

# ECE695: Reliability Physics of Nano-Transistors

## Lecture 10: Time dependent NBTI --- frequency and duty cycle dependencies

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# Outline

- I. NBTI stress and relaxation by R-D model
2. Frequency independence and lifetime projection
3. Duty cycle dependence
4. The magic of measurement
5. Conclusions

# Interface trap-generation with DC stress

$$\frac{dN_{IT}}{dt} = k_F(N_0 - N_{IT}) - k_R N_H(0) N_{IT}$$

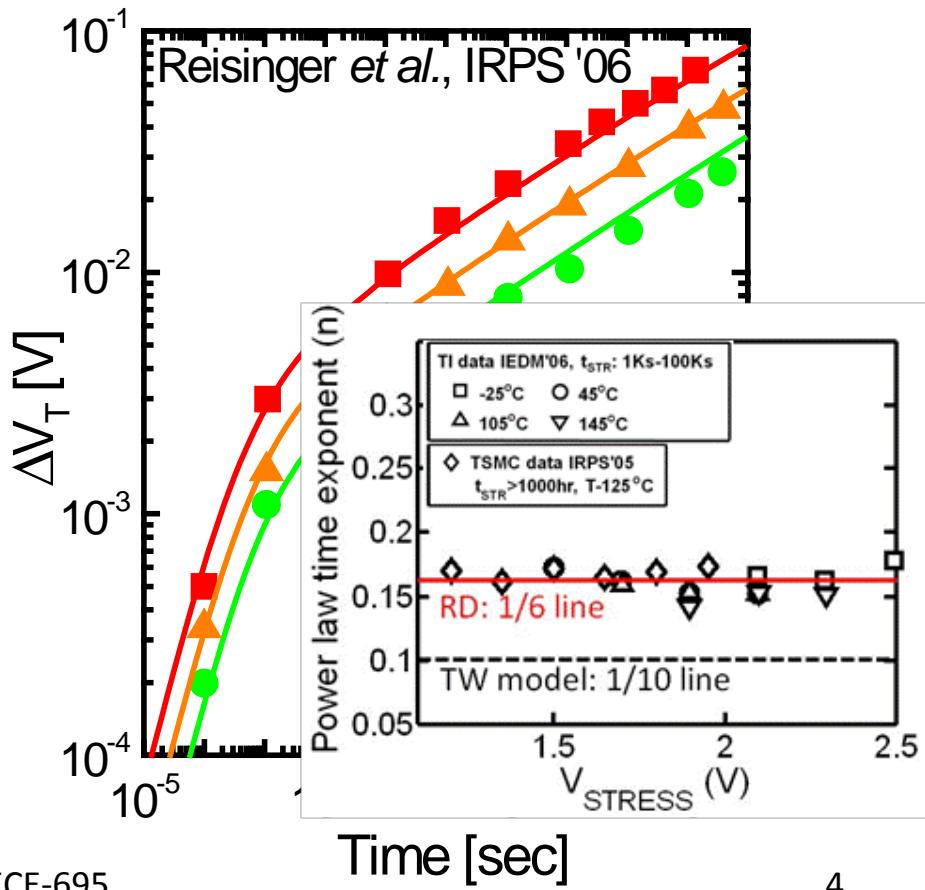
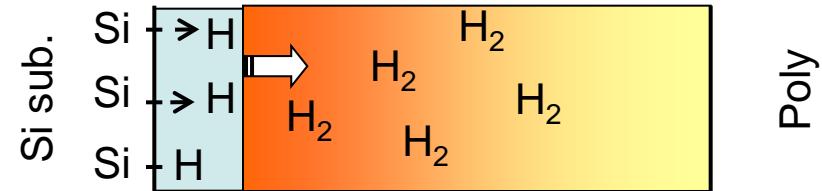
$$\left( \frac{k_F N_0}{k_R} \right) \approx N_H(0) N_{IT}$$

$$N_{IT}(t) = \frac{1}{2} N_H(0) \sqrt{D_{H_2} t}$$

$$const. = \frac{N_H(0)^2}{N_{H_2}(0)} (2H \square H_2)$$

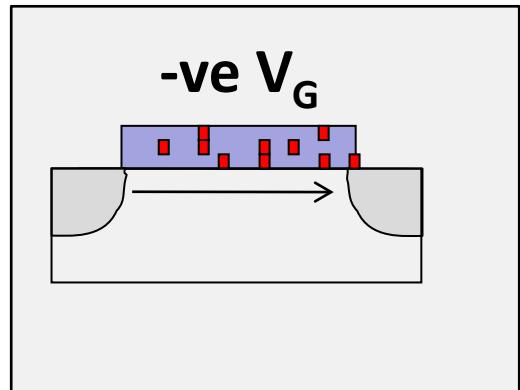
Combining the three, we get

$$N_{IT}(t) = \sqrt{\frac{k_F N_0}{2k_R}} (D_{H_2} t)^{1/6} \equiv A \times t^n$$

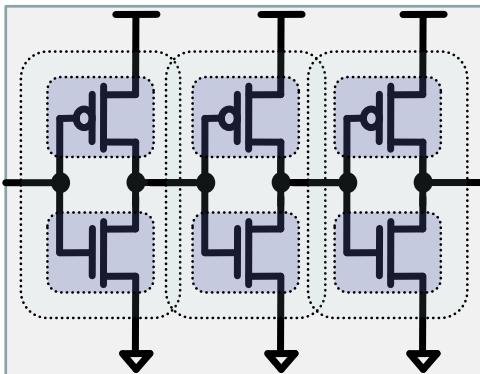


# Three topics of NBTI lifetime projection

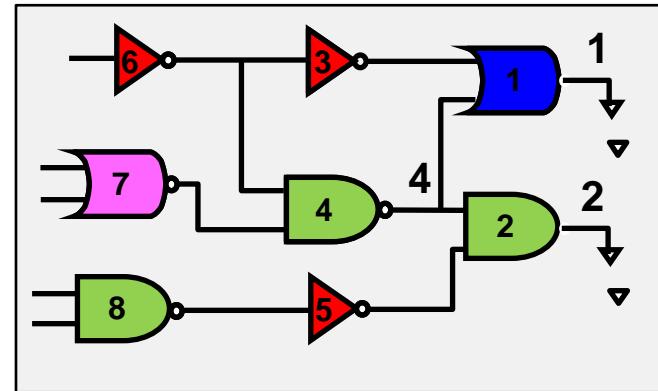
DC



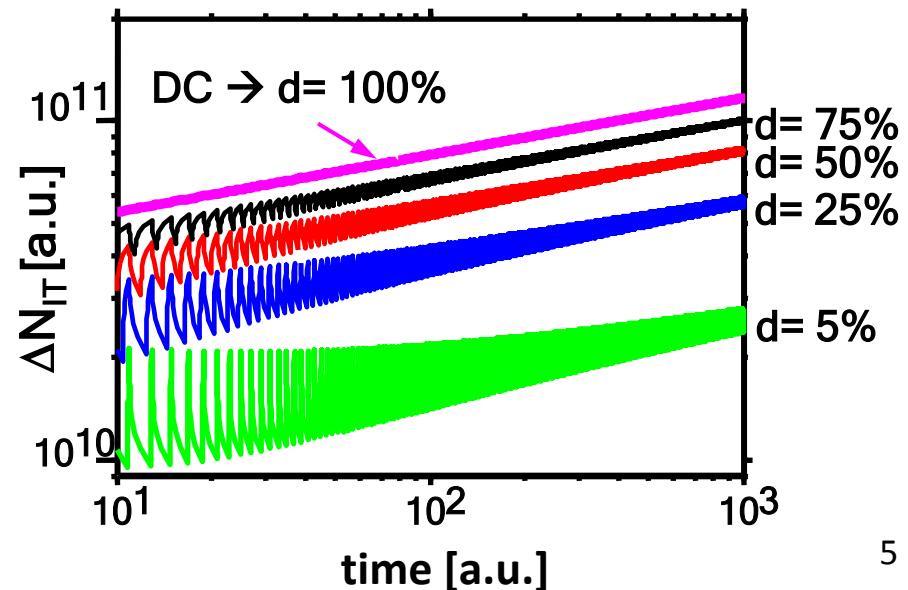
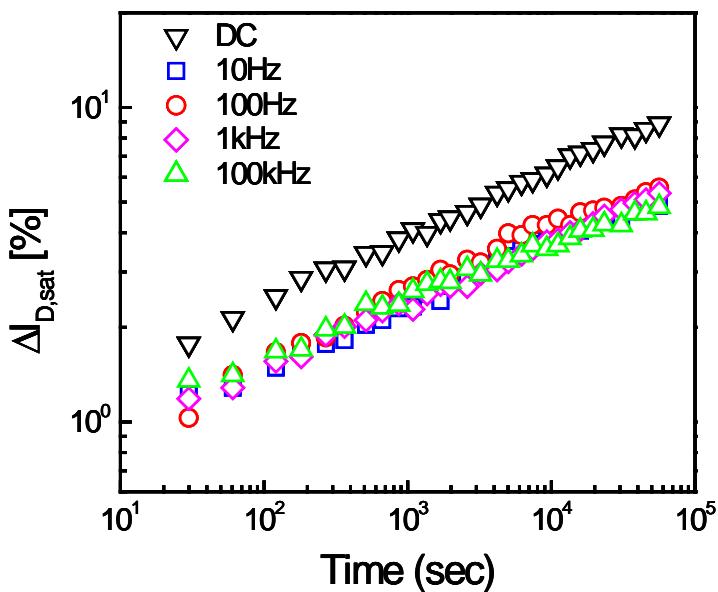
AC



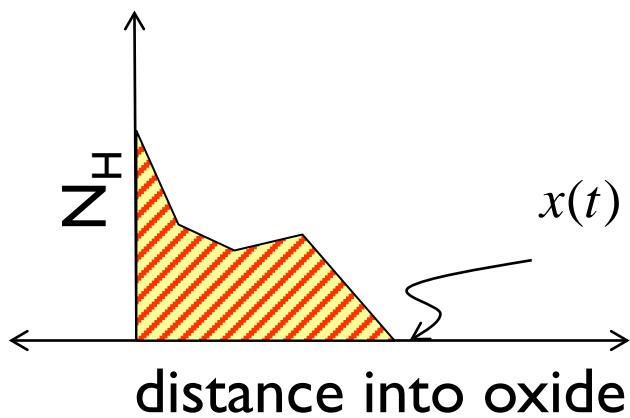
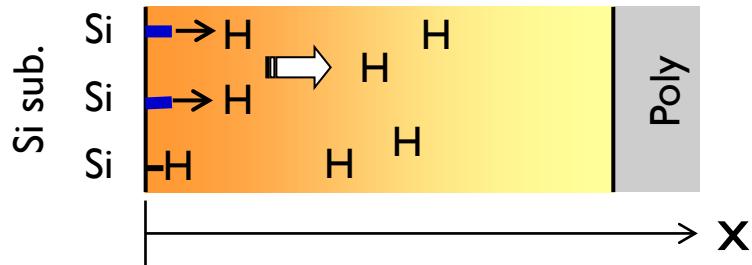
Duty Cycle



$$\Delta V_{IT} \sim A(f, d) \times t^n$$



# The reaction-diffusion model



$$\frac{d}{dx} \left[ \frac{1}{2} \delta \times N_x(0) \right] = \frac{dN_{IT}}{dt} - D_x \frac{dN_x}{dx} \Big|_0$$

$$\frac{dN_{IT}}{dt} = k_F (N_0 - N_{IT}) - k_R N_x(0) N_{IT}$$

$k_F$ : Si-H dissociation rate const.

Creates broken-bond NIT

$k_R$ : Rate of reverse annealing of Si-H

$N_0$ : Total number of Si-H bonds

$$\frac{dN_x}{dt} = D_H \frac{d^2 N_x}{dx^2} + \frac{d}{dx} (N_x \mu_x E)$$

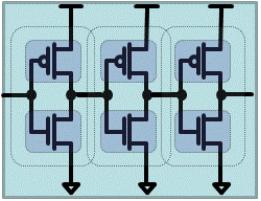
$N_H$ : Hydrogen density

$D_H$ : Hydrogen diffusion coefficient

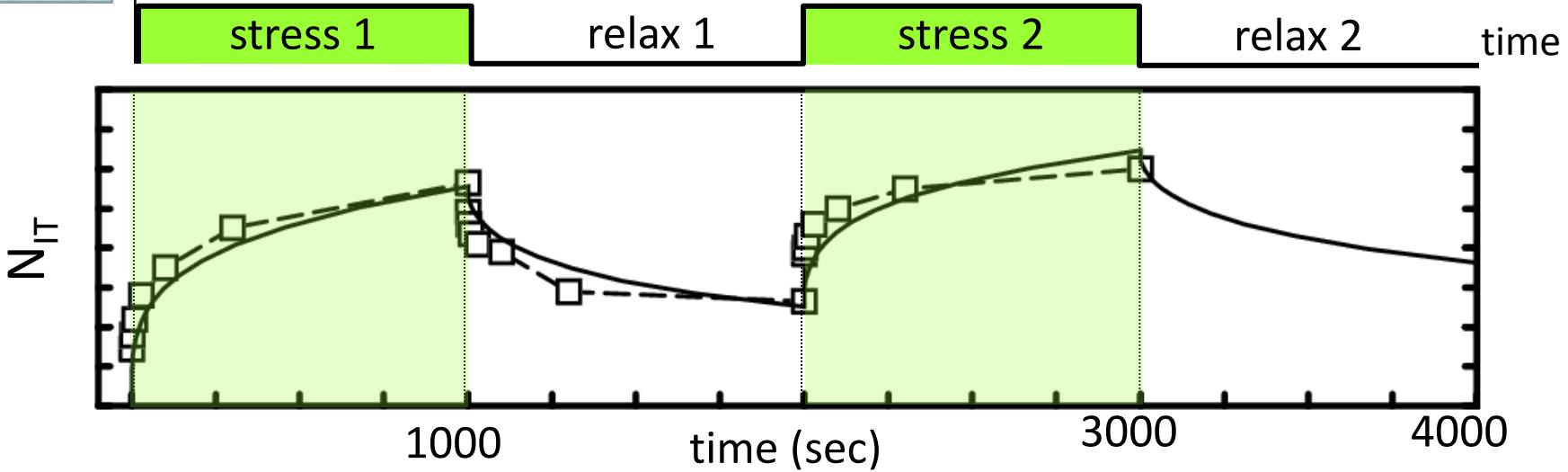
$m_H$ : Hydrogen mobility

# Outline

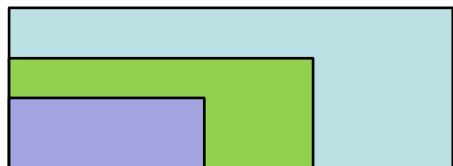
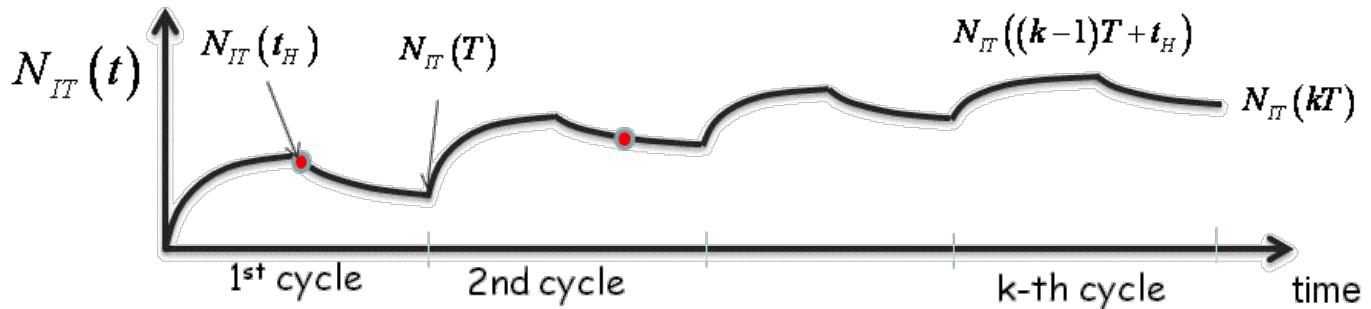
- I. NBTI stress and relaxation by R-D model
2. Frequency independence and lifetime projection
3. Duty cycle dependence
4. The magic of measurement
5. Role of hole trapping
6. Conclusions



