# An Analytical Model for Negative Bias Temperature Instability (NBTI)

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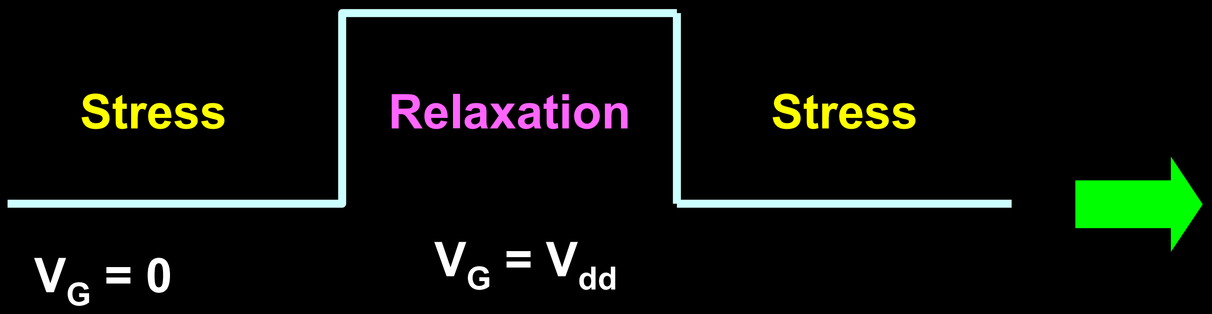
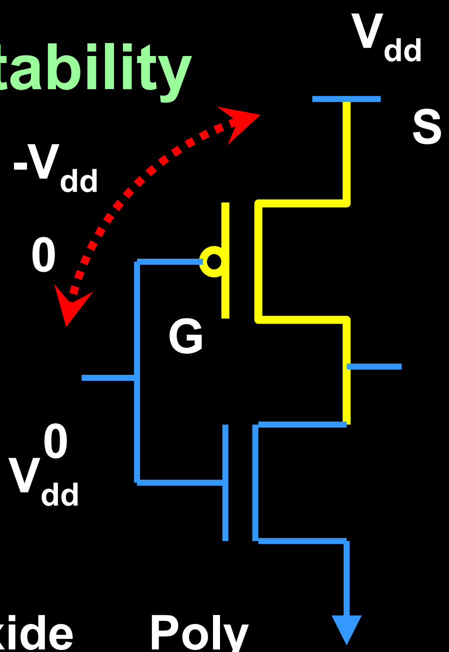
# Outline

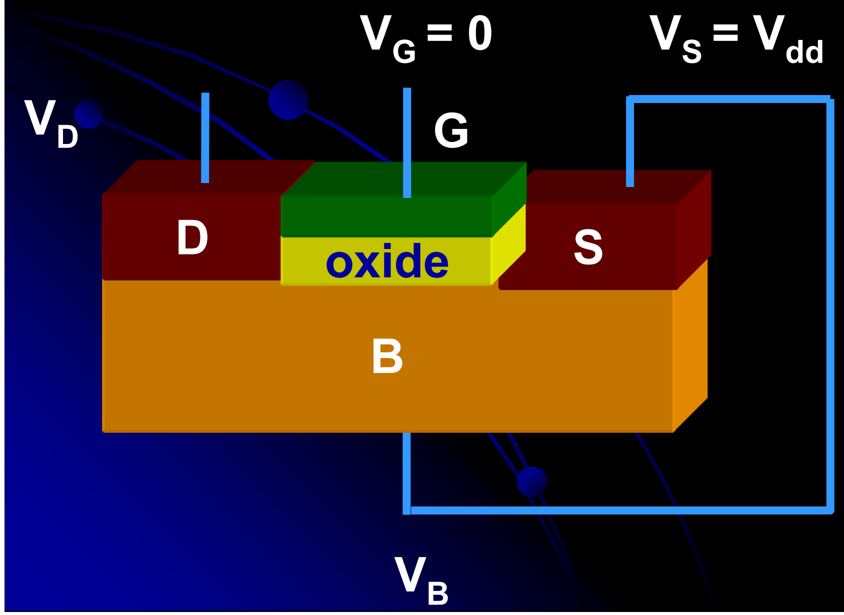
- NBTI Overview
- Reaction-Diffusion (R-D) Model
- Our Analytical NBTI Model
- Frequency Independence
- Delay Estimation using NBTI Model

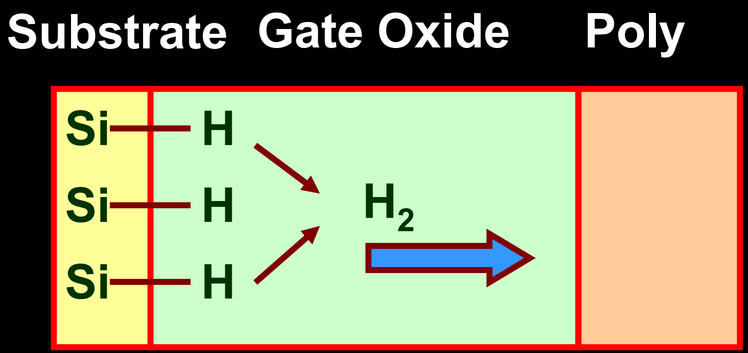
# An Overview of NBTI

## Negative Bias Temperature Instability







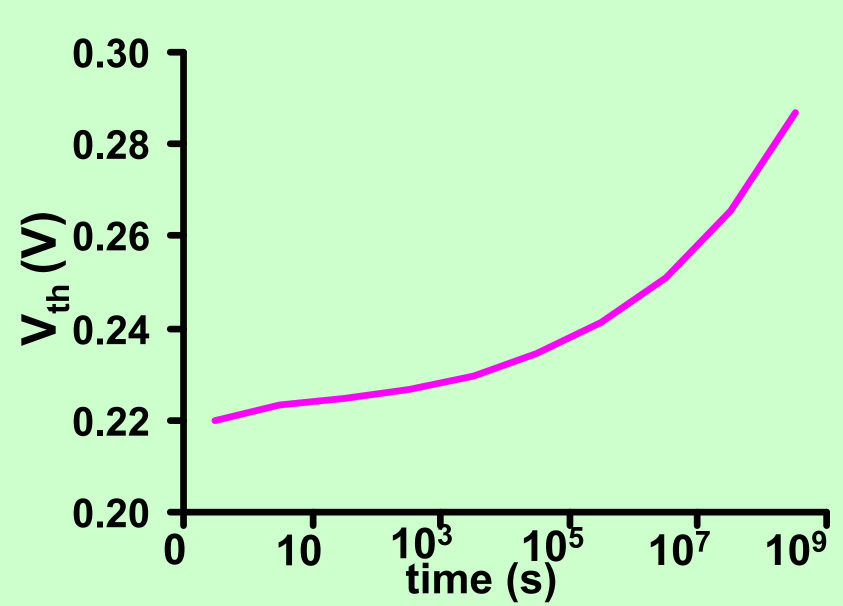


$$SiH + h^+ \rightarrow Si^+ + H$$

$$H + H \rightarrow H_2$$

# NBTI Effect

- 25-30% degradation in PMOS $V_{th}$
  - Effect increases with technology scaling
- Around 10% delay degradation
- Effect worsens if thermal nitrides used instead of plasma nitrides in gate-oxide
  - Up to 25% delay degradation reported



**PMOS $V_{th}$ versus time for a 65nm PMOS transistor**

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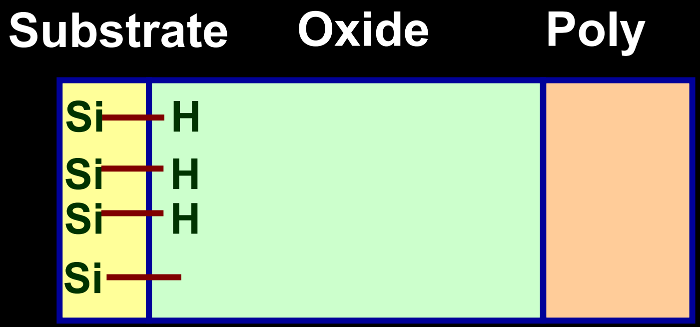
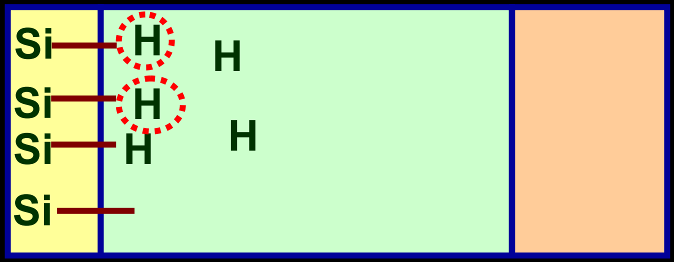
# Reaction Diffusion (R-D) Model

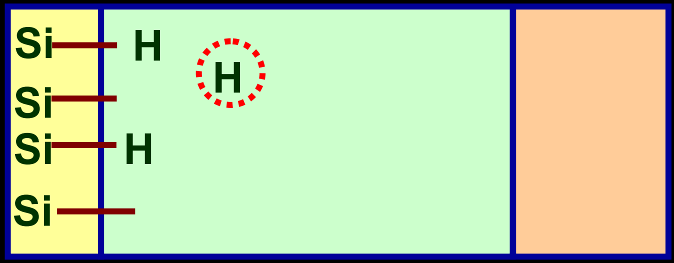


Initial Si-H concentration = $N_0$

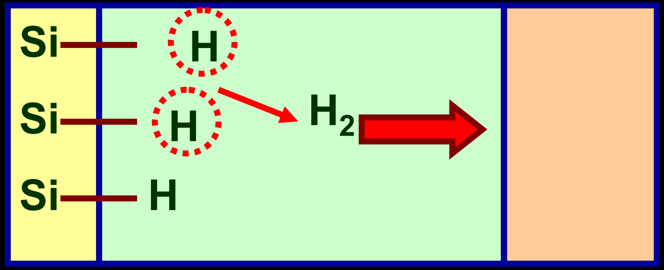
$$SiH + h^+ \underset{k_r}{\overset{k_f}{\rightleftharpoons}} Si^+ + H$$



