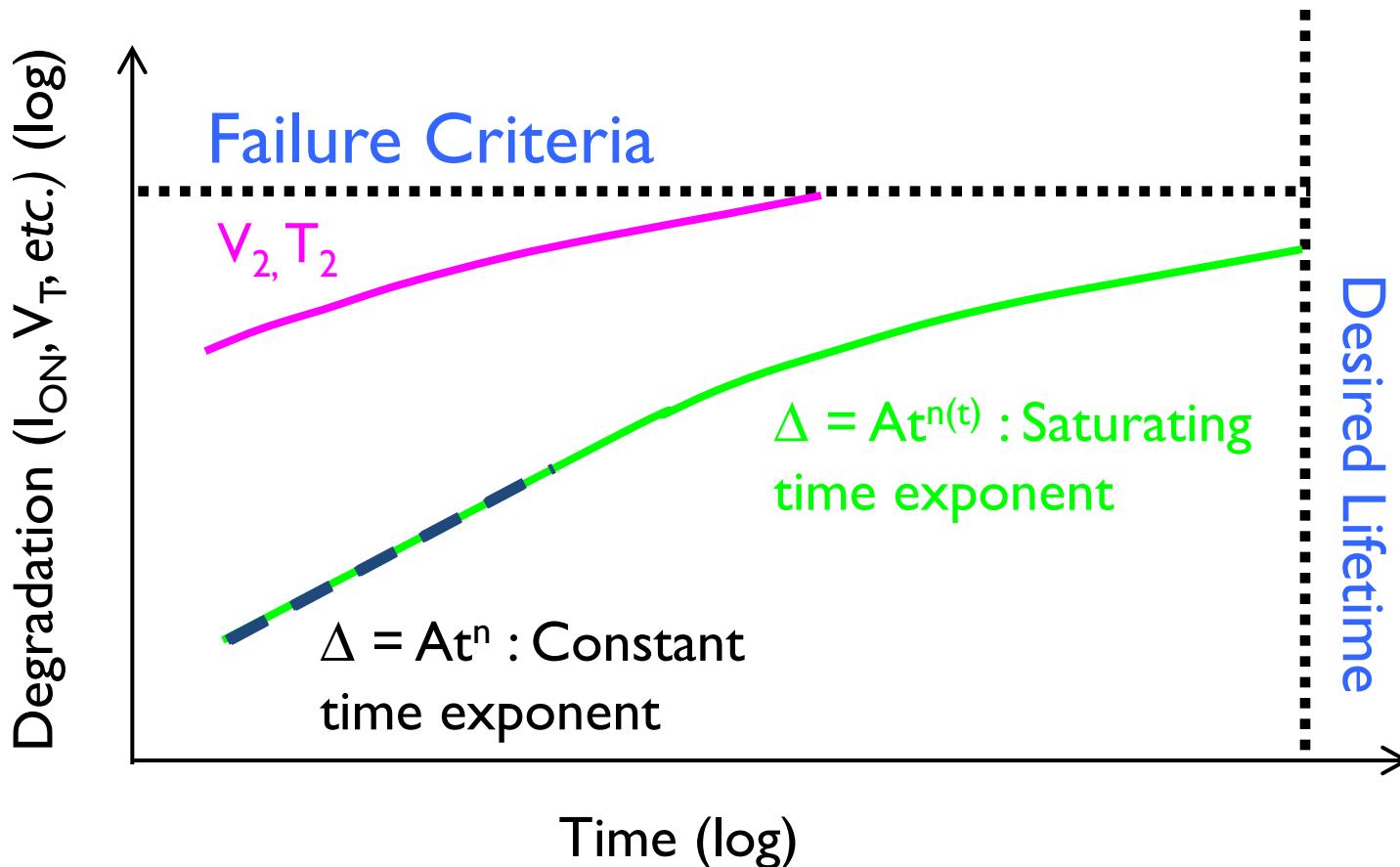
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Outline

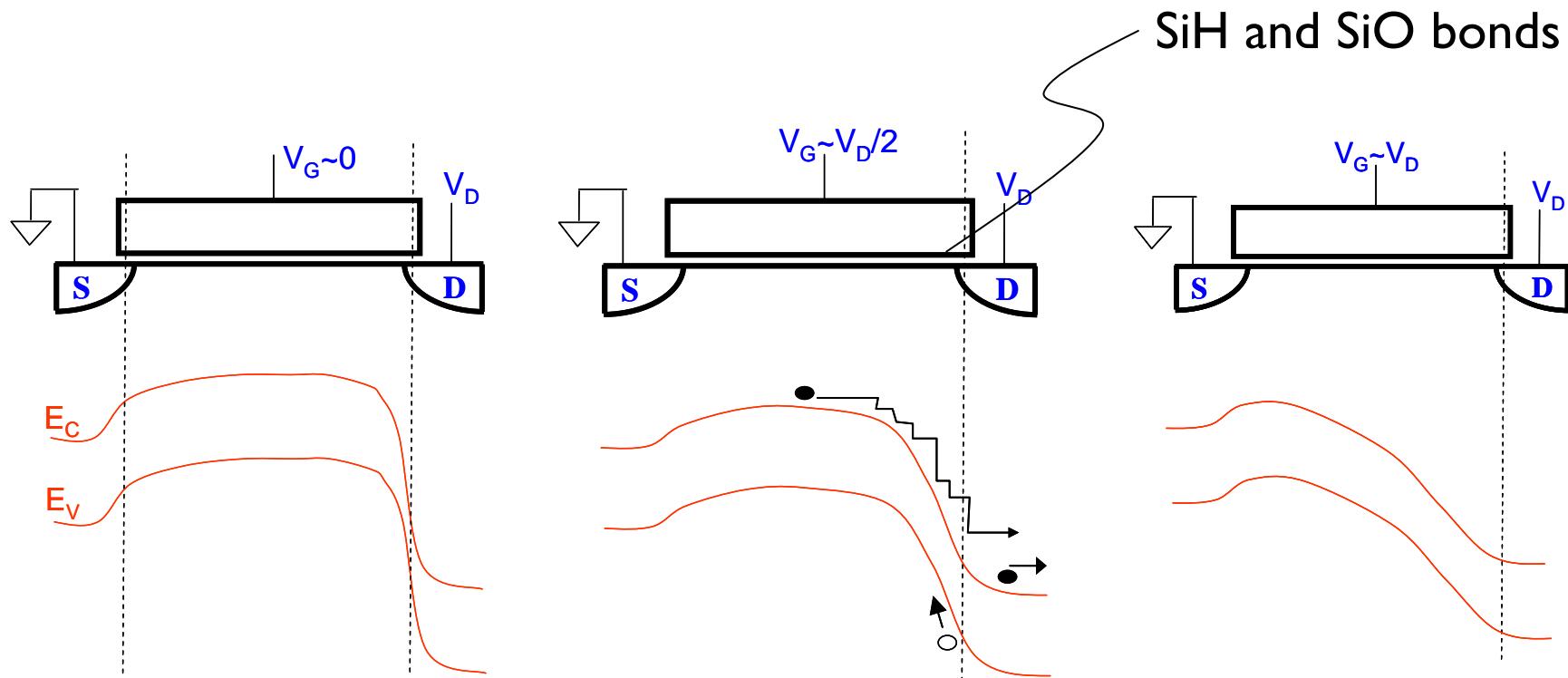
- I. Background and Empirical Observations
2. Theory of Hot Carriers: Hydrodynamic Model
3. Theory of Hot Carriers: Monte Carlo Model
4. Theory of Hot Carriers: Universal Scaling
5. Conclusion
6. Appendices

Voltage acceleration

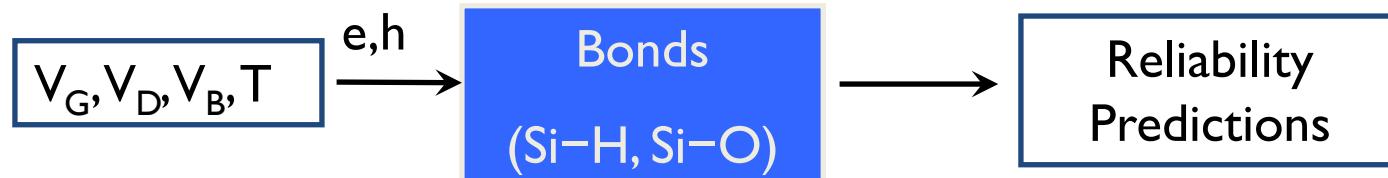


How does the degradation scale with voltage and temperature?