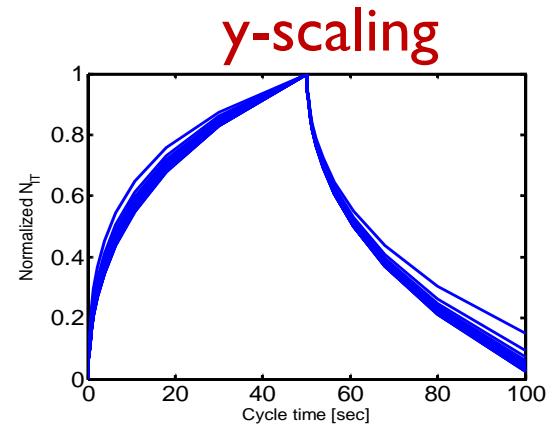
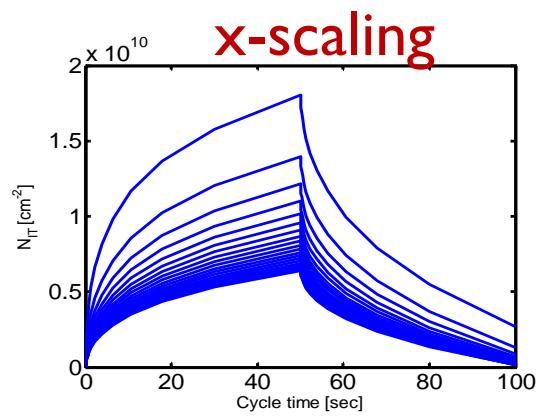
# Self-healing at AC stress



# Self-affine periodicity

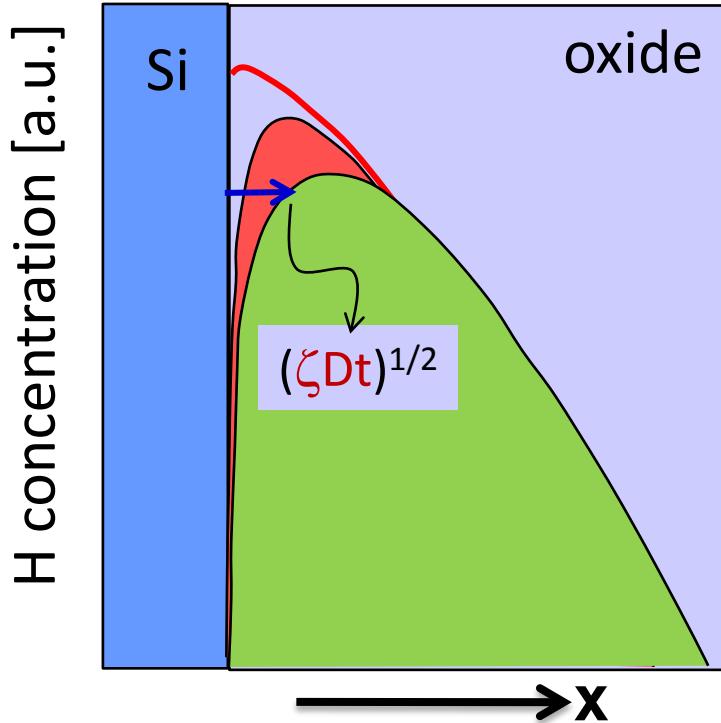


Two-scale factors

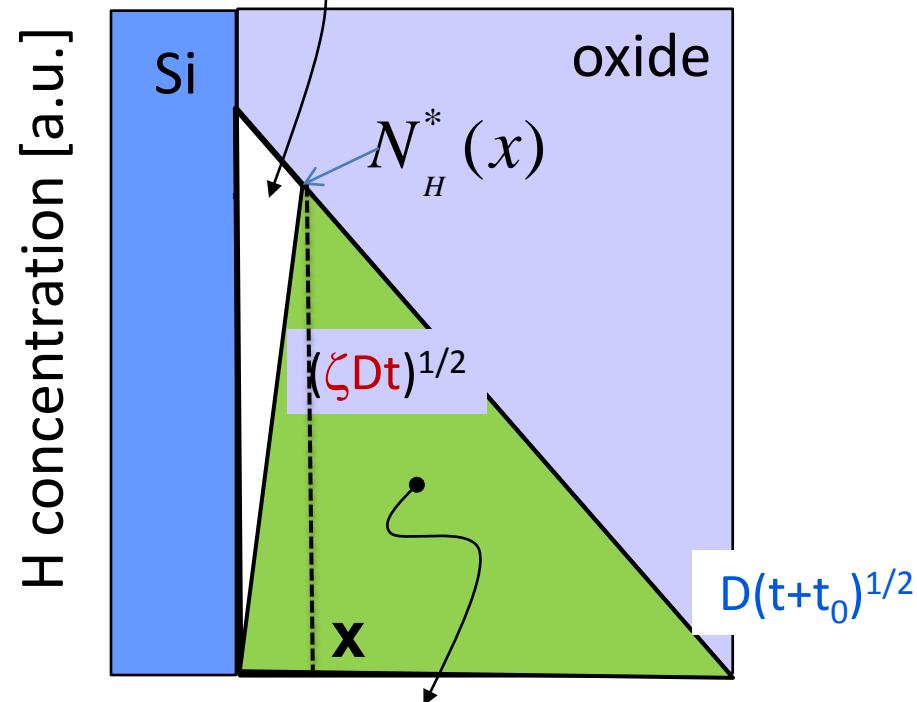


# Analysis of NBTI relaxation

$$N_{IT}(t_H) = \frac{N_H(0)}{2} \sqrt{2D_H t_H} = A t_H^{1/4}$$



$$N_{IT}^*(t + t_H) = \frac{1}{2} \sqrt{2\xi D_H t} N_H^*(x)$$



$$N_{IT}(t + t_H) + N_{IT}^*(t + t_H) = N_{IT}(t_H)$$

$$N_{IT}(t + t_0) = \frac{1}{2} \sqrt{2D_H(t + t_0)} N_H^*(x)$$

# Analytical solution of NBTI relaxation

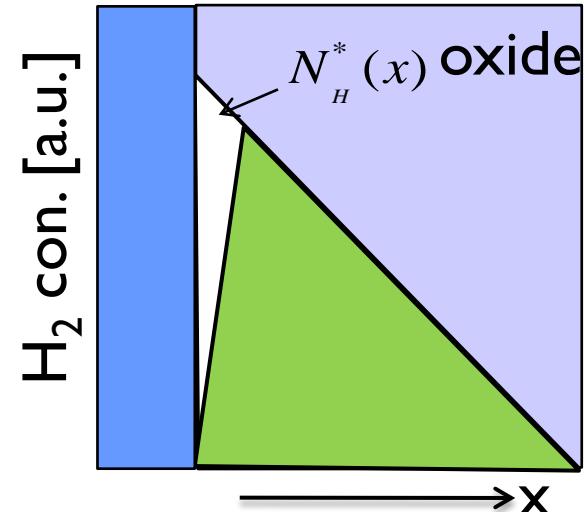
$$N_{IT}^*(t + t_H) = \frac{1}{2} \sqrt{2\xi D_H \times t} \times N_H^*(x) \quad \# \text{ of Hydrogen Recombined}$$

$$N_{IT}(t + t_H) = \frac{1}{2} \sqrt{2D_H(t + t_H)} N_H^*(x) \quad \# \text{ of Hydrogen in oxide}$$

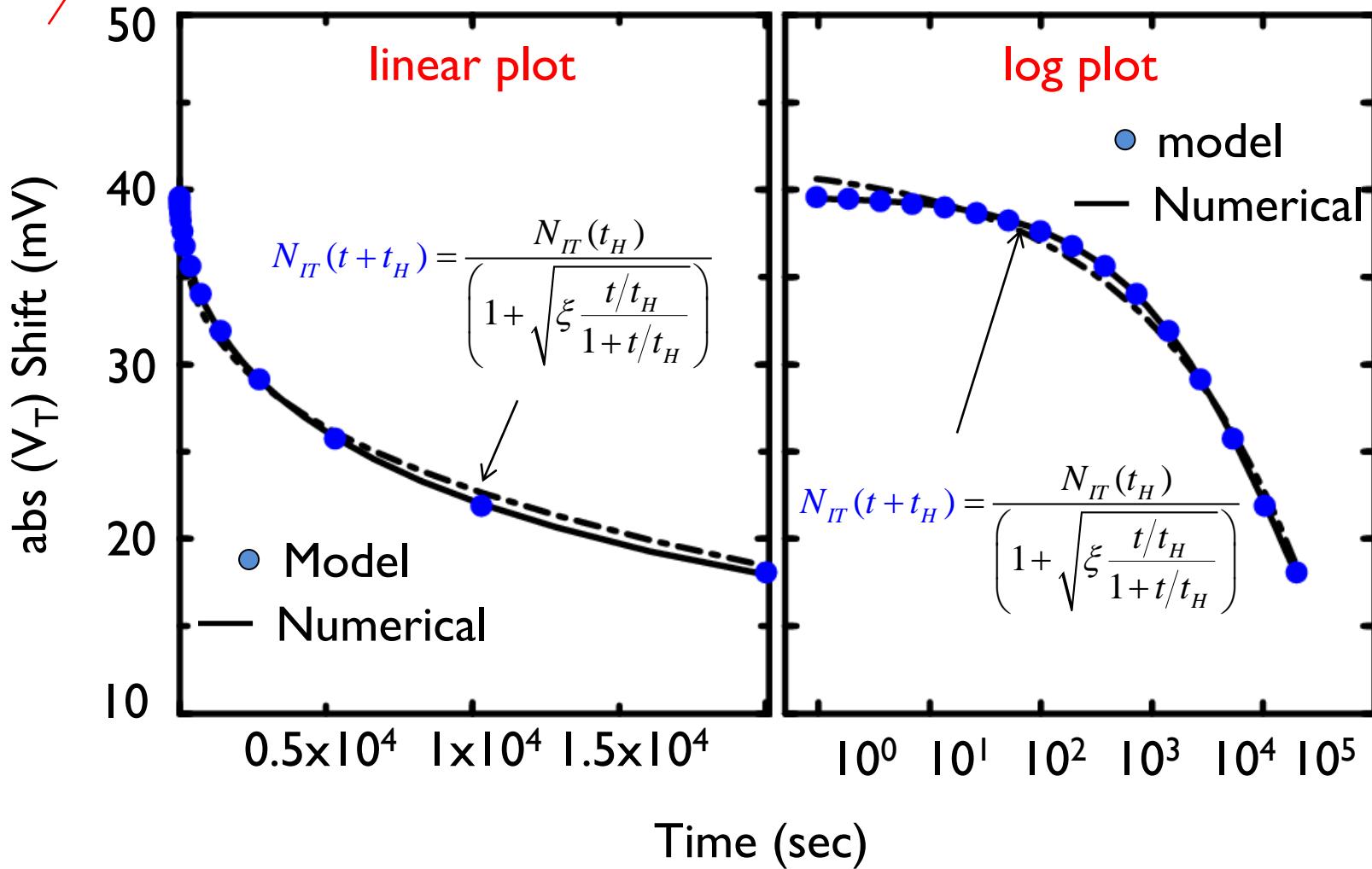
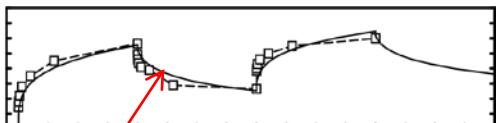
No of H recombined + No of H in oxide = Initial # of H

$$N_{IT}^*(t + t_H) + N_{IT}(t + t_H) = N_{IT}(t_H)$$

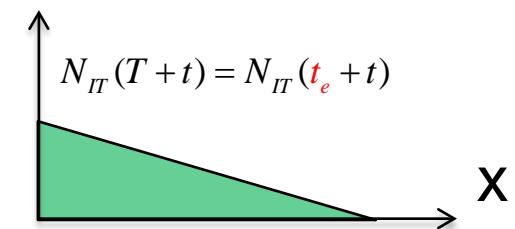
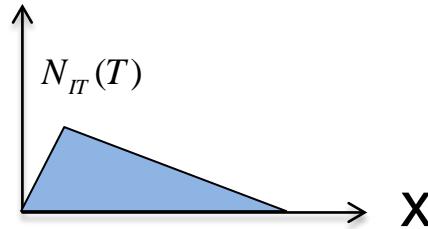
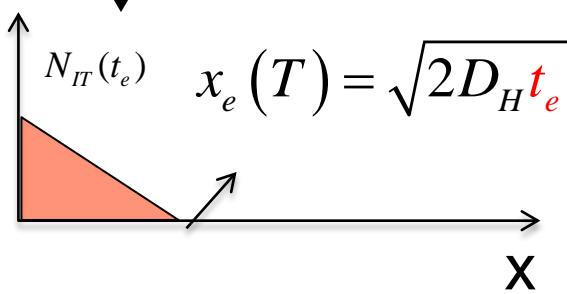
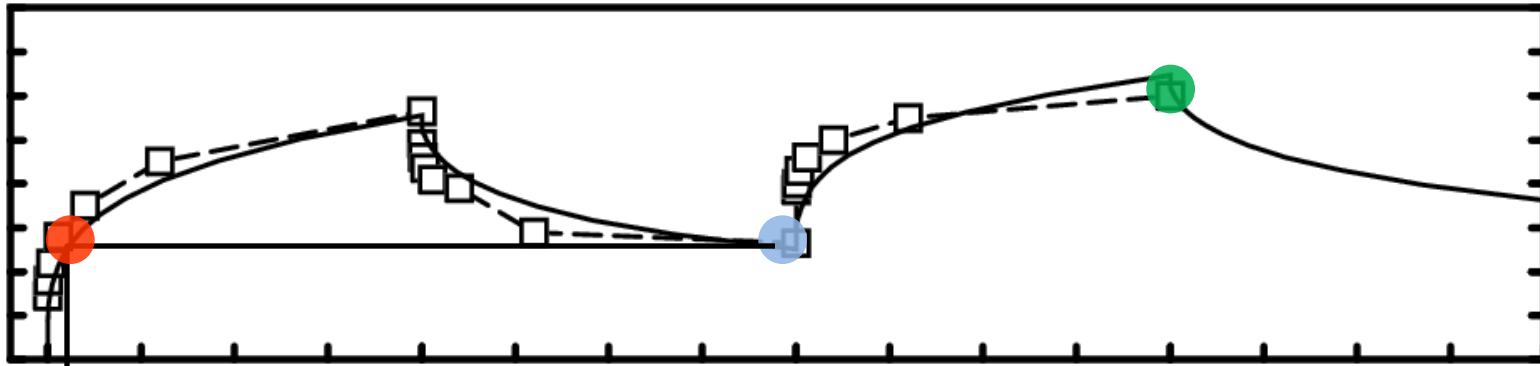
$$\frac{N_{IT}^*(t + t_H)}{N_{IT}(t + t_H)} = \sqrt{\frac{\xi t}{t + t_H}} \quad N_{IT}(t + t_H) = \frac{N_{IT}(t_H)}{\left(1 + \sqrt{\xi \frac{t/t_H}{1 + t/t_H}}\right)}$$



