Reliability Impact and Scaling Trends

RTN and Residual Random Charge

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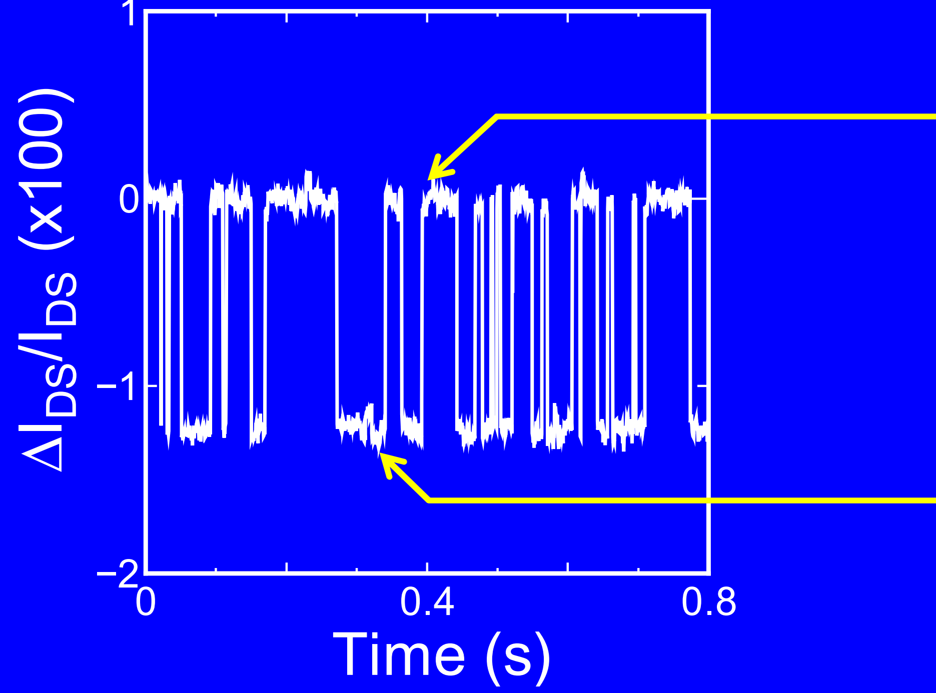
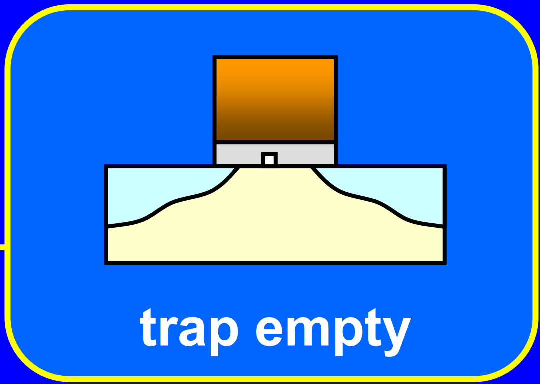
Outline

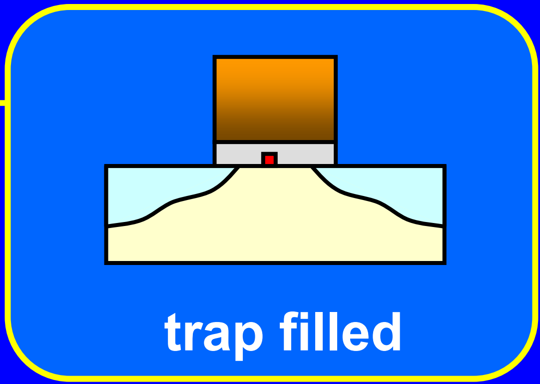
- Background
- Measurement of RTN
  to determine single charge response
- Modeling of worst case amplitude
  for RTN and i-channel FET fluctuation
- Results of model projection
- Conclusion

This talk is based on a Symp. VLSI Tech. 2009 presentation.

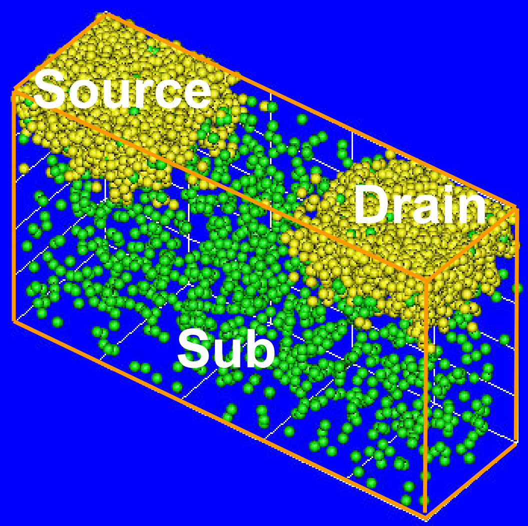
Random Telegraph Noise (RTN)



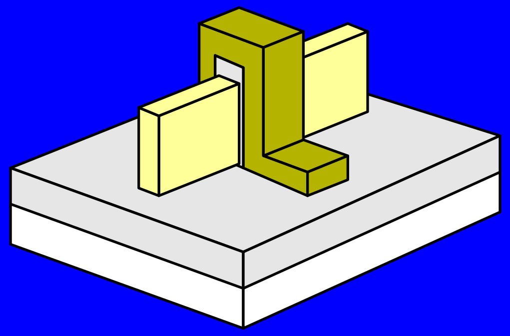




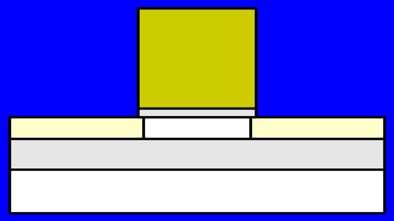
Intrinsic Channel FETs



Random dopant fluctuation (RDF) is serious in bulk FETs.



i-channel FinFET



i-channel UTB-SOI FET

New device architectures without channel doping can reduce RDF, but …

Residual Charge Fluctuation

Traps, surface states and impurities cannot be completely eliminated.

⇩

Random placement of residual charges

"Residual charge fluctuation"

$10^{10}cm^{-2}$ ⟷ 1 in every 100nm square

Background Summary

Scaling is continued. MOSFETs become sensitive to single charge perturbation.

Random Telegraph Noise

RDF becomes serious.
Intrinsic channel FETs (Fin, SOI) are required.

Residual charge fluctuation

Motivation

Conventional RDF modeling:

- Many charges are involved.
- Normal distributions often assumed.
- Knowing standard deviation σ is enough.

RTN / Residual charge modeling:

- Only 1 ~ a few charges are involved.
- New modeling required.

⇓

Proposal of single-charge-based modeling.