Classical Hot Carrier Degradation



Rate eqn.



Lifetime scales inversely with V_D at I_{sub} Max

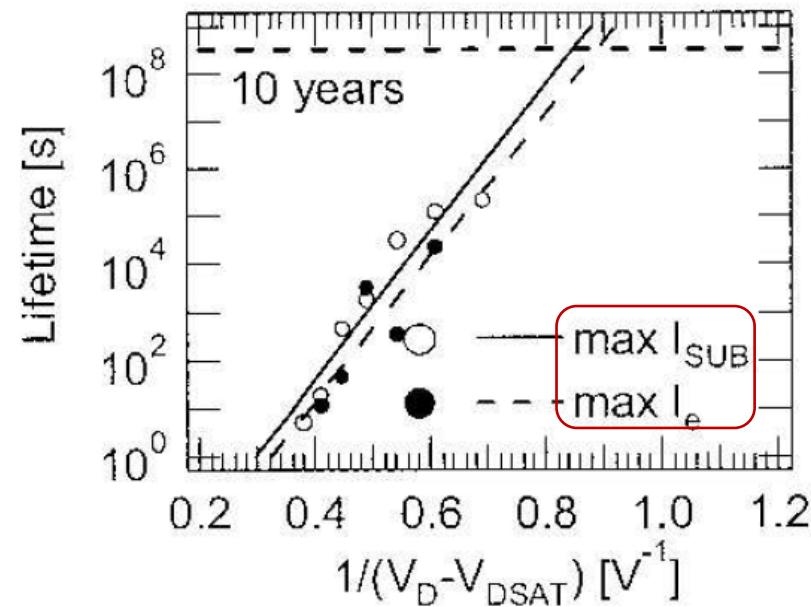
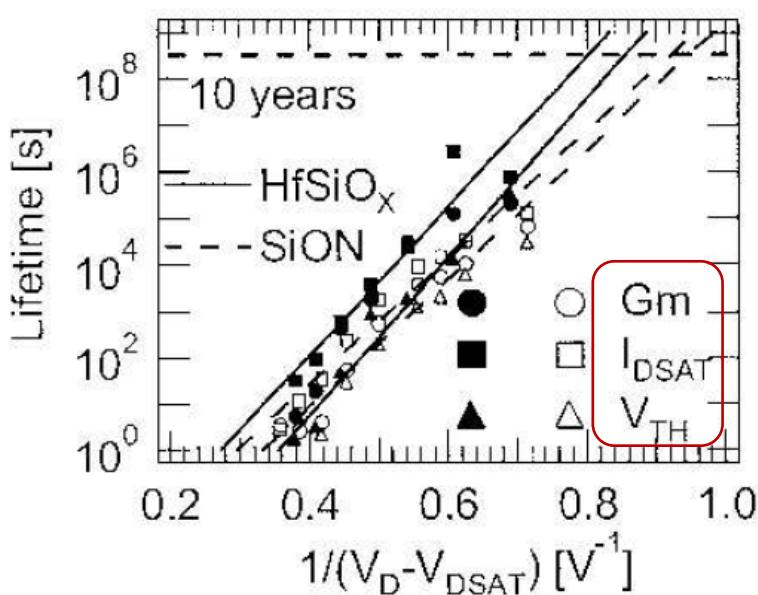
HOT CARRIER DEGRADATION ON N-CHANNEL HfSiON MOSFETS: EFFECTS ON THE DEVICE PERFORMANCE AND LIFETIME

