

Body biasing fault injection:
Enhancements, analysis, modeling, and simulation
PhD thesis defense

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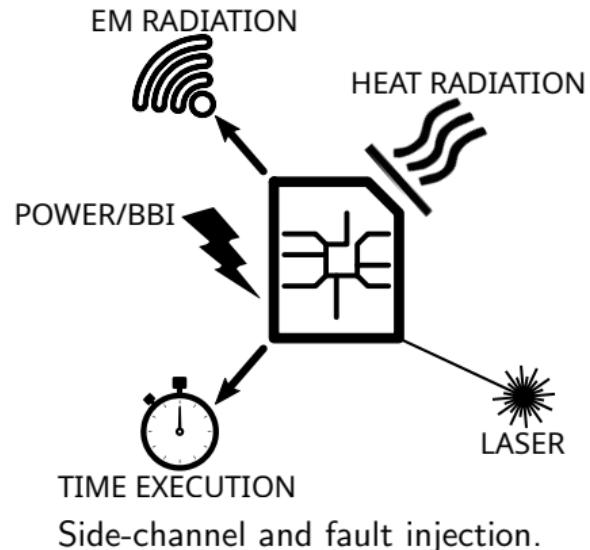
Jean-Luc Danger (Examiner)
Jean-Max Dutertre (Rapporteur)

Giorgio Di Natale (Rapporteur)
Jean-Marc Gallière (Co-supervisor)

Philippe Maurine (Director)
Pascal Nouet (President)

Context: hardware security

- Electronics are found in every economic sector
- In IoT, CPS, debit cards, phones, bank systems
- They embed cryptographic algorithms to ensure security
- These algorithms are fallible, they leak data and can be disturbed



Fault injection attacks

Fault injection objectives:

- Denial of service (DoS) → Stop circuit operation and the related services
- Verification bypass → Modify data on the fly to fake authenticity
- Confidential data extraction → Modify data to perform differential fault analysis

Thanks to a fault injection platform:

- Power Glitch Fault Injection (PW-GFI)
- Clock Glitch Fault Injection (CK-GFI)
- Laser Fault Injection (LFI)
- Electromagnetic Fault Injection (EMFI)
- **Body Biasing Fault Injection (BBI)**

Body biasing injection: state-of-the-art

2011	"Yet another fault injection technique : by forward body biasing injection"
2012	"Voltage spikes on the substrate to obtain timing faults"
2016	"Body biasing injection attacks in practice"
2020	"Low-cost body biasing injection (BBI) attacks on WLCSP devices"
2022	"Breaking a Recent SoC's Hardware AES Accelerator Using Body Biasing Injection"

Body biasing injection: industrial and academic platforms

Langer



Current source:

- 4 A in 1Ω
- $\pm 1 \text{ ns}$ jitter
- 2 ns rise time

Riscure



Voltage source:

- Probe 64 A
- $450 \text{ V} \pm 45 \text{ V}$
- Max. PW 50 ns

Voltage source:

- 150 V to 450 V
- PW: 15 ns to 480 ns
- 220 ps jitter



NewAE
ChipSHOUTER

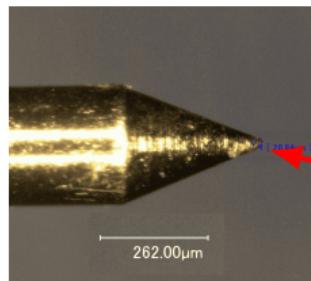
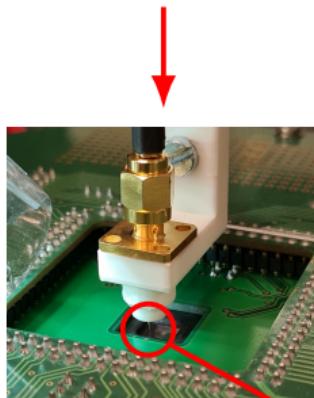
Voltage source (AC):

- Up to 250 V
- PW: 85 ns in 50Ω
- Up to 200 mW



NewAE
Pico-EMP

Body biasing injection: LIRMM BBI platform



Main platform characteristics:

V_{PULSE}	[150 ; 750] V
P_W	[6 ; 20] ns
$T_R T_F$	4 ns
Propagation delay	$[150 \cdot 10^{-9}; 1] s$
Input jitter	$\pm 100 ps \pm 0.03\%$
Output coupling	DC
Gen. I_{MAX} (50Ω)	16 A
Probe \varnothing	20 μm

Thesis objectives

- What is the spatial resolution of BBI?
- What is the time resolution of BBI?
- Is thinning the substrate useful in any way?
- How BBI induced faults occur?
- How to model BBI?

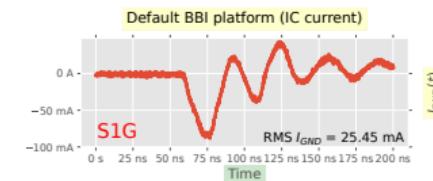
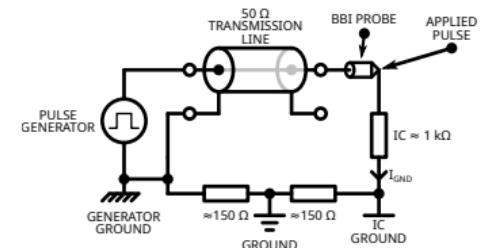
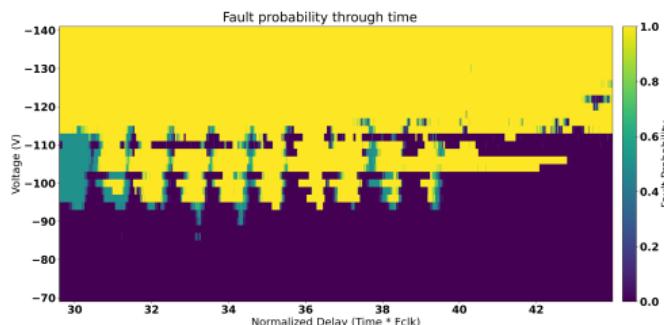
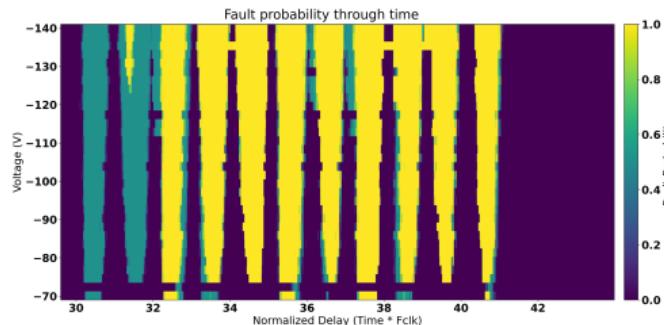
Thesis agenda

- Enhancing the practice of Body Biasing Injection
- Integrated circuits modeling for BBI
- Enhanced simulation flow
- Substrate thinning analysis in a BBI context
- Conclusion and outlooks

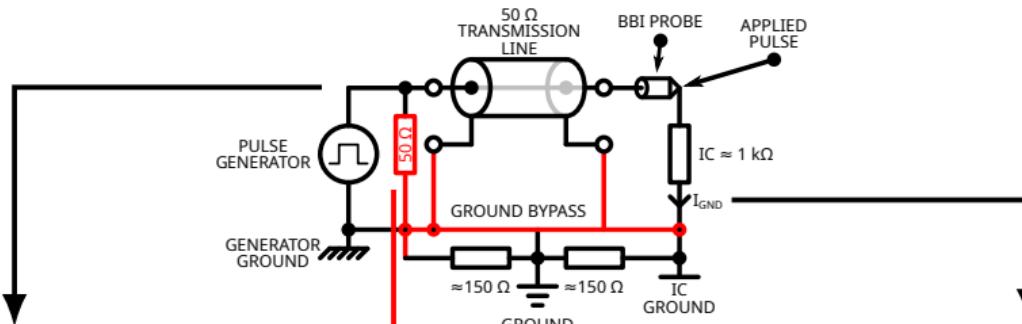
BETTER PRACTICES FOR BODY BIASING INJECTION

