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ECE695: Reliability Physics of Nano-Transistors
Lecture 18: DC-IV and Charge Pumping Methods

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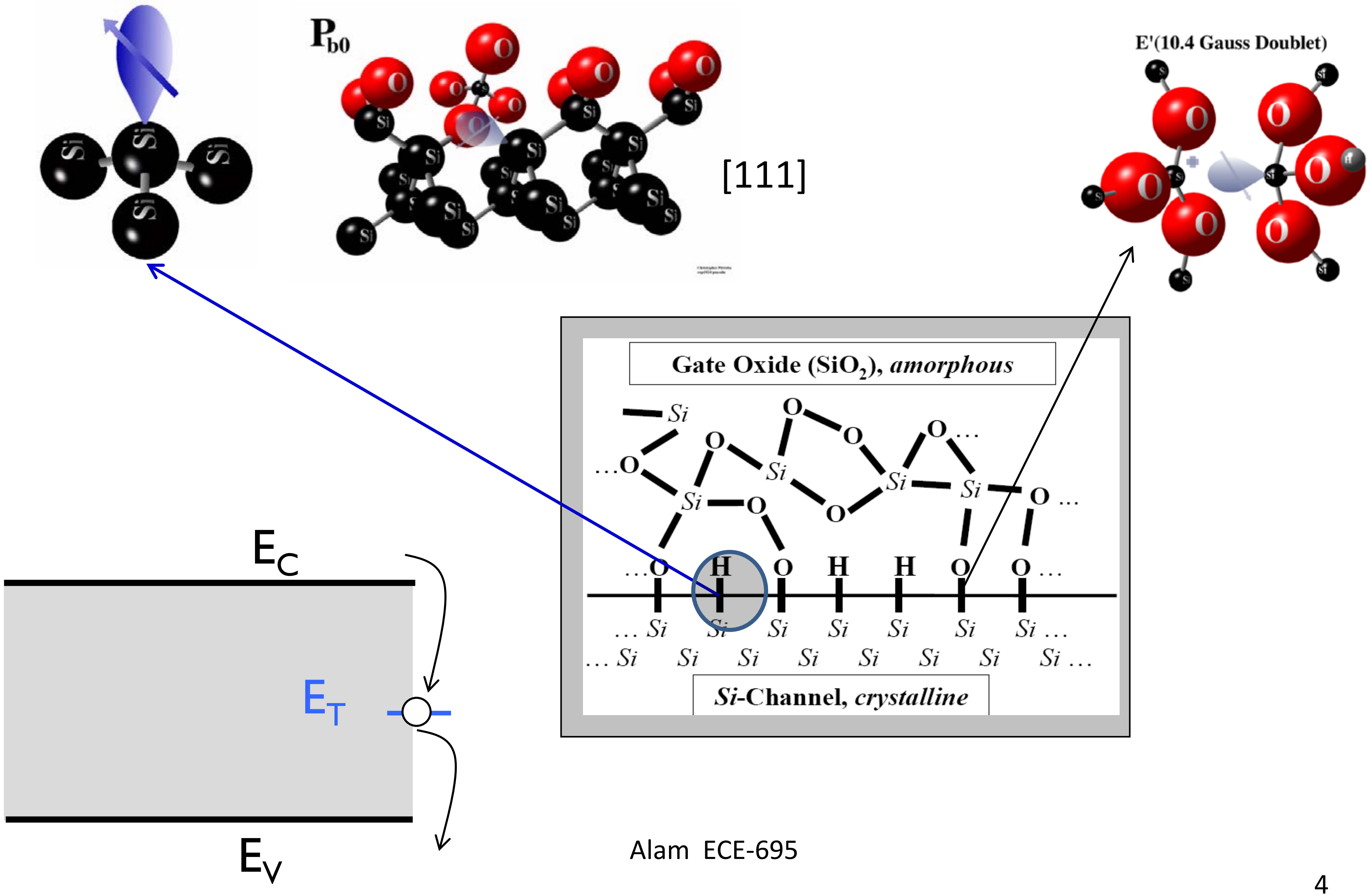
Outline

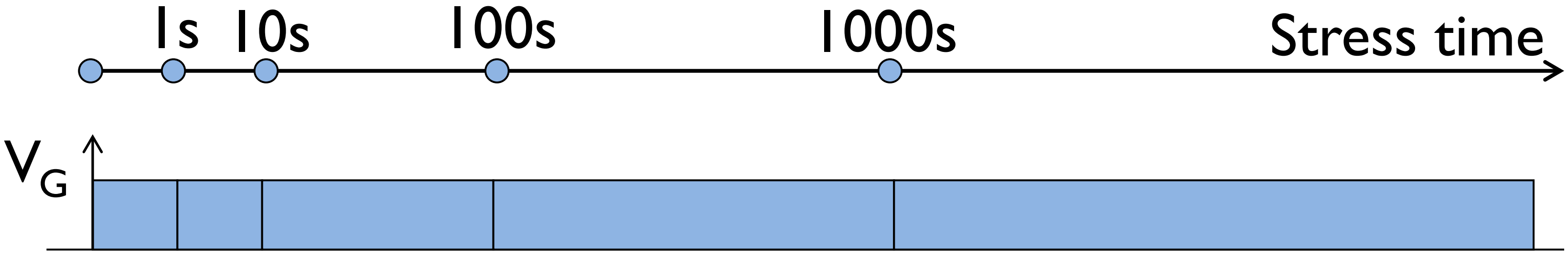
1. Recall: Properties of Interface Defects
2. Flux-based method 1: Direct Current-Voltage method
3. Flux-based method 2: Charge pumping method
4. Conclusions

Review and background

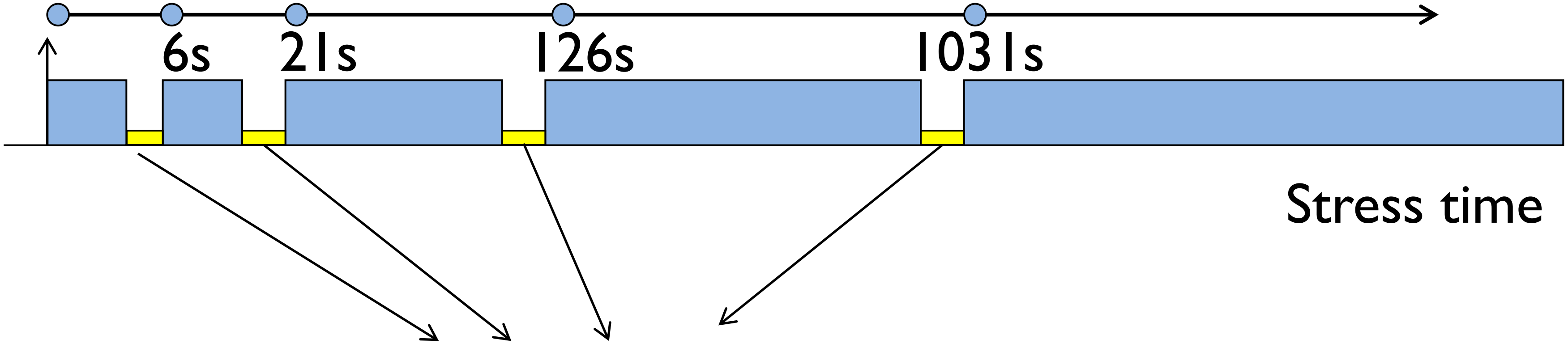


Measurement is a complex process

We periodically stop the stress and measure defects …



The measurements are often complex and interpretation of data depends on our interpretation of measurement



C-V, SILC, SDR, Idlin, DCIV, CP methods, …..

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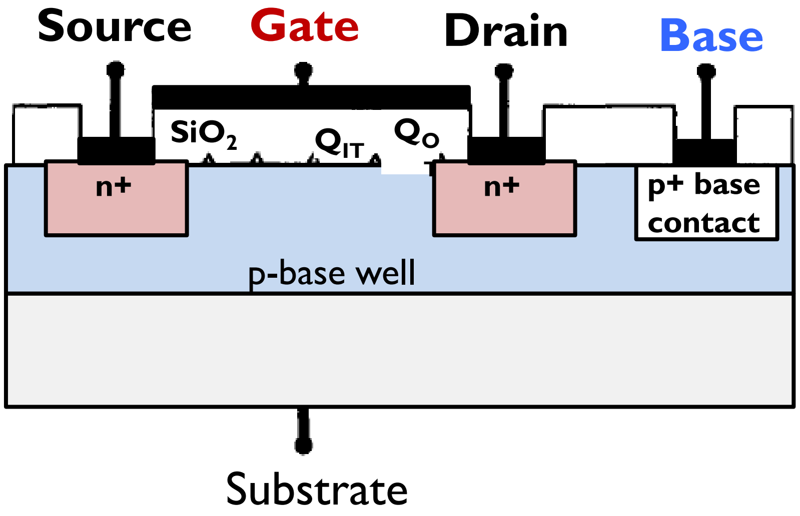
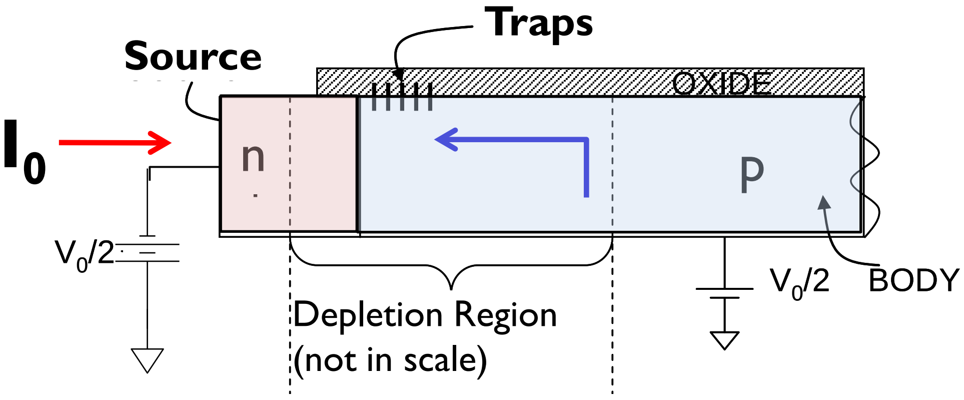
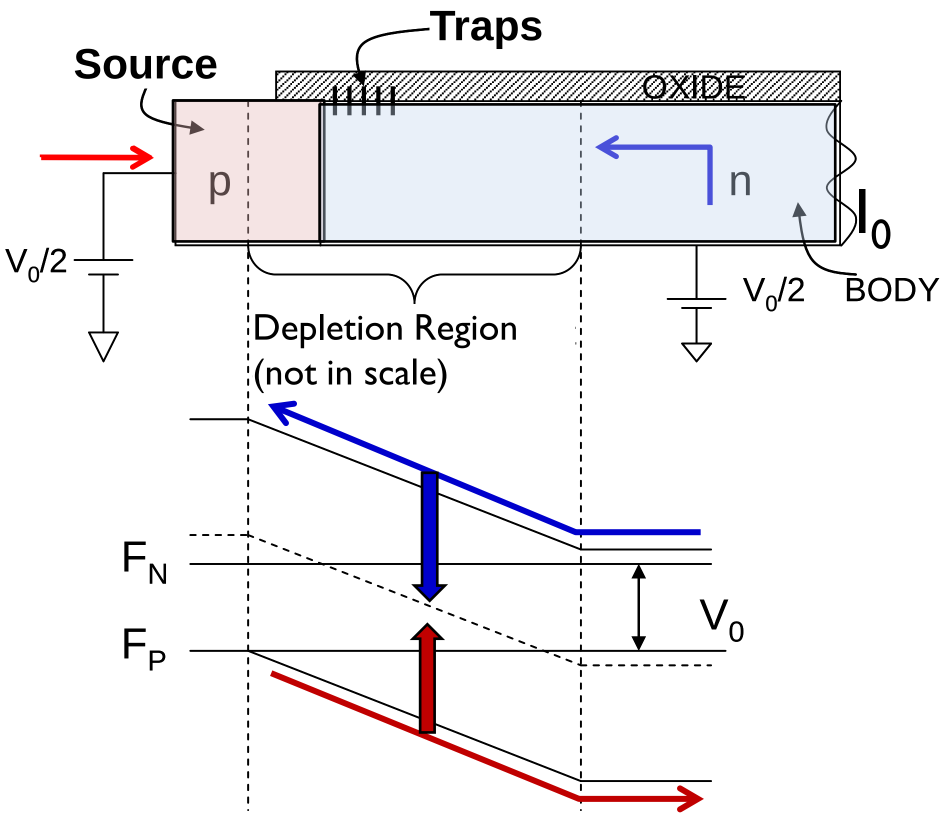
Algorithm of DC-IV measurement

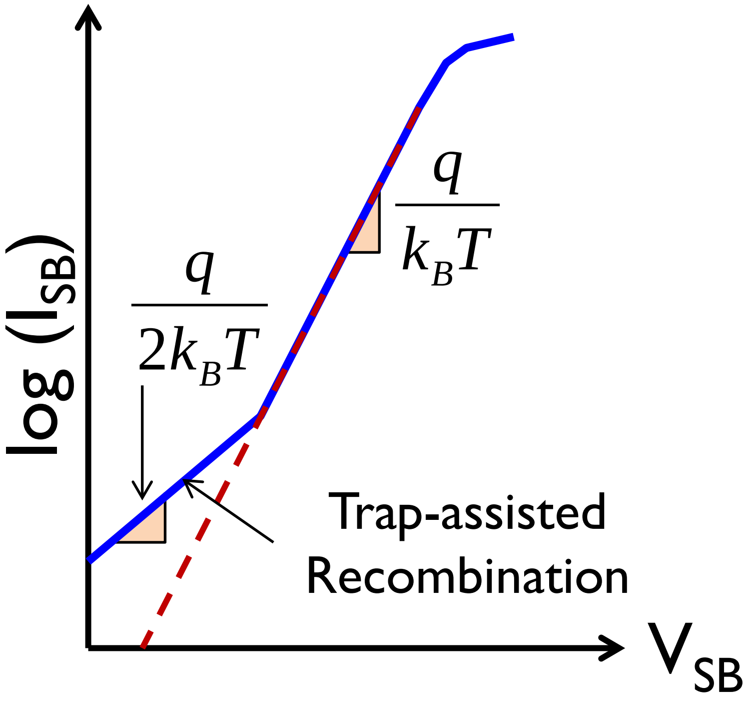




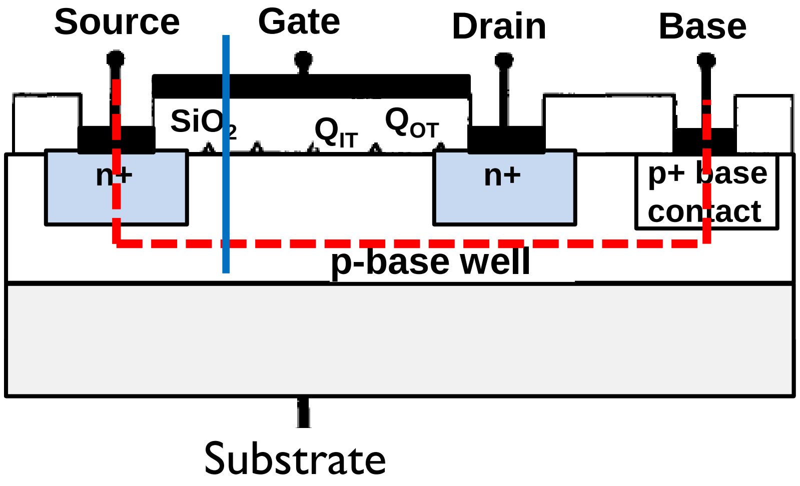
1. Initialize by Forward biasing the source-substrate junction with a small V_0 so that just a small forward current exists.
2. Stress to the device by increasing VG for stress duration
3. For measurement, set $V_G=0$ and measure/record terminal current. Observe the change in current. *Back to step 2.*

