Characterization and Modeling of SET Effects in Standard Combinational Cells

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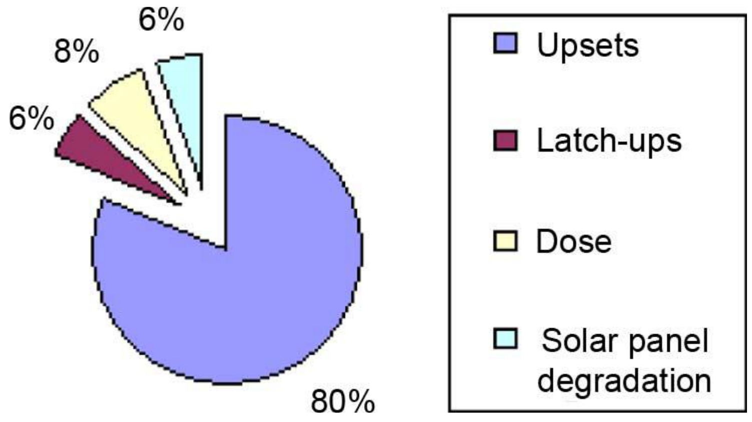
Outline

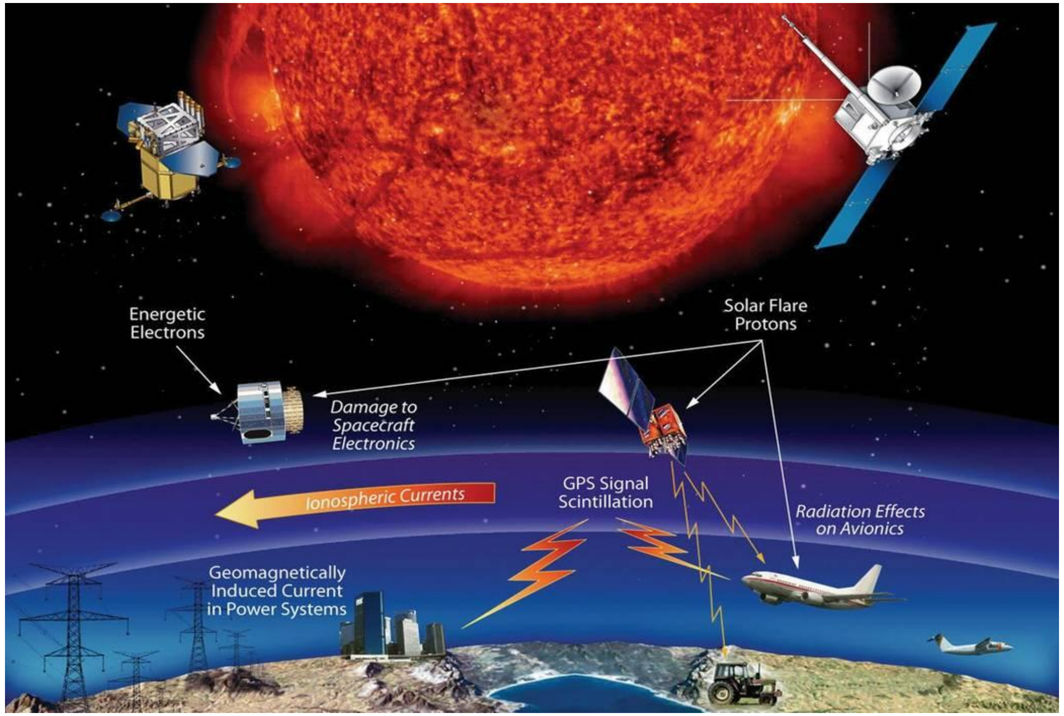
1. Introduction to SET Effects

Soft errors are a major reliability issue for digital circuits employed in space applications

- Manifested as bit-flips, resulting in data loss and system malfunction
- Caused by energetic particles such as heavy ions, neutrons, protons



Source: **R. Ecoffet, Overview of In-Orbit Radiation Induced Spacecraft Anomalies, IEEE Transactions on Nuclear Science, 2013.**

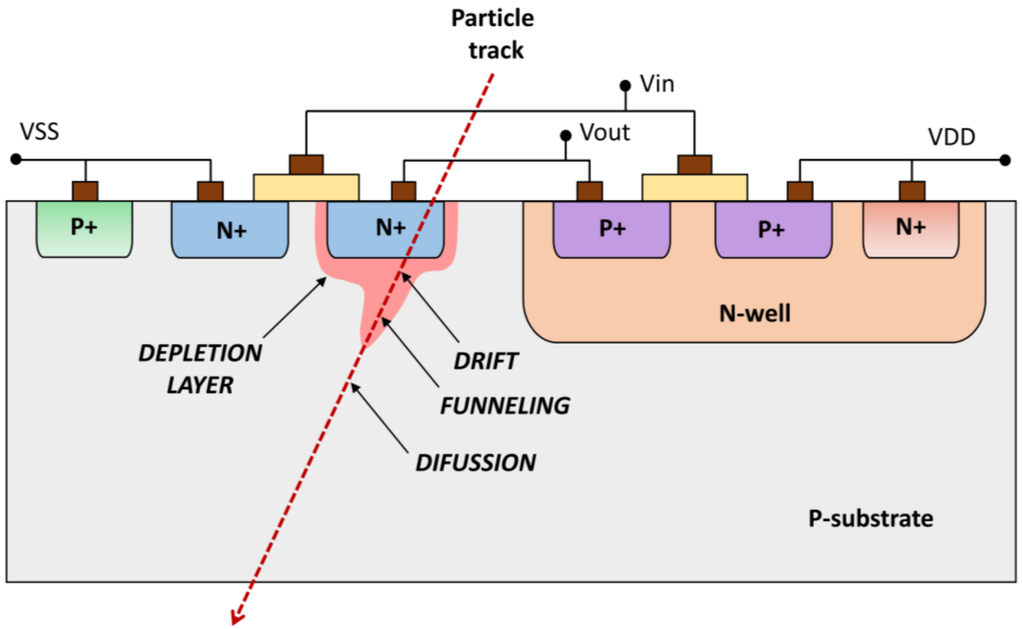


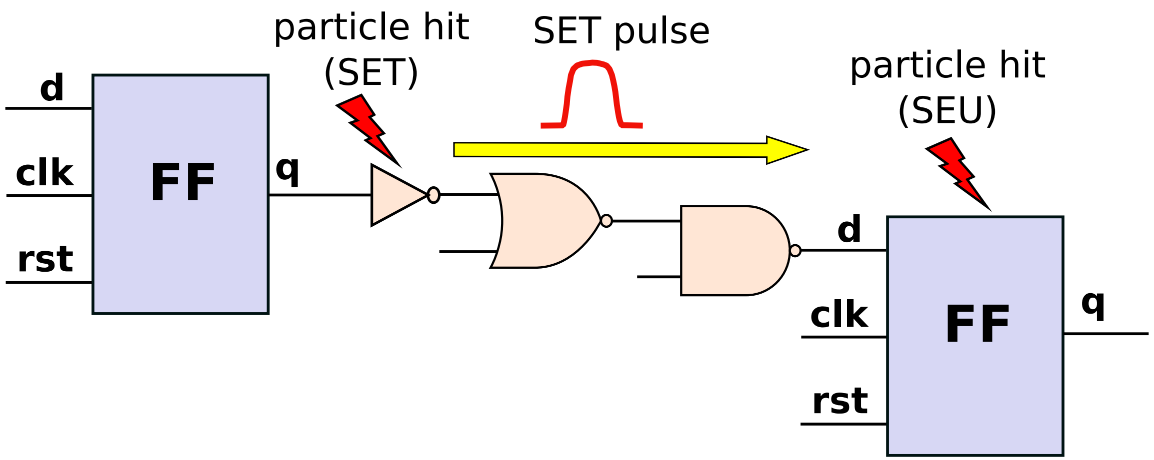
[Source: NASA]

1. Introduction to SET Effects

How soft errors occur?

