Integration of High Performance Robust Lateral DMOS Devices in Advanced Smart Power BCD Platform

R. Depetro[1], G. Croce[1], P. Galbiati[1],
A. Tallarico[2], S. Reggiani[2], F. Giuliano[2], C. Fiegna[2]

[1] Technology R&D, STMicroelectronics, Agrate Brianza, Italy
[2] ARCES-DEI, University of Bologna, Cesena, Italy

life.augmented

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA
ARCES

ECPE

OUTLINE

- History and evolution
- Where and what robustness count
- How (to try) to address problems …
- Examples
- Conclusions

OUTLINE

- History and evolution
- Where and what robustness count
- How (to try) to address problems…
- Examples
- Conclusions

BCD Technology Segmentation

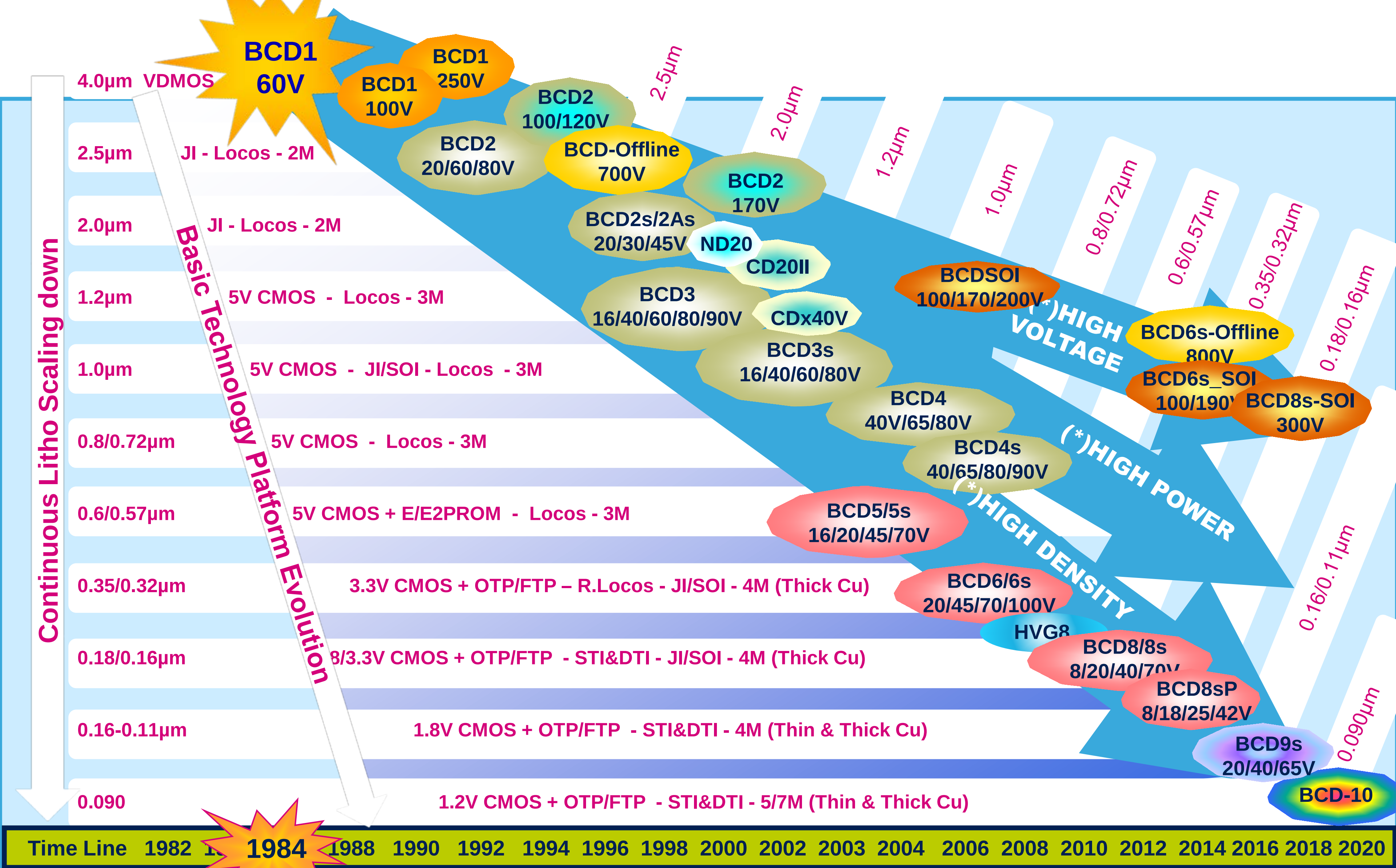
SEGMENT		TECHNOLOGY PLATFORM	APPLICATION FIELDS
High Voltage BCD	0.32µm	**BCD6s Offline** 3.3V / 5V CMOS – 25V/800V/1200V	Lighting, Motors, Electrical Car
	0.32µm	**BCD6s HV Transformer** 3.3V CMOS - Galvanic Isolation 4-6KV	
SOI BCD	0.32µm	**SOI-BCD6s** 3.3V CMOS - 20V/50V/100V/190V	Full digital amplifier, Echography, AMOLED, Pico-projector
	0.16µm	**SOI-BCD8s** 1.8V CMOS - 70V/100V/140V/200V	
Advanced BCD	0.16µm	**BCD8sP - 0.16µm** 1.8V CMOS - 10V/18V/27V/42V/60V	HDD, Airbag, Power Line modems, Audio amplifier, Printers, ABS, ESP, Power Supply, Automotive, Power Management for Mobile
	0.16µm	**BCD8sAUTO - 0.16µm** 3.3V CMOS - 20V/40V/65V/100V	
	0.11µm	**BCD9s - 0.11µm** 1.8V CMOS - 10V/40V/60V	
	0.11µm	**BCD9sL - 0.11µm** 3.3V CMOS - 20V/40V/65V/100V	
	0.11µm	**BCD9sE - 0.11µm – ePCM** 1.8V CMOS - 10V/40V/60V	
	90nm	**BCD10 - 90nm - ePCM** 1.2V CMOS - 8V/20V/40V/65V	

life.augmented

ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA
ARCES

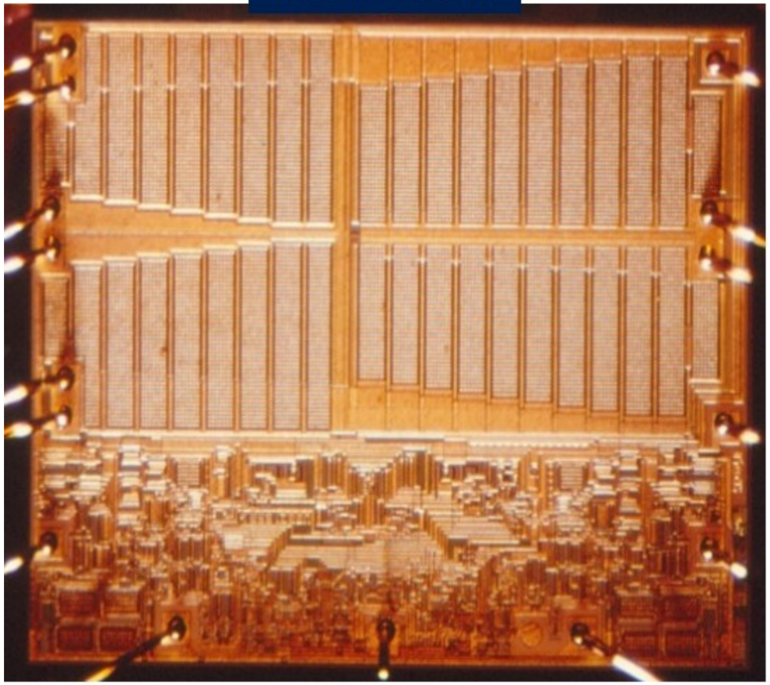
“More Than Moore” BCD Diversification

Roadmap Splitting in Three Main Directions(*)



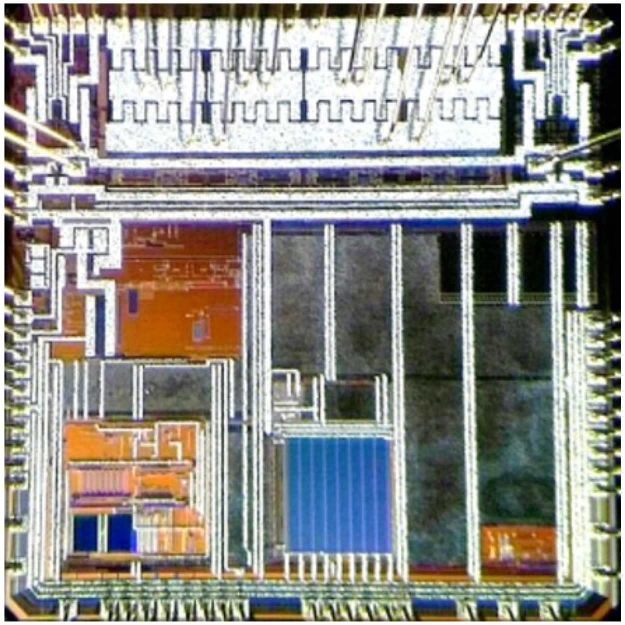
What Does This Evolution Mean?

