Variation Characterization

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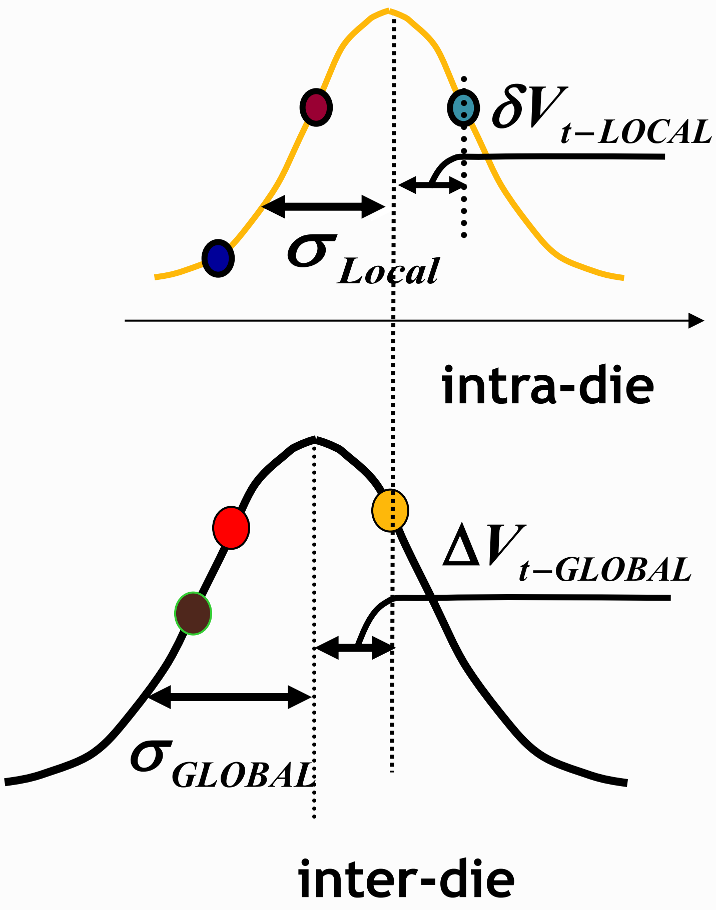
Characterization Circuits

- Process Characterization
  - Understand effect of different process steps
  - Characterize extent and impact of various effects
  - Feed back to modeling and technology team
  - Guidelines for good topologies, design styles
  - Examples
    - Array of Devices for I-V Characterization
    - Local vs Global Variation Sensors
    - NBTI / PBTI Isolation Circuits
- Mature Process
  - Topologies to ensure that process is well behaved
  - Process corner detection circuits for static compensation
  - Dynamic (on-line) characterization for adaptive systems
  - Sensors for debug of failure mechanisms
  - Examples
    - Critical Path Monitors / Skitter Circuits
    - Slew Monitor
    - In-situ Power Monitor

Characterization Challenges

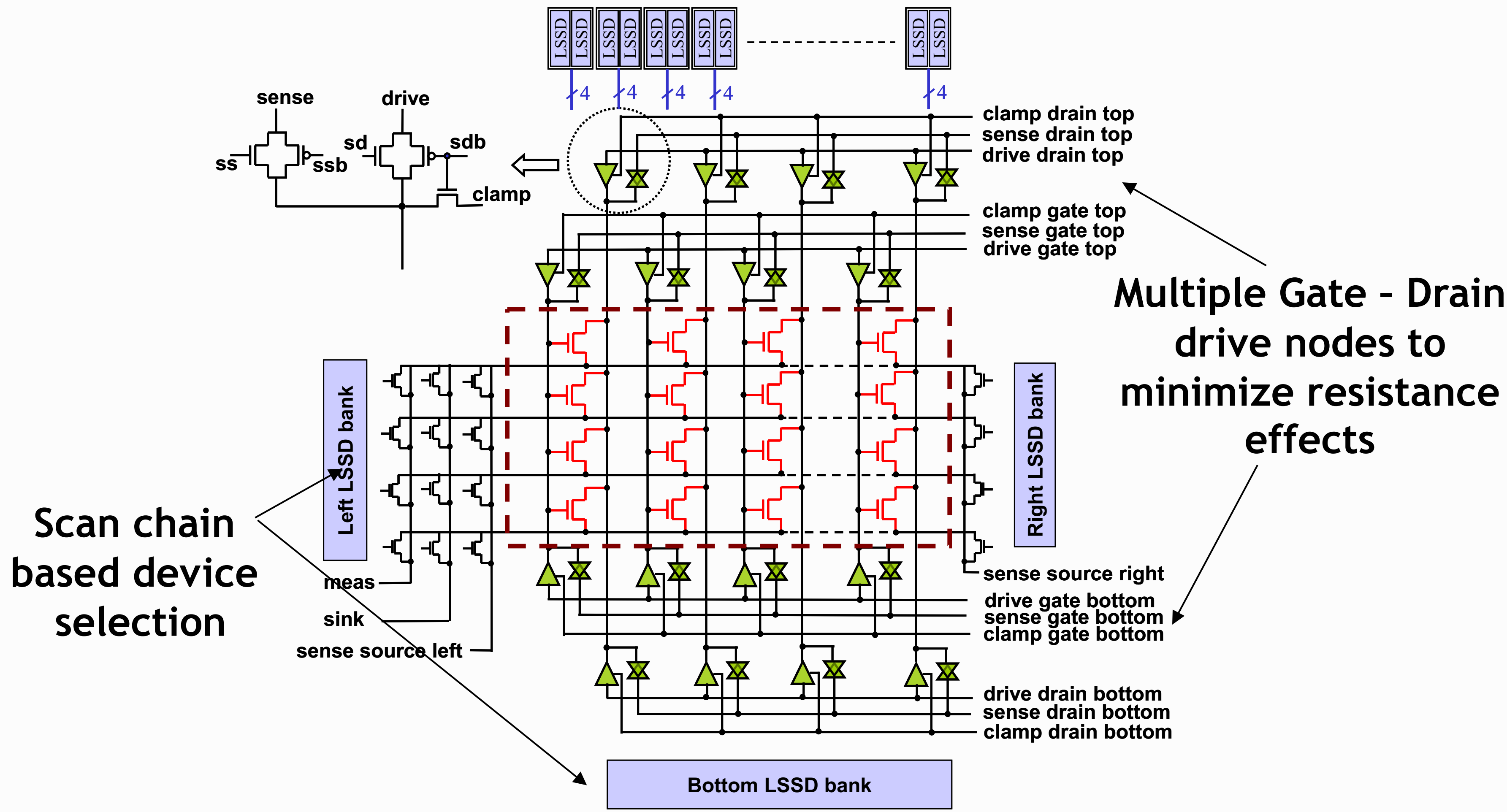
- Limited silicon and characterization resources
- I-V Characterization Simplifications
  - Limited physical configurations (neighborhood/density, stress-related geometries, device sizes)
  - Limited operating conditions (voltage, history, self-heating)
  - Sampling of manufactured devices
  - Snapshot of process and lifetime

Global vs Local Characterization



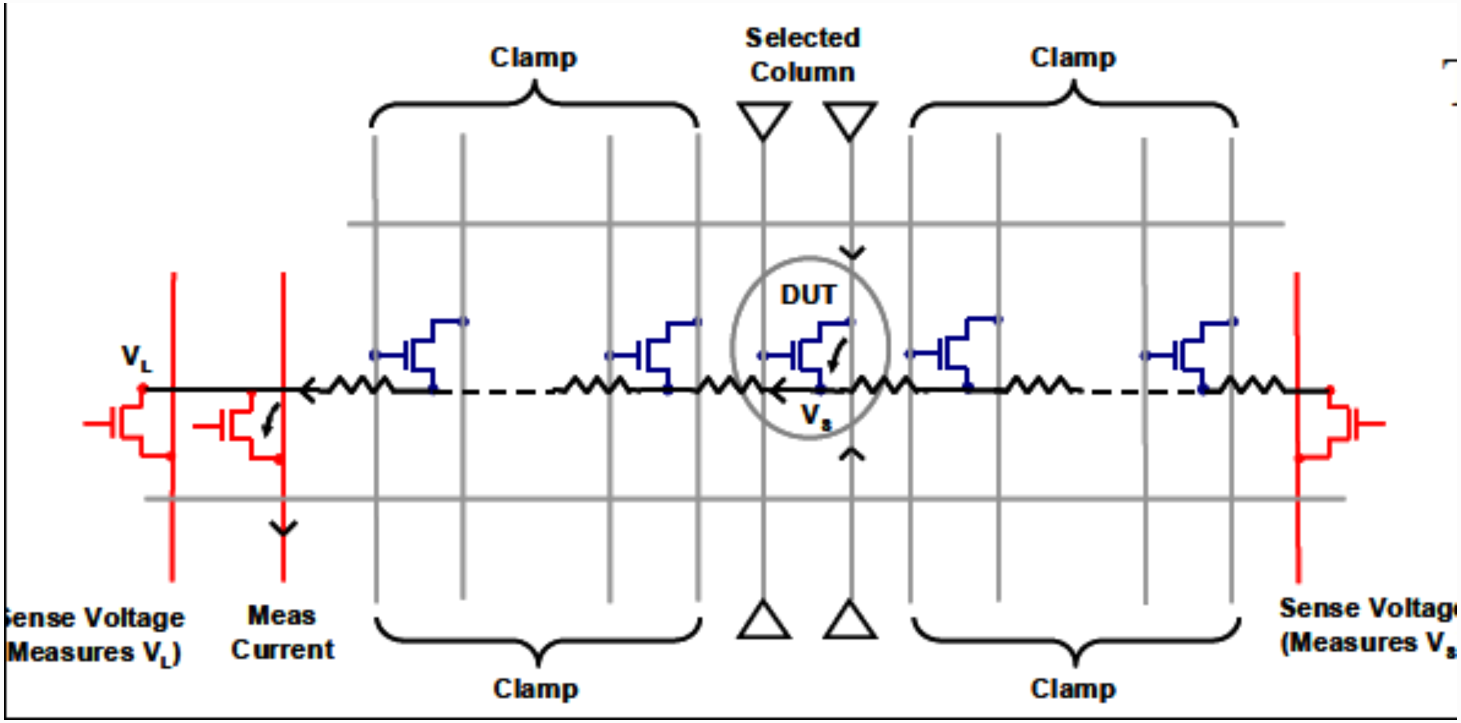
- Local Variation Sensors
  - Eliminate the influence of global and systematic variations that effects all devices equally
  - Minimize noise due to common environmental factors
- Methods
  - I-V measurements
  - Measuring digital signatures of analog variations
  - Measurement of mismatch and measurement of individual device variations