Forward Reaction Rate = $k_f$



Reverse Reaction Rate = $k_r$



Diffusion of $H_2$ into oxide

# NBTI Modeling: R-D model

- Reaction-Diffusion (R-D) model to determine the number of interface traps. [Alam-IEDM'03]

**Reaction Phase**

**Rate of diffusion of hydrogen**

$$\mathrm{SiH} + h^{+} \underset{k_r}{\overset{k_f}{\rightleftharpoons}} \mathrm{Si}^{+} + \mathrm{H}$$

$$\frac{dN_{IT}}{dt} = k_f\left[N_0 - N_{IT}\right] - k_r N_0 N_H$$

**Diffusion Phase**

**Rate of diffusion of hydrogen**

$$\frac{dN_{H_2}}{dt} = D^2 \frac{dN_{H_2}}{dx^2}$$

- R-D model solved to obtain analytical equations for a stress phase followed by a relaxation phase
- Numerical solution thenceforth

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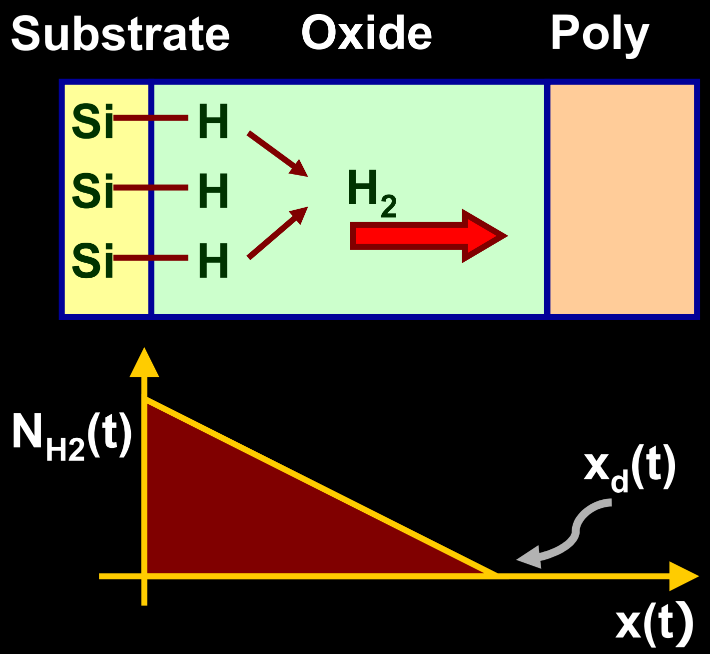
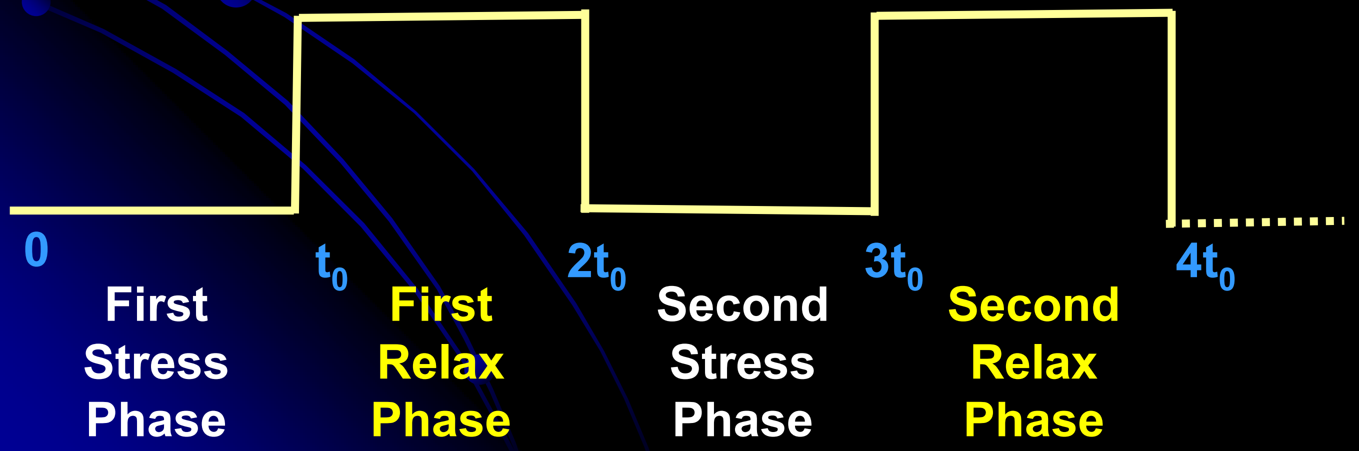
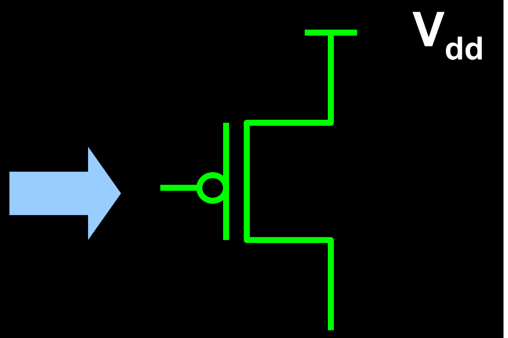
# Approach

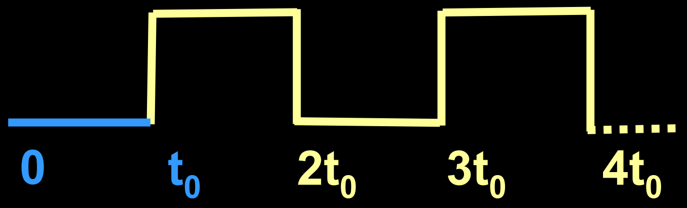
- Use R-D model
  - Mechanism is diffusion limited
  - Track the profile of $H_2$ diffusion
- Model shown for the special case of square waveforms
  - Equal periods of stress and recovery