BCD1
4000nm
1000 Transistors



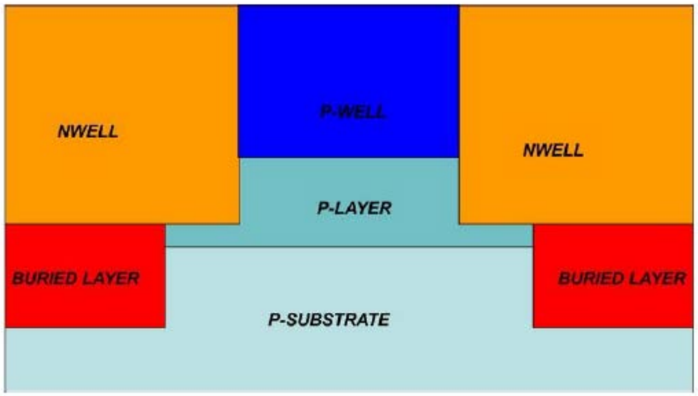
2x Half-bridges

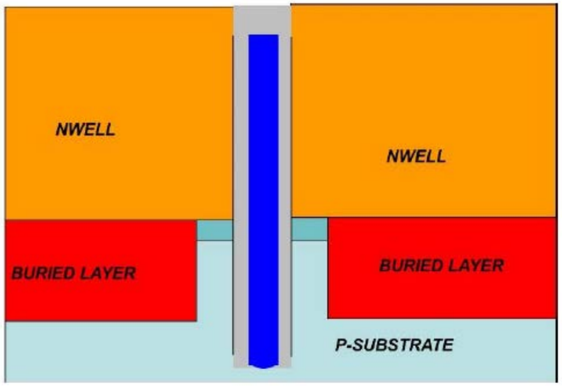
BCD9s e-PCM
110nm
1 Million Transistors

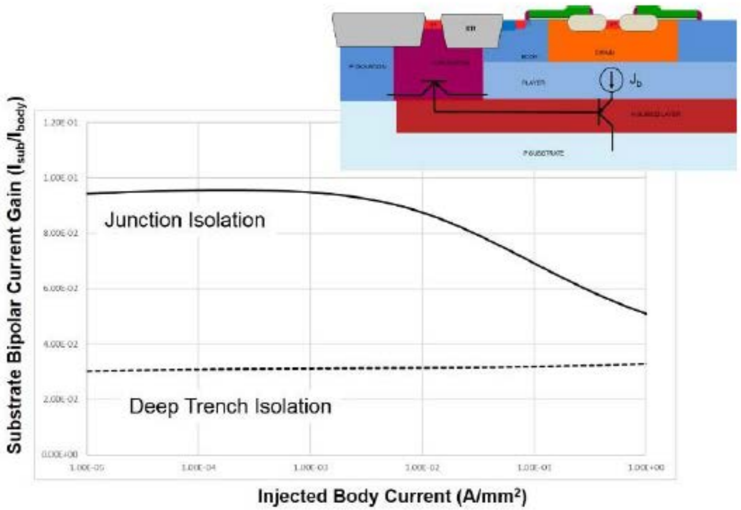


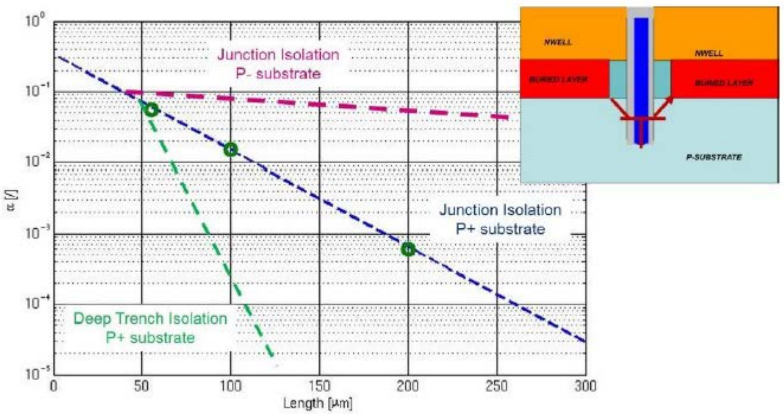
4x Half-Bridges
8x 40V gate drivers ARM Cortex-M4
32KB ePCM and 8KB RAM
2x DACs and 1x ADC