# Analytical model vs. numerical model



# Notion of an ‘Equivalent DC Time’

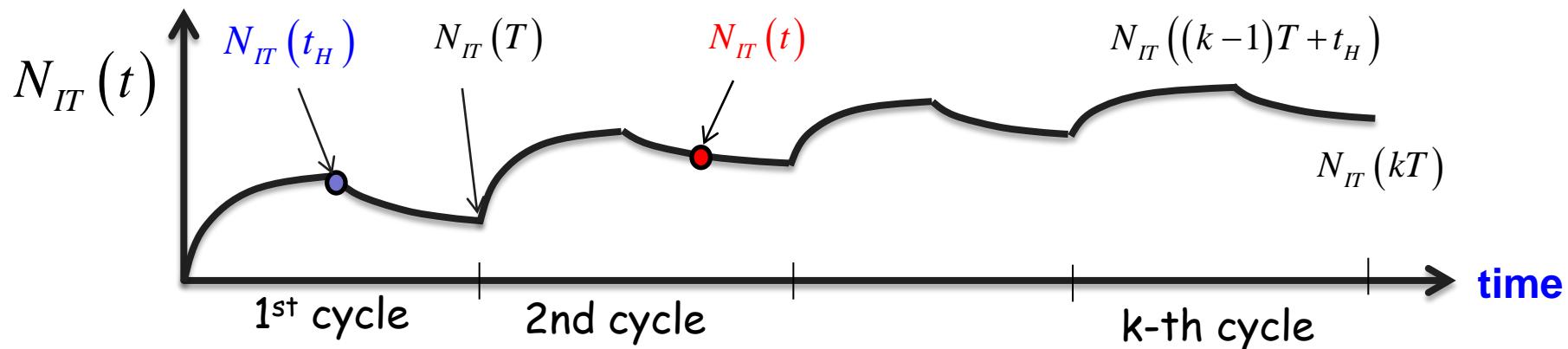
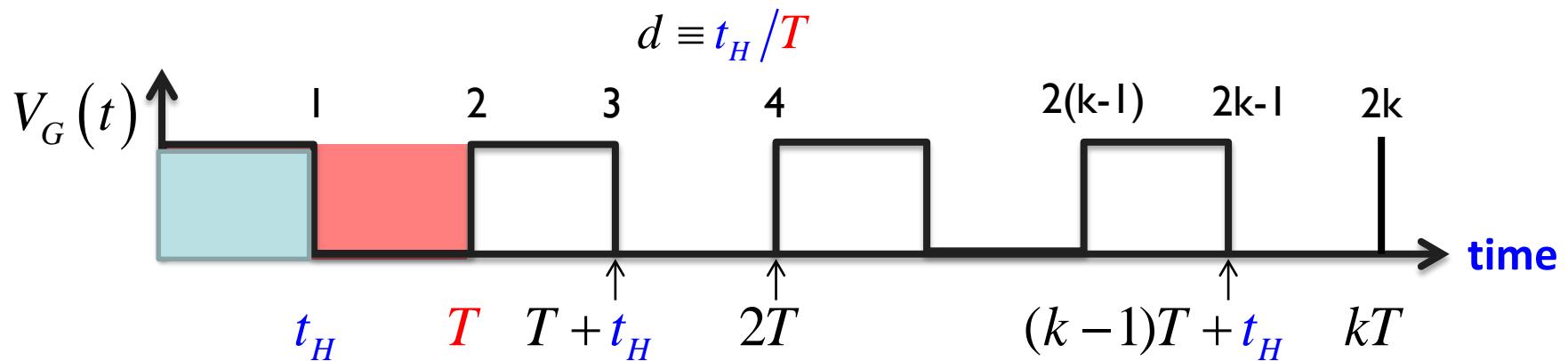


$$A \times t_e^n \equiv N_{IT}(T) = R_2 \times (At_H)^n$$

$$\Rightarrow t_e/t_H = (R_2)^{1/n}$$

$$\begin{aligned} &= \frac{1}{2} N_H^{(0)} \sqrt{2D_H (t_H + t_e)} \\ &= A(t_H + t_e)^n \end{aligned}$$

# Frequency and duty cycle dependence

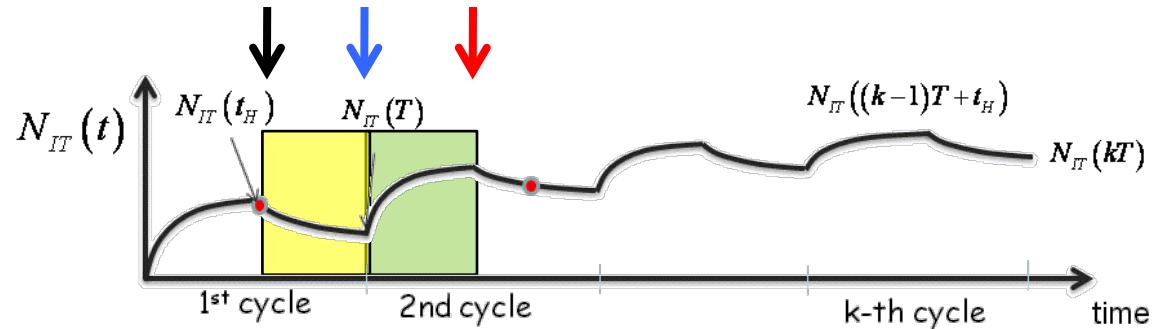


$$R(t) \equiv \frac{N_{IT}(t)}{N_{IT}(t_H)}$$

# Solution of RD model by recursion

$$N_{IT}(t_H) = At_H^n$$

$$R_1 \equiv R(t_H) \equiv \frac{N_{IT}(t_H)}{N_{IT}(t_H)} = 1$$



$$R_2 = \frac{N_{IT}(T_H + \textcolor{magenta}{T}_L)}{N_{IT}(t_H)} = \frac{1}{\left(1 + \sqrt{\xi \textcolor{magenta}{T}_L / T}\right)} = \frac{1}{\left(1 + \sqrt{\xi(1 - d)}\right)} R_1 \quad d \equiv \frac{t_H}{\textcolor{blue}{T}}$$

$$R_3 = \frac{N_{IT}(T + t_H)}{N_{IT}(t_H)} = \frac{A(t_H + \textcolor{magenta}{t}_e)^n}{A(t_H)^n} = \left(1 + (R_2)^{1/n}\right)^n \quad (\text{see notes})$$

Odd-even cycle ...

$$(R_{2k-1})^{1/n} = 1 + (R_{2k-2})^{1/n}$$

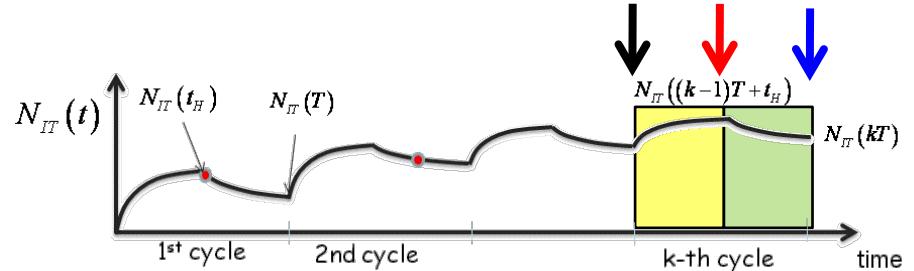
even-odd cycle ...

$$R_{2k} = \frac{1}{1 + \sqrt{\xi(1 - d)}} R_{2k-1} + \frac{\sqrt{\xi(1 - d)}}{1 + \sqrt{\xi(1 - d)}} R_{2k-2}$$

# Recursive relation between Stress/Relaxation

Odd-even cycle ...

$$(R_{2k-1})^{1/n} = 1 + (R_{2k-2})^{1/n}$$

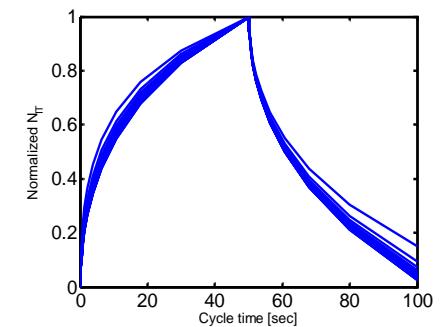
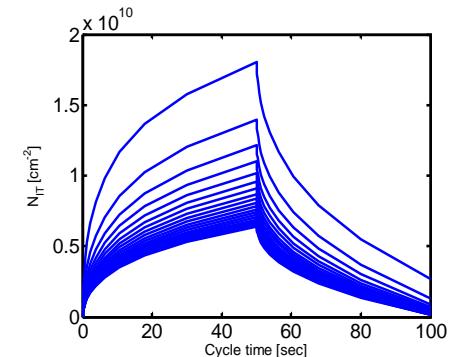


Even-odd cycle ...

$$R_{2k} = \frac{1}{1 + \sqrt{\xi(1-d)}} R_{2k-1} + \frac{\sqrt{\xi(1-d)}}{1 + \sqrt{\xi(1-d)}} R_{2k-2}$$

$$R_{2k-1}^{1/n} \approx \frac{1}{1 + \sqrt{\xi(1-d)}} + R_{2k-3}^{1/n} \quad (\text{by iteration})$$

$$= \frac{1}{1 + \sqrt{\xi(1-d)}} (k-1) + R_1^{1/n} \approx \frac{1}{1 + \sqrt{\xi(1-d)}} (k-1)$$



# Recursion solution for AC response

$$(R_{2k-1})^{1/n} = 1 + (R_{2k-2})^{1/n}$$

$$R_{2k} = \frac{1}{1 + \sqrt{\xi(1-d)}} R_{2k-1} + \frac{\sqrt{\xi(1-d)}}{1 + \sqrt{\xi(1-d)}} R_{2k-2}$$

$$R_{2k-4} = (R_{2k-3}^{1/n} - 1)^n$$

$$R_{2k-1}^{1/n} = 1 + \left[ \frac{1}{1 + \sqrt{\xi(1-d)}} R_{2k-3} + \frac{\sqrt{\xi(1-d)}}{1 + \sqrt{\xi(1-d)}} (R_{2k-3}^{1/n} - 1)^n \right]^{1/n}$$

$$= 1 + R_{2k-3}^{1/n} \left[ \frac{1}{1 + \sqrt{\xi(1-d)}} + \frac{\sqrt{\xi(1-d)}}{1 + \sqrt{\xi(1-d)}} \left( 1 - \frac{1}{R_{2k-3}^{1/n}} \right)^n \right]^{1/n}$$

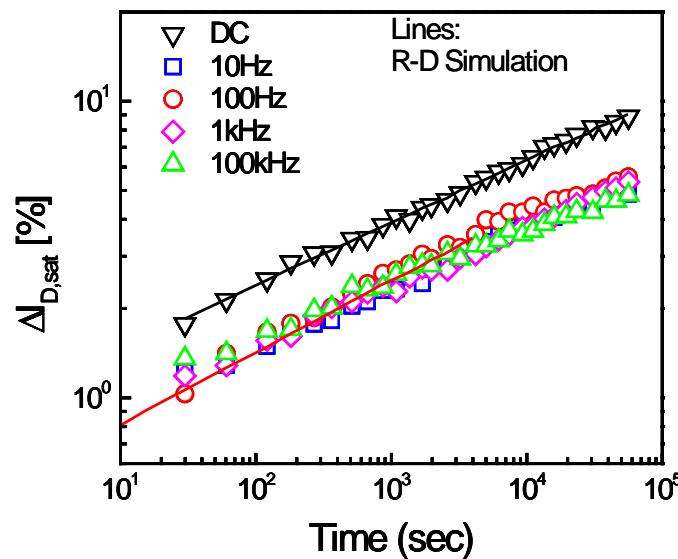
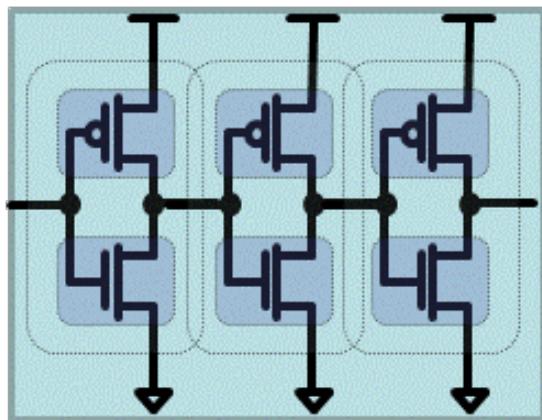
$$R_{2k-1}^{1/n} \approx 1 + R_{2k-3}^{1/n} \left[ 1 - \frac{n\sqrt{\xi(1-d)}}{1 + \sqrt{\xi(1-d)}} \frac{1}{R_{2k-3}^{1/n}} \right]^{1/n} \approx \frac{1}{1 + \sqrt{\xi(1-d)}} + R_{2k-3}^{1/n}$$

# Frequency independence by R-D model

$$R_{2k-1}^{1/n} \approx \frac{1}{1 + \sqrt{\xi(1-d)}}(k-1) \approx \frac{2}{3}k$$