State-of-the-art BBI platform: limiting factors

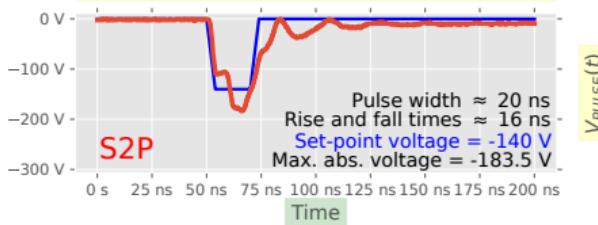
- Impedance mismatch → Ringing and set-point error
- Floating grounds → Set-point error



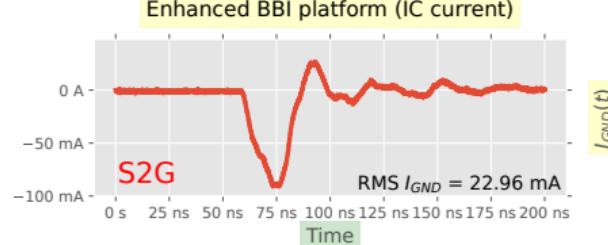
Enhanced BBI platform



Enhanced BBI platform (Generator voltage)



Enhanced BBI platform (IC current)

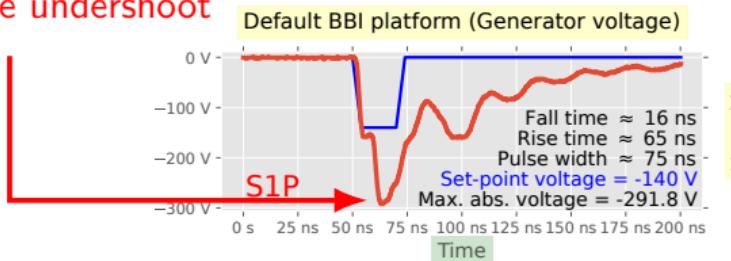


Enhanced BBI platform

Summary

275 % PW overshoot

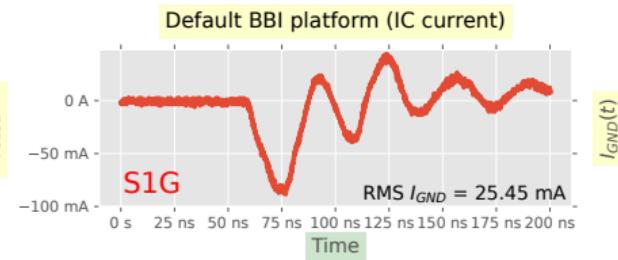
-108 % pulse undershoot



-31 % pulse undershoot

Matched pulse width

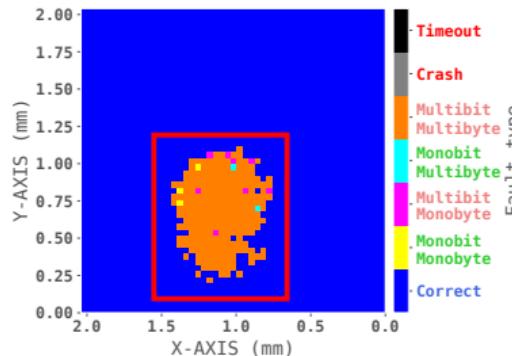
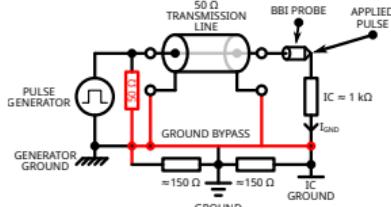
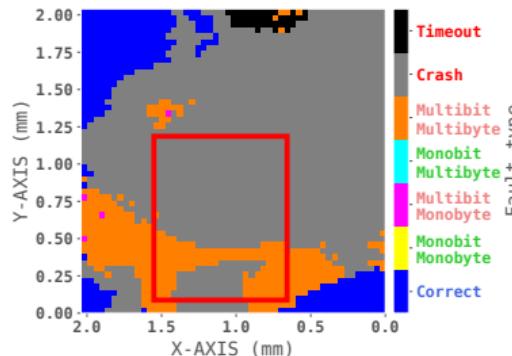
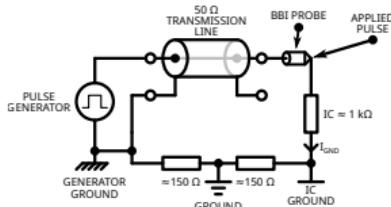
Ringing: more than 100 ns



Ringing: 15 ns

Enhanced BBI platform benefits

Giraud's single bit fault attack



Giraud's DFA → impossible No single bit faults
2601 tested locations

5 locations → single bit faults
14 secret-key bytes out of 16
2 remaining bytes → brute force

MODELING AND SIMULATING BODY BIASING INJECTION

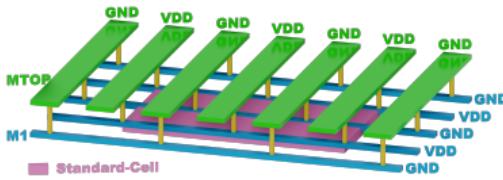
Why modeling and simulating BBI?

Observe the signals inside the IC:

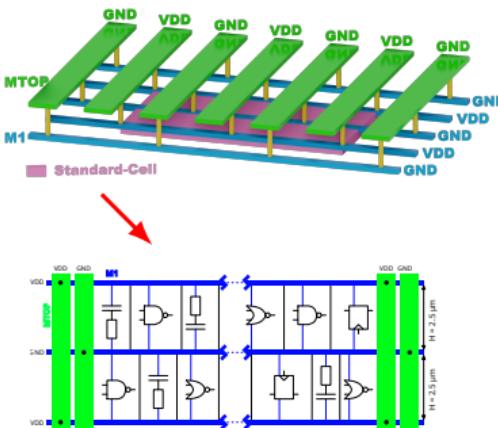
- Embedded sensors → costly and long to implement
- Will be disturbed by the voltage pulses