- Particle hits a storage element, resulting in a bit-flip (**Single Event Upset - SEU**)
- Particle hits a combinational element, resulting in a voltage glitch (**Single Event Transient - SET**), which may propagate to one or more storage elements and cause one or more bit-flips

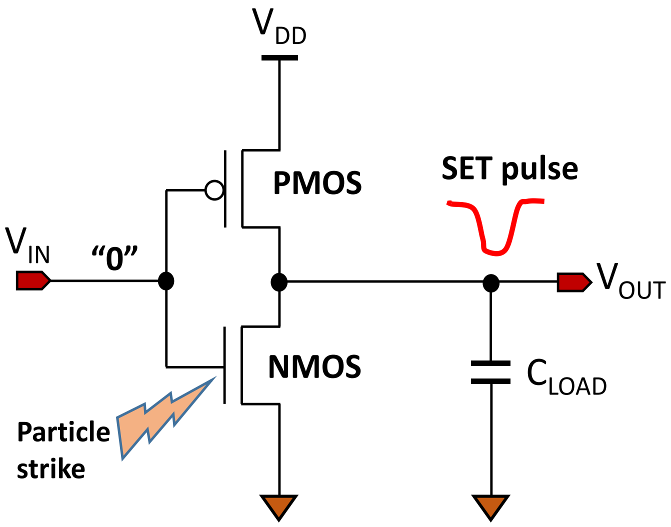


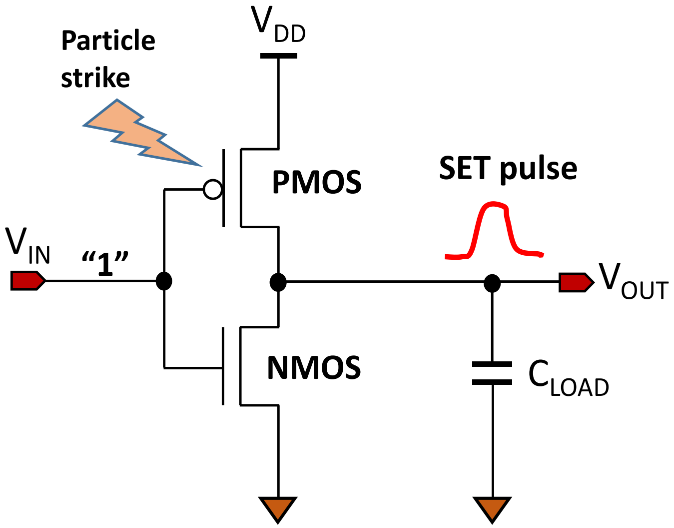


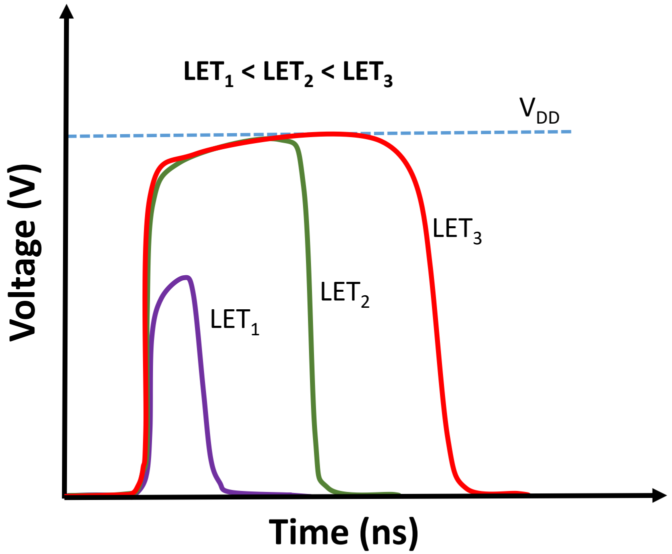
1. Introduction to SET Effects

SET generation

- If the charge released as a result of particle strike exceeds the critical charge of the circuit node, a SET voltage pulse will be formed
- Generated SET pulse width is in the order of **tens to hundreds picoseconds**, and it depends on particle Linear Energy Transfer (LET) and technology/design/operating parameters



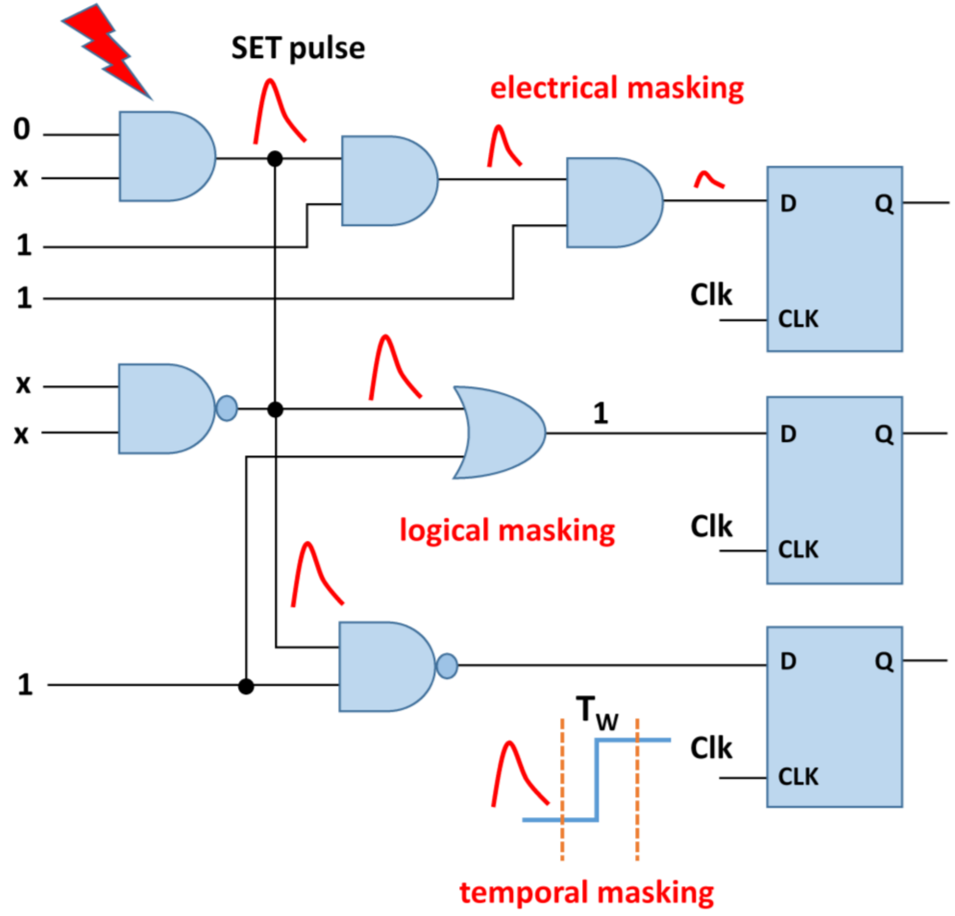




1. Introduction to SET Effects

SET propagation

- SET propagation depends on input pulse width, circuit design and operating parameters
- SETs longer than propagation delay of logic gates may propagate through the circuit
- SETs may be masked by 3 masking effects: electrical, logical and temporal masking
- SET pulse width may increase during propagation due to Propagation-induced Pulse Broadening (PIPB)



1. Introduction to SET Effects

Basic SET sensitivity metrics

- **SET generation metrics: critical charge and generated SET pulse width**
- **SET propagation metrics: propagated SET pulse width**
- **Combinational Soft Error Rate (SER) – number of SET-induced soft errors in a given time interval**

$$SER = \sum_{i=1}^{N} SER_{NOMINAL}(i) \cdot SER_{DERATING}(i)$$

N = number of components in the system

$$SER_{NOMINAL} = k \cdot Flux \cdot Area \cdot e^{-\frac{Q_{CRIT}}{Q_S}}$$

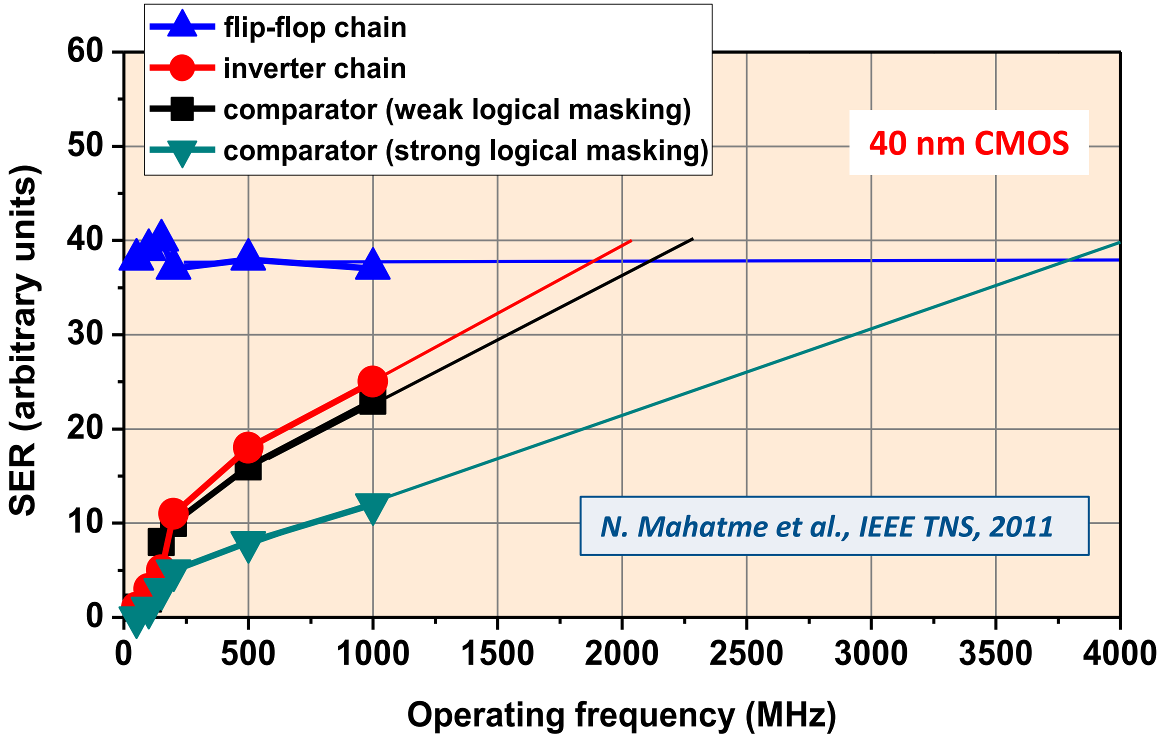
$$SER_{DERATING} = Logical_{DER} \cdot Electrical_{DER} \cdot Timing_{DER}$$