# First Stress Phase



$N_{H2}$ is a linear function in x

$$x_d(t) = \sqrt{2Dt}$$

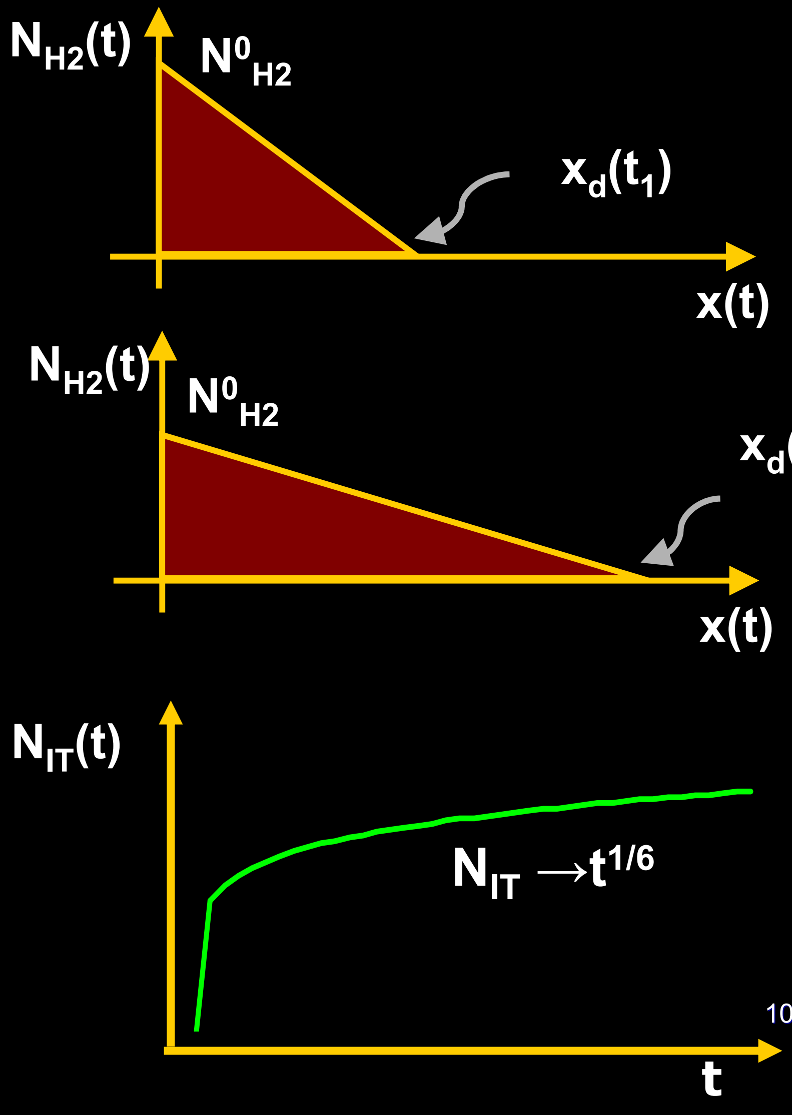
$N_{IT}$ = Number of H atoms

$$N_{IT}(t) \propto N^0_{H_2} x_d(t)$$ es

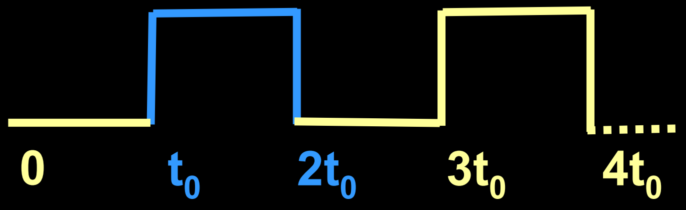
= ½ Area of the triangle

N ne

$$N_{IT}(t) = Ct^{\frac{1}{6}}$$



# First Relaxation Phase

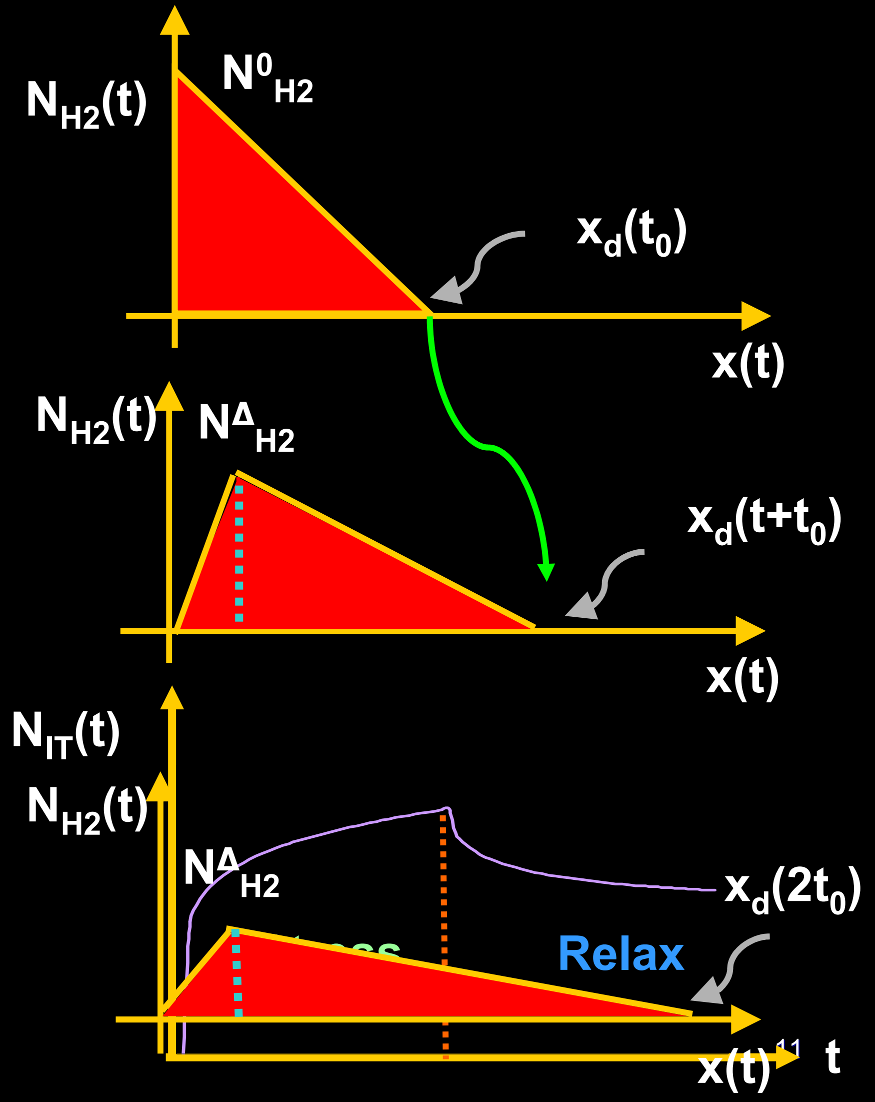


**Annealing of traps due to re-formation of bonds**

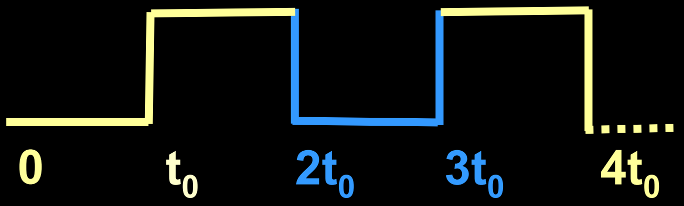
**Si-H bond re-formation highest close to the interface**