Robustness in the Integration





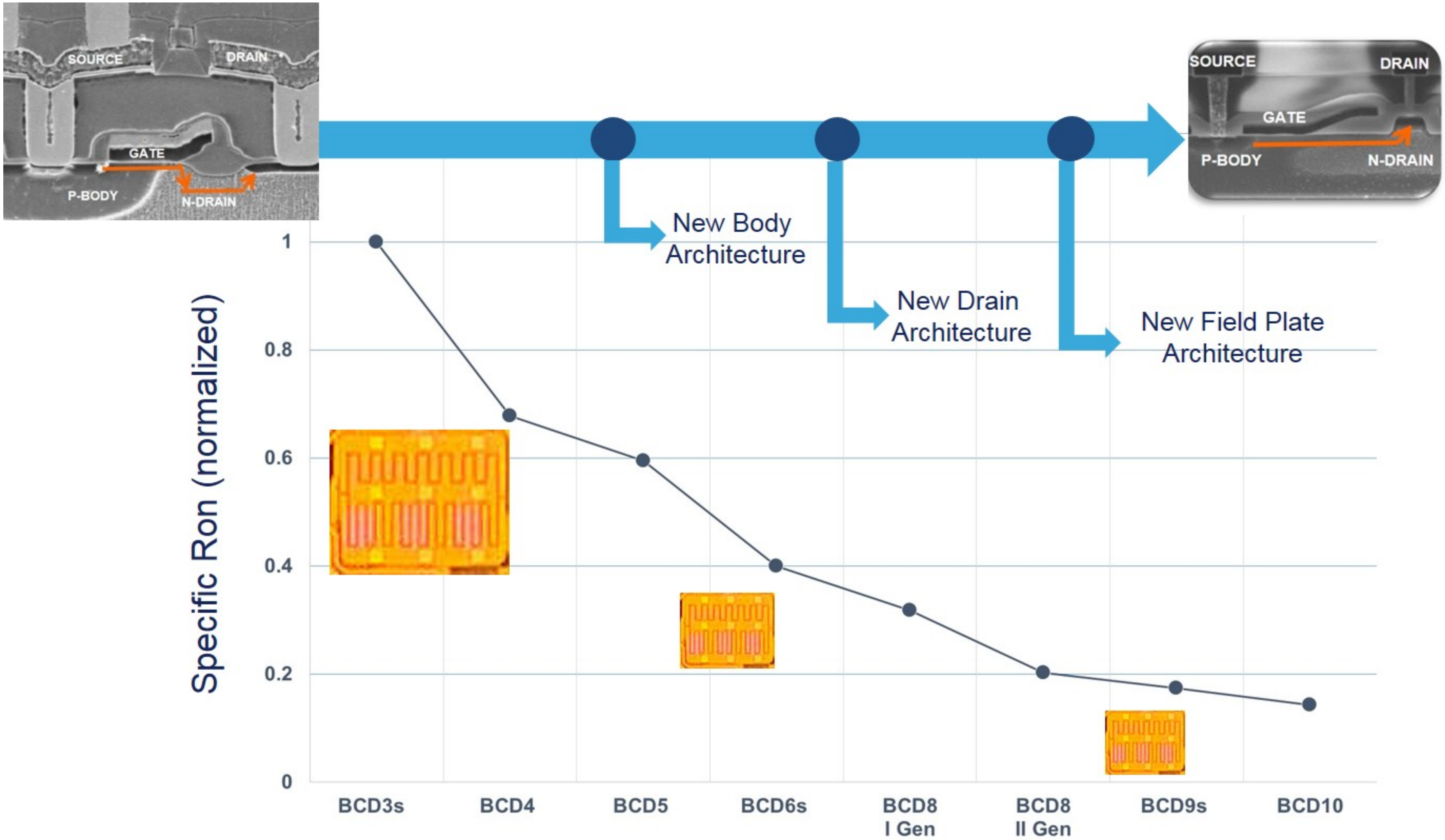




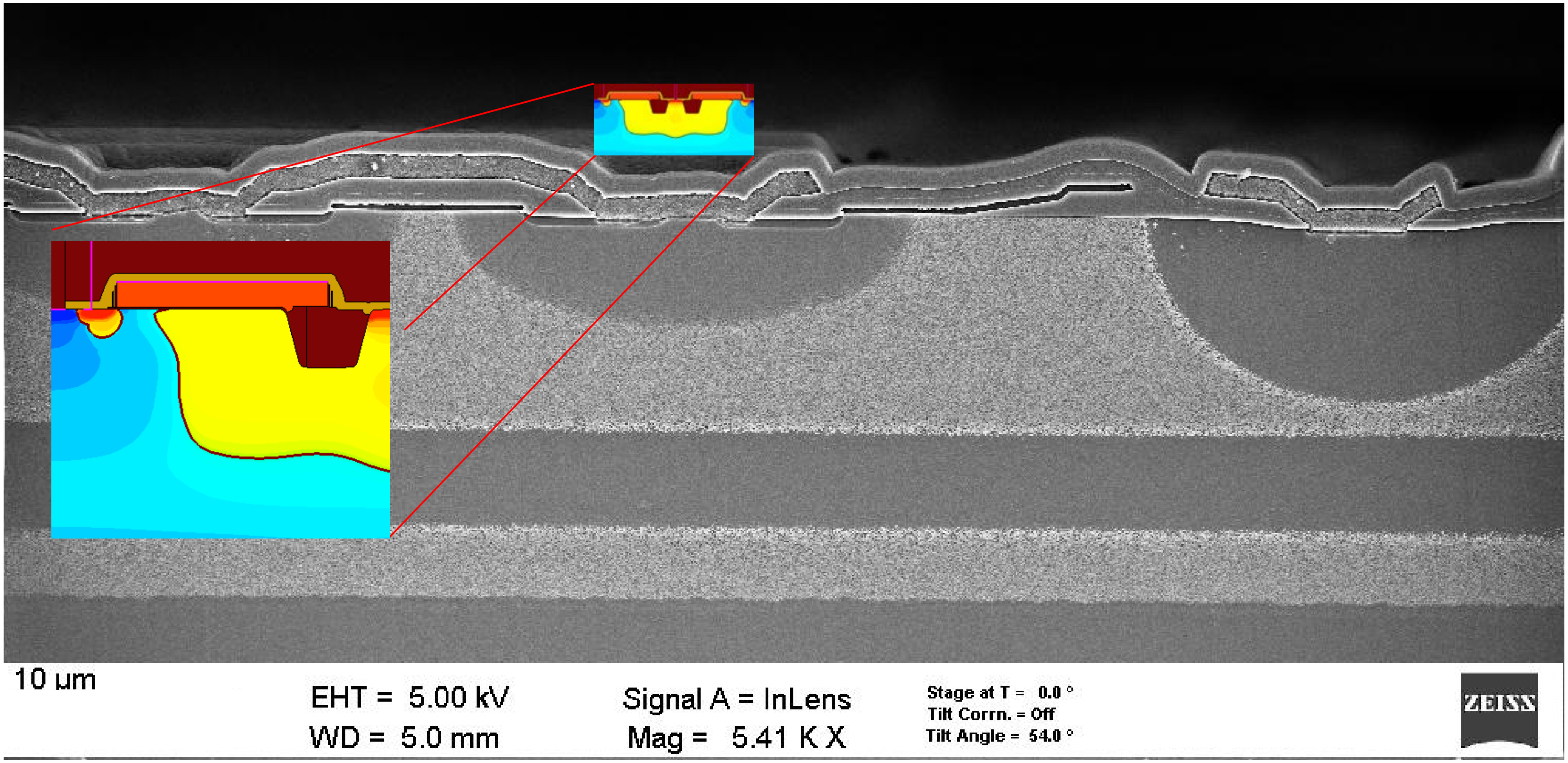
life.augmented

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA
ARCES

How to Continue to Improve
on HV Devices



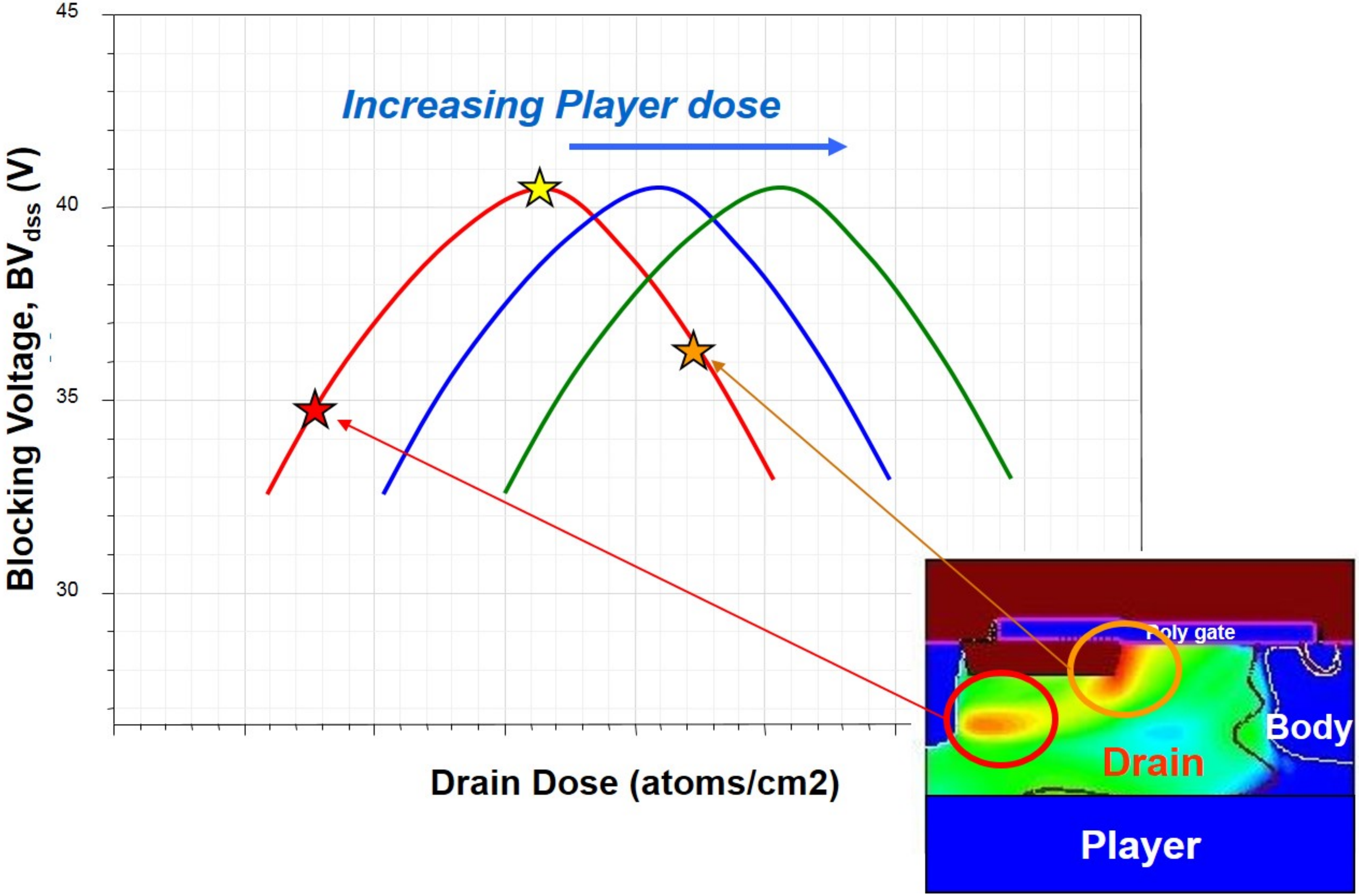
Tapered oxide usage evolution from BCD I to BCD 10



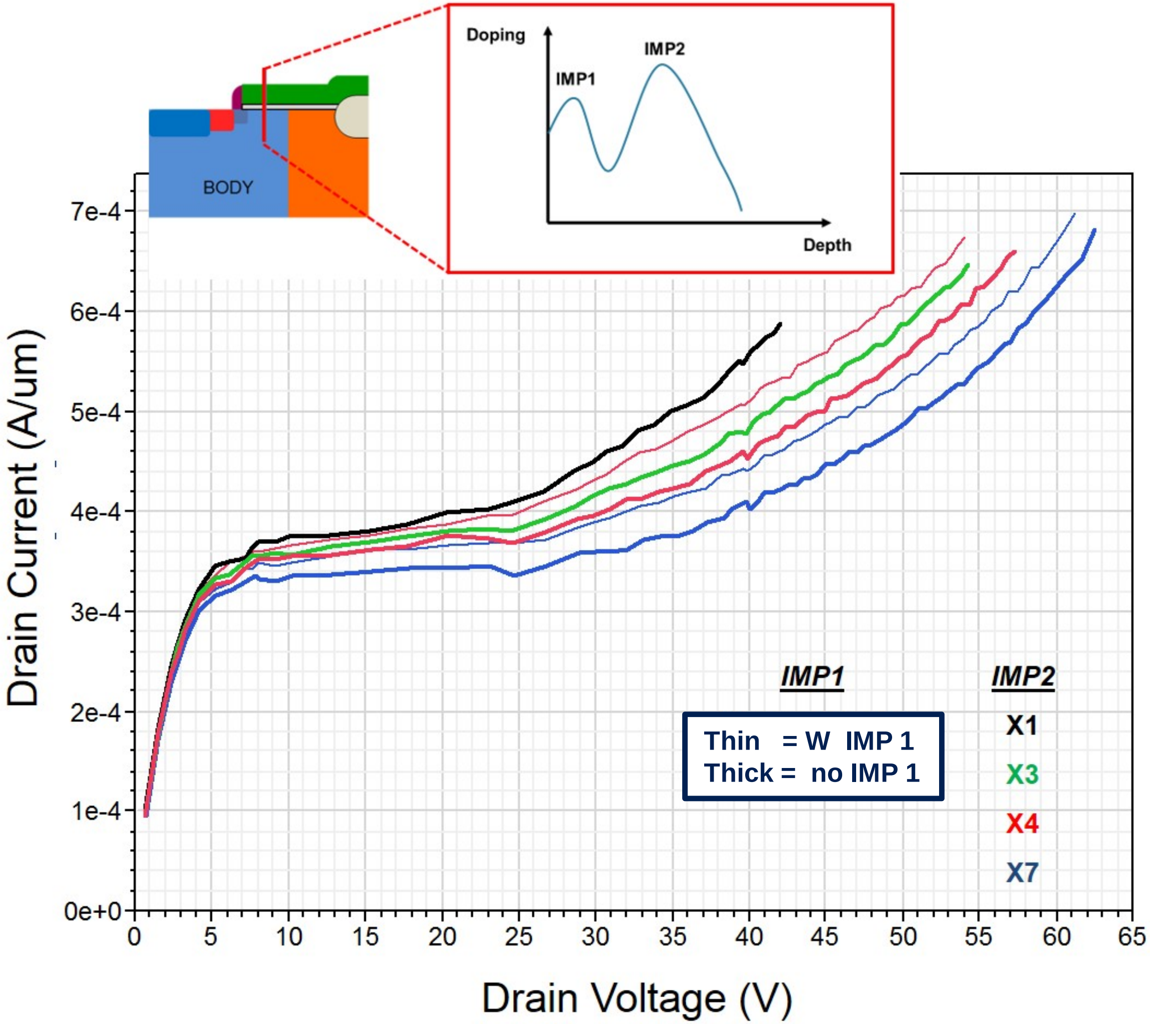
OUTLINE

- History and evolution
- Where and what robustness count
- How (to try) to address problems…
- Examples
- Conclusions

