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Failure analysis of MOS devices using spatial statistics

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Outline

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- Review basic concepts about oxide reliability
- Breakdown spots visualization methods
- Localization methods in 1D and 2D
- Point pattern analysis using spatial statistics
- Application to MOS and MIM devices
- Conclusions

Scaling rules of MOS devices

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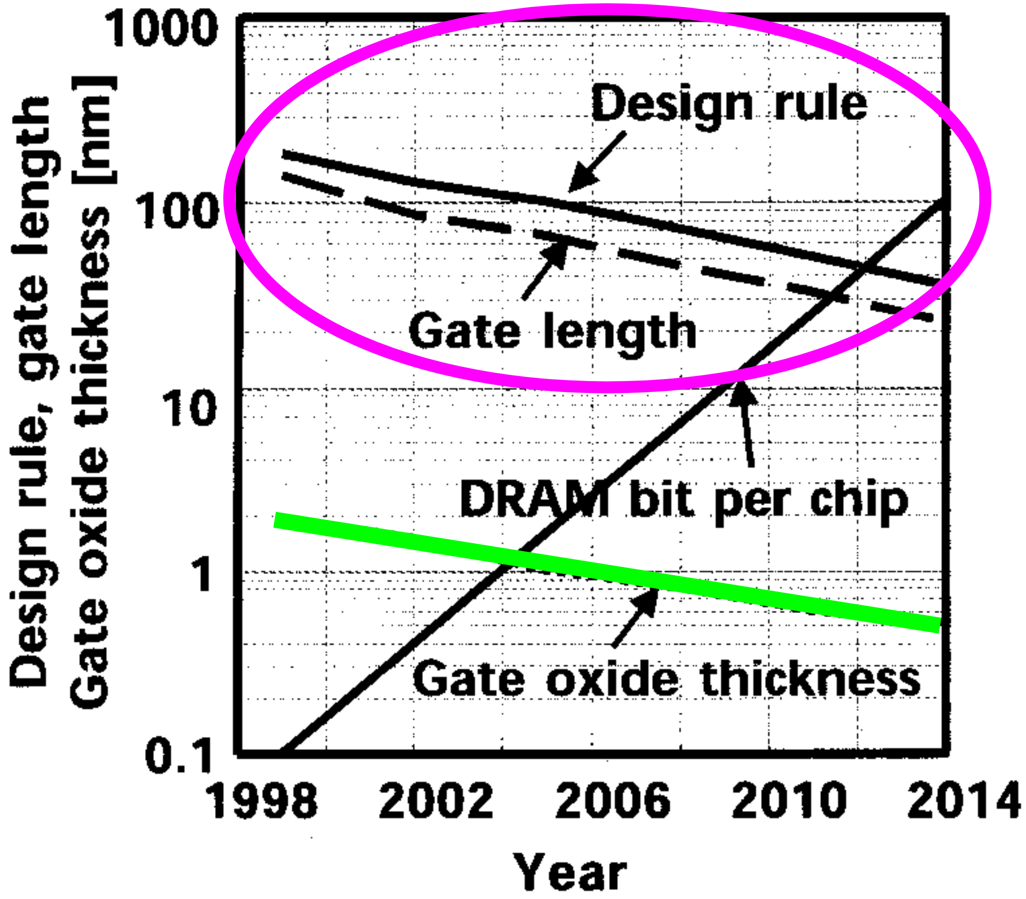

Smaller devices

⇓

integration density ↑
switching speed ↑
cost per function ↓

REDUCTION OF THE GATE OXIDE THICKNESS

Gate leakage current vs. oxide thickness

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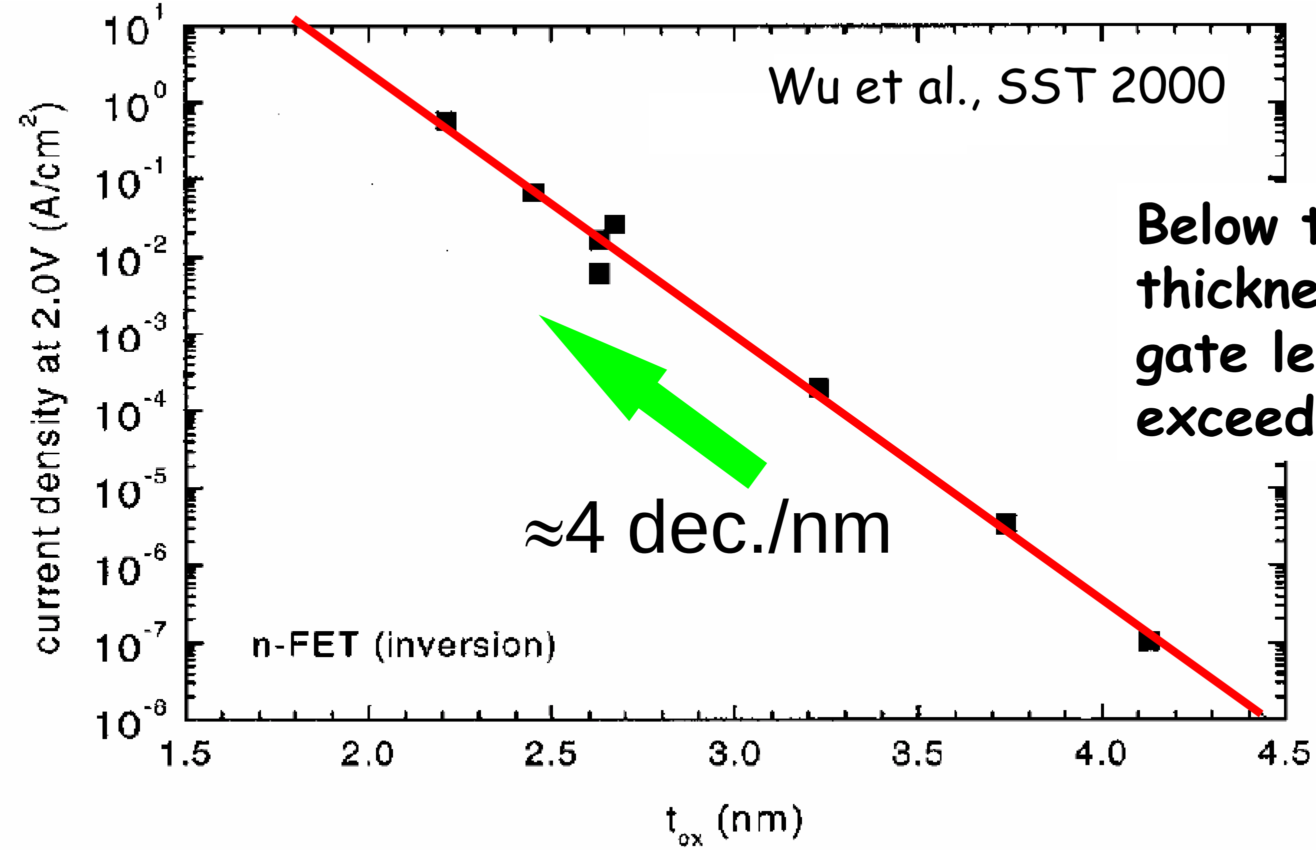

Below the physical thickness of 1.5nm the gate leakage current exceeds 1A/cm^2

Thinner oxides ⇒ higher tunneling currents

GROWING POWER CONSUMPTION

Time-to-breakdown vs. oxide thickness

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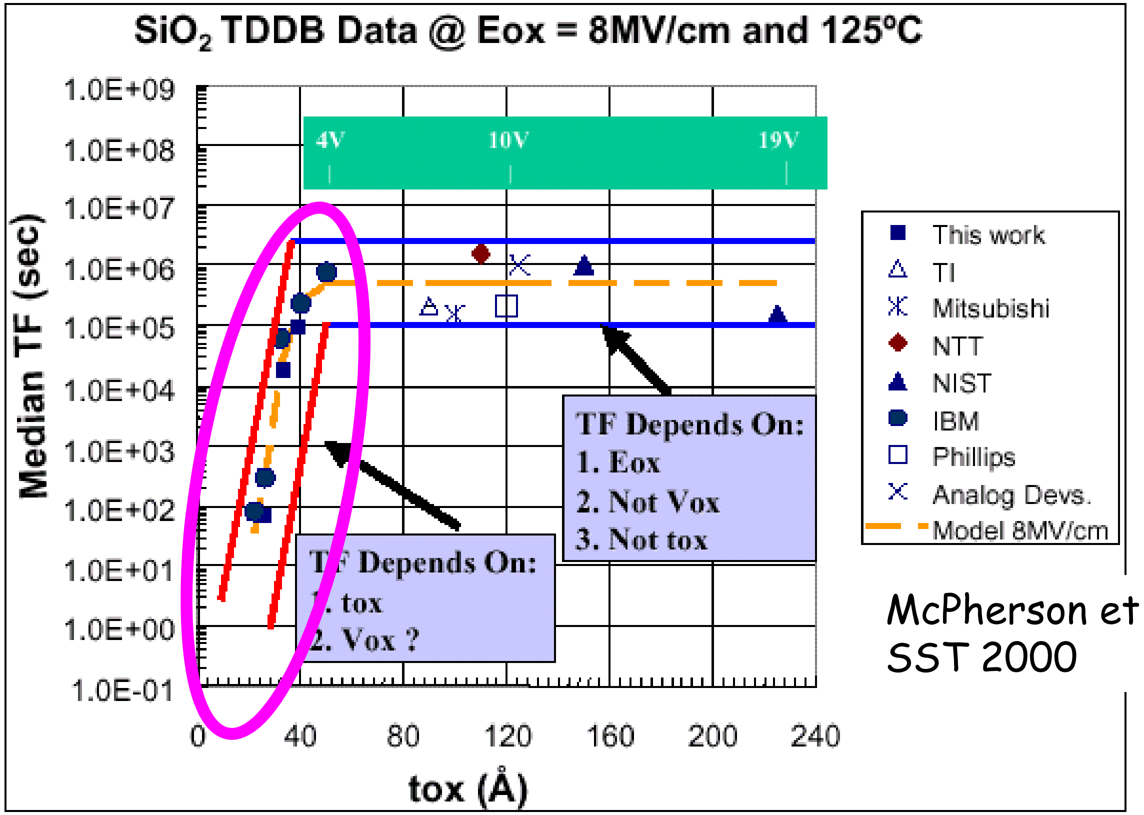
Thinner oxides $\Rightarrow$ Reduction of the time-to-failure



McPherson et al., SST 2000

LESS RELIABLE DEVICES

What is a breakdown event?

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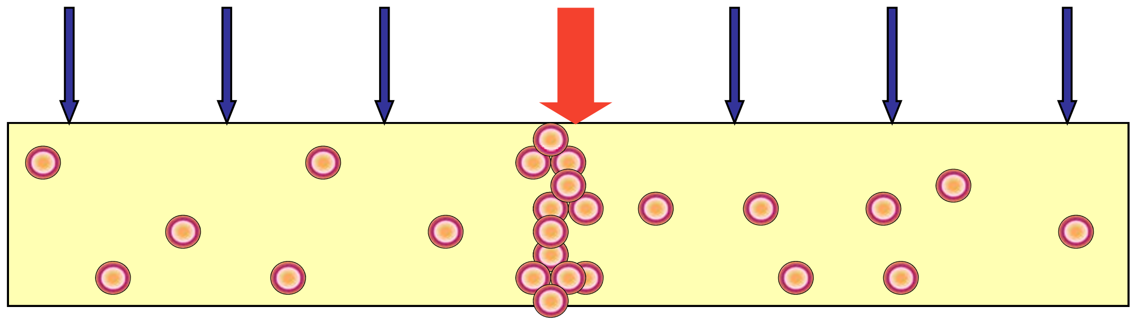
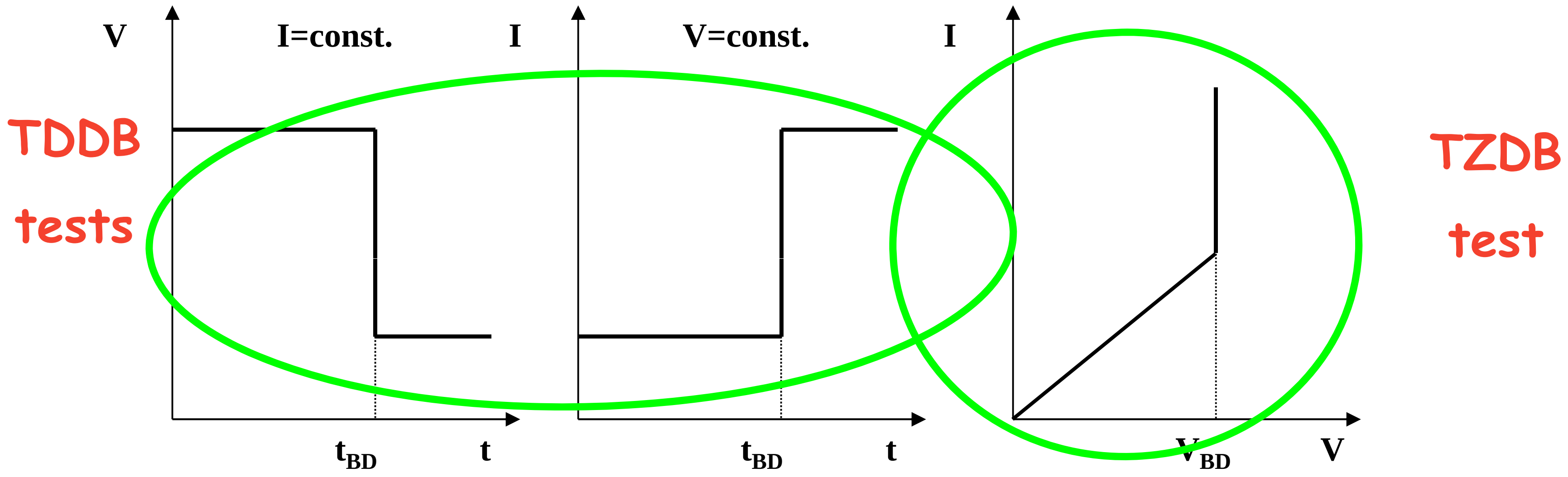
Local lost of the insulating capability as a result of the generation and accumulation of defects