Array Based I-V Characterization Circuits

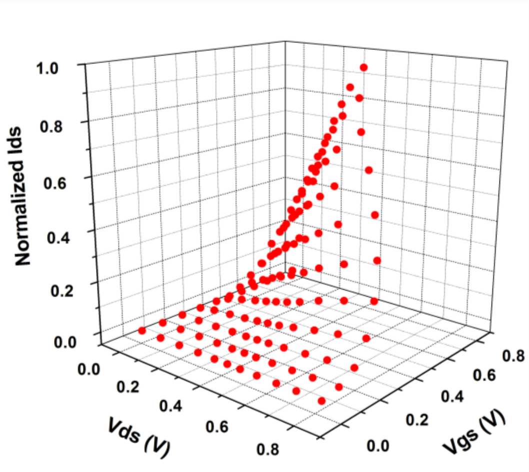


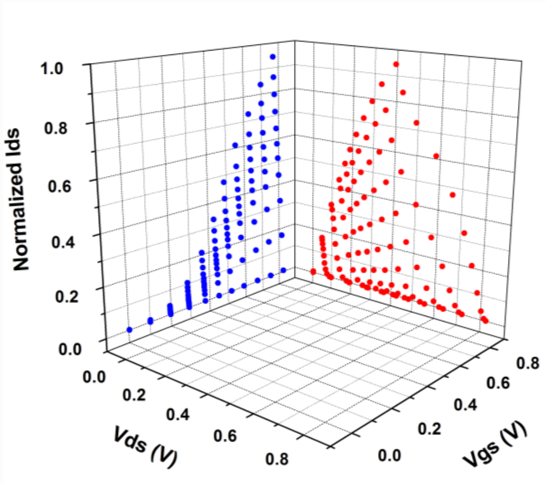
- Measure I-V of devices in an array
- Extract Vt mismatch from "current difference" between identical transistors

Array Based I-V Characterization Circuits

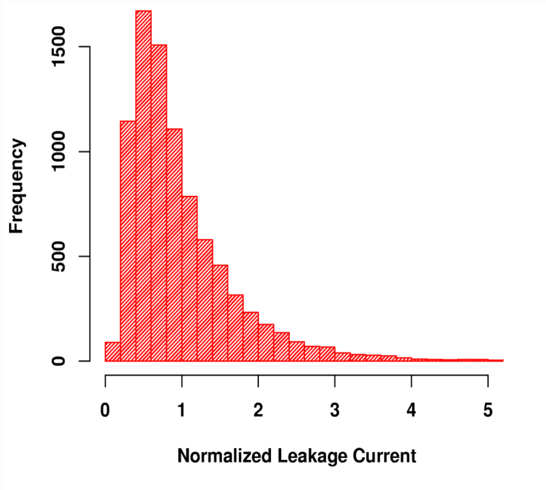


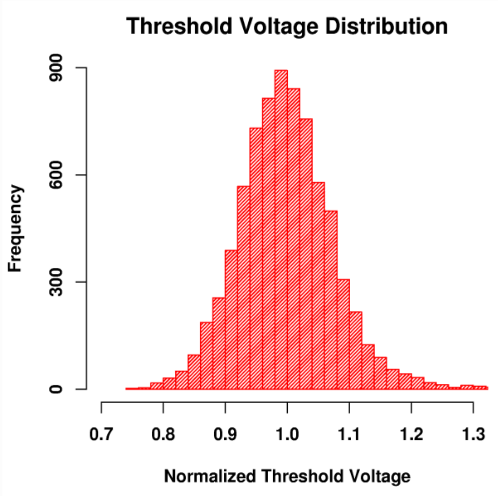
Array Based I-V Characterization Circuits