Therefore: simulation → conclusions → verification

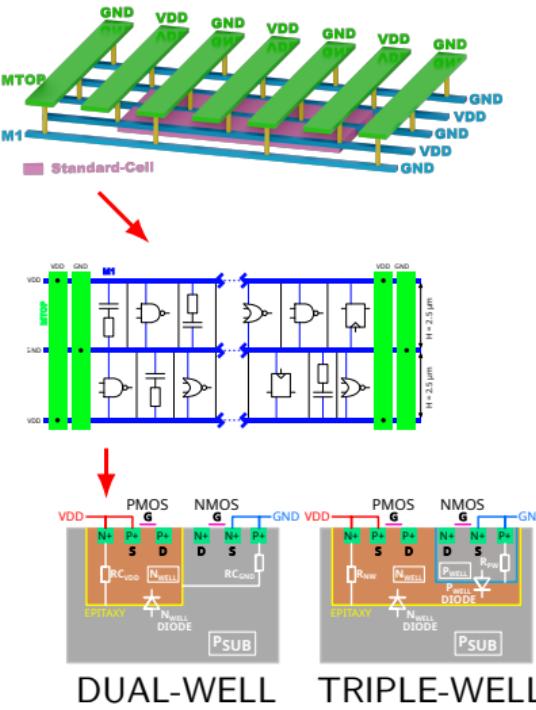
Simulation models



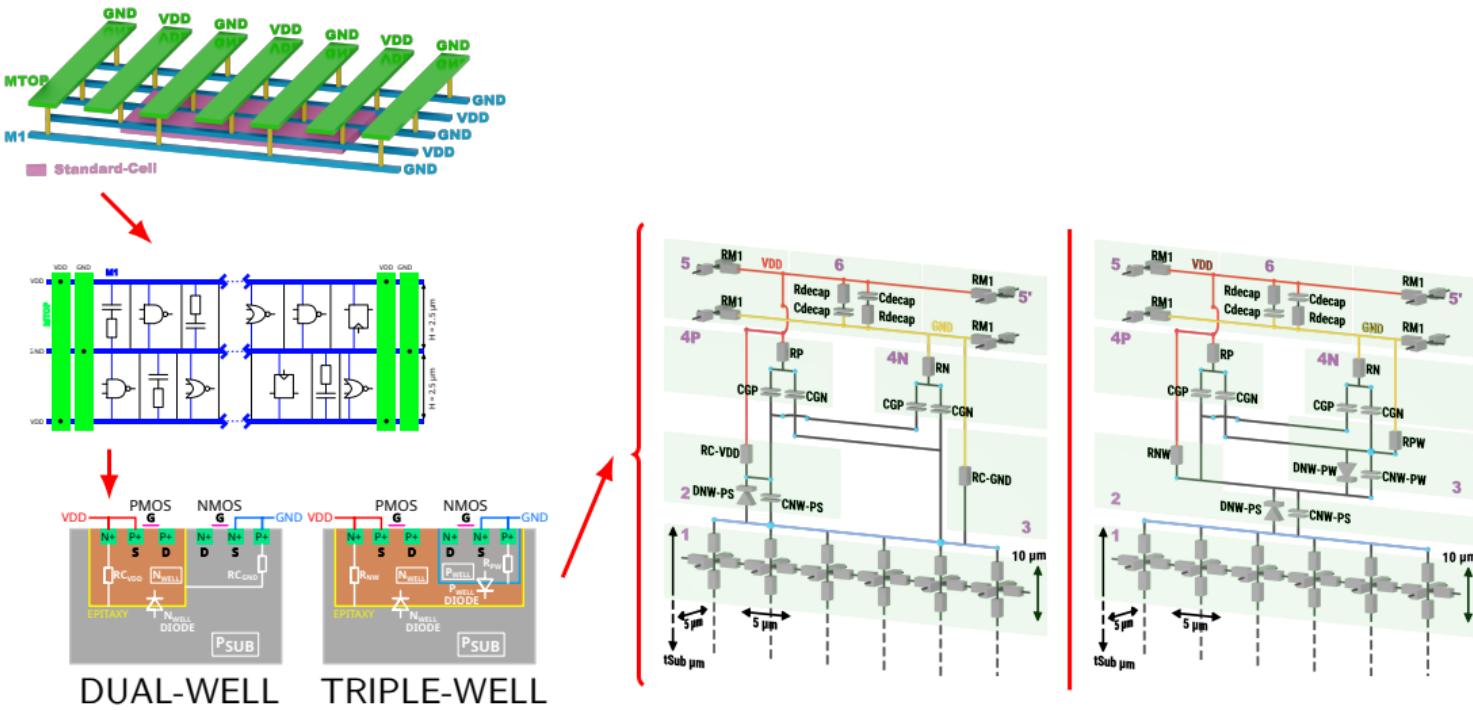
Simulation models



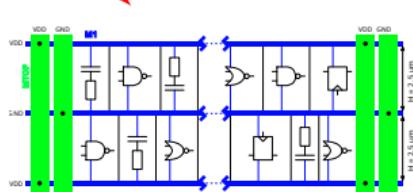
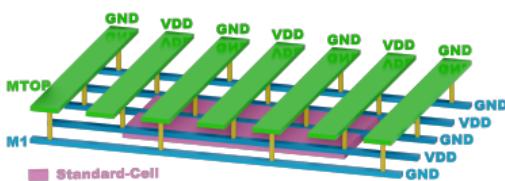
Simulation models



Simulation models



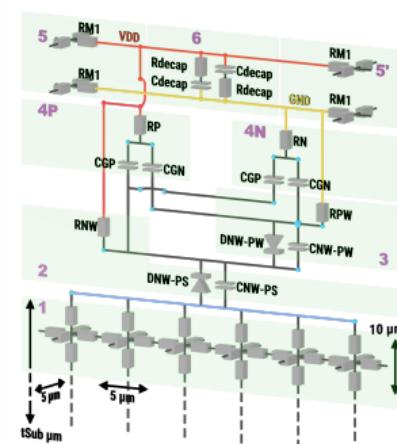
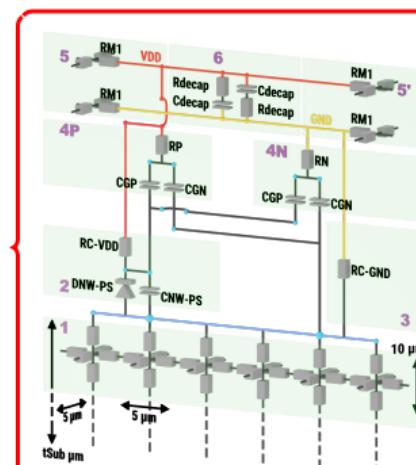
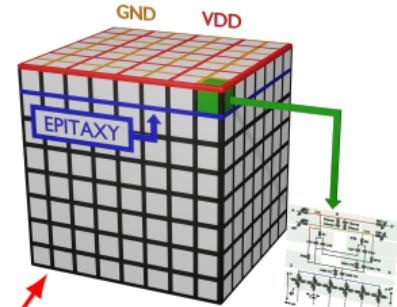
Simulation models



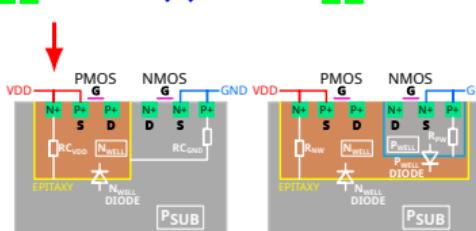
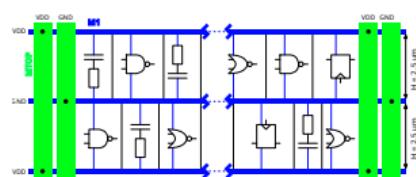
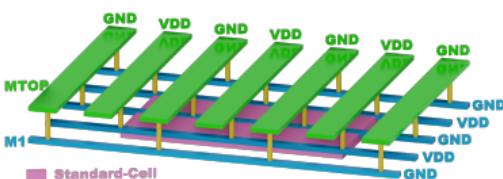
The diagram illustrates the detailed layout of a CMOS inverter. It features two main sections: the PMOS stage on the left and the NMOS stage on the right. Each stage includes a resistor (R_{C,VDD} and R_{C,GND}) and a diode (N_{MELL} DIODE) connected between the source/drain and the substrate (PSUB). The PMOS section has a red arrow pointing to its gate contact, while the NMOS section has a blue arrow pointing to its gate contact. The layout uses standard CMOS design rules with various colors (red, blue, yellow, green) to distinguish between different components and layers.

DUAL-WELL

TRIPLE-WELL

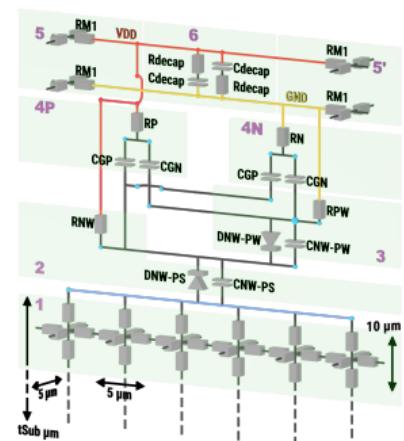
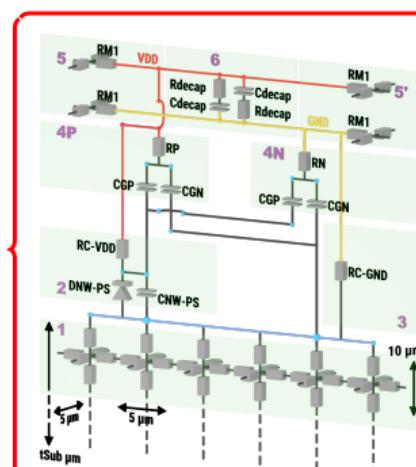
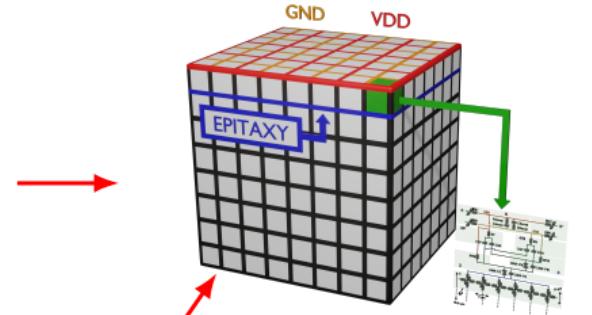
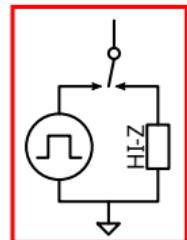