Evaluation of time or charge-to-breakdown

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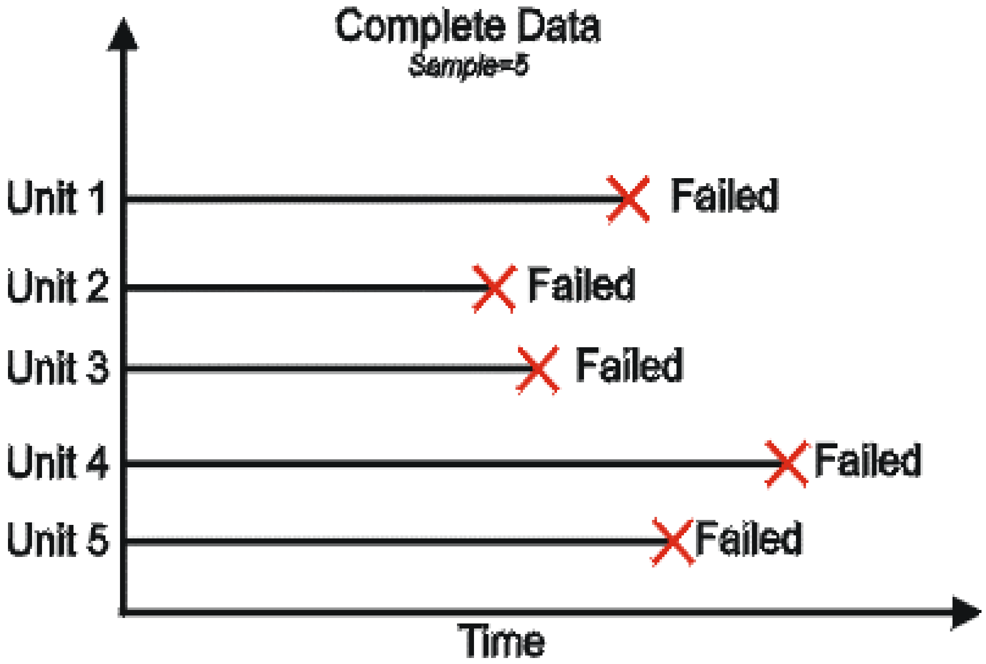
Samples are subjected to identical stress conditions



Theoretical population models are required to characterize lifetimes

The Weibull distribution

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$$F(t) = 1 - e^{-(t/c)^{\beta}}$$

c: characteristic life or scale parameter
β: Weibull slope or shape parameter

$$\ln[1 - F(t)] = -(t/c)^{\beta}$$

"Weibit"

$$\ln\{-\ln[1 - F(t)]\} = \beta \ln t - \beta \ln c$$

$$Y = \beta\ X + b$$

Weibull data are fitted by a straight line with slope β

The importance of knowing β

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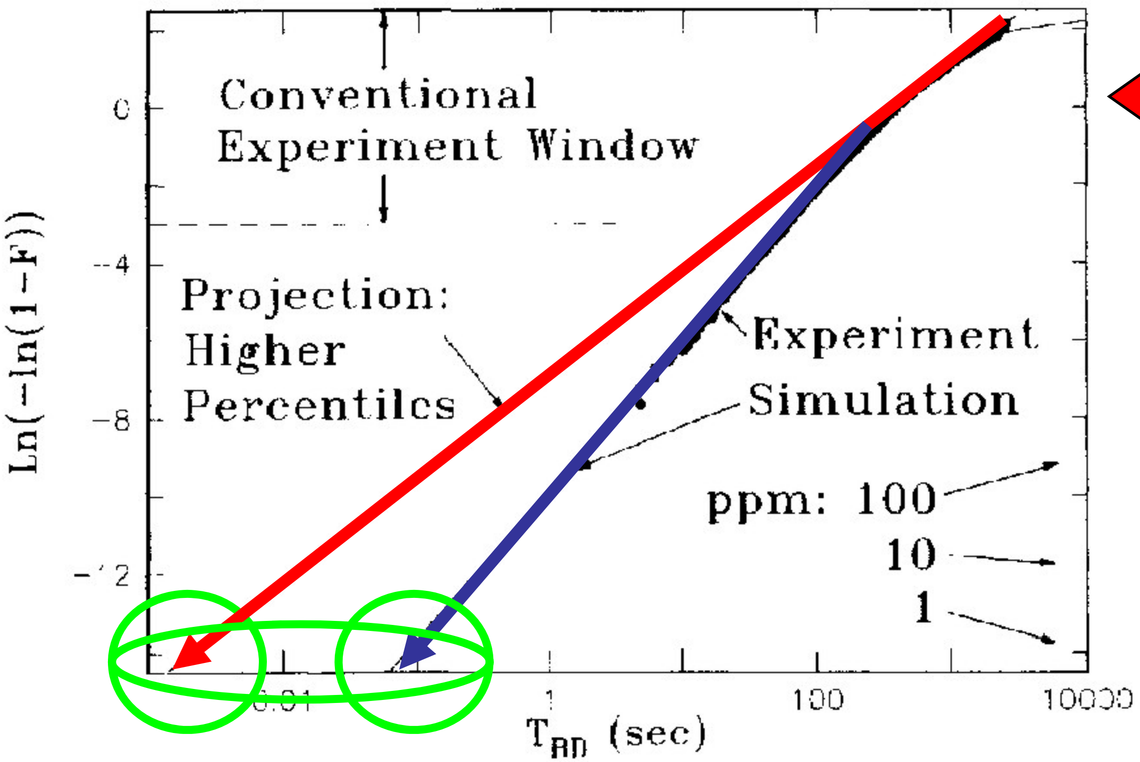
Wu et al., SST 2000



Caution should be excercised when projecting failure data

Recall that product failure rate must be specified at the low percentiles (parts per million)

Bad extrapolations underestimate or overestimate lifetimes

GOOD UNDERSTANDING OF β IS STRONGLY REQUIRED

Thickness scaling of BD data

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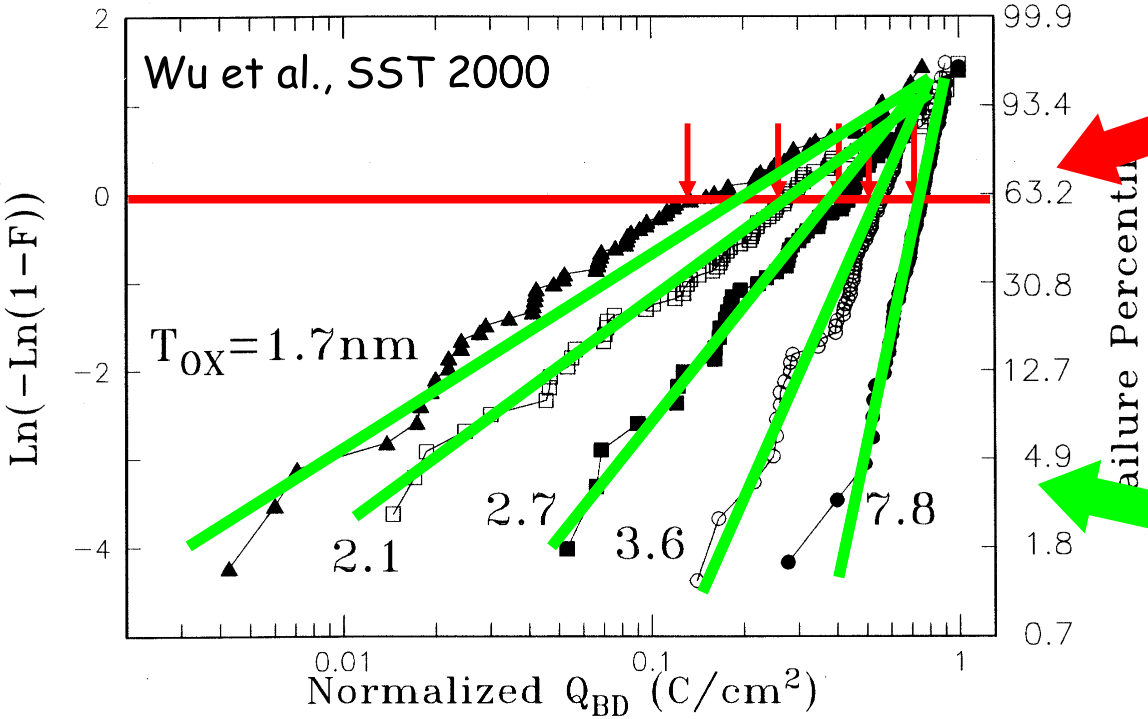

Reduction of the mean time- or charge-to-breakdown

Reduction of β with thickness

PERCOLATION THEORY

the shallower distributions for thinner oxides are due to:

- **decrease of critical defect density**
- **increase of statistical spread to form a conducting path**

BD statistics and area scaling

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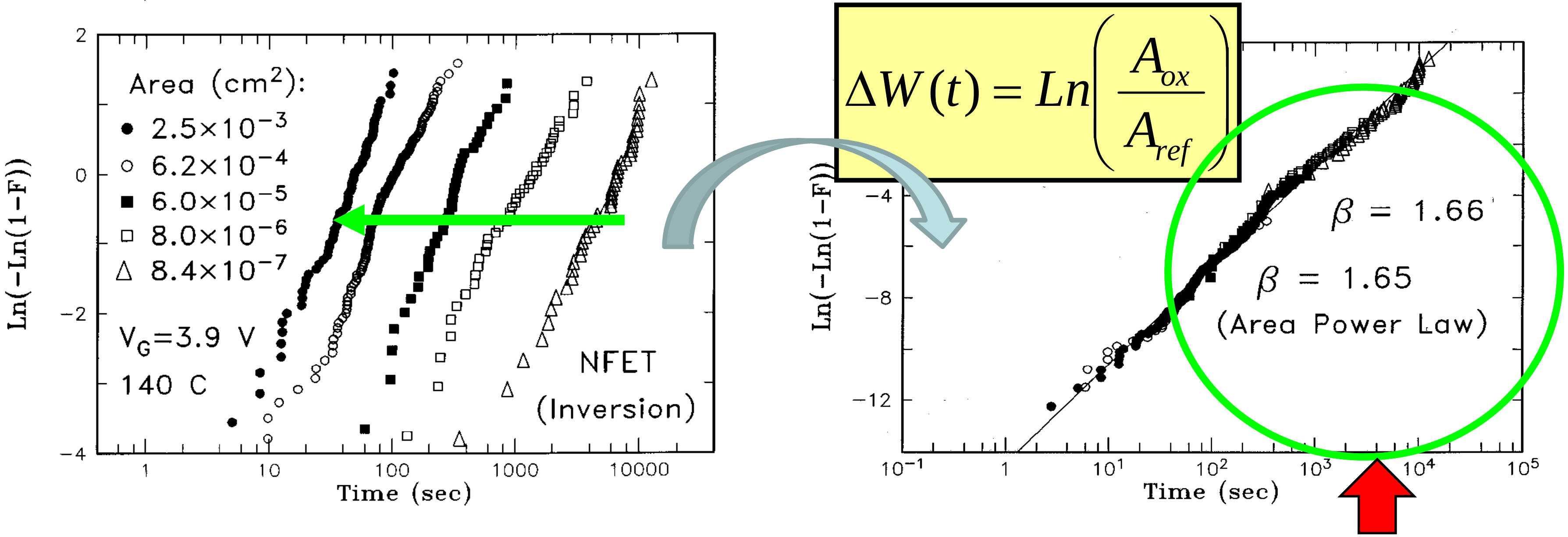
Larger areas exhibit lower time-to-breakdown <u>with same β</u>



$$\Delta W(t) = Ln\left(\frac{A_{ox}}{A_{ref}}\right)$$

All curves can be merged into a single one by a vertical shift

Breakdowns are randomly distributed over the device area which is indicative of a Poisson process

The task of a reliability engineer

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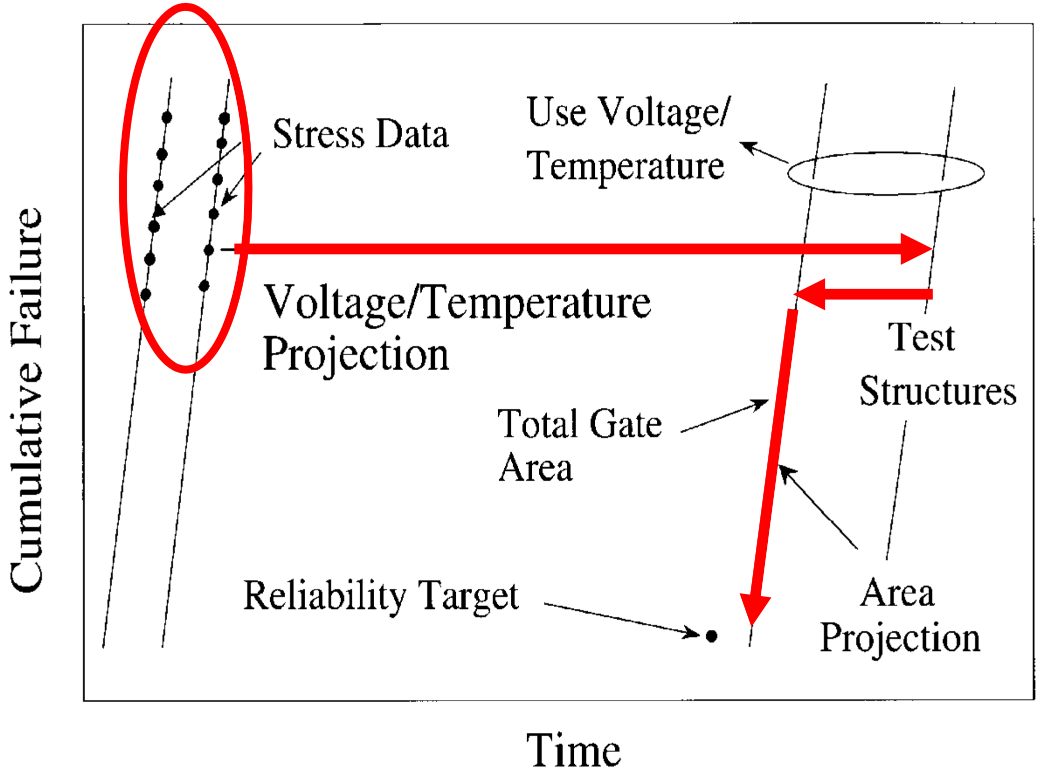


Data are obtained under accelerated stress in test structures

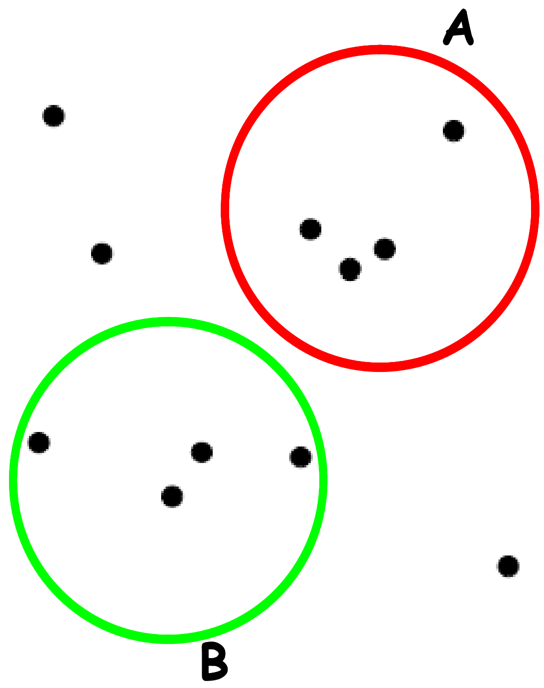
Assuming Poisson statistics

- Extrapolation to operating conditions (voltage and temperature)
- Extrapolation to total gate area (circuit level)
- Extrapolation to low percentiles (parts per million)

2D Poisson process

- **Basic 'reference' or 'null model' model of a point process in the plane, also called Complete Spatial Randomness (CSR)**