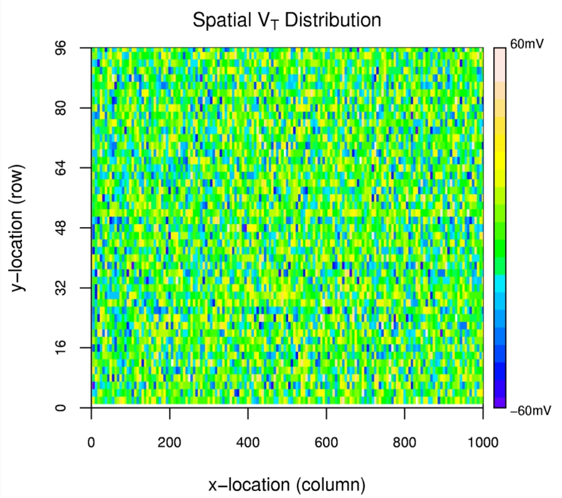


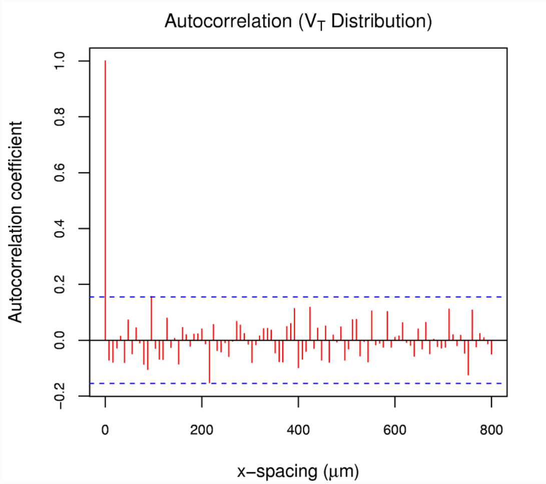
Sample I-V curves





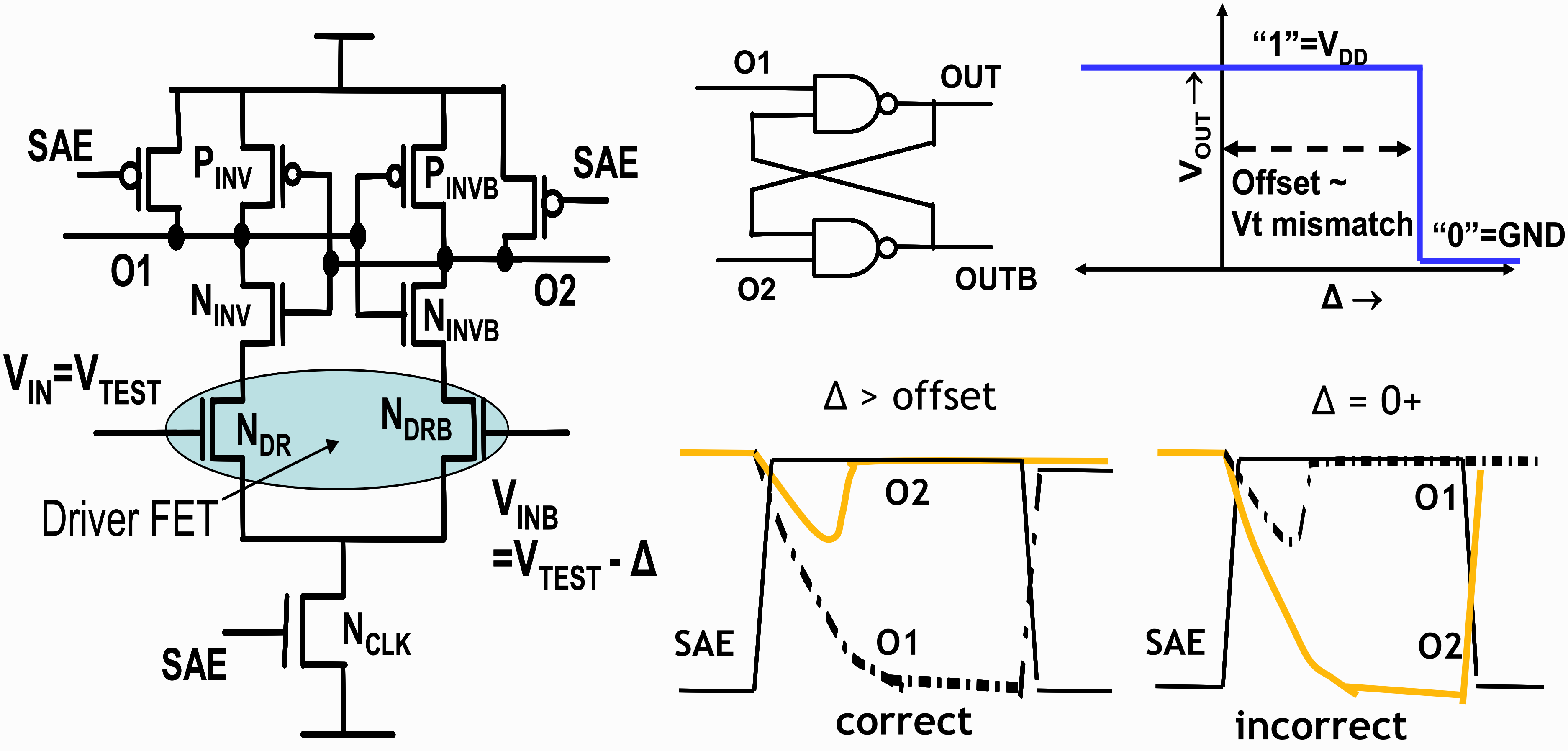
Parameter Distributions





Spatial Correlation

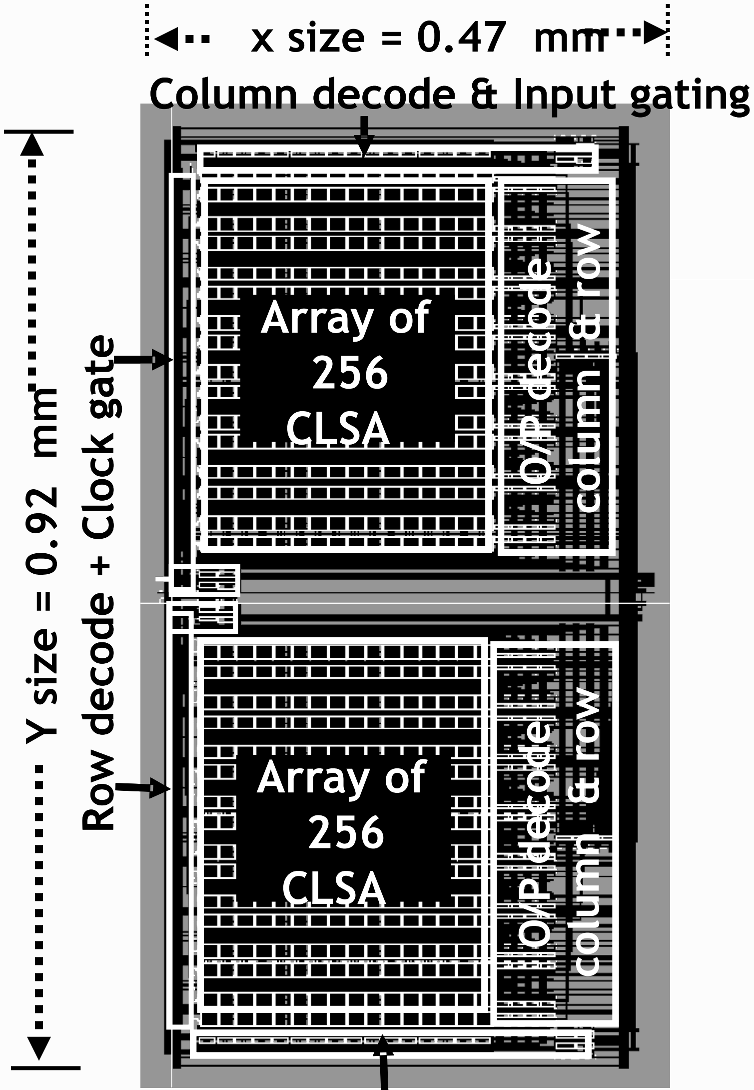
Digital Characterization with Current Latch based Sense Amplifier



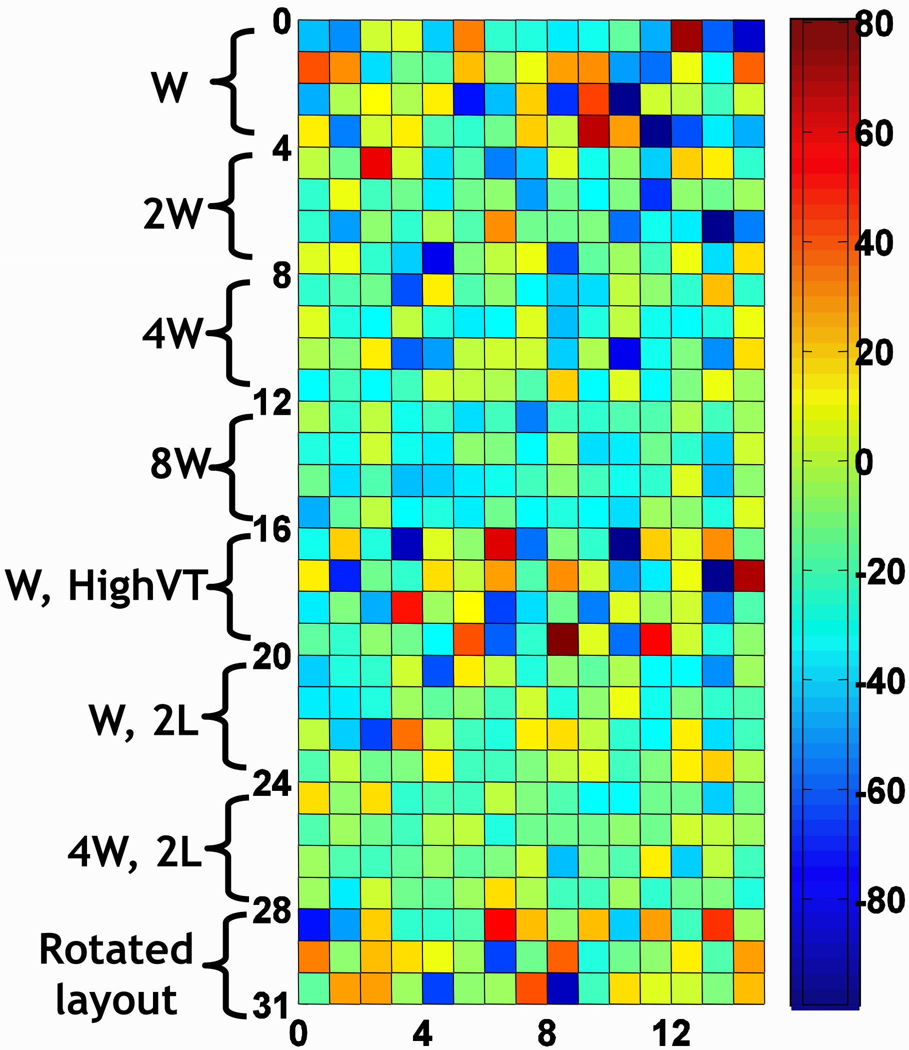
Minimum input voltage difference required for correct sensing (offset) indicates local random mismatch