The logic of DC-IV measurement



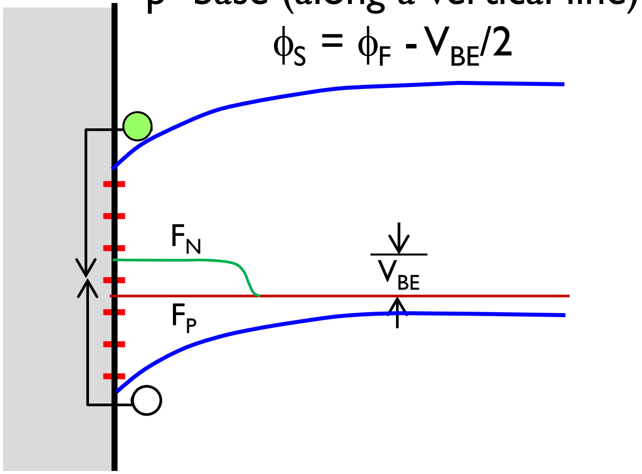


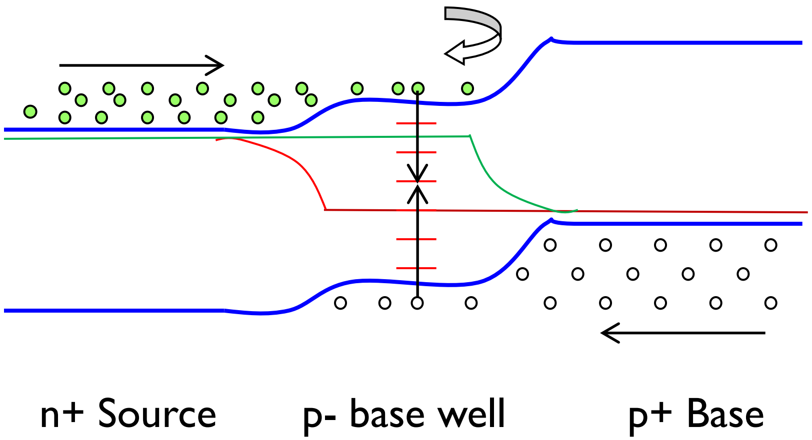
Another View



p- base (along a vertical line)

$\phi_S = \phi_F - V_{BE}/2$





Neugroschel, TED 42(9), pp 1657, 1995

DC-IV measurement: Short Derivation

$$\frac{I_R}{W} = \Delta n(x=0) \times S^* \times q \times (x_n + x_p) \propto D_{IT}(x=0,t)$$

(1) $$n \times p = n_i^2 \exp\left(F_N - F_p / k_B T_L\right) = n_i^2 \exp\left(qV_o / kT\right)$$

$$n = p = n_i^2 \exp\left(qV_0 / 2k_B T\right)$$

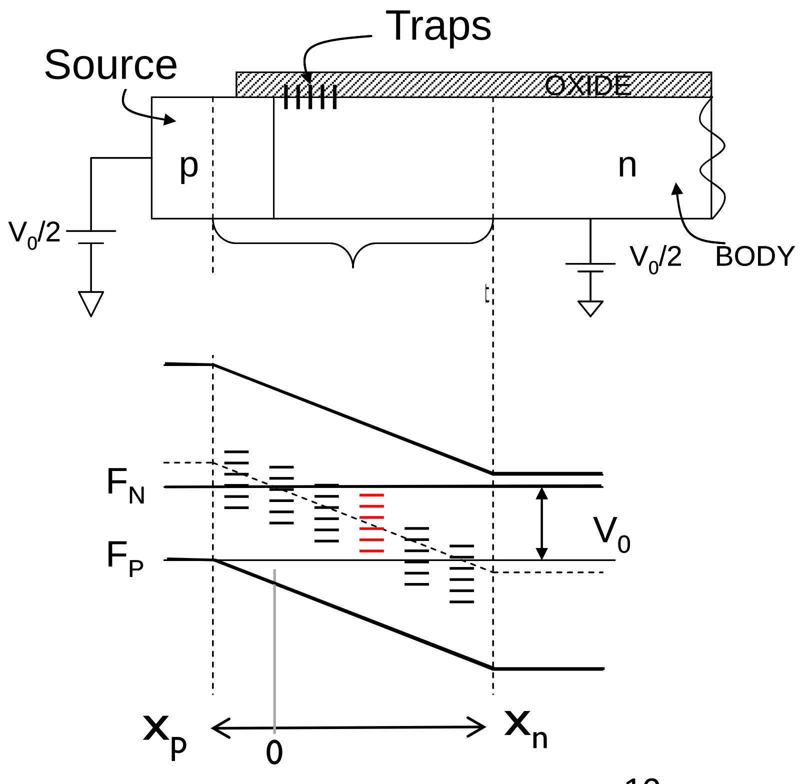
$$\Delta n = n - n_i = n_i \times \left[\exp\left(qV_0 / 2k_B T_L\right) - 1\right]$$

$$\approx n_i \times \exp\left(qV_0 / 2k_B T_L\right)$$

(2) $$S^* \approx \sigma_o \upsilon_{th} D_{IT} \left(F_N - F_P\right)$$

$$= \sigma_o \upsilon_{th} D_{IT} q V_0$$

(3) $$x_n + x_p \approx \sqrt{V_{BI} - V_0}$$

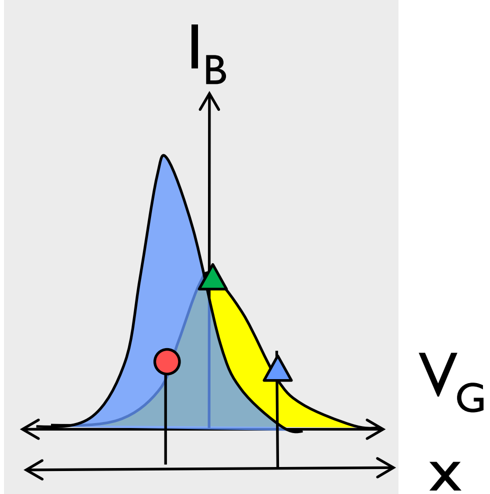


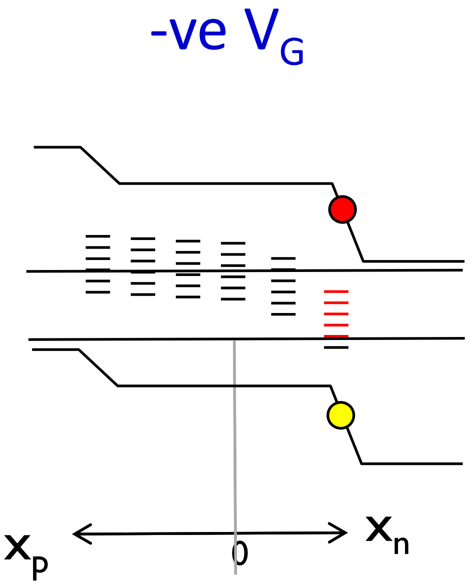
Spatial Profiling: VG-dependent Peak

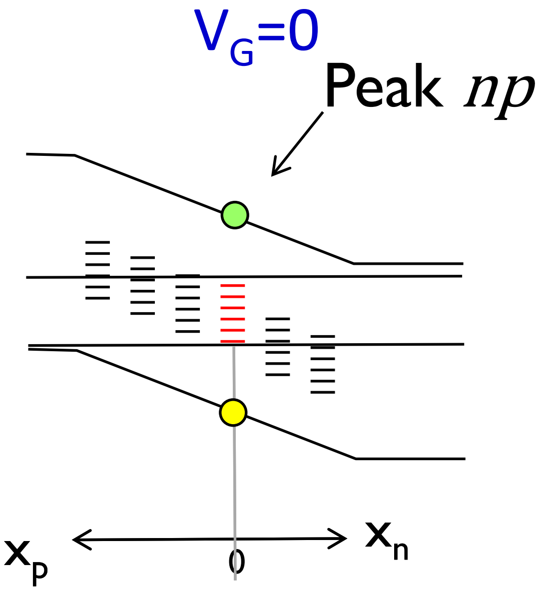
$$\frac{I_R(V_G,t_{stress})}{W} = \Delta n\left(x@n=p\right)\times S^*\times q\times\left(x_n+x_p\right)\propto D_{IT}(x(V_G),t_{stress})$$

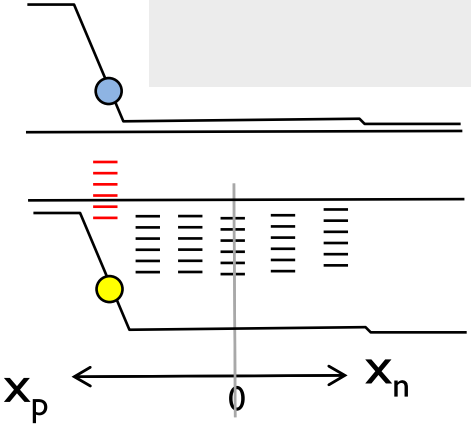
$$n\times p = n_i^2\exp\left(F_N - F_p/k_BT_L\right) = n_i^2\exp\left(qV_o/kT\right)$$

$$n\left(x(V_G)\right) = p\left(x(V_G)\right) = n_i^2\exp\left(qV_0/2k_BT\right)$$