1. Introduction to SET Effects

Contribution of SETs to the total Soft Error Rate (SER) of digital circuits increases with technology scaling trends

- Decrease in transistor size
- Decrease in supply voltage
- Decrease in logic path length
- Increase in clock frequency

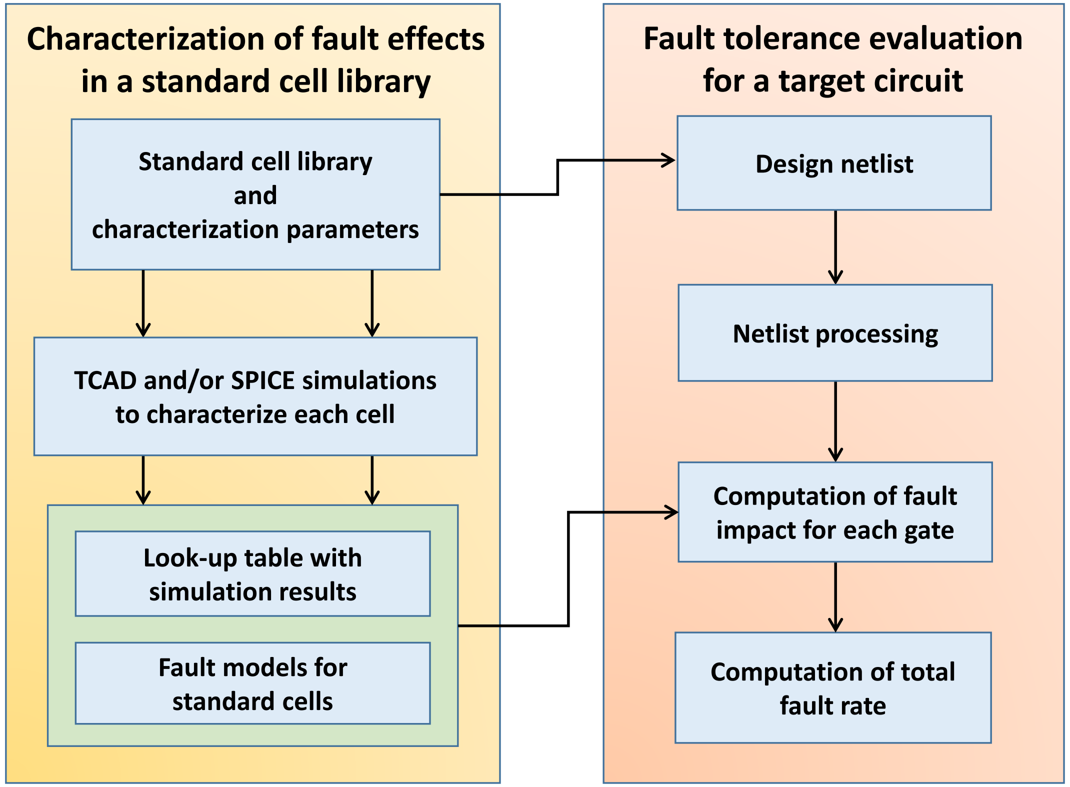
At GHz clock frequencies, SER of simple combinational circuits may be comparable or larger than SET of flip-flops



2. SET Characterization Methodology

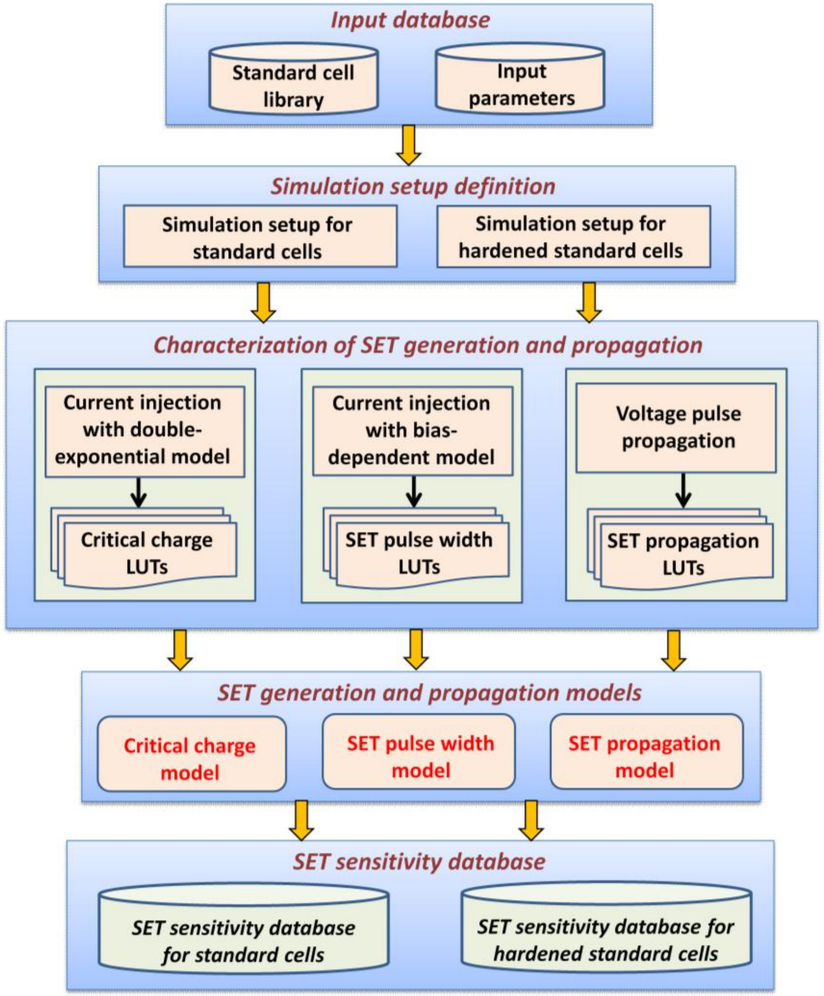
SET analysis with combined simulations and analytical methods

- ➢ Simulations are used to characterize fault effects for a given technology and standard cell library, and this process is performed only once
- ➢ Analytical methods are used to analyze fault tolerance of a complex design
- ➢ Benefits
  - Accurate analysis of fault effects
  - Low runtime (fast analysis)



2. SET Characterization Methodology

- **Joint characterization of SET sensitivity of standard cells and their hardened variants**
  - SPICE simulations are used to analyze SET sensitivity of each standard cell and its hardened variants in a given technology
  - SET sensitivity is analyzed as a function of various parameters:
    - Irradiation parameters – particle LET, SET current/voltage parameters
    - Design parameters – target gate size, load size, wire capacitance
    - Operating parameters – supply voltage, temperature, input vectors
  - Simulation results are stored in look-up tables (LUTs)
  - Analytical models for SET sensitivity metrics are derived from LUTs