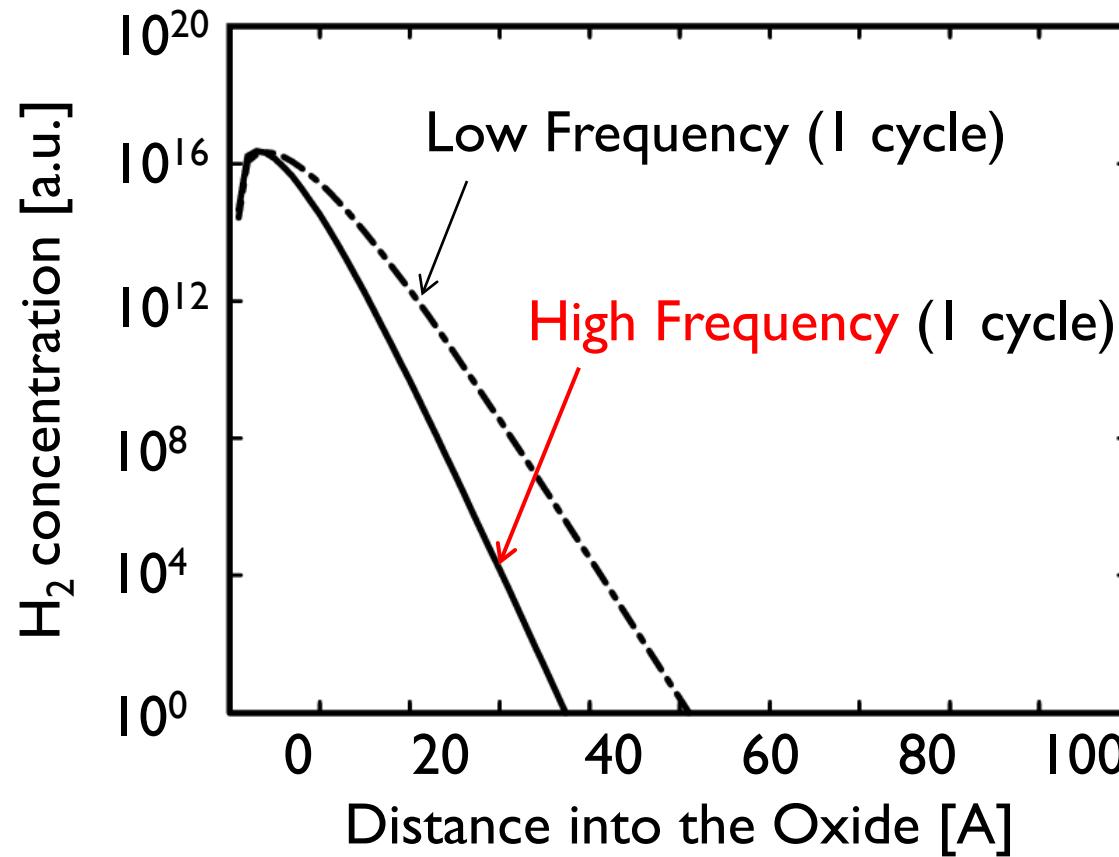
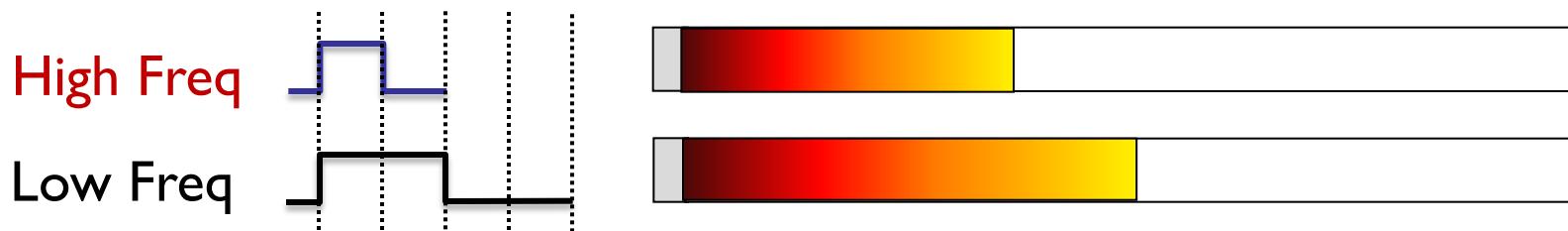
$\xi=0.5$  and  $d=0.5$

$$\frac{N_{IT1}(t)}{N_{IT2}(t)} \equiv \frac{N_{IT,f_1}(k_1 T_1)}{N_{IT,f_2}(k_2 T_2)} = \frac{R_{k1} \times N_{IT}(t_1)}{R_{k2} \times N_{IT}(t_2)} \approx \left(\frac{k_1}{k_2}\right)^n \left(\frac{t_1}{t_2}\right)^n = 1 !$$

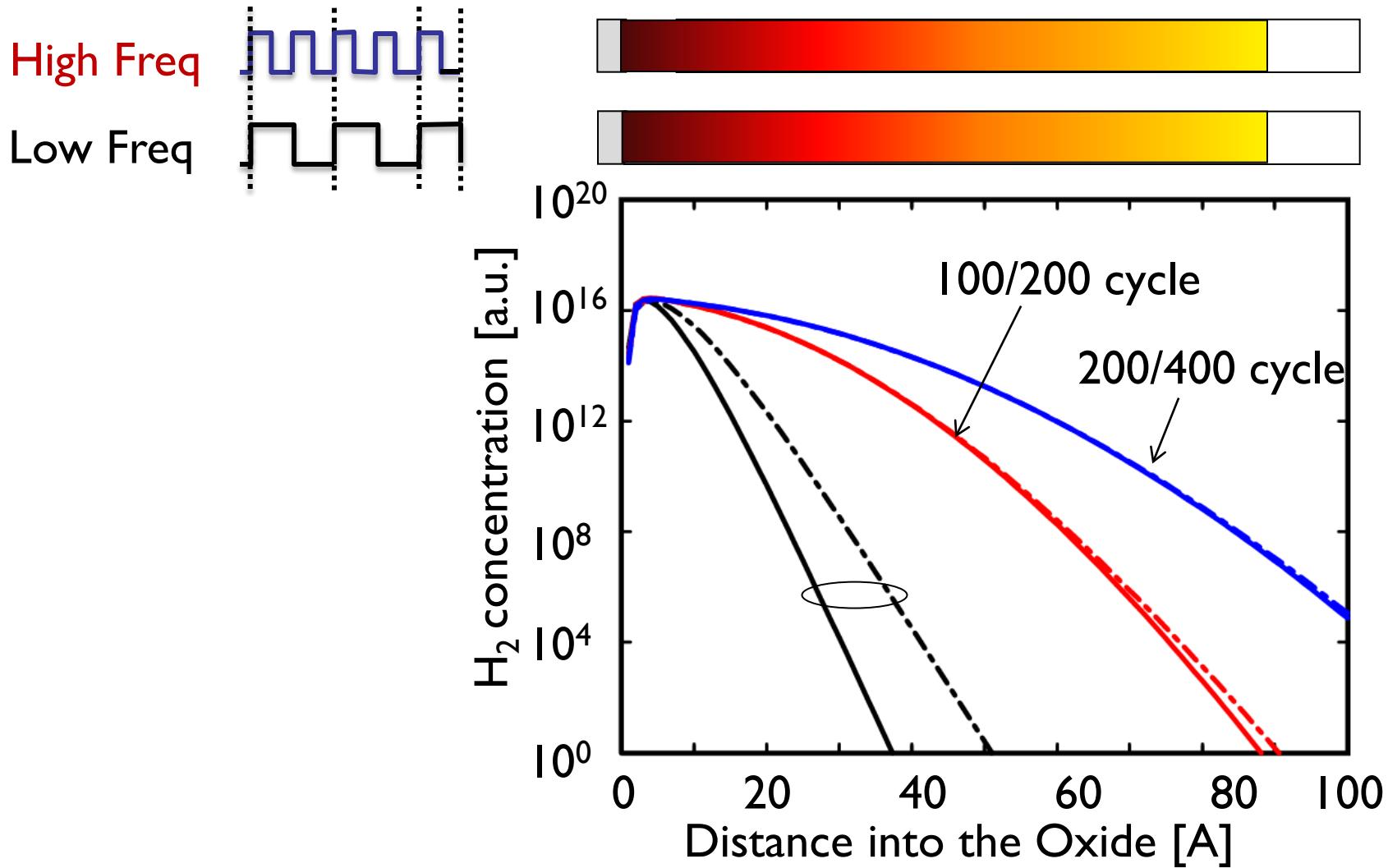


Robust frequency independence regardless of model parameters

# The meaning of frequency independence



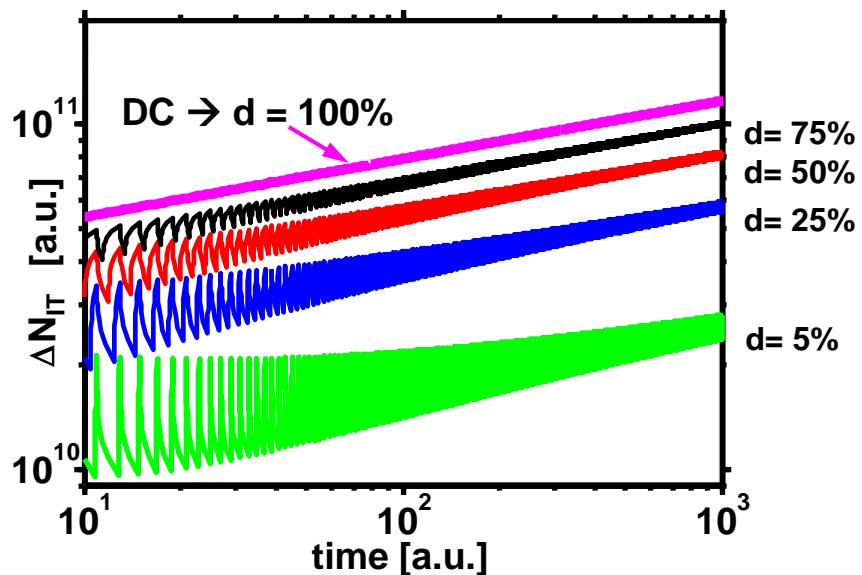
# The meaning of frequency independence



# Outline

1. NBTI stress and relaxation by R-D model
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3. Duty cycle dependence
4. The magic of measurement
5. Conclusions

# Duty cycle dependence due to NBTI



Empirically ...

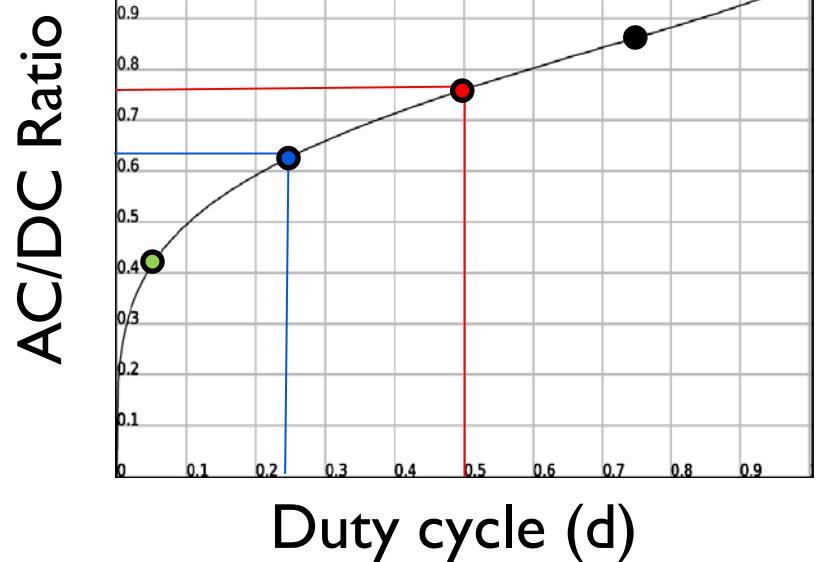
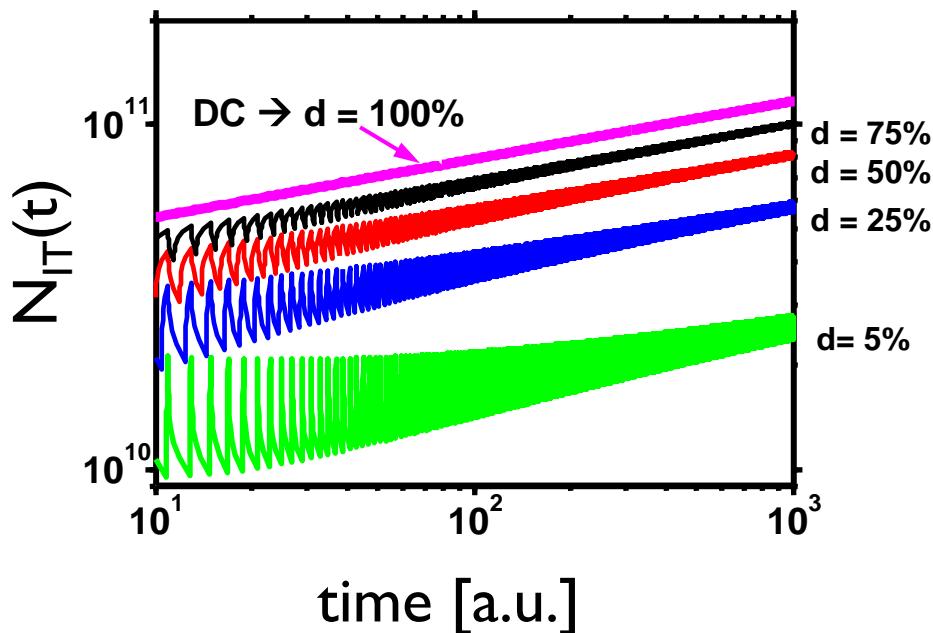
$$N_{IT}(t) = A \times (\alpha \times d^{\frac{2}{3}}) \times t^{\frac{1}{6}}$$

\*A.T.Krishnan et.al., IEDM 2005

# Dependence on Duty Cycle at same freq.

$$R_{2k-1}^{1/n} \approx \frac{1}{1 + \sqrt{\xi(1-d)}} (k-1) \approx \frac{1}{1 + \sqrt{\xi(1-d)}} k \equiv pk$$

$$\frac{N_{IT,AC}((k-1)T + t_H)}{N_{IT,DC}(kT)} = \frac{R_{2k-1} N_{IT}(t_H)^n}{N_{IT,DC}(kT)} = \frac{(pk)^n A(t_H)^n}{A(kT)^n} = \left[ \frac{d}{1 + \sqrt{(1-d)/2}} \right]^n$$

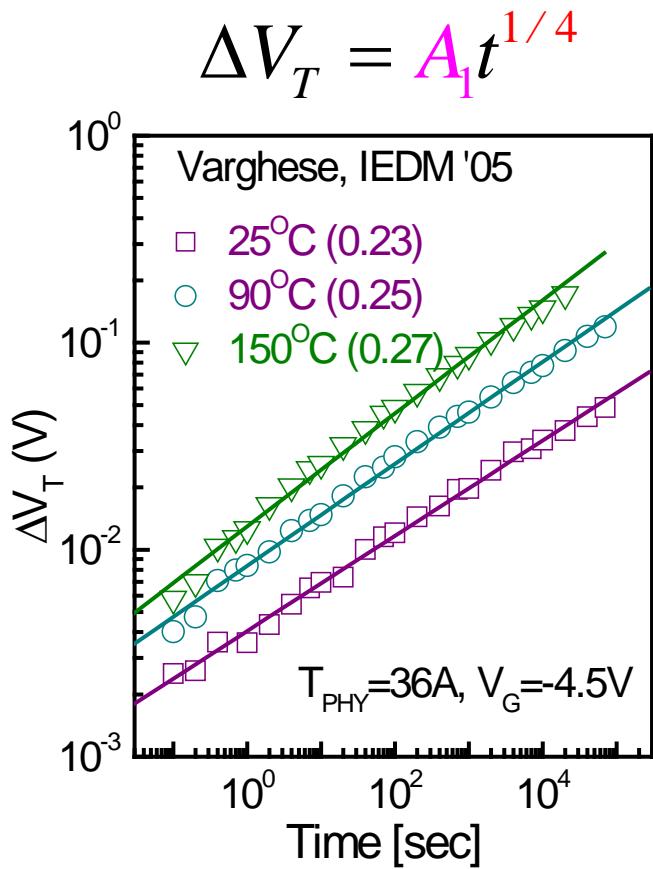


# Outline

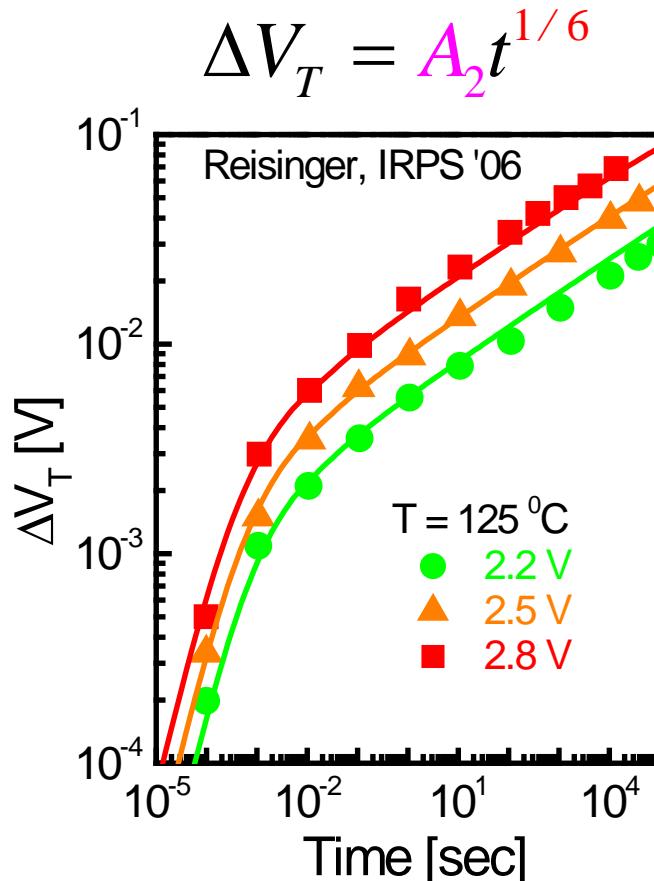
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# An enduring puzzle