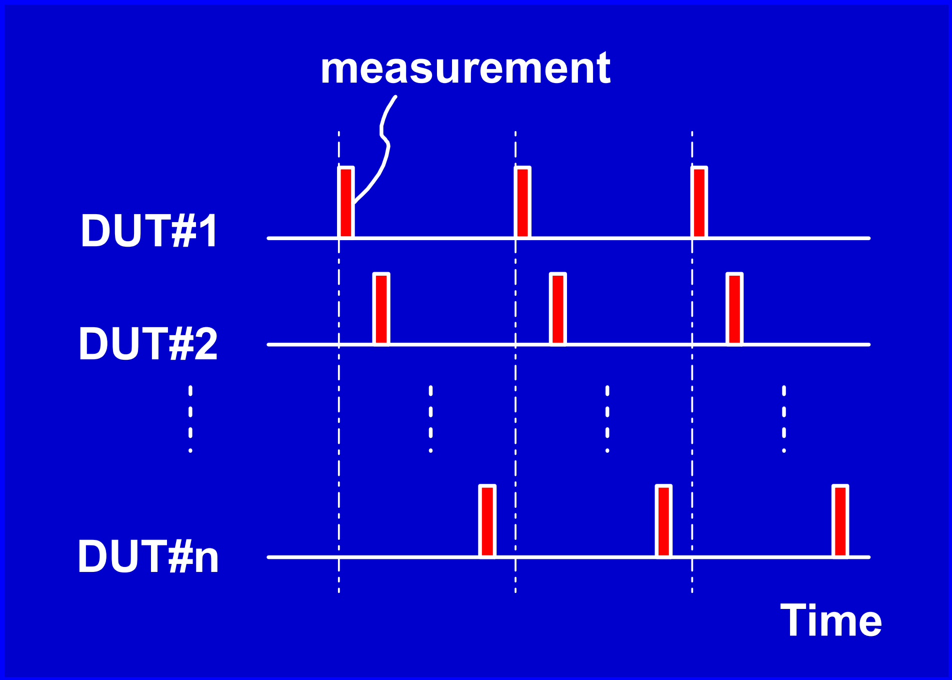
Obtaining basic information for modeling

Single charge response:
change of device characteristics (e.g. ΔV_{TH}) by adding one charge to a device.

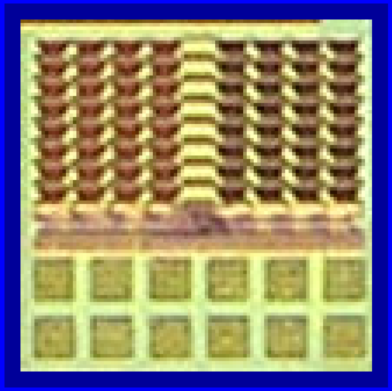
RTN provides unique opportunity for directly measuring single charge response.

Response is not constant, but *statistical*. Many devices must be measured.

Measurement of RTN Amplitude



Measurement sequence [2]



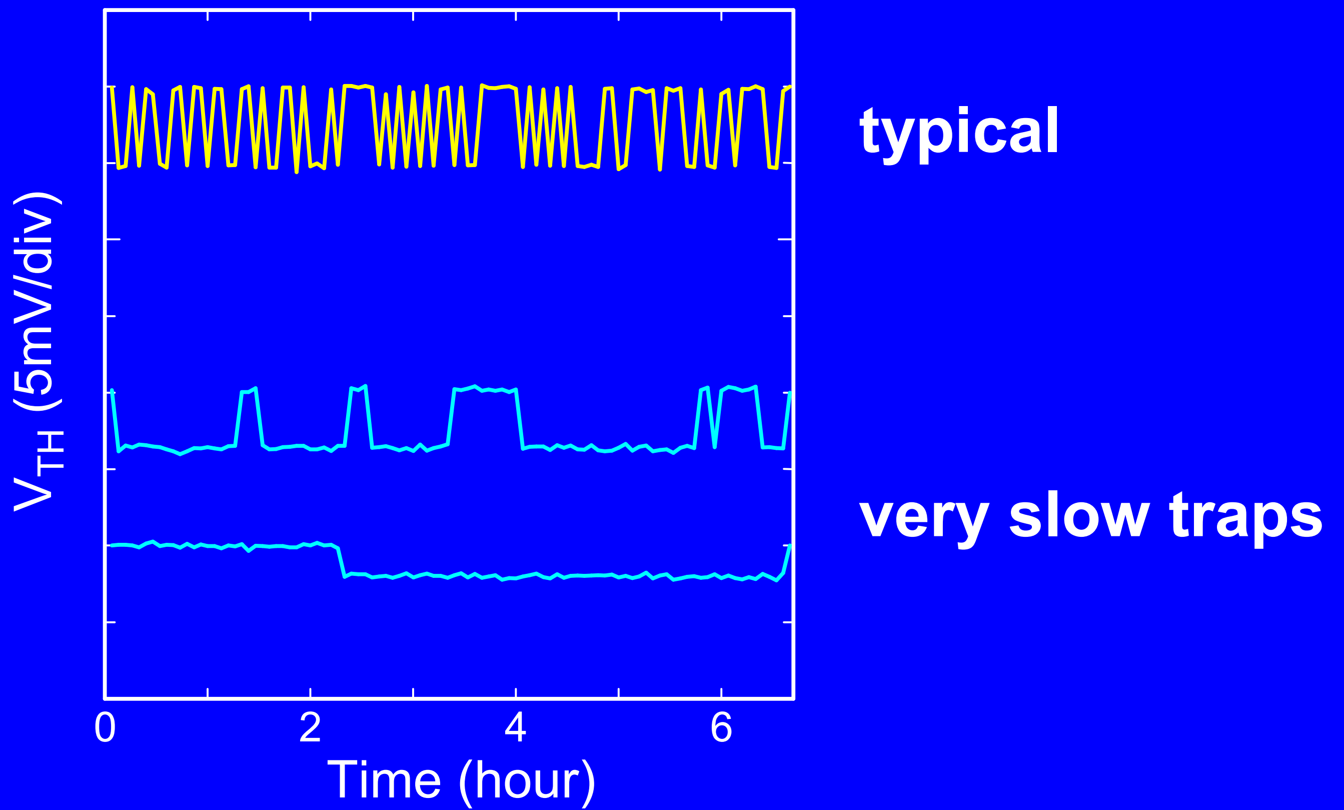
Device Matrix Array (DMA)