Simulation models



DUAL-WELL

TRIPLE-WELL



Simulation results

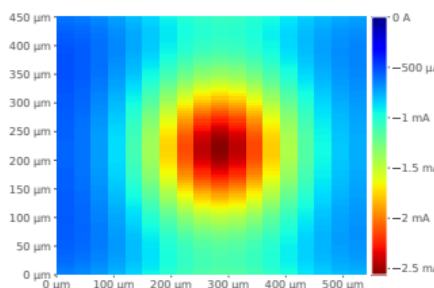
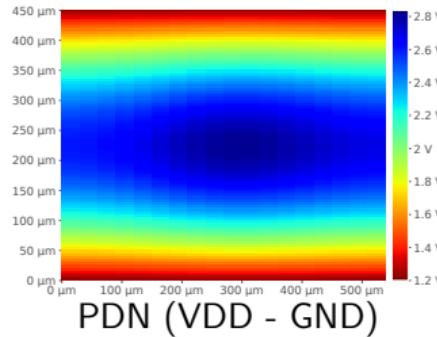
What we observe:

- Dual-well
- Triple-well
- Picture at the apex of the pulse
- $550 \mu m (W) \times 450 \mu m (D) \times 140 \mu m (T)$: integrated circuit \rightarrow 1620 SCS
- 90 nm Bulk CMOS

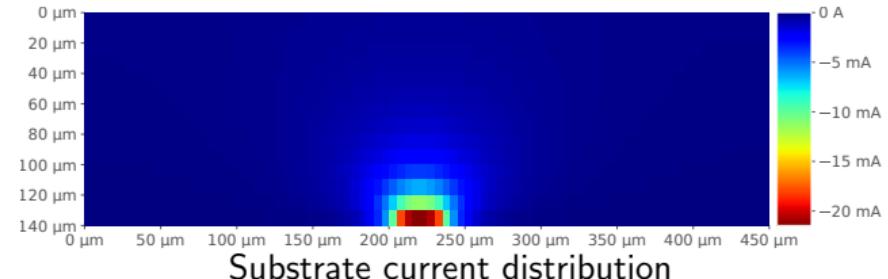
Simulation conditions:

- Voltage pulse amplitude: $\pm 300 V$
- Voltage pulse width: 20 ns
- Rise and fall times: 8 ns
- Approximate impedance matching

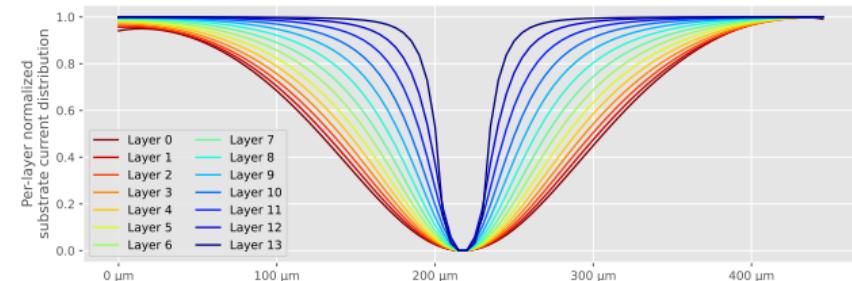
Simulation results: Dual-Well negative pulse



Epitaxy current distribution

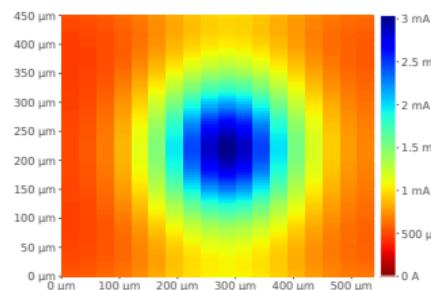
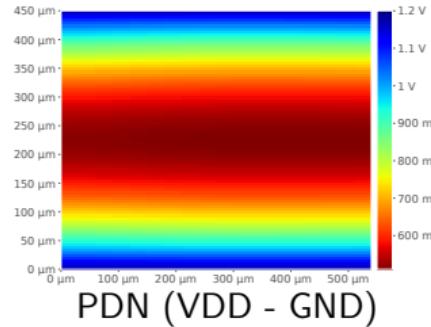


Substrate current distribution

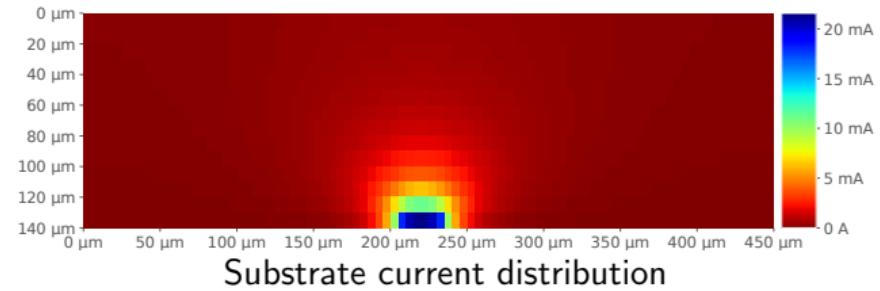


Per-layer normalized substrate current density

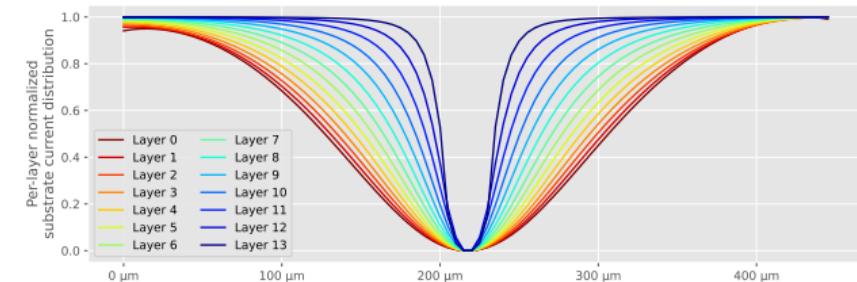
Simulation results: Dual-Well positive pulse



Epitaxy current distribution

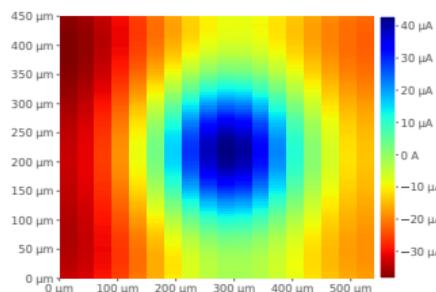
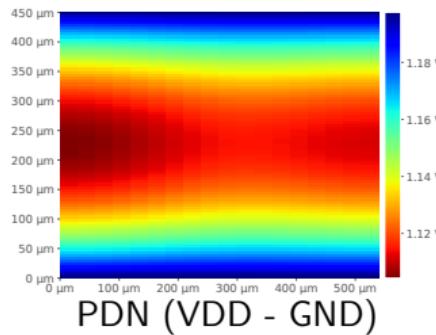