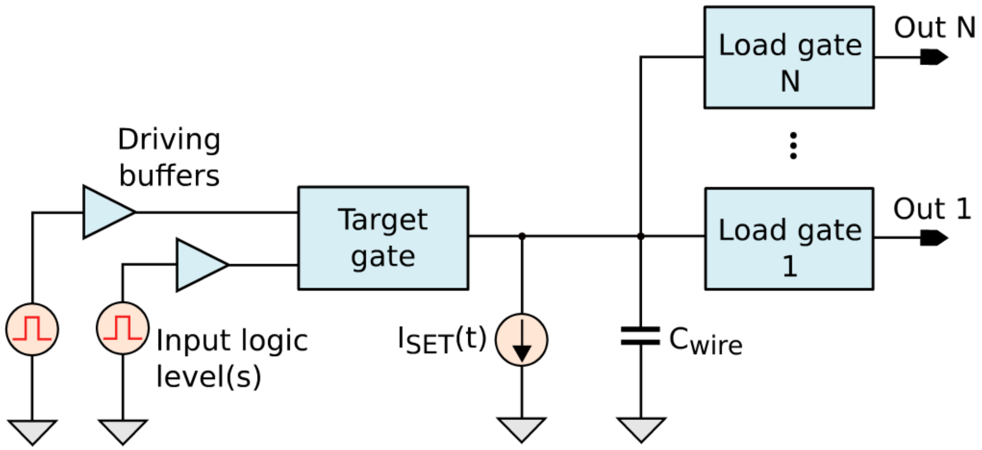


2. SET Characterization Methodology

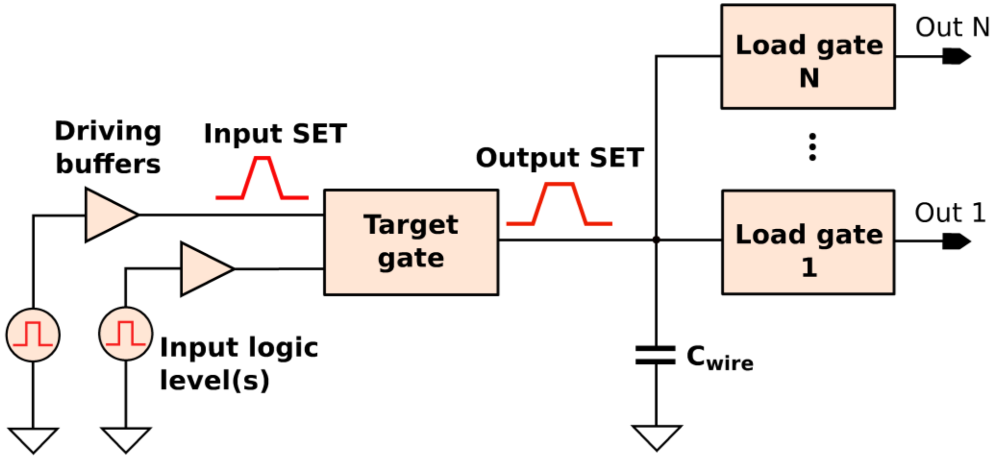
SET generation and SET propagation simulation setups

- Double-exponential current source is used to determine critical charge
- Bias-dependent current model is used to determine generated SET pulse width
- Trapezoidal voltage pulse is used to evaluate SET propagation

SET generation simulation setup



SET propagation simulation setup



2. SET Characterization Methodology

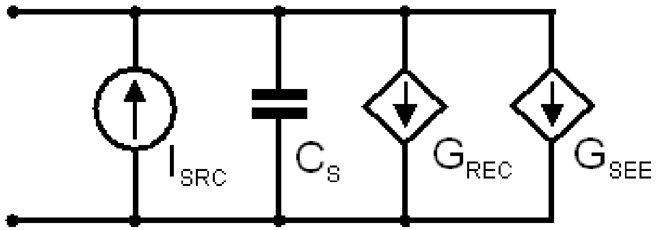
Bias-dependent current model (by Kaupilla et al., *IEEE TNS*, 2009)

- Composed of double-exponential current source and two voltage-controlled current sources
- Takes into account the plateau region in current pulse that occurs for high LET values
- User-defined parameters: LET, rise and fall time for current pulse

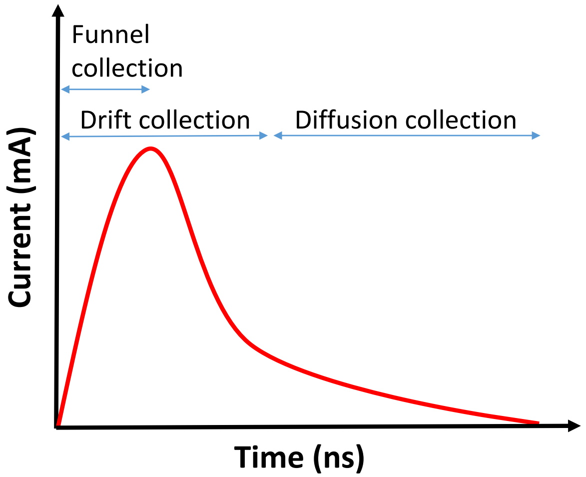
Double-exponential current model

$$I_{SRC}(t) = \frac{Q_{COLL}}{\tau_f - \tau_r}\left(e^{-t/\tau_f} - e^{-t/\tau_r}\right)$$

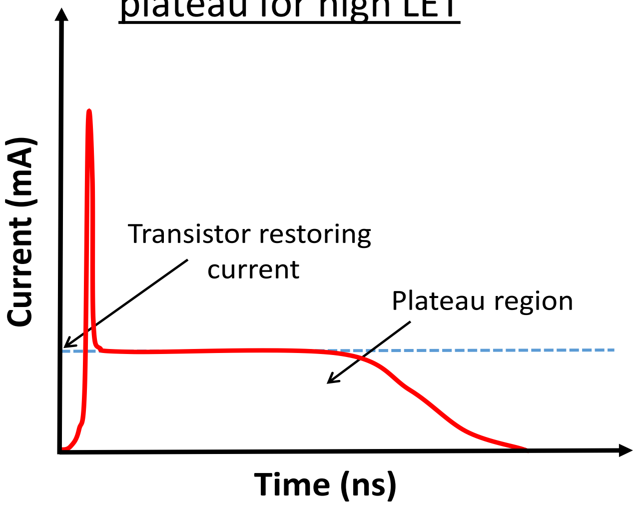
Bias-dependent current model



Double-exponential current pulse



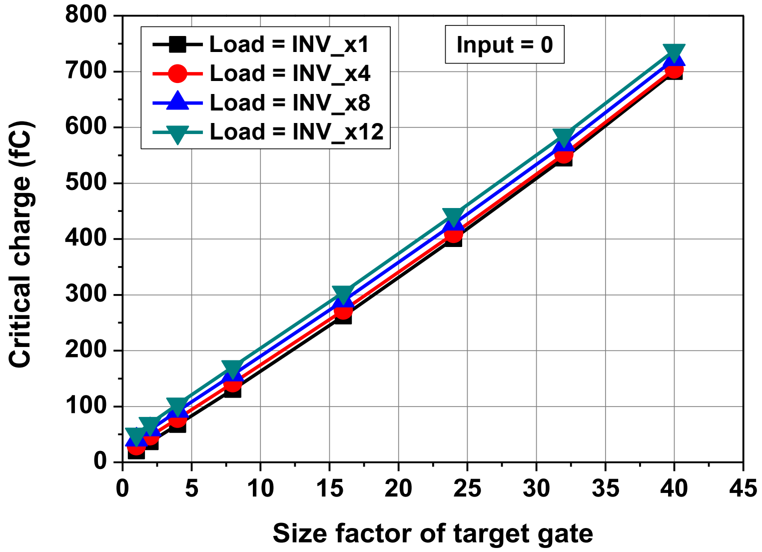
Current pulse with plateau for high LET

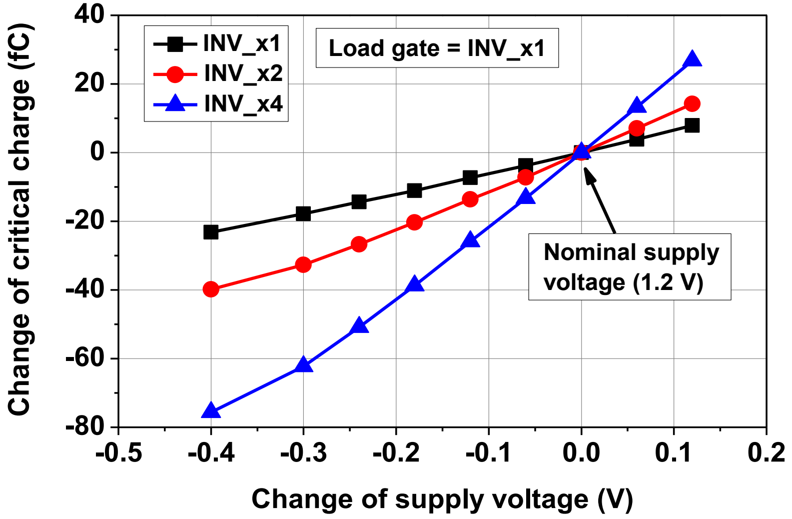


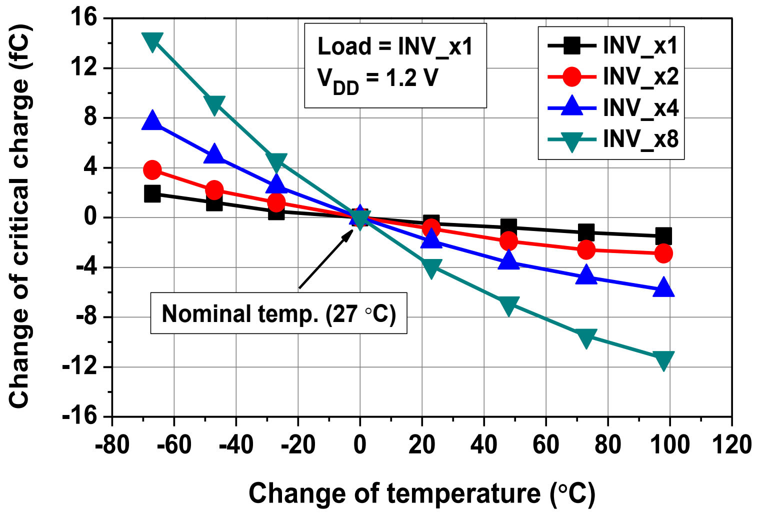
3. SET Characterization for IHP's 130nm Standard Cells