  - The number of points falling in any region *A* has a Poisson distribution
  - Given that there are *n* points inside region *A*, the locations of these points are uniformly distributed inside *A*
  - The contents of two disjoint regions *A* and *B* are independent



One BD event in many small devices is equivalent to many BD events in a single large area device

Visualization by light emission microscopy

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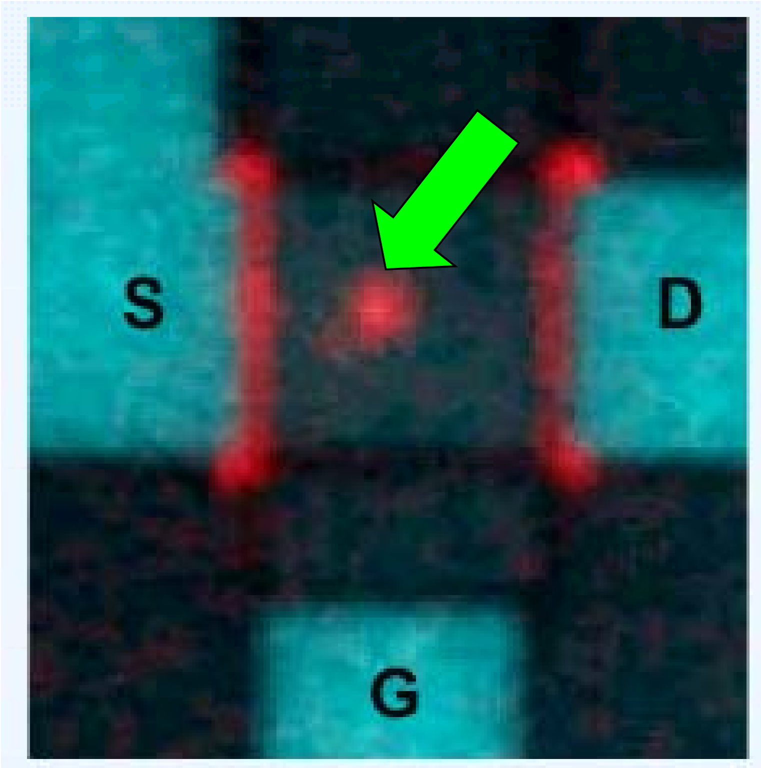
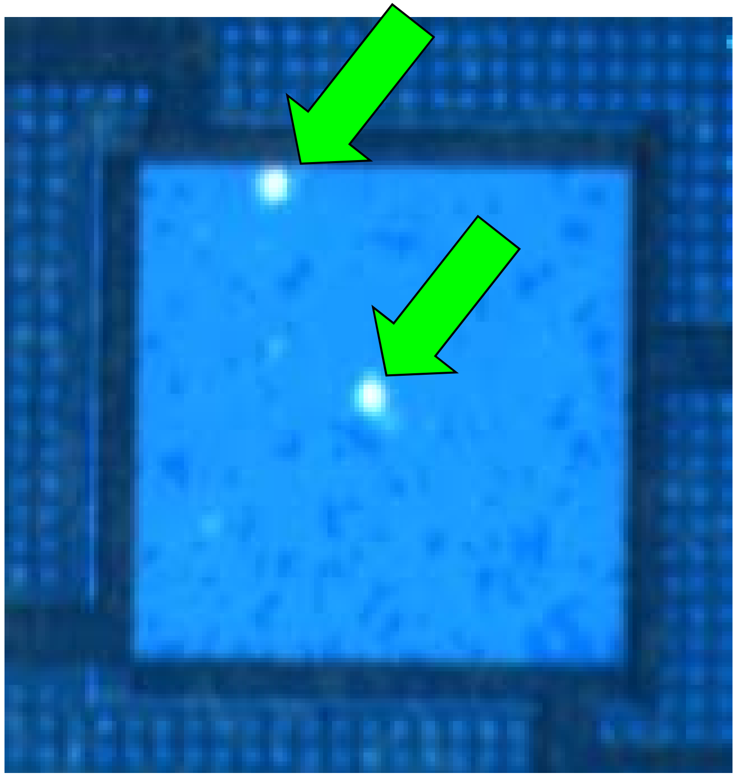


IMEC (2001)



Bruyère *et al*, IRPS 2000

One or several BD spots can be detected in a single device

Imaging BD spots with a Conductive-AFM

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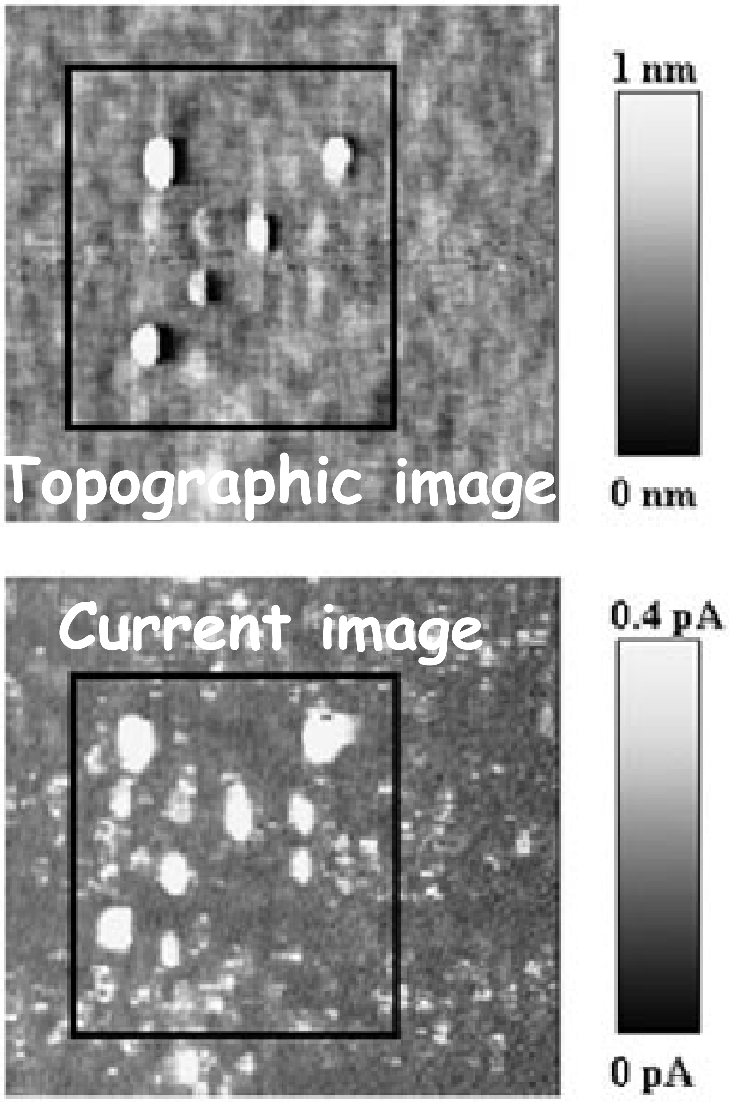
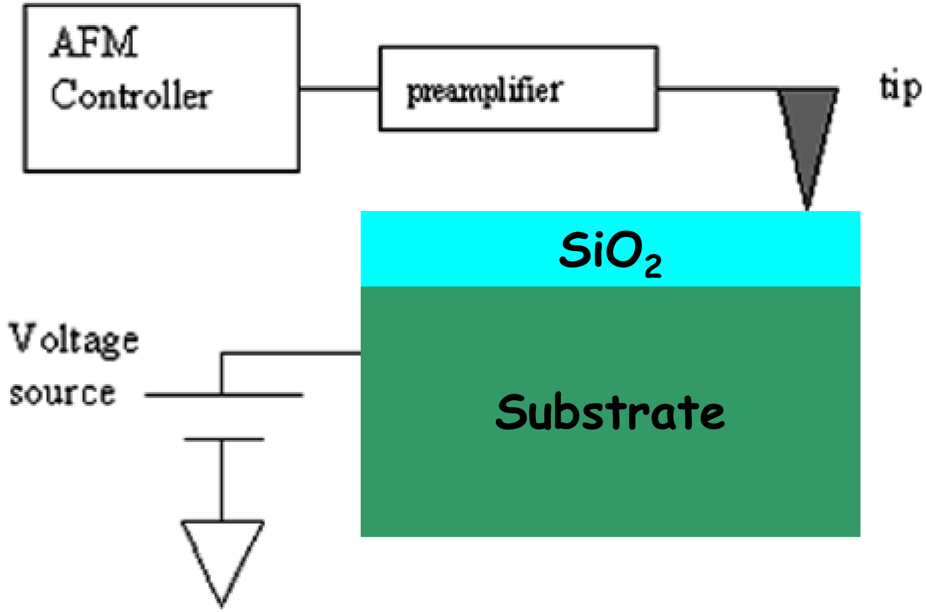


Porti *et al*, TDMR 2002



The conductive tip plays the role of the metal electrode of a MOS capacitor

Direct visualization in MOS capacitors

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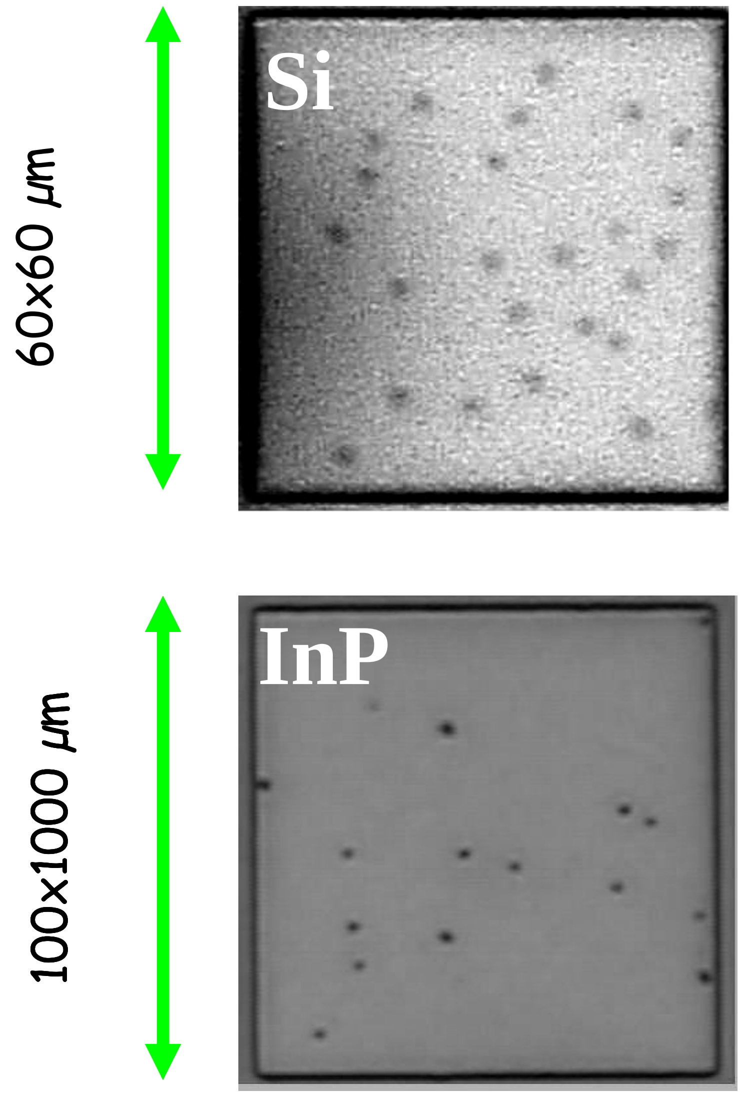