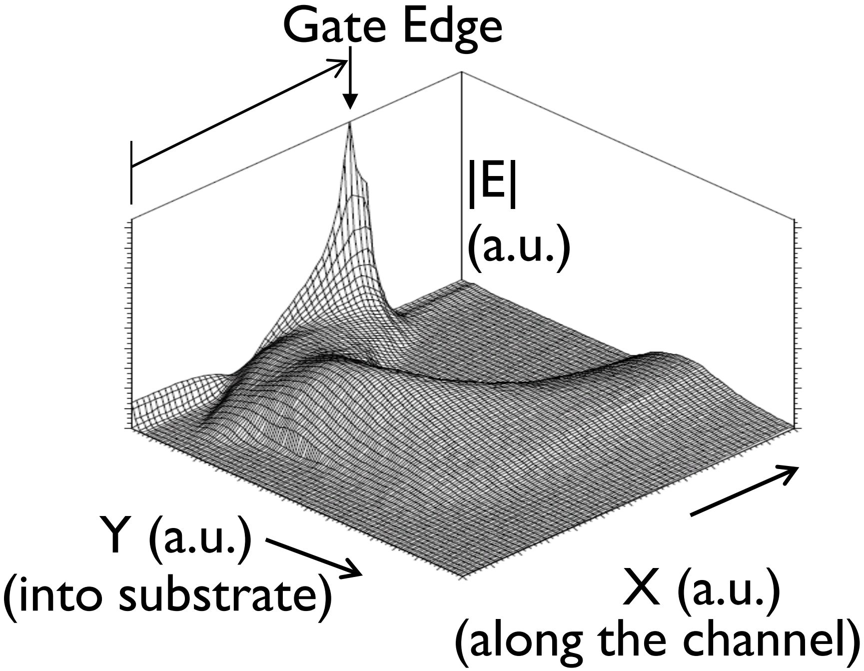


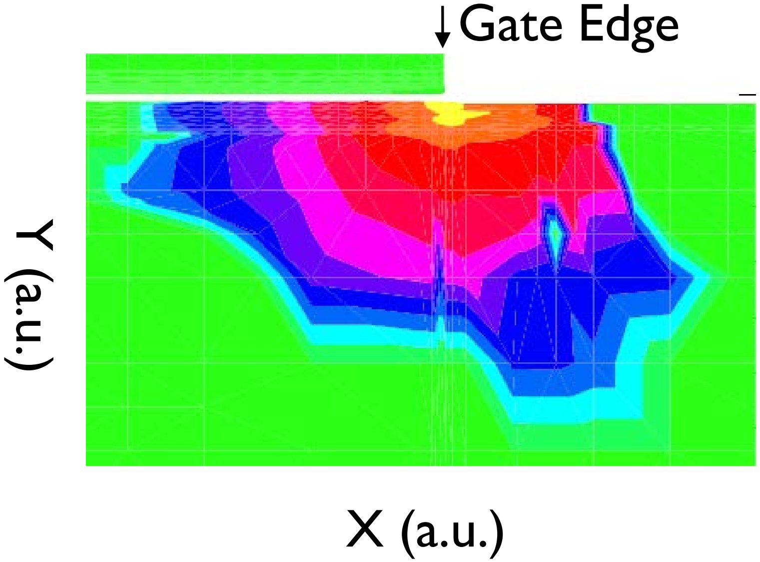




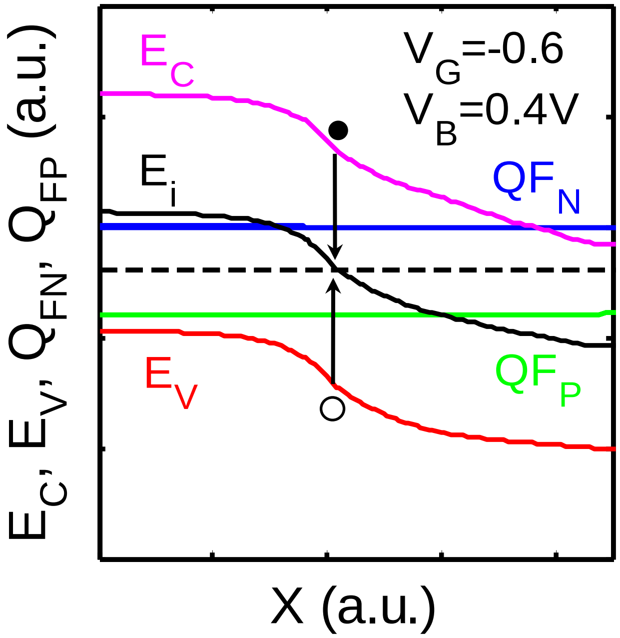


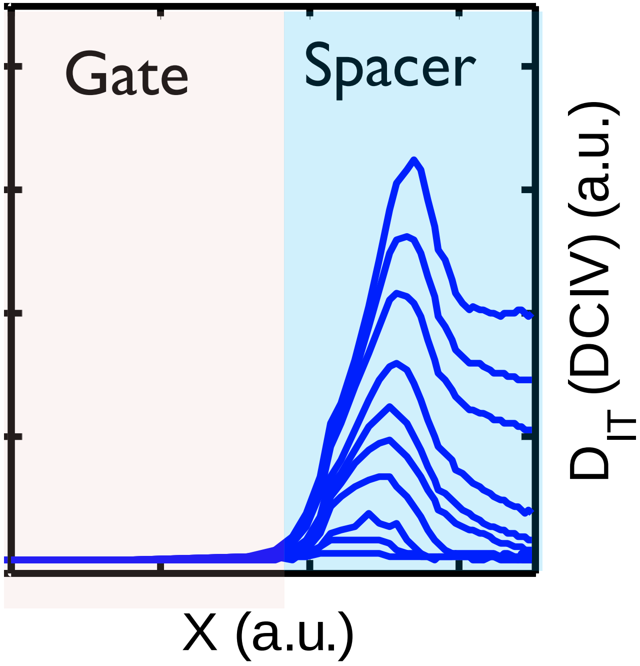
An Example: Profiling based on DV-IV





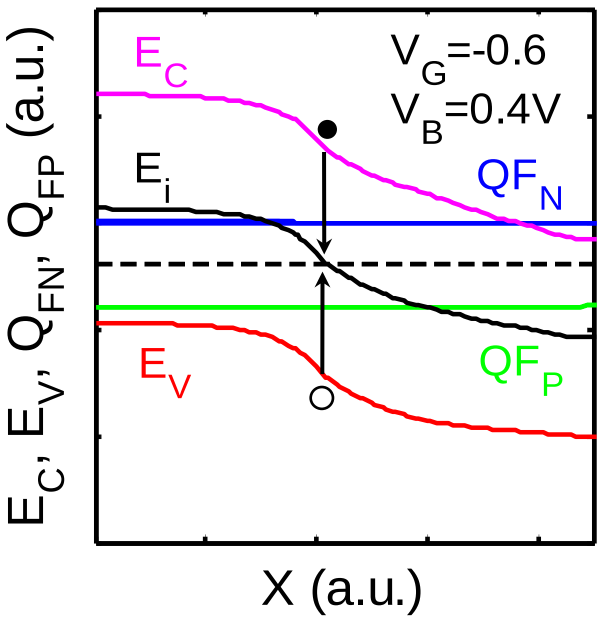
An Example: Profiling based on DC-IV

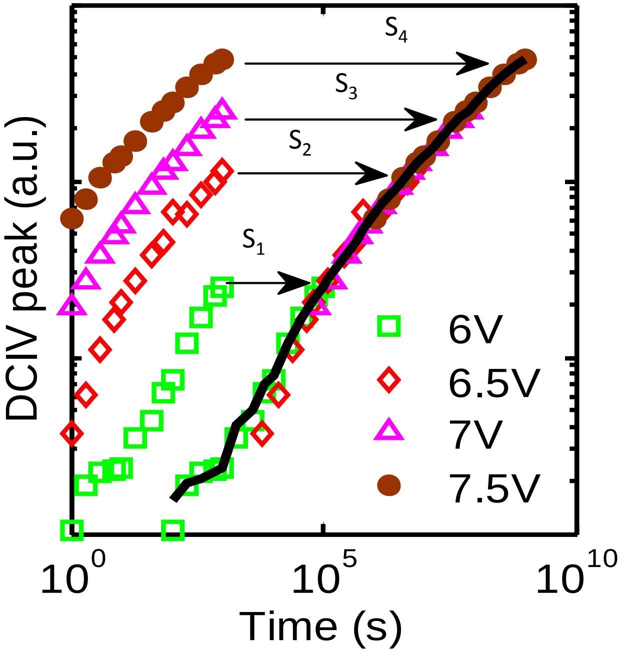




An Example: DC-IV and lifetime prediction

How DC-IV is used to detect universality of HCI degradation





Evolution of defect in each location can be traced

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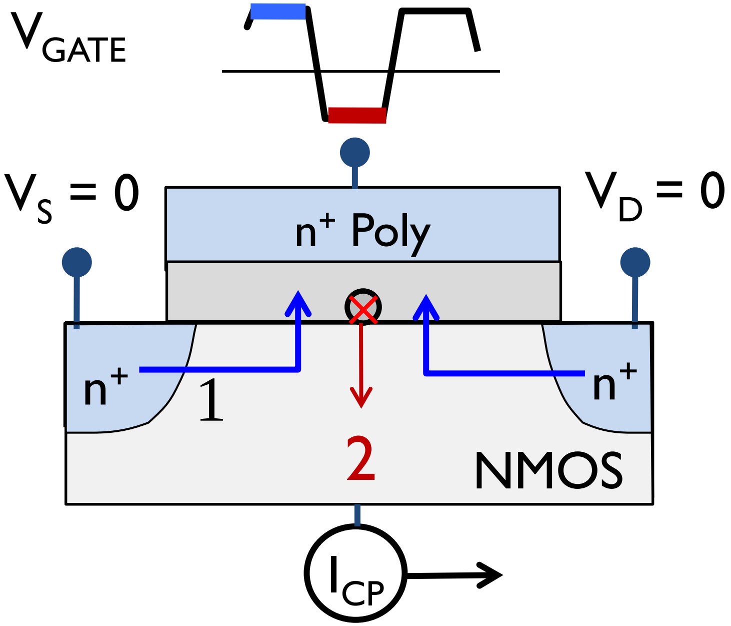
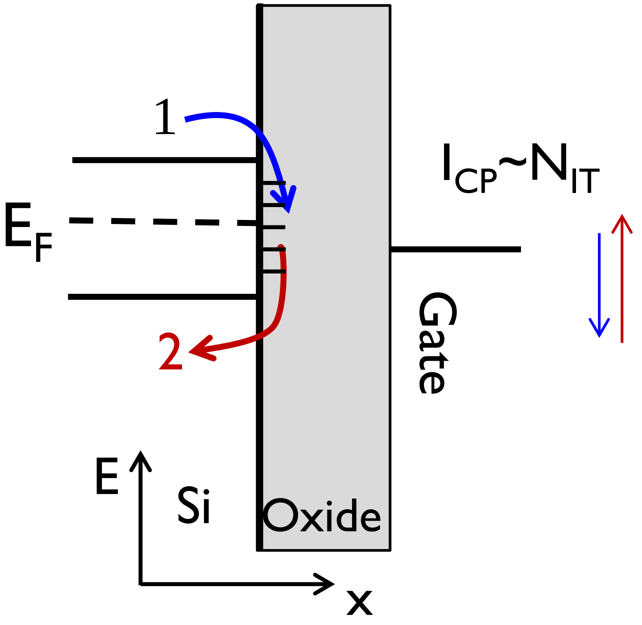
Appendices

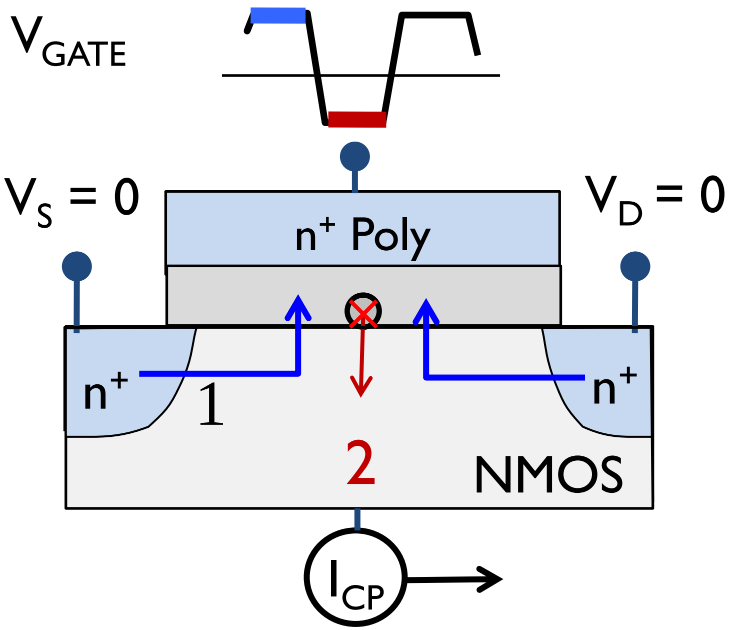
Algorithm of charge pumping method

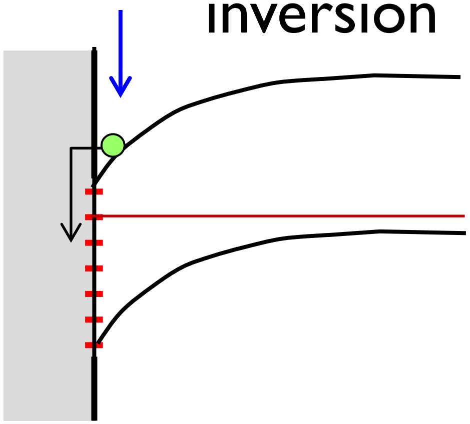


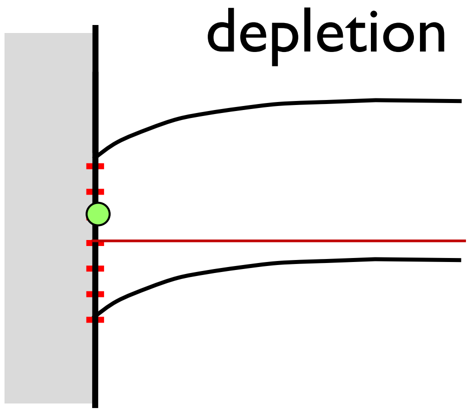


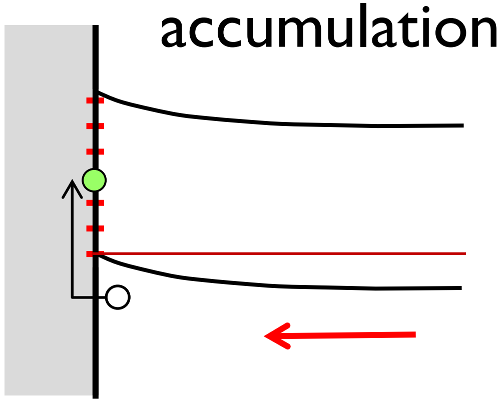
$$I_{cp} \propto f \times A_G \times \langle D_{IT} \rangle$$