Double RESURF Exploitation

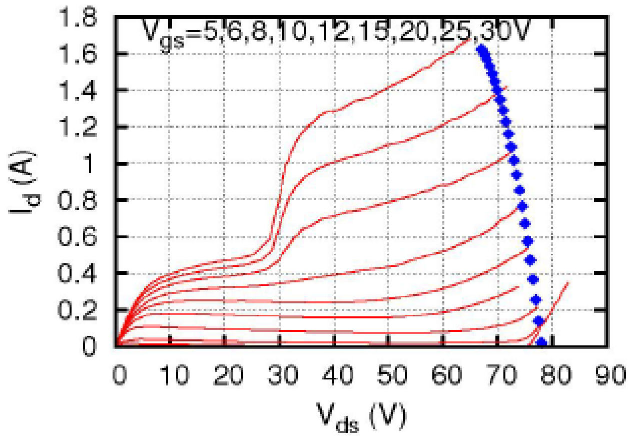


Safe Operating Area and Body Doping

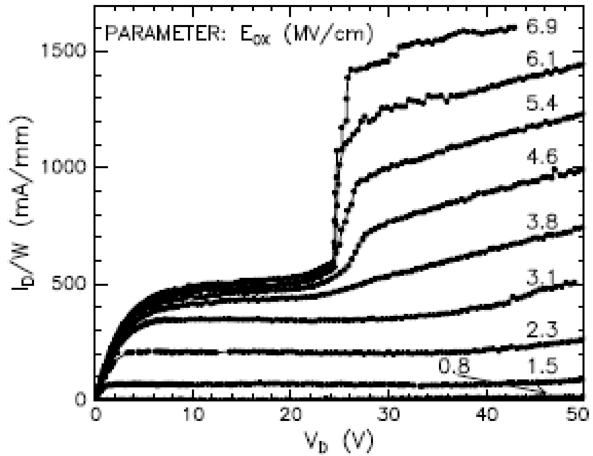


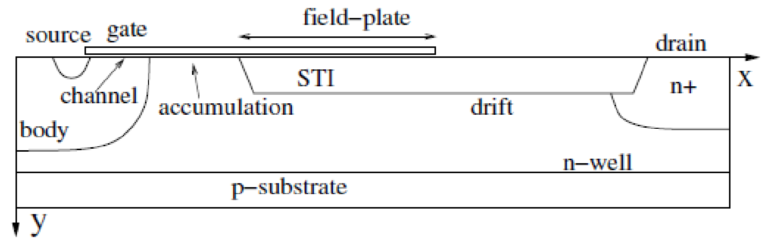
Having Wide SOA

J. Lin et al., ISPSD 2006



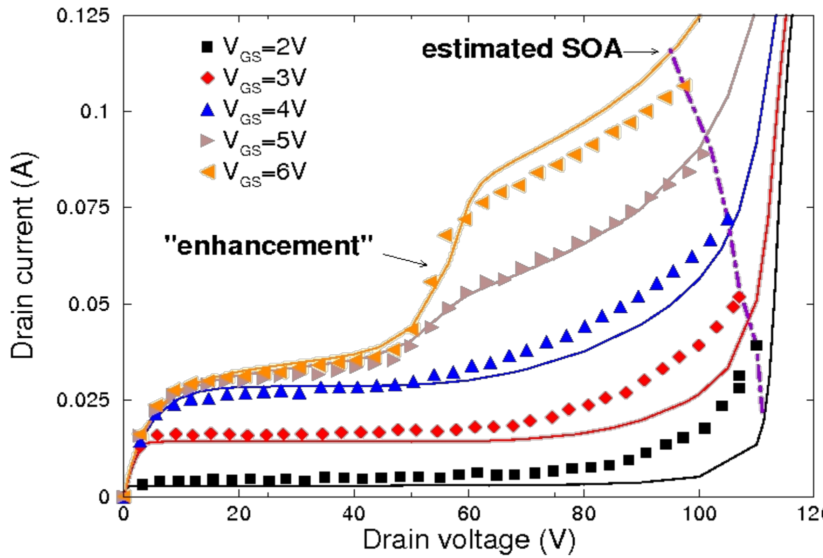
R. Roggero et al., ISPSD 2013





S. Reggiani et al., IEEE TED 2009

lines: simulations; symbols: experiments

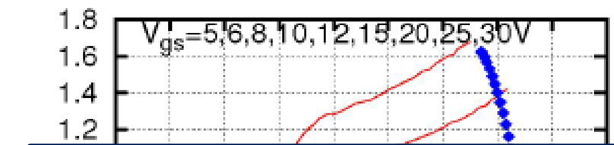


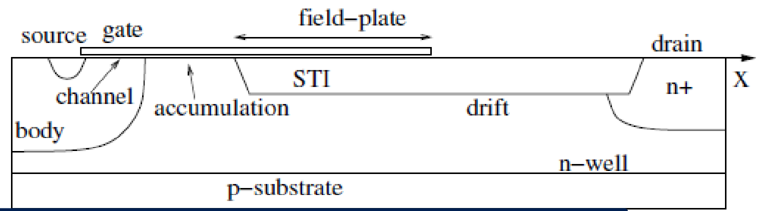
life.augmented

ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA
ARCES

Having Wide SOA

J. Lin et al., ISPSD 2006

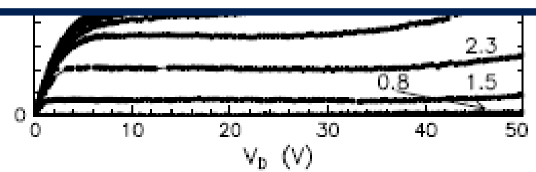


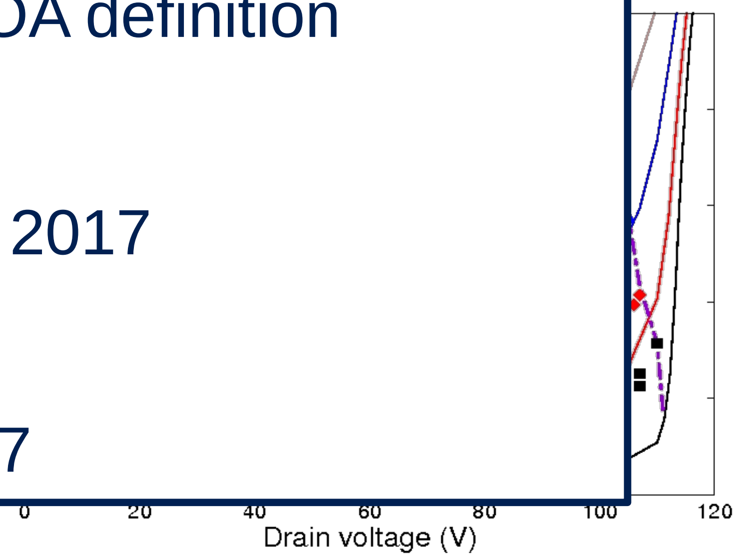


R.

Robust devices need also high reliability under stressing conditions: Hot Carrier Stress must be taken into account in the SOA definition

- J. Hao et al., IRPS 2016
- S. Liu et al., TED August 2017
- F. Jin et al., ISPSD 2017
- T. Mori et al., ISPSD 2017





What is Degrading

- LDMOS device working condition is generally limited by degradation of

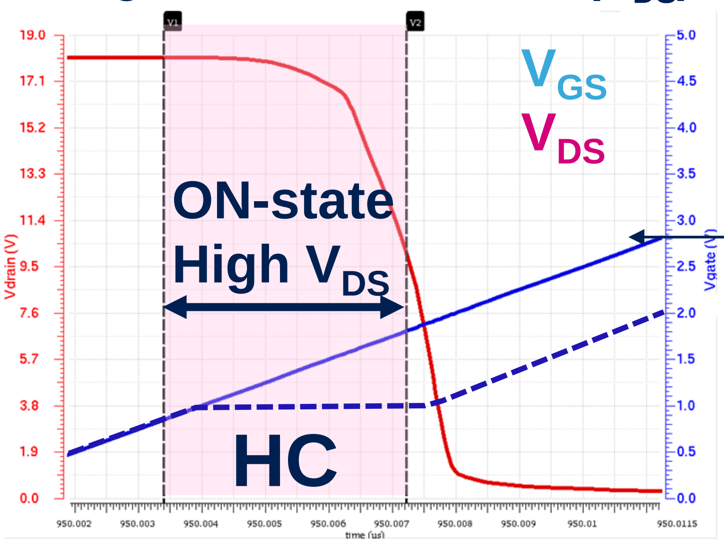
➢ Maximum linear current ($|\Delta I_{d,lin}| = \Delta R_{on}$) for high V_{DS} and low V_{GS} (standard working conditions in switching applications)

➢ Threshold voltage (ΔV_t) for high V_{DS} and high V_{GS} (more related to spikes)

When Degradation Occurs

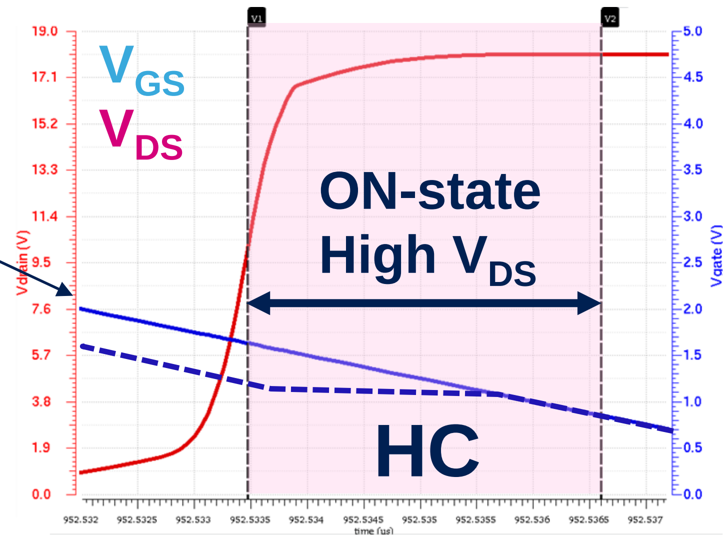
- HC degradation in a real application: Switching phase

High to Low transition (V_{DS})



Approximated nodes behavior

Low to High transition (V_{DS})



life.augmented

ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA
ARCES

OUTLINE

- History and evolution
- Where and what robustness count
- How (to try) to address problems…
- Examples
- Conclusions

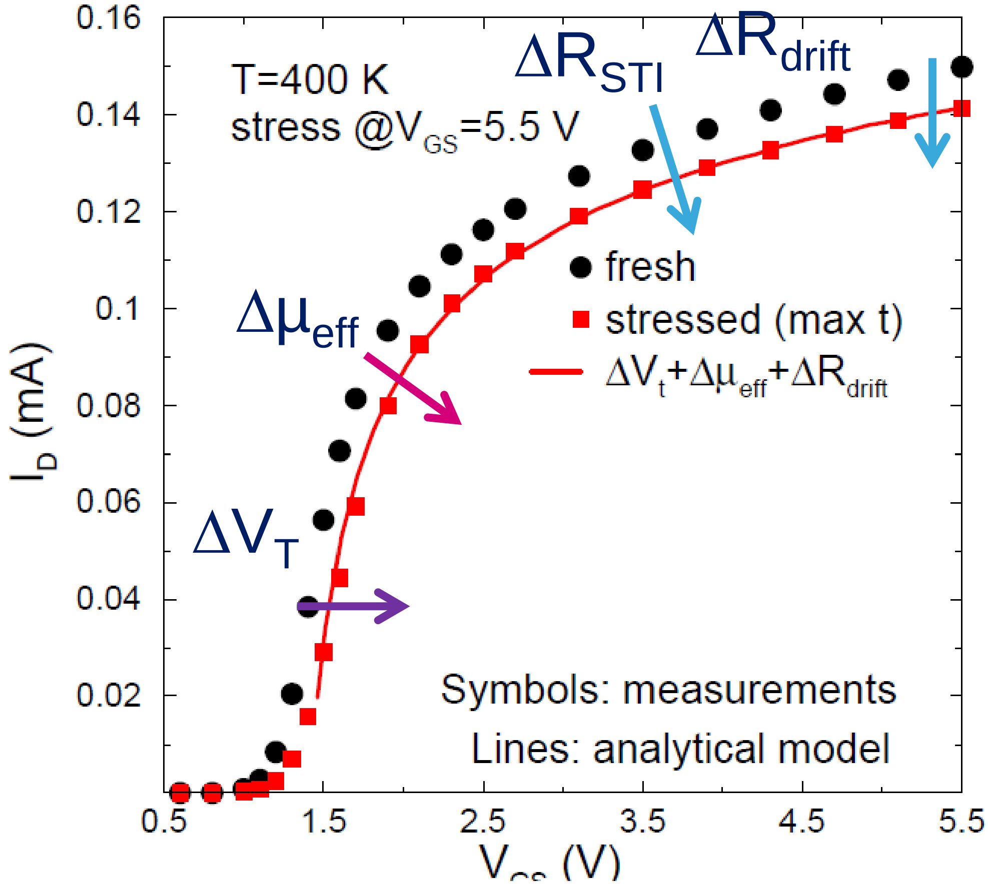
The Design Tool-kit for the Total SOA

- Technology Computer Aided Design (TCAD) commercial tools for process and device simulations
- Device simulation approach
  - 2D domain
  - Poisson + drift-diffusion transport equations
  - Impact-ionization accurate model

- … But TCAD is now helpful to quantitatively predict the HCS (Hot Carriers Stress) degradation induced by defects generated at the Si/SiO2 interface!