Substrate current distribution

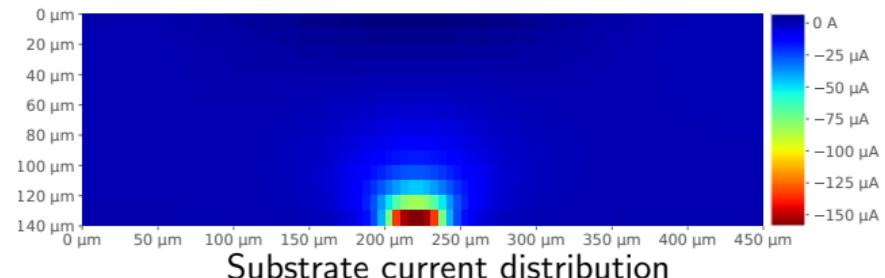


Per-layer normalized substrate current density

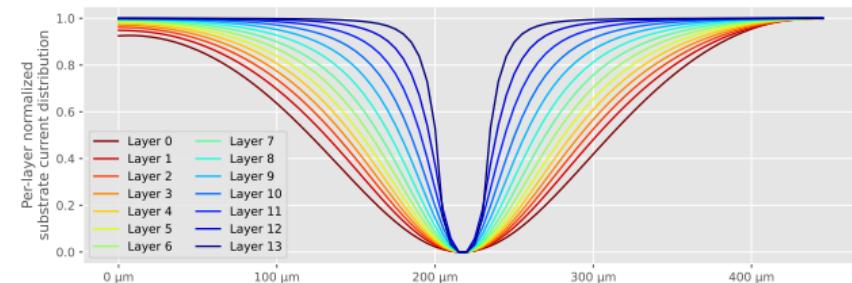
Simulation results: Triple-Well negative pulse



Epitaxy current distribution

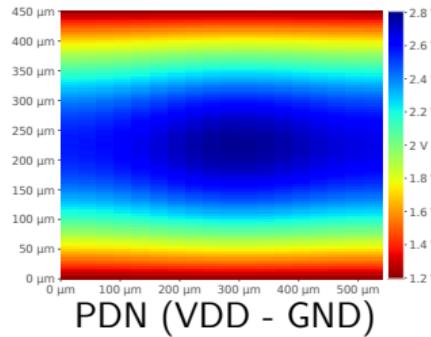


Substrate current distribution

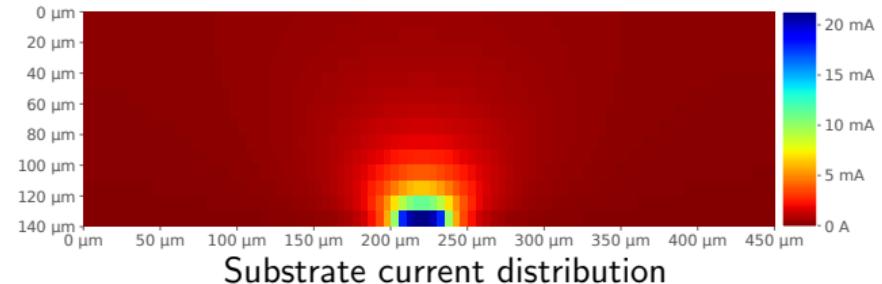


Per-layer normalized substrate current density

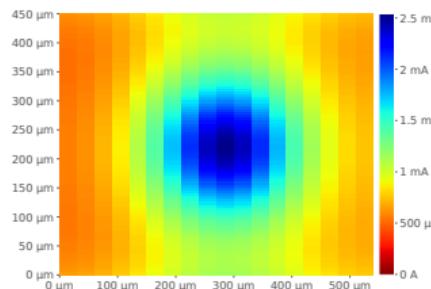
Simulation results: Triple-Well positive pulse



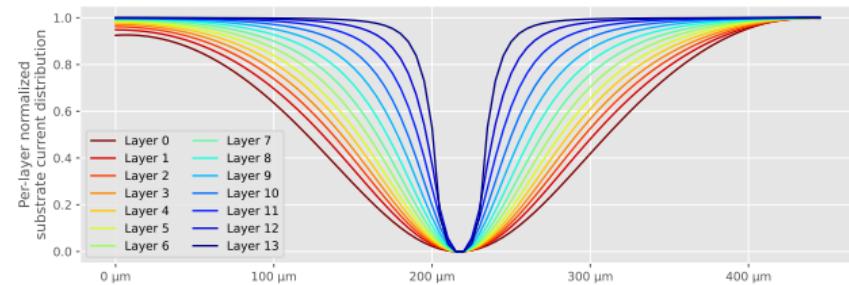
PDN (VDD - GND)



Substrate current distribution



Epitaxy current distribution



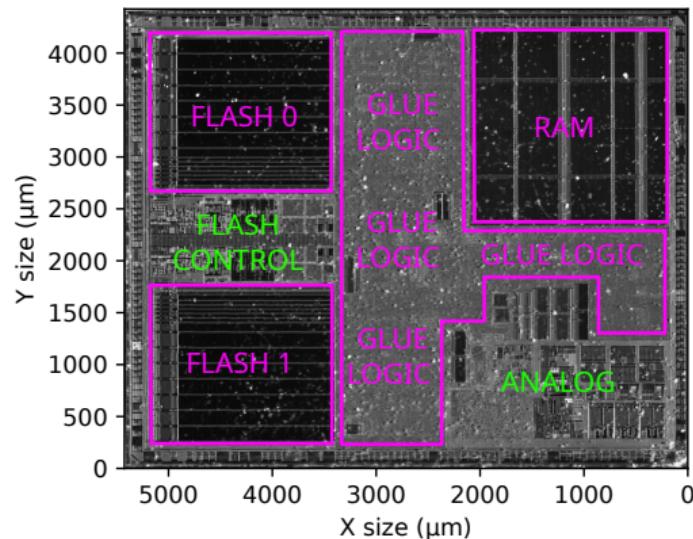
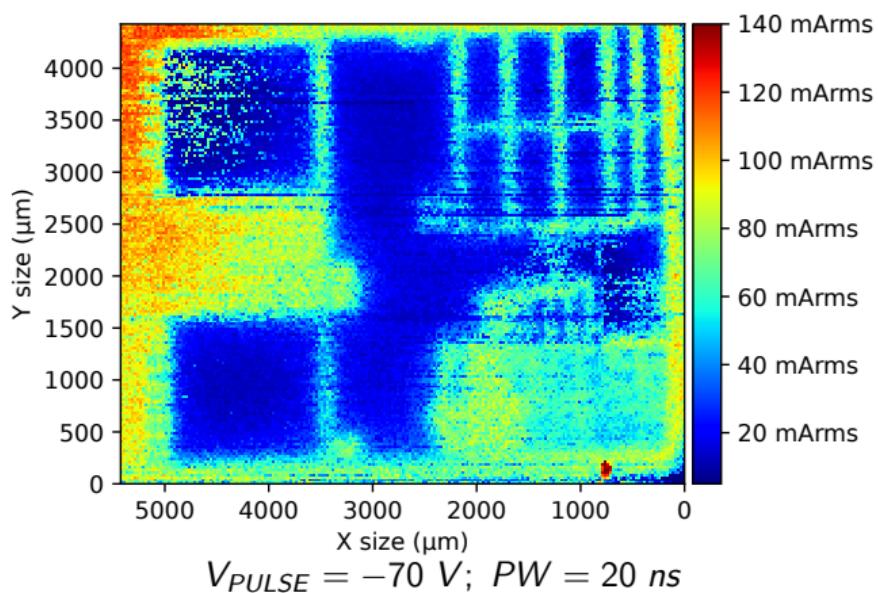
Per-layer normalized substrate current density