DMA + virtual parallel measurement

→ increased number of samples

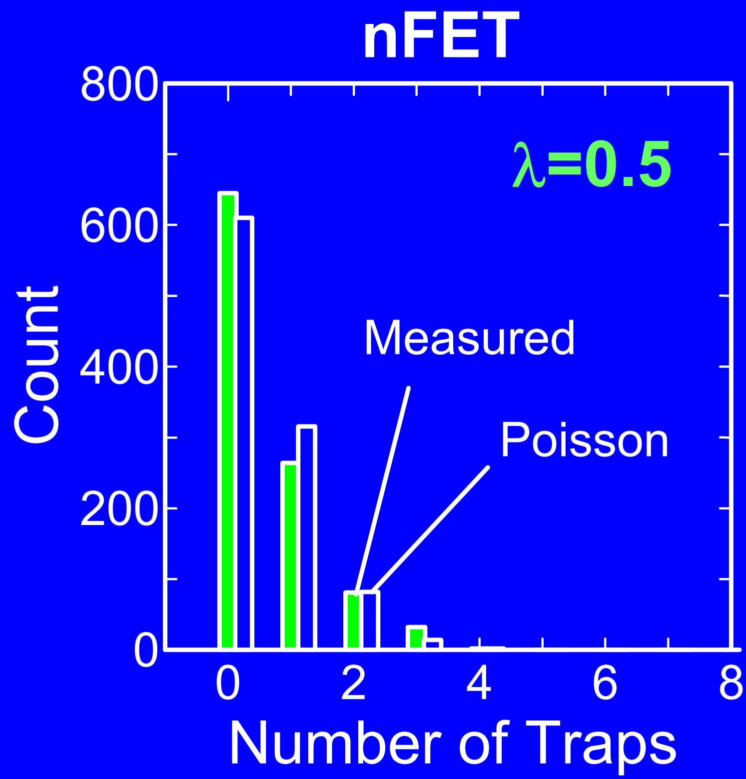
→ credible statistical data

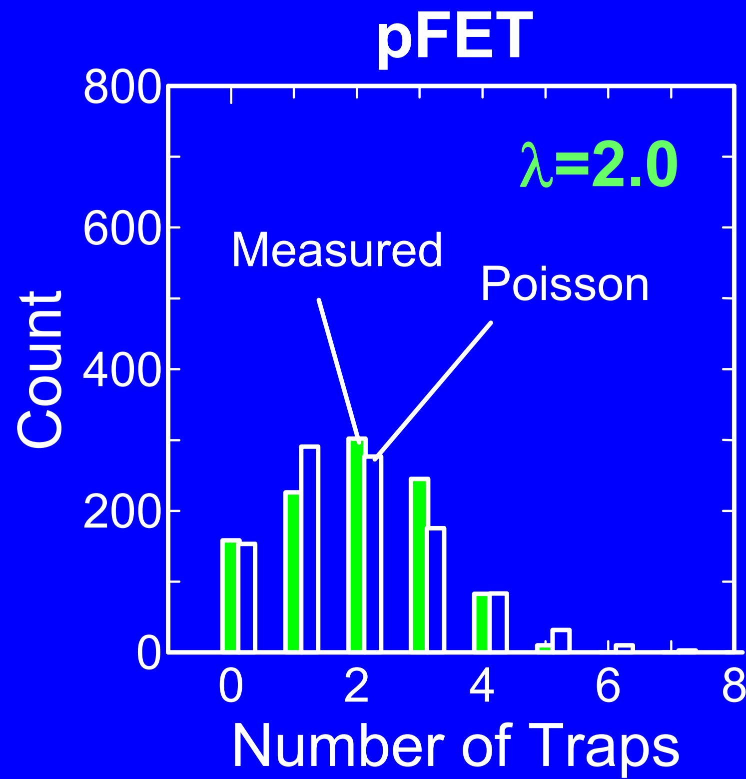
Waveform Examples



Long time measurement with short sampling time possible for many DUTs.

Trap Number Distributions





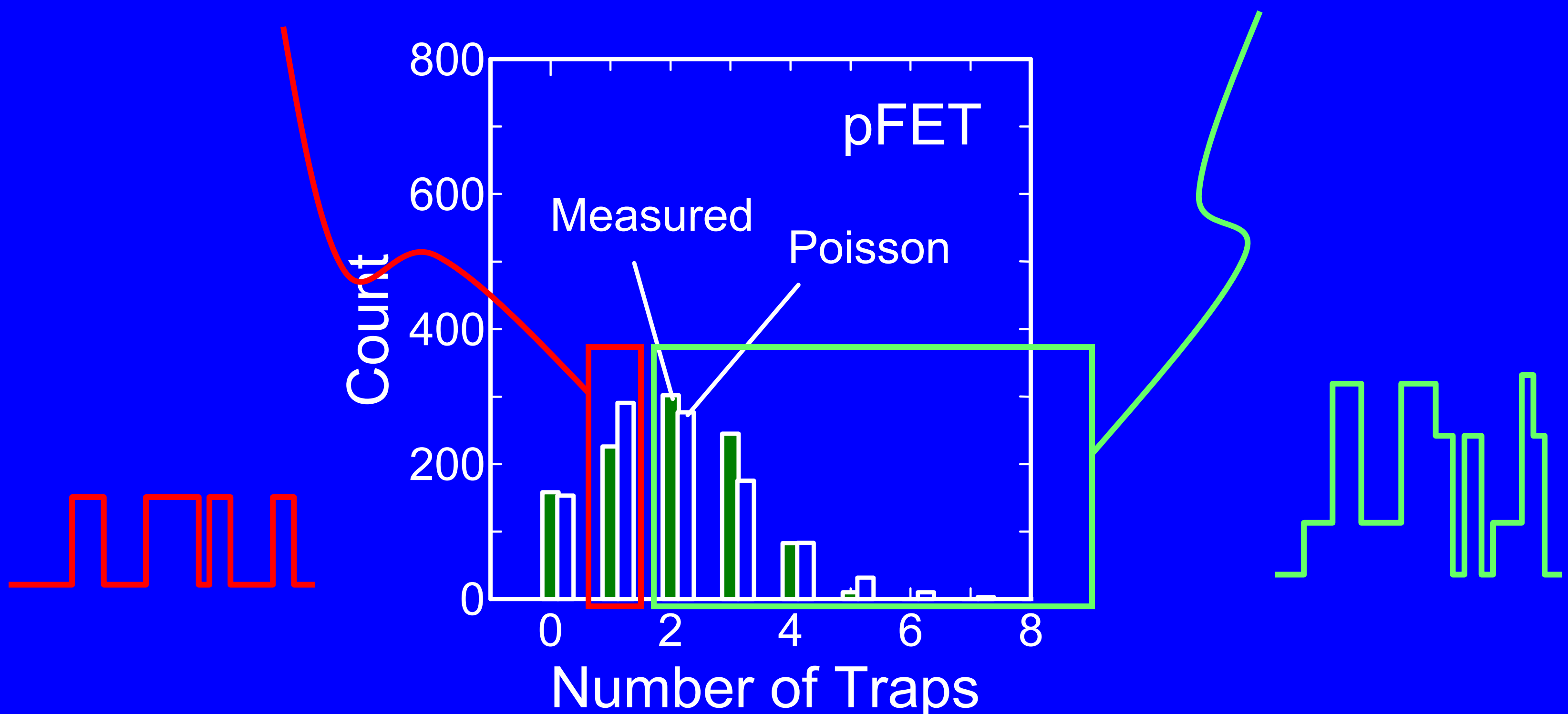
Number distributions are nearly Poisson.

Trap density is much higher in pFETs.