$$x_d(t+t_0)=\sqrt{2D(t+t_0)}$$

$$N_{IT}(t_0+t)=\frac{N_{IT}(t_0)}{1+f(t,t_0)}$$



# Second Stress Phase



Existing front diffuses beyond $x(2t_0)$

New front begins at x=0 for time > $2t_0$

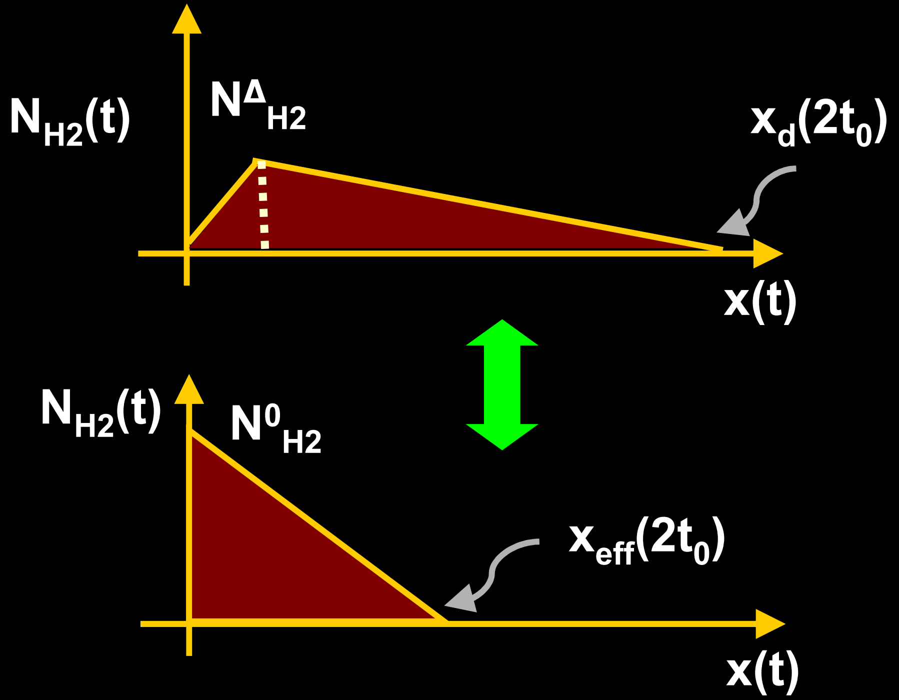
Combine into single “effective” front

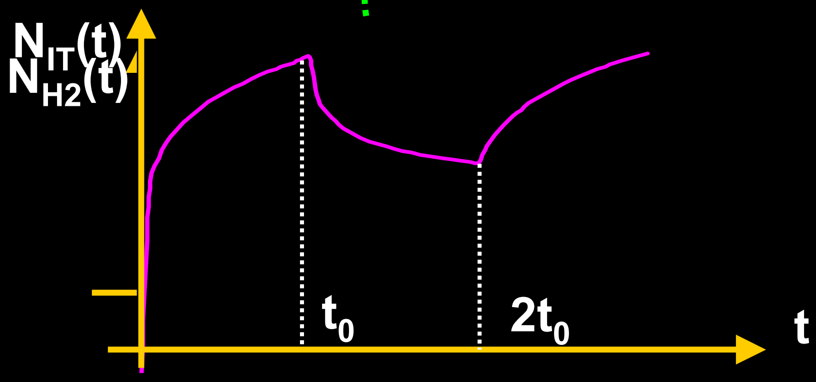
**Boundary Conditions:**

Equate area at time $2t_0$ and solve for $x_{eff}(2t_0)$

$\chi$ Diffusion continues beyond $x_{eff}(2t_0)$ for time > $2t_0$ $)^2$

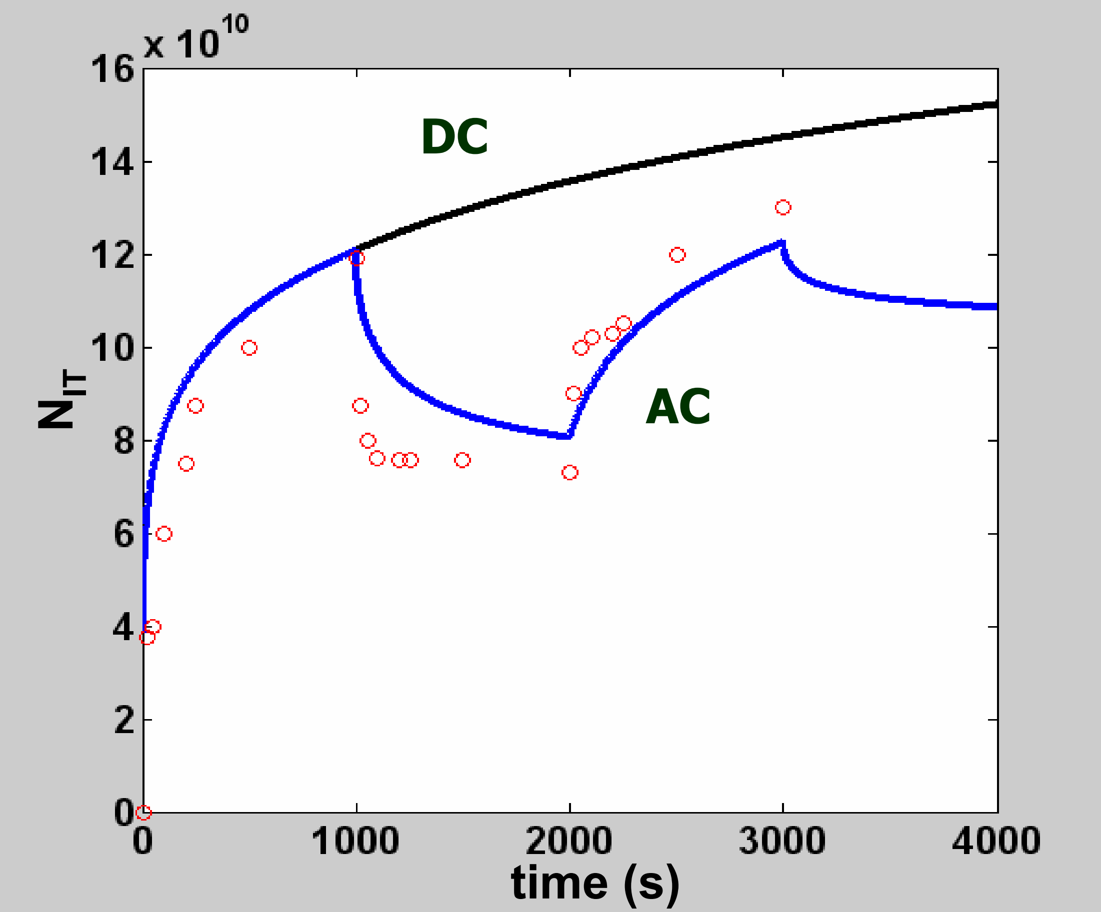
$$N_{IT}(2t_0+t)=C\left[\frac{t}{t_0}+\left(\frac{2}{3}\right)^6\right]^{\frac{1}{6}}$$

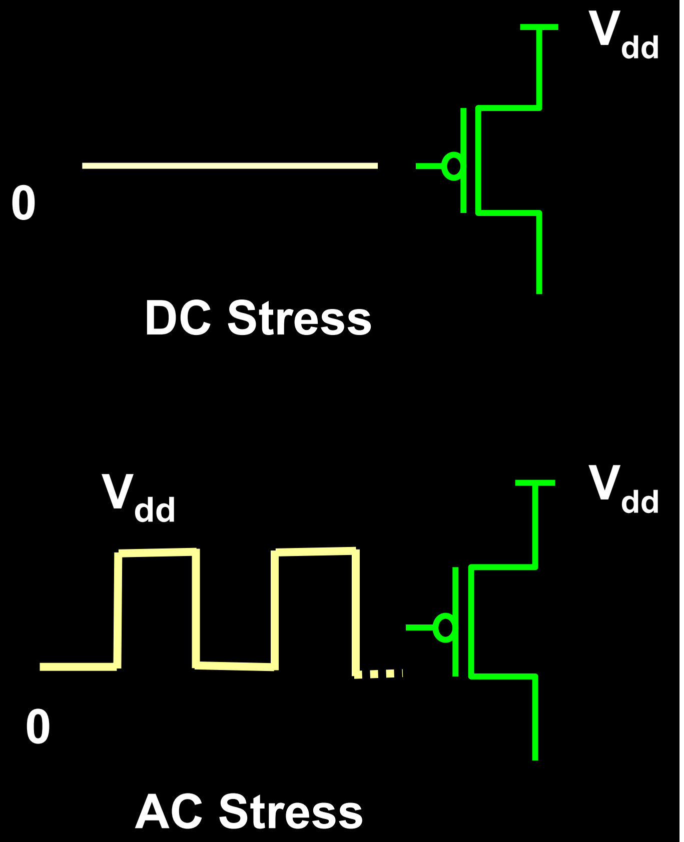




$t_0)$

# Comparison with Experimental Data

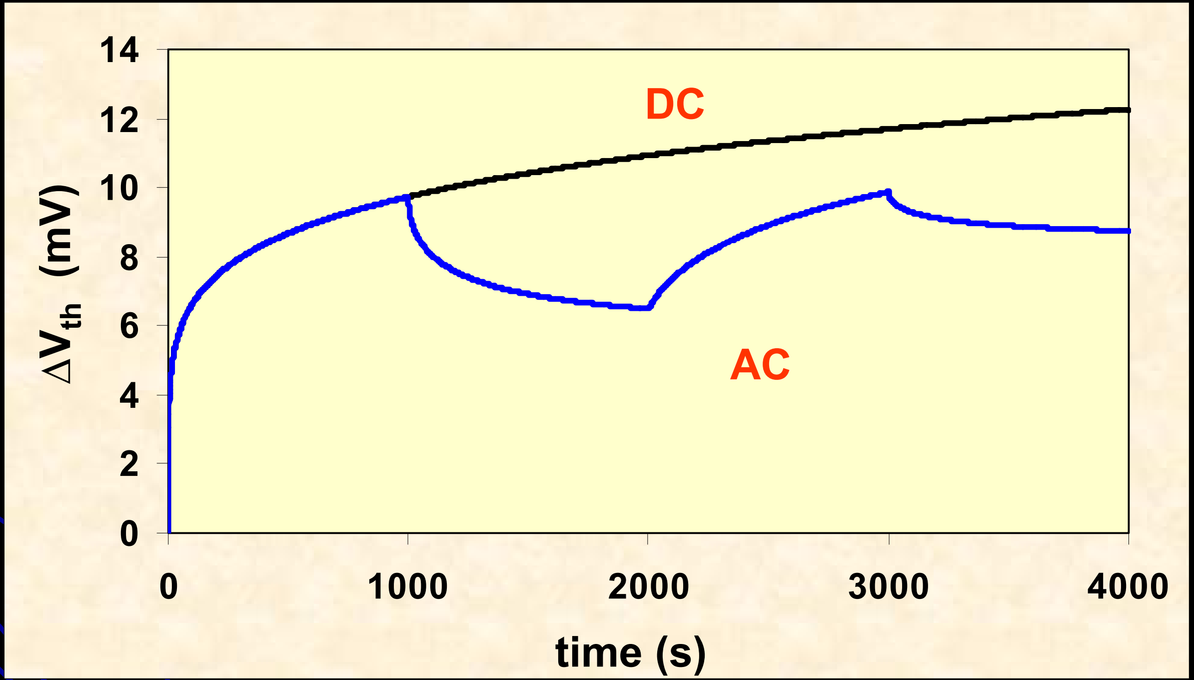




**Comparison of our model with experimental data from Chakravarthi-IRPS'04.**

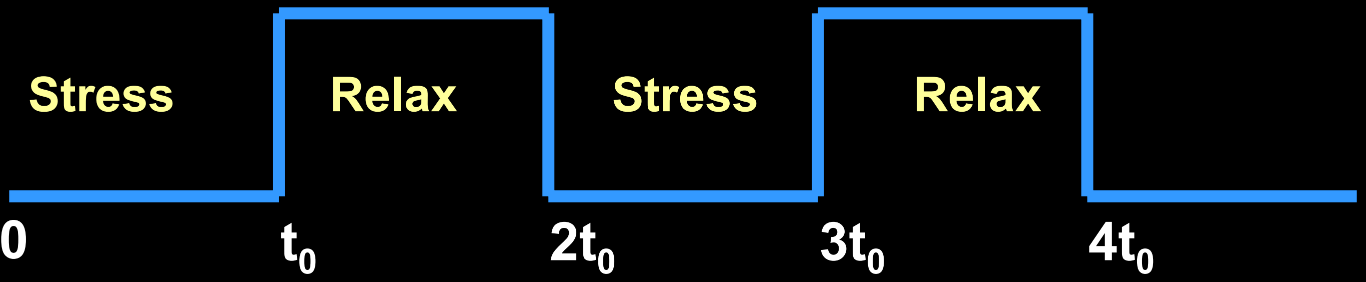
# Threshold Voltage Degradation

$$\Delta V_{th} \propto N_{IT}$$



**$V_{th}$ degradation larger for static NBTI stress (DC) as compared with dynamic NBTI (AC)**

# "$s_k$" Notation

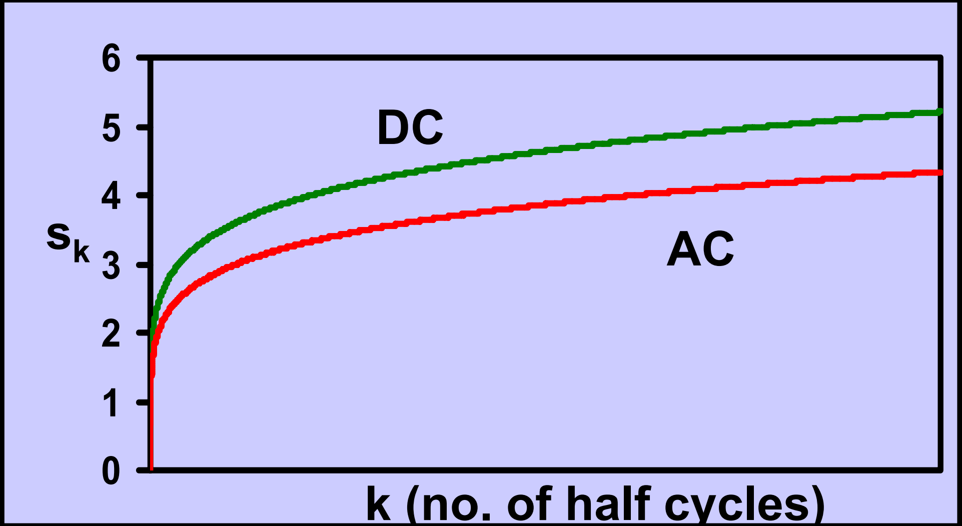


$$s_k = \frac{\Delta V_{th}(kt_0)}{\Delta V_{th}(t_0)}$$

Can obtain closed form expression using $s_k$ notation

# “$s_k$” Notation

For DC, $s_k$ is simply $k^{1/6}$



For AC, $s_k$ is given by

$$s_k = \begin{cases} 0 & k = 0 \\ 1 & k = 1 \\ \left(1 + s_{k-1}^6\right)^{\frac{1}{6}} & k > 1, k \text{ odd (stress)} \\ \frac{2}{3} s_{k-1} + \frac{1}{3} s_{k-2} & k > 1, k \text{ even (relax)} \end{cases}$$