Dual-well vs Triple-well

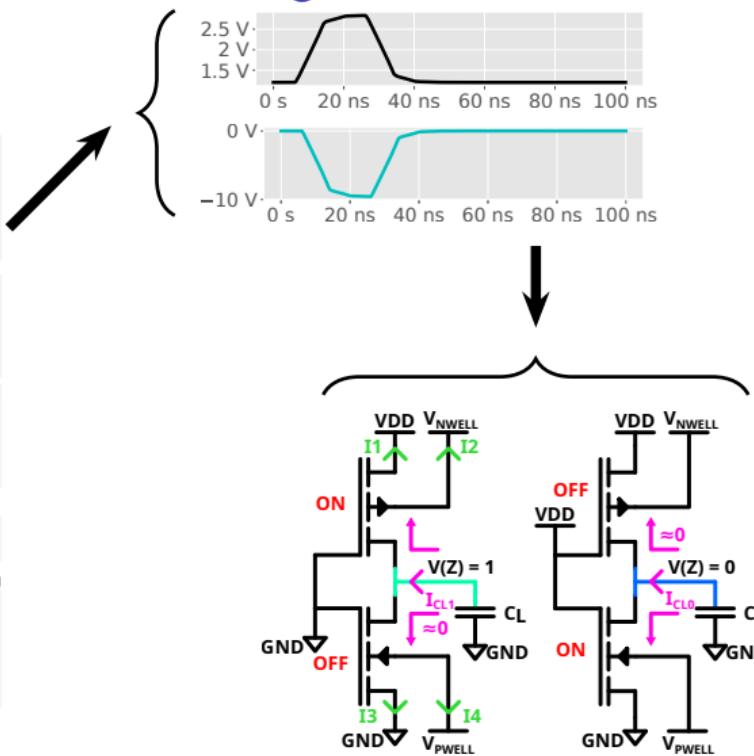
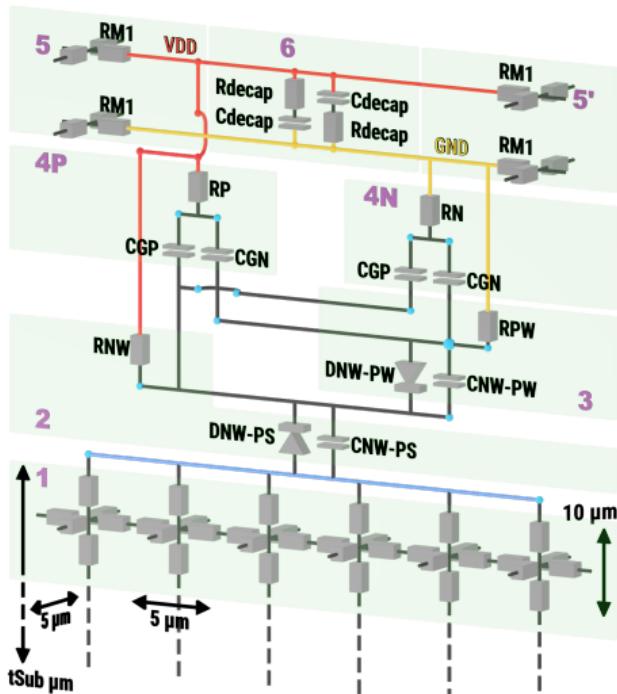
Differences between Dual-well and Triple-well circuits:

Substrate	Polarity	NMOS	Coupling PMOS	Circuit	Danger
Dual-well	Negative	DC	AC	DC	
Dual-well	Positive	DC	DC	DC	
Triple-well	Negative	AC	AC	AC	
Triple-well	Positive	AC	DC	DC	

Simulation results verification

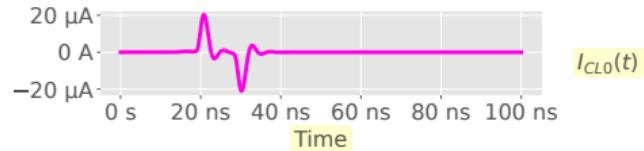
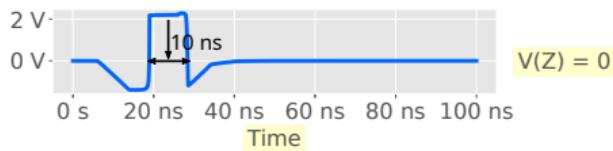
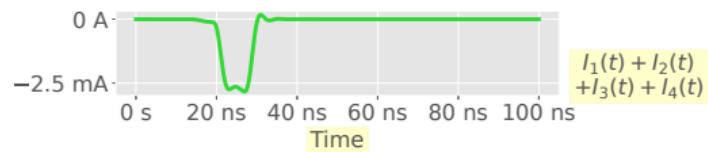
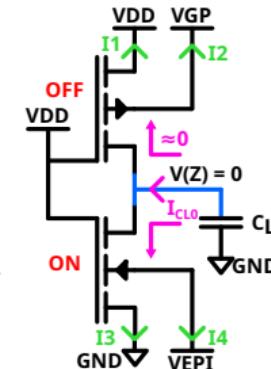
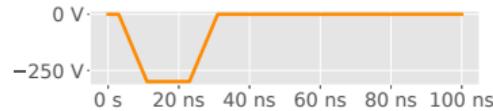
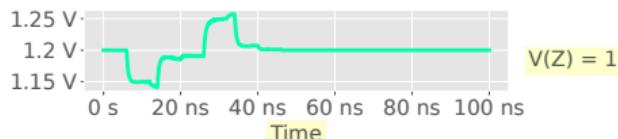
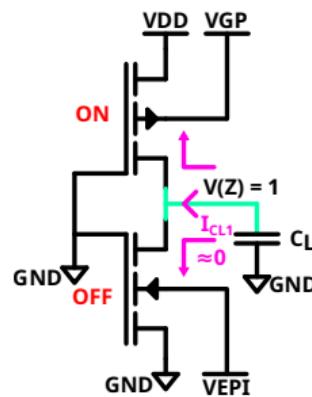


SCS incomplete models: how to consider logic function?



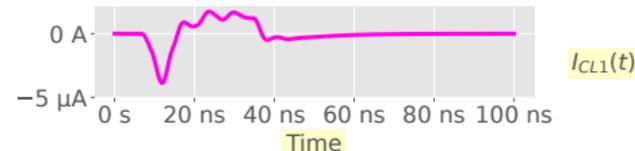
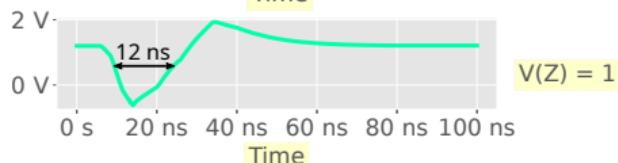
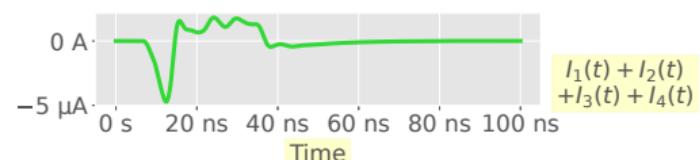
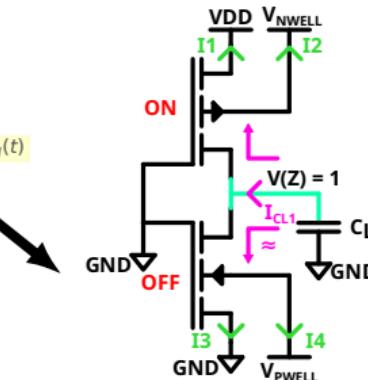
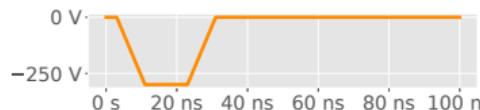
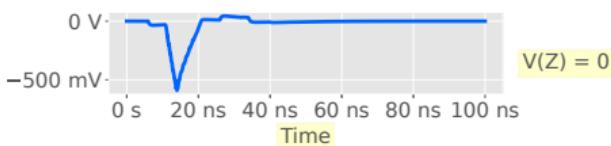
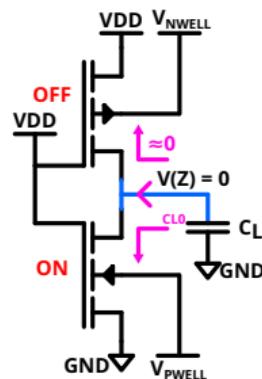
How faults occur under BBI?

Dual-well inverters



How faults occur under BBI?

Triple-well inverters



How faults occur under BBI?

Fault model

BBI injects or absorbs charges from the probe up to the power delivery network

The resulting current charges or discharges the logic gates output

BBI → electron vacuum cleaner

Data dependent faults → can BBI be used to perform safe-error attack?