Critical charge

- ➢ Q_{CRIT} increases with the size of target gate and load gate, where target gate has stronger impact than load gate(s)
- ➢ A logic gate is more robust to particle strikes at higher supply voltage and lower temperature



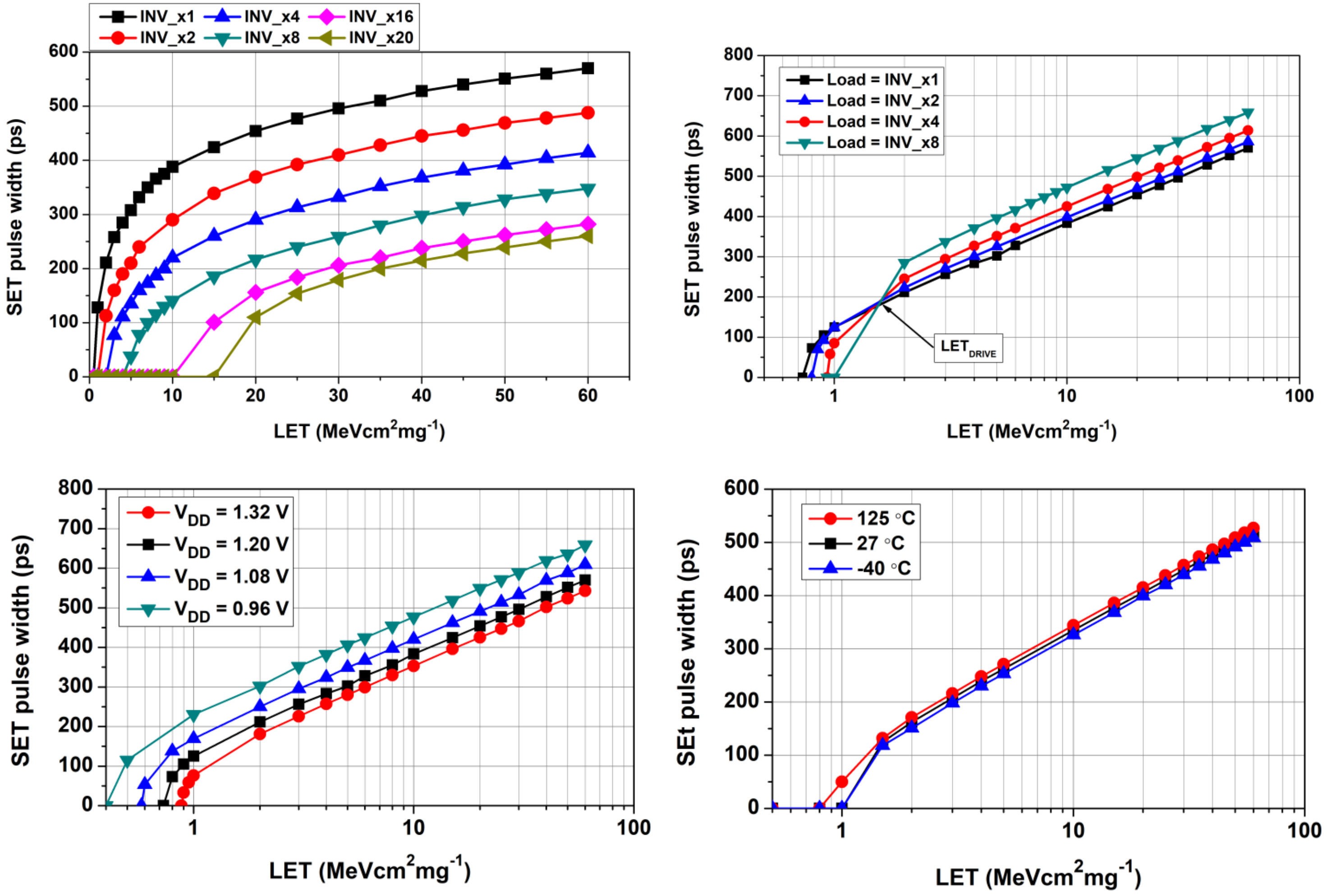




3. SET Characterization for IHP's 130nm Standard Cells

Generated SET pulse width

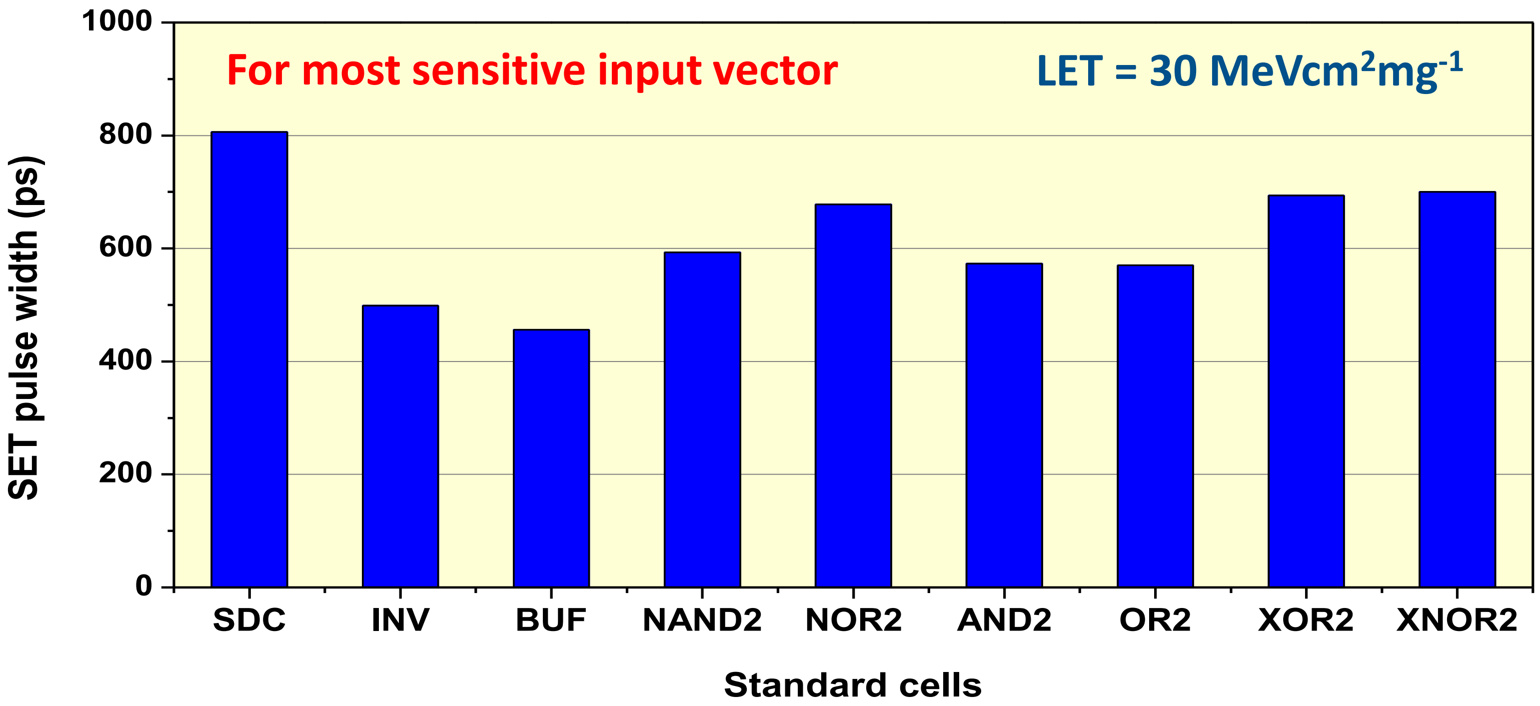
- SET pulse width increases with LET
- Increase of gate size reduces the SET pulse width
- Large load increases the SET pulse width for higher LET
- V_{DD} increase leads to a decrease in SET pulse width
- T_{EMP} decrease leads to a decrease in SET pulse width