S. Mukhopadhyay, et. al. JSSC 2008

Measured Values of Local Mismatch



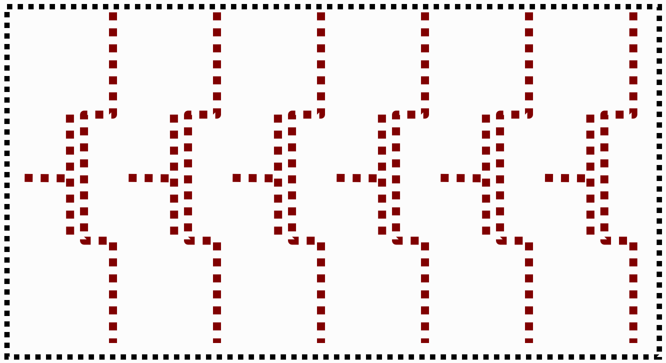
Layout of the proposed test-structure



Vt mismatch values (in mV) measured in different location

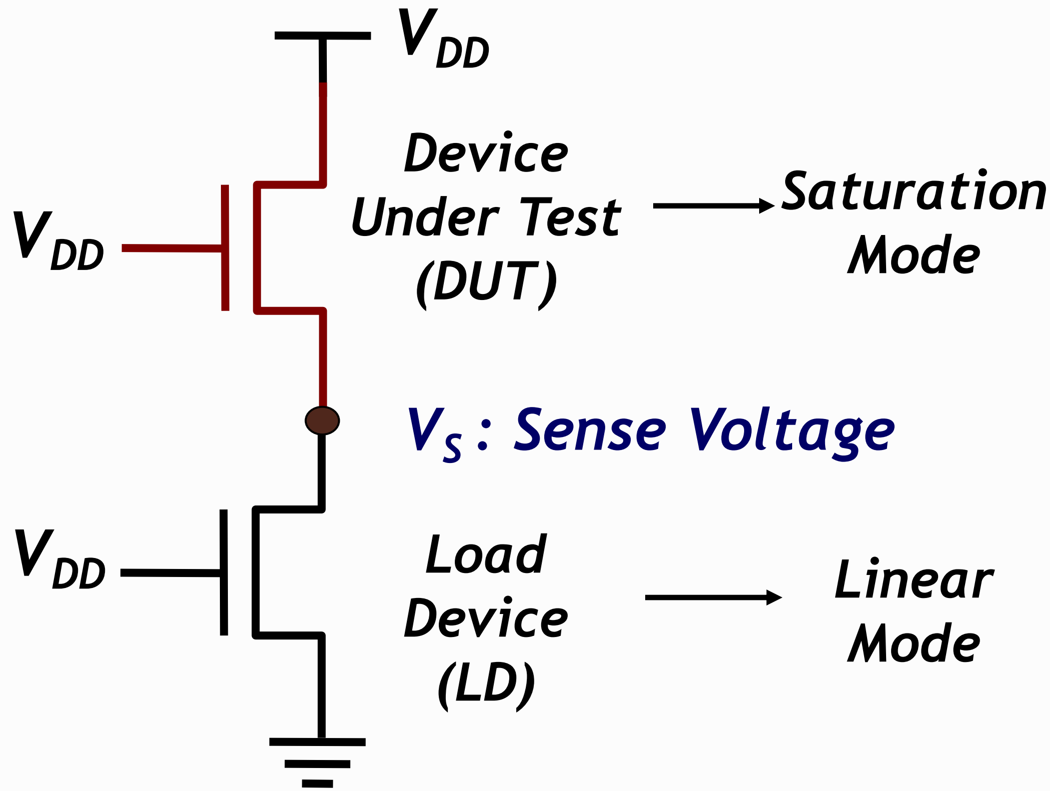
S. Mukhopadhyay, et. al. JSSC 2008

Statistical Characterization of Local Variations of Individual Device



Array of identical devices

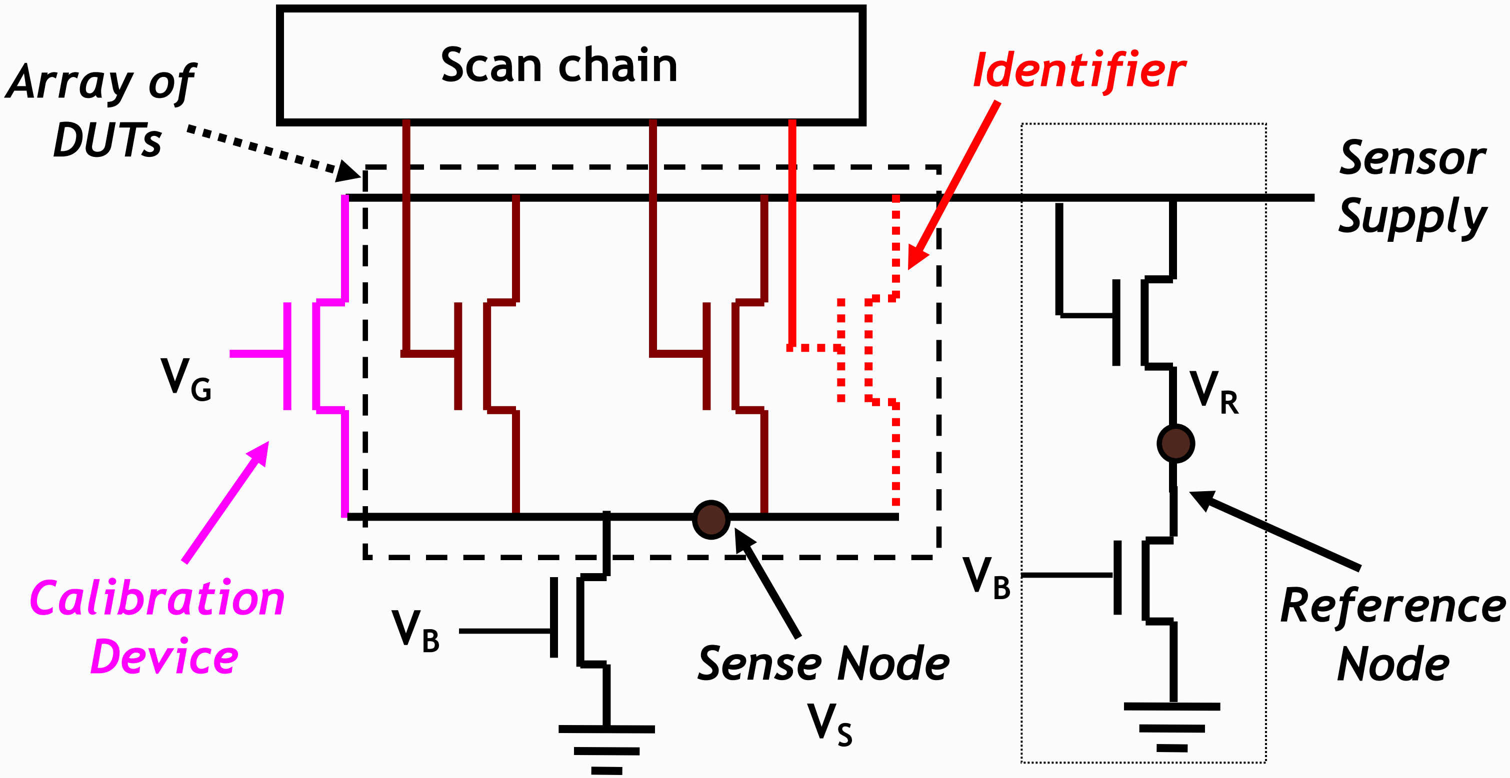
Test structure consisting of array of devices arranged in a stacked configuration with a common load device for local variability characterization



$$V_{S1} = f\,(V_{TH}\,(DUT1),\ V_{TH}\,(LD))$$

$$V_{S2} = f\,(V_{TH}\,(DUT2),\ V_{TH}\,(LD))$$

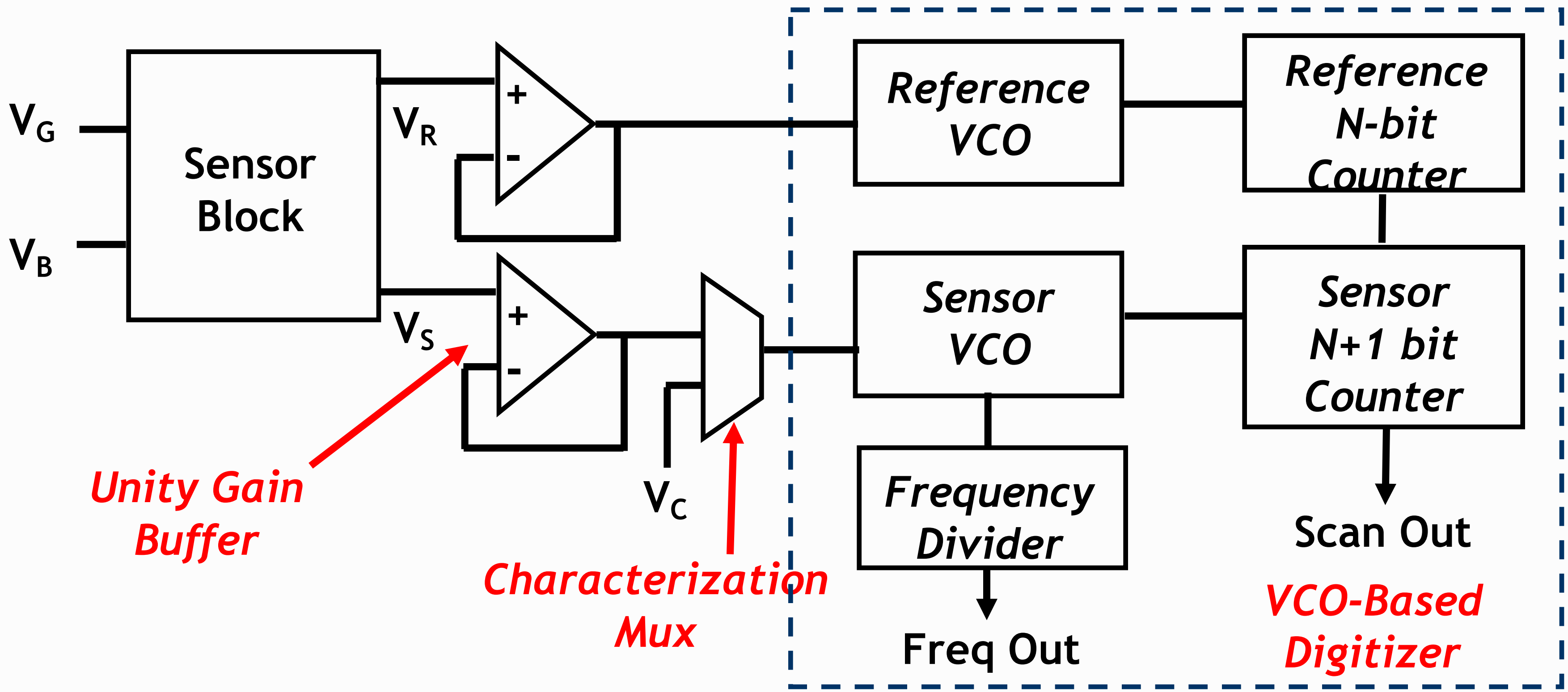
Sensor Block



- Select each DUT individually to form stacked configuration with load device
- Determine Sense Node Voltage (V_S)
- Difference in V_S represents current mismatch between the DUTs

R. Rao et. al. JSSC 2009

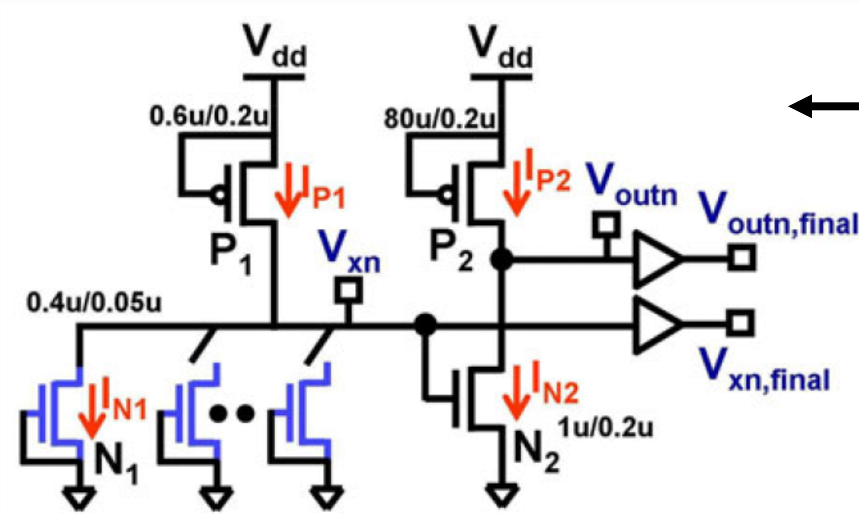
Block Diagram



- Unity Gain Buffer protects sense node from mux / VCO noise
- Reference VCO sets up time – base for Sensor Counter
- Output of Sensor counter is digital indication of sensor VCO frequency and hence a representation of threshold voltage of DUT

R. Rao et. al. JSSC 2009

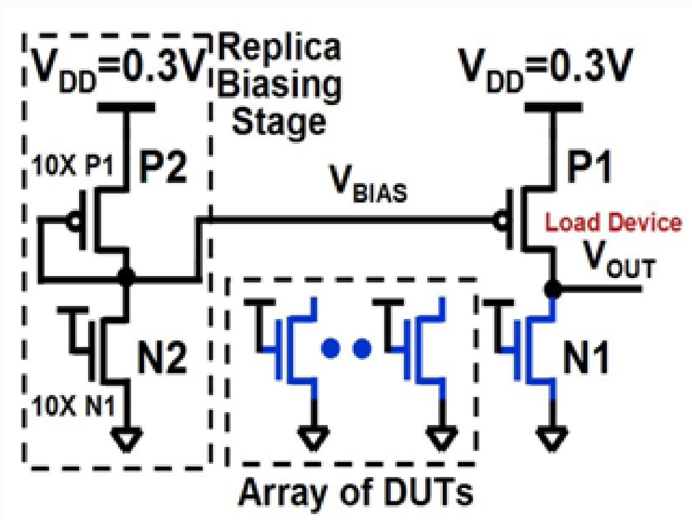
High Sensivity Variation Sensor



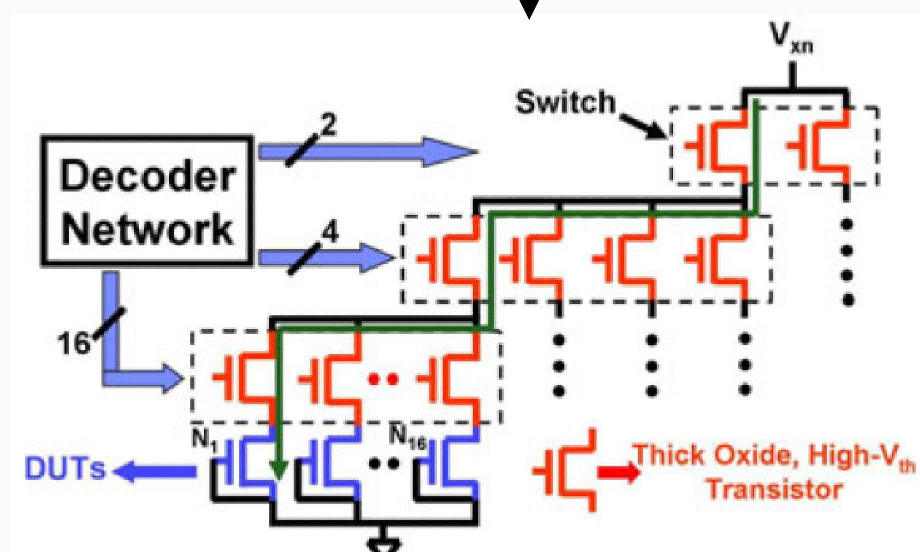
Biasing DUTs in sub-threshold mode to enhance sensitivity