The mechanism of charge pumping

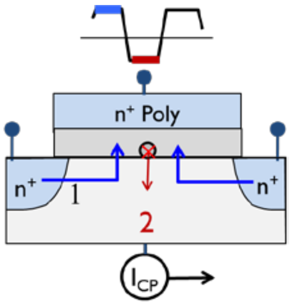


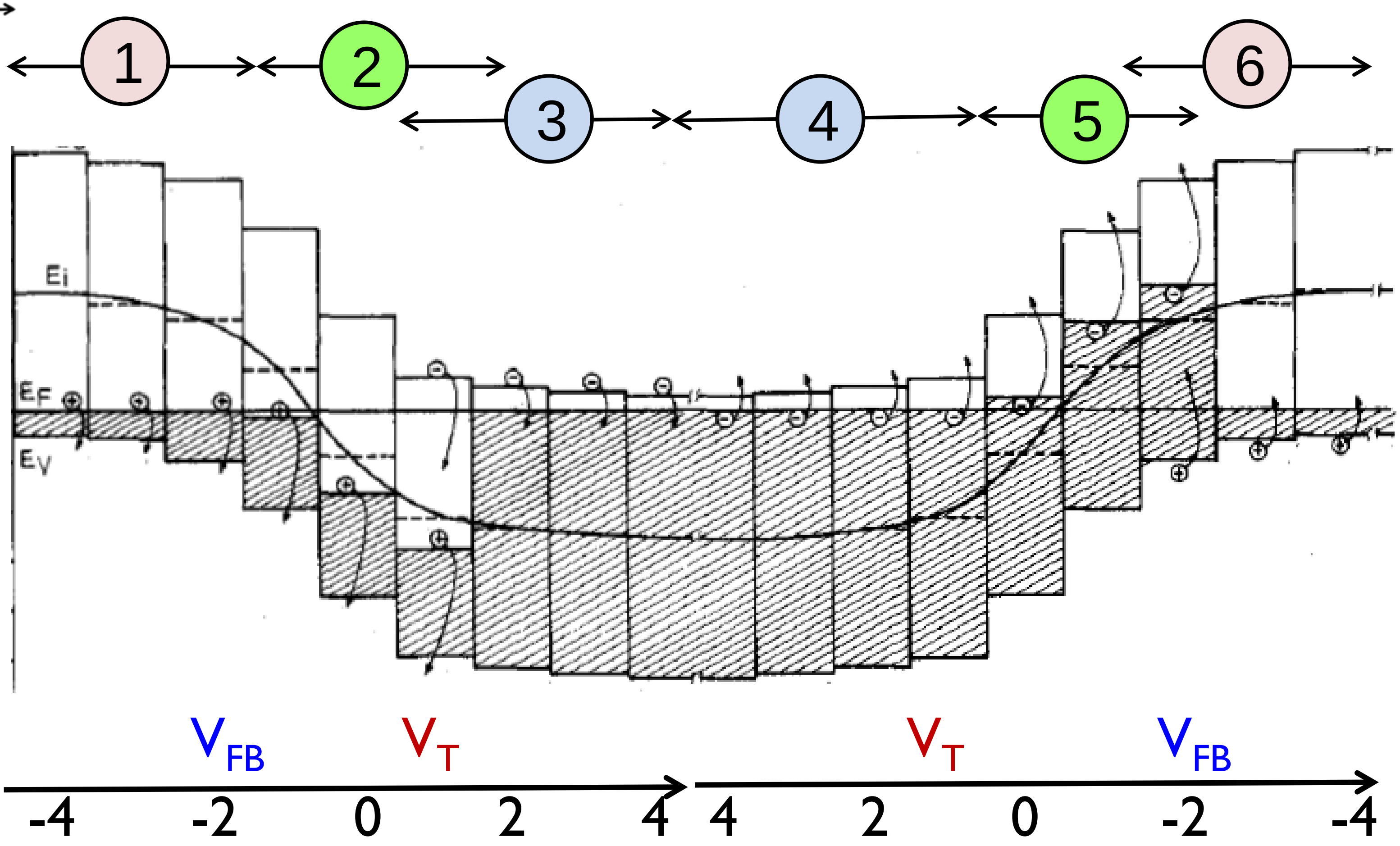






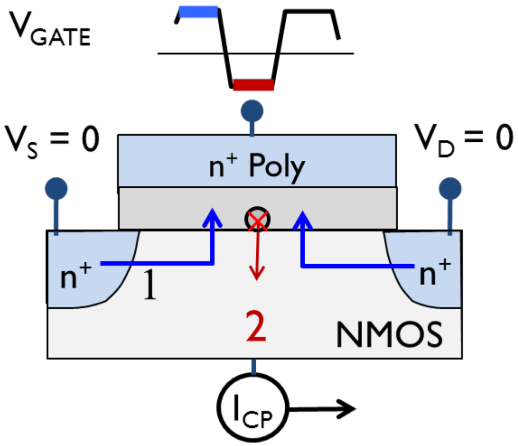
How do charges flow

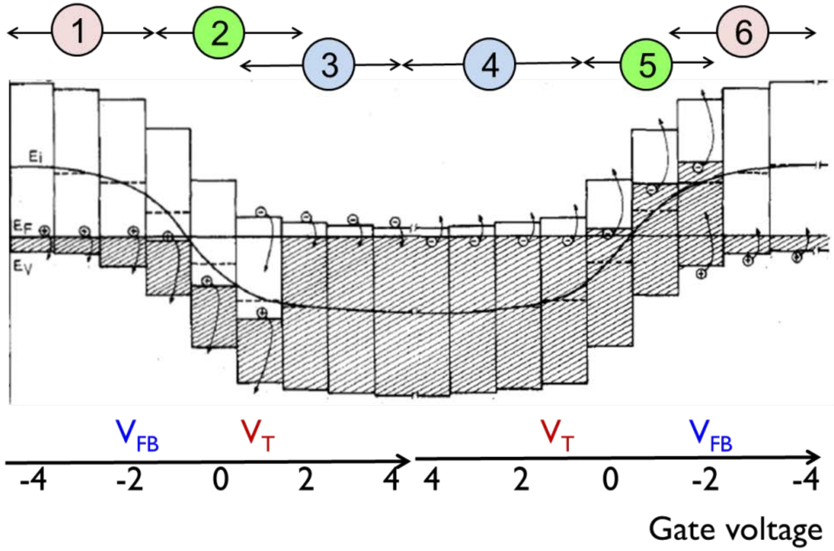


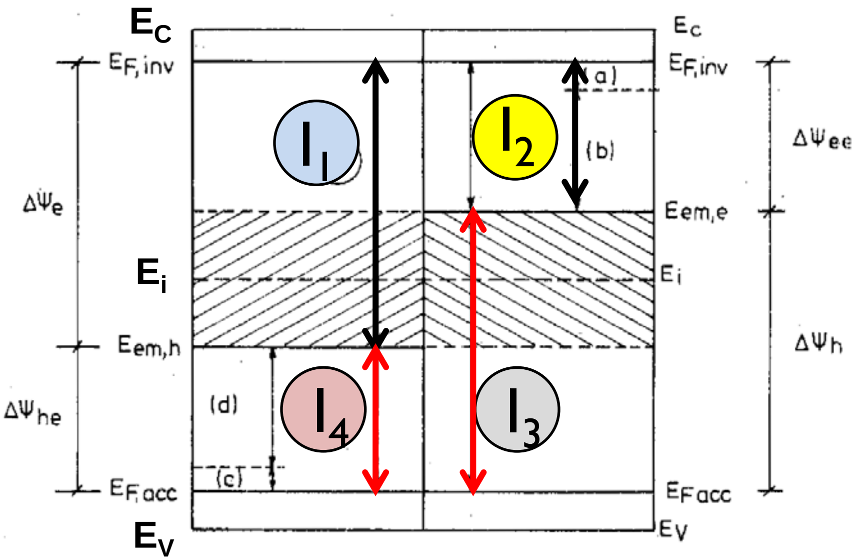


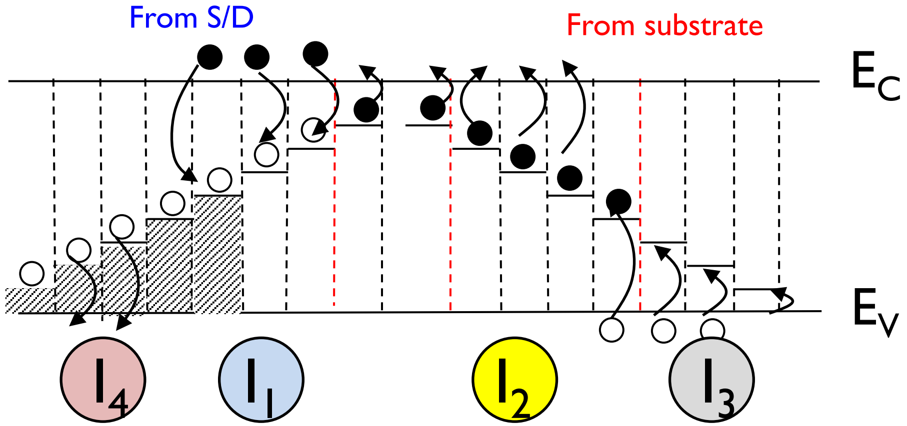
Gate voltage

Algorithm of Charge Pumping Technique





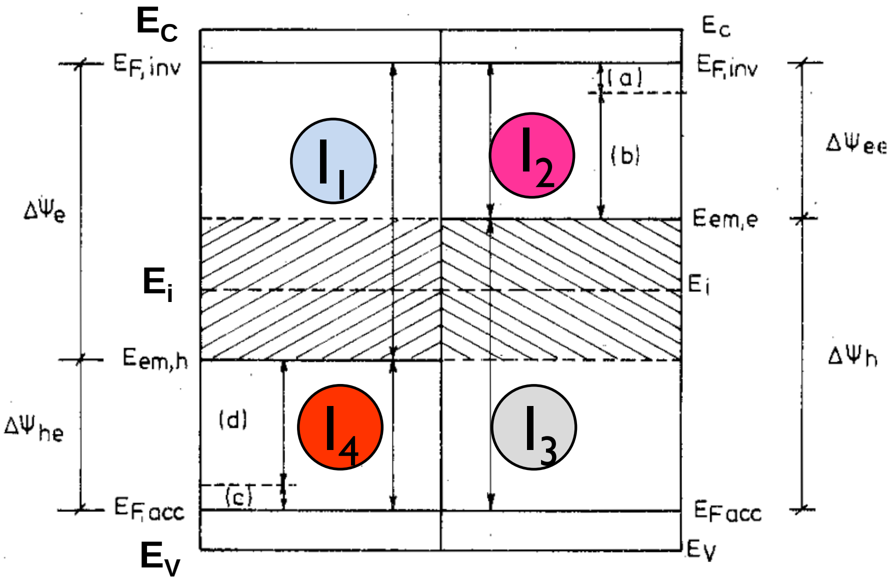




Charge pumping Flux Components

$$Q_{ss} = A_G q \int_{q\psi_{\min}}^{q\psi_{\max}} D_{IT}(E)\,dE \;= A_G q^2 \langle D_{IT} \rangle \Delta\psi \qquad \Delta\psi \equiv \left[\psi_{\max} - \psi_{\min}\right]$$

$$I_{cp} = Q_{ss}/T_{cycle} = f \times A_G q^2 \langle D_{IT} \rangle \times \Delta\psi$$



$$\begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{bmatrix} = q^2 A_G \langle D_{IT} \rangle . f \begin{bmatrix} \Delta\psi_e \\ \Delta\psi_{ee} \\ \Delta\psi_h \\ \Delta\psi_{h,e} \end{bmatrix}$$

$$I_{S/D} = I_1 - I_2 = q^2 A_G \langle D_{IT} \rangle \times f \times \left[\Delta\psi_e - \Delta\psi_{ee}\right]$$

$$I_{S/D} = q^2 A_G \langle D_{IT} \rangle \times f \times \left[E_{em,h} - E_{em,e}\right]$$

Homework: A few steps in the derivation

$$r_N = -\left(\frac{dn}{dt}\right)_{R-G} = c_n p_T n - e_n n_T \qquad \Rightarrow e_n = c_n \left(p_{T0} / n_{T0} \right) n_0 = c_n n_1$$

$$e_n \equiv \tau_{em}^{-1} \quad c_n \equiv \tau_c^{-1} = \left(\upsilon_{th}\sigma\right)^{-1} \qquad n_1 = n_i \times e^{\frac{E_T^{'} - E_i}{k_B T}}$$

Eq. 5.18, SDF

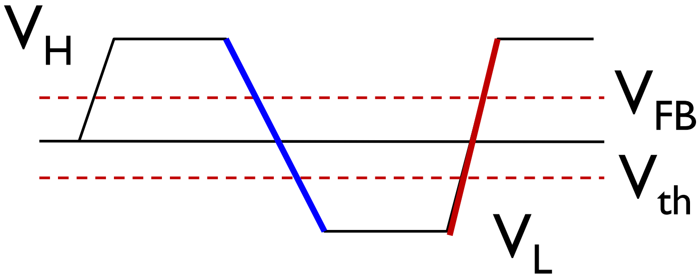
$$E_T^{'} - E_i = -k_B T_L \ln\left(\upsilon_{th}\, \sigma\, n_i\, \tau_{em}\right)$$

$$I_{CP} = I_{S/D} = q^2 A_G \left\langle D_{IT} \right\rangle \times f \times \left[E_{em,h} - E_{em,e} \right]$$

$$= 2q^2 A_G \left\langle D_{IT} \right\rangle \times f \times k_B T_L \left[\ln\left(\upsilon_{th} \sqrt{\sigma_n \sigma_p}\, n_i\right) + 0.5 \times \ln(\tau_{em,e} \times \tau_{em,h}) \right]$$

Charge Pumping Technique

$$\frac{I_{CP}}{2q^2 A_G k_B T_L} = \langle D_{IT} \rangle f \left[\ln\left(\upsilon_{th} \sqrt{\sigma_n \sigma_p} n_i \right) + 0.5 \times \ln(\tau_{em,e} \times \tau_{em,h}) \right]$$

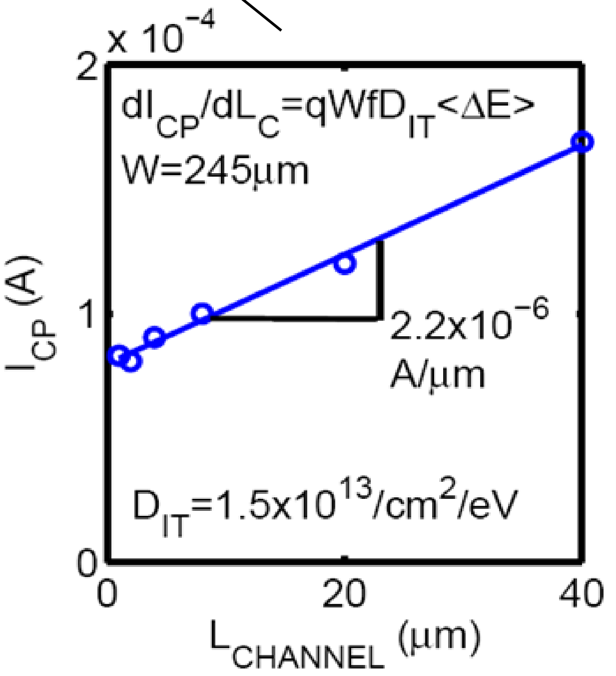


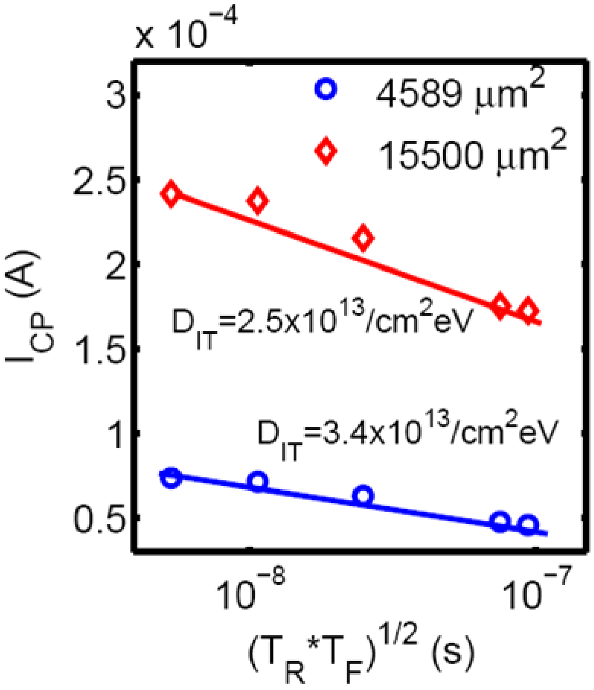
$$\tau_{em,e} \equiv \frac{\left|V_{FB} - V_{th}\right|}{\left|V_{G,H} - V_{G,L}\right|} \times t_f \qquad \tau_{em,h} \equiv \frac{\left|V_{FB} - V_{th}\right|}{\left|V_{G,H} - V_{G,L}\right|} \times t_r$$

$$\frac{I_{CP}}{2q^2 A_G \ k_B T_L} = \langle D_{IT} \rangle f \left[\ln\left(\upsilon_{th} \sqrt{\sigma_n \sigma_p} n_i \right) + \ln\left(\frac{\left|V_{FB} - V_{th}\right|}{\left|V_{G,H} - V_{G,L}\right|} \right) \sqrt{t_r t_f} \right]$$

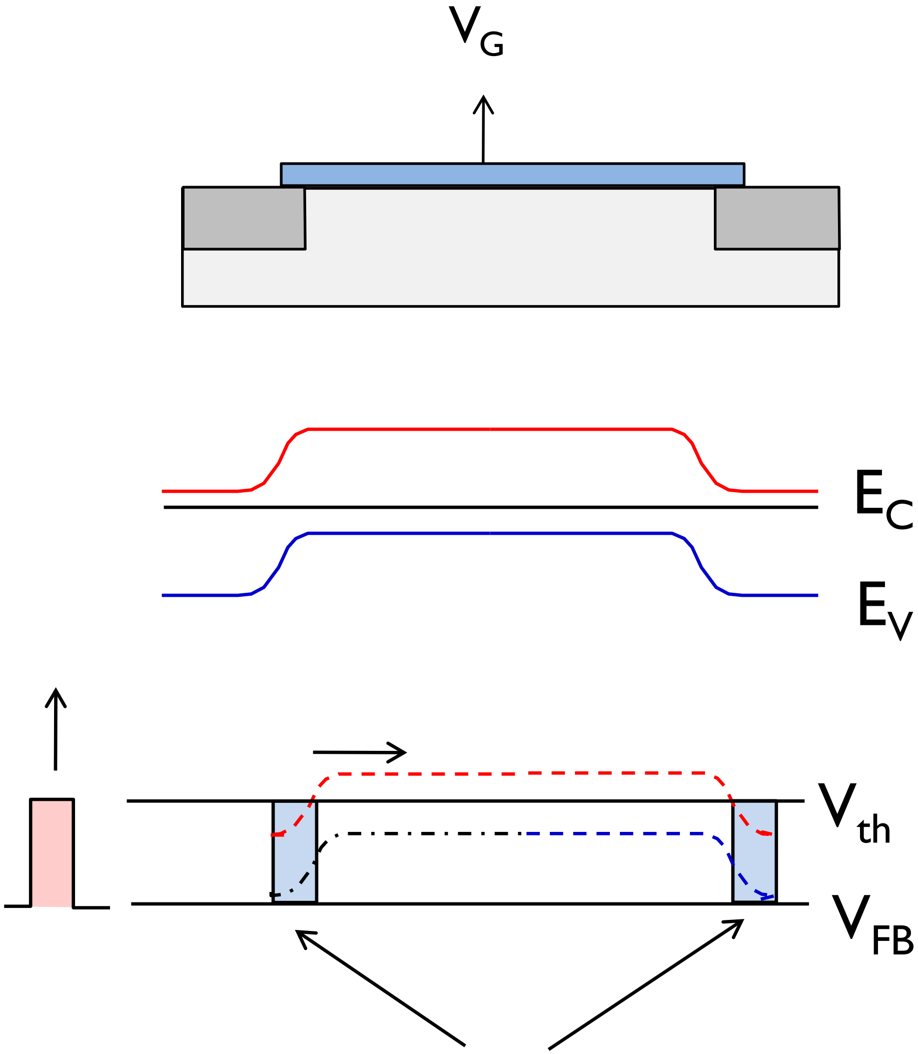
Obviating the need of capture coefficients

$$I_{CP} = 2q^2\left(L \times W\right)\langle D_{IT}\rangle f \times k_B T_L \left[ln\left(\upsilon_{th}\sqrt{\sigma_n \sigma_p}\, n_i\right) + ln\left(\frac{\left|V_{FB} - V_{th}\right|}{\left|V_{G,H} - V_{G,L}\right|}\right) \sqrt{t_r t_f} \right]$$