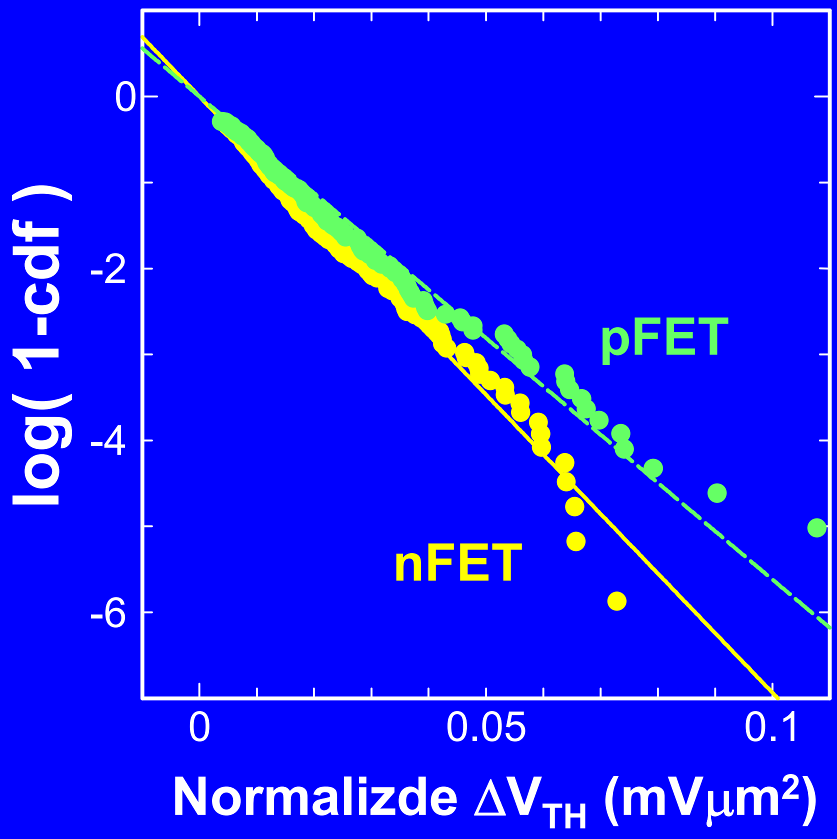
Extraction of Single Trap Amplitude

Use these samples having only one trap per device.

Waveform is complex due to multiple traps.



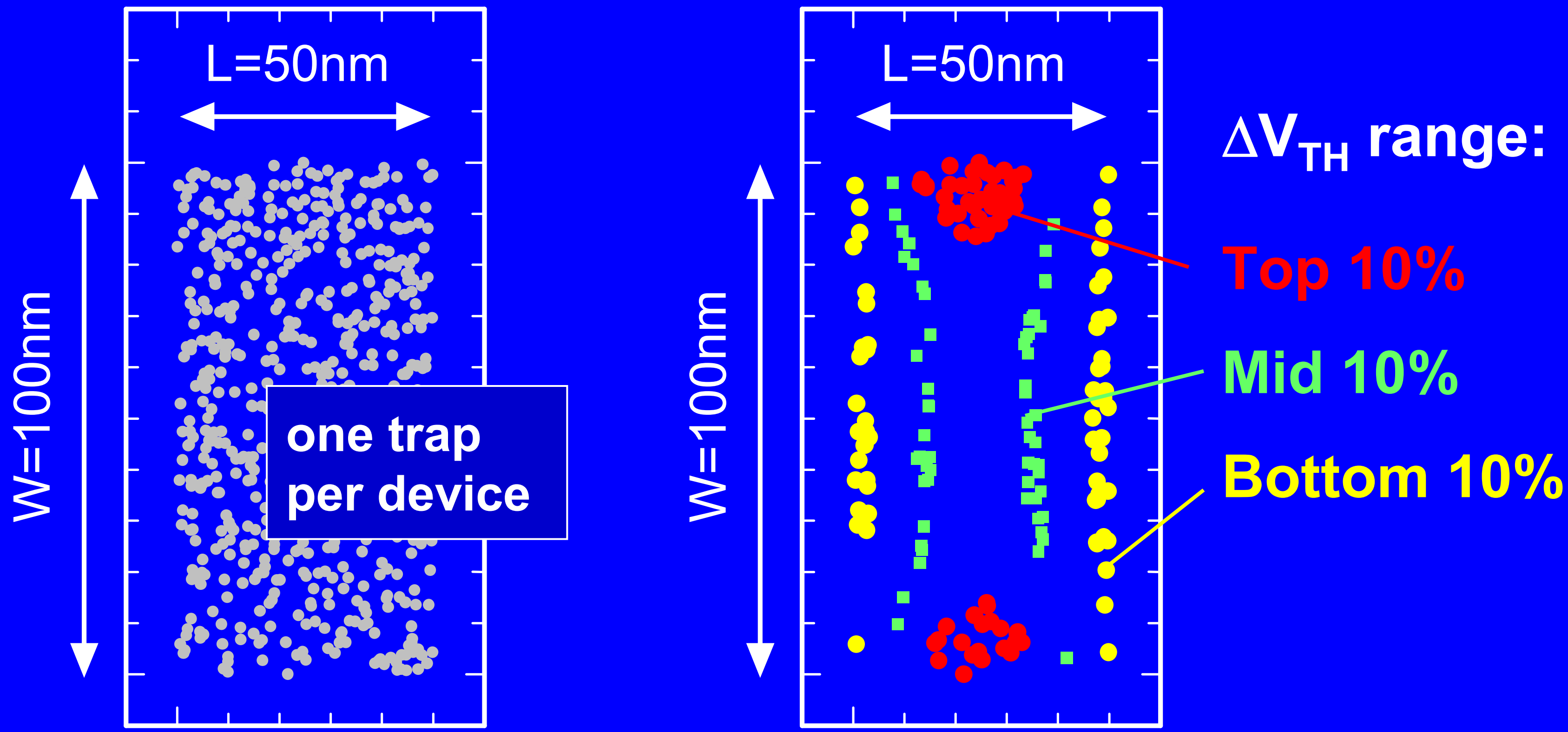
Measured Single Charge Response



cdf =
cumulative distribution function

Similar *exponential distributions* for both n and pFETs, if normalized by area.

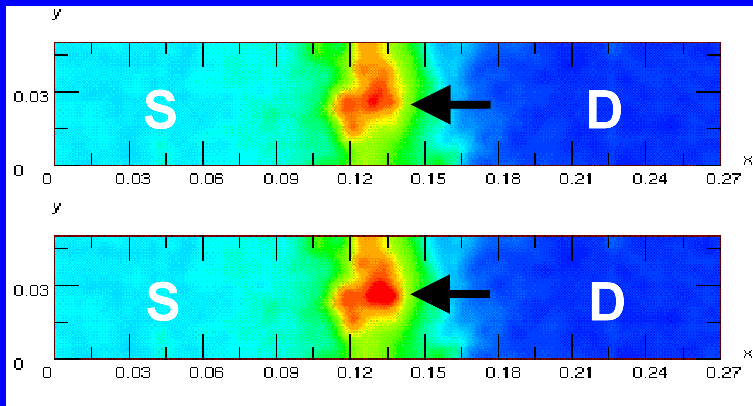
Origin of Amplitude Variation - 1



Random trap positions for RTN TCAD sim.
RDF not included.

Trap positions corresponding to specific ΔV_{TH} ranges.