2nd stage is for amplification

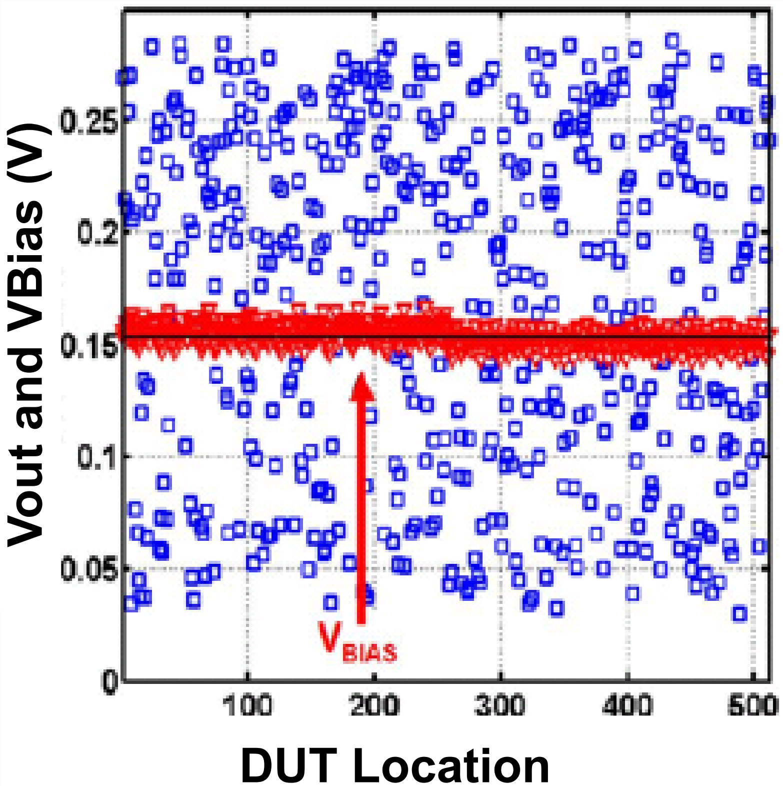
Hierarchical Switch Network to minimize leakage noise from unselected DUTs



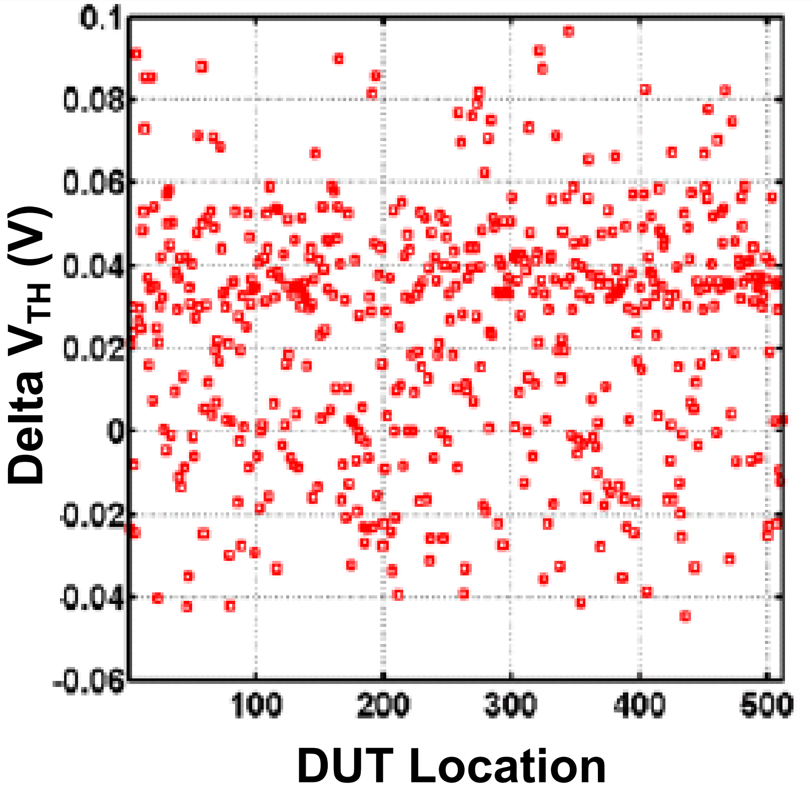
On-chip generation of VBias



High Sensivity Variation Sensor



Measurement for 512 minimum sized DUTs



Extracted V_{TH} from measurement

Improving Signal to Noise Ratio

- Approaches used to improve signal to noise during measurement include

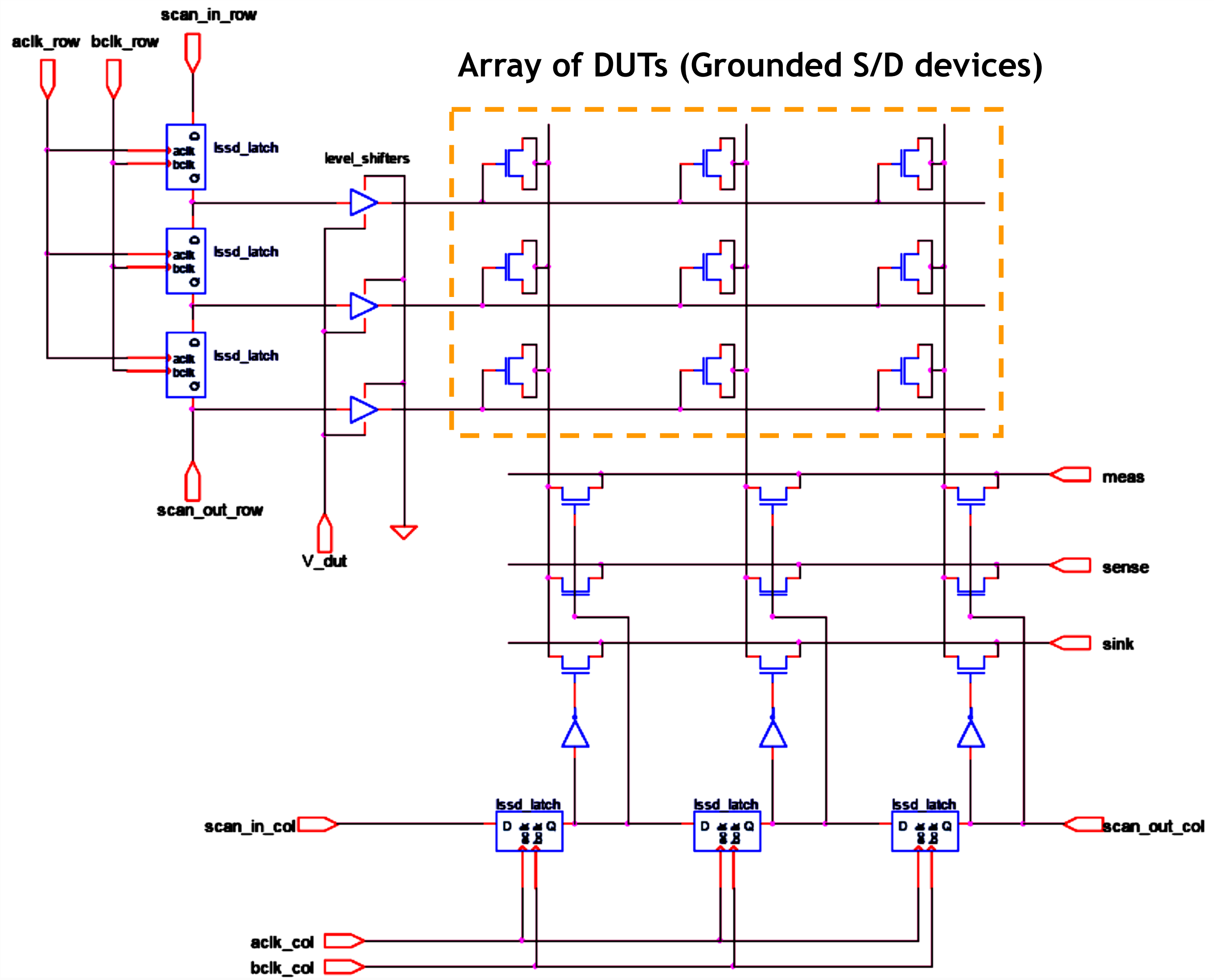
a) Clamp gates of unselected DUTs to a negative voltage

b) Raise the voltage applied to the selection devices

c) Use voltage measurement instead of current measurement

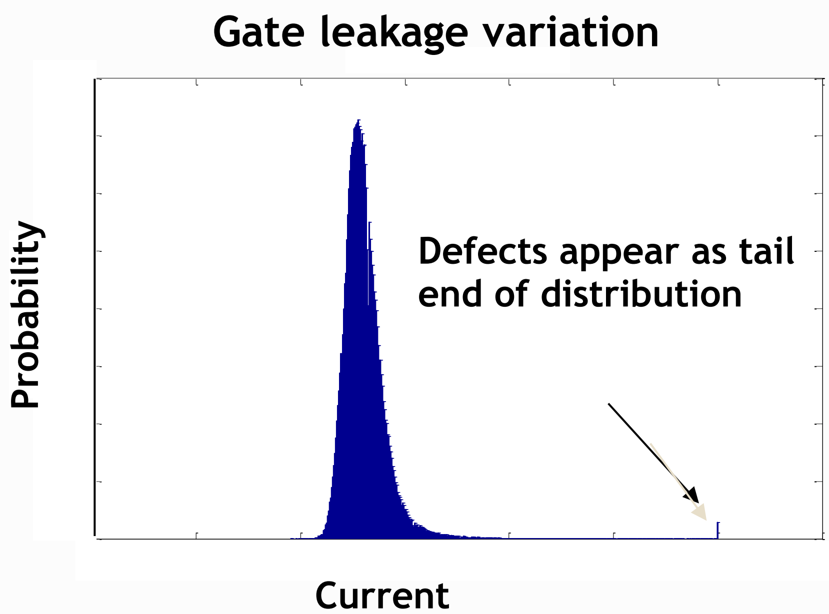
d) Use forced stacking on the selection devices