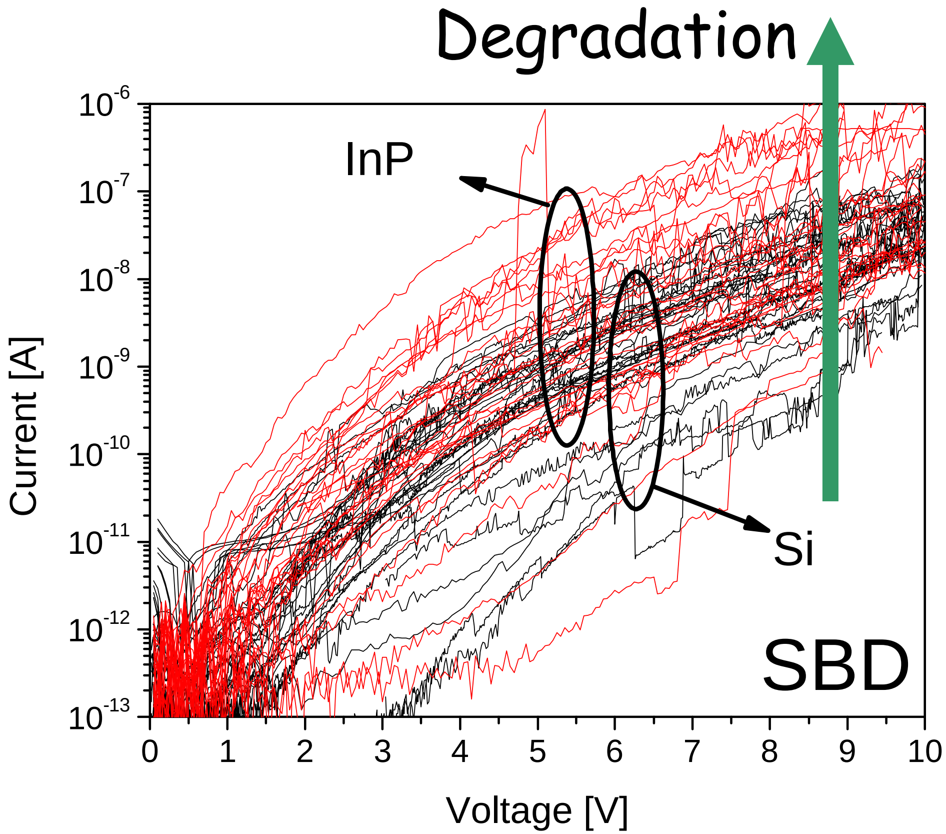

I-V characteristics after successive voltage sweeps

Miranda *et al*, ECS 2010

Direct visualization in MOS capacitors

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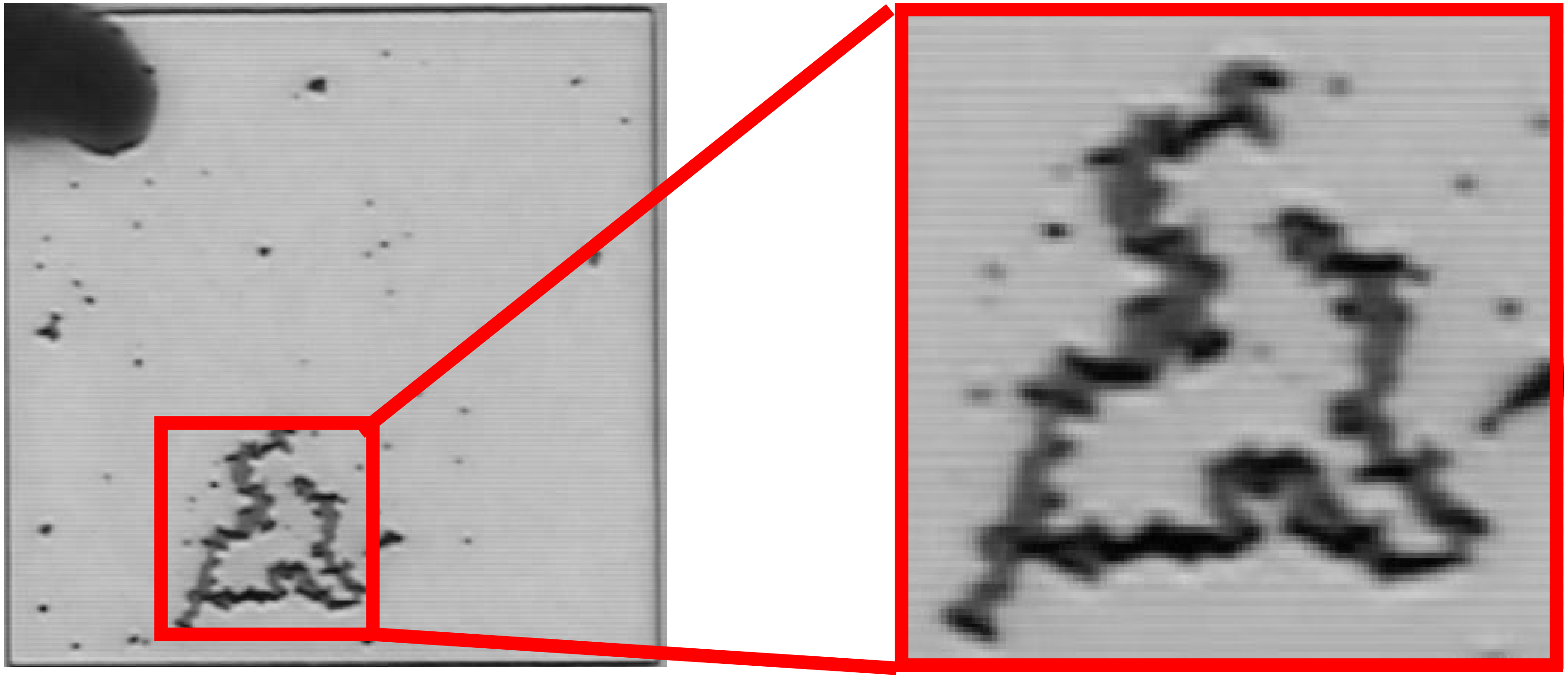

Lateral propagation of damage in the form of random walks

Multiple BD spots generation

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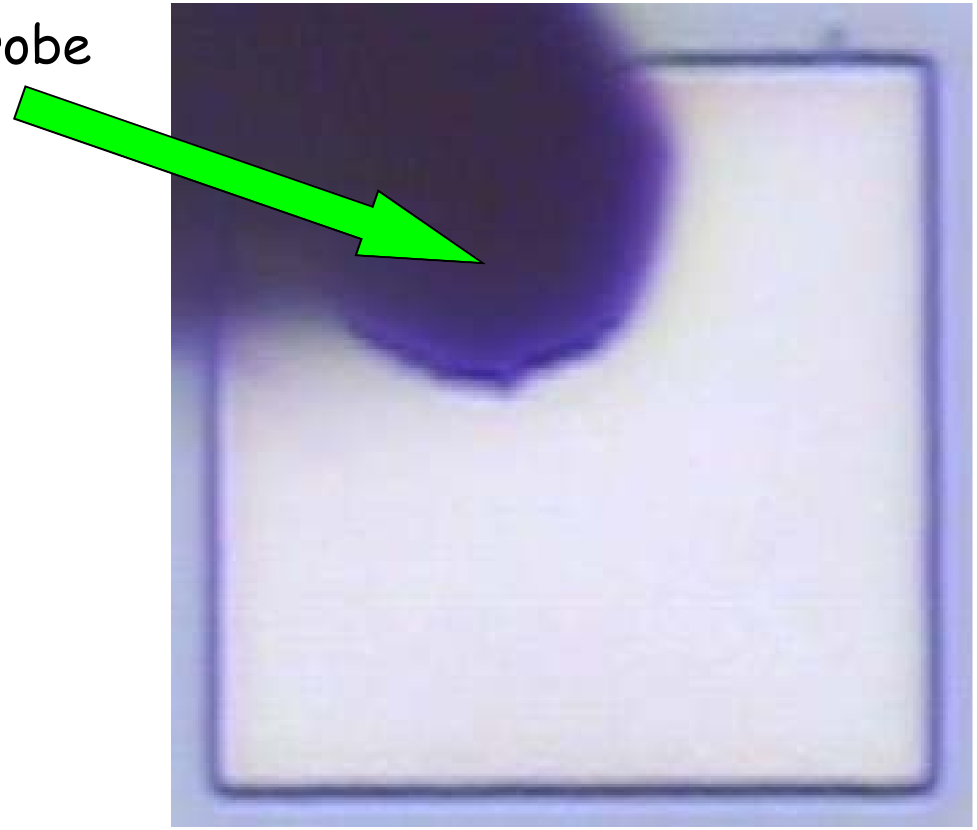
NiSi/MgO/InP (metal gate/High-K/III-V structure)

Voltage probe needle



Multiple BD spots generation

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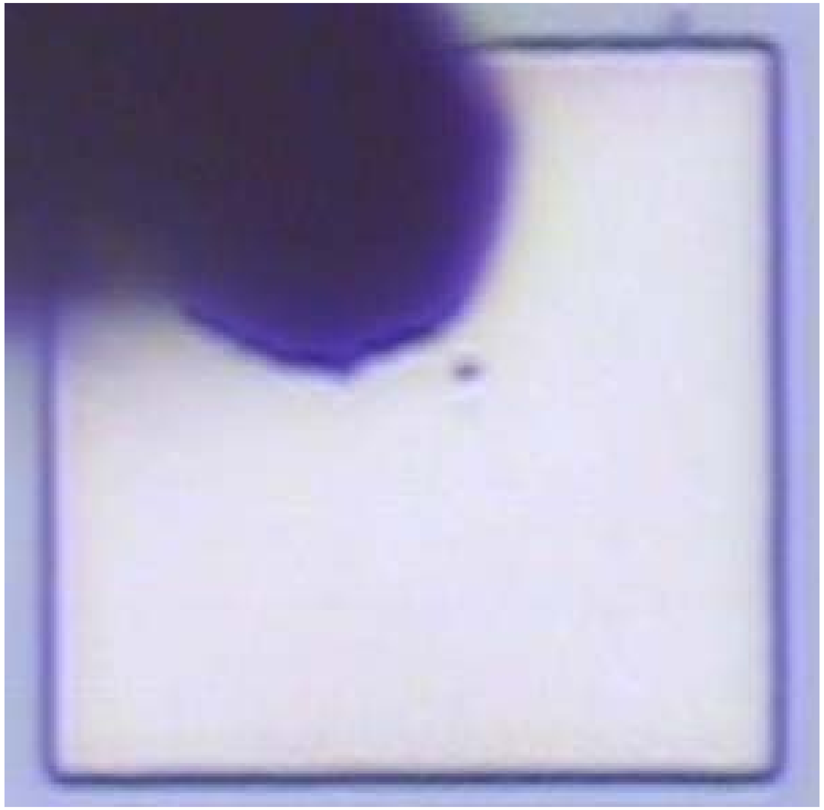

Multiple BD spots generation

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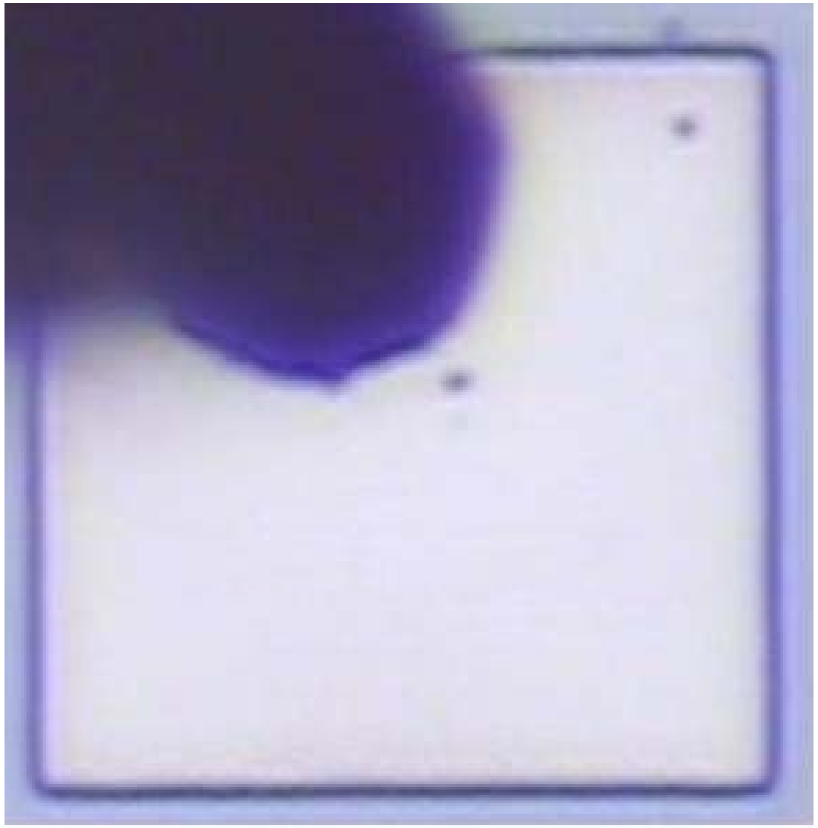
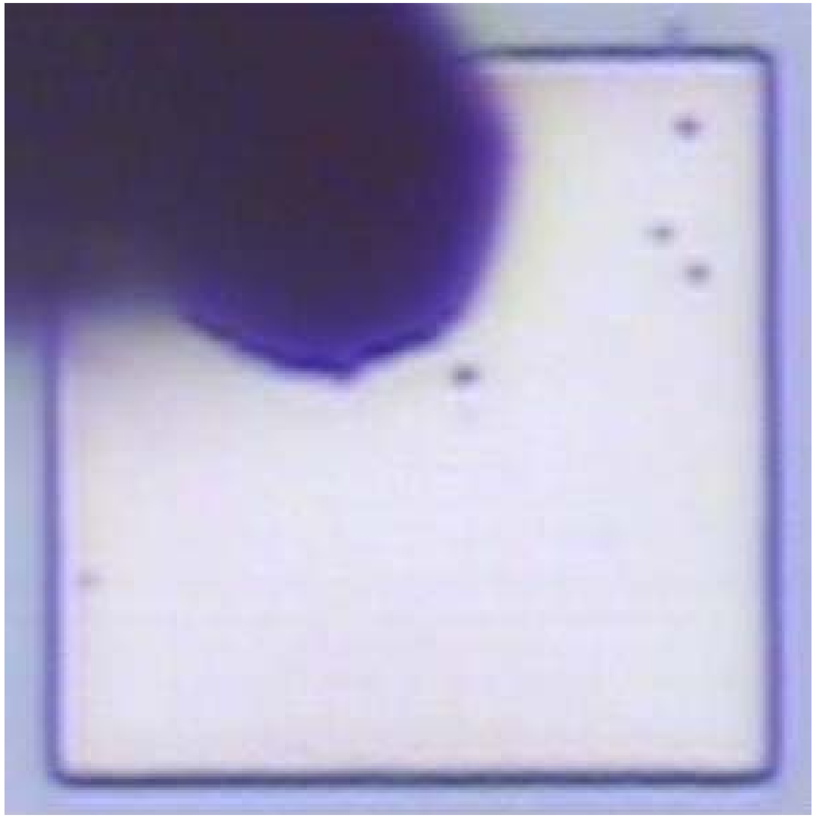


Multiple BD spots generation



Multiple BD spots generation

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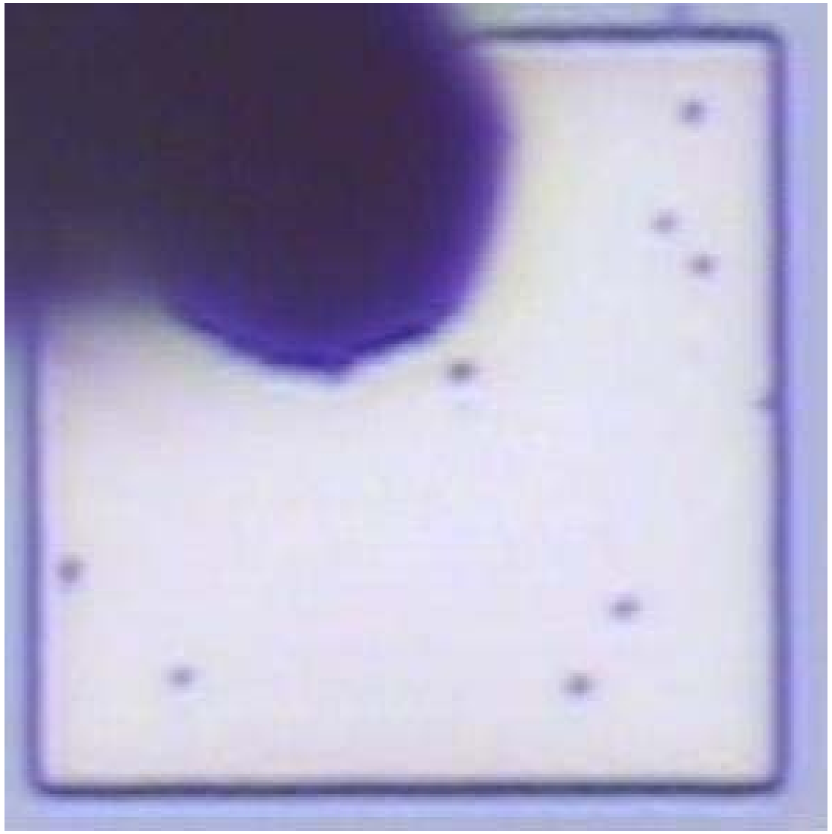
Is the BD spot distribution compatible with a Poisson process?



Is there any interaction among them?