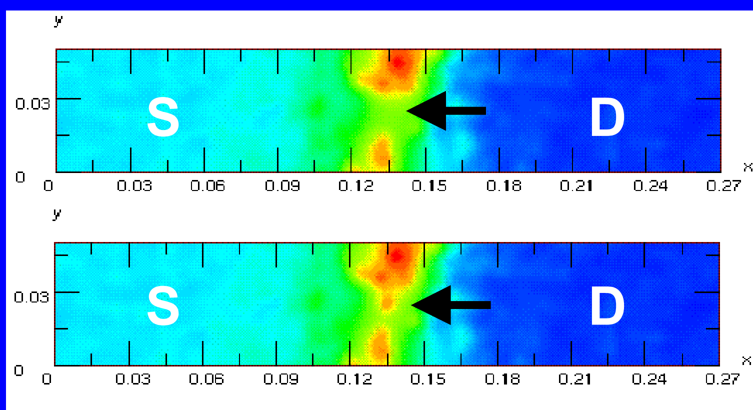
Origin of Amplitude Variation - 2



empty

ΔV_{TH}=3mV

filled



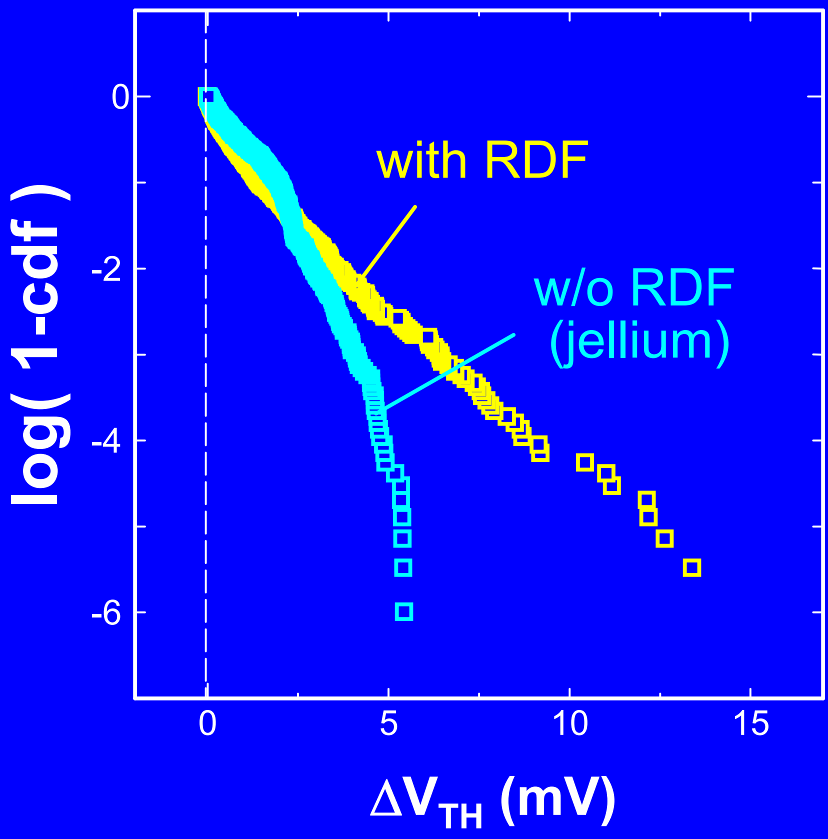
empty

ΔV_{TH}=30mV

filled

TCAD simulations including RDF.
One trap is placed at the center of channel.

Single Charge Response by TCAD



RDF:
random dopant fluctuation

3D Monte Carlo TCAD simulation

RDF is responsible for the long tail of exponential distributions.

Amplitude for Random Charge Counts

Number distribution (Poisson)

$$a_N = e^{-\lambda} \lambda^N / N!$$

Pdf of single charge response (exponential)

$$P_1(x) = (1/\Lambda)\exp(-x/\Lambda)$$

Pdf of amplitude by *N* traps (multiple convolutions)

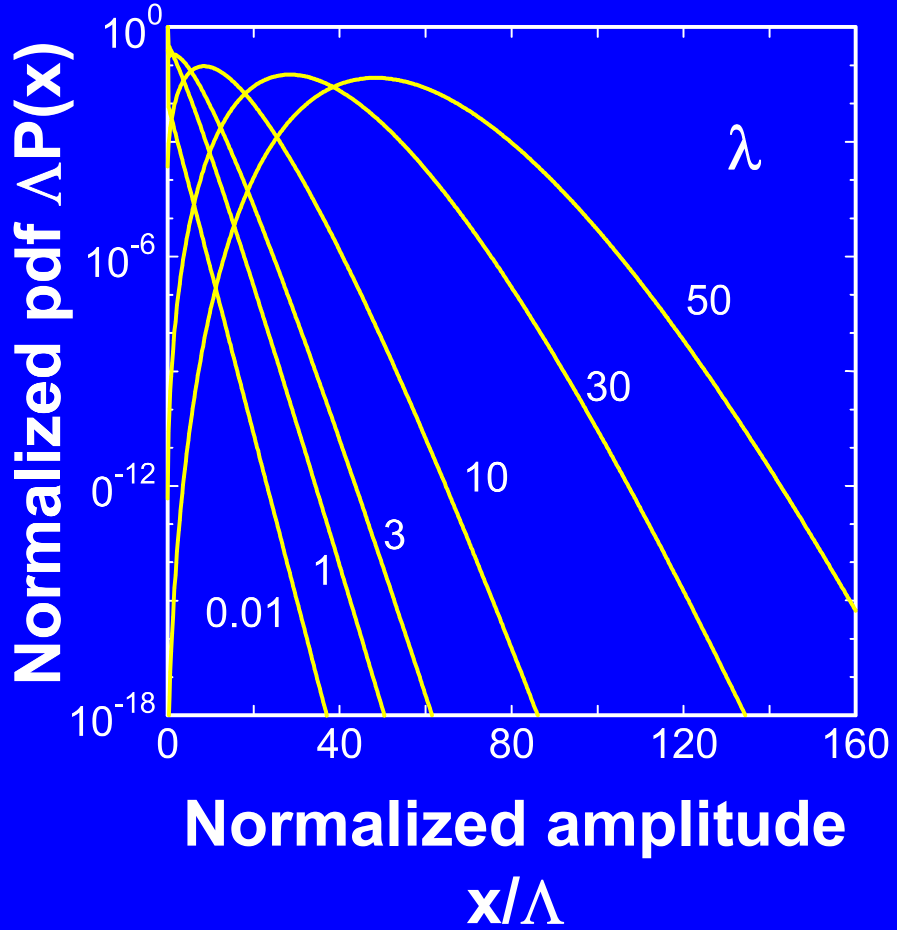
$$P_N(x) = \int_{-\infty}^{\infty} P_{N-1}(x-t) P_1(t) dt$$