Spatial Profiling by Charge Pumping

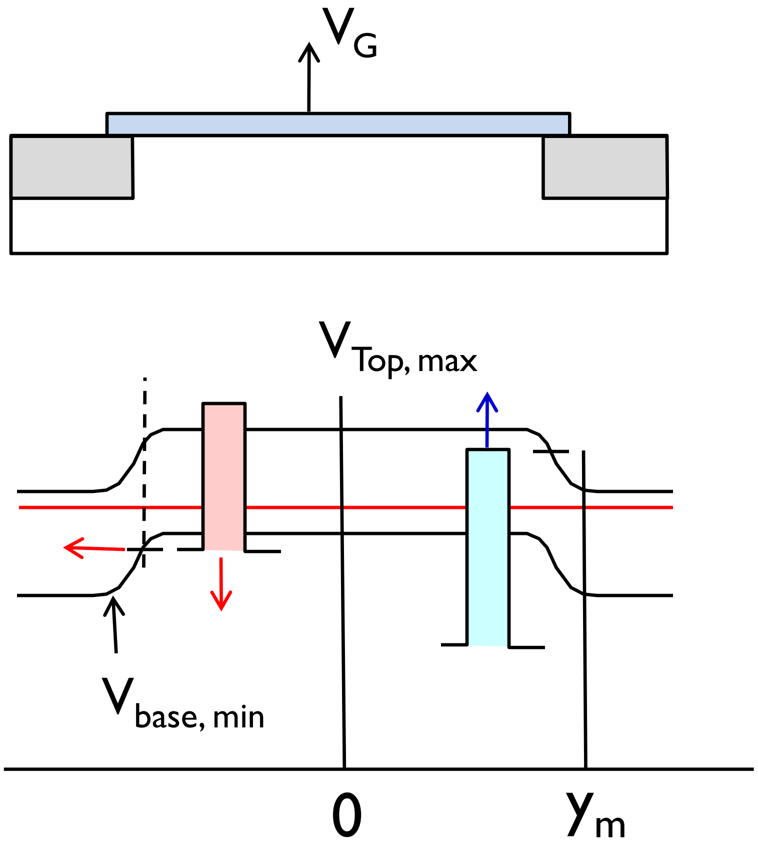


Pumped region

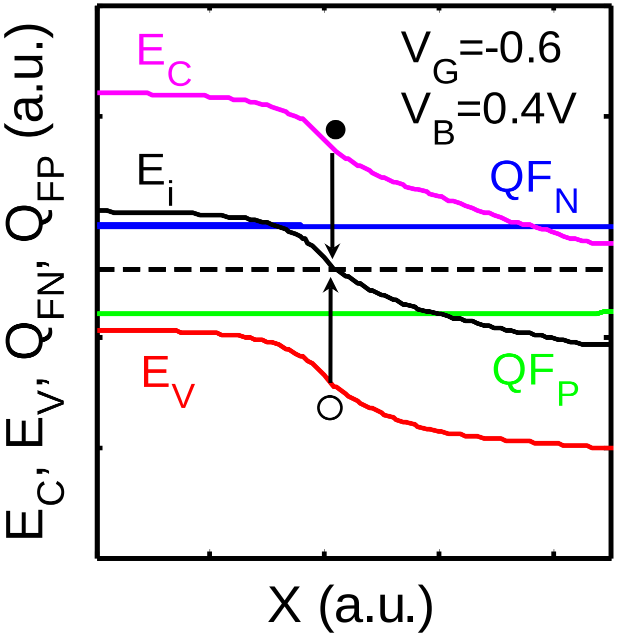
Homework: Defect Profiling by CP

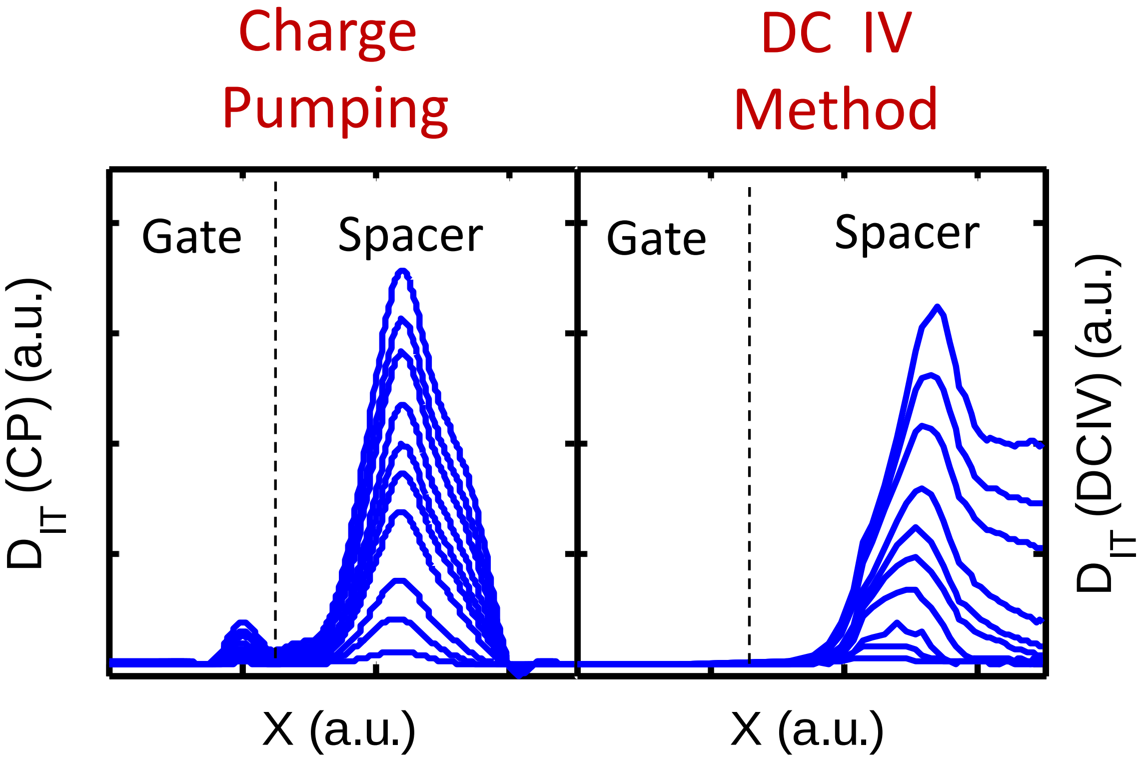
$$
\begin{aligned}
\Delta I_{CP}(V_{base}) &= \Delta I_{CP,s}(V_{base}) - \Delta I_{CP}(V_{base}) \\
&\propto \int_{-y_1}^{0} N_{IT}(y)dy + \int_{0}^{y_{1,s}} N_{IT,s}(y)dy \\
&\quad - \int_{-y_1}^{0} N_{IT}(y)dy - \int_{0}^{y_1} N_{IT}(y)dy \\
&= \int_{0}^{y_{1,s}} \left(N_{IT,s}(y) - N_{IT}(y) \right) dy + \int_{y_1}^{y_{1,s}} N_{IT}(y)dy \\
&= \int_{0}^{y_{1,s}} \Delta N_{IT,s}(y)dy + \int_{y_1}^{y_{1,s}} N_{IT}(y)dy
\end{aligned}
$$

↑ NBTI stress ↑ HCI stress



Example: Profiling based on CP and DV-IV




Charge Pumping

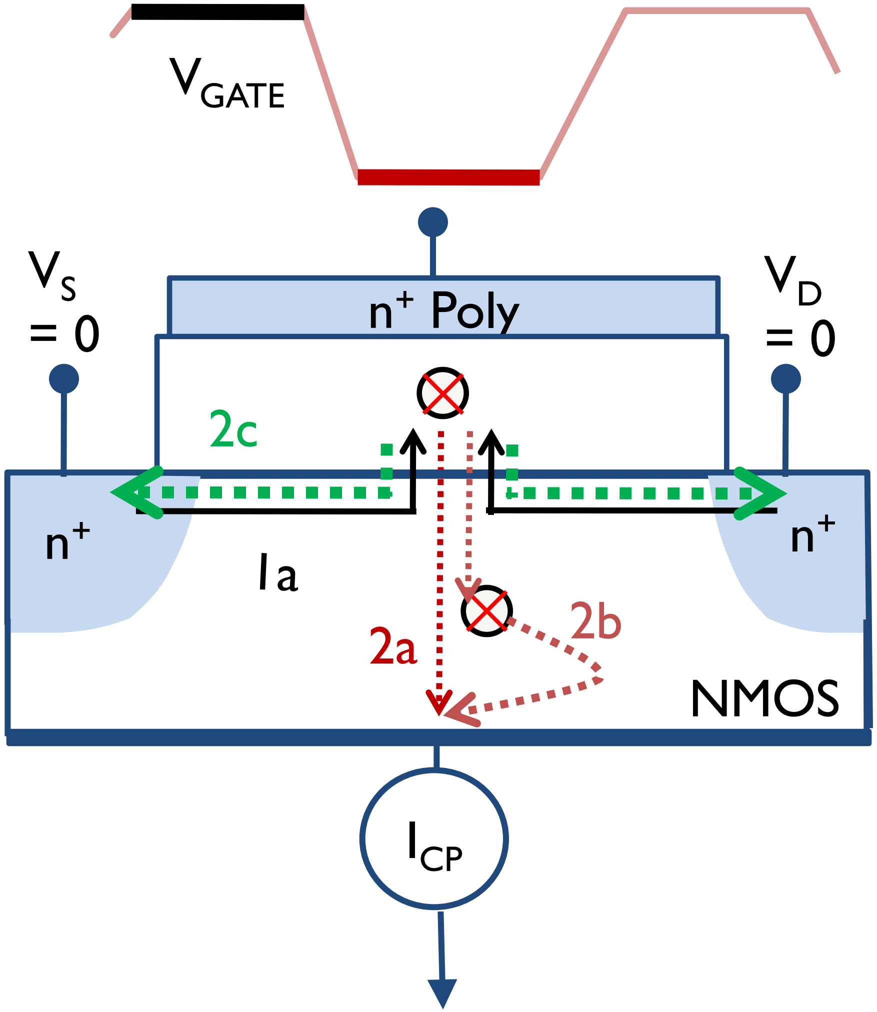
DC IV Method

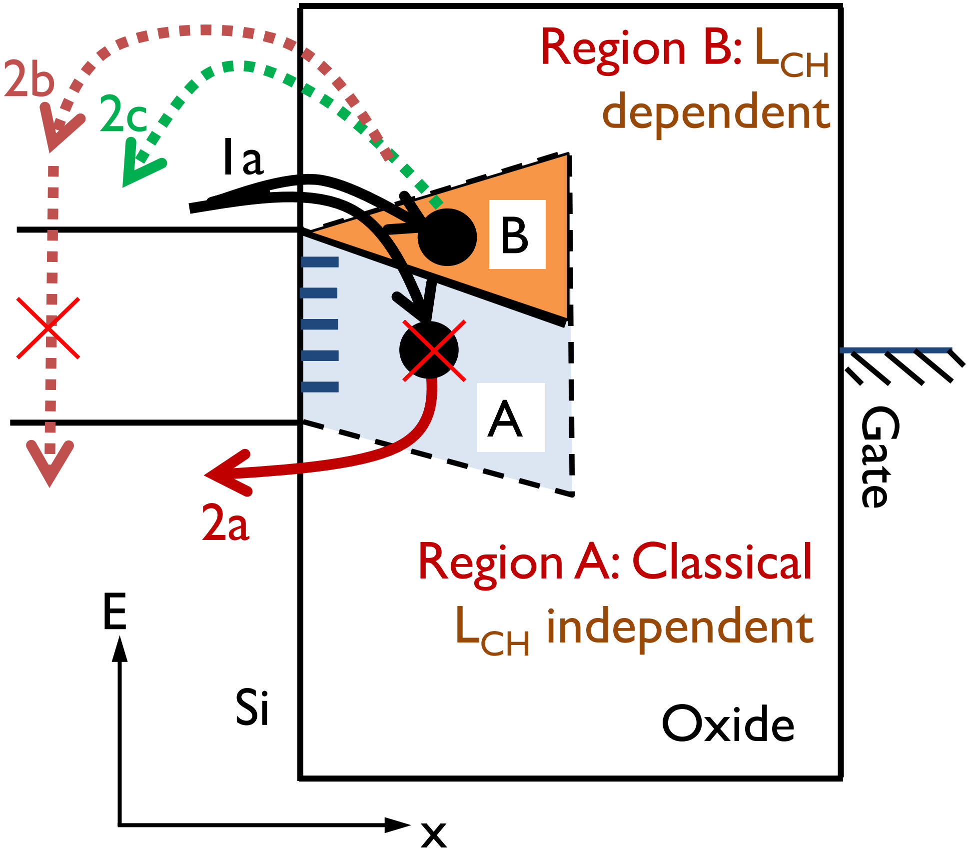
Both anticipate peaks in similar position

Both confirm universal scaling

MFCP: Bulk trapping at low frequency

M. Masuduzzaman TED, 55(12), 3421, 2008.





Conclusions

☐ Careful measurement techniques is the first step of doing physics – reliability physics is no exception.

☐ Both DC-IV and CP methods are widely used because of their simplicity and ability to provide wealth of information.

☐ CP method constantly evolving. Modern variants like multi-frequency CP can probe bulk traps, transient CP can measure defect in SOI, etc.

☐ Once the NBTI relaxation issues were understood, CP and DCIV method needed to be augmented by on-the-fly methods.

Notes and References

- Schroeder has an excellent book on Device Characterization. See Semiconductor Materials and Device Characterization, 3rd Edition, John Wiley.
- The DC-IV method is a generalization of the gated-diode method. It was originally developed by CT Sah (see for example, Proc. IRE, p. 1623, 1961; TED, p. 1962, 1962. and then generalized by in modern form by Neugroschel, See for example, TED 42(9), pp 1657, 1995. Also, see TED, 43(1), 137, 1996)
- Note that the DCIV method is closely related to gated diode method and GIDL techniques. These related methods are easier to interpret, but difficult to measure with high accuracy.

- The original paper by Guido Groesenekan still remains the best. A reliable approach to charge pumping in MOS transistors, 31(1), 41, 1984. The first order by JS Brugler and PGA Jespers, TED, 16(3), 297, 1969.
- Determining the capture cross-section is always a challenge. I explained one method by rise-and-fall time. Other approaches involving 3-level CP is also possible, see NS Saks, EDL, 11(8), 339, 1990.

- Spatial profiling of defects by with variable base CP is discussed in detail in Solid State Electronics, 43, 915, 1999 by S. Mahapatra et al.
- M. Masuduzzaman generalized the technique to explore bulk defects see Exploring the Capability of Multi-frequency Charge Pumping in Resolving Location and Energy Levels of Traps Within Dielectric, 55(12), 3421, 2008.
- The CP method relevant to SOI which does not have bulk gate devices is discussed in EDL, 23(5), 279, 2002 by S. Okhonin.

Self-Test Questions

1) Between DCIV and CP methods, which one is easier and why?
2) In what ways are CP and DCIV methods better at characterizing traps compared to C-V methods?
3) What are the problems of using CP, DCIV, C-V methods for NBTI measurements?
4) Which method does not suffer from the same problem as CP, DCIV, etc. for NBTI and HCI applications?
5) What method would you use to determine the density of midgap states?
6) CP frequency has to be kept relatively high to probe interface traps; can you explain why?
7) Why can you not use classical CP for SOI devices?

Appendices

1. A detailed derivation of the DC-IV method
2. Spatial profiling by DC-IV method by two techniques
3. Difference between gated-diode and DC-IV
4. Spatial profiling by charge pumping method
5. Multi-frequency charge pumping method

DC-IV measurement: Short Derivation

$$\frac{I_R}{W} = \Delta n\left(x=0\right)\times S^{*}\times q\times\left(x_n + x_p\right)\propto D_{IT}(x=0,t)$$

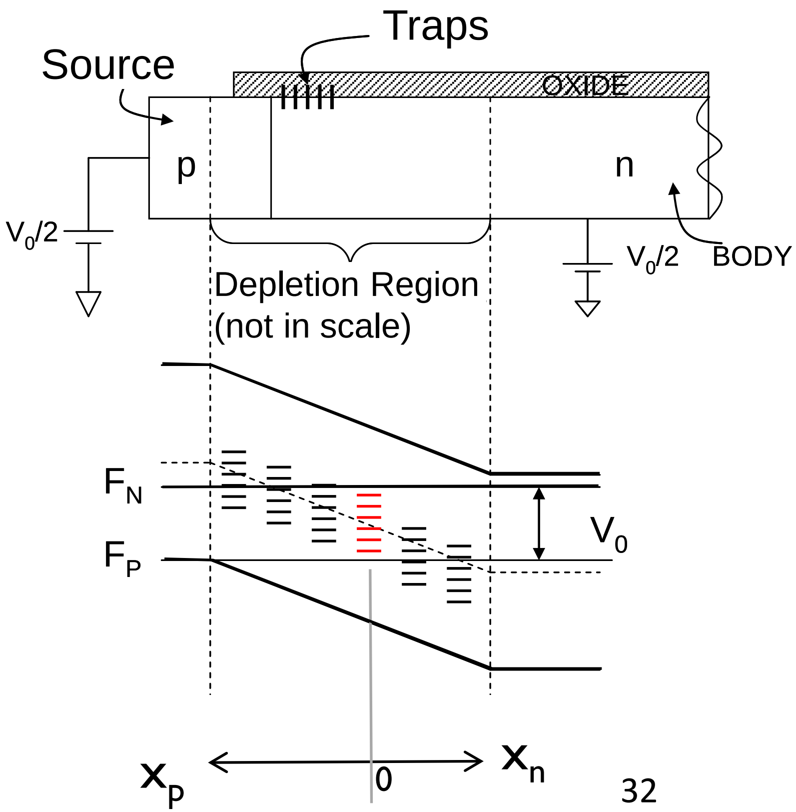
(1) $$n\times p = n_i^2\exp\left(F_N - F_p/k_BT_L\right) = n_i^2\exp\left(qV_o/kT\right)$$

$$n = p = n_i^2\exp\left(qV_0/2k_BT\right)$$

$$\Delta n = n - n_i = n_i\times\left[\exp\left(qV_0/2k_BT_L\right) - 1\right]$$
$$\approx n_i\times\exp\left(qV_0/2k_BT_L\right)$$

(2) $$S^{*}\approx\sigma_o\upsilon_{th}D_{IT}\left(F_N - F_P\right)$$
$$= \sigma_o\upsilon_{th}D_{IT}qV_0$$