$s_k$ values computable for any arbitrary waveform

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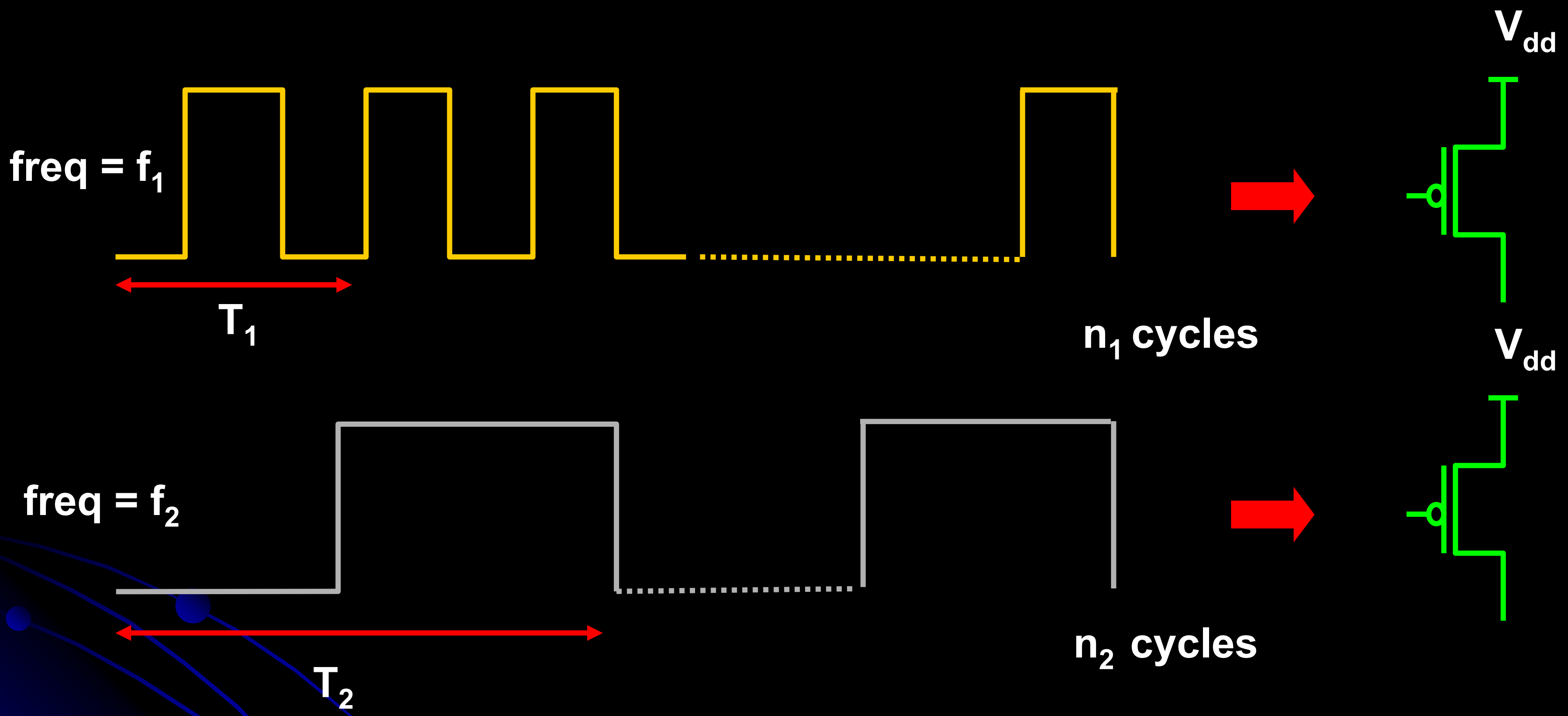
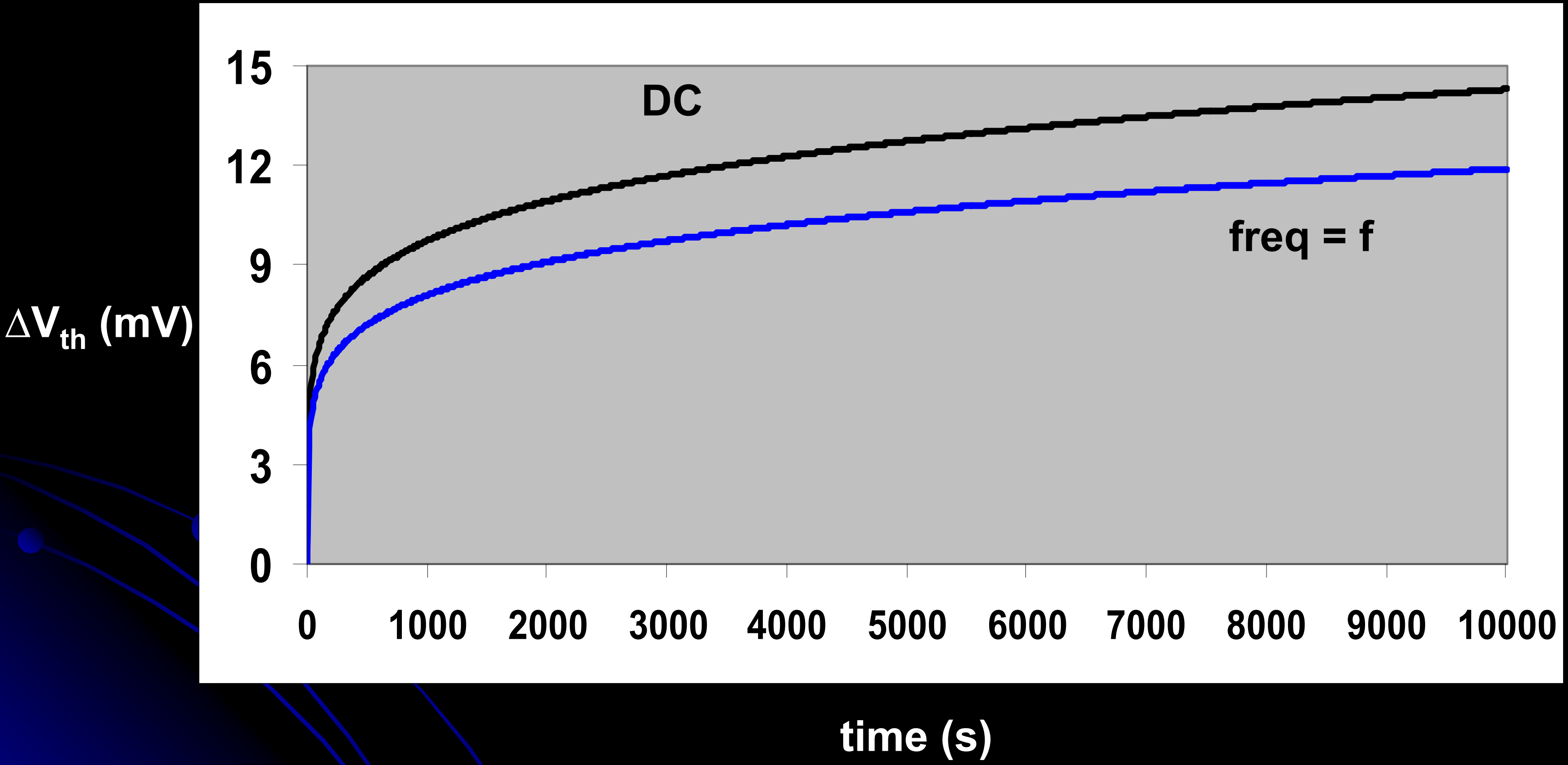
# Frequency Independence