Reliability concern

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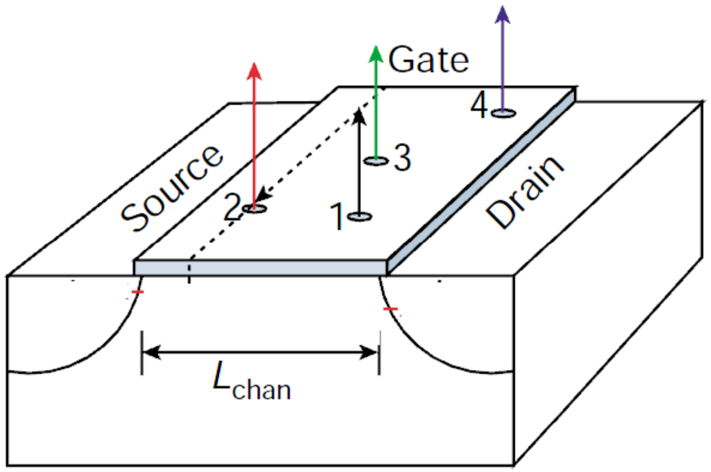

- ICs may continue to operate immediately after a BD event

- "if the localized current through the first spot forces a subsequent BD to occur in close proximity then the transistor could rapidly become inoperative"

M. Alam, IRPS'03

Therefore, it is critically important to precisely establish the degree of correlation among the positions and times of breakdown events

Temporal correlation

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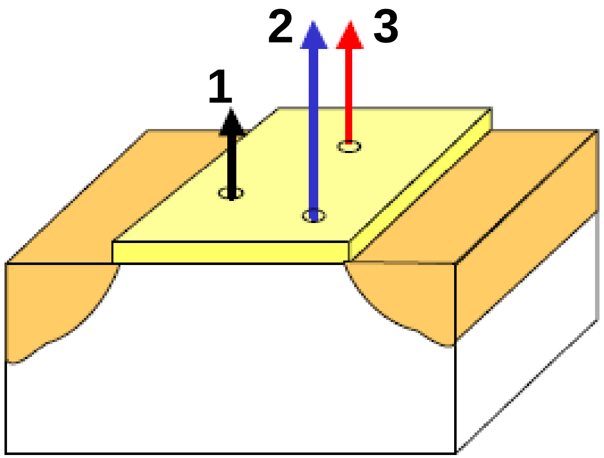
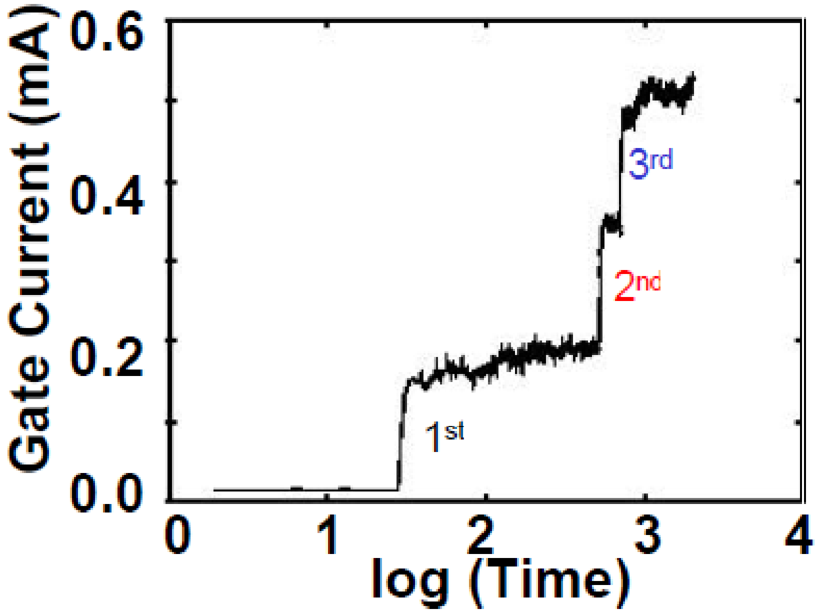


Does the time to n-breakdown depend on the time to n-1 breakdown?

Each step in the current evolution is associated with the creation of a BD spot



M. Alam, IRPS'03

Weibits for successive BD events

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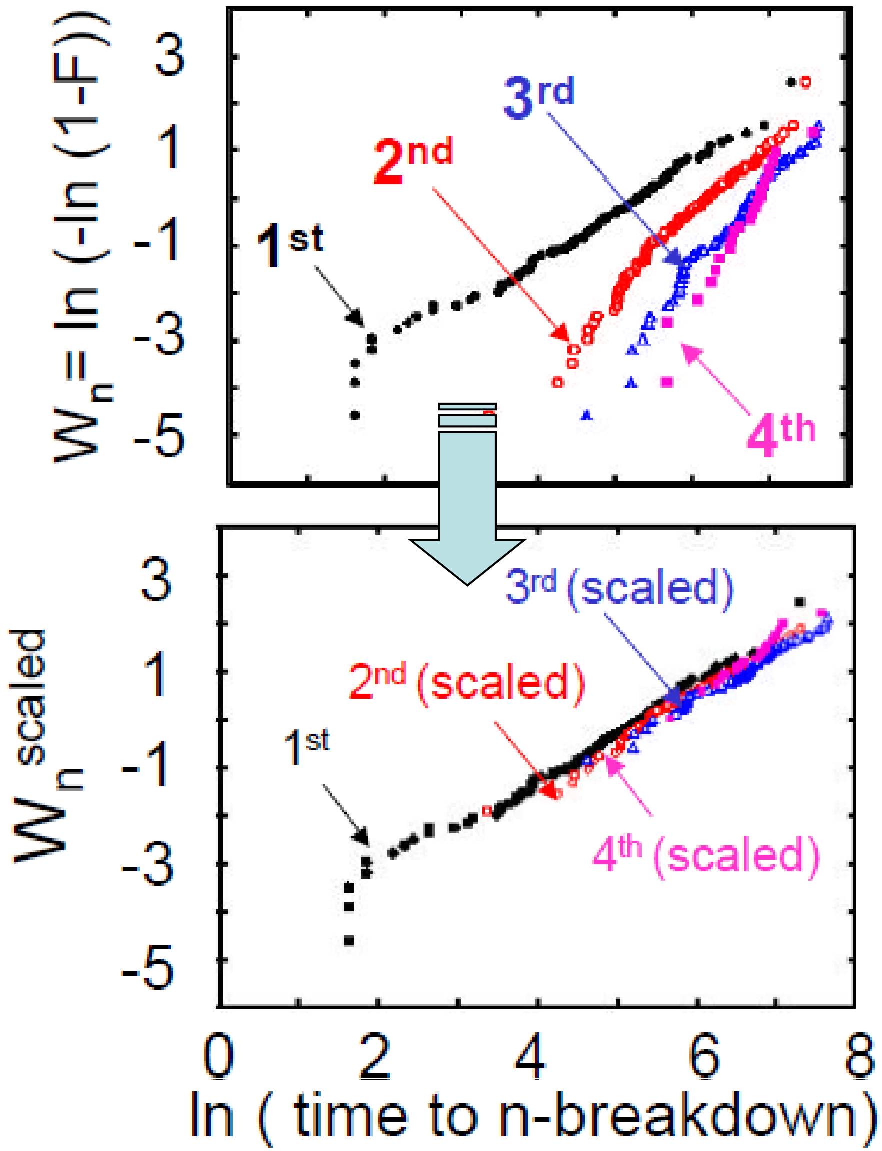
Distribution of the time to n-breakdown as measured (order statistics)

Transformed data assuming temporal uncorrelation

The BD spots do not exhibit temporal correlation



Modeling of BD order statistics

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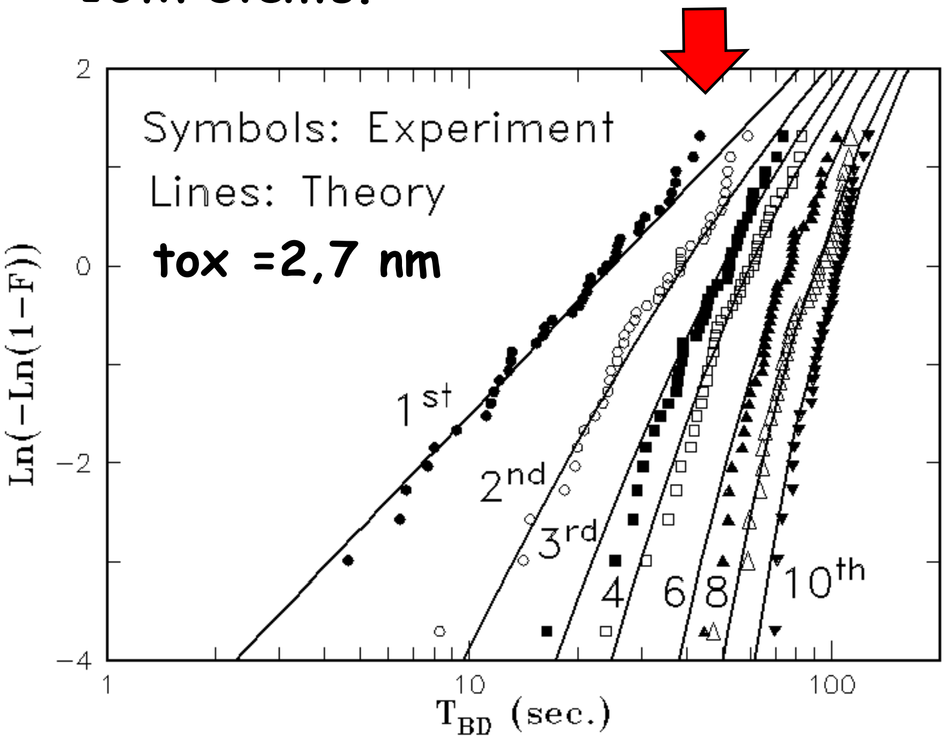
Successive BD distributions for the 1st, 2nd, 3rd, 4th, 6th, 8th, and 10th events.



- These are not straight lines in the Weibull plot
- Order statistics can be modeled assuming that the generation of successive BD paths is uncorrelated and uniform across the oxide area

Again, it is concluded that the BD spots are temporally and spatially uncorrelated

Suñé *et al*, EDL 2003

Localization of a single BD spot

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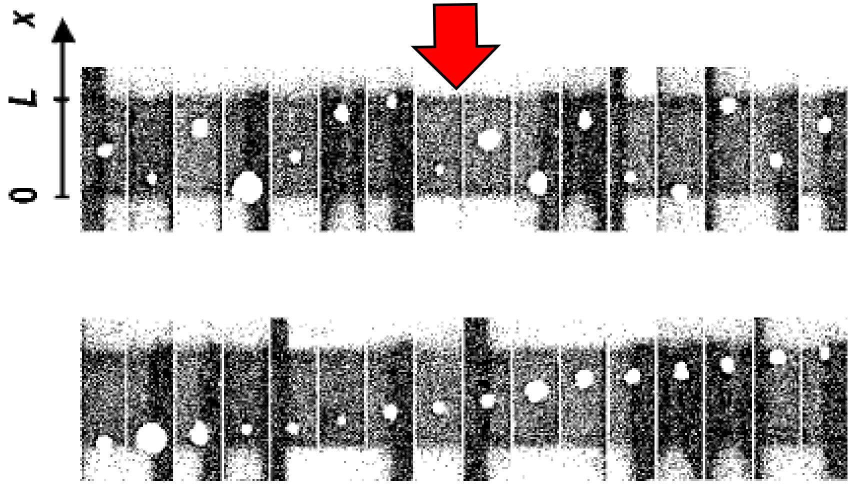
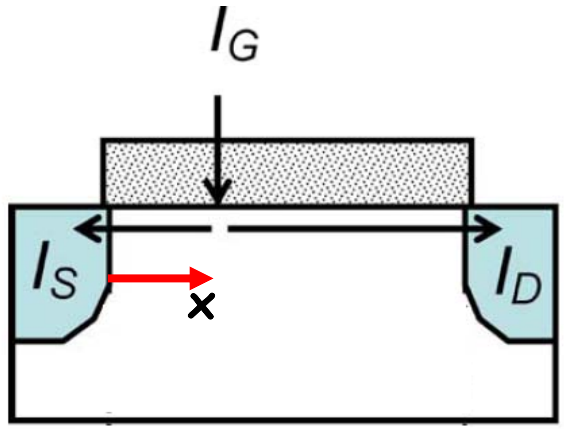
Emission microscope images of 16 nFETs

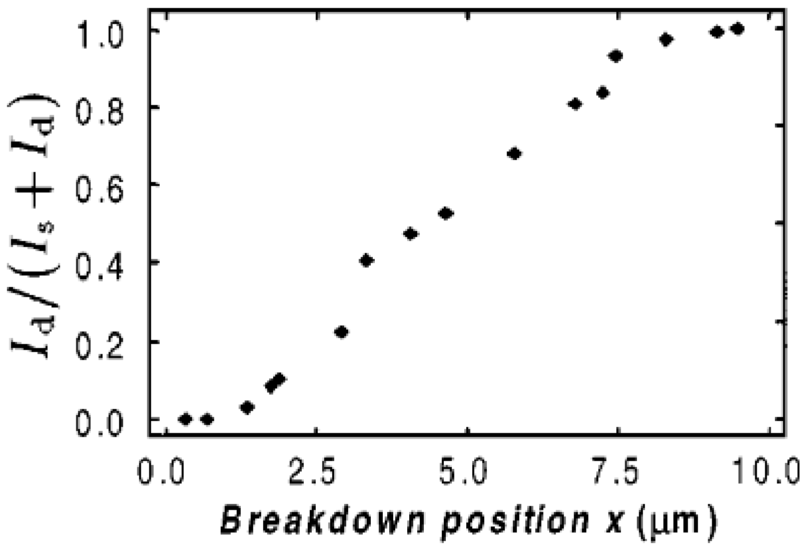


Unsorted

Sorted



$$\frac{x}{L} = \frac{I_{Drain}}{I_{Drain} + I_{Source}}$$



Approximately uniform distribution of the breakdown spots along the gate length

Degraeve *et al*, TDMR 2001

1D theory for the current-ratio method

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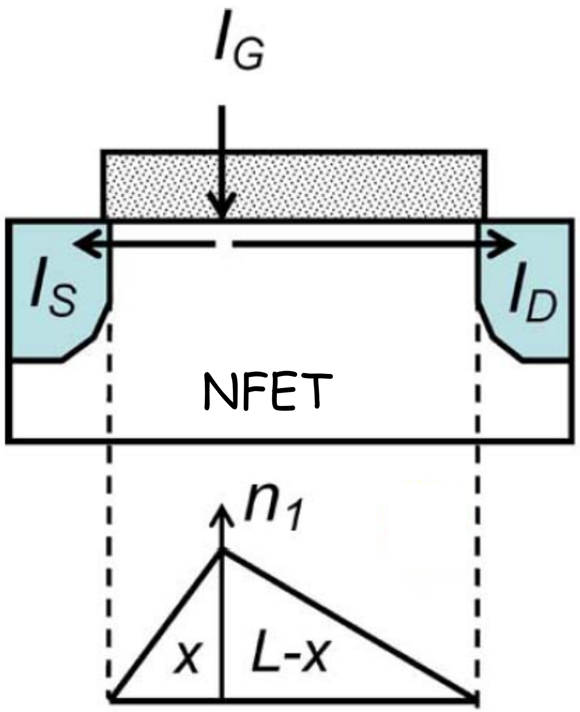