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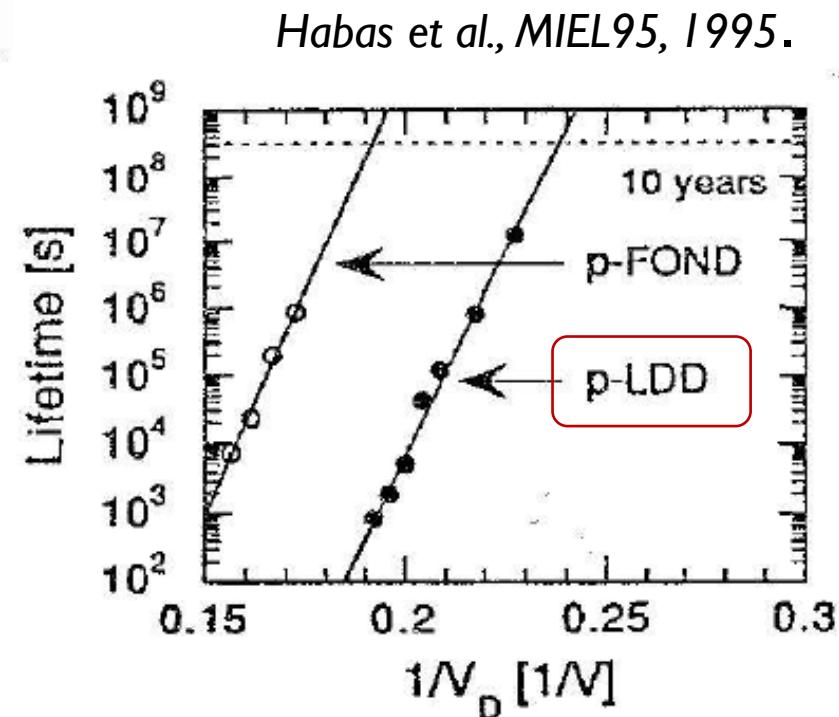
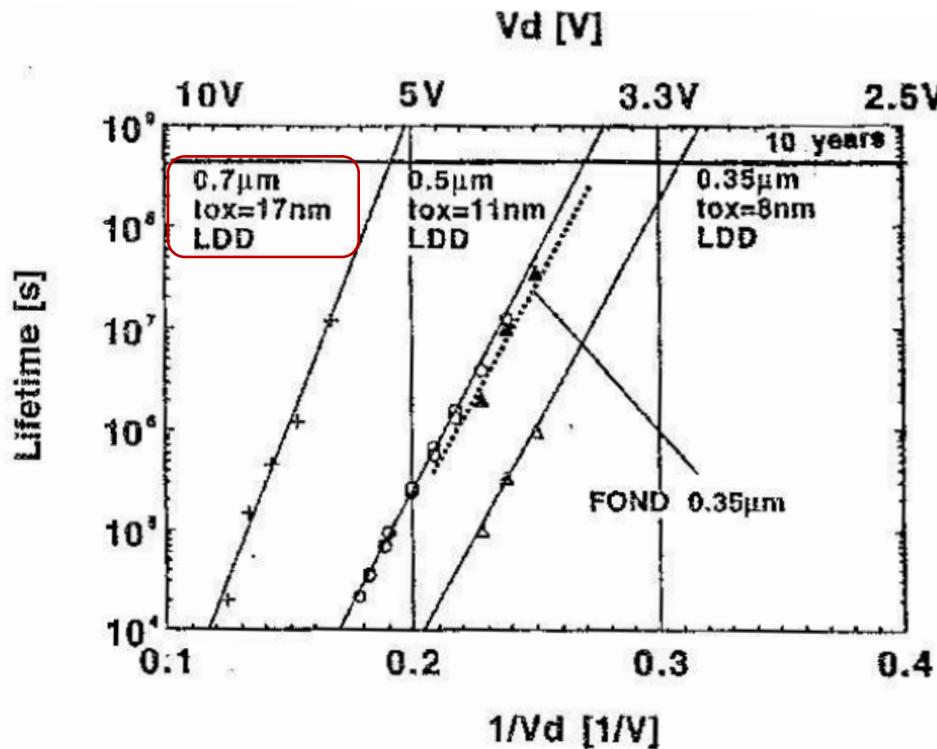
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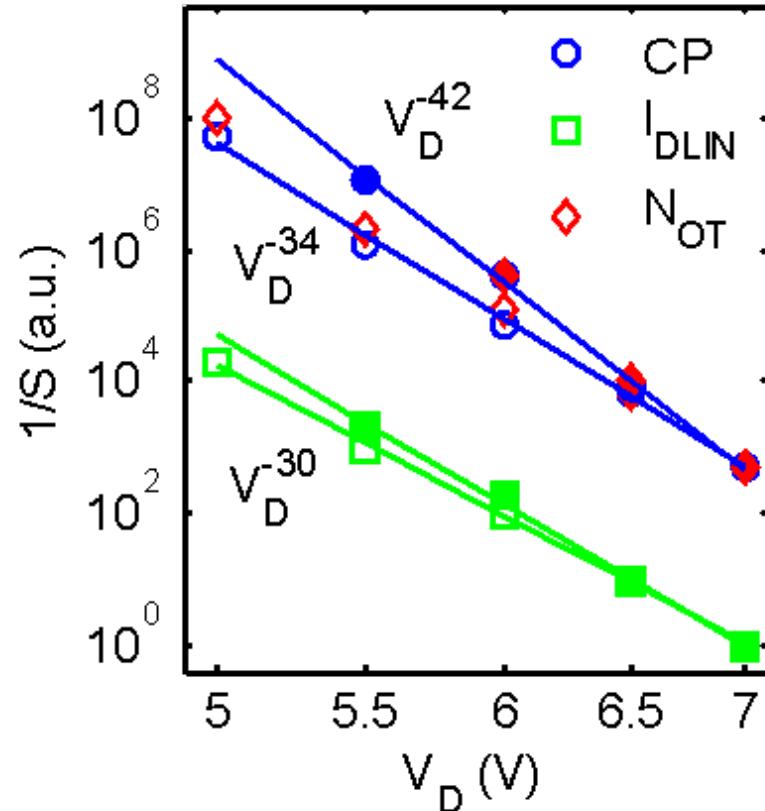
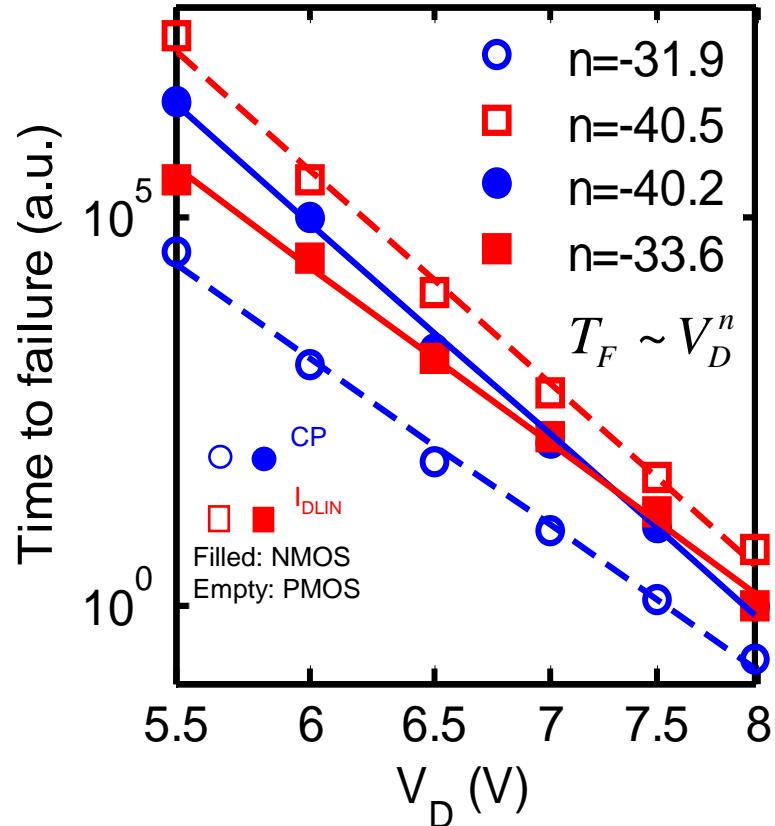
$$\log(t_0^{HCl}) \propto k / (V_D - V_{Dsat})$$

Lifetime scales exponentially with V_D (at $I_{sub} \text{ Max}$)



$$\log(t_0^{HCl}) \propto k / (V_D - V_{Dsat})$$

Lifetime described by power-law



$$\log(t_0^{HCl}) \propto -\alpha V_D \Rightarrow t_0^{HCl} \sim (1/V_D)^\alpha$$

Outline

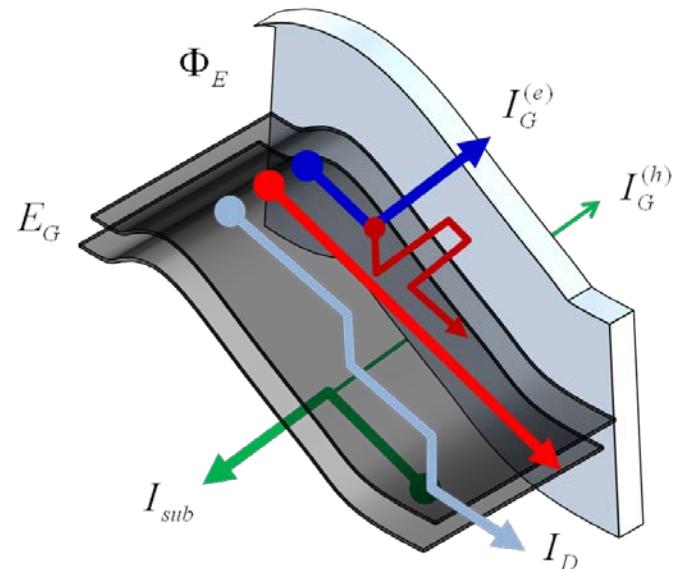
1. Background and Empirical Scaling
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Time and voltage dependencies