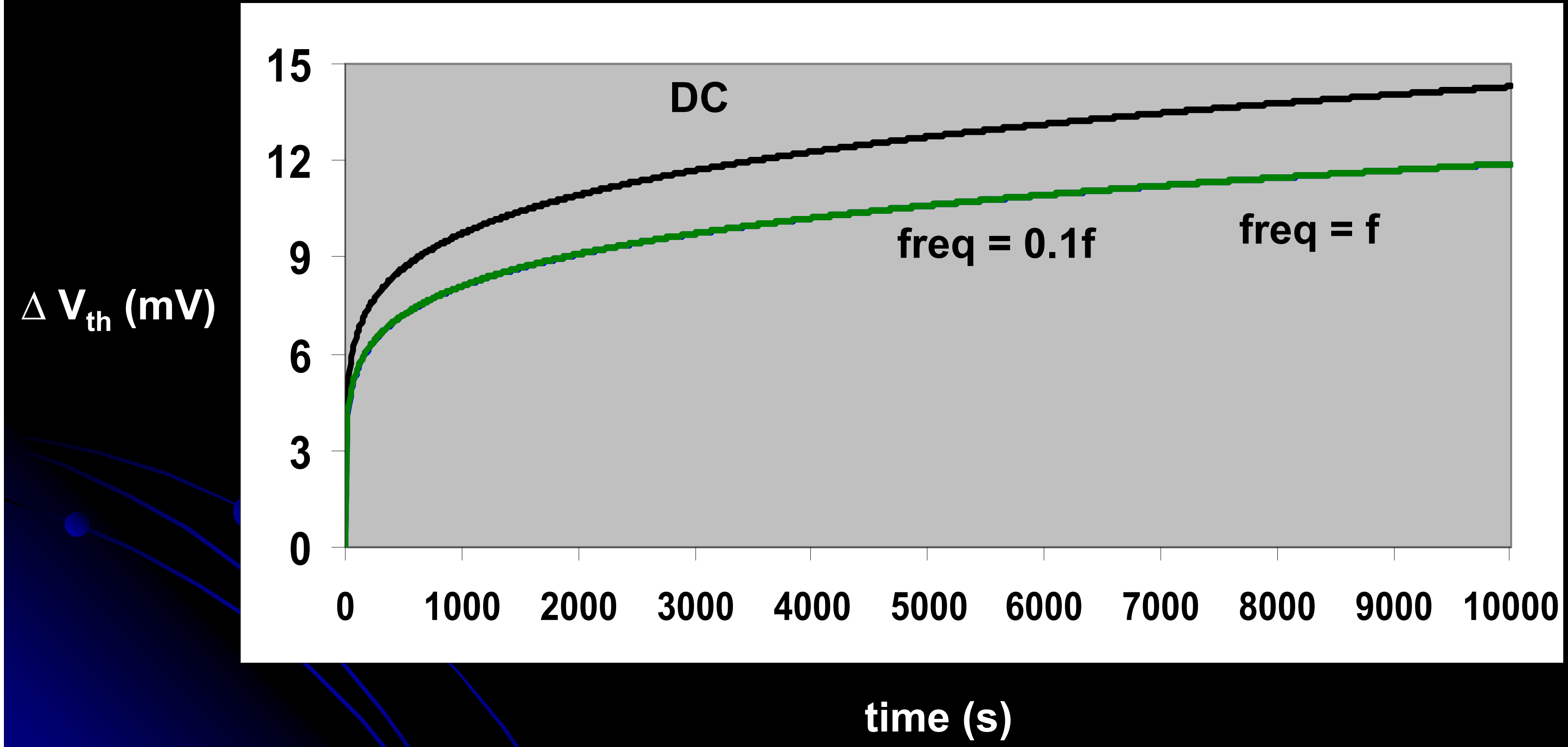
**Number of interface traps for both cases same**

**Trap generation independent of frequency**

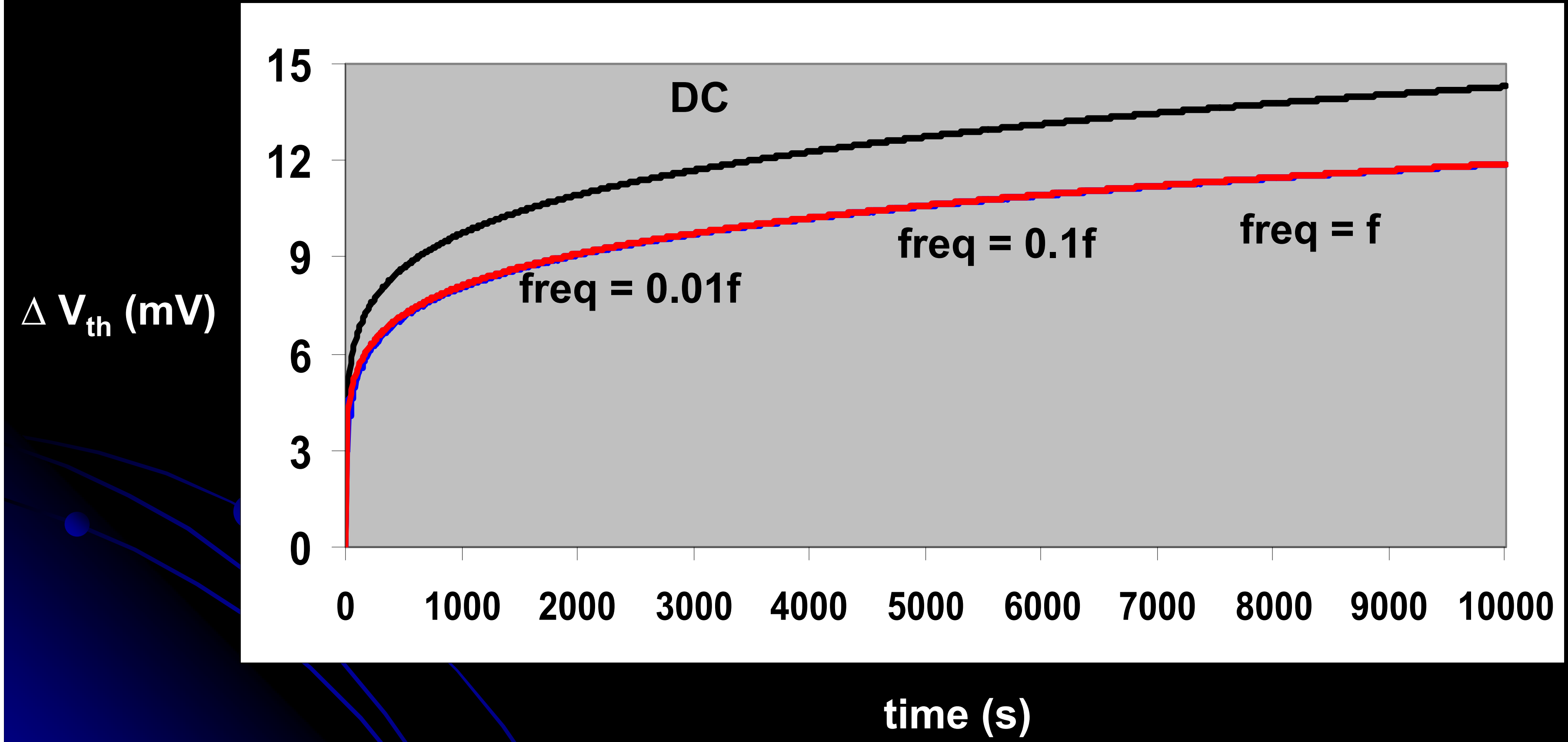
# Frequency Independence Plots



# Frequency Independence Plots



# Frequency Independence Plots



**$V_{th}$ degradation same for all three cases**

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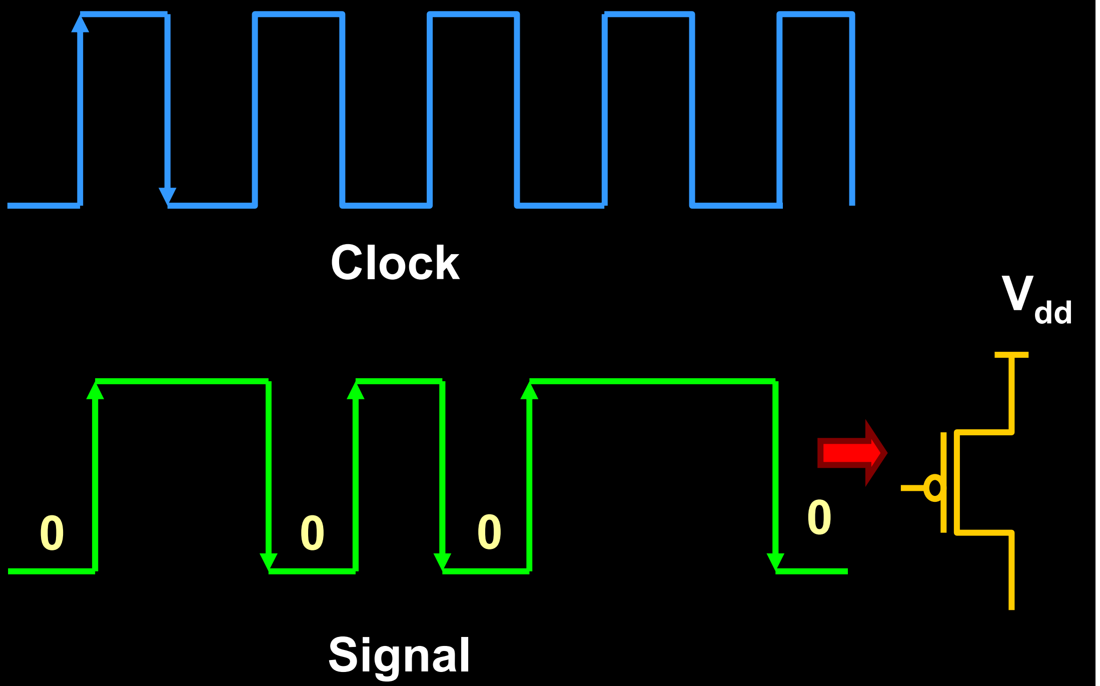
# Issues

- Estimate the delay degradation after a time period equal to 10 years of operation, i.e., (~3X$10^8$ s)
  - f=1GHz implies $10^{17}$ cycles
  - Need “fast-forwarding”
- NBTI effect is temporal
  - Requires exact nature of stress and relaxation to determine $N_{IT}$
  - Impossible to determine temporal input activity
- Need to use statistical inputs