From the drift-diffusion equation in accumulation:

$$J = \cancel{qn\mu_n \nabla \phi} + qD_n \nabla n$$

n: electron density
μ_n: electron mobility
D_n: electron diffusion constant
Φ: channel potential

and using the continuity equation $\nabla \bullet J = 0$

$$D_n \nabla^2 n = 0$$

$$I_S = qAD_n n_1 / x$$

$$I_D = qAD_n n_1 / (L - x)$$

$$\boxed{\frac{x}{L} = \frac{I_D}{I_D + I_S}}$$

Alam *et al*, ED 2009

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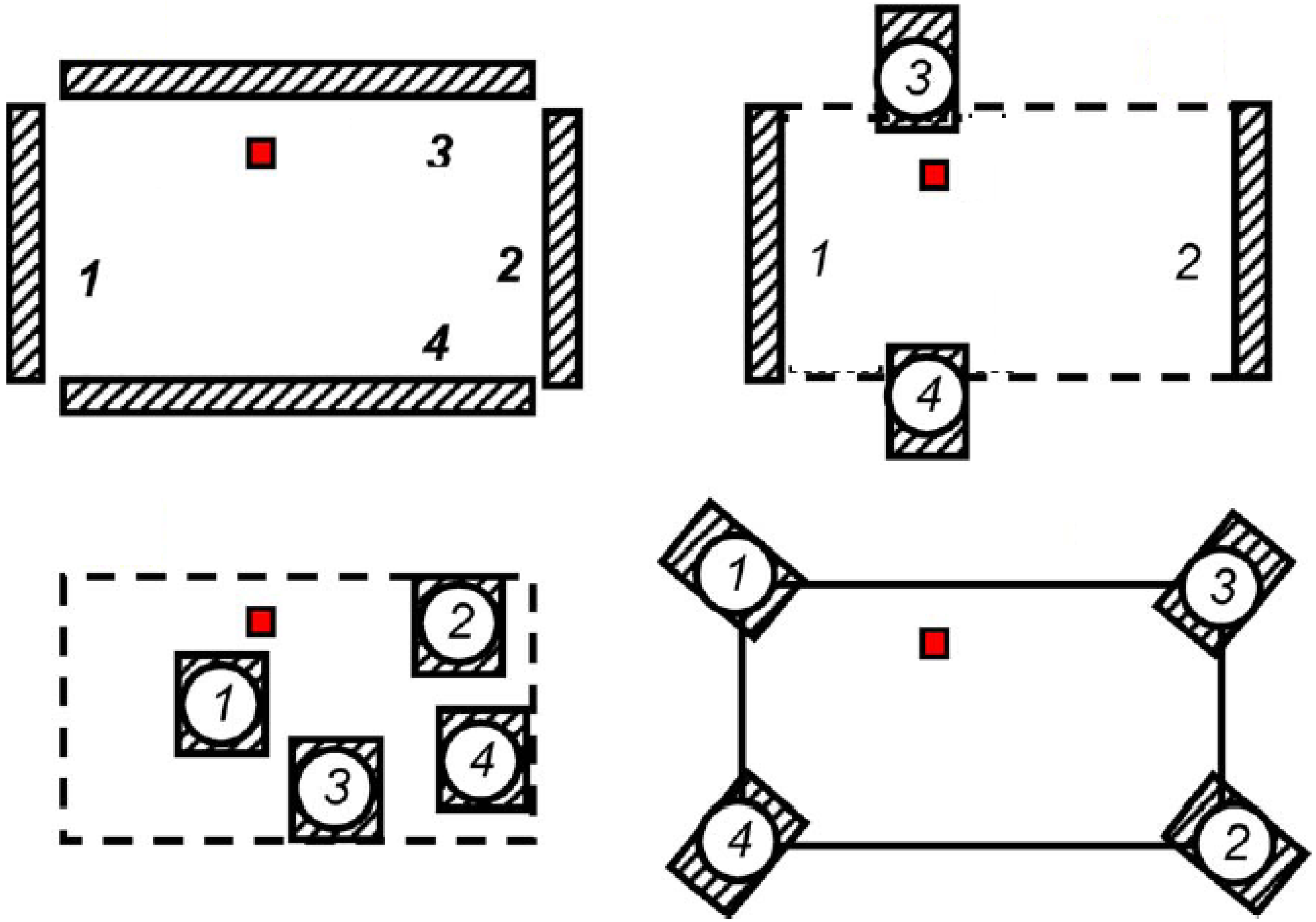
Five probe van der Pauw technique (5P-VDP)



Four different testers to locate the (x,y) positions of a BD spot

Localization in 2D

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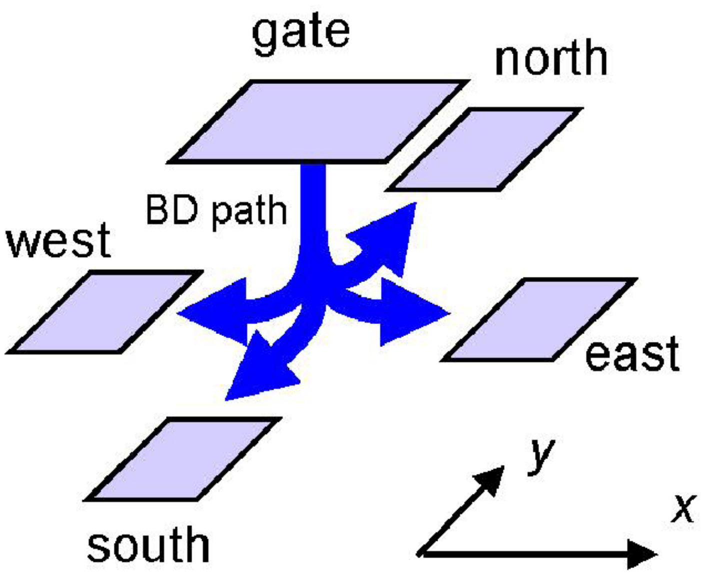
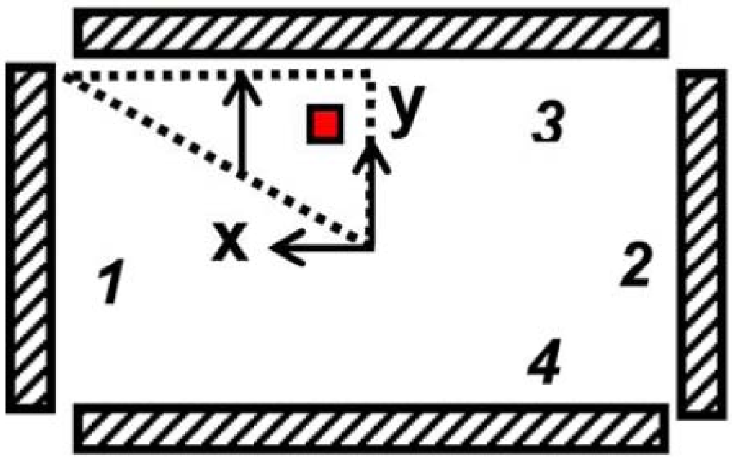


- The electrons injected through the BD spot are collected by the four grounded contacts
- The ratios of the currents depend on the relative distances of the BD spots from the respective contacts

The ordering $J_{max}>J_1>J_2>J_{min}$ allows locating the "triangle" within which the BD must have occurred



Localization in 2D

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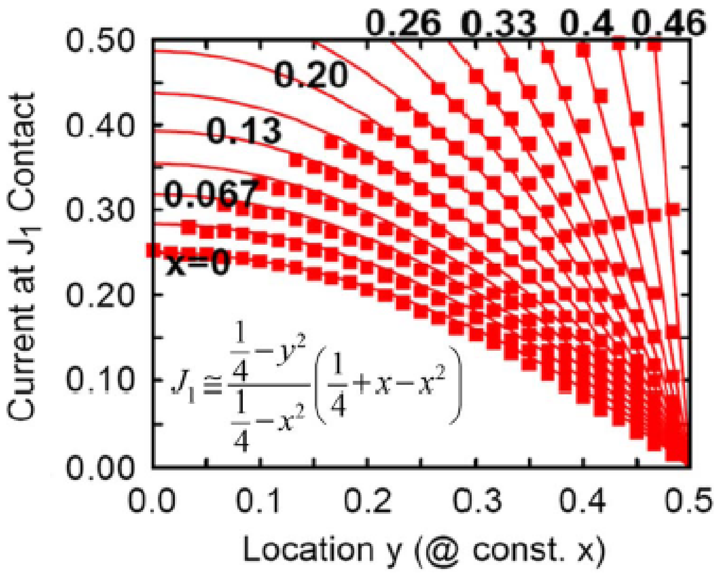
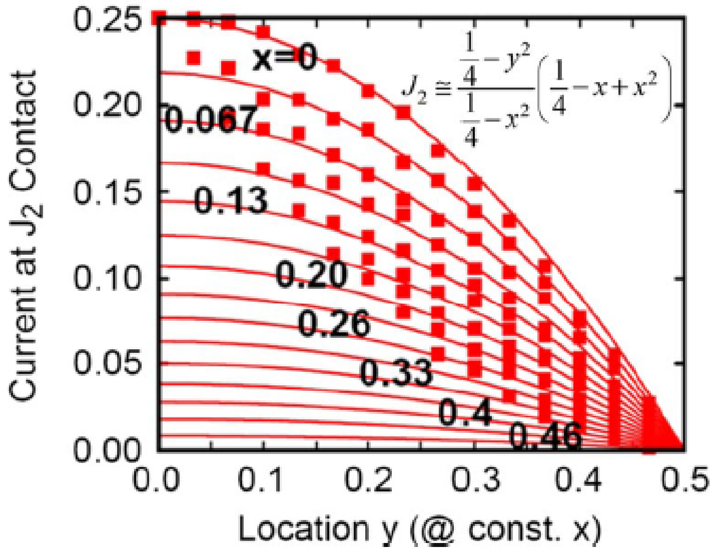




Using symmetry arguments

$$J_1 \approx \frac{(0.25 - y^2)}{(0.25 - x^2)}(0.25 + x - x^2)$$

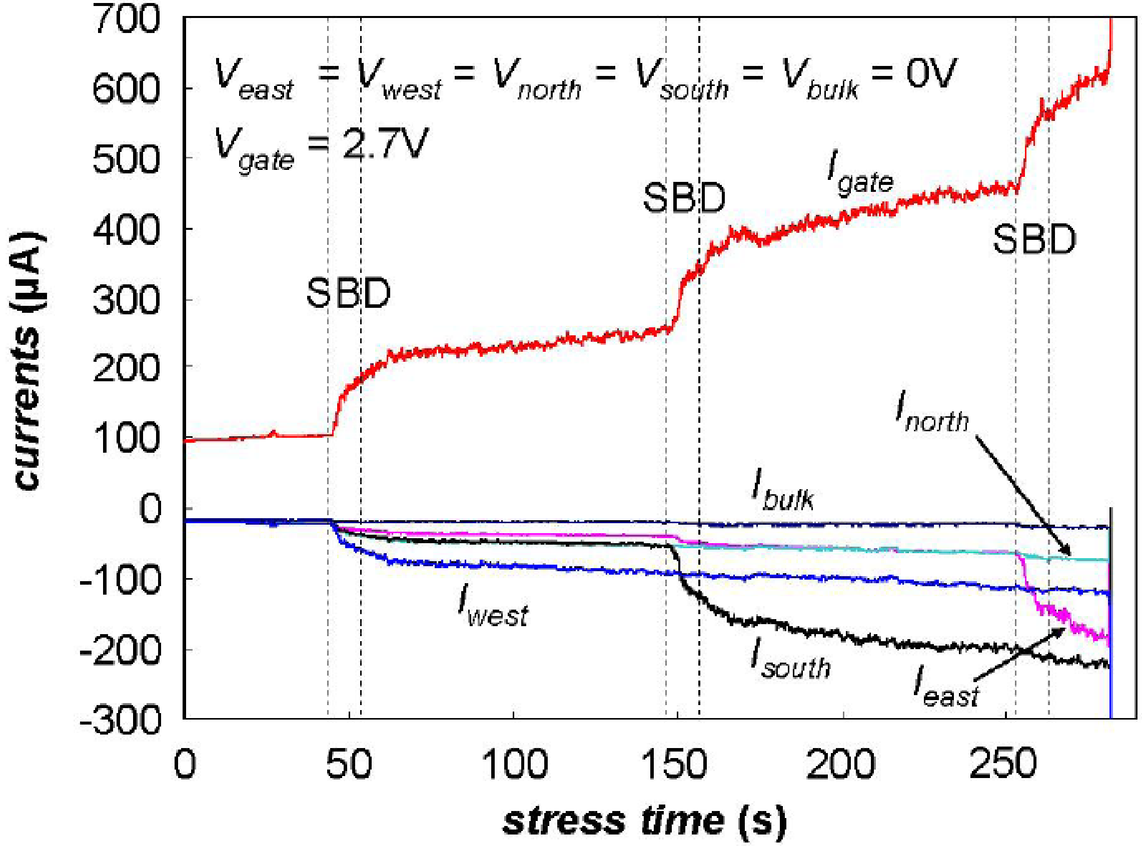
$$J_2 \approx \frac{(0.25 - y^2)}{(0.25 - x^2)}(0.25 - x + x^2)$$

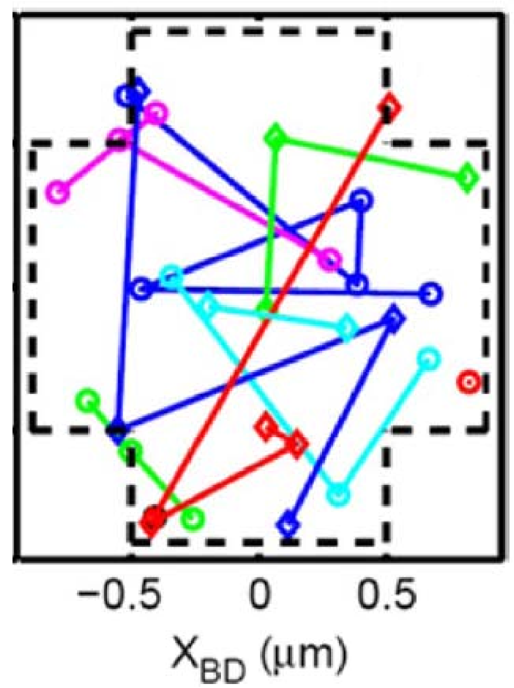
We can determine the position (x,y) from

$$\boxed{x = 0.5 - \sqrt{\frac{0.5 J_2}{J_1 + J_2}}}$$

$$\boxed{y = \sqrt{0.25 - 2(J_1 + J_2)(0.25 - x^2)}}$$

Localization in 2D



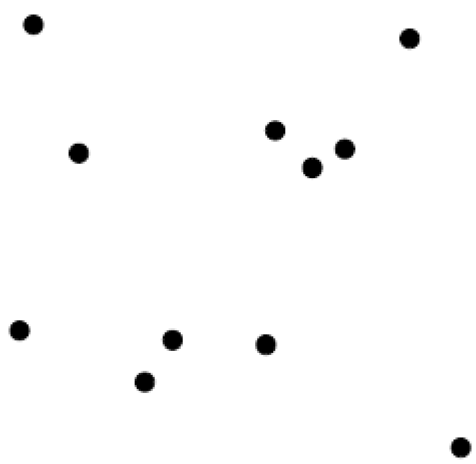


Current traces recorded during a constant voltage stress allow detecting the BD spots locations