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

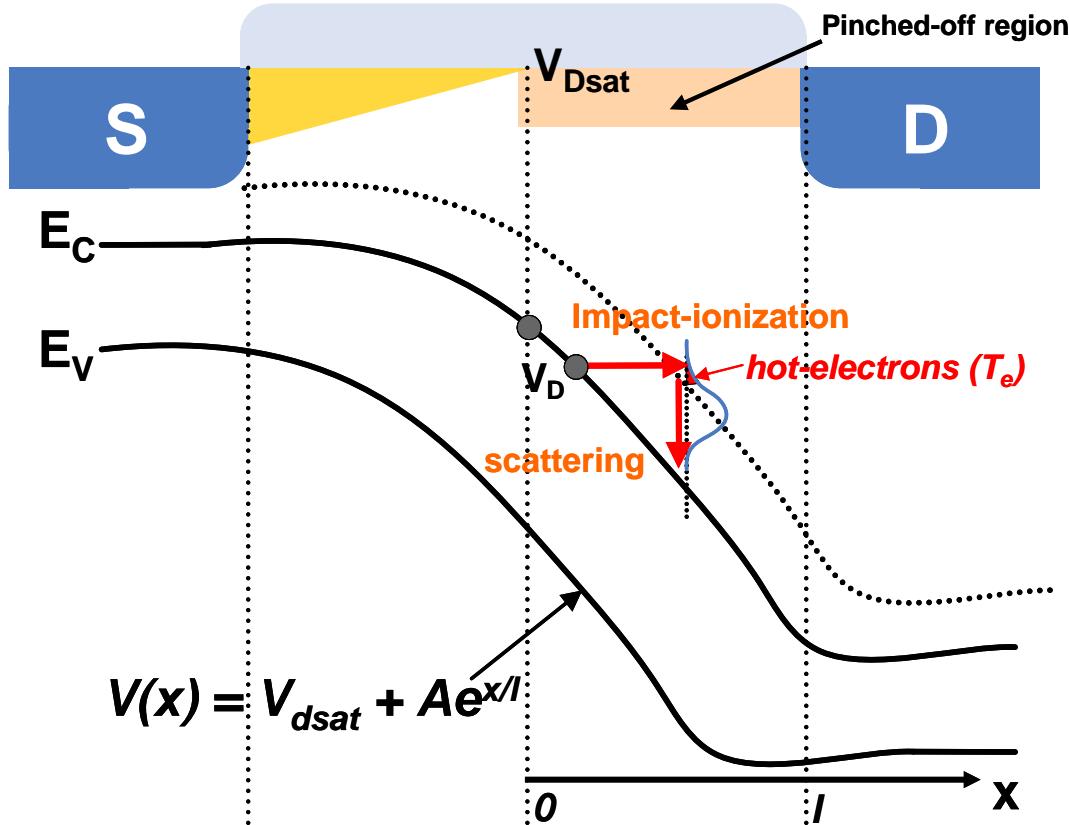
$$k_F^m t_0^n \propto N_{IT}^{crit}$$
$$t_0(V_D) \propto \left[\frac{1}{k_F(V_D)} \right]^{m/n}$$

$$k_F = C \times I_G^{(e)}, I_G^{(h)},$$



Recall the analogy with NBTI

Voltage dependence: Balance Equation



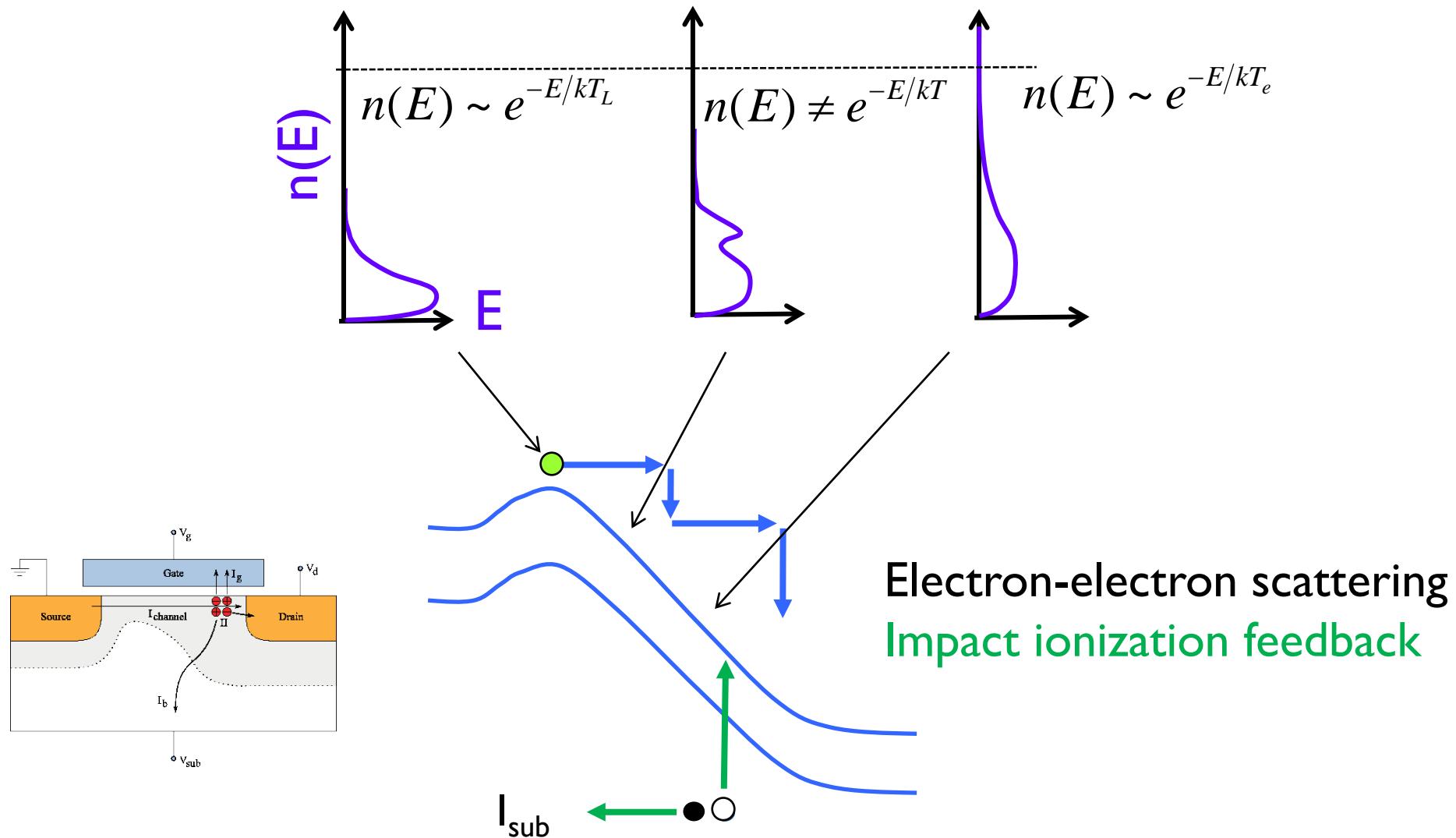
Monte Carlo

Hydrodynamic

Drift-Diffusion

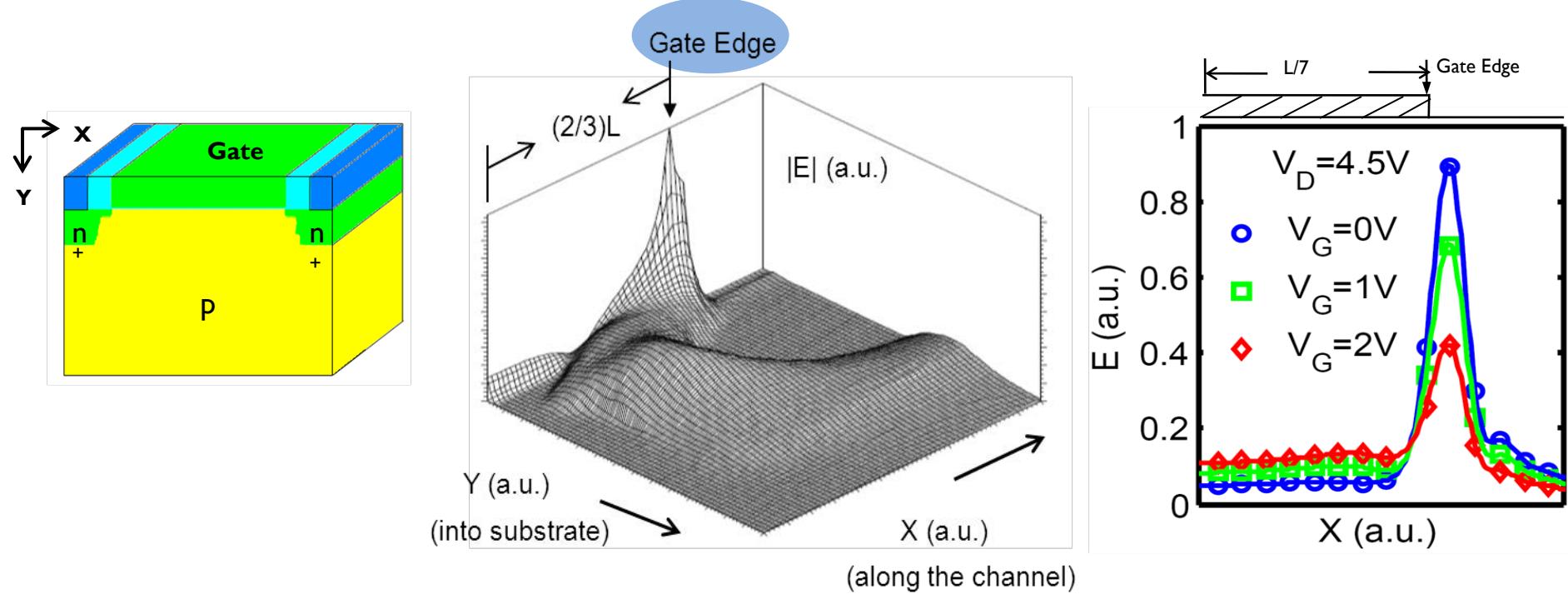
(see Prof. Lundstrom's EE656 Notes at Nanohub.org)

What is hot electron distribution?