Classical measurement



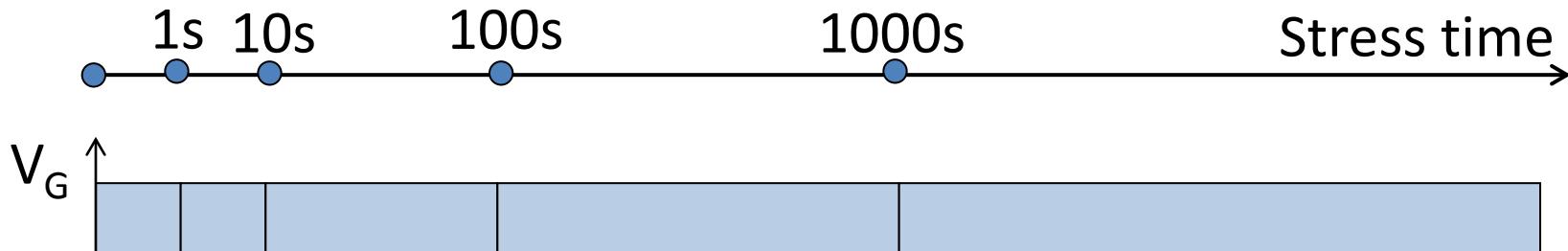
Modern on-the-fly meas.



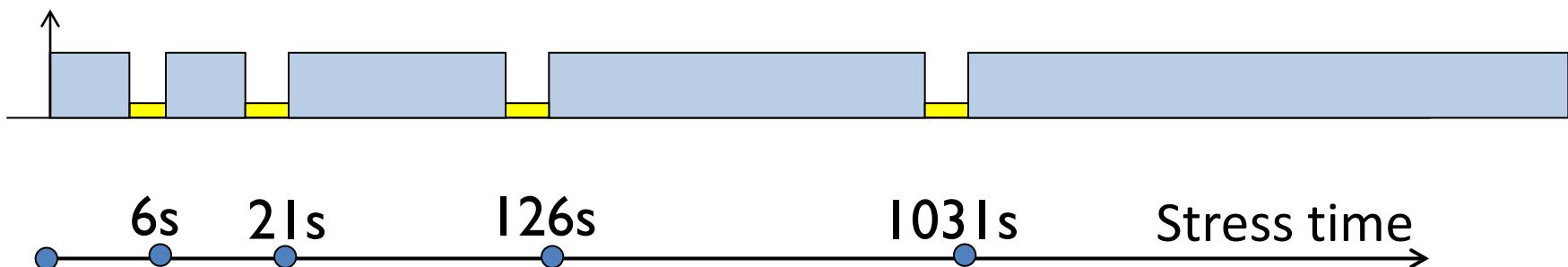
Two different ways of measurement give two different results !

# Measurement modifies the NBTI degradation

What we **think** we do during measurement ...  $r=10$



What we **actually** do during measurement ...



\* 5 sec. measurement window (for example).

S. Rangan, Intel, IEDM 2003.

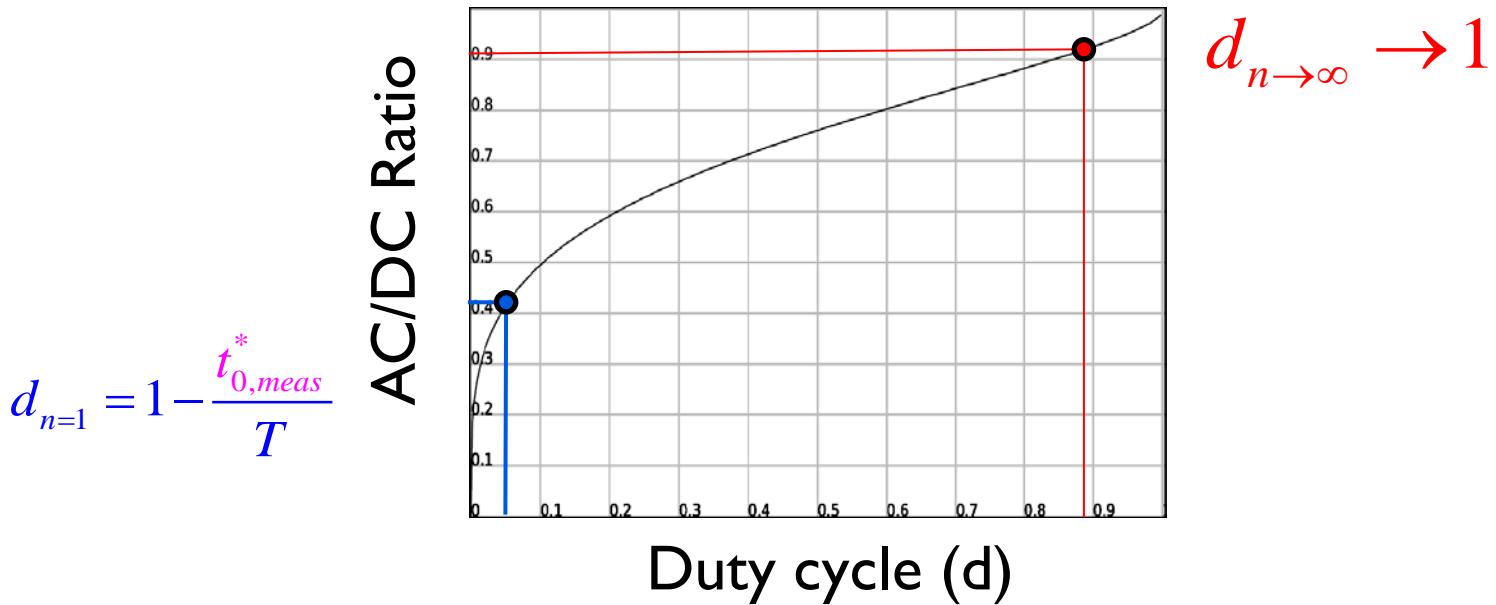
Measurement is like a  
variable frequency AC stress ....

$$d_n = 1 - \frac{nt_{0,\text{meas}}^*}{T(r^n - 1)/(r - 1)}$$

# Variable duty cycle ....

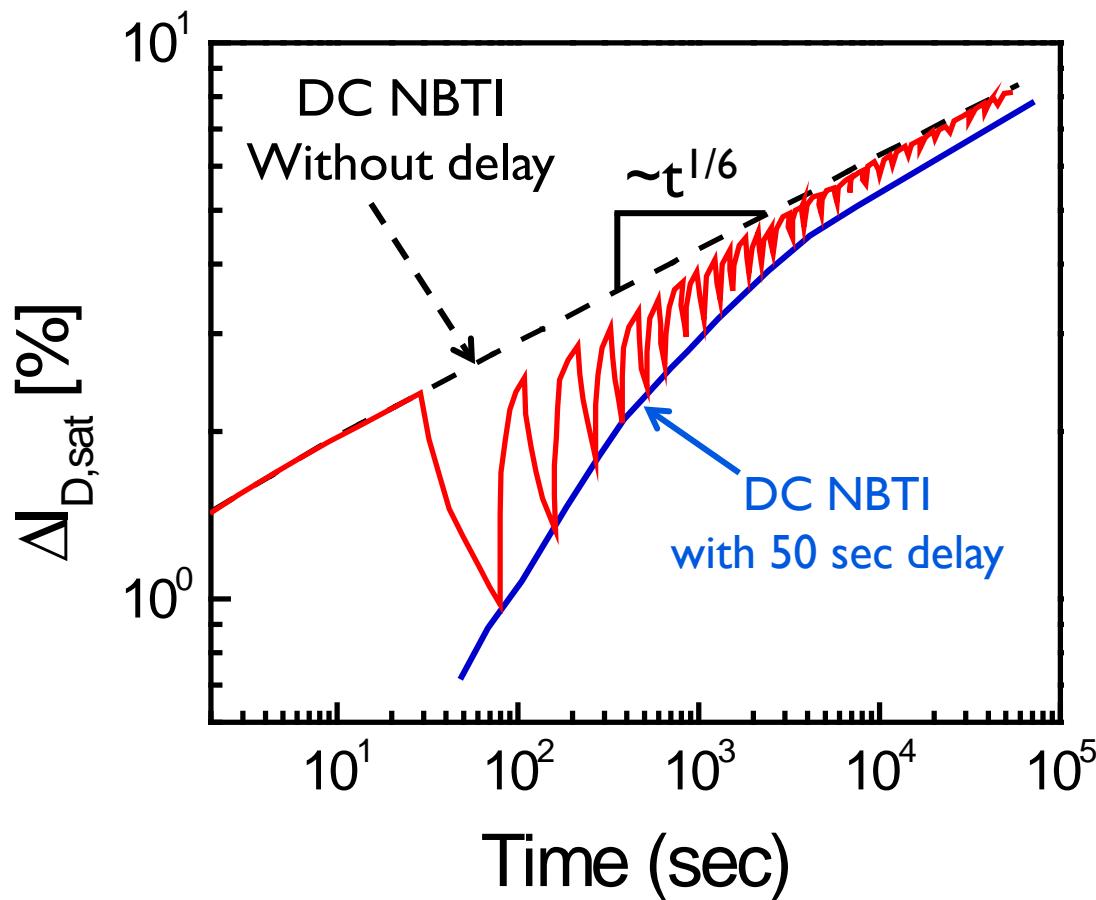
$$\text{Ratio} = \left[ \frac{d_n}{1 + \sqrt{(1-d_n)/2}} \right]^n$$

$$d_n = 1 - \frac{n \times t_{0,\text{meas}}^*}{T(r^n - 1)/(r - 1)}$$



At early stage, measurement related relaxation is significant,  
Because  $d$  is close to 0, later  $d$  approaches 1 and the effect disappears.

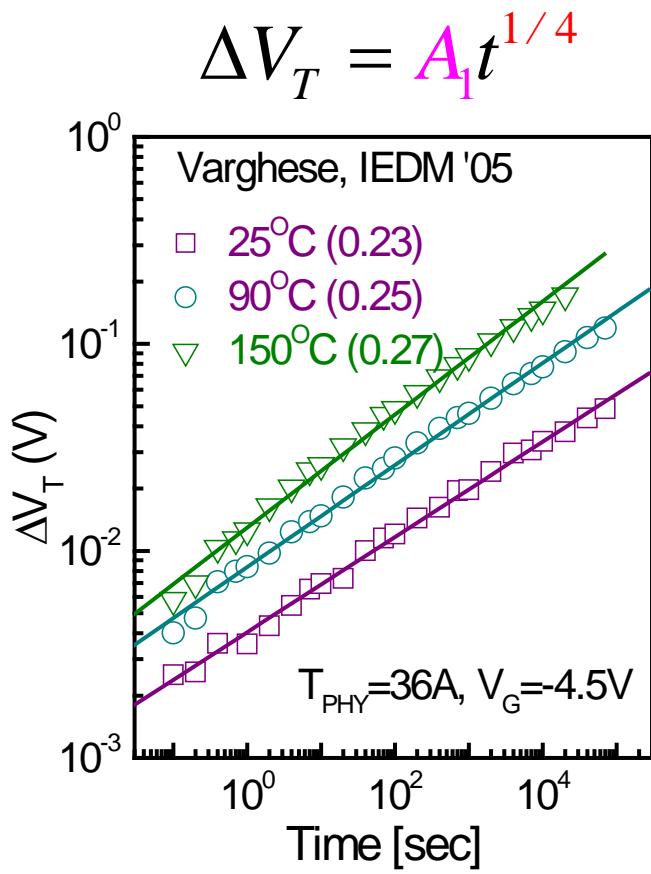
# More measurement & less (!) accuracy



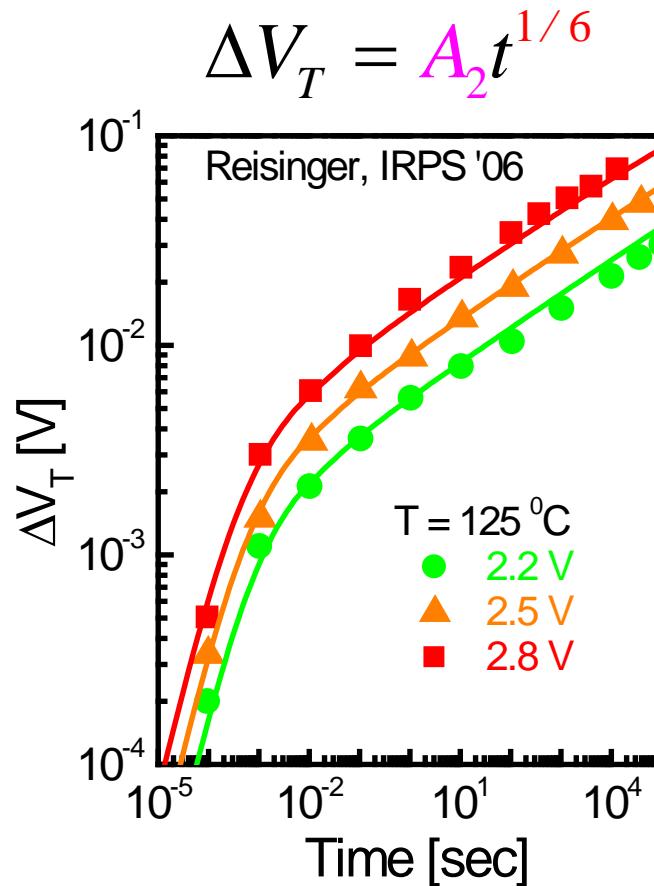
Actually,  $n=0.16$  at all times ( $H_2$  diffusion), measurement delay makes it appear  $n=0.25$  at short times. A 40 year old puzzle finally resolved !