➢ **HCS degradation model**

HCS Degradation Analysis
on the Localization



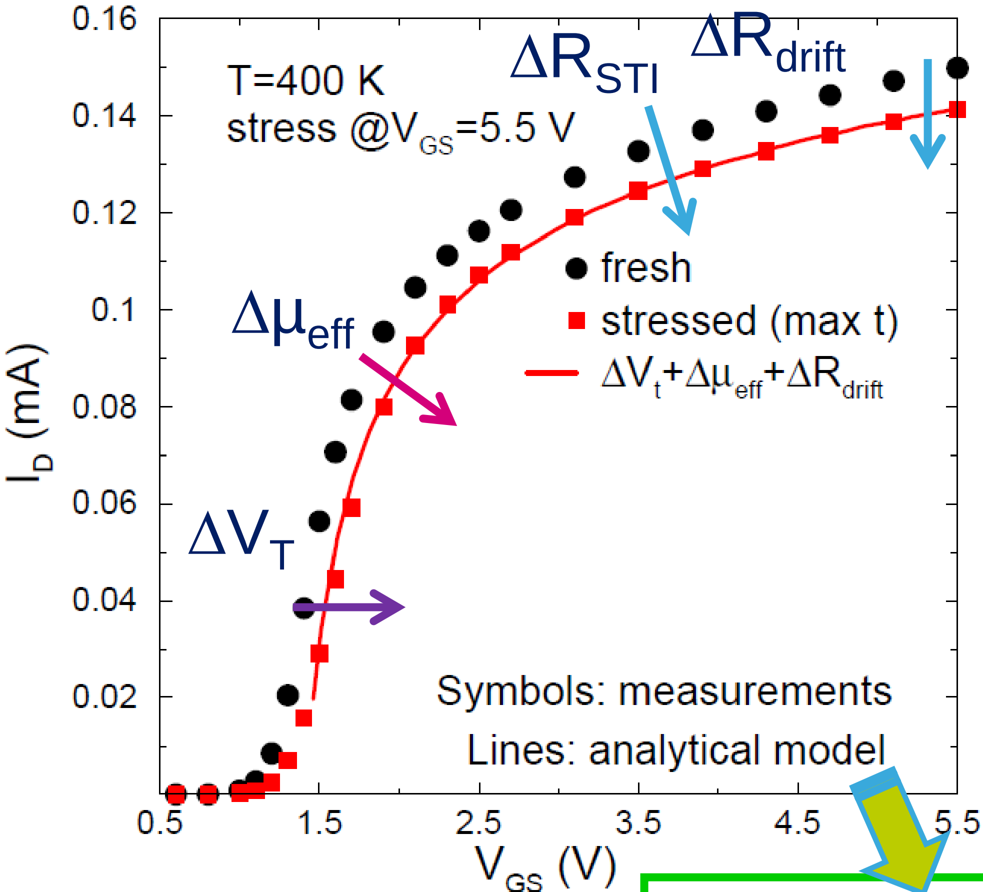
S. Reggiani et al., IEEE TED 2011

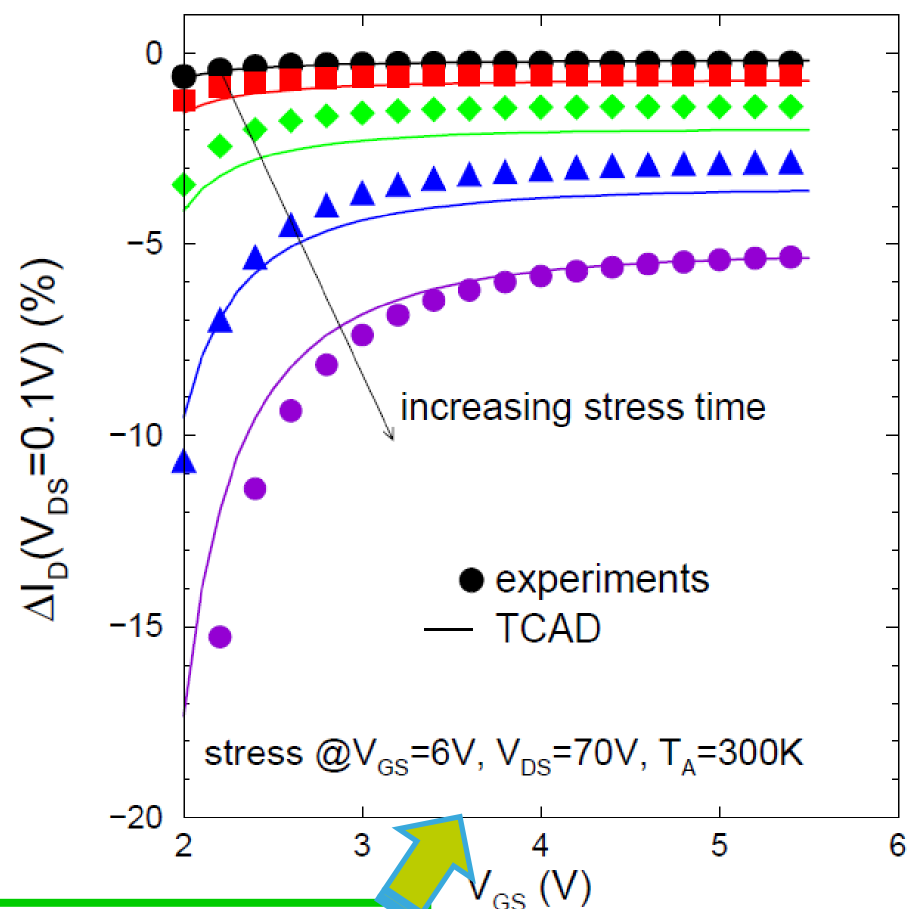
1. Trap formation in the channel → V_T shift (ΔV_T in R_{ch})
2. Trap formation in the channel → effective mobility reduction ($\Delta\mu_{eff}$ in R_{ch})
3. Trap formation in the drift → drift resistance increase (ΔR_{STI} and ΔR_{drift})

The different dependences on V_{GS} are used to check the localization of degradation.

life.augmented
ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA
ARCES

Degradation Along Turn-on Sweep





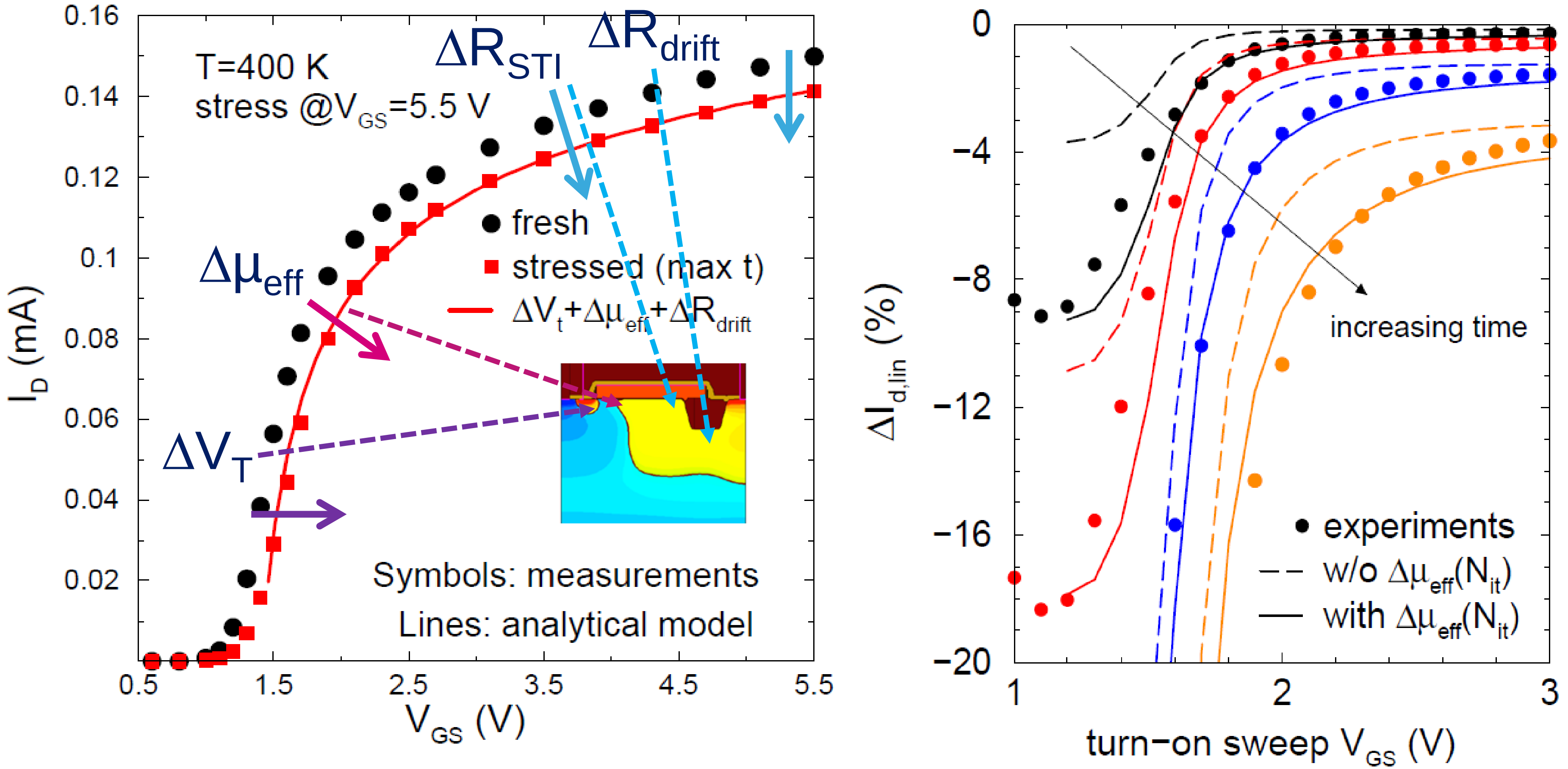
$$\frac{\Delta I_D}{I_D}(V_{GS}) = \frac{I_D(V_{GS}) - I_D^0(V_{GS})}{I_D^0(V_{GS})}$$