(3) $$x_n + x_p \approx \sqrt{V_{BI} - V_0}$$



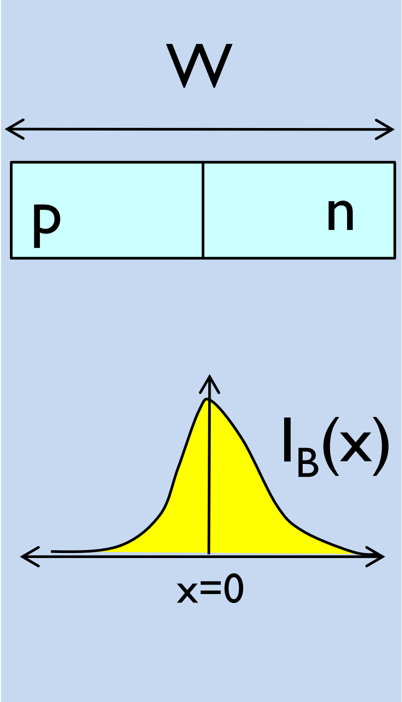
Theory of DC-IV: Proper Derivation

$$R_s = \int_{x_p}^{x_n}\left(\int_{F_P}^{F_N}\frac{D_{IT}(E).\sigma_o v_{th}}{\left(n_s+n_{1s}\right)+\left(p_s+p_{1s}\right)}.dE\right).(n_s p_s - n_i^2)dx$$

In forward bias, $n_s \geq n_{1s}$ & $p_s \geq p_{1s}$

$$R_s = \int_{x_p}^{x_n}\left(\int_{F_P}^{F_N} D_{IT}(E).\sigma_o v_{th}.dE\right).\left(\frac{n_s p_s - n_i^2}{n_s + p_s}\right).dx = I \times S^*$$

$$I \equiv \int_{x_p}^{x_n}\left(\frac{n_s p_s - n_i^2}{n_s + p_s}\right).dx \qquad S^* = \int_{F_P}^{F_N} D_{IT}(E).\sigma_o v_{th}.dE$$



$$F_n - E_i = qV_0\left(\frac{x}{W}+\frac{1}{2}\right) \quad E_i - F_p = -qV_0\left(\frac{x}{W}-\frac{1}{2}\right)$$

Ex. 5.6, ADF

Theory of DC-IV: Proper Derivation

$$I_B^{total} \equiv \int_{x_p}^{x_n} \left(\frac{n_s p_s - n_i^2}{n_s + p_s} \right).dx = \int_{x_p}^{x_n} \left(\frac{n_i^2 e^{qV_0/k_bT}}{n_i\, e^{q(F_N - E_i)/k_bT} + n_i\, e^{q(E_i - F_P)/k_bT}} \right).dx$$

$$= \int_{x_p}^{x_n} \left(\frac{n_i^2 e^{qV_0/k_bT}}{n_i\, e^{qV_o\left(\frac{x}{w}+\frac{1}{2}\right)/k_bT} + n_i\, e^{-qV_o\left(\frac{x}{w}-\frac{1}{2}\right)/k_bT}} \right).dx$$

$$a \equiv \frac{qV_0}{k_B T}$$

$$= n_i e^{a/2} \frac{W}{a} \int_{-\infty}^{\infty} \frac{dp}{e^p + e^{-p}} = n_i \frac{W}{a} e^{a/2} \left[tan(\infty) - tan(-\infty) \right]$$

$$p = \frac{ax}{W}$$

$$W = x_n + x_p$$

$$= \frac{\pi}{2} \frac{W}{a/2} e^{a/2} \qquad = n_i \frac{\pi}{2} \frac{W k_B T}{qV_0} e^{qV_0/2k_BT}$$

$$I_B^{total} = I \times S^* = \left(W \frac{2k_BT}{qV_0} n_i e^{qV_0/2k_BT} \right) \times \left(\frac{\pi}{2} \int_{F_P}^{F_N} D_{IT}(E).\sigma_o v_{th}.dE \right)$$

Theory of DC-IV: Proper Derivation

$$I_B^{peak} \equiv \frac{n_s p_s - n_i^2}{n_s + p_s} S^* = \frac{n_i^2 e^{qV_0/k_bT} \times S^*}{n_i\, e^{qV_o\left(\frac{x=0}{w}+\frac{1}{2}\right)\big/k_bT} + n_i\, e^{-qV_o\left(\frac{x=0}{w}-\frac{1}{2}\right)\big/k_bT}} = n_i\, e^{qV_0/2k_bT} S^*$$

$$I_B^{Total} = \frac{\pi}{2} \frac{2Wk_BT}{qV_0} n_i e^{qV_0/2k_BT} S^*$$

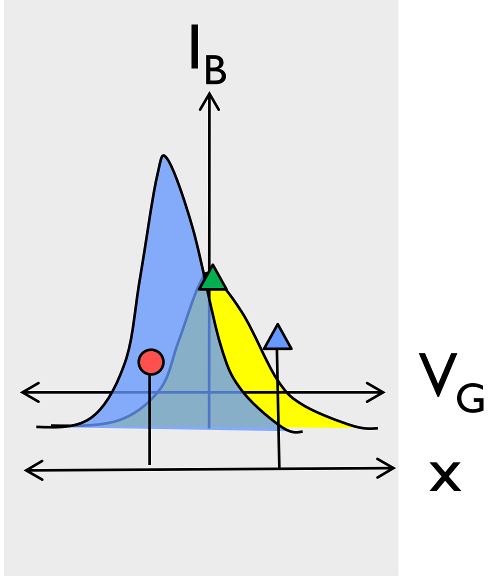
$$\frac{I_B^{peak}}{I_B^{Total}} \equiv \frac{Wn_i\, e^{qV_0/2k_bT} S^*}{\frac{\pi}{2} \frac{Wk_BT}{qV_0} n_i e^{qV_0/2k_BT} S^*} = \frac{2}{\pi} \frac{qV_0}{2k_BT}$$

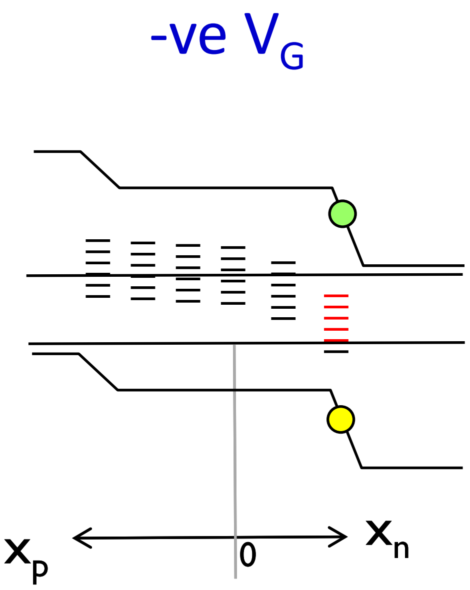
2. Spatial Profiling:
VG-dependent Peak Location

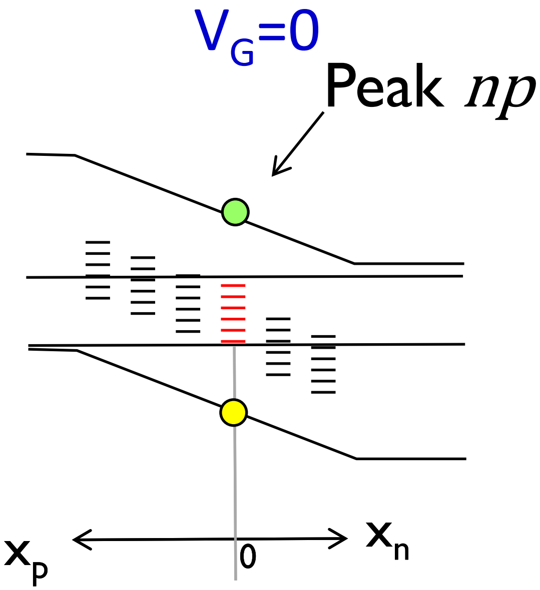
$$\frac{I_R(V_G,t_{stress})}{W} = \Delta n(x@n=p)\times S^*\times q\times\left(x_n+x_p\right)\propto D_{IT}(x(V_G),t_{stress})$$

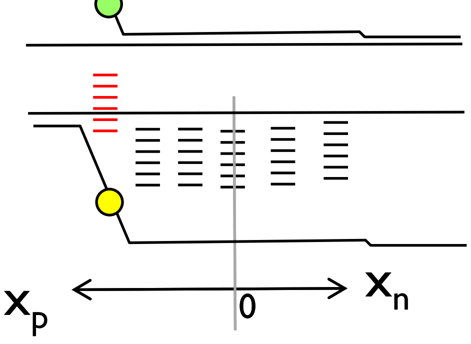
$$n\times p = n_i^2 exp\left(F_N - F_p/k_BT_L\right) = n_i^2 exp\left(qV_o/kT\right)$$

$$n\left(x(V_G)\right) = p\left(x(V_G)\right) = n_i^2 exp\left(qV_0/2k_BT\right)$$

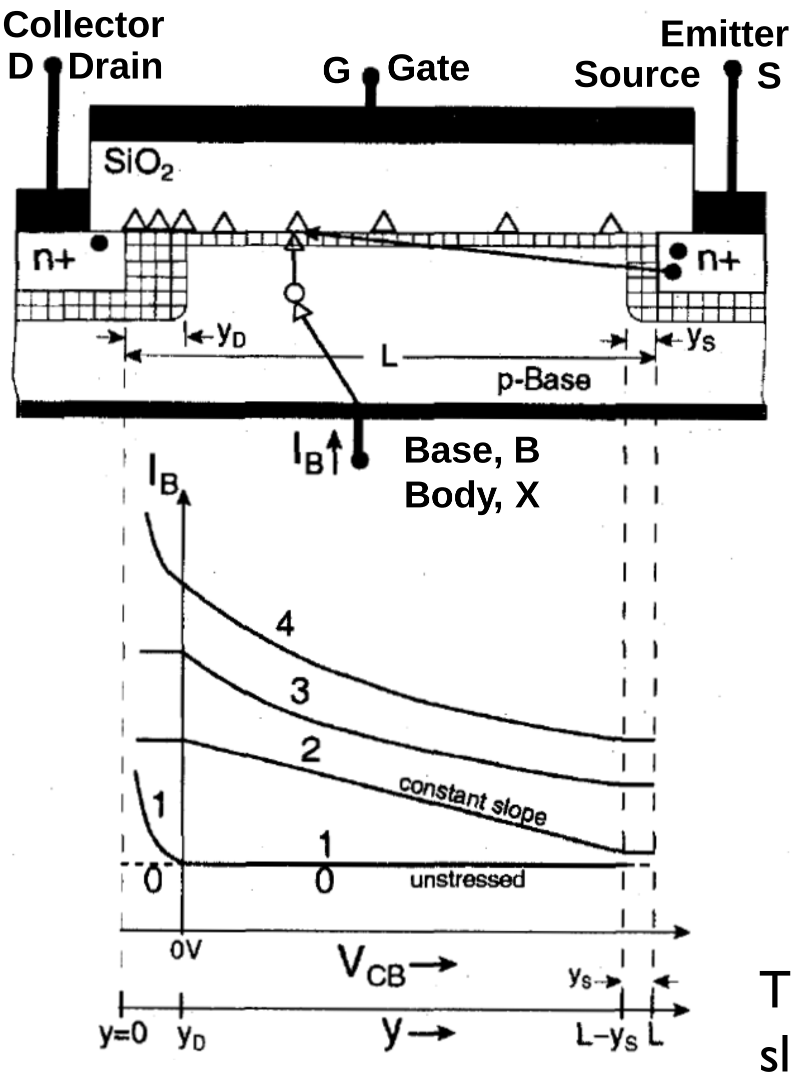








Spatial Profiling: Localized vs. Delocalized Damage



Sah, EDL, 17(2), 1996.

Measure I_B vs. V_{DB}

$$I_B = qW\int_{y_D(V_{DB},V_{GB})}^{L-y_S(V_{SB},V_{GB})} D_{IT}(y)R_{SRH}(y,V_{GB},V_{SB})dy$$

$$\frac{dF}{d\alpha} = \frac{d}{d\alpha}\int_{\psi(\alpha)}^{\phi(\alpha)} f(x,\alpha)dx$$

$$= f(\phi,\alpha)\frac{d\phi}{d\alpha} - f(\psi,\alpha)\frac{d\psi}{d\alpha} + \int_{\psi(\alpha)}^{\phi(\alpha)} \frac{d}{d\alpha} f(x,\alpha)dx$$

$$\frac{dI_B}{dV_{DB}} = -qWD_{IT}(y)R_{SRH}(y,V_{GB},V_{SB})\frac{dy_D}{dV_{DB}}$$

The method discussed in previous slide works for localized defects only

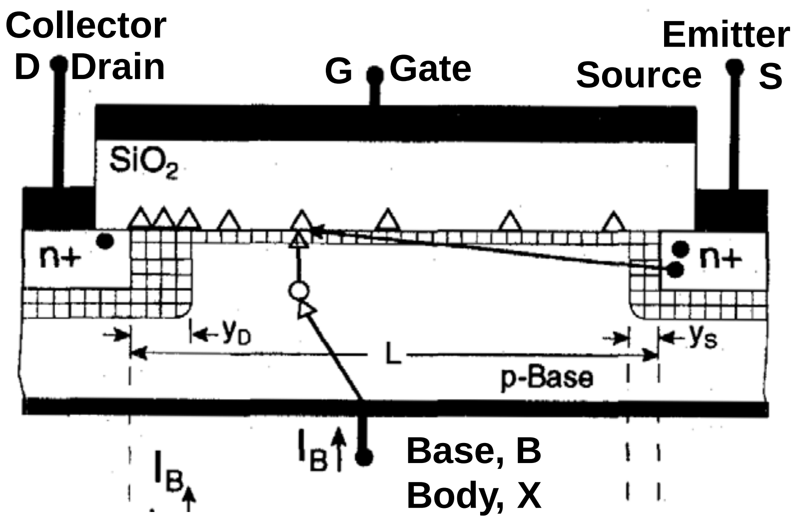
3. Difference between Gated Diode and DC-IV

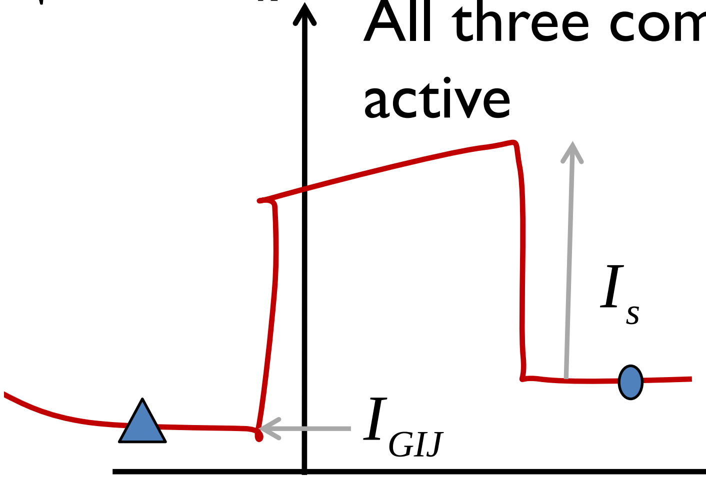
Gated Diode	DCIV
Typically reversed biased	Forward biased
Small current Also IB=IE	Large current IB<<IE better resolution
1D potential	2D potential approx. as 1D

Difference between Gated Diode and DC-IV

$$W_J = \sqrt{\frac{2\kappa_s x_0 \left(V_{D1} + V_{bi}\right)}{qN_A}}$$

$$W_G = \begin{cases} \left(\dfrac{\kappa_s x_0}{\kappa_{ox}}\right)\left(\sqrt{1 + 2\dfrac{V_G{}'}{V_\delta}} - 1\right) & 0 < \phi_s < V_{D1} + 2\phi_F \\ \sqrt{\dfrac{2\kappa_s x_0 \left(V_{D1} + 2\phi_F\right)}{qN_A}} & \phi_s > V_{D1} + 2\phi_F \end{cases}$$