# Resolution of an enduring puzzle

Classical measurement



Modern On-the-fly meas.



Two different ways of measurement give two different results !

# Conclusions

- I. NBTI can heal itself if the stress is turned off. The power-law during the stress phase and relaxation are flip sides of the same coin and both are consequence of R-D model.
2. NBTI is frequency independent – therefore the effect will not unfortunately disappear at high-frequency. *However, this also means that one can study the physics of NBTI at low frequencies and extrapolate to high-frequency.*
3. Duty-cycle dependence is a NBTI feature that allows additional margin for lifetime.
4. Relaxation and hole trapping complicate measurements in nontrivial ways – it may change observed power-laws. Indeed, the process of measurement changes what is being measured.

# Self-Test Questions

1. Why does NBTI recover?
2. What is the difference between recovery of NBTI and hole trapping?
3. If we reduce the duty cycle, can we improve NBTI of CMOS logic?
4. Sometimes ‘less is more’ – what does it mean in NBTI context?
5. Do you think NBTI would be frequency independent if it were not described by power-laws?
6. Is there any limit to the frequency-dependence of NBTI degradation?
7. If NBTI is reduced by a factor of 2 due to AC, what is the net improvement in lifetime (assume  $n=1/6$ ) ? For a 10 yrs AC lifetime, how long a DC test is sufficient for product qualification?

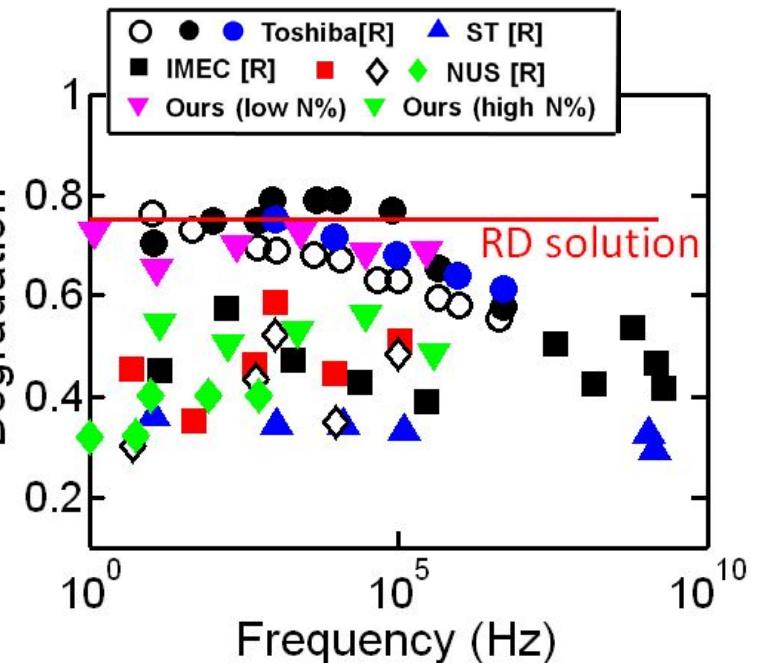
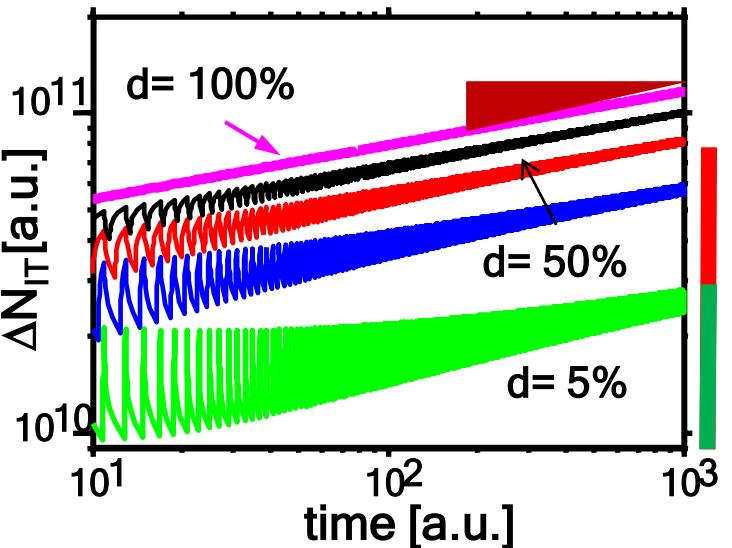
# References

- For the original derivation of first-cycle relaxation and numerical validation of frequency independence, see Alam, IEDM, 2003. Alam/Mahapatra, MR, 2005.
- The analytical formulation of frequency independence is based on "An analytical model for negative bias temperature instability, SV Kumar, CH Kim, SS Sapatnekar Computer-Aided Design, 2006. ICCAD, 2006. The role of hole trapping on AC NBTI degradation is discussed in Mahapatra, IRPS, 2011.
- The role of measurement as a variable frequency AC stress was first pointed out by S. Rangan at IEDM 2003. Universal recovery behavior of negative bias temperature instability [PMOSFETs]

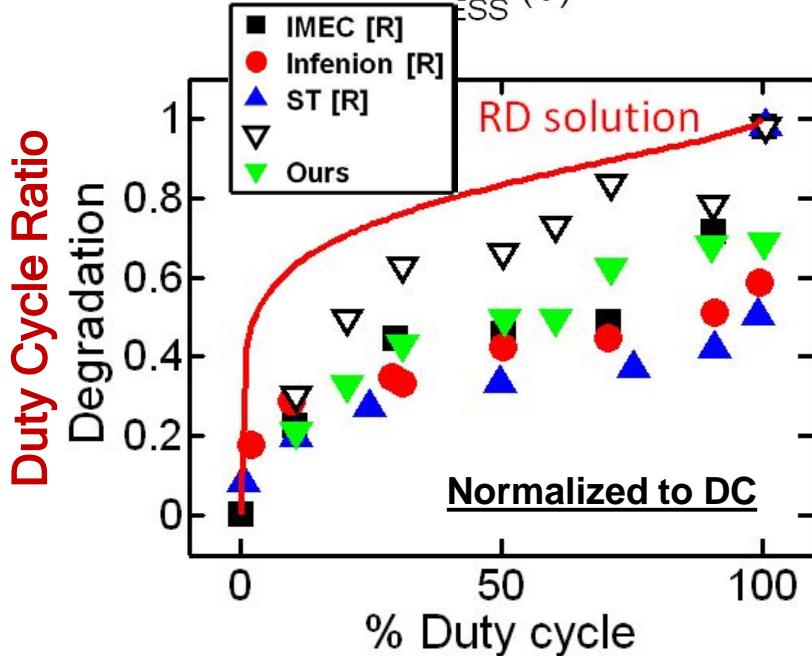
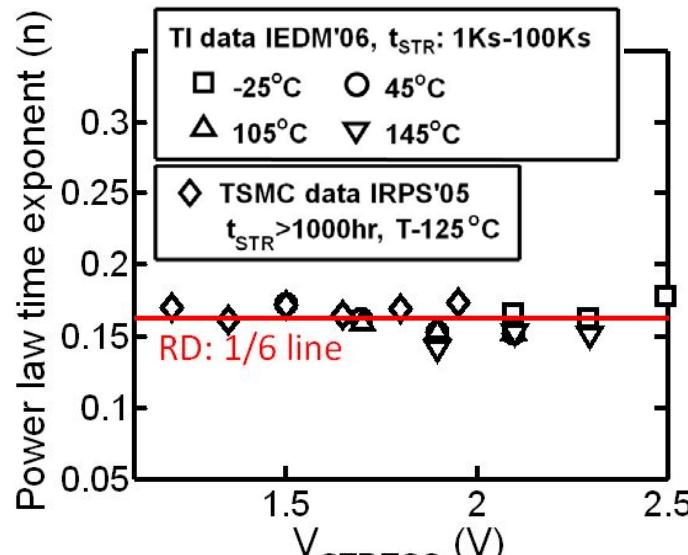
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6. Role of hole trapping (appendix)

$$\Delta V_{IT} \sim A(f, d) \times t^n$$

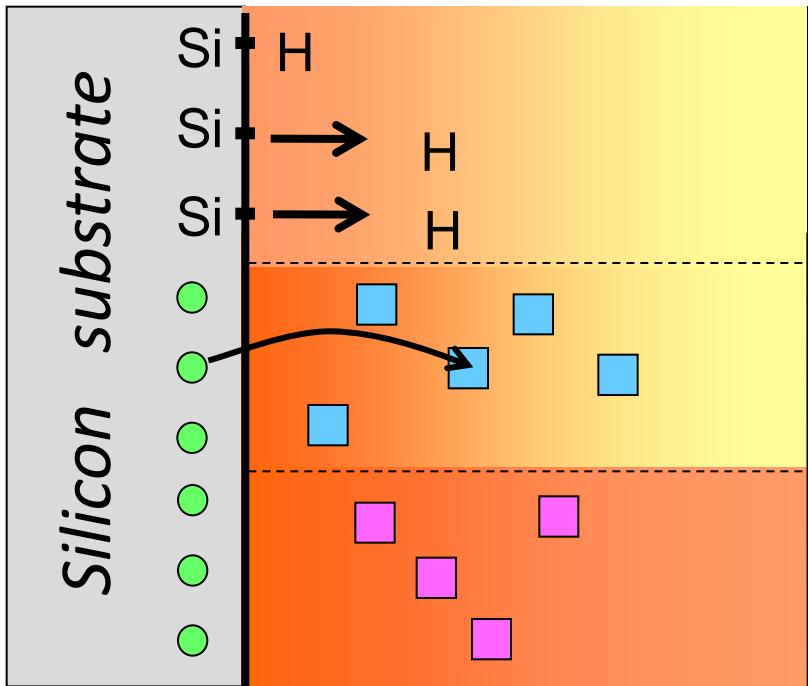


# Industry-Wide Data

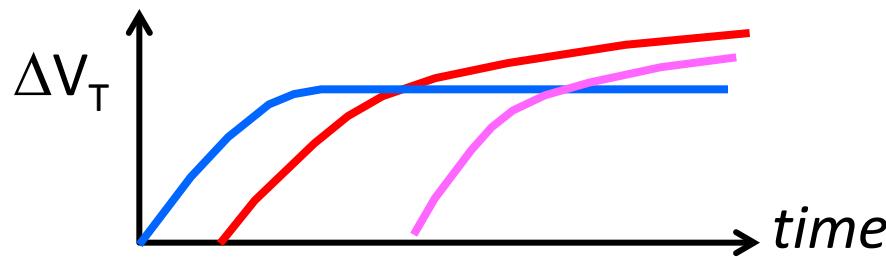


How to interpret the large scatter in AC data ?

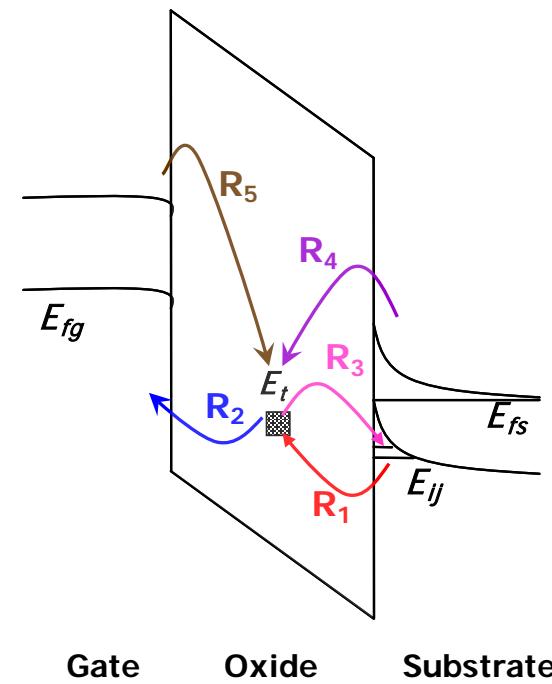
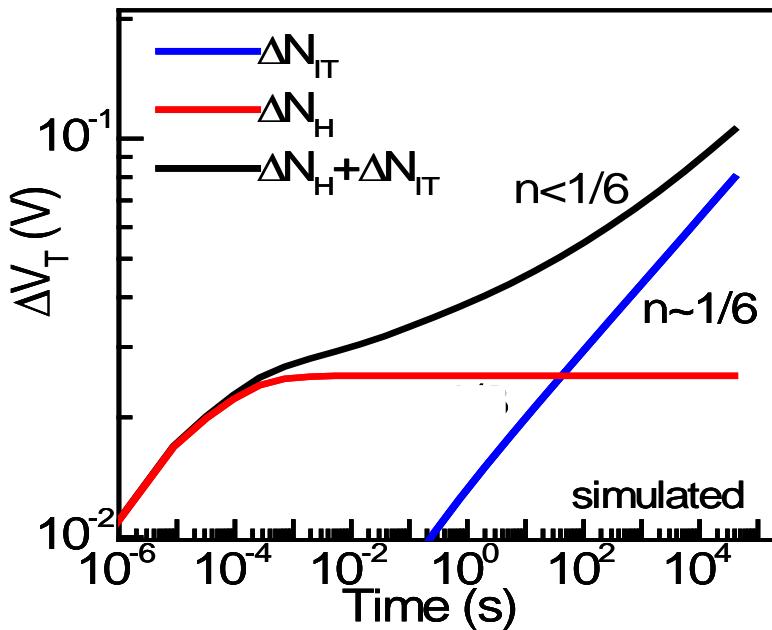
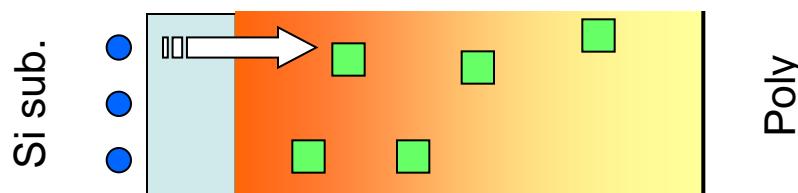
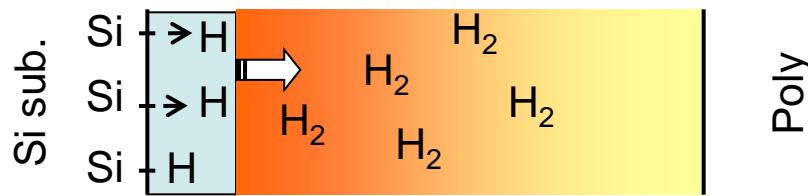
# Three components of VT shift



- 1  $N_{IT}$  interface trap generation  
(NBTI; *low  $N_2$  film*)
- 2 Hole trapping (NBTI, PBTI;  
*High  $N_2$  film, high-k*)
- 3 Bulk trap. Gen.(PBTI; NBTI *high-k*)