Gate Oxide Monitor



J. Sivagnaname, et. al, US Patent 7409372

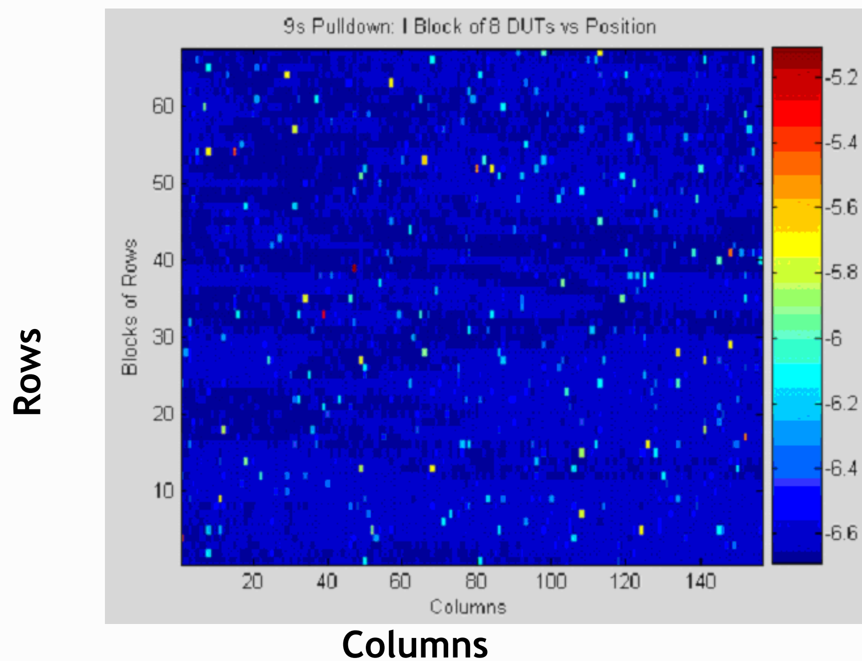
Gate Oxide Monitor



- Characterizes Gate Oxide Defects

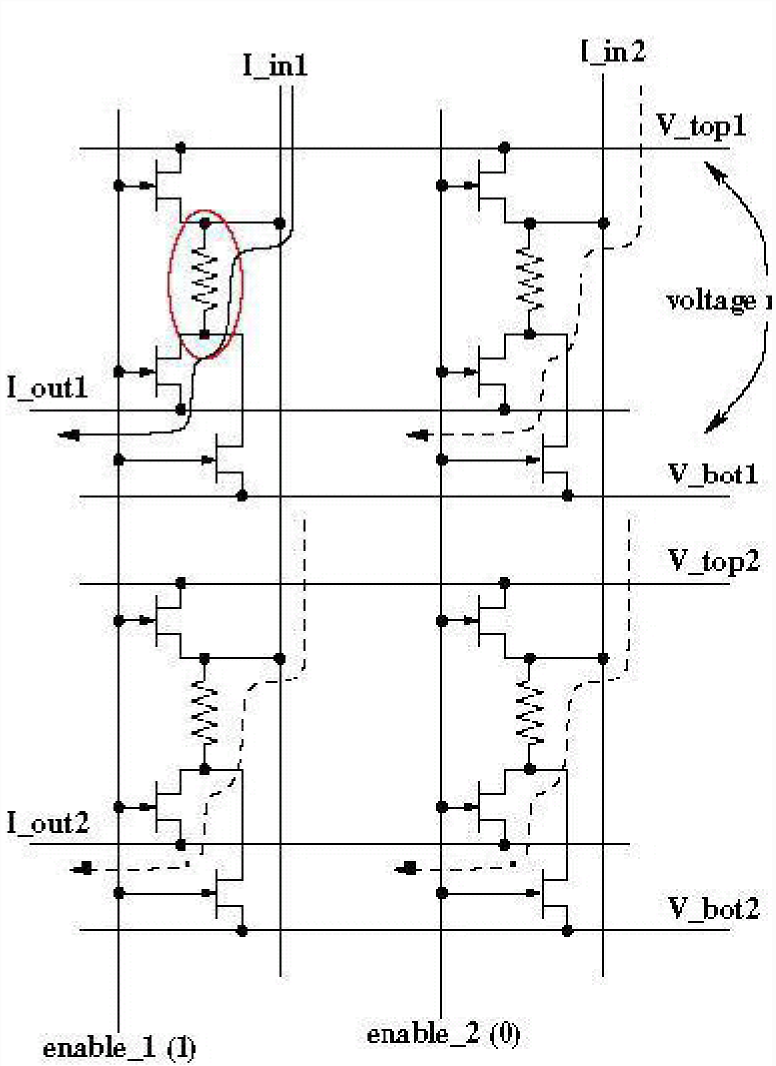
- Millions of SRAM devices in an individually addressable array

- Measure gate leakage currents to identify defects



J. Sivagnaname, et. al, US Patent 7409372

Contact Resistance Sensor

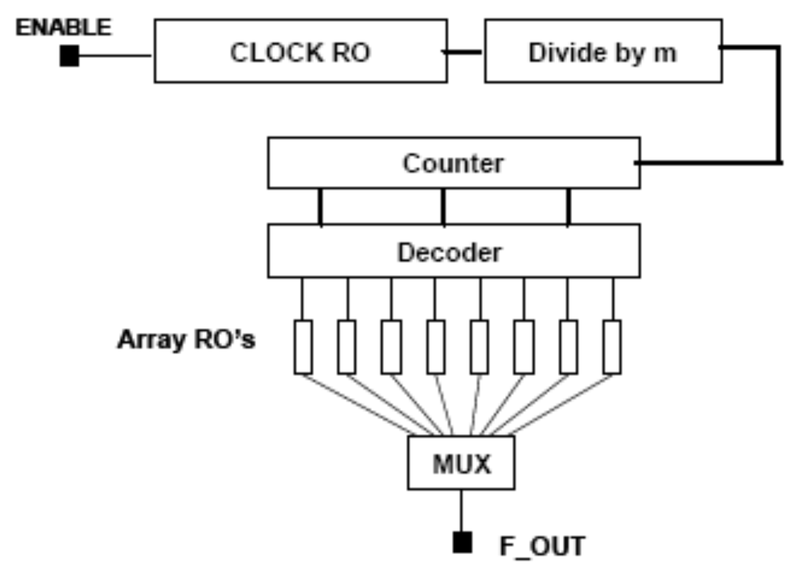


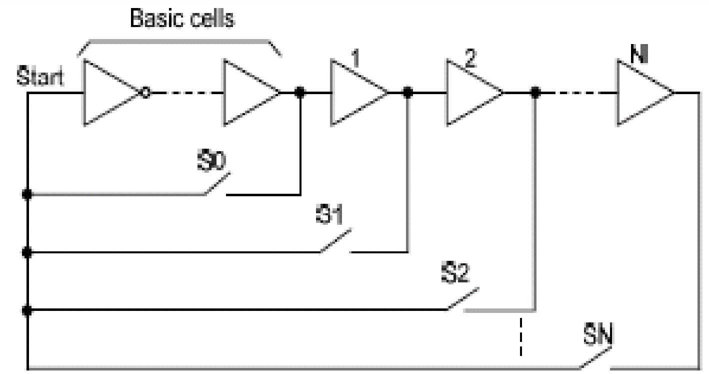
- Array of Contact cells
- Each Row has V_top(i), V_bot(i) and I_out(i)
- Each column has I_in(j) and enable(j)
- For selected DUT, enable(j) ensures that I_in(j) is steered to I_out(i)
- V_top(i) and V_bot(i) are sensed to estimate CA resistance
- For unselected columns, Enable is kept below 0 to reduce leakage noise

How to characterize global or systematic variations in process ?

- Challenge
  - Sense and characterize observable circuit parameters that depend on process parameters
- Methods
  - Delay based sensing
  - Slew based sensing
  - Leakage based sensing

Ring Oscillator Structures



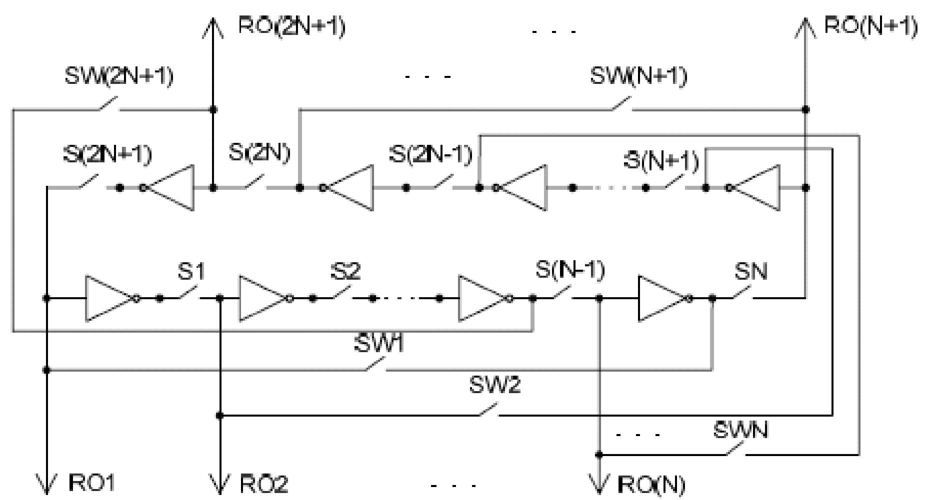


Modified Ring Oscillator

Oscillators of different gate lengths by tapping multiple nodes

Ring Oscillator (RO)