SUBSTRATE THINNING ANALYSIS

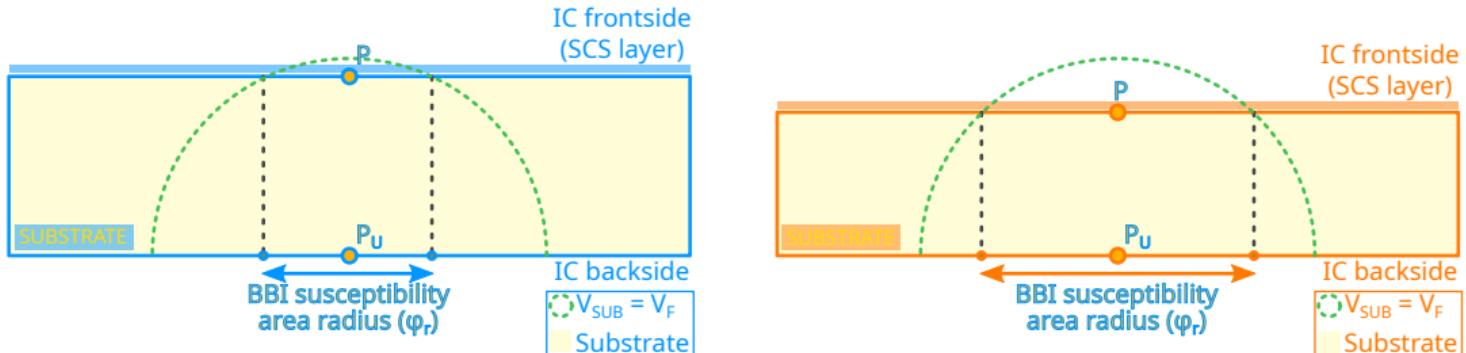
Substrate thinning in a BBI context

In Laser Fault Injection, substrate thinning has been proven useful
Is it the case concerning BBI?

Section agenda:

- Geometric approach
- Electrical simulation approach
- Experimental validation

Geometric approach

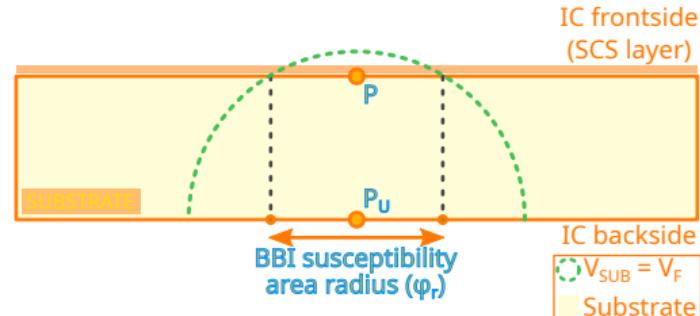
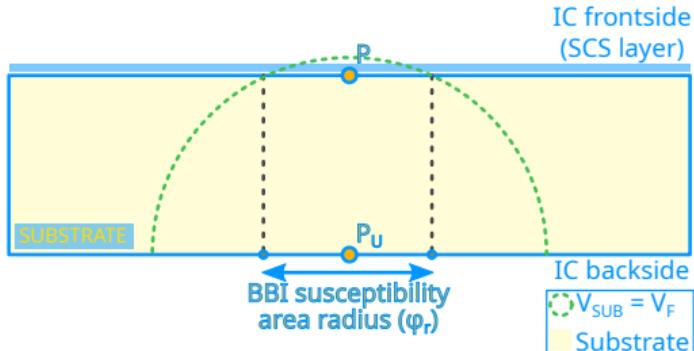


$$\phi_r(t) = 2 \cdot \sqrt{r(t)^2 - t_{SUB}^2}$$

$$\frac{\phi_r^{THIN}}{\phi_r^{THICK}} = \sqrt{\frac{r^2 - t_{THIN}^2}{r^2 - t_{THICK}^2}} > 1$$

Higher susceptibility area → greater current density

Geometric approach



$$V_{PU}^* = \frac{t_{THIN}}{t_{THICK}} \cdot V_{PU} + V_F \cdot \left(1 - \frac{t_{THIN}}{t_{THICK}}\right)$$

Geometric approach outcomes

- Thinning the substrate → Reduce the voltage pulse for a given susceptibility area
- Thinning the substrate → Susceptibility area increases at constant voltage
- Thinning the substrate → No improvement in resolution

Simulation approach

What we observe:

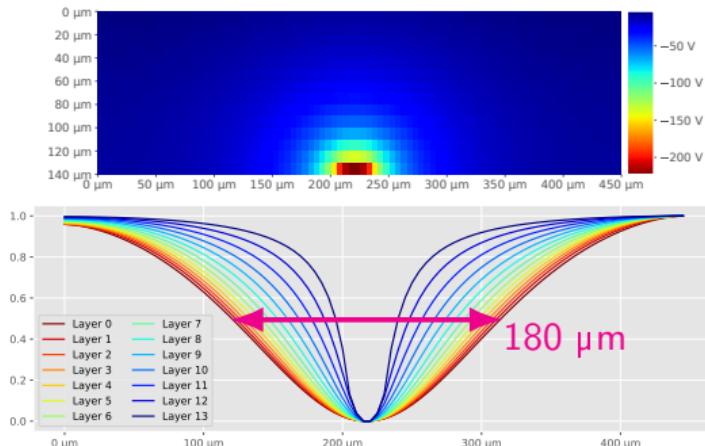
- Dual-well substrate IC
- Picture at the apex of the pulse
- $550 \mu m (W) \times 450 \mu m (D)$: integrated circuit $\rightarrow 1620$ SCS
- $140 \mu m (T)$ IC
- $60 \mu m (T)$ IC

Simulation conditions:

- Voltage pulse amplitude: -300 V
- Voltage pulse width: 20 ns
- Rise and fall times: 8 ns

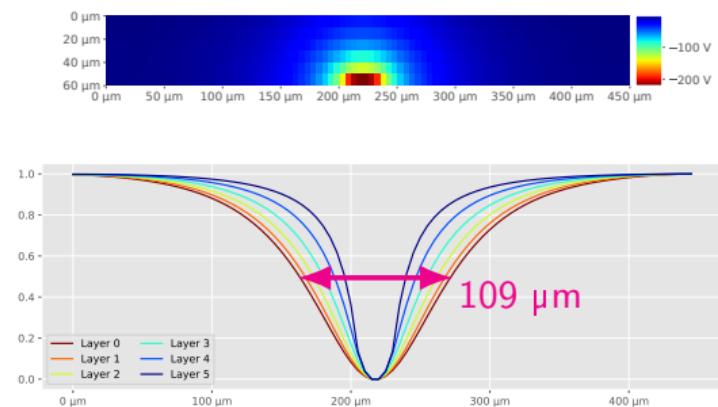
Simulation approach

Substrate voltage distribution (140 µm)



Substrate normalized current density (140 µm)
Highest layer @ 0.5 density diameter: 180 µm

Substrate voltage distribution (60 µm)



Substrate normalized current density (60 µm)
Highest layer @ 0.5 density diameter: 109 µm