Pdf of added amplitude

$$P(x) = a_0 \delta(x) + \sum_{i=1}^{\infty} a_i P_i(x)$$

pdf :
probability density function

Calculated Amplitude Distributions

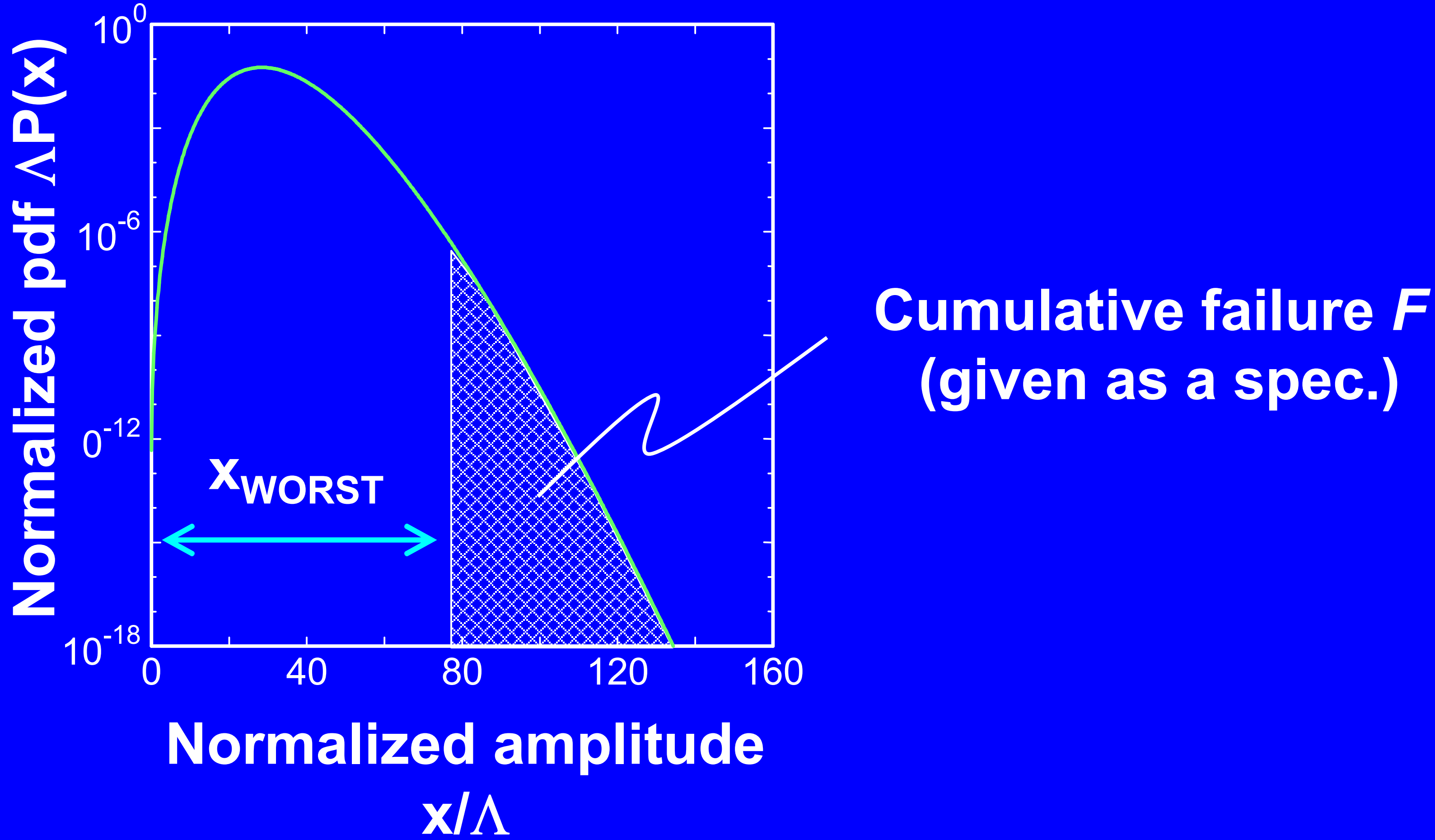


pdf :
probability
density function

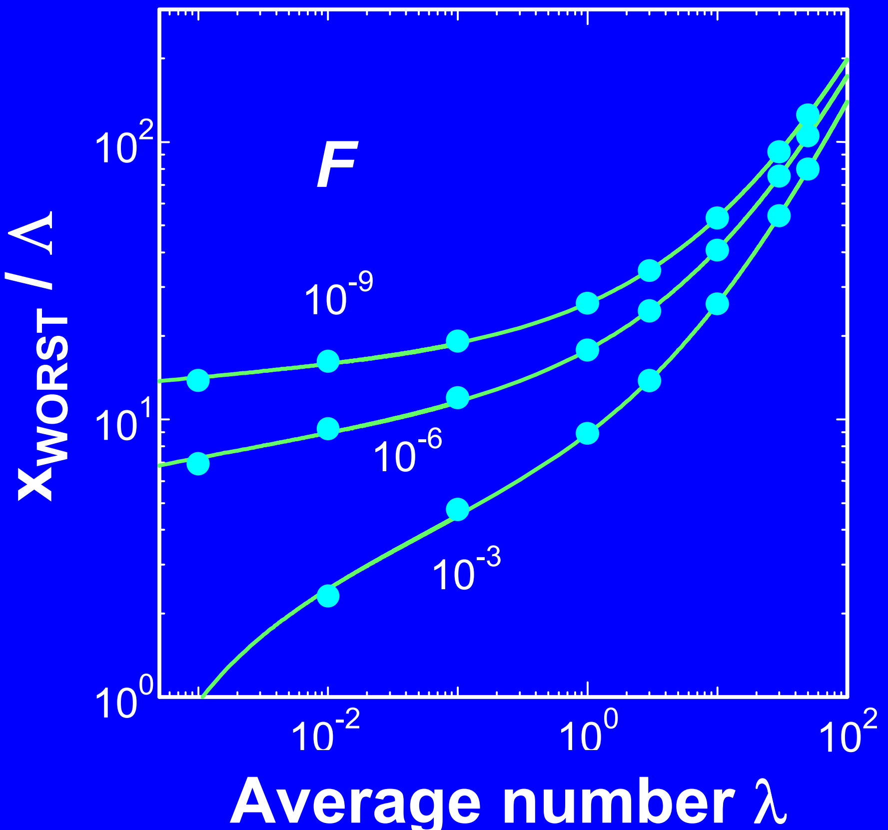
λ: average number of charges

Λ: average single charge amplitude

Definition of Worst Case Amplitude



Worst Case Amplitude vs λ and F



Fitting function

$$x_{WORST}/\Lambda = a_0 + a_1\sqrt{\lambda} + \lambda + a_2 \log\lambda$$