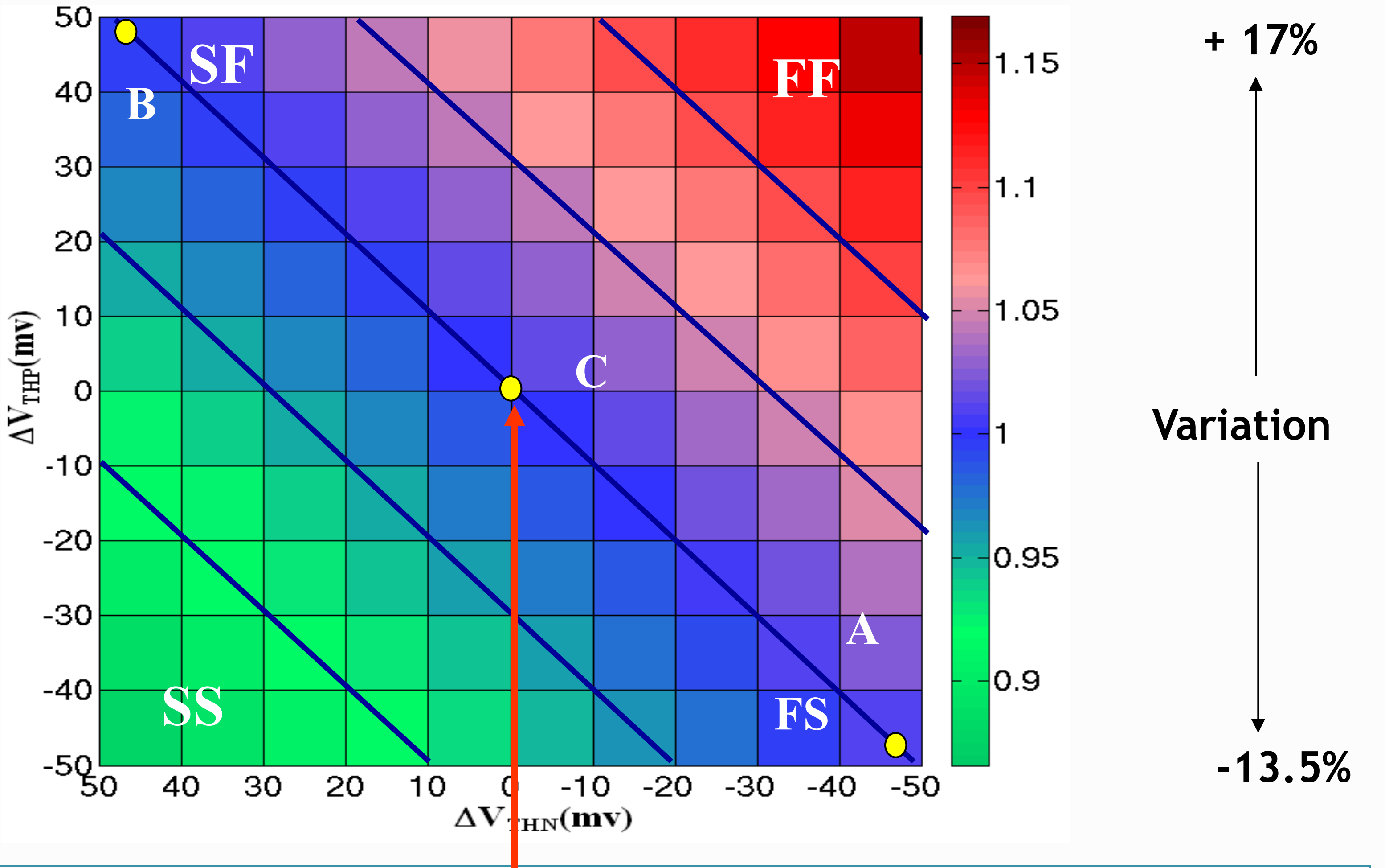
- **FET to FET variation averaged out with large number of stages**
- **Multiple ROs selected through a finite state machine (or counter)**
- **Frequency is independent of down-stream delay of the multiplexer**