Temperature a proxy of describing energy of the hot electrons

Field distribution at on state



Drift-diffusion simulation shows that field peaks close to the drain edge, as expected.

Outline of the solution

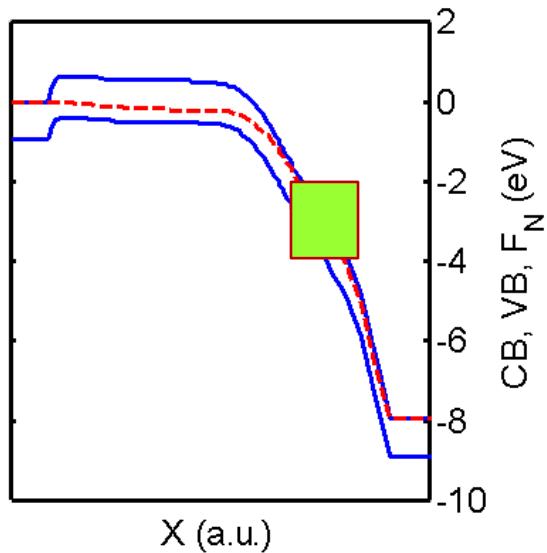
$$t_0(V_D) \leftarrow \textcolor{magenta}{k}_F(V_D, V_G) \leftarrow I_G(V_D, V_G) \leftarrow I_{sub}(V_D, V_G)$$

$$t_0(V_D) \propto \textcolor{magenta}{k}_F(V_D)^{-m/n}$$

$$\textcolor{magenta}{k}_F(V_D) \propto I_G \approx \frac{I_D}{v_{sat}} e^{\mathcal{B}/V_D}.$$

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

Electron/Hole temp: balance equation



$$t_0(V_D) \propto k_F(V_D)^{-m/n}$$
$$k_F = C \times I_G^{(e)}(\mathbf{T}_e), I_G^{(h)}(\mathbf{T}_h)$$

Long channel current:

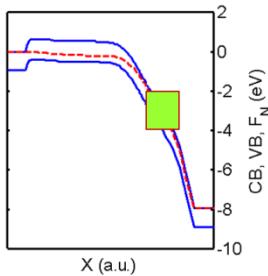
$$\mathbf{J}_n = \frac{1}{A} \frac{C_o \mu_e}{L_c} (V_G - V_{TH})^\alpha$$

Energy balance at steady state:

$$0 = -\frac{d}{dx} \left[(W + nk_B \mathbf{T}_e) v - \kappa \frac{d\mathbf{T}_e}{dx} \right] + (\mathbf{J}_n \times \mathbf{E}_x) - \left(\frac{W - W^0}{\tau_e} \right).$$

Self Energy-flux Work against pressure Carrier heating Relaxation to lattice

Electron temp. @ Pinch-off



$$0 = -\frac{d}{dx} \left[(W + nk_B \mathbf{T}_e) v - \kappa \frac{d\mathbf{T}_e}{dx} \right] + (\mathbf{J}_n \times \mathcal{E}_x) - \left(\frac{W - W^0}{\tau_e} \right)$$

$$W = \frac{3}{2} nk_B \mathbf{T}_e + \frac{1}{2} nm^2 v^2 \approx \frac{3}{2} nk_B \mathbf{T}_e$$

$$-\frac{d}{dx} \left[\frac{5}{2} nk_B \mathbf{T}_e v \right] + q n v_{sat} \mathcal{E}_x - \frac{3}{2} n \frac{k_B \mathbf{T}_e}{\tau_e} = 0.$$

$$v_{sat} = \sqrt{\frac{\hbar \omega}{m^*}}$$

$$\frac{k_B \mathbf{T}_e}{q} = \frac{2}{5} \int_0^x \mathcal{E}_x(x') e^{\frac{-3(x-x')}{5\tau_e v_{sat}}} dx' = \frac{2}{3} (\tau_e v_{sat}) \mathcal{E}_x \equiv \lambda_e \mathcal{E}_x$$

Electric Field in the Pinch Off Region

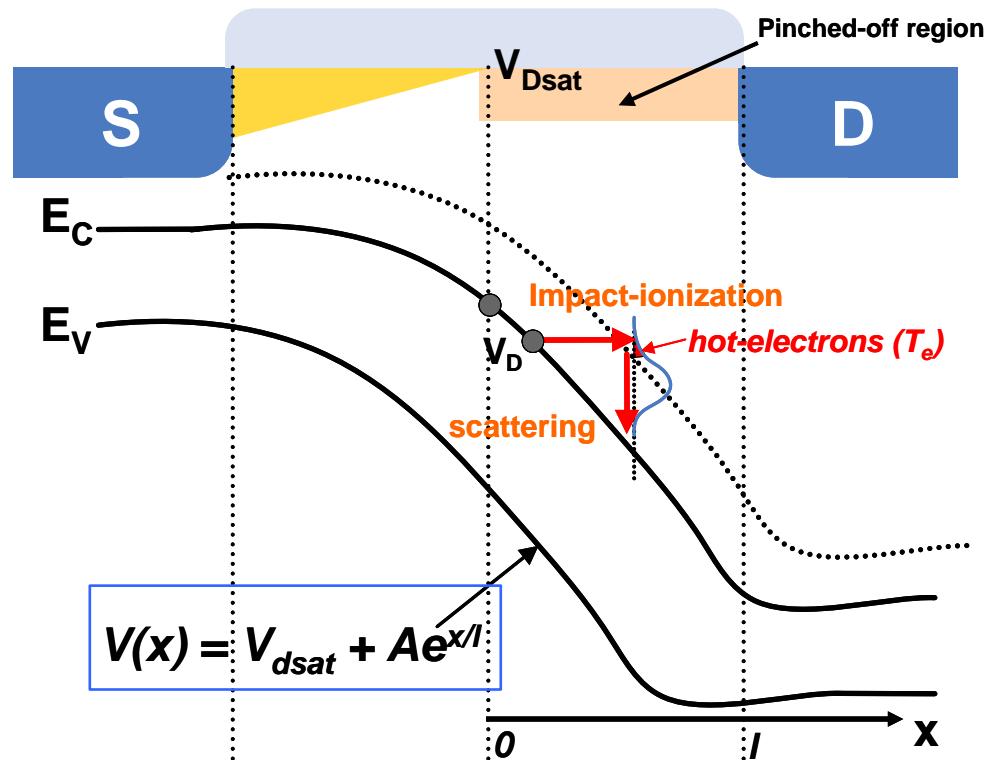
$$I_D = \frac{C_o \mu_e}{L_c} (V_G - V_T)^\alpha$$

$$\frac{x}{L_c} = \frac{(V_G - V_T)V - \frac{V^2}{2}}{(V_G - V_T)V_D - \frac{V_D^2}{2}}.$$

In the pinch off region ..