S. Reggiani et al., IEEE TED 2011

life.augmented

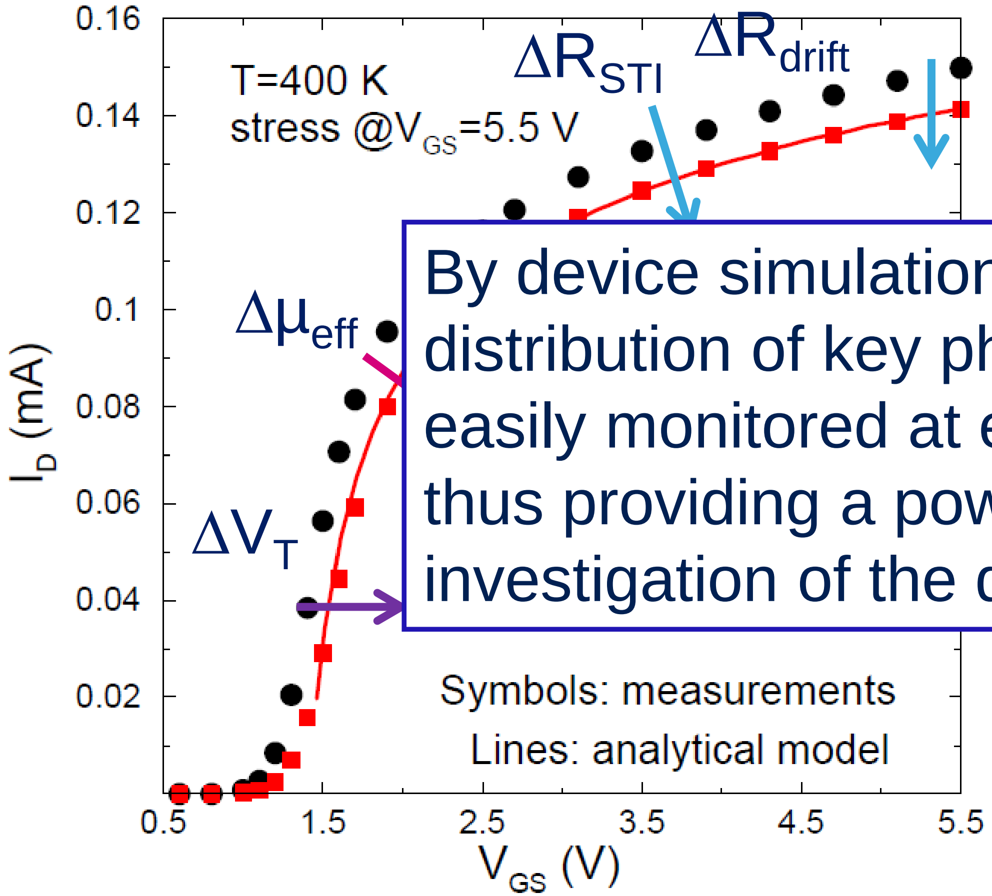
ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA
ARCES

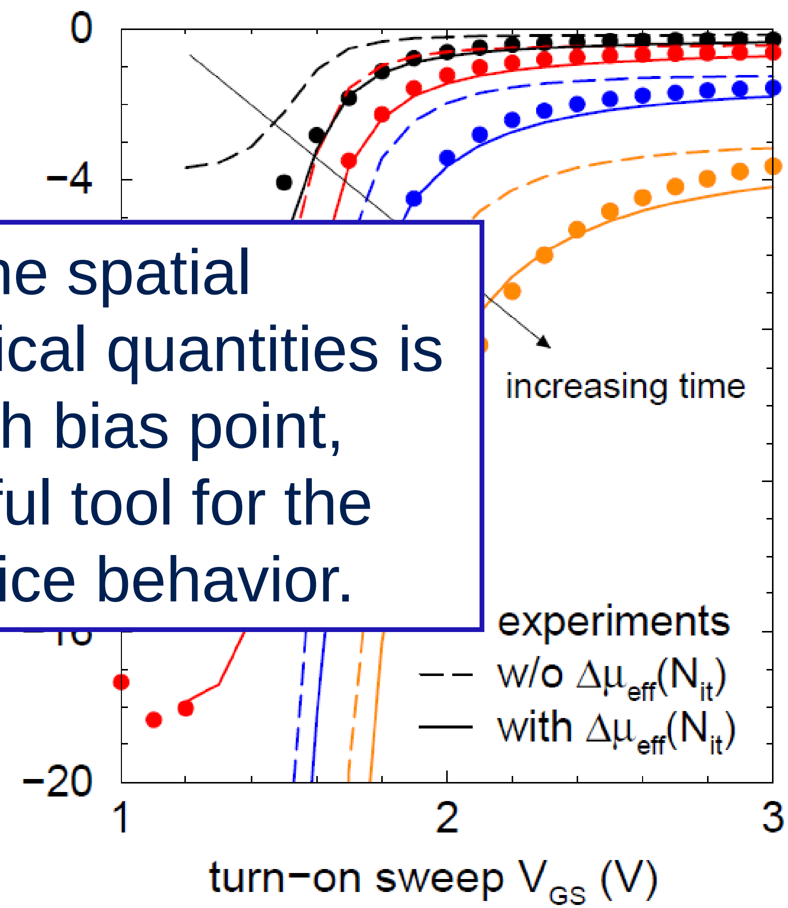
$\Delta\mu_{eff}(t)$



S. Reggiani et al., IEEE TED 2011

$\Delta\mu_{eff}(t)$





By device simulation, the spatial distribution of key physical quantities is easily monitored at each bias point, thus providing a powerful tool for the investigation of the device behavior.

S. Reggiani et al., IEEE TED 2011

Kinetic Equations of the Trap Generation: 1

Single-particle process (SP)

$$N_{it,SP}(\boldsymbol{r}, t, E_{SP}) = P_{SP}N_0[1 - e^{-k_{SP}(\boldsymbol{r}, E_{SP})t}]$$

P_{SP}: probability for SP generation

$$k_{SP}(\boldsymbol{r}, E_{SP}) = \int_{E_{SP}}^{\infty} f(\boldsymbol{r}, E)g(E)v(E)\sigma_{SP}(E)dE$$

$f(\boldsymbol{r}, E)$ - distribution function $g(E)$ – density of states $v(E)$ – group velocity

3.1eV [S. Tyaginov, MR 2010; K. Hess et al., IEDM 2000]

11 [I.A. Starkov et al., J. Vac. Sci. Technol. B, 2011]

$$\sigma_{SP}(E) = \sigma_{SP0}\left(\frac{E - E_{SP}}{k_B T}\right)^{p_{SP}}$$

Cross-section models the electronic excitation, the expected normalization to $k_B T$ was added [S. Reggiani, TED 2013]

σ_{SP0}: fitting parameter

life.augmented

ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA ARCES

Kinetic Equations of the Trap Generation: 2

$$N_{it,MP}(\boldsymbol{r}, t, E_{MP}) = P_{MP}N_0\left[\frac{P_{emi}}{P_{pass}}\left(\frac{P_u}{P_d}\right)^{N_1}(1 - e^{-P_{emi}t})\right]^{1/2}$$

Fitting parameters

P_{MP}: probability for MP generation

$\nu_{emi/pass}$: emission/passivation frequency;

E_{pass}: passivation energy

Excitation induced by incoming electrons (multiple-vibrational electron-phonon interaction)

$$k_{MP}(\boldsymbol{r}, E_{MP}) = \int_{E_{MP}}^{\infty} f(\boldsymbol{r}, E)g(E)v(E)\sigma_{MP}(E)dE$$

E_{ph}=0,25 eV [I.A. Starkov et al., J. Vac. Sci. Technol. B, 2011]

$$\sigma_{MP}(E) = \sigma_{MP0}\left(\frac{E - E_{MP}}{k_B T}\right)^{p_{MP}}$$

0.1 [I.A. Starkov et al., J. Vac. Sci. Technol. B, 2011]

σ_{MP0}: fitting parameter

Kinetic Equations of the
Trap Generation: 3

Thermally-activated dielectric degradation (TH)

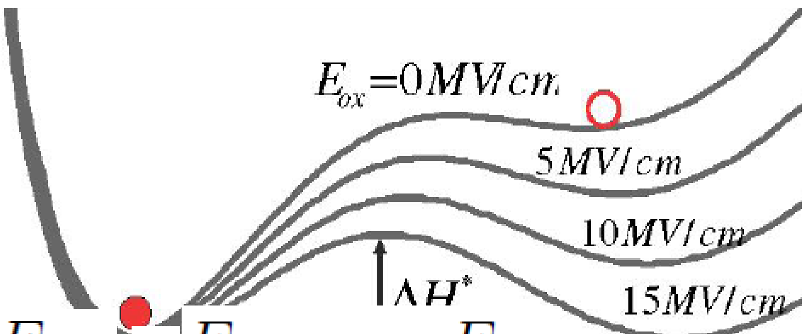
$$N_{\mathrm{it,TH}}(\boldsymbol{r}, t, E_{\mathrm{TH}}) = P_{\mathrm{TH}} N_0 [1 - e^{-k_{\mathrm{TH}}(E_{\mathrm{TH}})t}]$$

[S. Reggiani, TED 2013]

P_{MP}: probability for TH generation

Field-induced dipolar effect:

$$k_{\mathrm{TH}}(E_{\mathrm{TH}}) = \nu_{\mathrm{TH}} \exp\left[-\frac{E_{\mathrm{TH}}}{k_B T}\right]$$



$$E_{\mathrm{TH}} = E_{\mathrm{TH,0}} - pE_{\mathrm{ox}}$$

ν_{TH}: lattice collision frequency

J.W. McPherson et al., J. Appl. Phys. 88, 2000

TCAD implementation

- The physics-based models for the reaction rates need **a semiclassical transport solution** → numerical solution of the full-band Boltzmann Transport Equation (BTE) for the determination of the electron distribution function

…implemented in TCAD!

- Deterministic solution the spherical-harmonics expansion of the BTE

- Full-band structure obtained from the nonlocal empirical pseudopotential method.