3. SET Characterization for IHP's 130nm Standard Cells

Generated SET pulse width - comparison

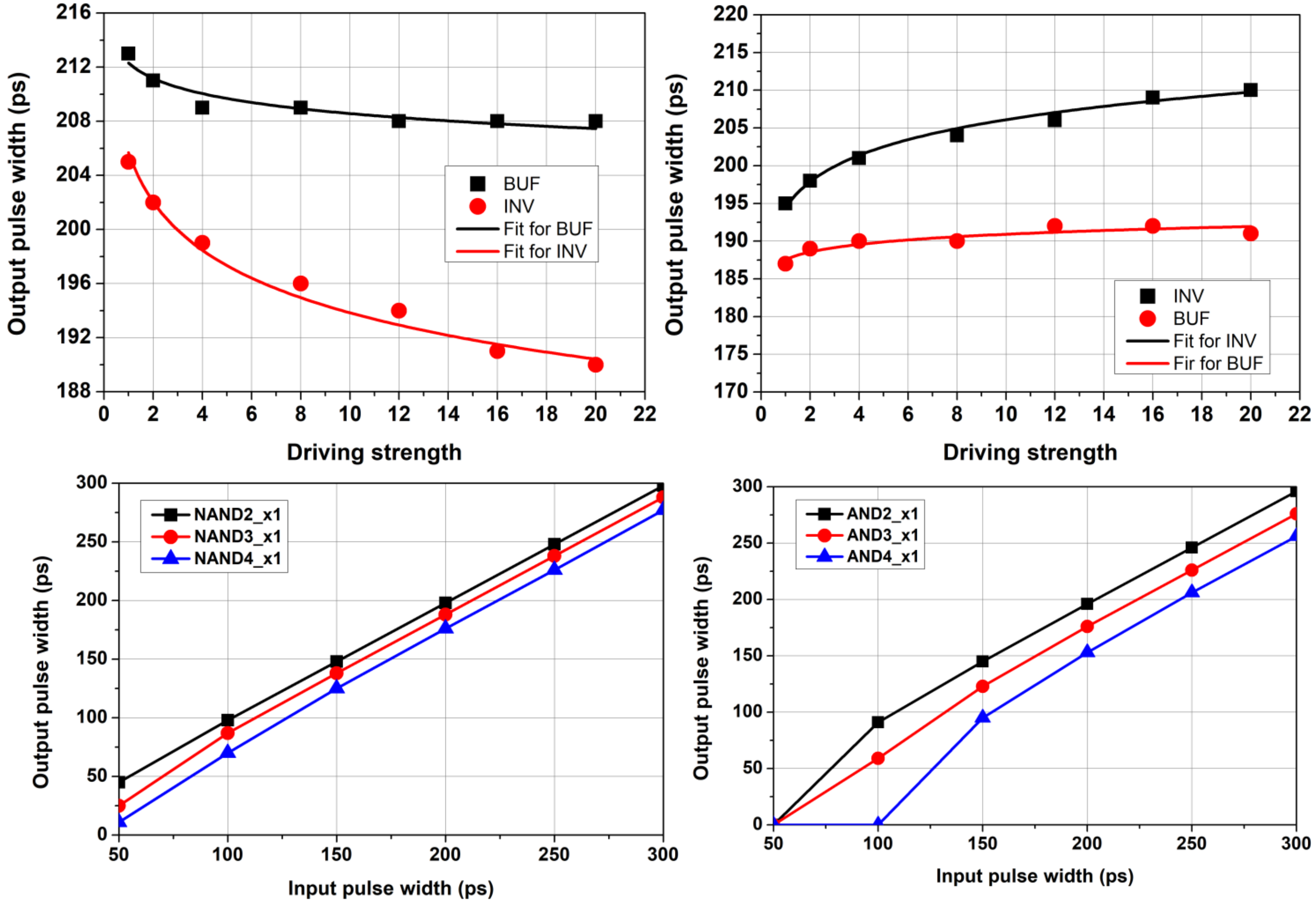
- SET pulse width may vary by several hundred picoseconds depending on gate type



3. SET Characterization for IHP's 130nm Standard Cells

- **Propagated SET pulse width**
  - Increases or decreases with respect to input pulse width, depending on input pulse polarity
  - Varies significantly depending on load capacitance, supply voltage, and temperature

- **More complex gates have better SET filtering capability**



3. SET Characterization for IHP's 130nm Standard Cells

- **Propagated SET pulse width – Short combinational paths may cause significant SET broadening**

10-gate combinational paths (all gates are with driving strength x1)	Output pulse width (ps)					
	Positive input pulse = 200 ps			Negative input pulse = 200 ps		
	LVT	TVT	HVT	LVT	TVT	HVT
INV	208	206	204	195	196	197
BUF	367	322	293	0	68	108
NAND2	201	201	201	203	204	204
AND2	166	152	134	237	250	268
NOR2	223	216	214	151	176	185
OR2	925	748	645	0	0	0
Alternating OR2 and AND2	542	447	387	0	0	0
Alternating AND3 and OR4	499	416	359	0	0	0
Alternating NAND2 and NOR3	667	563	506	0	0	0
Alternating XNOR3 and NOR2	0	0	0	173	243	252

4. SET Sensitivity Prediction with Fitting Models

- **By fitting the simulation results with standard fitting models, analytical models for SET sensitivity metrics can be derived**
- **Storing the model parameters in LUTs reduces the characterization database**

Standard SET sensitivity database

LUT4: Q_{CRIT} (S_T, S_L) for V_{DD4}

LUT3: Q_{CRIT} (S_T, S_L) for V_{DD3}

LUT2: Q_{CRIT} (S_T, S_L) for V_{DD2}

LUT1: Q_{CRIT} (S_T, S_L) for V_{DD1}

	S_L=1	S_L=2	S_L=4	S_L=8
S_T=1	$Q_{CRIT}(1,1)$	$Q_{CRIT}(1,2)$	$Q_{CRIT}(1,4)$	$Q_{CRIT}(1,8)$
S_T=2	$Q_{CRIT}(2,1)$	$Q_{CRIT}(2,2)$	$Q_{CRIT}(2,4)$	$Q_{CRIT}(2,8)$
S_T=4	$Q_{CRIT}(4,1)$	$Q_{CRIT}(4,2)$	$Q_{CRIT}(4,4)$	$Q_{CRIT}(4,8)$
S_T=8	$Q_{CRIT}(8,1)$	$Q_{CRIT}(8,2)$	$Q_{CRIT}(8,4)$	$Q_{CRIT}(8,8)$

Proposed SET sensitivity database

Critical charge model LUT				
	Input 1	Input 2	...	Input 2^P - L
Q_{NOM}	$Q_{NOM}(1)$	$Q_{NOM}(2)$	...	$Q_{NOM}(2^P\text{-}L)$
a_0	$a_0(1)$	$a_0(2)$	...	$a_0(2^P\text{-}L)$
a_1	$a_1(1)$	$a_1(2)$	...	$a_1(2^P\text{-}L)$
a_2	$a_2(1)$	$a_2(2)$	...	$a_2(2^P\text{-}L)$
a_3	$a_3(1)$	$a_3(2)$	...	$a_3(2^P\text{-}L)$
a_4	$a_4(1)$	$a_4(2)$	...	$a_4(2^P\text{-}L)$
a_5	$a_5(1)$	$a_5(2)$	...	$a_5(2^P\text{-}L)$
a_6	$a_6(1)$	$a_6(2)$	...	$a_6(2^P\text{-}L)$

4. SET Sensitivity Prediction with Fitting Models

- **SET sensitivity of each gate can be expressed with 3 LUTs**
  - **Critical charge LUT**
  - **Generated SET pulse width LUT**
  - **Propagated SET pulse width LUT**

Critical charge model LUT				
	Input 1	Input 2	...	Input 2^P - L
Q_{NOM}	$Q_{NOM}(1)$	$Q_{NOM}(2)$	...	$Q_{NOM}(2^P\text{-}L)$
a_0	$a_0(1)$	$a_0(2)$	...	$a_0(2^P\text{-}L)$
a_1	$a_1(1)$	$a_1(2)$	...	$a_1(2^P\text{-}L)$
a_2	$a_2(1)$	$a_2(2)$	...	$a_2(2^P\text{-}L)$
a_3	$a_3(1)$	$a_3(2)$	...	$a_3(2^P\text{-}L)$
a_4	$a_4(1)$	$a_4(2)$	...	$a_4(2^P\text{-}L)$
a_5	$a_5(1)$	$a_5(2)$	...	$a_5(2^P\text{-}L)$
a_6	$a_6(1)$	$a_6(2)$	...	$a_6(2^P\text{-}L)$