$$V(x) = V_{Dsat} + U_0 e^{x/l}$$

$$\mathcal{E}_x(x) = dV/dx = U_0 e^{x/l} / l \quad l = \sqrt{3x_0 W_D}$$



Mansy, 2D Model for IGFET in Saturation, ITED, 24(3), p. 254, 1977

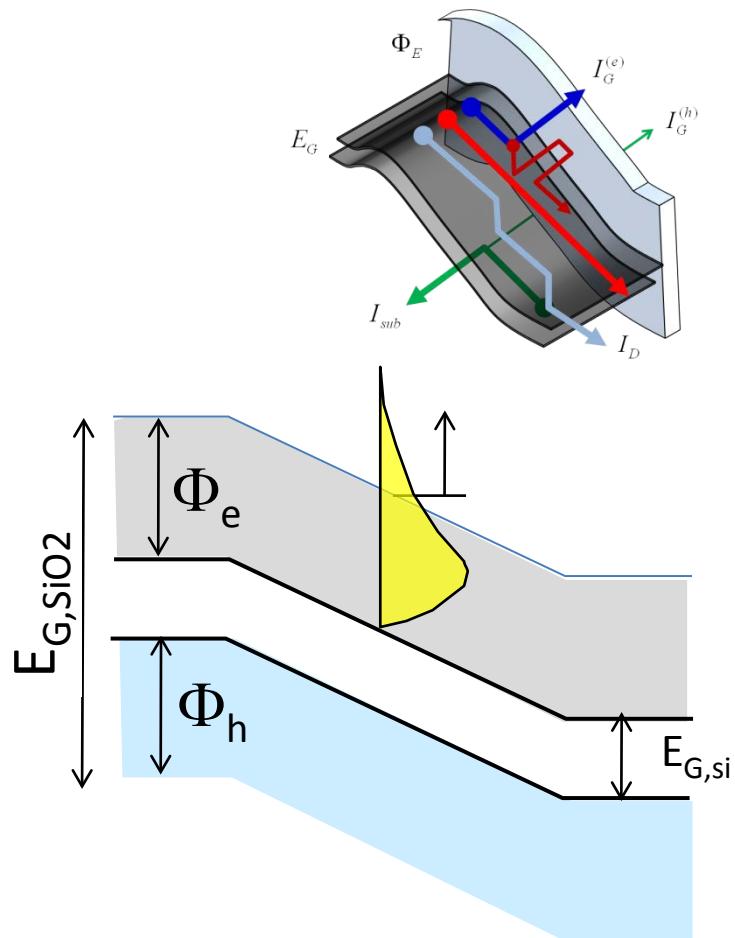
Position dependent gate current

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

$$= \left[\frac{I_D}{v_{sat}} \right] \int_0^l \left(\frac{k_B T_e(x)}{2\pi m^*} \right)^{1/2} e^{\frac{-\Phi_e}{q E_x \lambda_e}} dx.$$

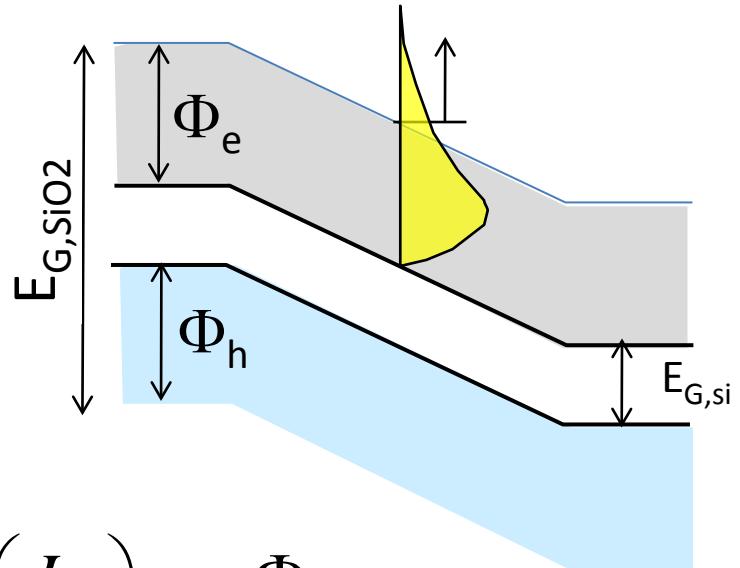
Recall the saddle point integration

$$\int_a^b e^{Mf(x)} dx = \sqrt{\frac{2\pi}{M |f''(x_0)|}} e^{Mf(x_0)} \quad \text{as } M \rightarrow \infty.$$



Hot Electron gate current

$$I_G = \left[\frac{I_D}{v_{sat}} \right] \int_0^l \left(\frac{k_B T_e(x)}{2\pi m^*} \right)^{1/2} e^{\frac{-\Phi_e}{q\mathcal{E}_x \lambda_e}} dx.$$



Saddle point integration

$$\approx \frac{I_D}{v_{sat}} \left[l \sqrt{\frac{q\mathcal{E}_m \lambda_e}{m^*} \frac{U_0 q}{\Phi_e} \frac{\lambda_e}{l}} \right] e^{\frac{-\Phi_e}{q\mathcal{E}_m \lambda_e}} \Rightarrow \log \left(\frac{I_G}{I_D} \right) = \frac{\Phi_e}{q\mathcal{E}_m \lambda_e} + c.$$

$$\propto \frac{I_D}{v_{sat}} e^{-(\Phi_e l / q\lambda_e) / (V_D - V_{Dsat})} \approx \frac{I_D}{v_{sat}} e^{\mathcal{B} / V_D}.$$

$V(x) = V_{Dsat} + U_0 e^{x/l}$

$\mathcal{E}_x = U_0 e^{x/l} / l \equiv (\mathcal{V}(x) - V_{Dsat}) / l$

$\mathcal{E}_m = \mathcal{E}_{x,\max} = (V_D - V_{Dsat}) / l$

Hot Carrier Lifetime

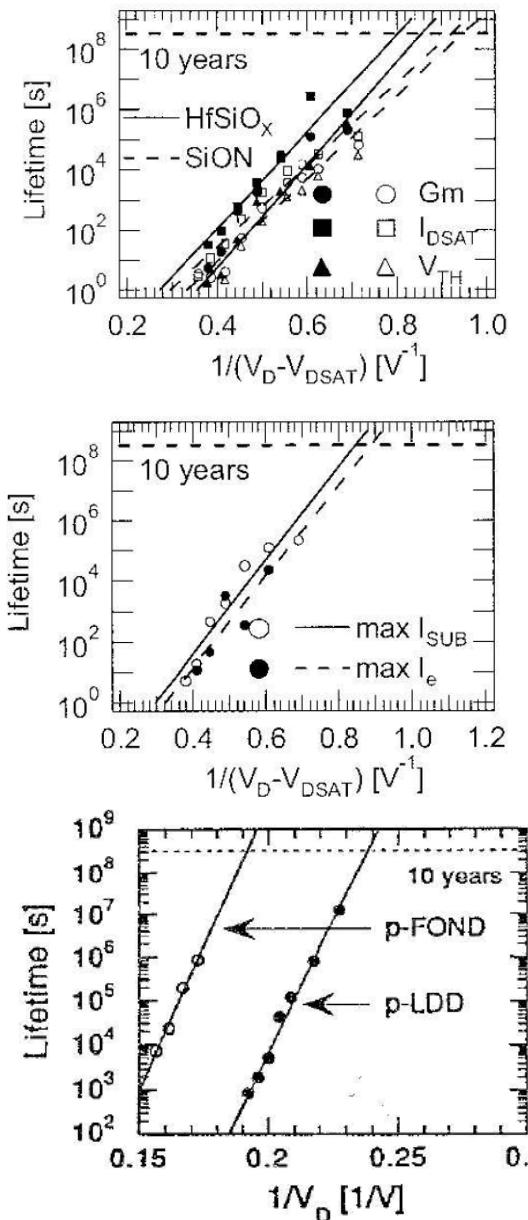
$$t_0(V_G, V_D) \propto k_F(V_G, V_D)^{-m/n}$$

$$t_0 \square \frac{1}{k_F(V_G, V_D)} = \frac{\mathcal{A}}{I_G} = \frac{\mathcal{A} v_{sat}}{I_D \times e^{-\mathcal{B}/(V_D - V_{D,sat})}}$$