For half of the normalized density → lower diameter → greater current density

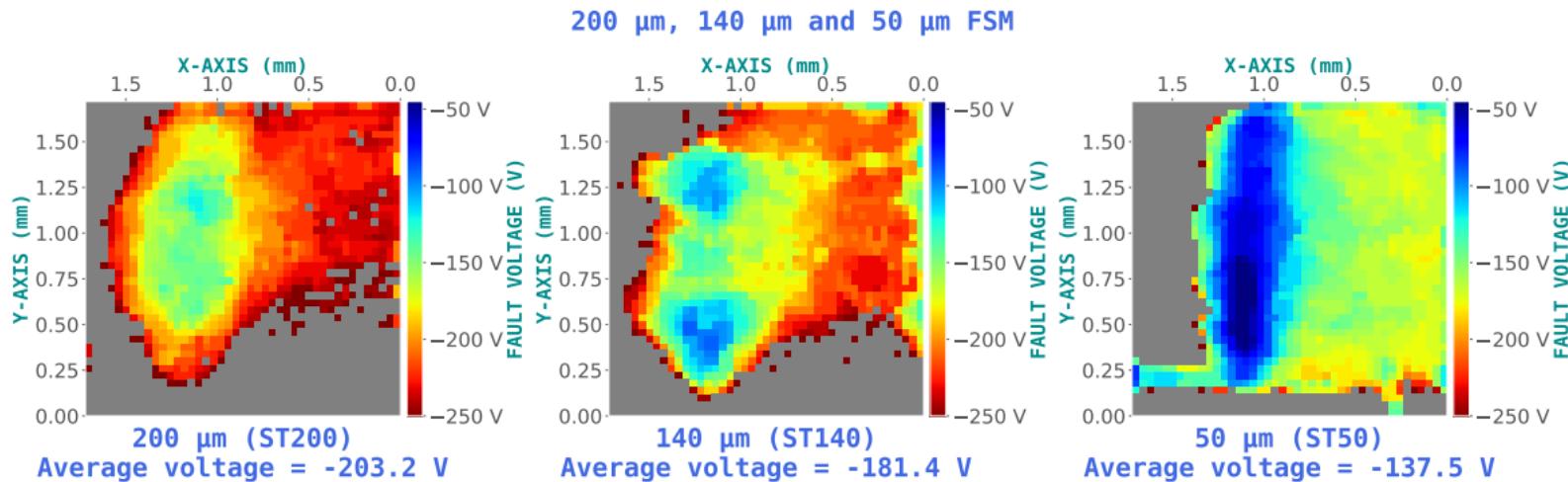
Substrate thinning in practice

Three experiments to verify the soundness of the outcomes:

- Fault susceptibility maps
- Susceptibility area spreading maps
- Susceptibility area comparison

Substrate thinning in practice

Fault susceptibility maps

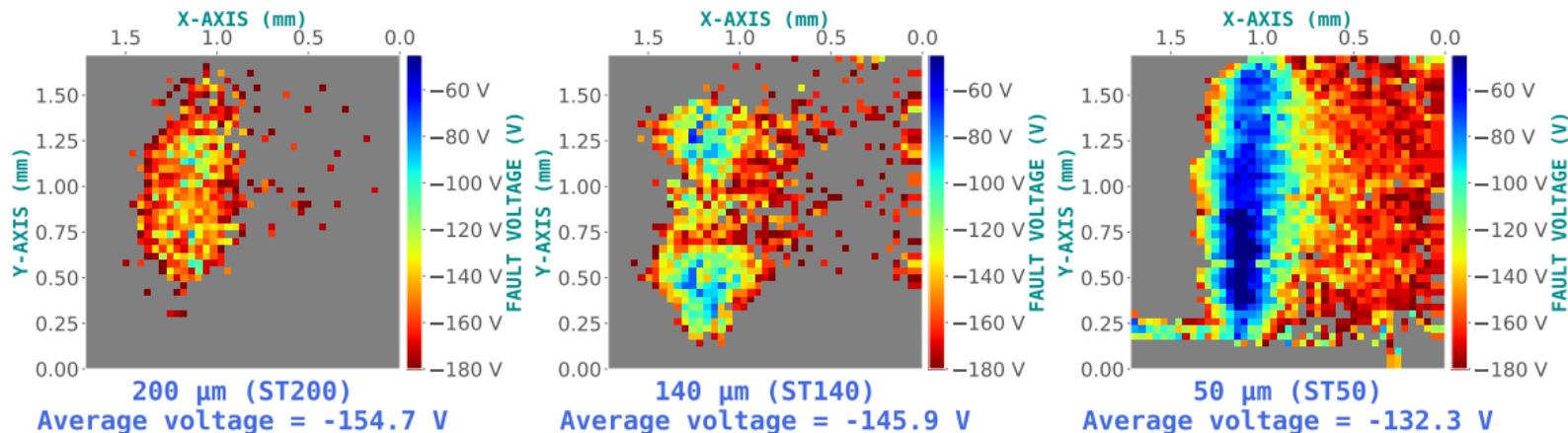


Thinning the substrate \rightarrow reduces the voltage required to induce faults

Substrate thinning in practice

Susceptibility area spreading

200 μm , 140 μm and 50 μm FSM

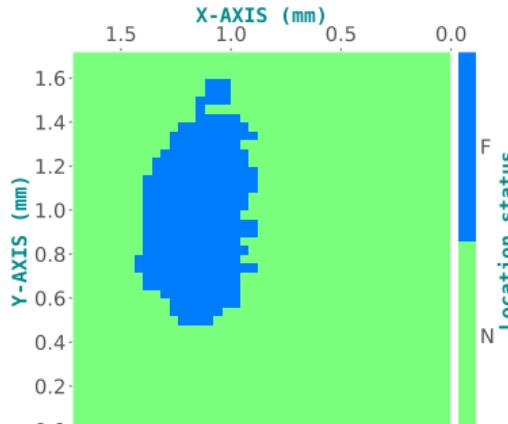


Thinning the substrate → increases the susceptibility for a given maximum voltage

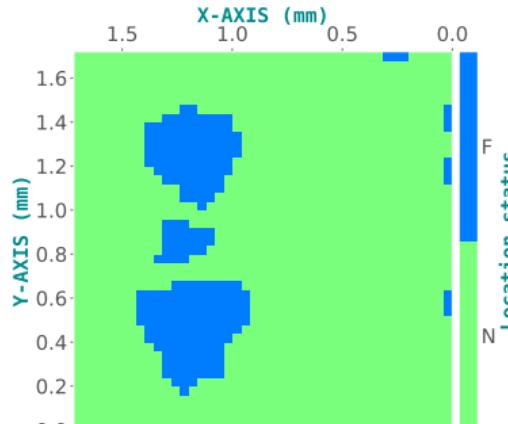
Substrate thinning in practice

Fault susceptibility maps areas comparison

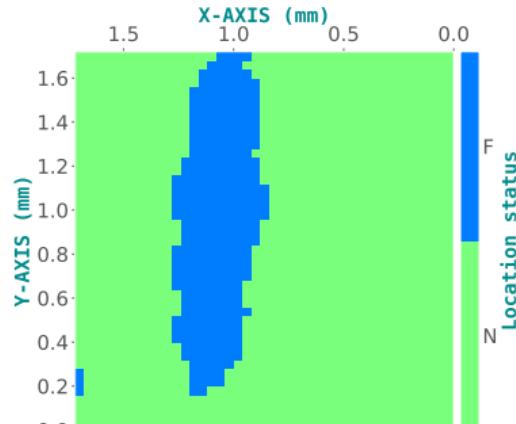
200 μm , 140 μm and 50 μm susceptibility areas comparison (F = FAULT, N = NO FAULT)



A1 : 200 μm (ST200), -170 V,
 0.416 mm^2 , $C_{A3-A1} = 64.6 \%$



A2 : 140 μm (ST140), -140 V,
 0.3824 mm^2 , $C_{A2-A1} = 44.2 \%$



A3 : 50 μm (ST50), -100 V,
 0.488 mm^2 , $C_{A3-A2} = 45.4 \%$

Same susceptibility areas with correct couple: (V_P , t_{SUB})
 No change in spatial resolution

CONCLUSION AND OUTLOOKS

Conclusion

- Better practices for BBI → successful DFA:
 - Impedance matching
 - Low impedance grounding
- Modeling and simulating BBI:
 - Local effect on ICs → [100, 200] μm
 - Thanks to a DC or AC coupling with the probe
 - Data-dependent faults (bit set and bit reset)
 - DW substrate / TW positive → dangerous
- Substrate thinning and BBI:
 - Lowers generator power requirements
 - Does not change spatial resolution → depends on (V_P , t_{SUB})

Outlooks

Further improvements:

- Adaptive impedance matching → increase repeatability
- Further study logic gates disturbance study → dynamic analysis
- Study memory elements and analog blocks (SRAM, FLASH, PLL)