Generated SET pulse width model LUT				
	Input 1	Input 2	...	Input 2^P - L
LET_{DRIVE}	$LET_{DRIVE}(1)$	$LET_{DRIVE}(2)$	...	$LET_{DRIVE}(2^P - L)$
b_0	$b_0(1)$	$b_0(2)$	...	$b_0(2^P - L)$
b_1	$b_1(1)$	$b_1(2)$	...	$b_1(2^P - L)$
b_2	$b_2(1)$	$b_2(2)$	...	$b_2(2^P - L)$
b_3	$b_3(1)$	$b_3(2)$	...	$b_3(2^P - L)$
b_4	$b_4(1)$	$b_4(2)$	...	$b_4(2^P - L)$
b_5	$b_5(1)$	$b_5(2)$	...	$b_5(2^P - L)$
b_6	$b_6(1)$	$b_6(2)$	...	$b_6(2^P - L)$
b_7	$b_7(1)$	$b_7(2)$	...	$b_7(2^P - L)$
b_8	$b_8(1)$	$b_8(2)$	...	$b_8(2^P - L)$
b_9	$b_9(1)$	$b_9(2)$	...	$b_9(2^P - L)$

Propagated SET pulse width model LUT				
	Input 1	Input 2	...	Input P
c_0	$c_0(1)$	$c_0(2)$	...	$c_0(P)$
c_1	$c_1(1)$	$c_1(2)$	...	$c_1(P)$
c_2	$c_2(1)$	$c_2(2)$	...	$c_2(P)$
c_3	$c_3(1)$	$c_3(2)$	...	$c_3(P)$
c_4	$c_4(1)$	$c_4(2)$	...	$c_4(P)$
c_5	$c_5(1)$	$c_5(2)$	...	$c_5(P)$
c_6	$c_6(1)$	$c_6(2)$	...	$c_6(P)$

4. SET Sensitivity Prediction with Fitting Models

General SET sensitivity model – sum of contributing parameters

- **Impact of each parameter can be evaluated**

$$\mathbf{SET\_metric} = \mathbf{SET\_metric\_nominal} + \sum_{i=1}^{N} f_i \cdot (K_i - K_{iNOM})$$

f_i = fitting function
K_i = contributing parameter (e.g. size factor)

4. SET Sensitivity Prediction with Fitting Models

- **Models for critical charge, generated SET pulse width and propagated SET pulse width**

Critical charge model (8 fitting parameters per cell)

$$Q_{CRIT} = Q_{NOM} + f(S_T) + f(S_L) + f(C_L) + f(V_{DD}) + f(T_{EMP}) + f_{ERROR}$$

Generated SET pulse width model (12 fitting parameters per cell)

$$T_{SET} = f(LET, S_T = 1) + f(S_T = n) + f(S_L, C_L) + f(V_{DD}) + f(T_{EMP})$$

Propagated SET pulse width model (7 fitting parameters per cell)

$$T_{OUT} = T_{IN} \pm \Delta\tau = T_{IN} \pm c_0 \pm f(S_T) \pm f(C_L) \pm f(V_{DD}) \pm f(T_{EMP})$$

Average relative error for each model (with respect to SPICE) is less than 5 %.

Maximum error goes up 20%, for corner values

Fitting models are based on simplifications and do not take into account all dependencies

5. SET Sensitivity Prediction with ML Models

SET generation and propagation prediction with ML

- ML models are a promising solution for modeling complex dependencies
- Use of ML to aging and soft errors is investigated intensively in past years
- Very few papers address SET prediction with ML

Main approach: Train existing ML models with simulation datasets

1. Data pre-processing and machine learning (regression) model selection
2. Model training and parameter optimization
3. Model evaluation and assessment of model performance

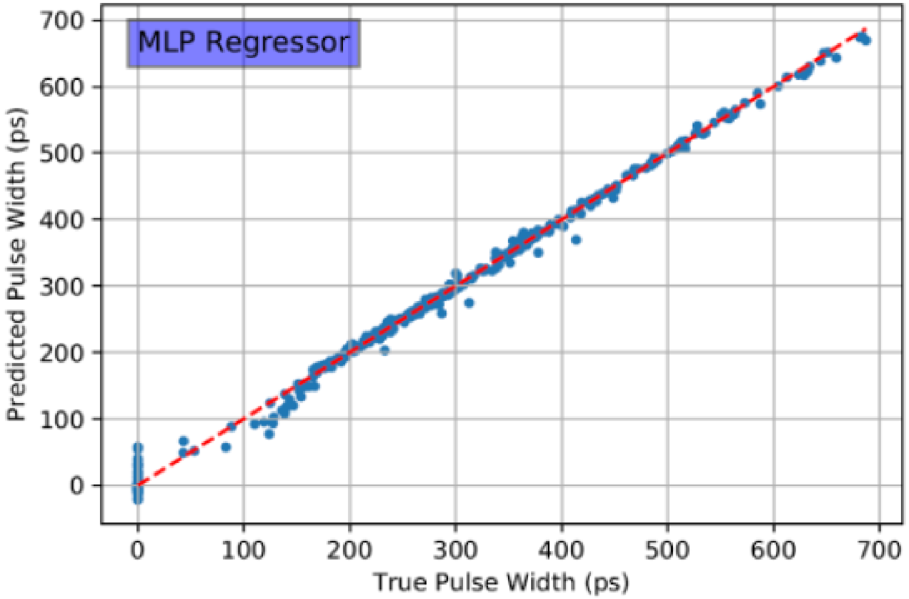
5. SET Sensitivity Prediction with ML Models

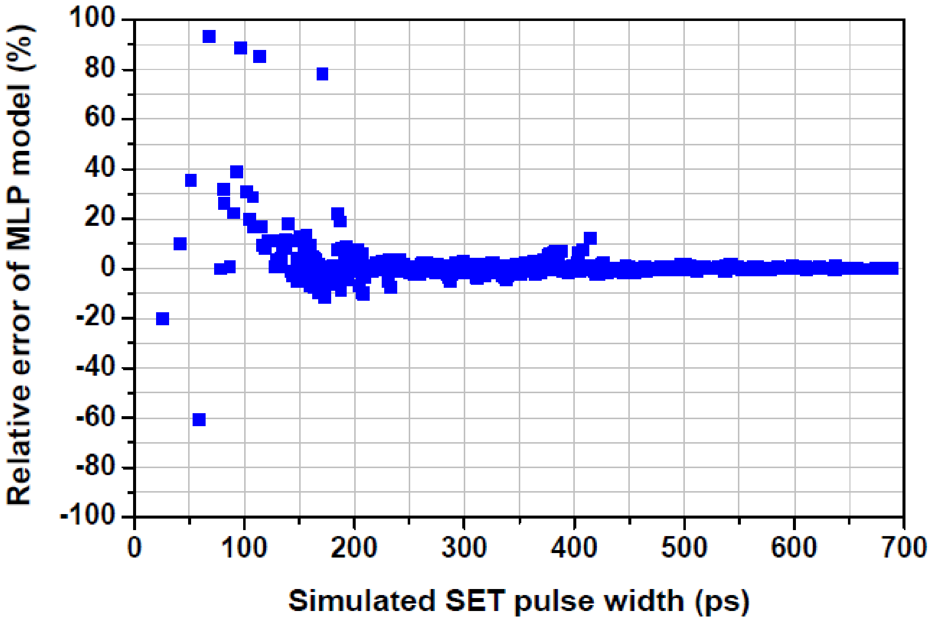
SET generation prediction

- 6 models have been studied: Linear Regression, Polynomial Regression, Support Vector Machine, Decision Tree, Random Forest, and Multilayer Perceptron
- INV cell from 130 nm library was studied
- 2560 SET pulse width results from SPICE simulations
- Analyzed parameters: target gate size, load gate size, Temp, Vdd, LET
- 60% training dataset, 40% validation dataset
- Evaluation metrics. MAE, RMSE, R^2

5. SET Sensitivity Prediction with ML Models

- **MLP has shown the best results for SET generation prediction (R^2 above 99%)**
- **Linear regression has worst prediction accuracy for SET generation (R^2 below 80%)**