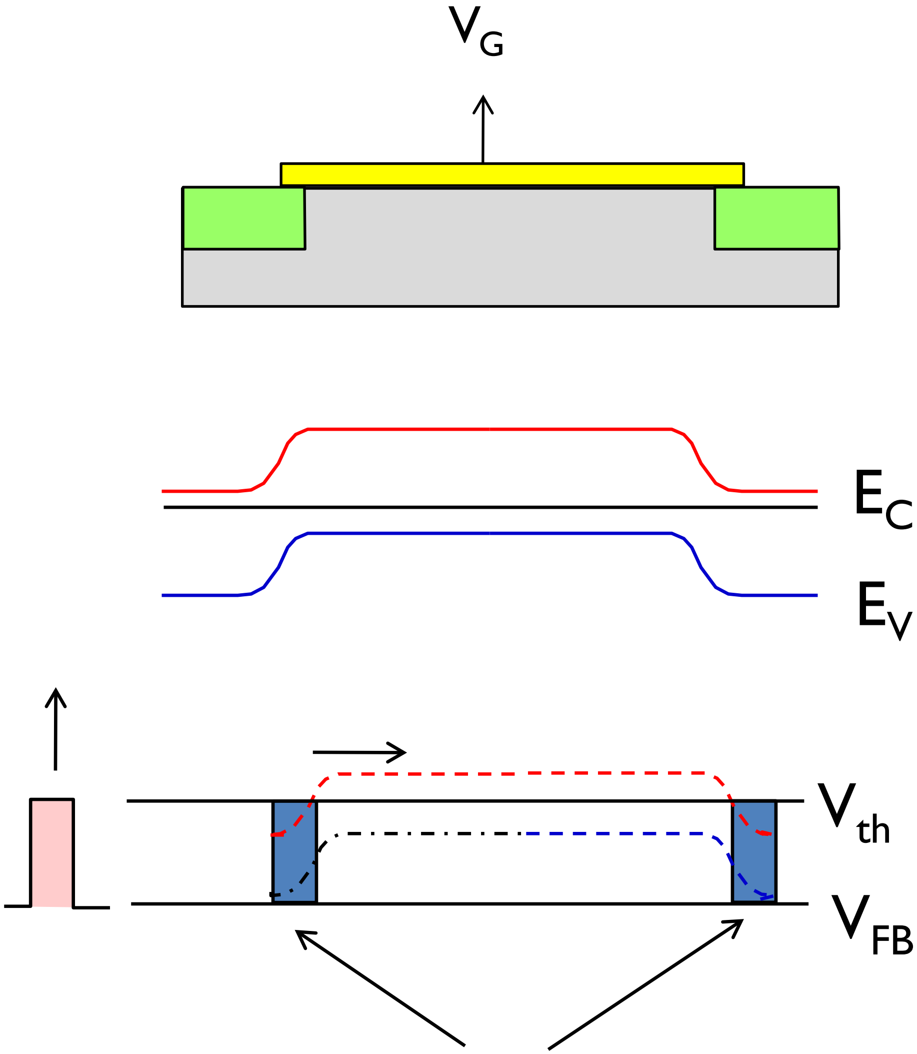
All three components active

Interface inaccessible after inversion

Only D-B depletion
In accumulation

$$I_T = I_J + I_{GIJ} + I_S = \frac{qn_i A_j W_J}{\tau_{g,J}} + \frac{qn_i A_G W_G}{\tau_{g,G}} + qn_i A_G W_G S^*$$

4. Spatial Profiling by Charge Pumping



Pumped region

Alam ECE-695

Spatial Profiling by Charge Pumping

Before stress …

$$I_{CP}(V_{base}) \propto \int_{-y_1}^{0} N_{IT}(y)dy + \int_{0}^{y_1} N_{IT}(y)dy$$

y_1 is defined by $V_{FB}(y_1) \equiv V_{base}$

$$I_{CP}(V_{top}) \propto \left(\int_{-y_m}^{-y_2} N_{IT}(y)dy + \int_{y_2}^{y_m} N_{IT}(y)dy \right)$$

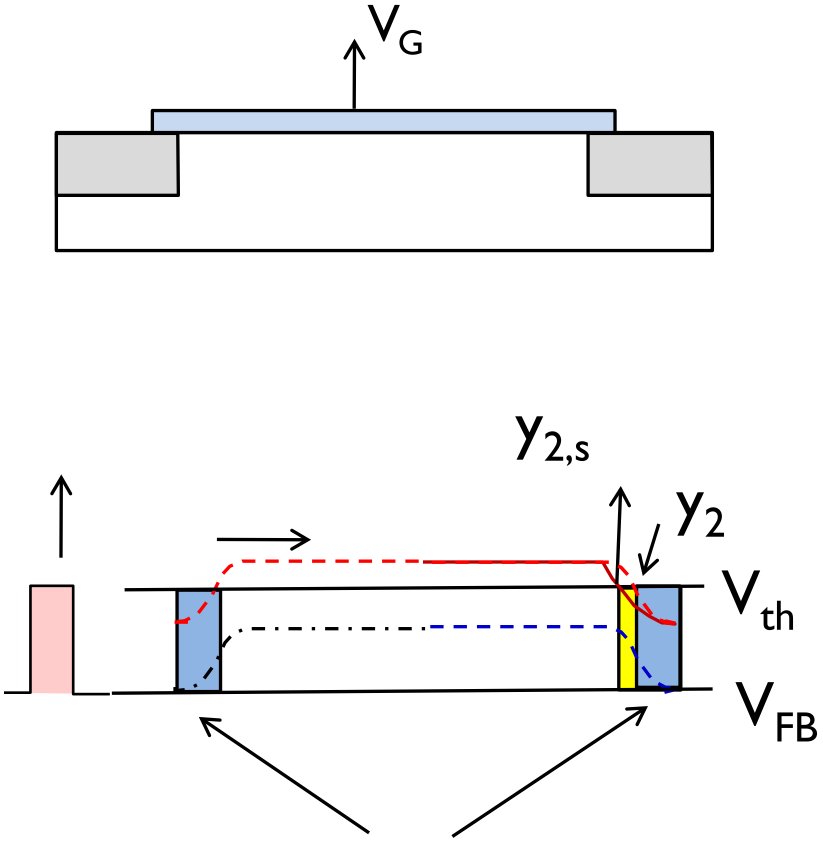
y_2 is defined by $V_{th}(y_2) \equiv V_{top}$

y_m is defined by $V_{FB}(y_m) \equiv V_{base,\min}$

After stress …

$$I_{CP}(V_{base}) \propto \int_{-y_1}^{0} N_{IT}(y)dy + \int_{0}^{y_{1,s}} N_{IT,S}(y)dy$$

$$I_{CP}(V_{top}) \propto \left(\int_{-y_m}^{-y_2} N_{IT}(y)dy + \int_{y_{2,s}}^{y_m} N_{IT}(y)dy \right)$$



Pumped region

Defect Profiling by Charge Pumping

$$\Delta I_{CP}(V_{base}) = \Delta I_{CP,s}(V_{base}) - \Delta I_{CP}(V_{base})$$

$$\propto \int_{-y_1}^{0} N_{IT}(y)dy + \int_{0}^{y_{1,s}} N_{IT,s}(y)dy$$

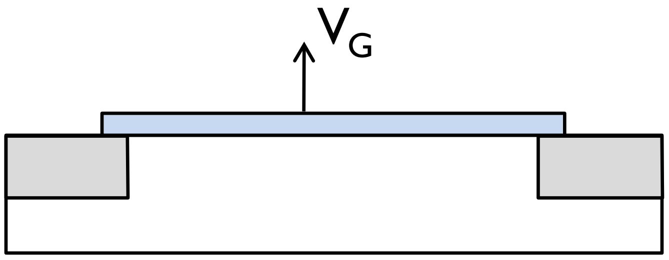
$$-\int_{-y_1}^{0} N_{IT}(y)dy - \int_{0}^{y_1} N_{IT}(y)dy$$

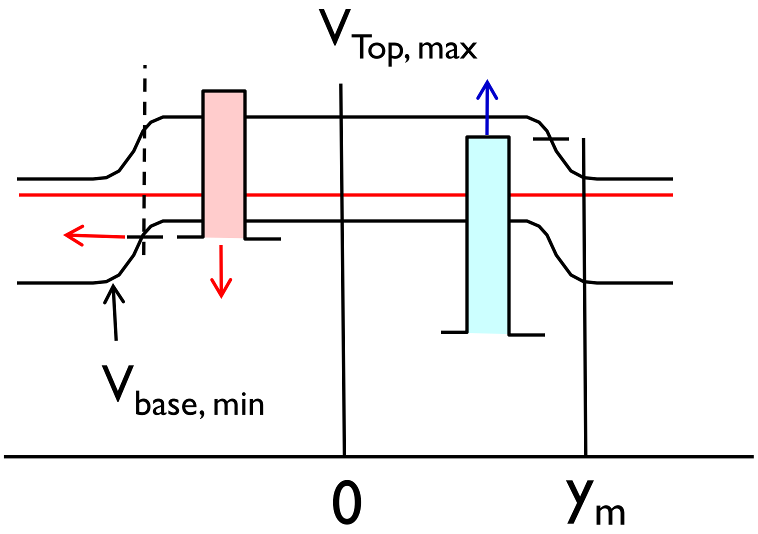
$$= \int_{0}^{y_{1,s}} \left(N_{IT,s}(y) - N_{IT}(y)\right)dy + \int_{y_1}^{y_{1,s}} N_{IT}(y)dy$$