# Signal Probability and Activity Factor

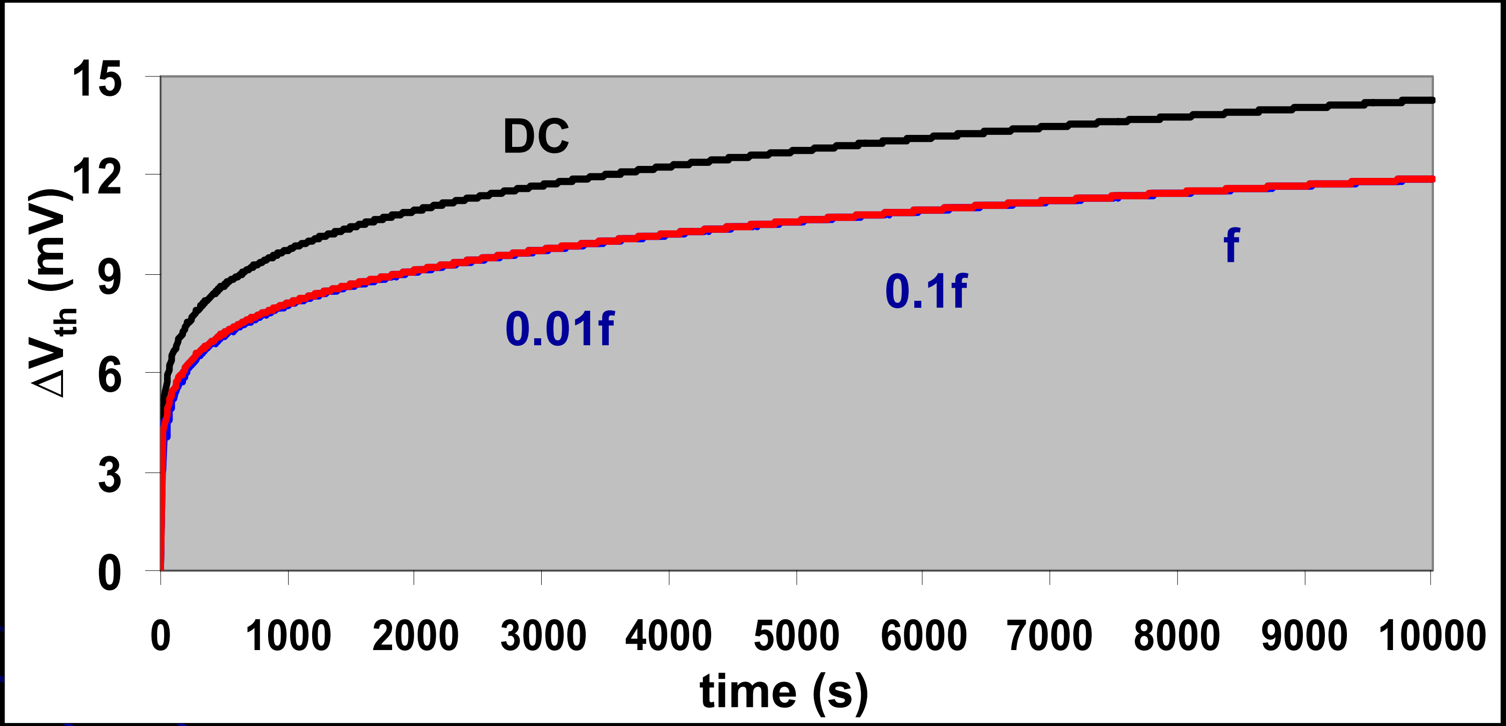
- Signal Probability (SP)
  - Probability that the signal is high (or low)
- Activity Factor (AF)
  - Probability that the signal switches



**SP = 0.4**

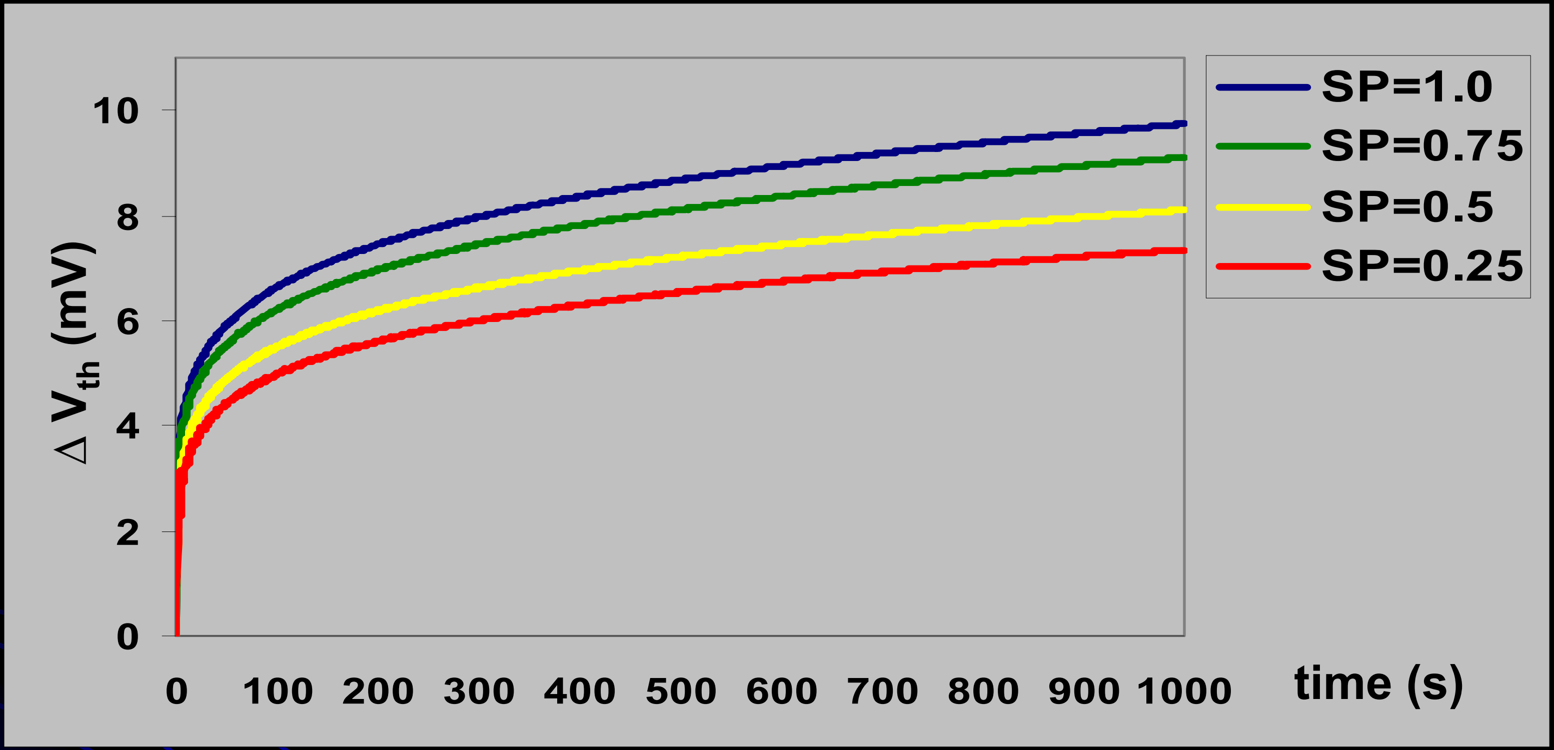
**AF = 0.6**

# NBTI – Activity Factor (AF) Independence



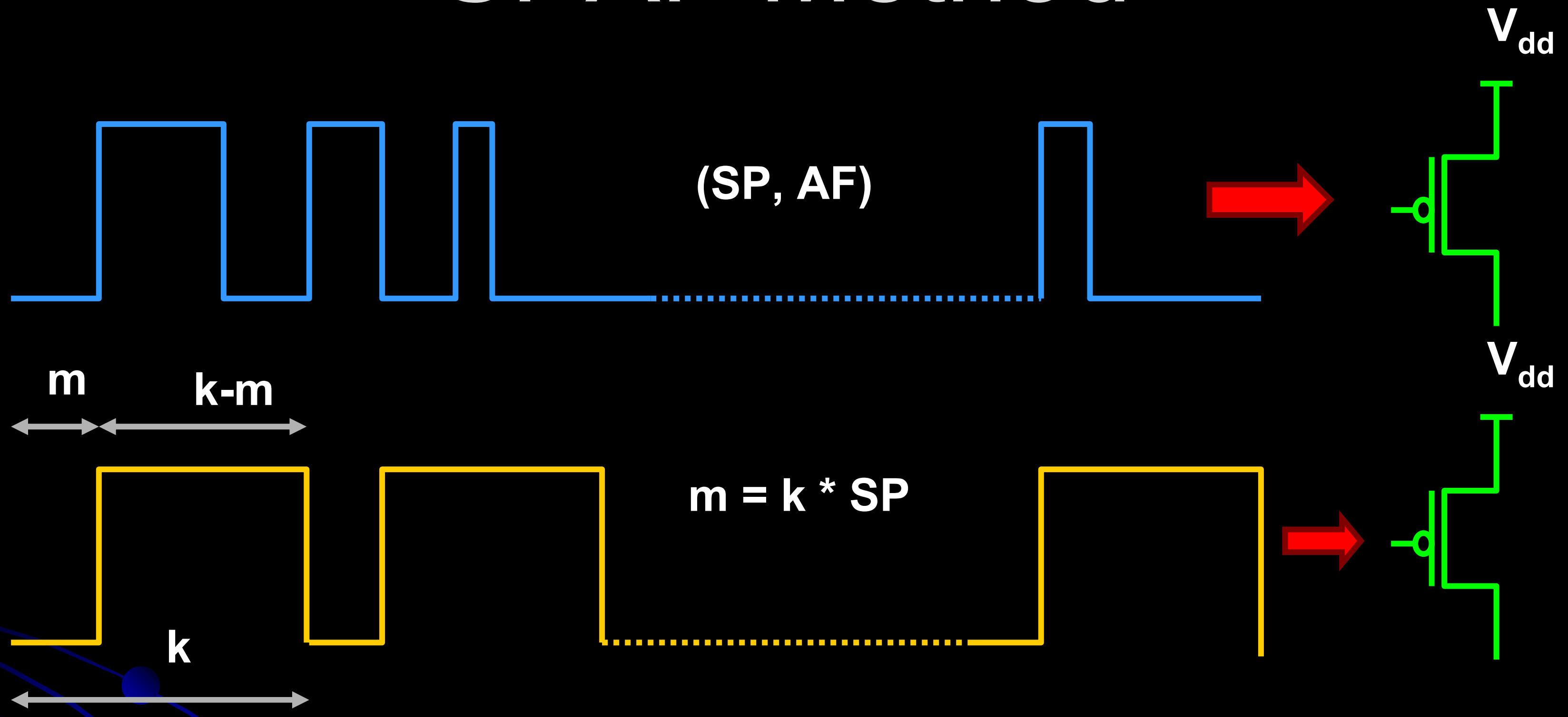
- Three square waveforms with same signal probability (SP) of 0.5
  - 1X, 0.1X and 0.01X activity factor (AF) values
- Same amount of $V_{th}$ degradation
  - Trap generation is AF independent