5. SET Sensitivity Prediction with ML Models

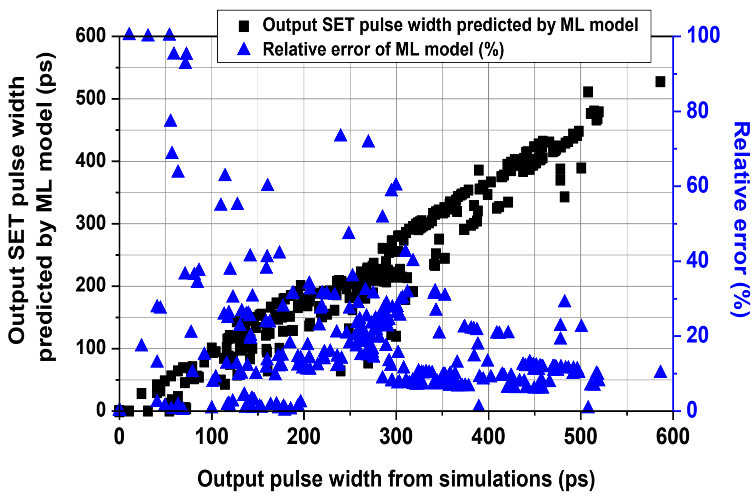
SET propagation prediction

- 10 ML models have bee studied: Linear Regression, Ridge Regression, Lasso Regression, Random Forest, Gradient Boosting, Support Vector Machine, Multilayer Perceptron, XGBoost, CatBoost, LightGBM
- INV, NAND2 and NOR2 gates from 130 nm standard cell library have been analyzed
- 25600 values for INV and 12800 values for NAND and NOR gates have been obtained from Spectre simulations
- Analyzed parameters: input pulse width and polarity, target and load gate sizes, Vdd and Temp
- Simulation dataset was divided into two datasets: 70% training dataset, 30% validation dataset
- ML valuation metrics: MAE, RMSE, R^2

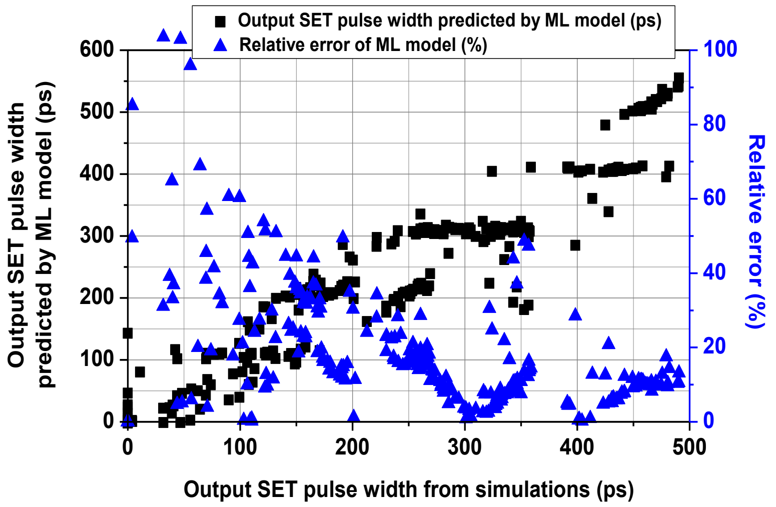
5. SET Sensitivity Prediction with ML Models

- **Different ML models have shown best accuracy for SET propagation prediction**
- **In all cases, R^2 was above 99% for best model**
- **However, relative error is high for prediction of short SET propagation**

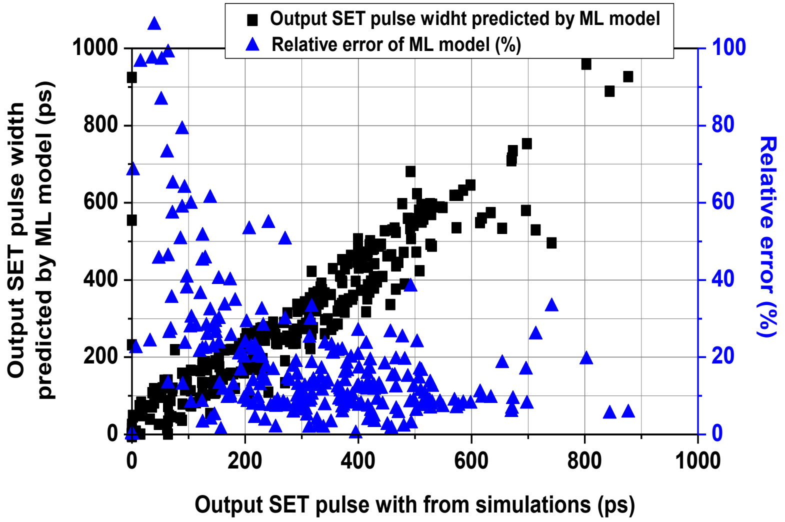
INV gate – XGBoost model



NAND2 gate – CatBoost model



NOR2 gate – CatBoost model



5. SET Sensitivity Prediction with ML Models

- **SET propagation prediction for short combinational paths (less than 10 gates)**

Settings	Output SET pulse width from ML model (ps)	Output SET pulse width from SPICE simulations (ps)	Relative error (%)
Path 1, Vdd=1.2V, Temp = 50 ^{o}C, Input PW = 150 ps (positive pulse)	109.4	165.7	34 %
Path 1, Vdd=1.2V, Temp = 50 ^{o}C, Input PW = 150 ps (negative pulse)	110.5	134.4	17.8 %
Path 1, Vdd=1.1V, Temp = 80 ^{o}C, Input PW = 380 ps (positive pulse)	510.2	400.6	27.4 %
Path 1, Vdd=1.1V, Temp = 80 ^{o}C, Input PW = 380 ps (negative pulse)	511.7	367.1	39.4 %
Path 2, Vdd=1.2V, Temp = -20 ^{o}C, Input PW = 240 ps (positive pulse)	215.4	302.7	28.8 %
Path 2, Vdd=1.2V, Temp = -20 ^{o}C, Input PW = 240 ps (negative pulse)	204.6	181.9	12.5%
Path 2, Vdd=1 V, Temp = 100 ^{o}C, Input PW = 480 ps (positive pulse)	517.7	588.3	12 %
Path 2, Vdd=1 V, Temp = 100 ^{o}C, Input PW = 480 ps (negative pulse)	502.3	381.3	31.7 %

6. Conclusion

- **Characterization of SET sensitivity of standard cells is essential for the rad-hard design**
- **SET sensitivity of a logic gate in a given technology is strongly influenced by a combined impact of design, operating and irradiation parameters**
- **Analytical models for SET sensitivity reduce the characterization database and runtime for analysis of a complex circuit**
- **Future work**
  - Derivation of more accurate SET generation and propagation models
  - Integration of SET sensitivity models into an automated toolflow for analysis of complex designs
  - Analysis of combined impact of multiple fault types

Thank you for your attention!

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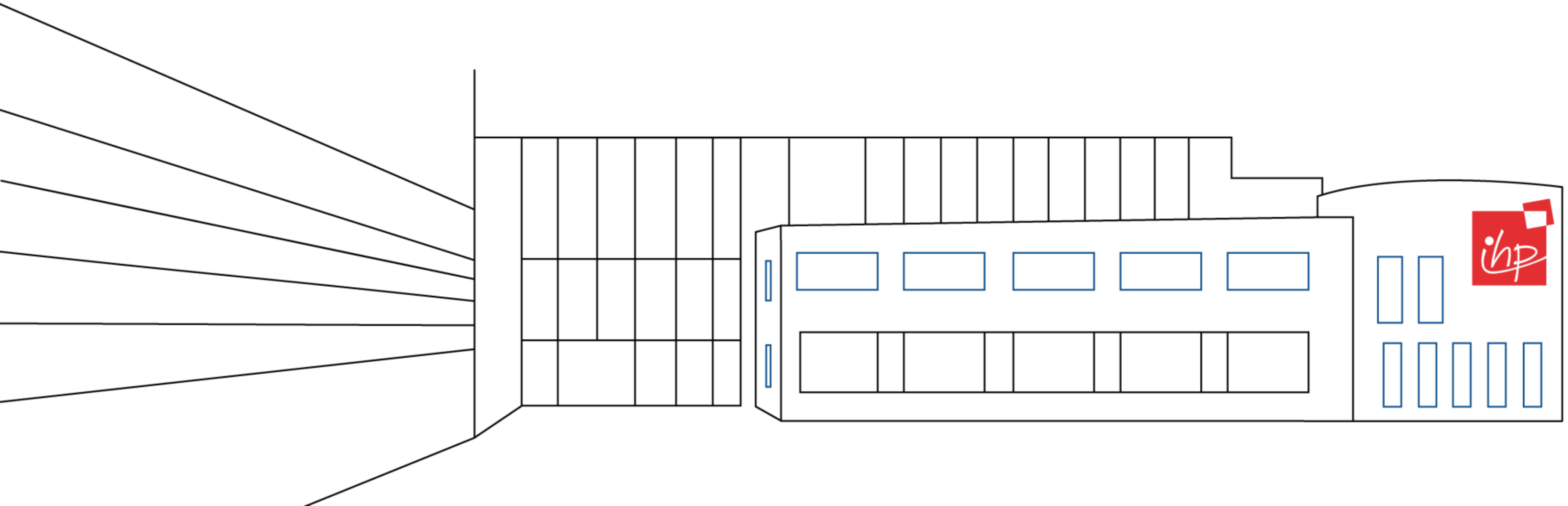

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