$$= \int_{0}^{y_{1,s}} \Delta N_{IT,s}(y)dy + \int_{y_1}^{y_{1,s}} N_{IT}(y)dy$$

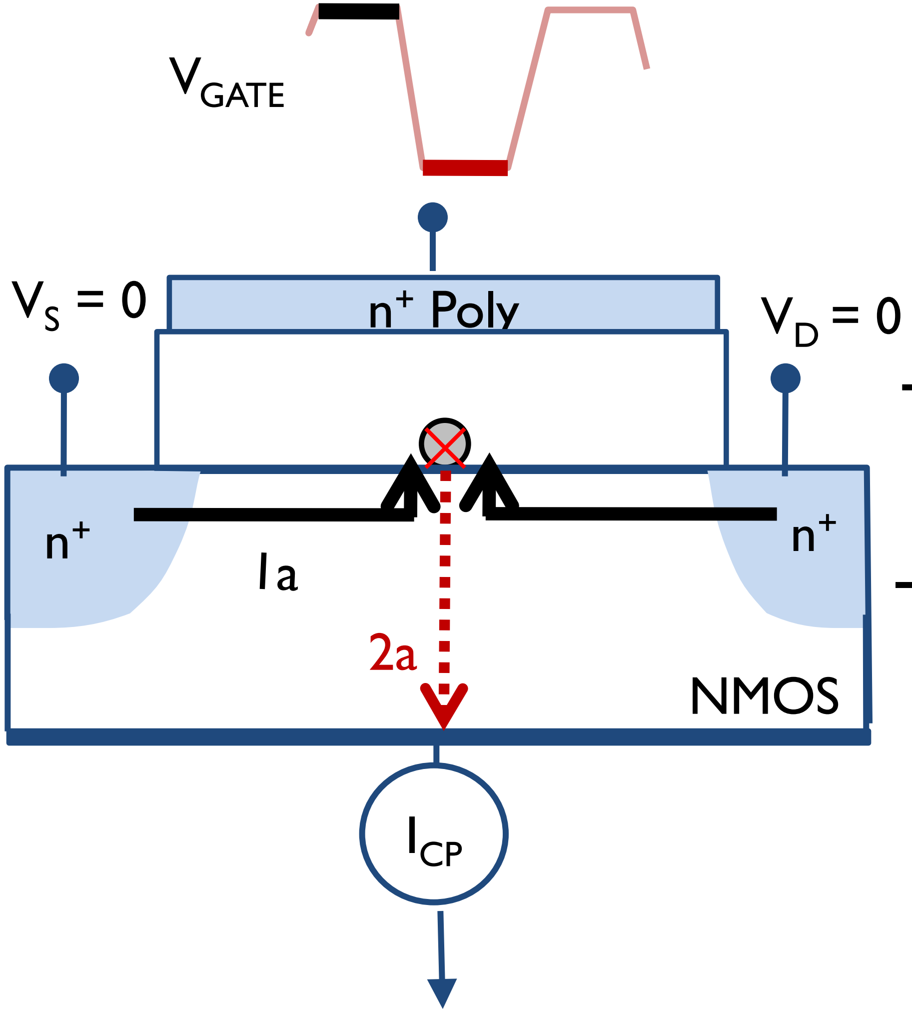
NBTI stress

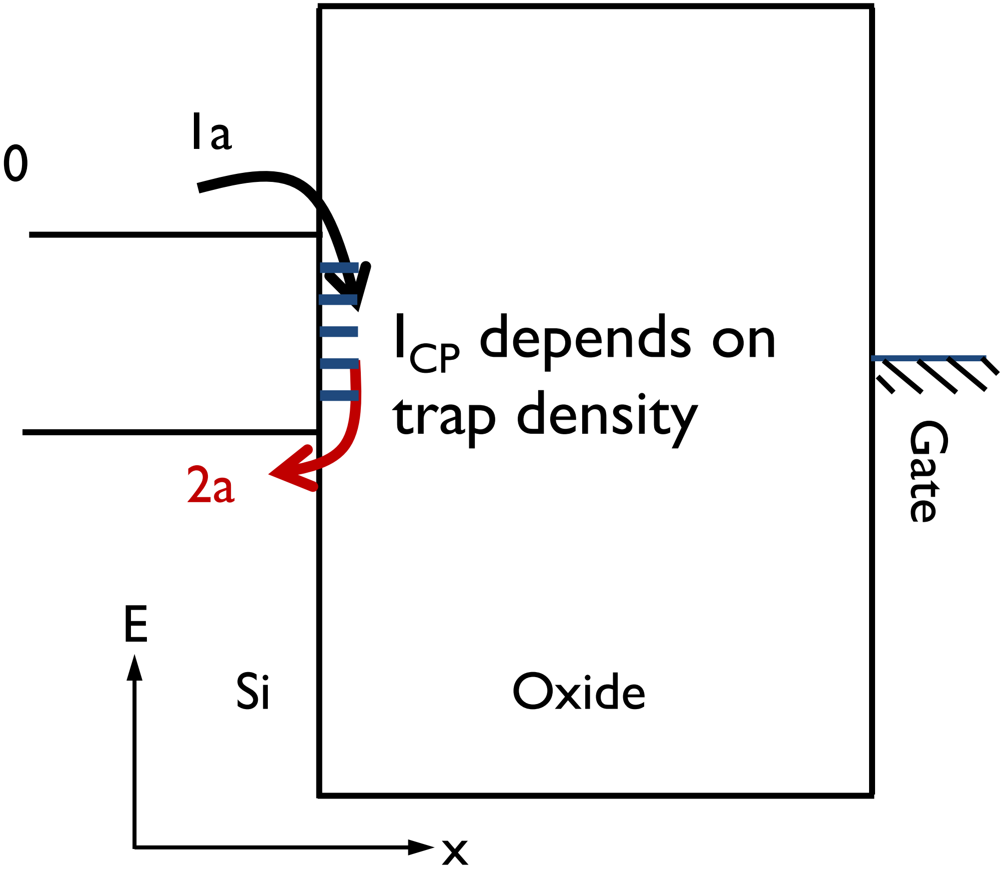
HCI stress





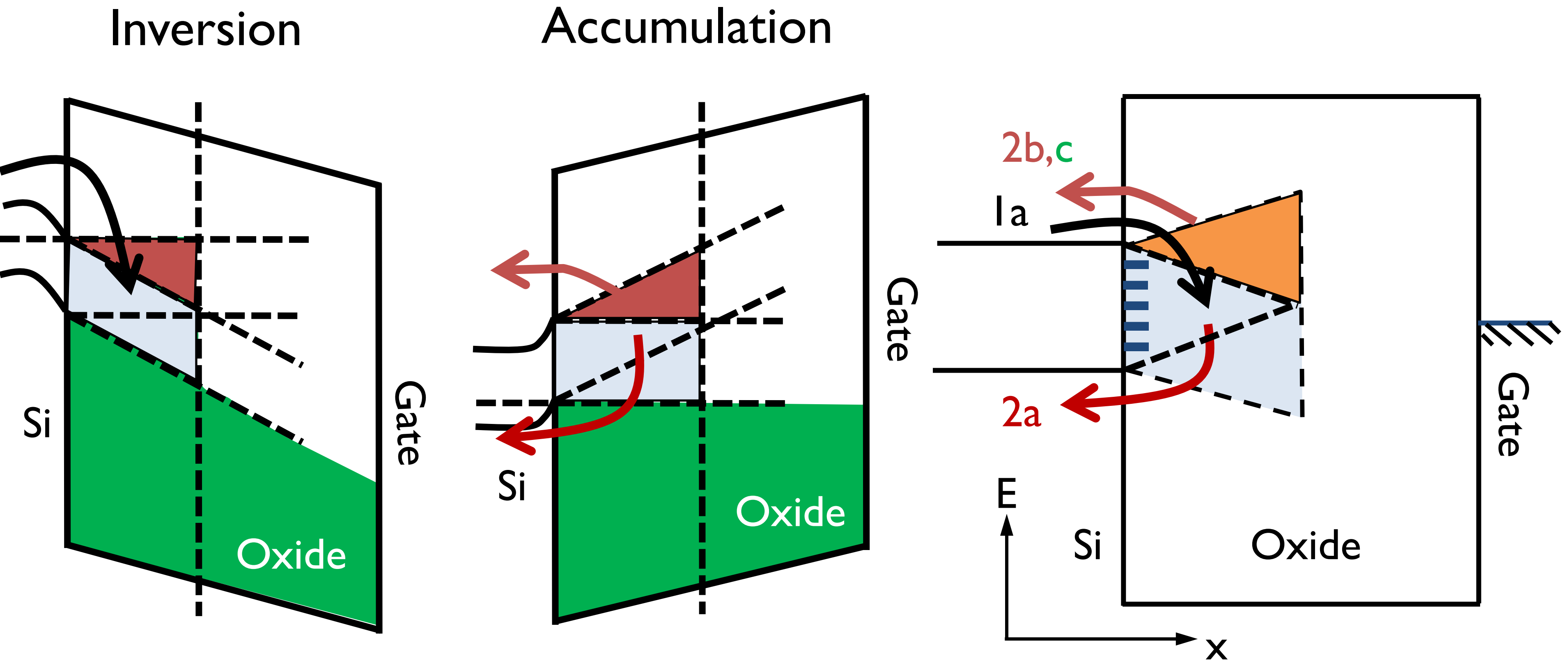
5. High frequency Charge Pumping



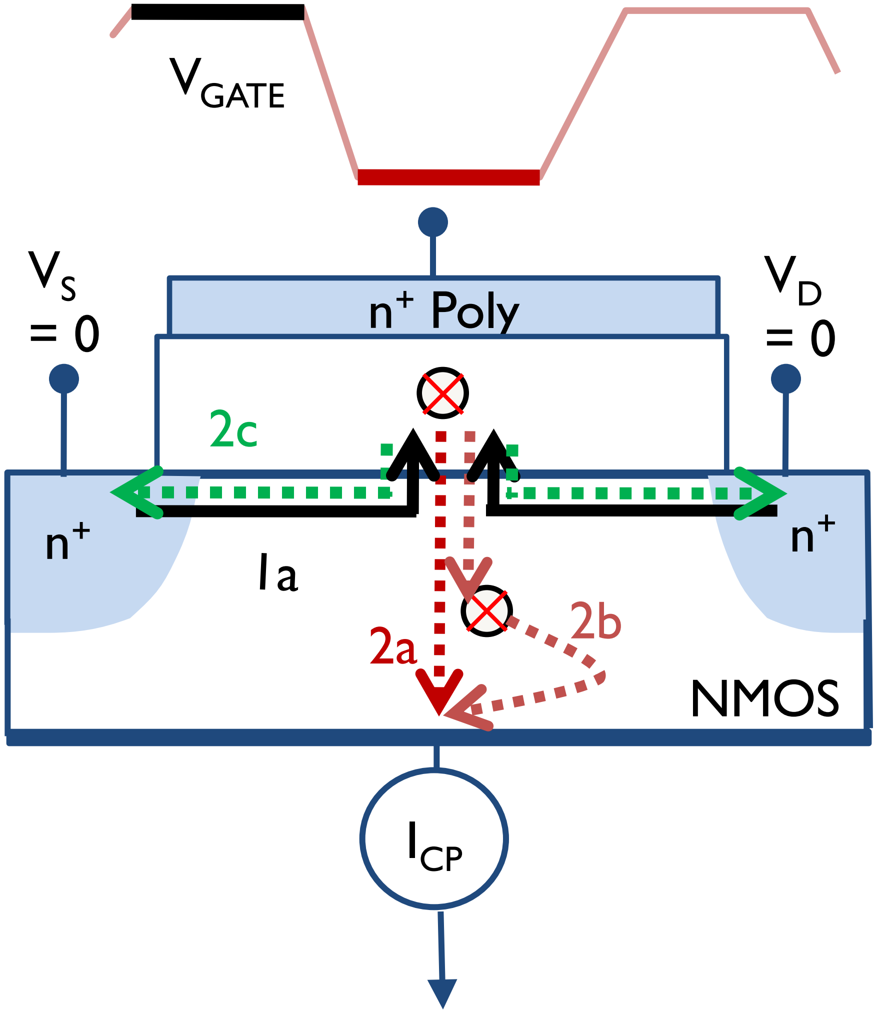


I_{CP} depends on trap density

Low frequency Charge Pumping

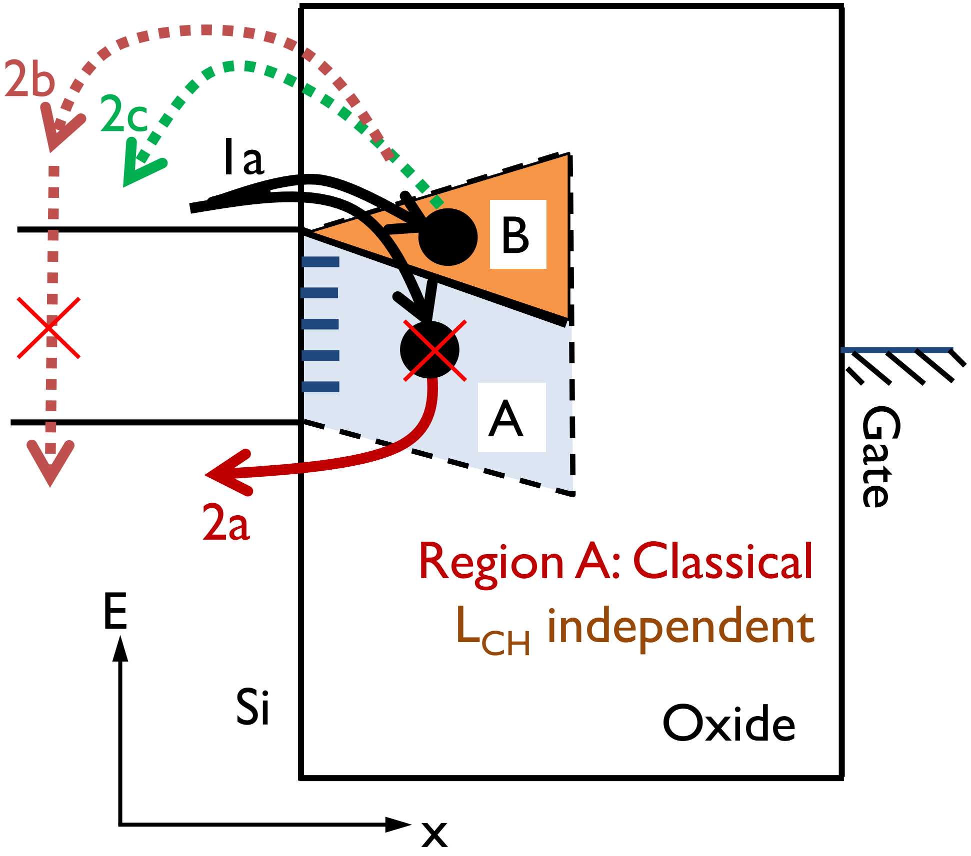


Two Regions of CP



Region B: Quasi-geometrical

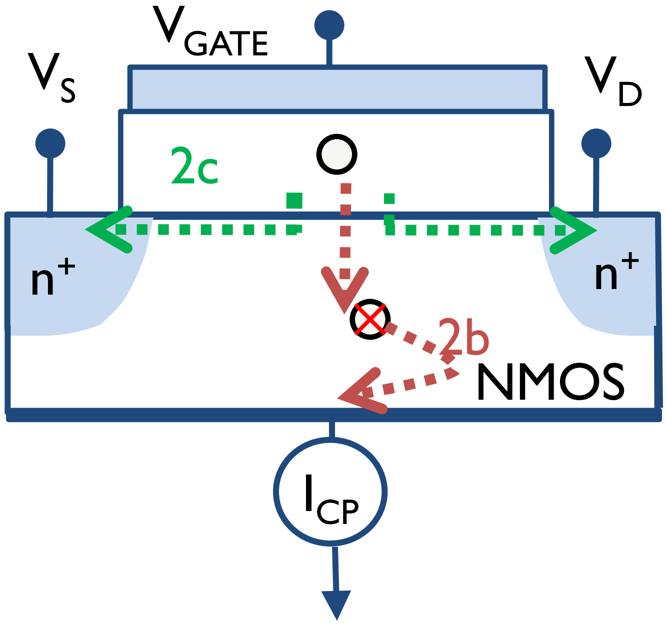
L_{CH} dependent

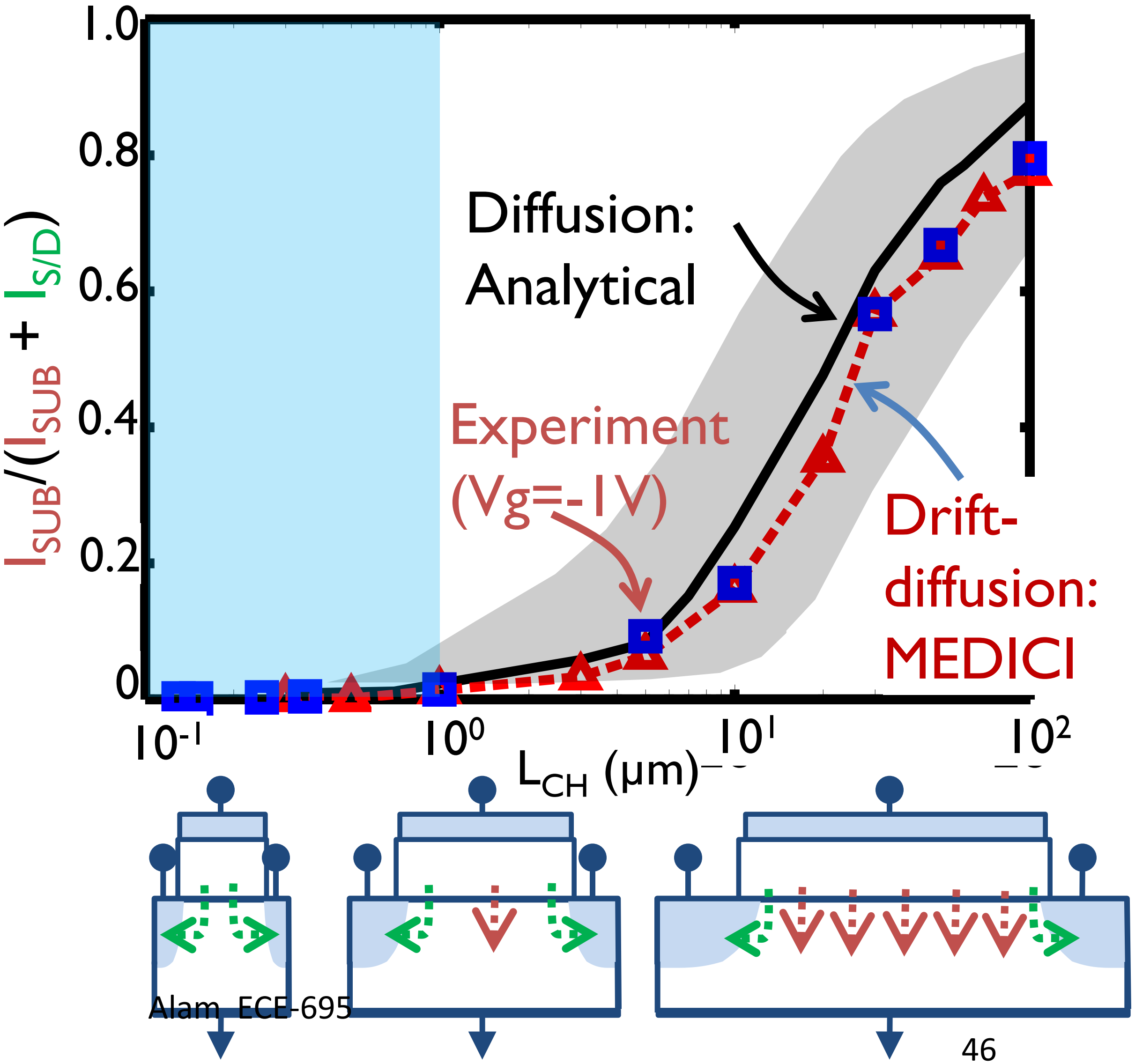


Region A: Classical

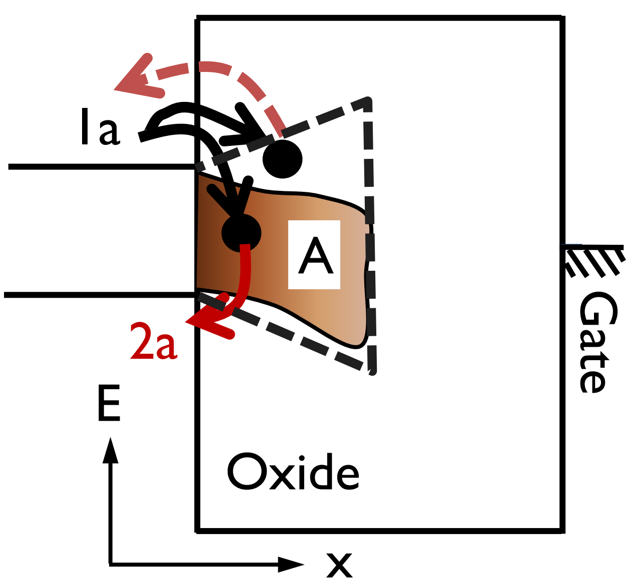
L_{CH} independent

L_{CH} dependent Quasi-geometrical CP

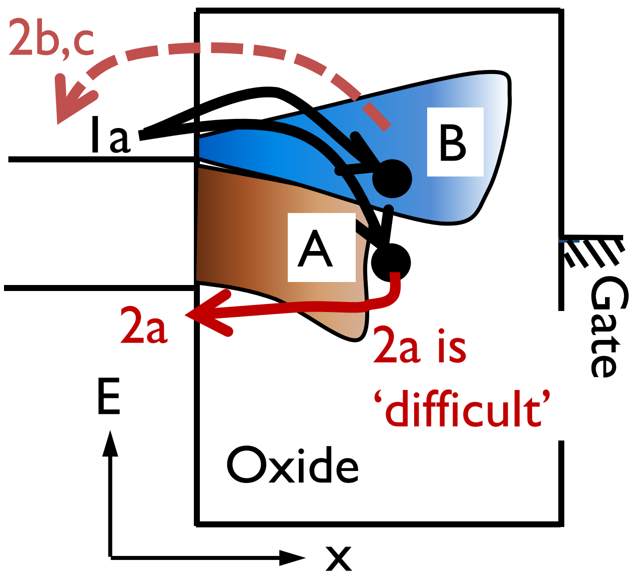




Low *f* CP Summary



Short L_{CH}



Long L_{CH}

Two consequences of the lower electron barrier*:

1) Skewed Region A towards Valance Band
2) Deeper scanning for Region B

* M Masuduzzaman *et. al.* TED '08