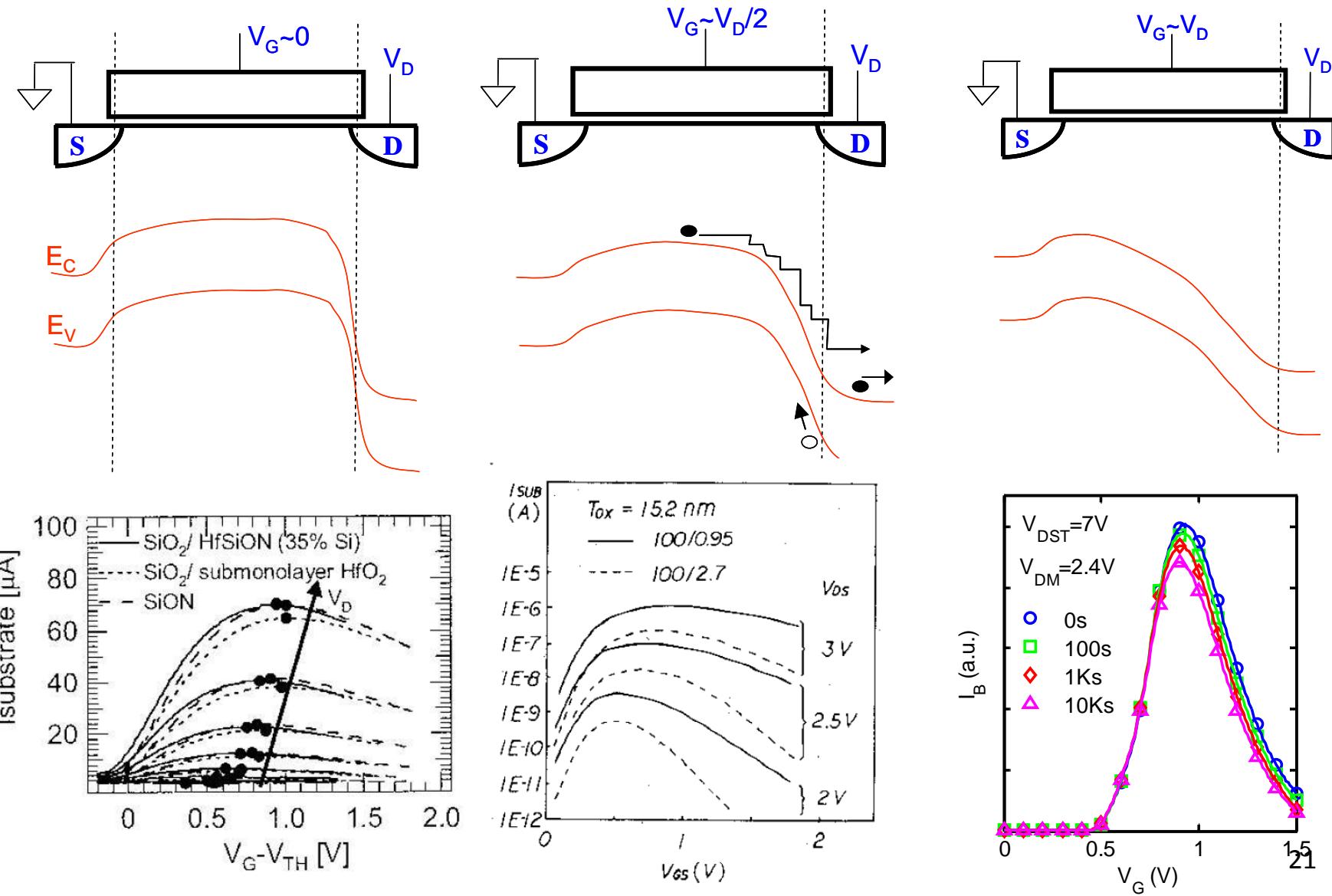
$$I_D(V_G, V_D) \times t_0 \square \mathcal{A} v_{sat} \times e^{\mathcal{B}/(V_D - V_{D,sat})}$$

$$\ln(I_D \times t_0) \square \ln \mathcal{A} v_{sat} + \mathcal{B} / (V_D - V_{D,sat})$$

Determine lifetime for several different voltages allows to calculate B.



Substrate current as a thermometer ...



Rate of impact ionization

For $E > \Phi_i$

$$\alpha_{ii} \approx C_i \left[(E/\Phi_i) - 1 \right]^\gamma$$

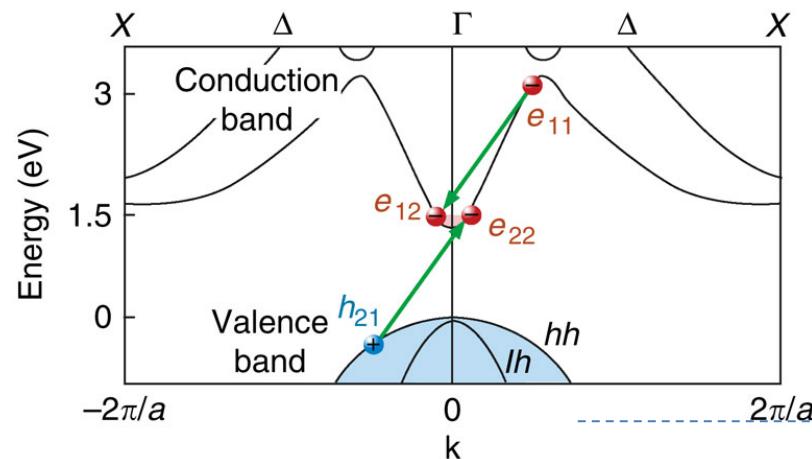
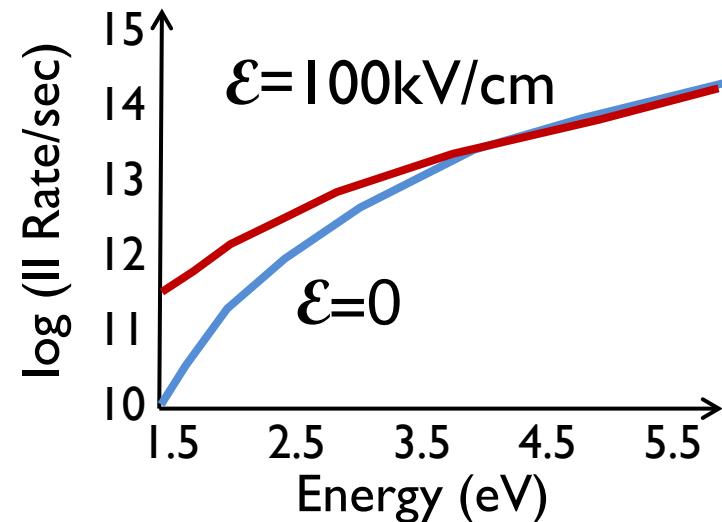
$$\Phi_i \approx E_G \left(1 + \frac{m_e}{m_e + m_h} \right)$$