# NBTI – Signal Probability (SP) Dependence



- Four waveforms with same frequency
  - SP values are 0.25, 0.5, 0.75, 1.00
- $\Delta V_{th}$ values differ significantly
  - NBTI effect is SP dependent

# SPAF Method



- Converting a random waveform to an "equivalent" deterministic periodic waveform
  - Don't care about AFs
  - Maintain same SP

# Validity of SPAF Method

**Generate a random waveform for 10000 cycles**

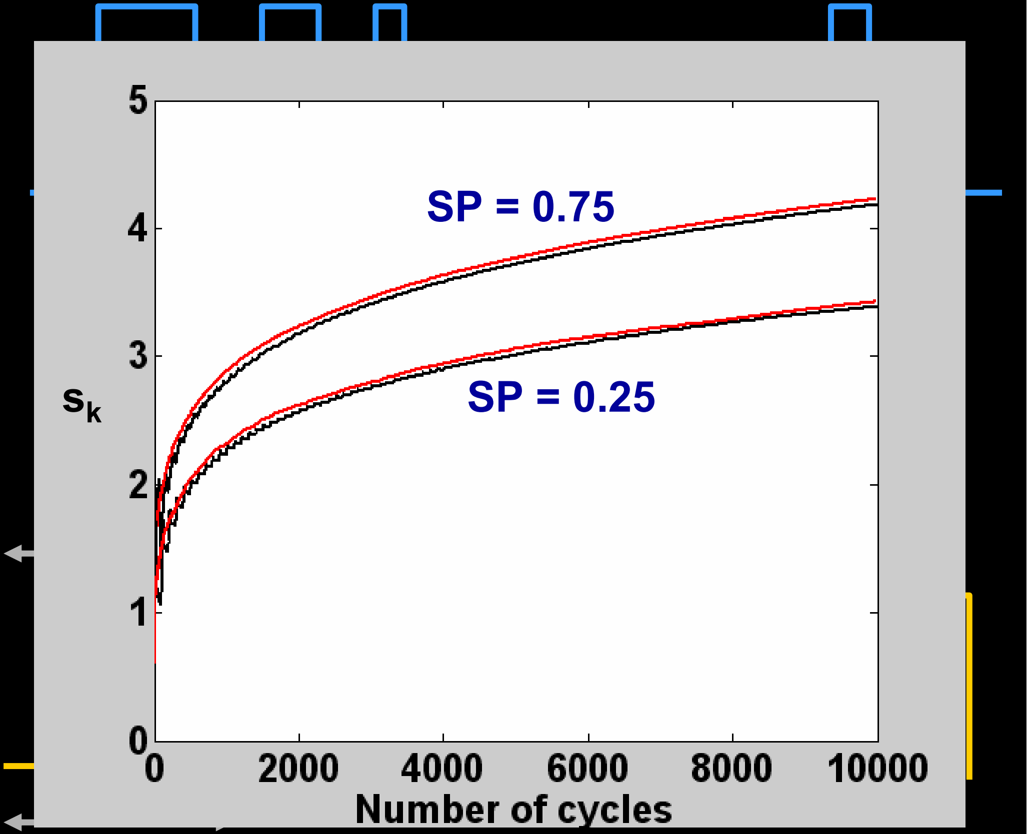
**Estimate number of traps**

**Determine SP for each sample**

**Build periodic waveforms with same SP value**

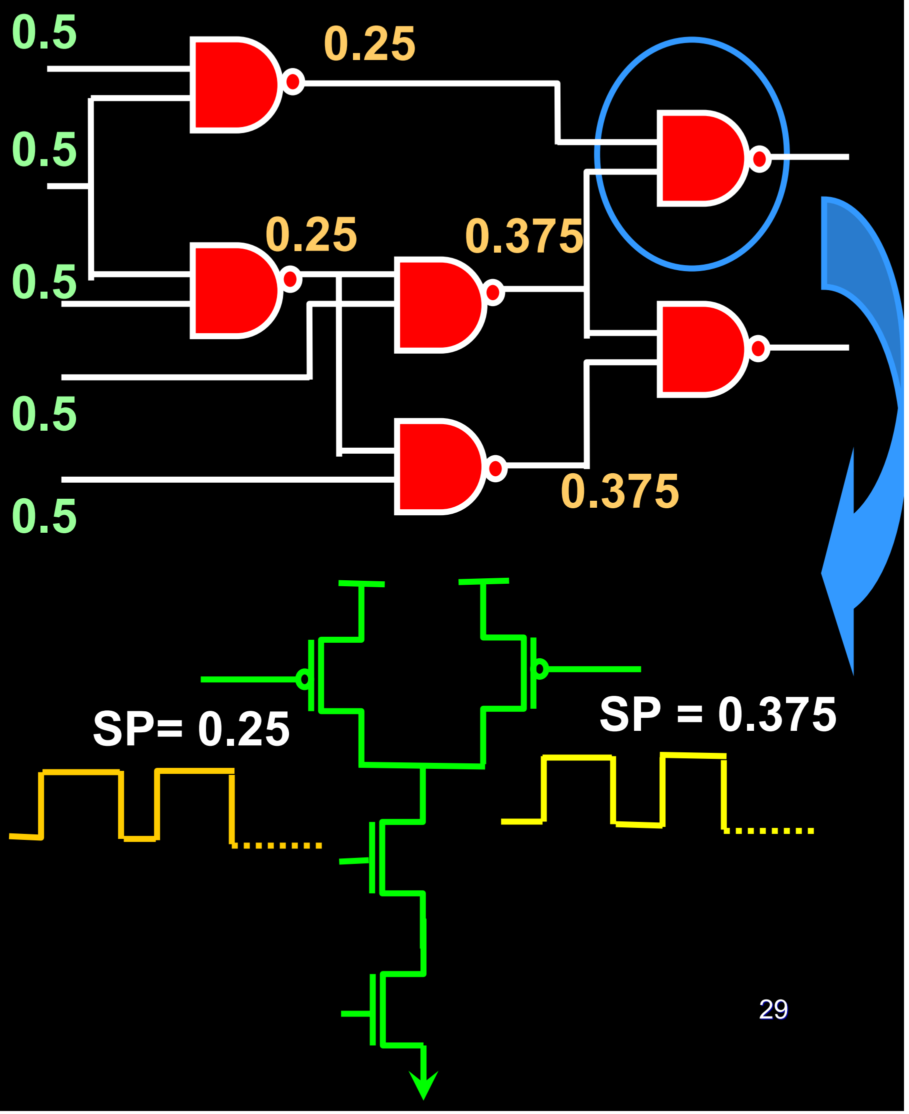
**Estimate number of traps**

**Compare $s_k$ values**



# Circuit Delay Estimation

- Simulations on ISCAS85 benchmarks – 65nm PTM technology
- Clock frequency = 1GHz



- Estimate $V_{th}$ of each transistor after 10 years using a $V_{th}$ – SP look-up table
- Calculate new arrival times

# Results

| Benchmark | Nominal Delay (ps) | NBTI Delay (ps) | % Increase |
|---|---|---|---|
| C17 | 73 | 80 | 9.59 |
| C432 | 897 | 966 | 7.69 |
| C499 | 684 | 745 | 8.92 |
| C880 | 619 | 671 | 8.40 |
| C1355 | 669 | 730 | 9.12 |
| C1908 | 982 | 1064 | 8.35 |
| C2670 | 709 | 771 | 8.74 |
| C3540 | 1229 | 1340 | 9.03 |
| C5315 | 1048 | 1139 | 8.68 |
| C6288 | 3556 | 3868 | 8.77 |
| Average | | | 8.73 |

~9% degradation in delay of circuits after
10 years of operation

# Conclusion

- NBTI – growing threat to reliability
- Need accurate estimation of its effect
  - NBTI Modeling
- Analytical model for NBTI presented
- Circuit delay characterized due to temporal NBTI stress and relaxation
  - 9% increase in delay estimated
- Model can be used for NBTI-aware design