Worst Case Amplitude vs *L* and *W*

$$x_{WORST} / \Lambda = a_0 + a_1 \sqrt{\lambda} + \lambda + a_2 \log \lambda$$

Area dependence

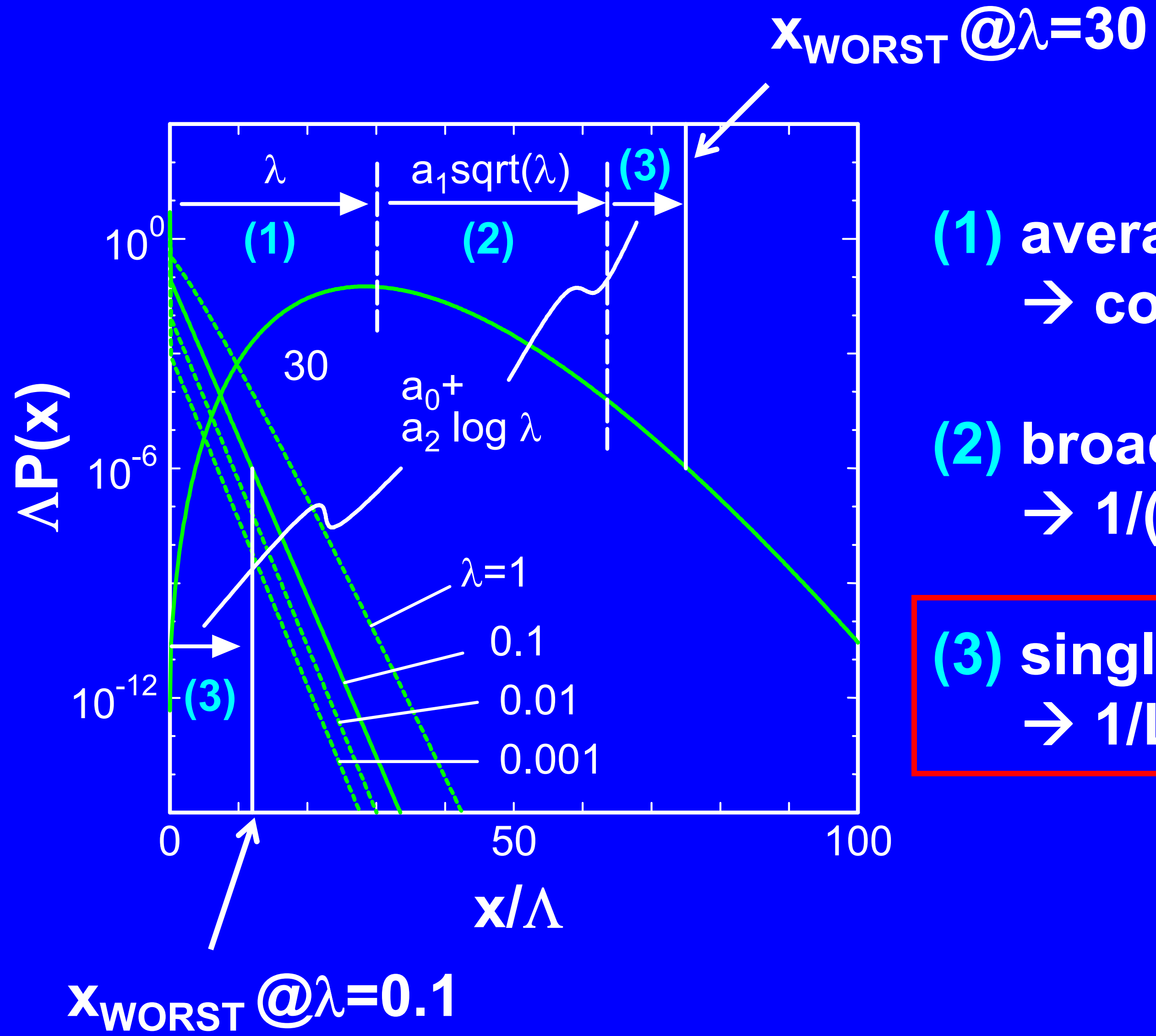
$$\Lambda = c_1 / LW$$ **average amplitude**

$$\lambda = c_2 LW$$ **average number**

$$x_{WORST} = c_1 c_2 + \frac{a_1 c_1 \sqrt{c_2}}{\sqrt{LW}} + \frac{c_1 \left(a_0 + a_2 \log\left(c_2 LW\right)\right)}{LW}$$

$a_0 \sim a_2$: functions of *F*.
$c_1 \sim c_2$: determined form measured data.