# .. plus Hole Trapping: time dependence

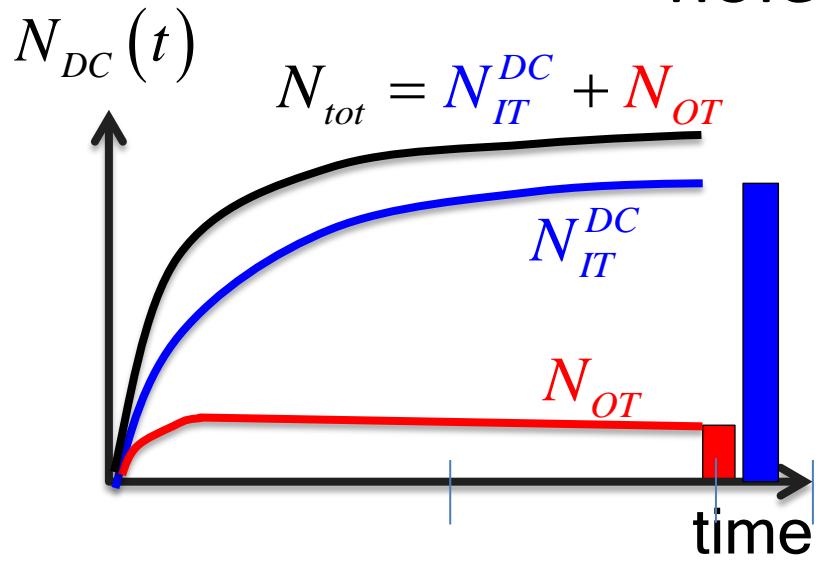


Hole trapping: Saturate quickly,  
weakly T activated, lowers n

Alam ECE-695

$$\frac{df_T}{dt} = (R_1 + R_4 + R_5)(1-f_T) - R_2 f_T - R_3 f_T$$

# Frequency and duty cycle dependence (with hole trapping)

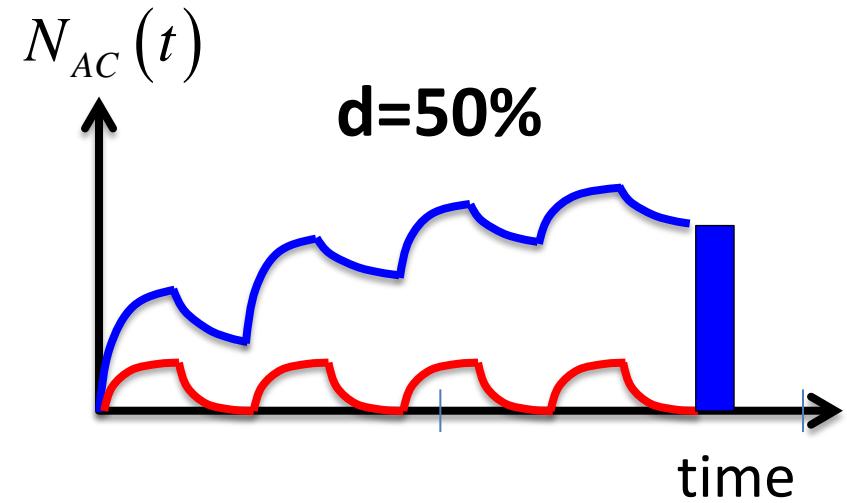
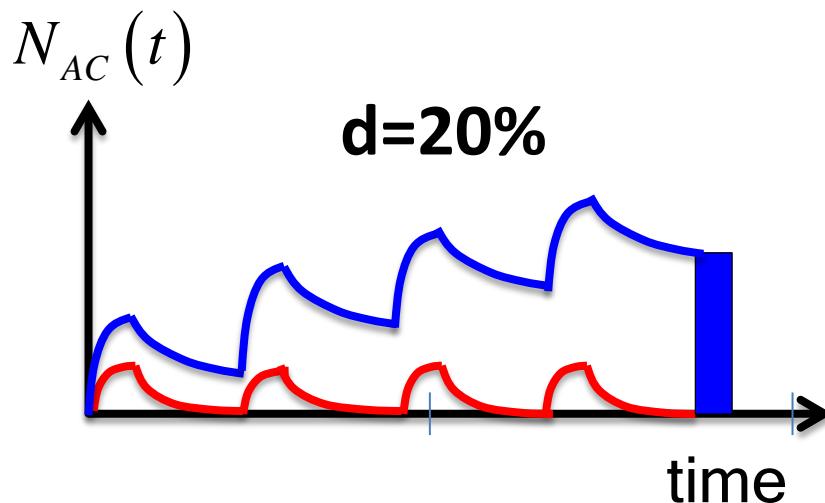


Sample dependent

$$\left( \frac{AC}{DC} \right)_{scattered} = \frac{N_{IT}(f, d; T)}{N_{IT}(0, 1; T) + N_{OT}}$$

Sample independent

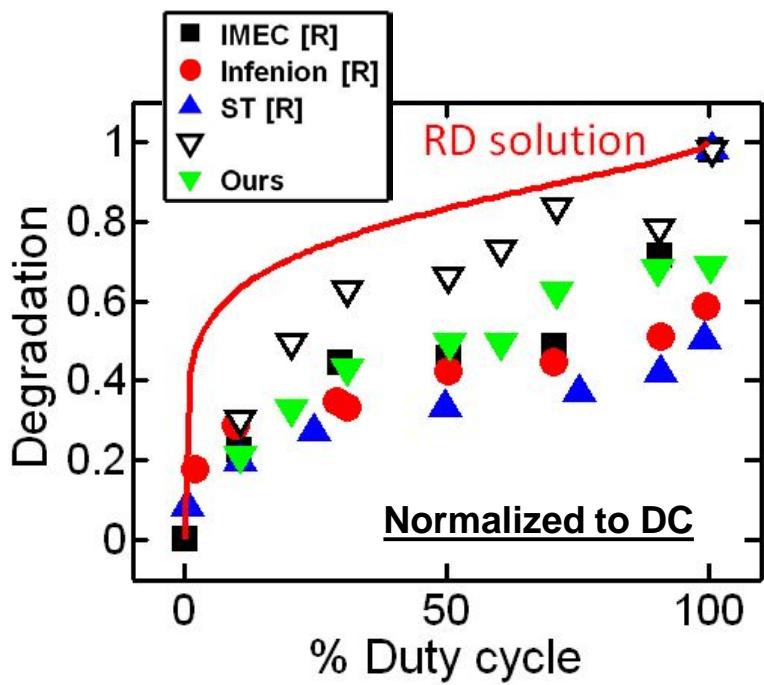
$$\left( \frac{AC}{AC(d=0.5)} \right)_{corrected} \approx \frac{N_{IT}(f, d; T)}{N_{IT}(f, d=0.5; T)}$$



# Universality of duty cycle dependence

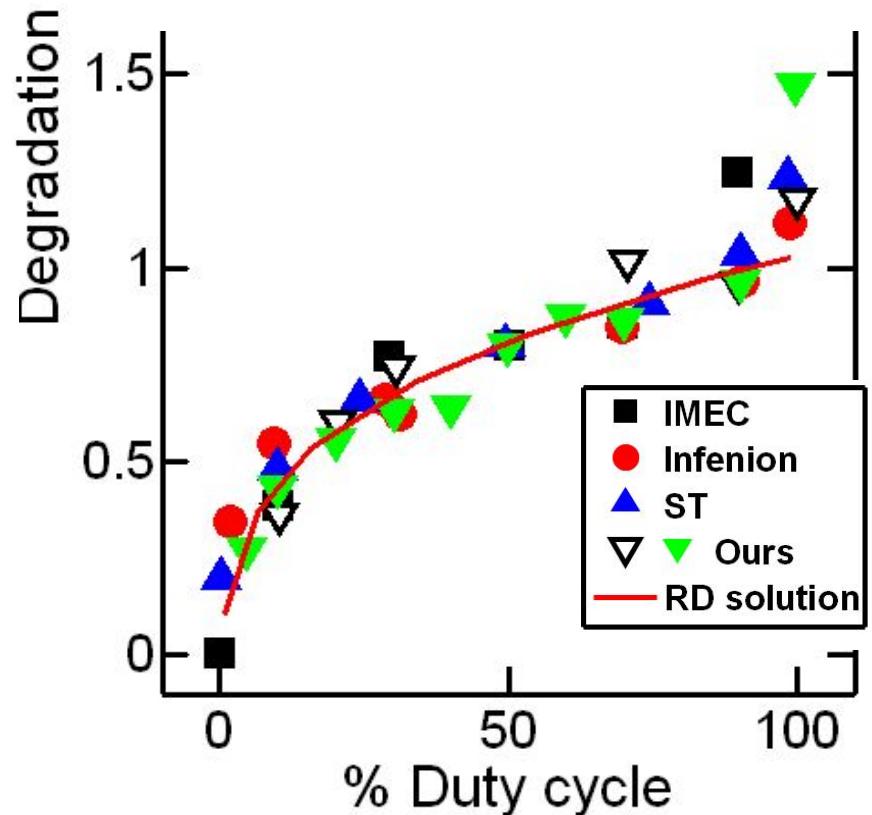
Sample dependent (inappropriate)

$$\left( \frac{AC}{DC} \right)_{\text{scattered}} = \frac{N_{IT}(f, d; T)}{N_{IT}(0, 1; T) + N_{OT}}$$



Sample independent (corrected)

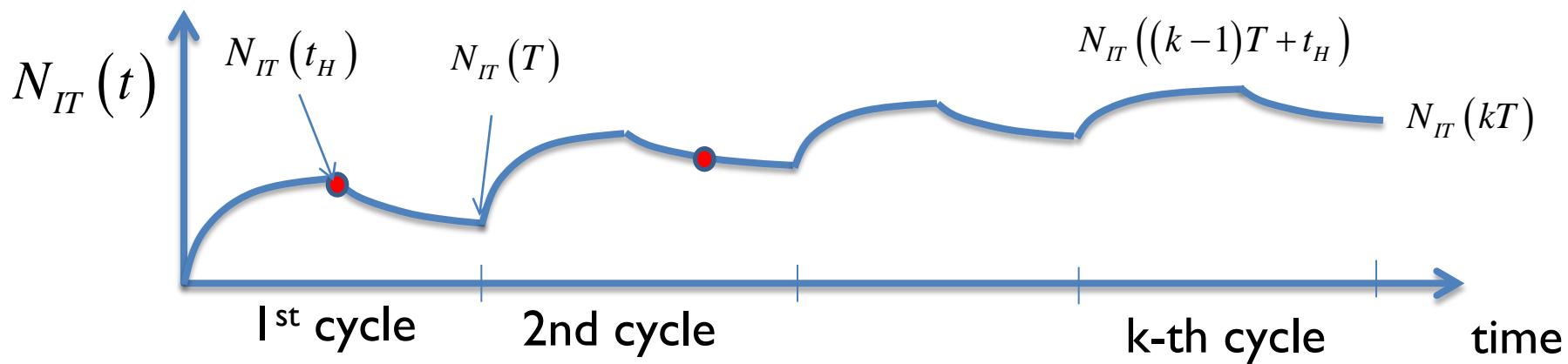
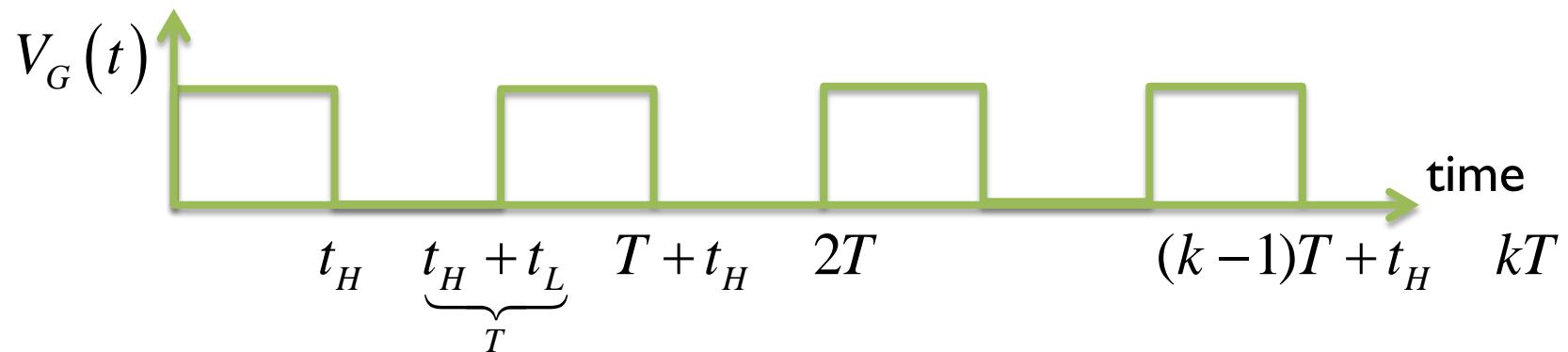
$$\left( \frac{AC}{AC(d = 0.5)} \right)_{\text{corrected}} \approx \frac{N_{IT}(f, d; T)}{N_{IT}(f, d = 0.5; T)}$$



Material independent Universality interpreted by R-D theory ...<sup>38</sup>

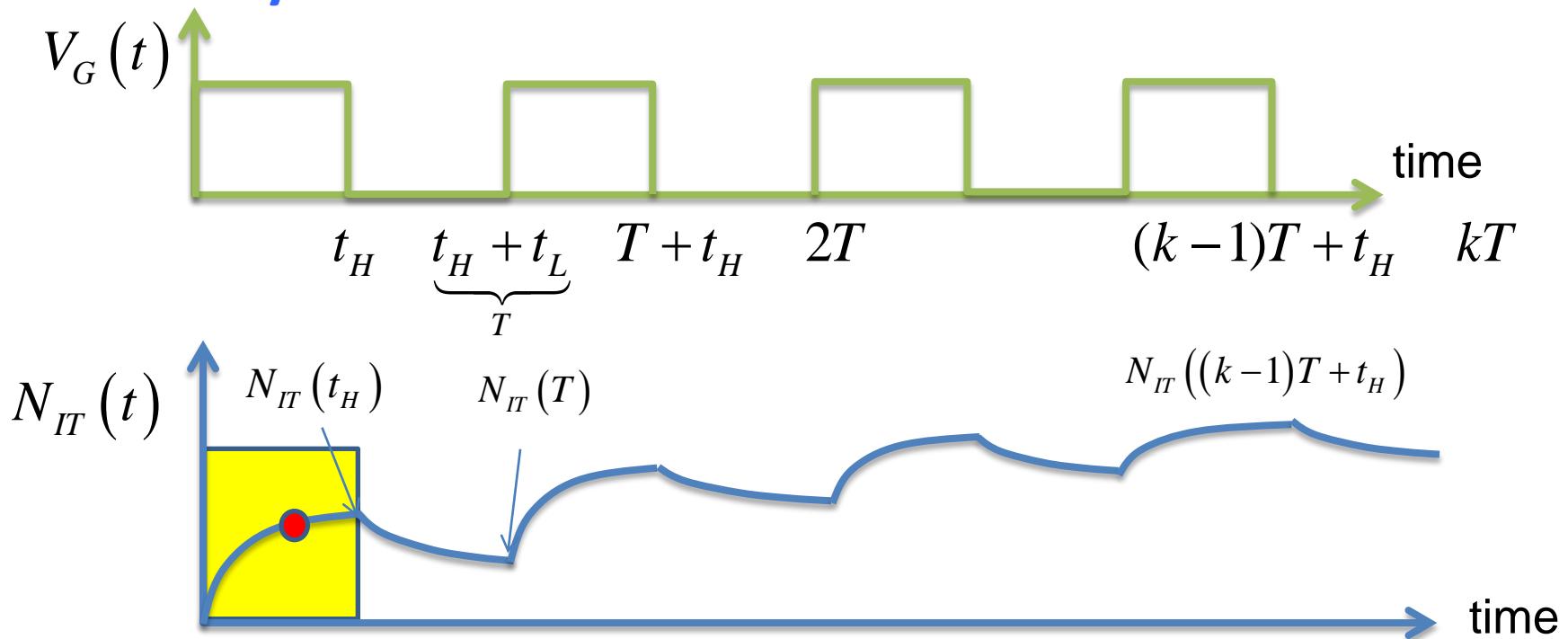
# Notes

# Derivation of Frequency Independence



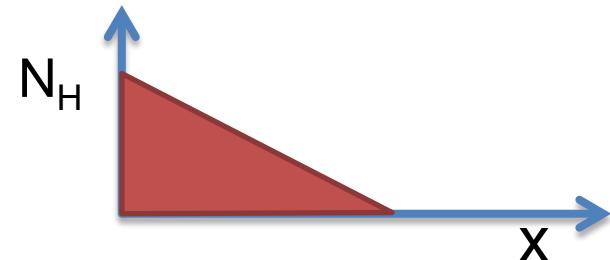
$$R(t) \equiv \frac{N_{IT}(t)}{N_{IT}(t_H)}$$