Kaczer *et al*, IPFA 2007

Spatial statistics

A spatial point process is a random pattern of points in d-dimensional space (usually d=2 or d=3): trees in a forest, bird nests, disease cases, the locations of point-like defects in a silicon crystal wafer or … breakdown spots



The objective is to assess whether they interact or not, i.e. if they are spatially correlated

Visual defect metrology

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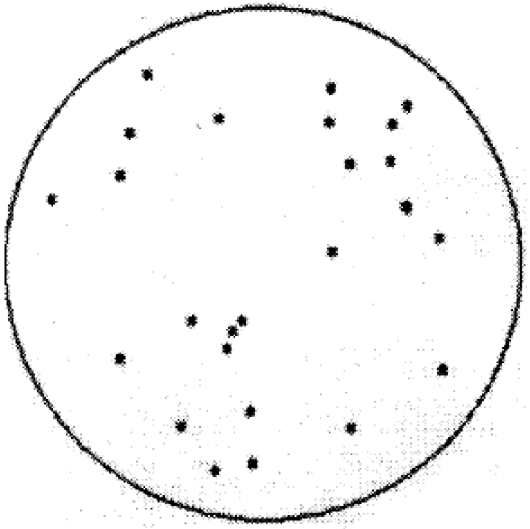
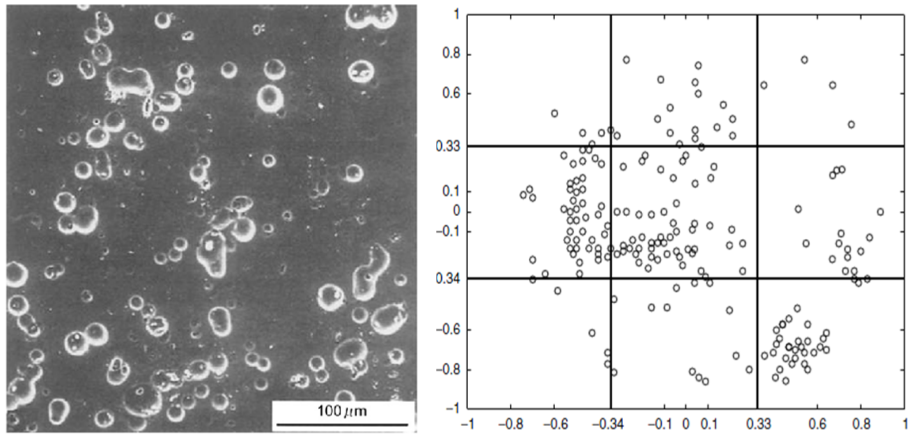
Wafer defect map (particles, opens, shorts, film thickness variations, discolorations etc.)



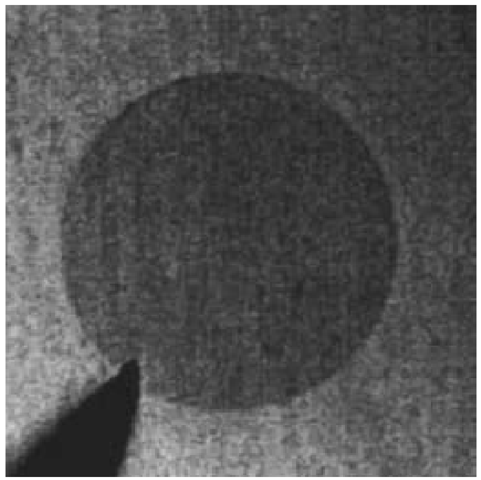
Cunningham *et al*, TSM (1998)

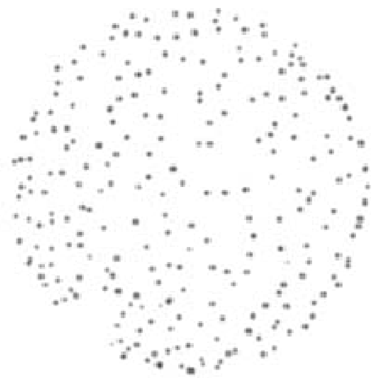
Corrosion patterning



Lopez de la Cruz *et al*, CS (2008)

Infrared light emission at breakdown sites in MIS tunnel diodes





Mihaychuk *et al*, JAP (2005)

Point pattern analysis techniques

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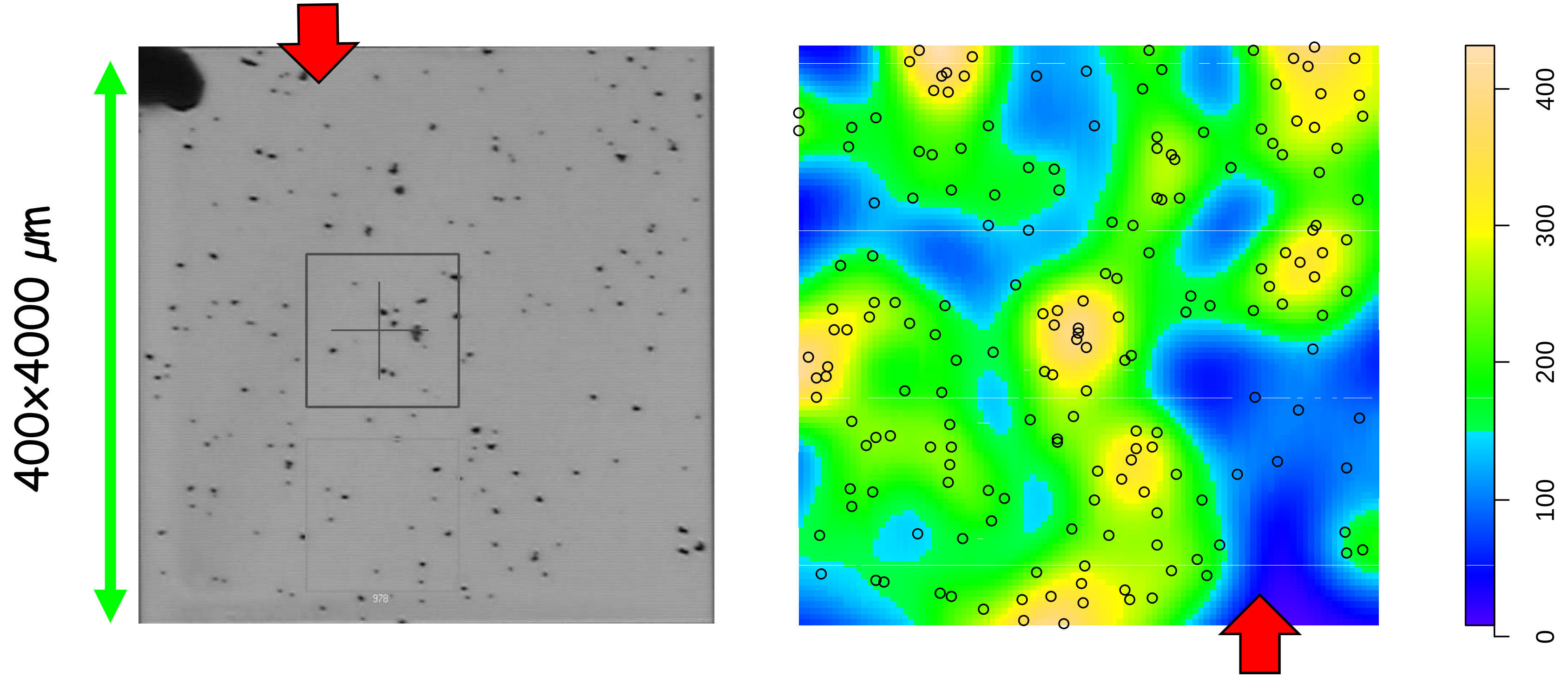
For this realisation 182 points were found



The intensity plot reveals that the points are not uniformly spread but there are empty gaps and clusters of points. This is consistent with a 2D homogeneous Poisson process

Miranda *et al*, IRPS 2010

Analysis of the BD spots spatial distribution

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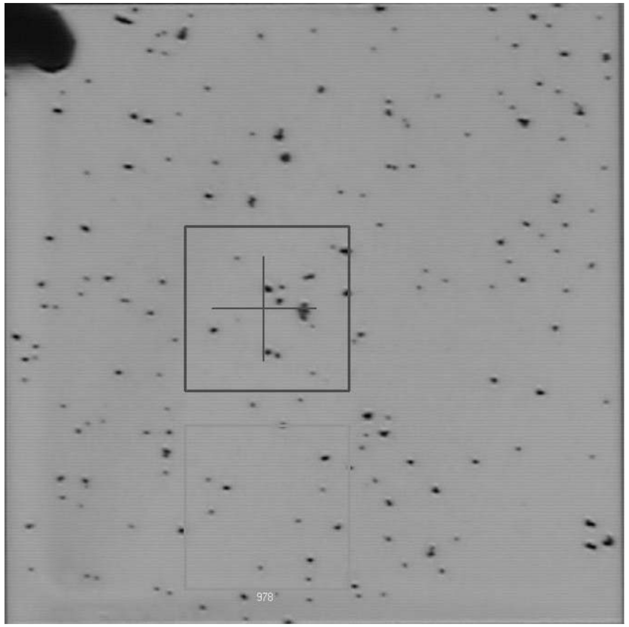

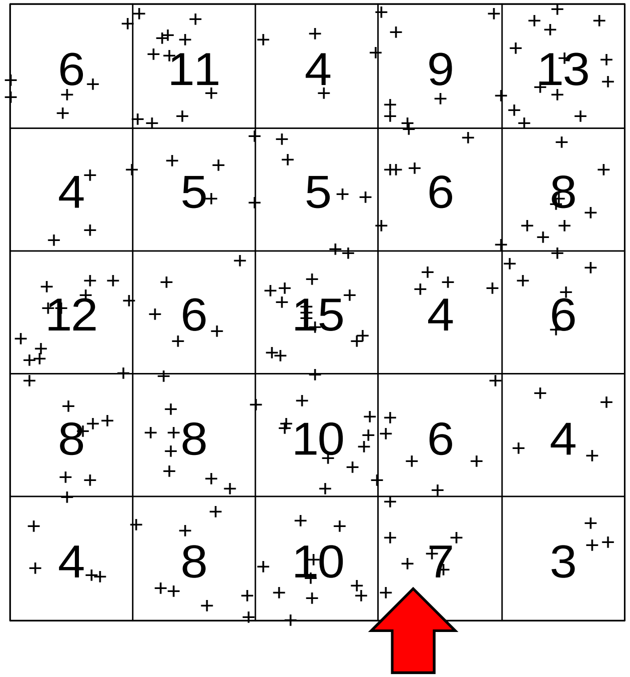

Quadrat count method: the frequency distribution of the number of events in each cell is used to compute the variance-to-mean ratio. If VTMR=1 the pattern is random

Interpoint distances distribution

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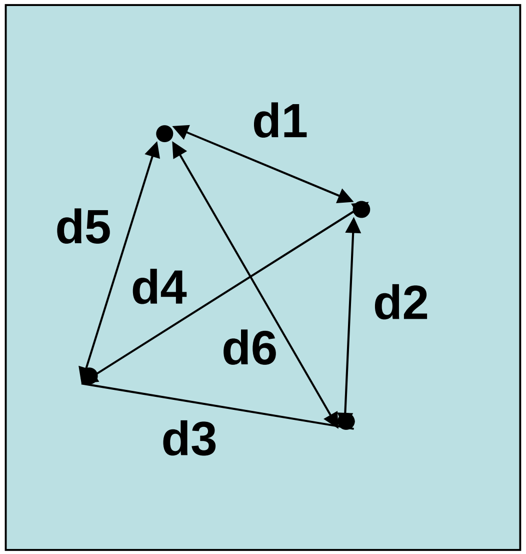

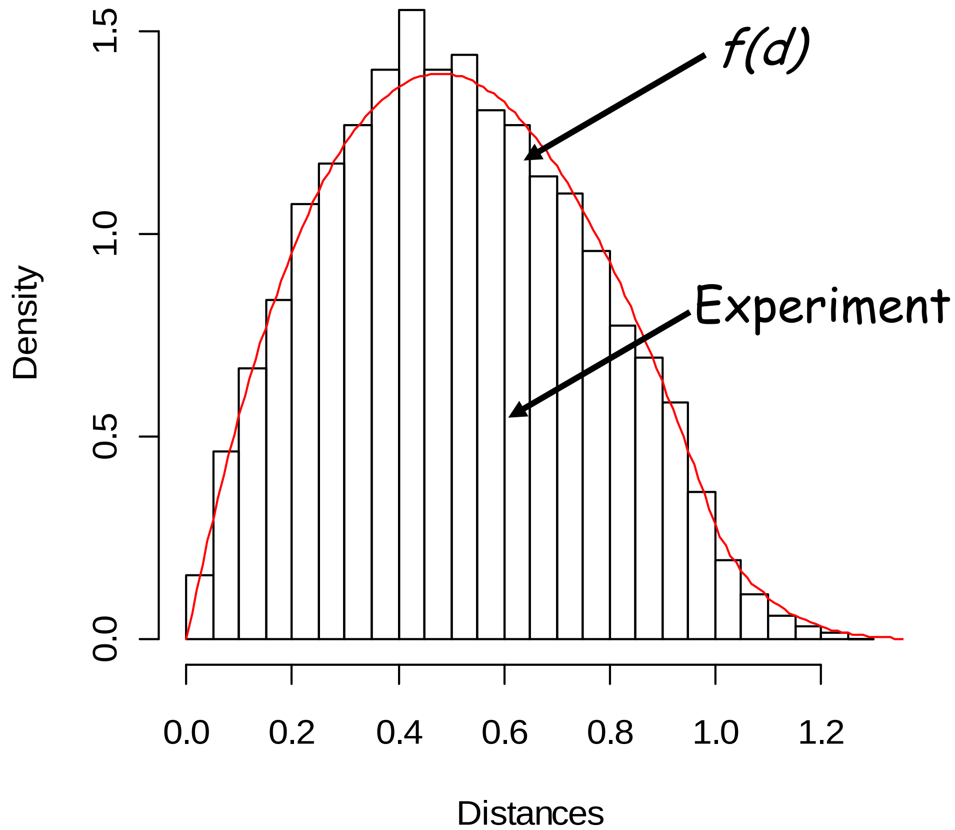

For random points in 1x1 :

$$
f(d) = \begin{cases} 4d\left[\dfrac{\pi}{2} - 2d + \dfrac{d^2}{2}\right] & 0 \le d \le 1 \\ 4d\left[\arcsin\left(\dfrac{1}{d}\right) - \arccos\left(\dfrac{1}{d}\right) - 1 - \dfrac{d^2}{2} + 2\sqrt{d^2 - 1}\right] & 1 < d \le \sqrt{2} \end{cases}
$$