Origin of 1/LW Term

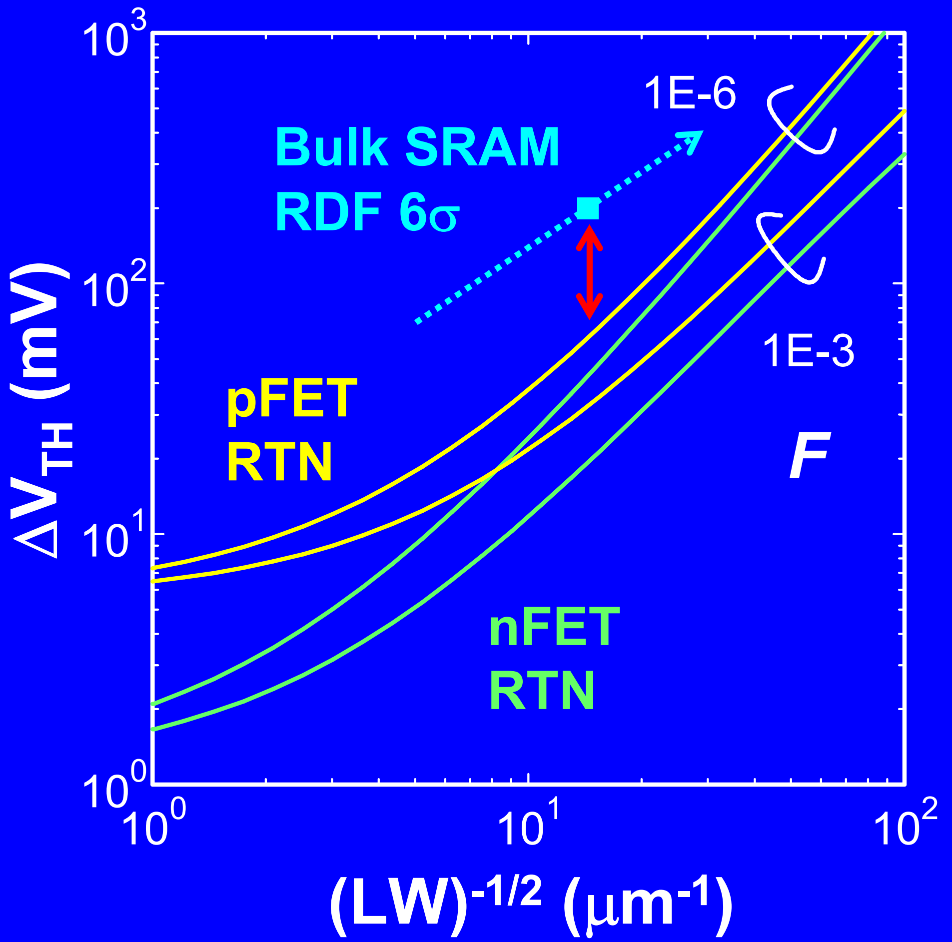


(1) average shift
→ const. term

(2) broadening
→ $1/(LW)^{1/2}$ term

(3) single charge tailing
→ 1/LW term

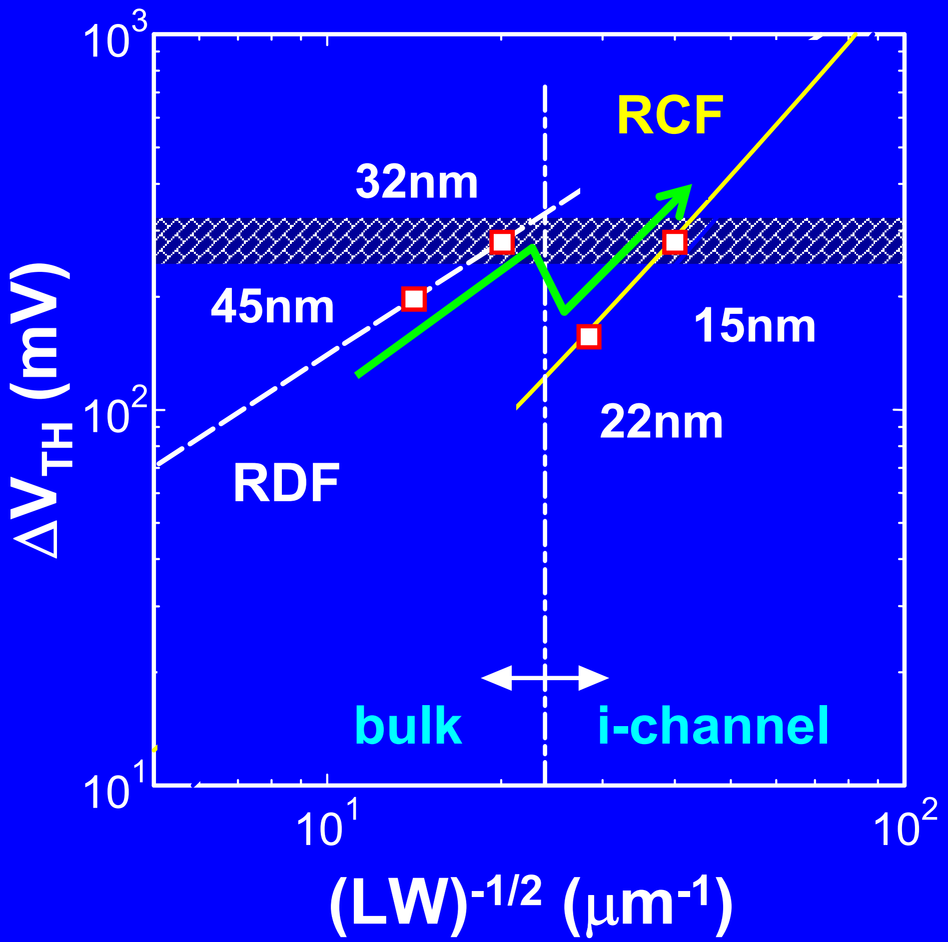
Impact of RTN on SRAM



- RTN cannot be ignored for SRAM design.
- RTN increases more rapidly than RDF due to 1/LW term.

RDF:
random dopant fluctuation
RTN:
random telegraph noise

Impact of Random Charges on Scaling

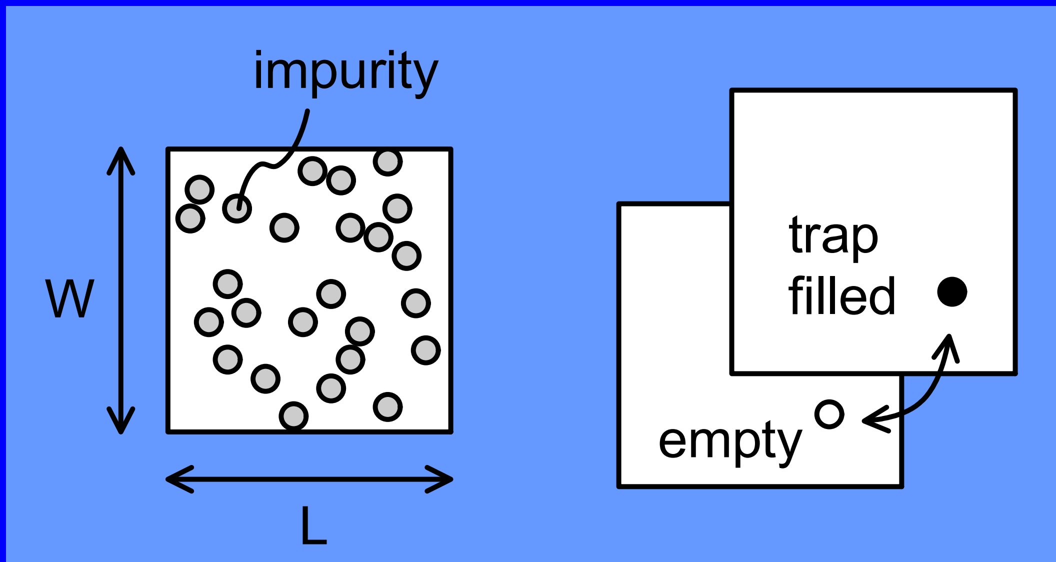


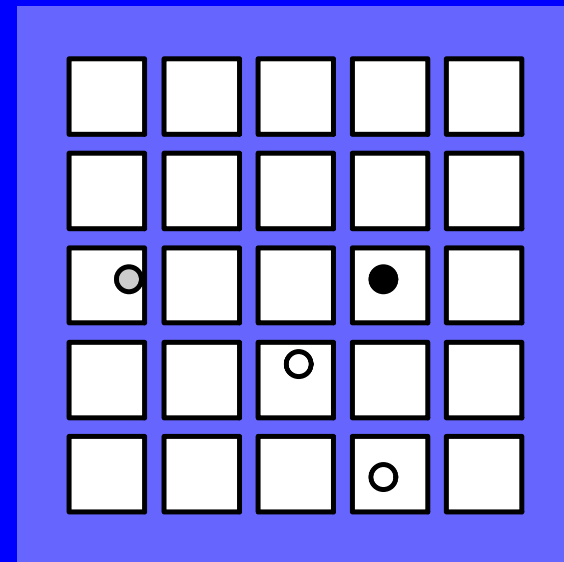
- I-channel FET scaling will be limited by residual charges.

RDF:
random dopant fluctuation

RCF:
residual charge fluctuation

Effects of Random Charges





RDF **RTN**

Bulk FETs

Ultra-small i-channel FETs

A single charge cannot be further divided.

Even if λ << 1, at least one charge will certainly exist in the worst device.

Summary

- Single-charge-based fluctuation model applicable to RTN and i-channel FETs is proposed. The model makes clear that 1/LW term exists.

- Statistical behavior of RTN was measured by using device matrix array, and explained by TCAD analyses. The results were utilized for the modeling.

- RTN should not be ignored for SRAM design. Rapid increase of RTN due to 1/LW term makes it more serious in the next generation.

- Residual charge fluctuation will limit i-channel FET scaling.