# Cycle 1: Generation Phase ....



$$N_{IT}(t) = \frac{1}{2} N_H^0 \sqrt{2D_H t} = \left( k_F N_0 / 2k_R \right)^{1/2} \left( 2D_H t \right)^{1/4} = At^{1/4}$$

$$R_1 = R(t_H) \equiv \frac{N_{IT}(t_H)}{N_{IT}(t_H)} = 1$$



# Cycle 1: Relaxation Phase

$$N_{IT}^*(t + t_H) = (1/2)\sqrt{2\xi D_H t} N_H^*(x)$$

$$N_{IT}(t + t_H) = (1/2)\sqrt{2D_H(t + t_H)} N_H^*(x)$$

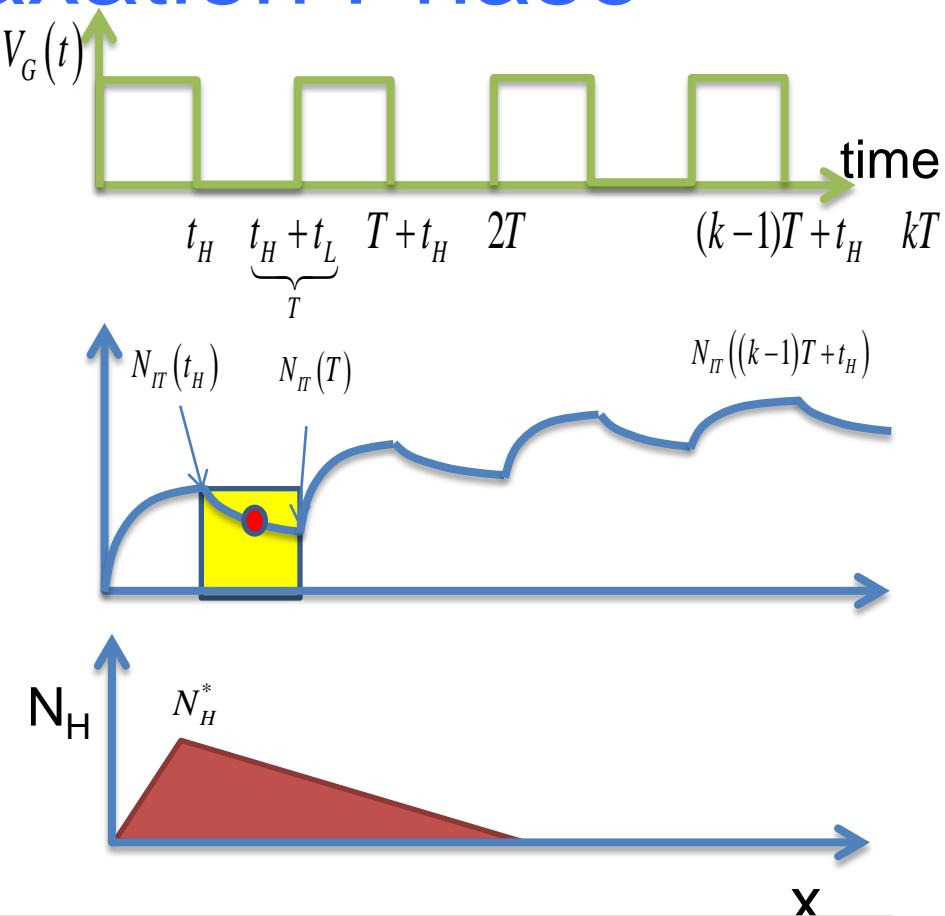
$$N_{IT}(t + t_H) + N_{IT}^*(t + t_H) = N_{IT}(t_H)$$

$$\frac{N_{IT}^*(t + t_H)}{N_{IT}(t + t_H)} = \sqrt{\frac{\xi t}{t + t_H}}$$

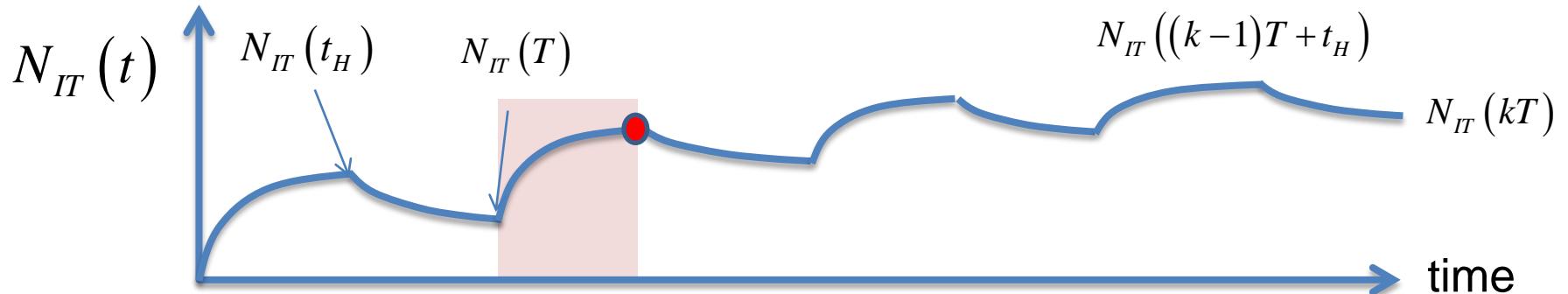
$$N_{IT}(t + t_H) = \frac{N_{IT}(t_H)}{1 + \sqrt{\frac{\xi t}{t + t_H}}}$$

$$R_2 = \frac{N_{IT}(T)}{N_{IT}(t_H)} = \frac{1}{\left(1 + \sqrt{\frac{\xi t_L}{T}}\right)} = \frac{1}{\left(1 + \sqrt{\xi(1-d)}\right)} R_1$$

duty cycle



# Cycle 3: Notion of an Equivalent Time

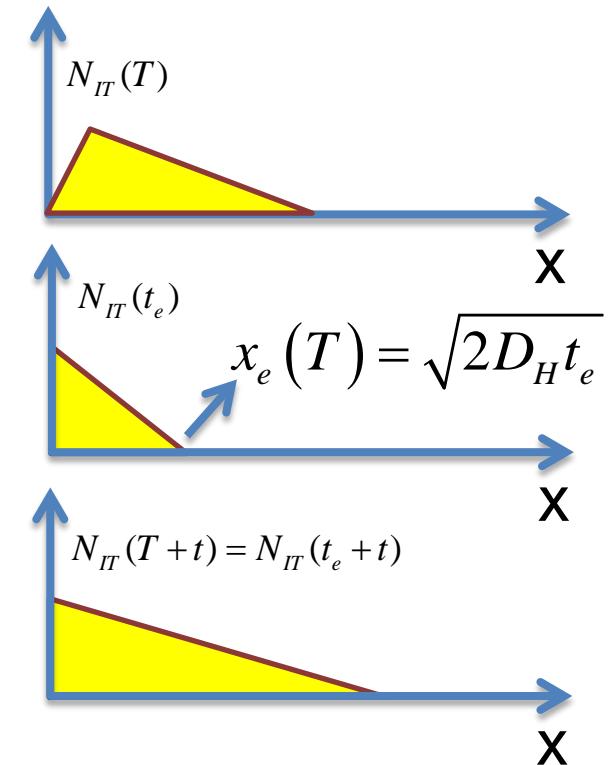


$$R_2 A t_H^n = N_{IT}(T) \equiv A t_e^n \Rightarrow t_e/t_H = (R_2)^{1/n}$$

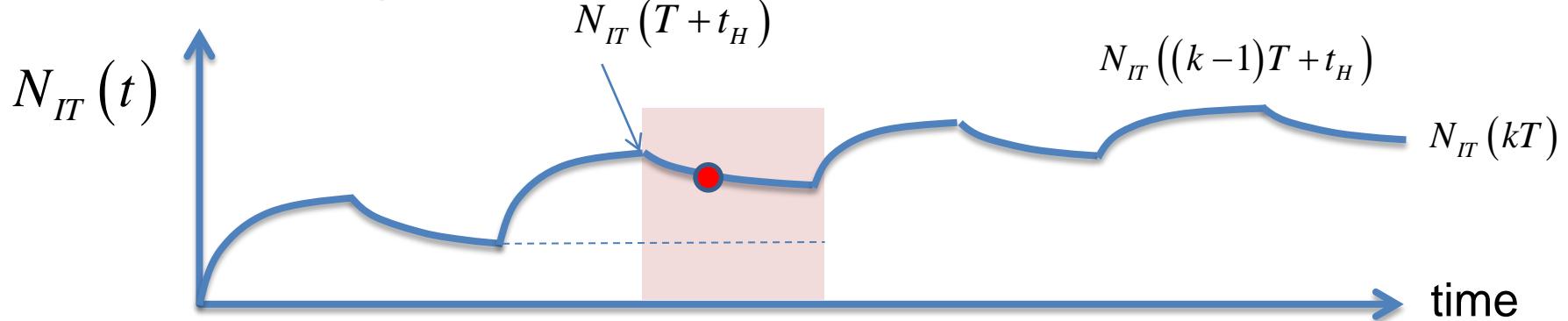
$$N_{IT}(T + t_H) = \frac{1}{2} N_H^{(0)} \sqrt{2 D_H (t_H + t_e)} = A(t_H + t_e)^n$$

$$R_3 = \frac{N_{IT}(T + t_H)}{N_{IT}(t_H)} = \frac{A(t_H + t_e)^n}{A(t_H)^n} = \left(1 + (R_2)^{1/n}\right)^n$$

$$(R_3)^{1/n} = 1 + (R_2)^{1/n} \quad (R_{2k-1})^{1/n} = 1 + (R_{2k-2})^{1/n}$$



# Cycle 2: Relaxation Phase

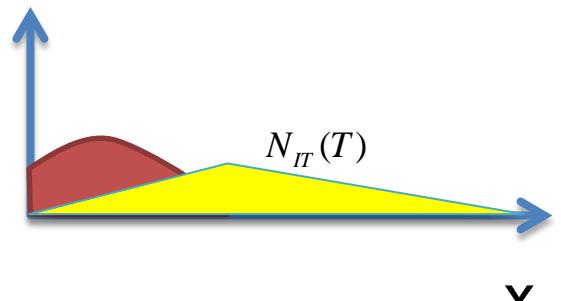
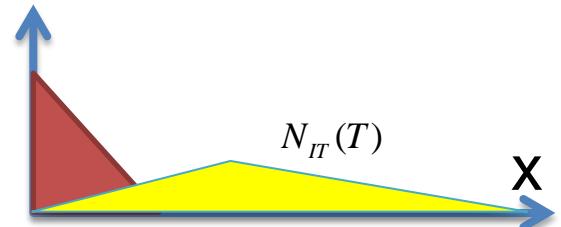


$$N_{IT}^*(T + t_H + t) = 1/2 N_H^* \sqrt{\xi 2Dt}$$

$$N_{IT}(T + t_H + t) - N_{IT}(T) = 1/2 N_H^* \sqrt{2D_H(t_H + t)}$$

Eliminating  $N_H^*$  and for  $t = t_L$

& using  $N_{IT}^*(2T) + N_{IT}(2T) = N_{IT}(T + t_H)$



$$N_{IT}(2T) = \frac{N_{IT}(T + t_H)}{1 + \sqrt{\xi(1-d)}} + \frac{\sqrt{\xi(1-d)}}{1 + \sqrt{\xi(1-d)}} N_{IT}(T)$$

## Cycle 2: Relaxation Phase....

$$\begin{aligned} R_4 &= \frac{N_{IT}(2T)}{N_{IT}(t_H)} = \frac{1}{1 + \sqrt{\xi(1-d)}} \frac{N_{IT}(T + t_H)}{N_{IT}(t_H)} + \frac{\sqrt{\xi(1-d)}}{1 + \sqrt{\xi(1-d)}} \frac{N_{IT}(T)}{N_{IT}(t_H)} \\ &= \frac{1}{1 + \sqrt{\xi(1-d)}} R_3 + \frac{\sqrt{\xi(1-d)}}{1 + \sqrt{\xi(1-d)}} R_2 \end{aligned}$$

$$R_{2k} = \frac{1}{1 + \sqrt{\xi(1-d)}} R_{2k-1} + \frac{\sqrt{\xi(1-d)}}{1 + \sqrt{\xi(1-d)}} R_{2k-2}$$

# Recursion for Odd Numbered Cycles

$$(R_{2k-1})^{1/n} = 1 + (R_{2k-2})^{1/n}$$

$$R_{2k} = \frac{1}{1 + \sqrt{\xi(1-d)}} R_{2k-1} + \frac{\sqrt{\xi(1-d)}}{1 + \sqrt{\xi(1-d)}} R_{2k-2}$$

$$R_{2k-4} = (R_{2k-3}^{1/n} - 1)^n$$

$$R_{2k-1}^{1/n} = 1 + \left[ \frac{1}{1 + \sqrt{\xi(1-d)}} R_{2k-3} + \frac{\sqrt{\xi(1-d)}}{1 + \sqrt{\xi(1-d)}} (R_{2k-3}^{1/n} - 1)^n \right]^{1/n}$$

$$= 1 + R_{2k-3}^{1/n} \left[ \frac{1}{1 + \sqrt{\xi(1-d)}} + \frac{\sqrt{\xi(1-d)}}{1 + \sqrt{\xi(1-d)}} \left( 1 - \frac{1}{R_{2k-3}^{1/n}} \right)^n \right]^{1/n}$$

$$R_{2k-1}^{1/n} \approx 1 + R_{2k-3}^{1/n} \left[ 1 - \frac{n\sqrt{\xi(1-d)}}{1 + \sqrt{\xi(1-d)}} \frac{1}{R_{2k-3}^{1/n}} \right]^{1/n} \approx \frac{1}{1 + \sqrt{\xi(1-d)}} + R_{2k-3}^{1/n}$$

# Recursion for Odd Numbered Cycles ...

$$R_{2k-1}^{1/n} \approx \frac{1}{1 + \sqrt{\xi(1-d)}} (k-1) + R_1^{1/n} \approx \frac{1}{1 + \sqrt{\xi(1-d)}} (k-1)$$