Functional summary estimator K

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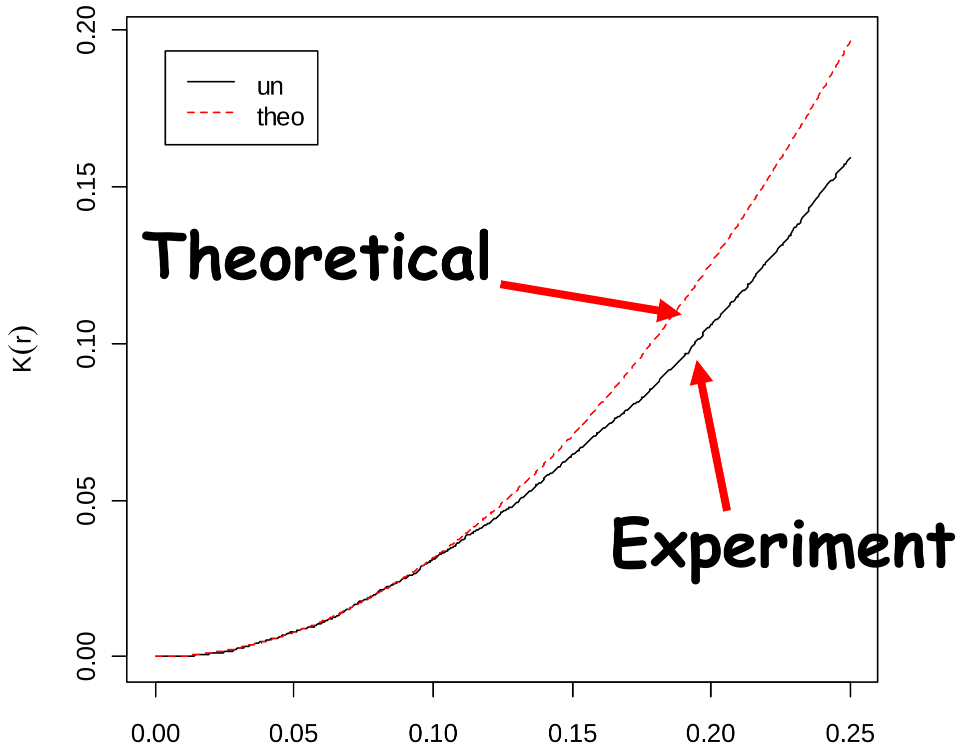
K(r) or **Ripley's function** is related to the expected number of other points of the process within a distance *r* of a typical point of the process



For a Poisson process, the number of points in a circle increases as the area of the circle:

$$K_{CSR}(r) = \pi r^2$$

Miranda *et al*, Mic Rel 2010

Pair correlation function

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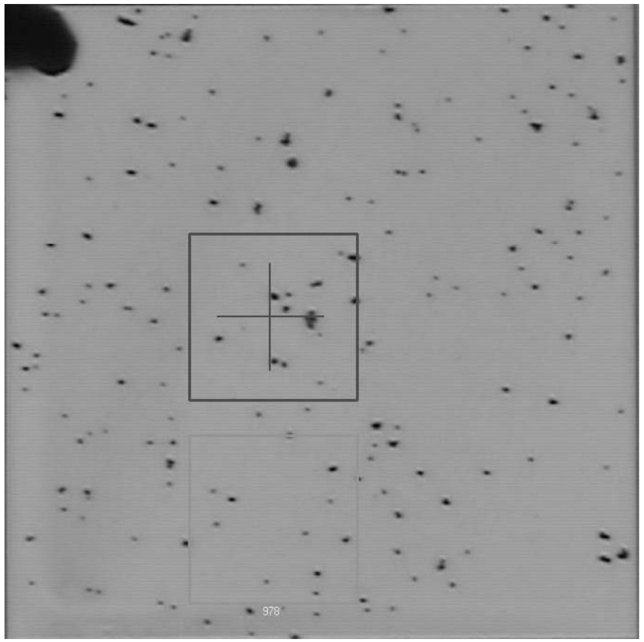
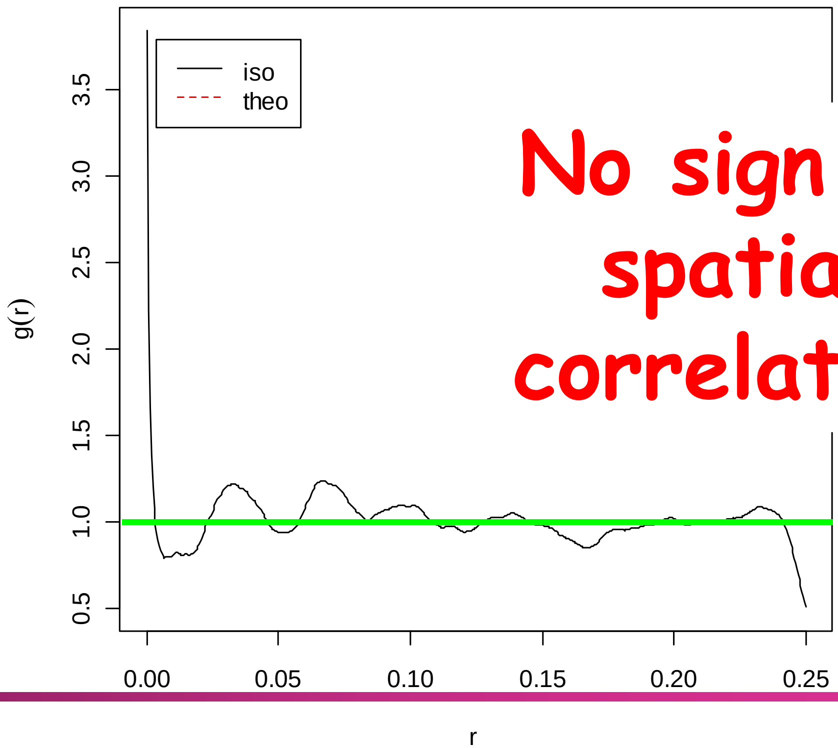
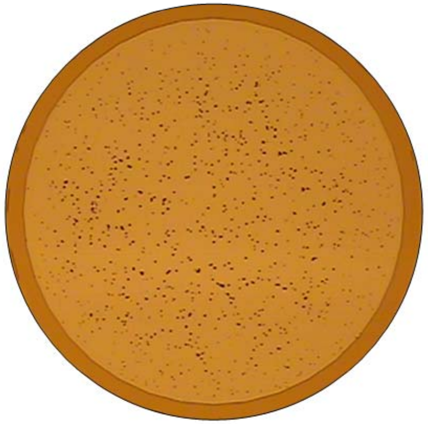
$$g(r) = \frac{1}{2\pi r}\frac{dK(r)}{dr}\begin{cases} = 1 & r \geq 0 & \textit{Poisson process} \\ \geq 1 & \textit{small } r & \textit{cluster process} \\ \leq 1 & \textit{small } r & \textit{regular process} \\ = 0 & r \leq r_0 & \textit{hard core potential} \end{cases}$$





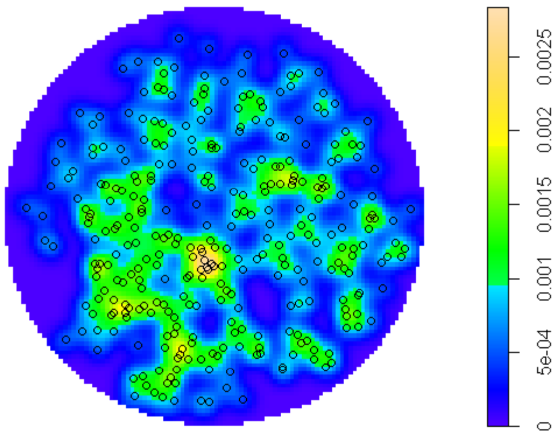
No sign of spatial correlation

Failure events in circular MIM capacitors*

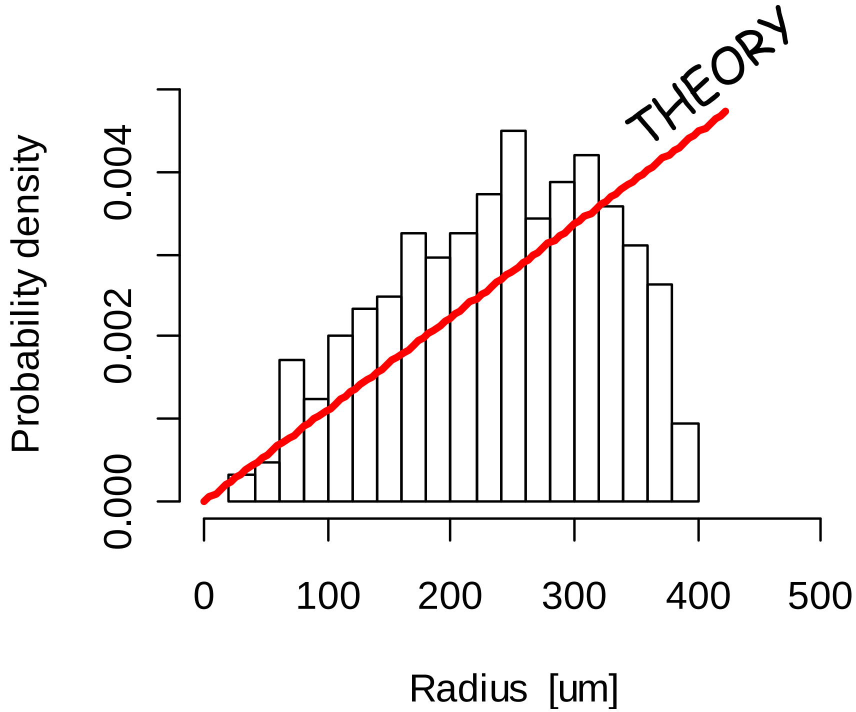


Pt/HfO_2/Pt

Should we always expect CSR in MOS/MIM devices?

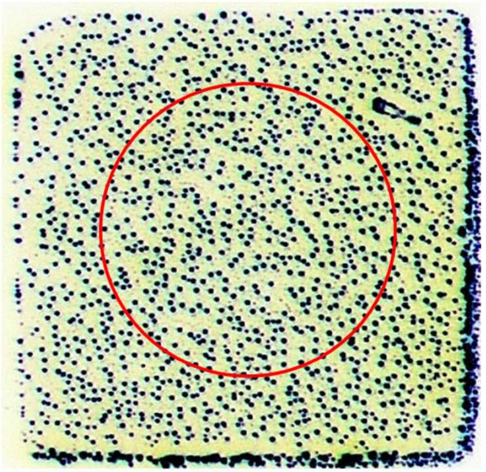


Low intensity at the edges



* In colaboration with Tyndall National Institute, Ireland

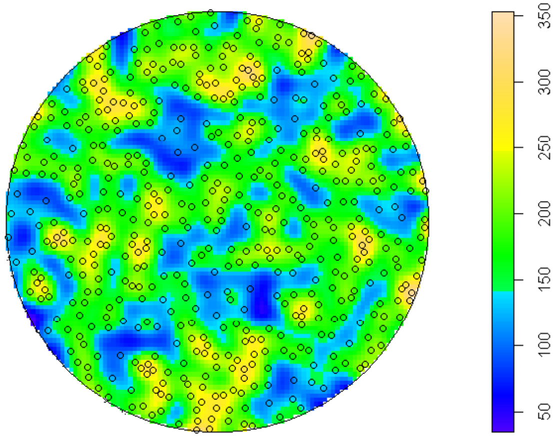
Failure events in high-K/III-V structures*

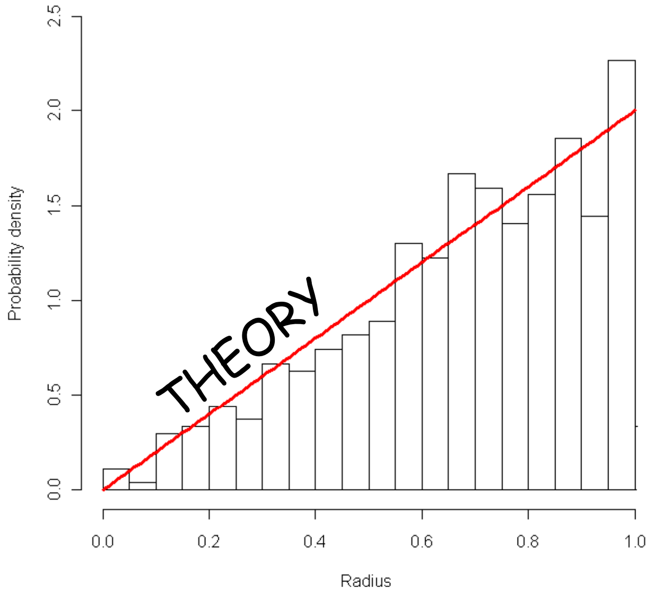


$(TiO_2)_x(Al_2O_3)_{1-x}$ / GaAs

High intensity at the edges

In case of clear nonuniformities a zoomed approach is performed:





* In colaboration with Indian Institute of Technology, India

Conclusions

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- Spatial statistics is a useful technique to investigate the dielectric breakdown phenomenon in MOS/MIM structures
- Caution should be excercised in reliability analysis when projecting in area failure data. This cannot be taken for granted.
- More generally, the methods described here can be easily applied to other systems exhibiting some kind of random spatial pattern
- Spatstat package for R language (freely available)

Thank you for your attention!

In case of any doubt you can contact me at:

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BIO

Enrique MIRANDA was born in Buenos Aires, Argentina in 1963. He has a PhD in Electronics Engineering from the Universitat Autònoma de Barcelona (UAB), Spain (1999) and a PhD in Physics from the Universidad de Buenos Aires (UBA), Argentina (2001). From 1987 to 2003, he was Assistant Professor at the Faculty of Engineering - UBA and from 2001 to 2003, Associated Researcher of the National Council of Science and Technology-CONICET, Argentina. Since 2003, he is Professor at the Escola d'Enginyeria-UAB. Dr. Miranda has received research fellowships from the Spanish International Cooperation Agency-AECI: INTERCAMPUS (Universidad de Zaragoza) and MUTIS (UAB), from the German Exchange Academic Agency-DAAD (Technical University Hamburg-Harburg), from the italian government (Universita degli Studi di Padova), from the Ministerio de Ciencia y Tecnología, Spain: RAMON y CAJAL (UAB), from the Matsumae International Foundation: MATSUMAE (Tokyo Institute of Technology, Japan), TAN CHIN TUAN (Nanyang Technological University, Singapore) and from the Science Foundation Ireland: WALTON visitor awards (Tyndall Insitute, Ireland). He has authored and co-authored around 90 papers most of them devoted to the electron transport problem through the gate insulator in MOS devices: direct and Fowler-Nordheim tunneling, effects of trapped charge, stress-induced leakage current and post-breakdown conduction. Dr. Miranda serves as member of the Distinguished Lecturer program of the Electron Devices Society (EDS-IEEE) and is reviewer of IEEE TED, IEEE EDL, JAP, APL, TSF, MJ and MR. He also serves as Editorial Advisor of the journal Microelectronics Reliability and forms part of INFOS, IRPS, ESREF, MIEL and EMRS Technical Committees. Dr. Miranda is Visiting Scientist (2009-2012) at the National Comission of Atomic Energy (CNEA), Argentina financially supported by the Abdus Salam International Centre for Theoretical Physics, Italy.