Accurate description of f(x,y,E) up to 10 eV

S. Jin et al.(SISPAD 2009) - implemented in SDevice-Synopsys

life.augmented

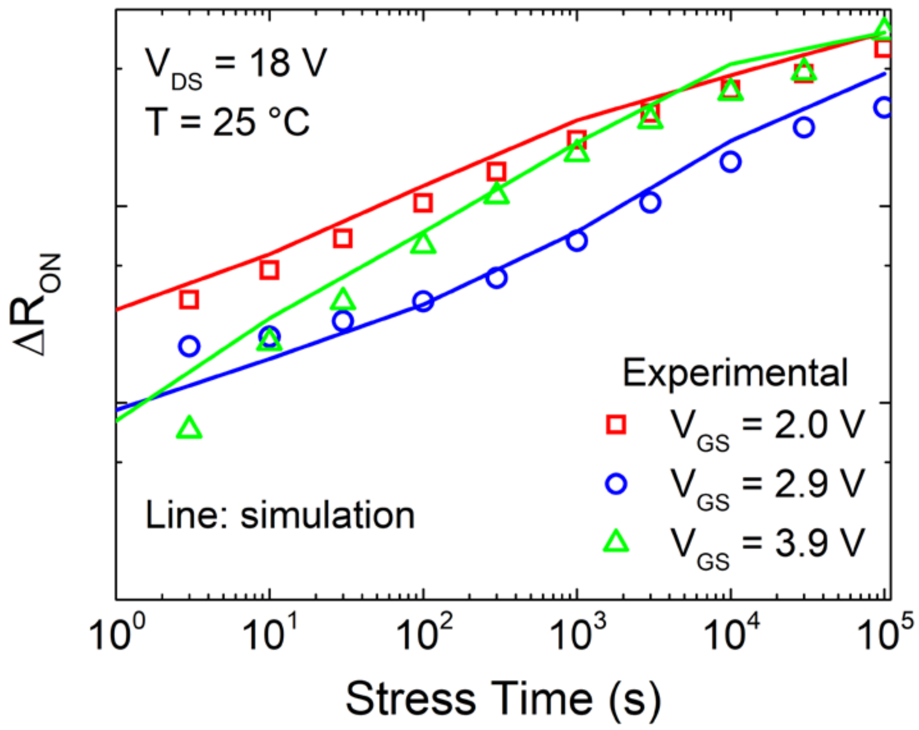
ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA ARCES

OUTLINE

- History and evolution
- Where and what robustness count
- How (to try) to address problems …
- Examples
- Conclusions

HC Degradation (TCAD)

- Single- and Multiple-particle processes accounted for in the simulation



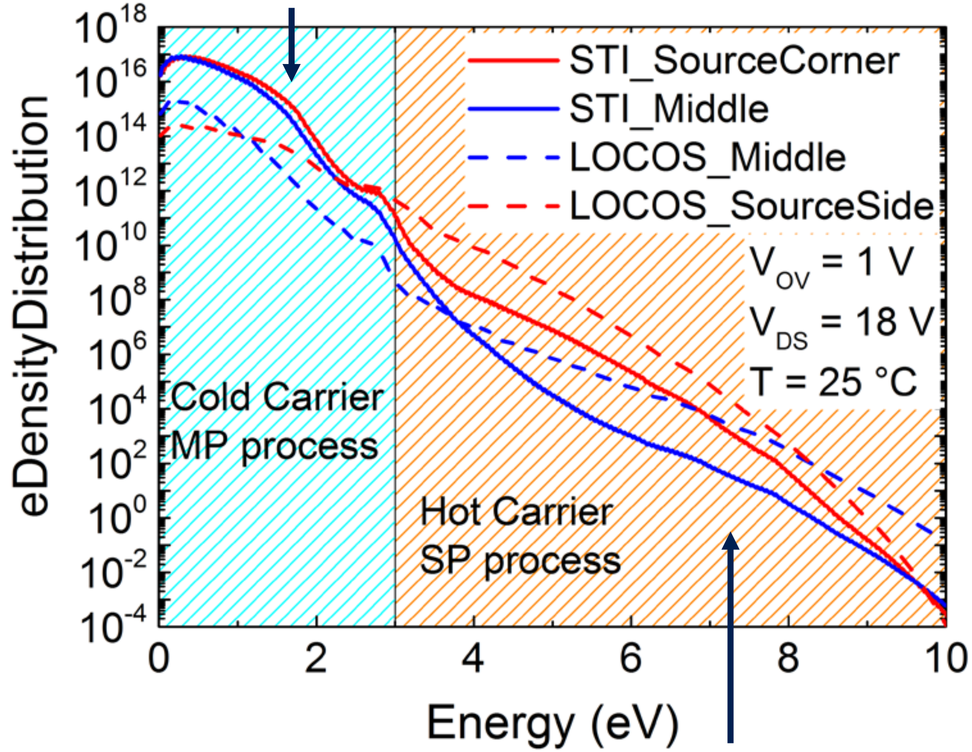
- Experimental ΔR_{ON} and its gate bias dependence are reproduced by means of TCAD simulation
- Model calibration (SP and MP) is required to better fit the short stress times

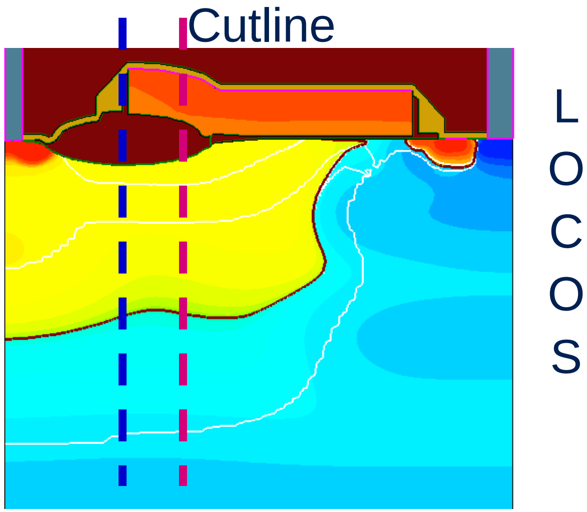
life.augmented

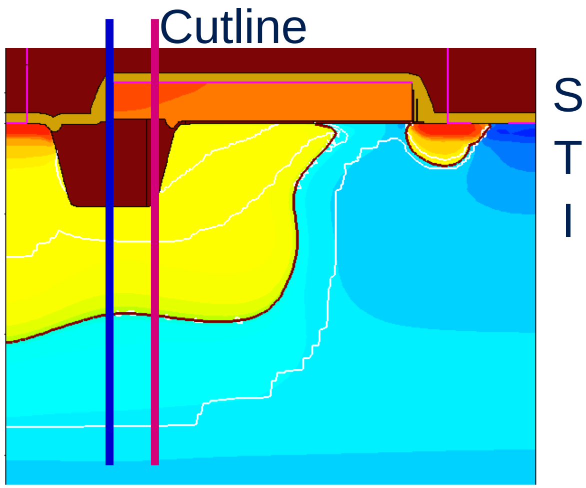
ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA ARCES

Electron Density Distribution
(LOCOS vs STI)

- A higher number of electrons may lead to higher number of interface traps in the STI structure due to multiple-particle process