$$\Phi_i = 1.75 \text{ eV},$$

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

$$\gamma = 1-2 \text{ (Keldysh)}$$

$$m = 0.5m_0$$



Hot Carrier lifetime by substrate current

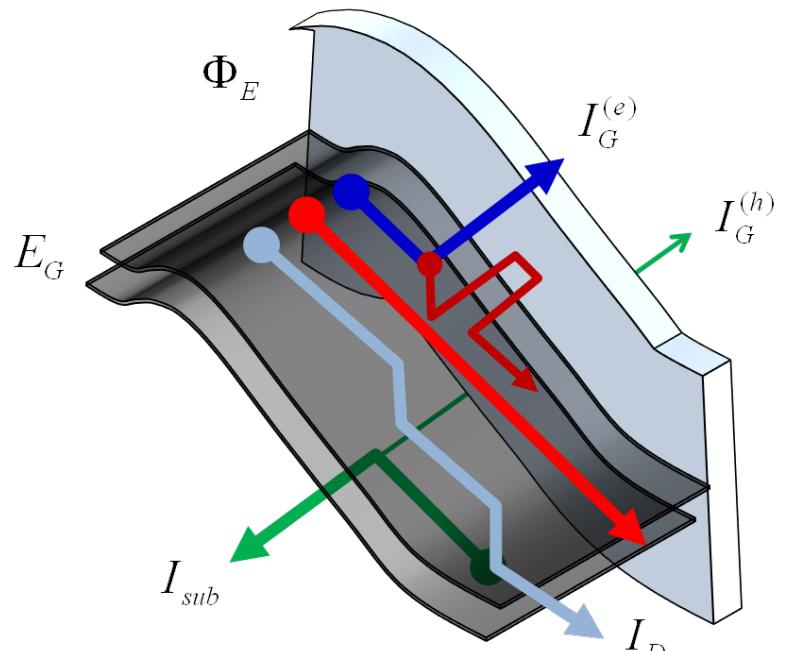
$$I_{sub} = \int_0^l I_D \cdot \alpha_{II}(x) \cdot dx$$

$$\alpha_{II}(x) = \alpha_0 e^{\frac{-\Phi_i}{k_B T_e(x)}} \approx \alpha_0 e^{\frac{-\Phi_i}{q\mathcal{E}_x \lambda_e}}$$

$$I_{sub} \propto I_D e^{\frac{-\Phi_i}{q\mathcal{E}_m \lambda_e}}$$

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

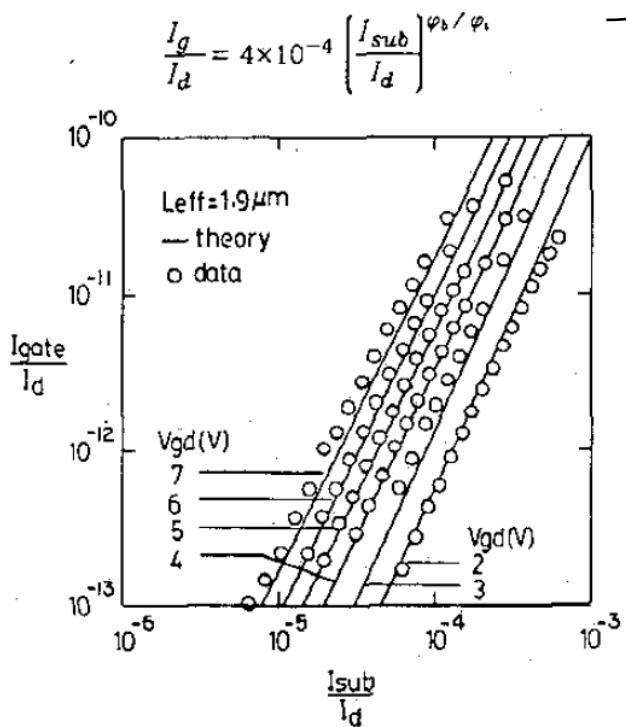
Threshold for impact ionization



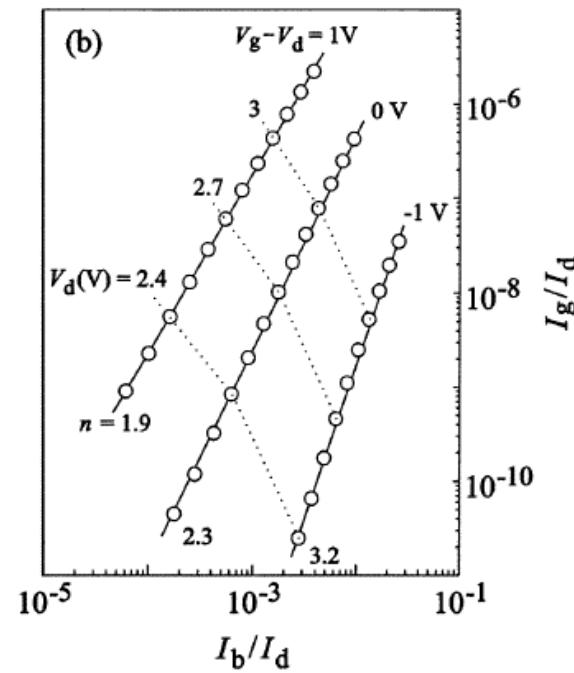
Substrate vs. gate current

$$\log\left(\frac{I_G}{I_D}\right) = \frac{\Phi_e}{qE_m\lambda_e} + c.$$

$$\log\left(\frac{I_{sub}}{I_D}\right) = \frac{\Phi_i}{qE_m\lambda_e} + b$$



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



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

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

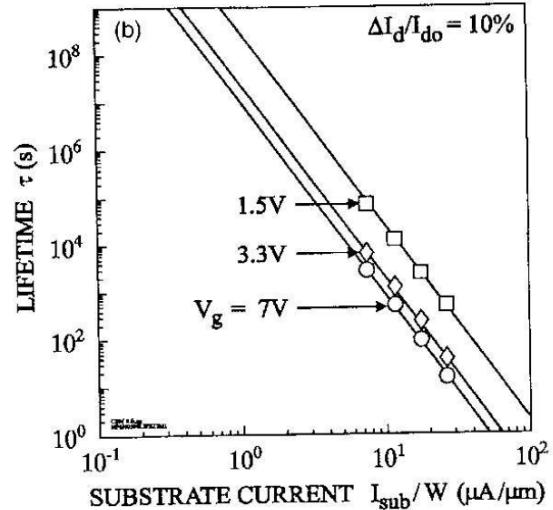
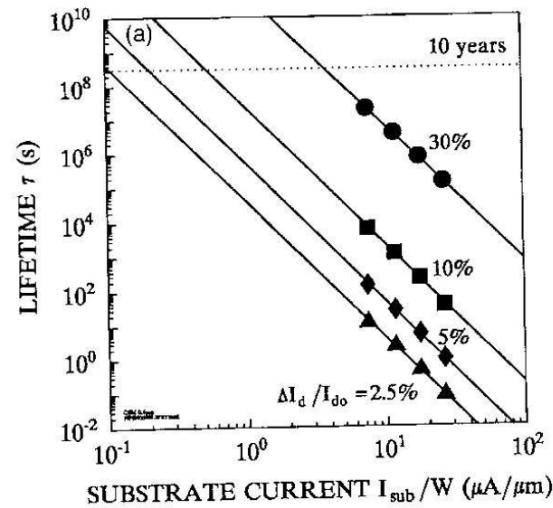
Voltage Scaling by Substrate Current

$$\left. \begin{aligned} \log\left(\frac{I_G}{I_D}\right) &= \frac{\Phi_e}{qE_m\lambda_e} + c. \\ \log\left(\frac{I_{sub}}{I_D}\right) &= \frac{\Phi_i}{qE_m\lambda_e} + b \end{aligned} \right\} \quad \frac{I_G}{I_D} = \left[e^{\frac{\Phi_i}{qE_m\lambda_e}} \right]^{\frac{\Phi_e}{\Phi_i}} = \left[\frac{I_{sub}}{I_D} \right]^{\frac{\Phi_e}{\Phi_i}}$$

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

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

Ang, Microelectronics Reliability, 39, 1311, 1999.



References

- The theory of HCl 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 phenomenological 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)