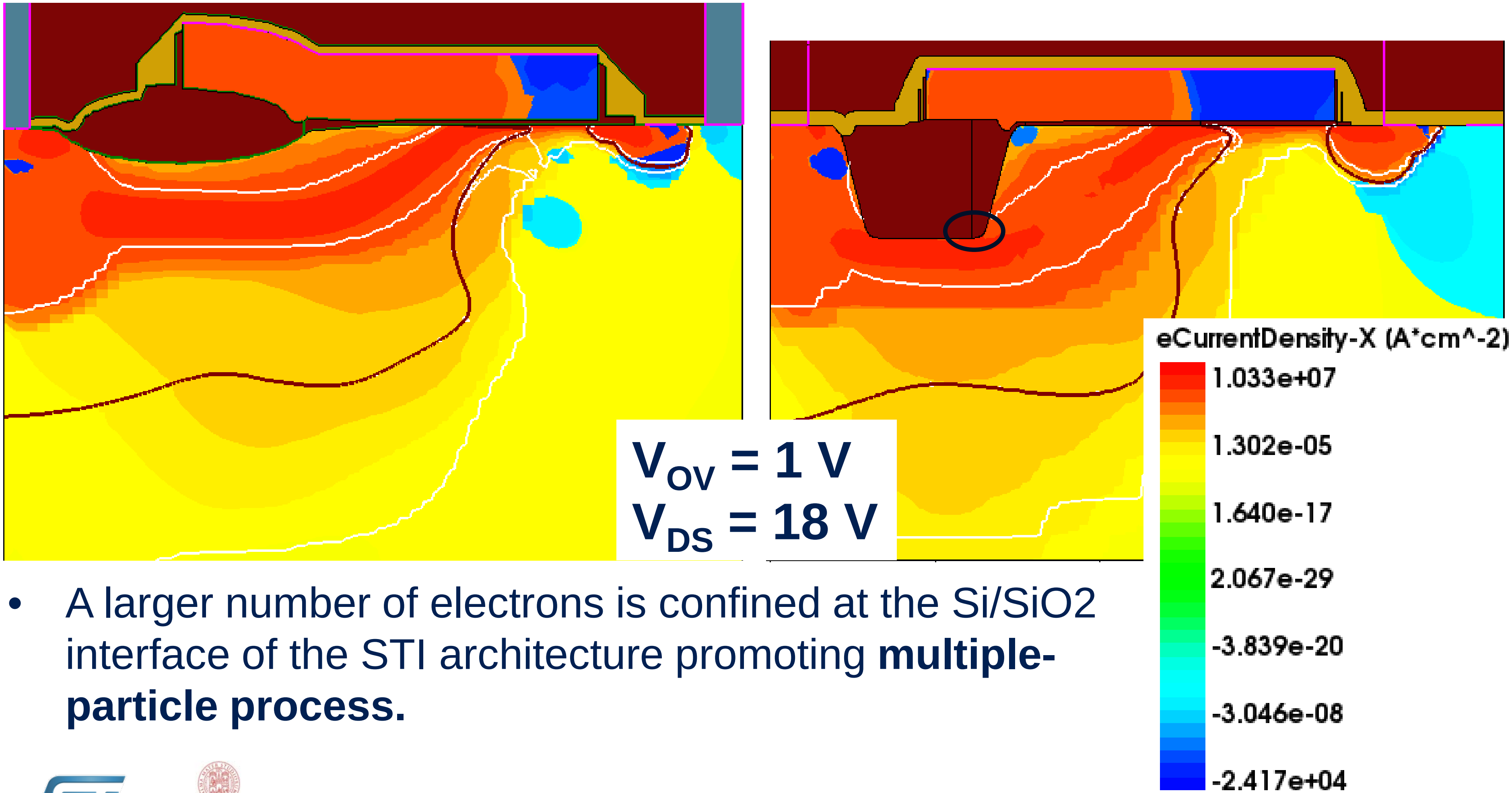




- Single-particle may be worse in LOCOS

Electron Current Density

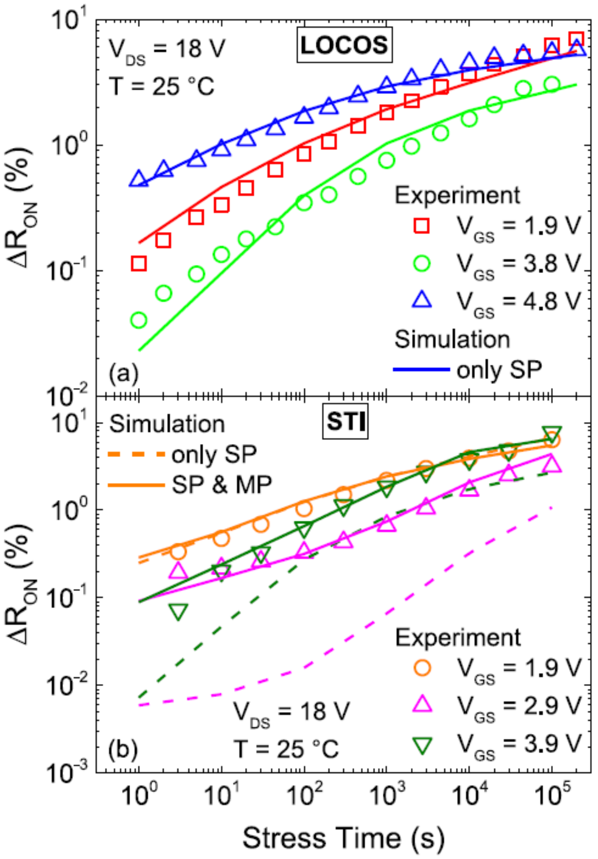
Selective LOCOS / STI



- A larger number of electrons is confined at the Si/SiO2 interface of the STI architecture promoting **multiple-particle process.**

Different Models Account
for Different Architectures

- Single particle model seems more valid for previous generation architectures
- Multi particle model better fits with STI based architectures due to current closer confinement to the surface



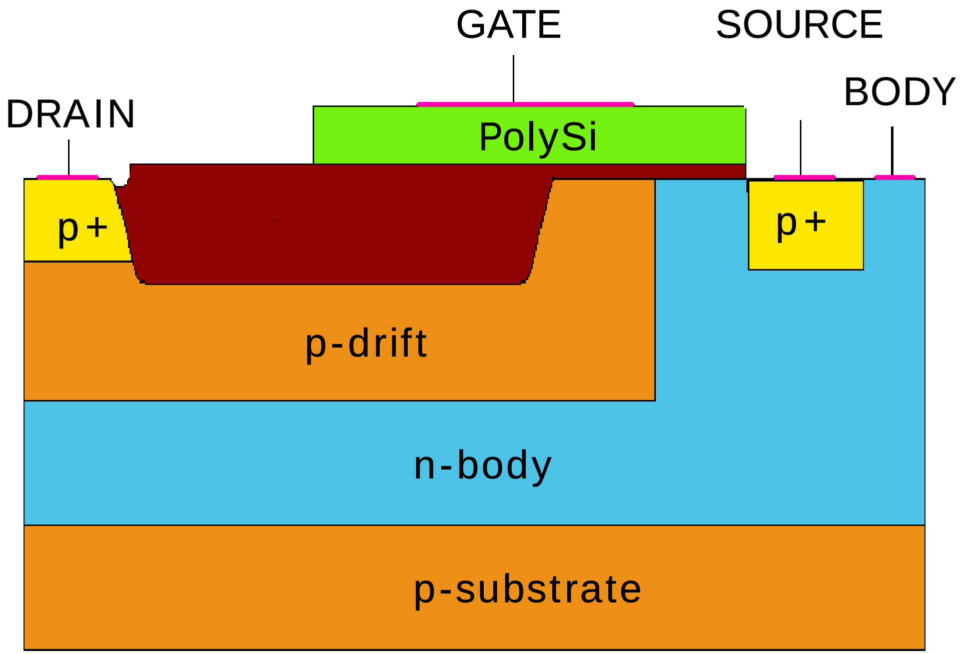
A. Tallarico et al., JEDS 2018

Is the Methodology Always Valid?

- Can the tool be used also other components?
- Parameters work for both carriers?

PLDMOS Structures

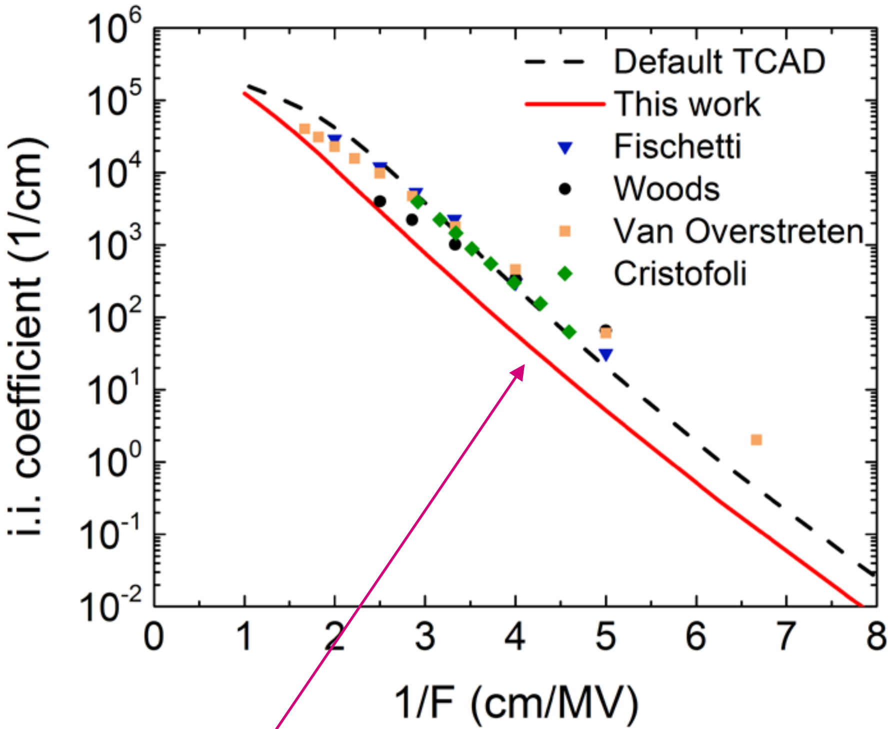
PCH structures must be considered



HV p-channel LDMOS

- STI oxide structure
- Gate, body and drain currents analyzed

Hole Avalanche Coefficient



F. Giuliano et al., ESSDERC 2019

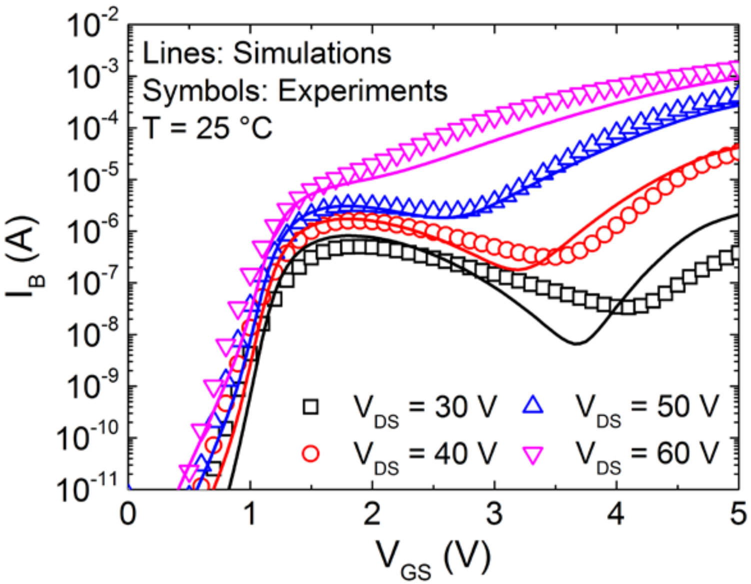
Reduction of the hole avalance coefficient of about a factor 4 needed to reproduce the avalanche regime

Parameters extrapolated from older technologies are no longer accurate for new generation technologies

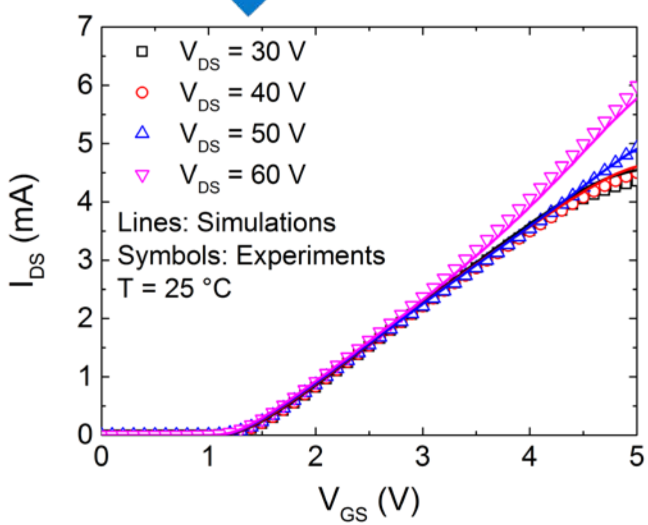
life.augmented

ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA ARCES

Body Current - PLDMOS



- I_B – V_{GS} curves
- Turn on characteristics in saturation regime



Impact ionization peak at V_{GS} about 2V
Body current decrease due to the reduction of the electric field

F. Giuliano et al., ESSDERC 2019

life.augmented

ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA ARCES

Conclusions

- An overview on some strategies to improve devices optimization devices robustness in mixed signal technologies was presented
- New and future technology process nodes must face the emerging of more stringent limitations in device operation due to the geometrical squizing
- TCAD tools will play a key role in trying to predict and help the device optimization going forward the classical breakdown and R_{on} optimization and speeding up the development phase

This work supported by:
ECSEL 2014-2-653933: R2POWER300 and H2020-EU ECSEL_737417: R3-PowerUP

life.augmented

ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA ARCES

Thank you for your attention