M. Bhushan, ICMTS, 2006

B. Zhao, ISCAS 2005

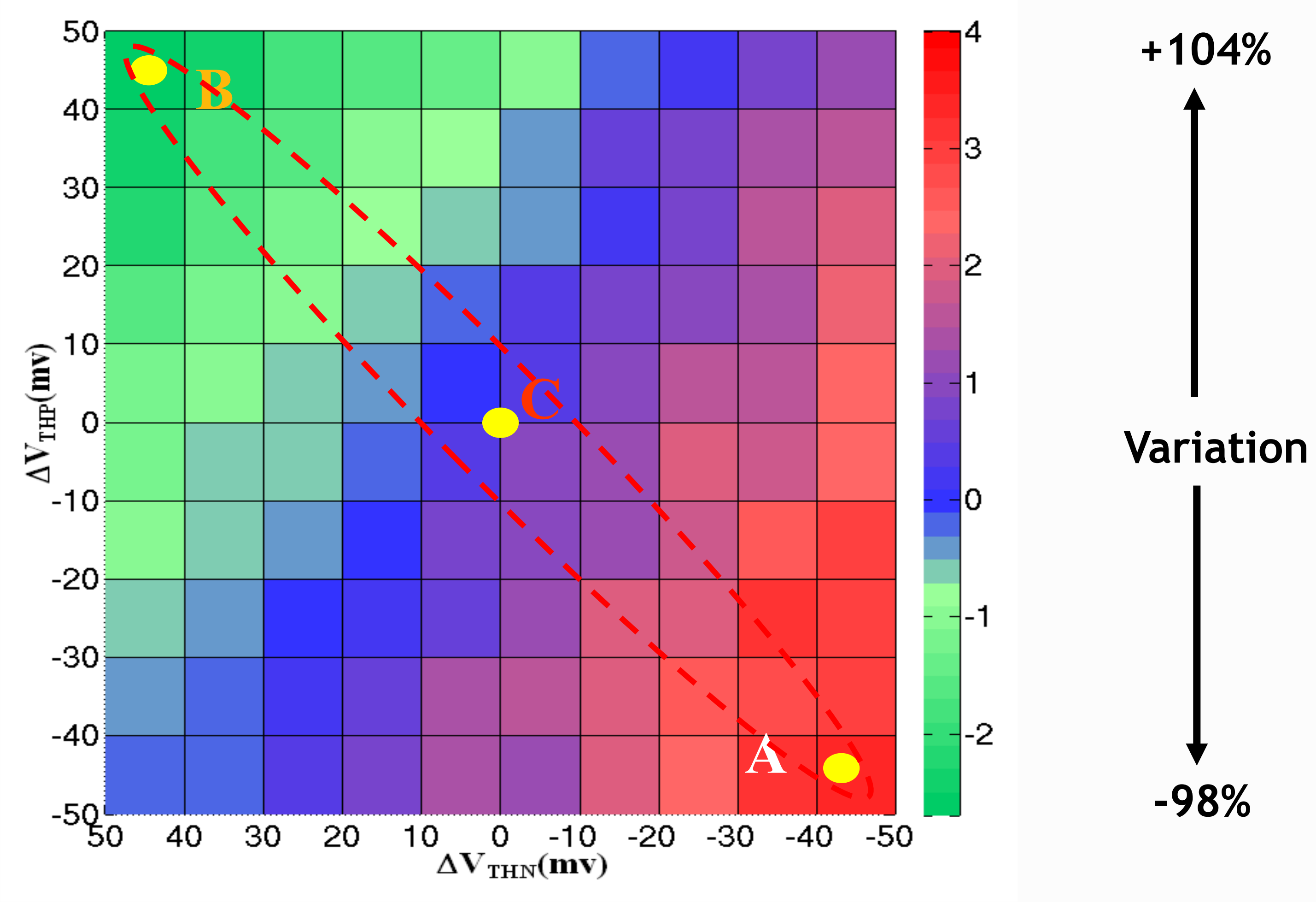
Delay Variation of a Ring Oscillator



Nominal operating point of the circuit with no threshold voltage variation

Delay is good for detection of Slow-Slow and Slow-Fast Corners

Normalized Slew

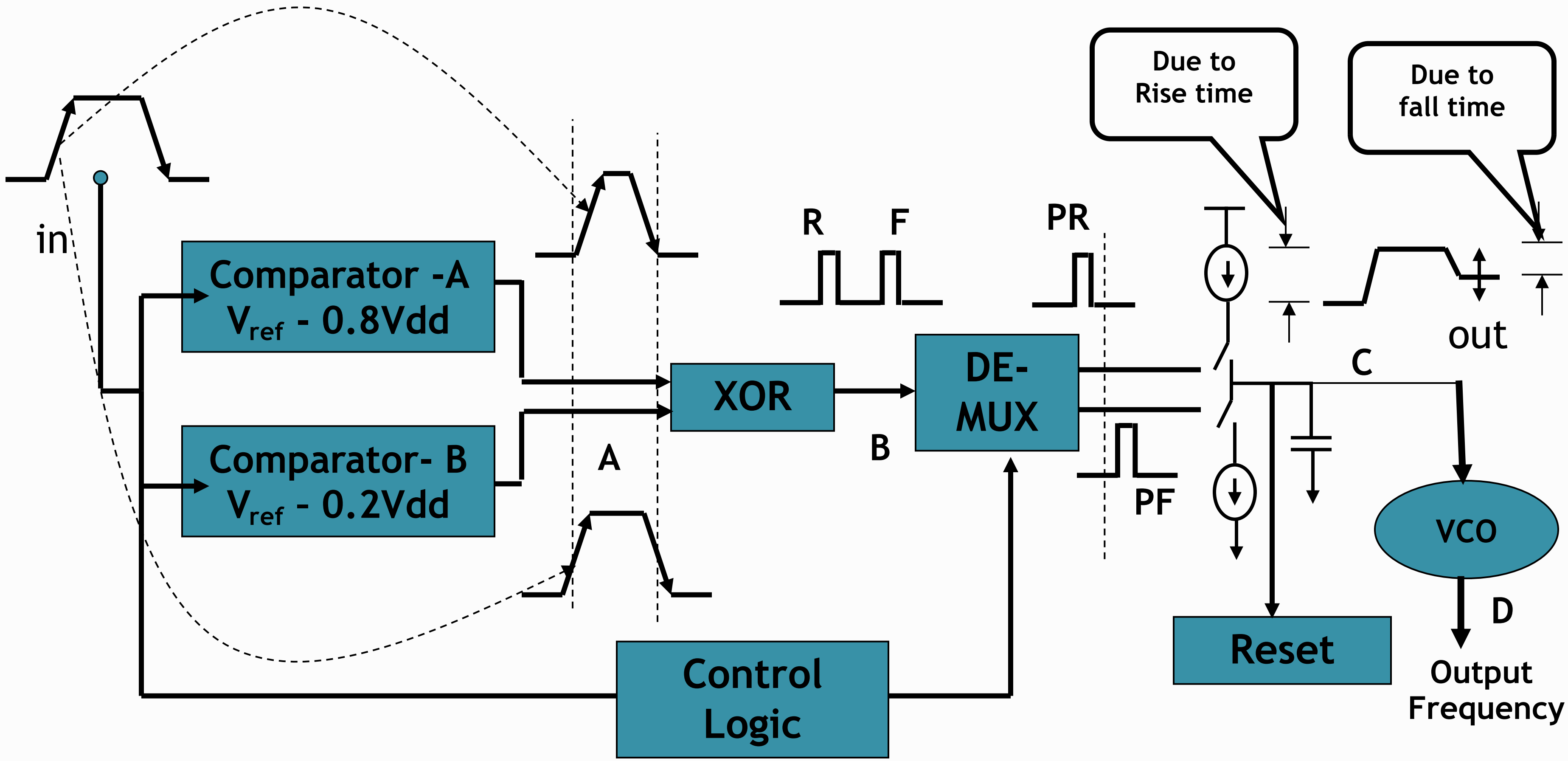


Slew is more sensitive to mismatch in device strengths

Good for detection of Slow-Fast and Fast-Slow Corners

Slew Monitor

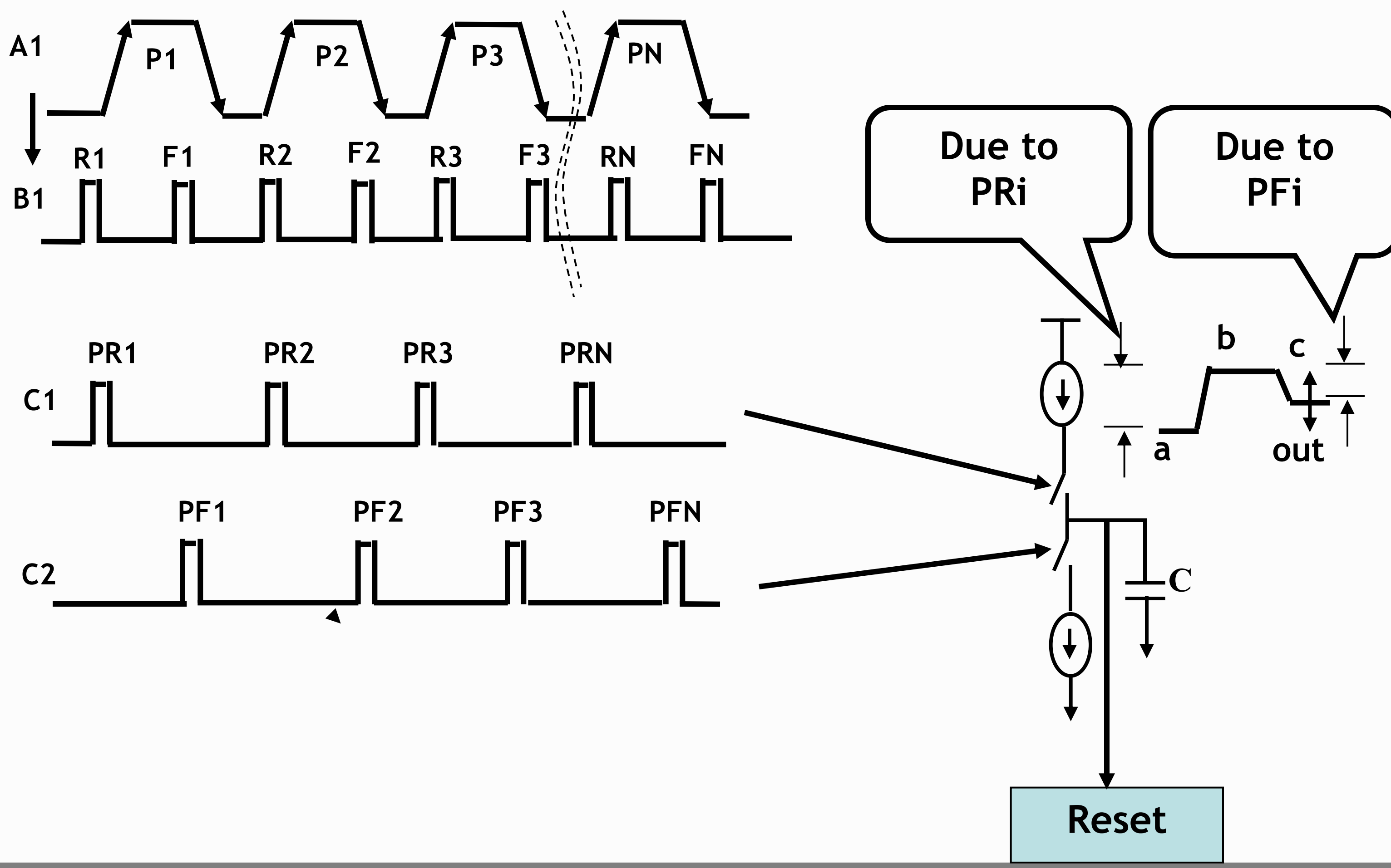
$\Delta_{rise\text{-}fall}$ - the relative mismatch between the strength of the NMOS and PMOS devices



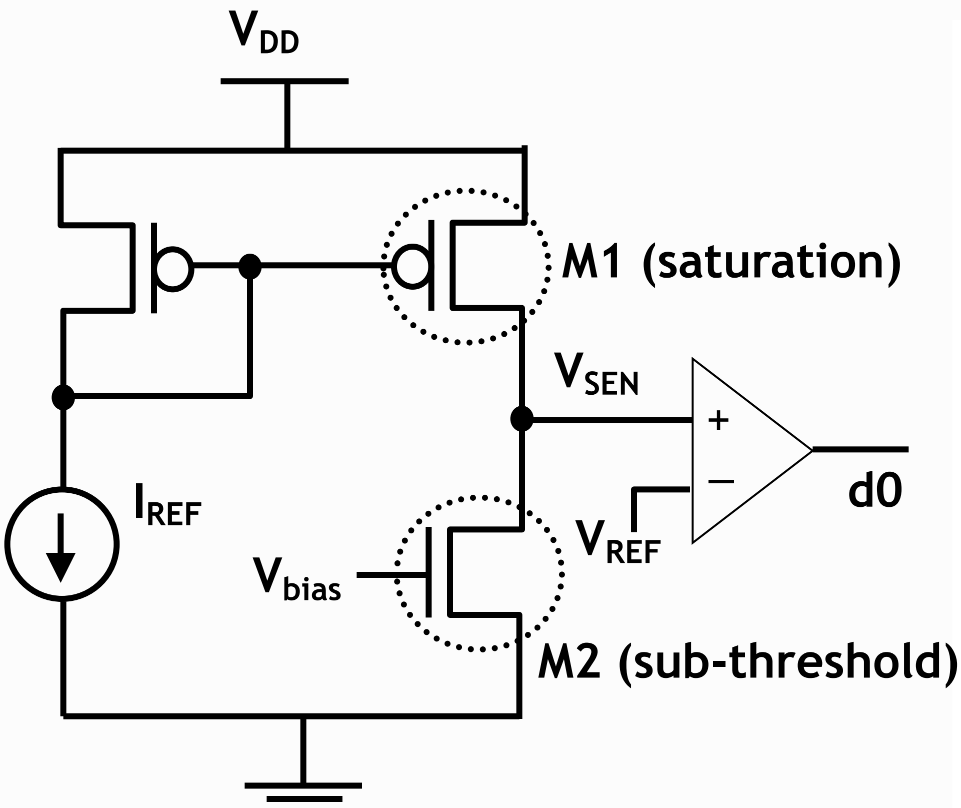
Can be used to drive body bias compensation for NMOS and PMOS devices for leakage control

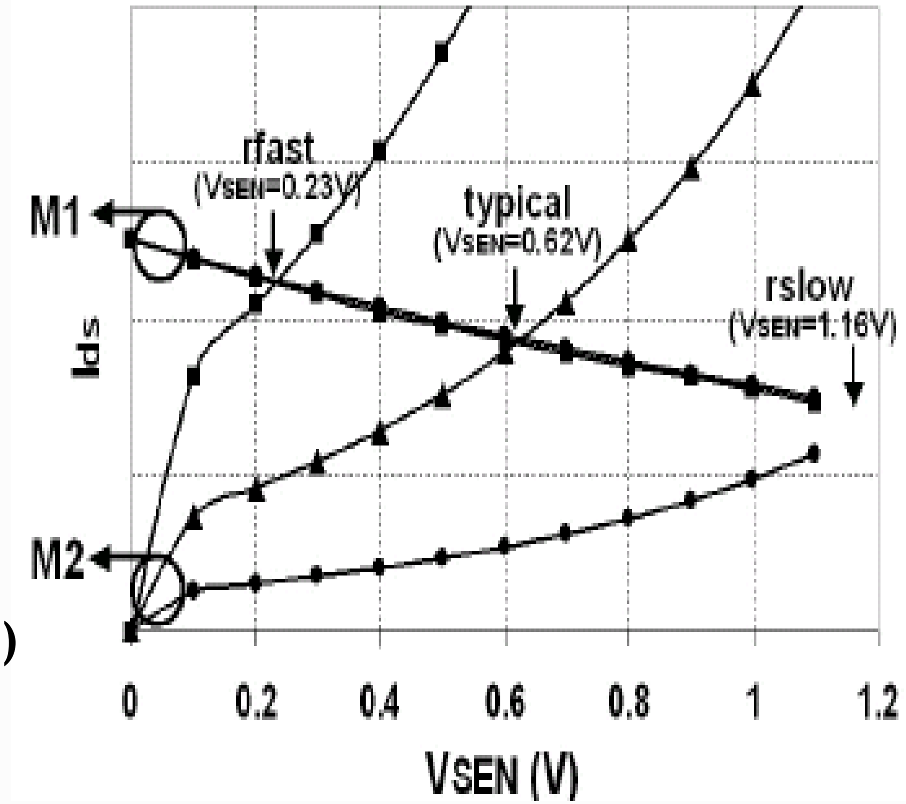
A. Ghosh et. al, VLSI 2008

Using Multiple Pulses to Improve Sensitivity



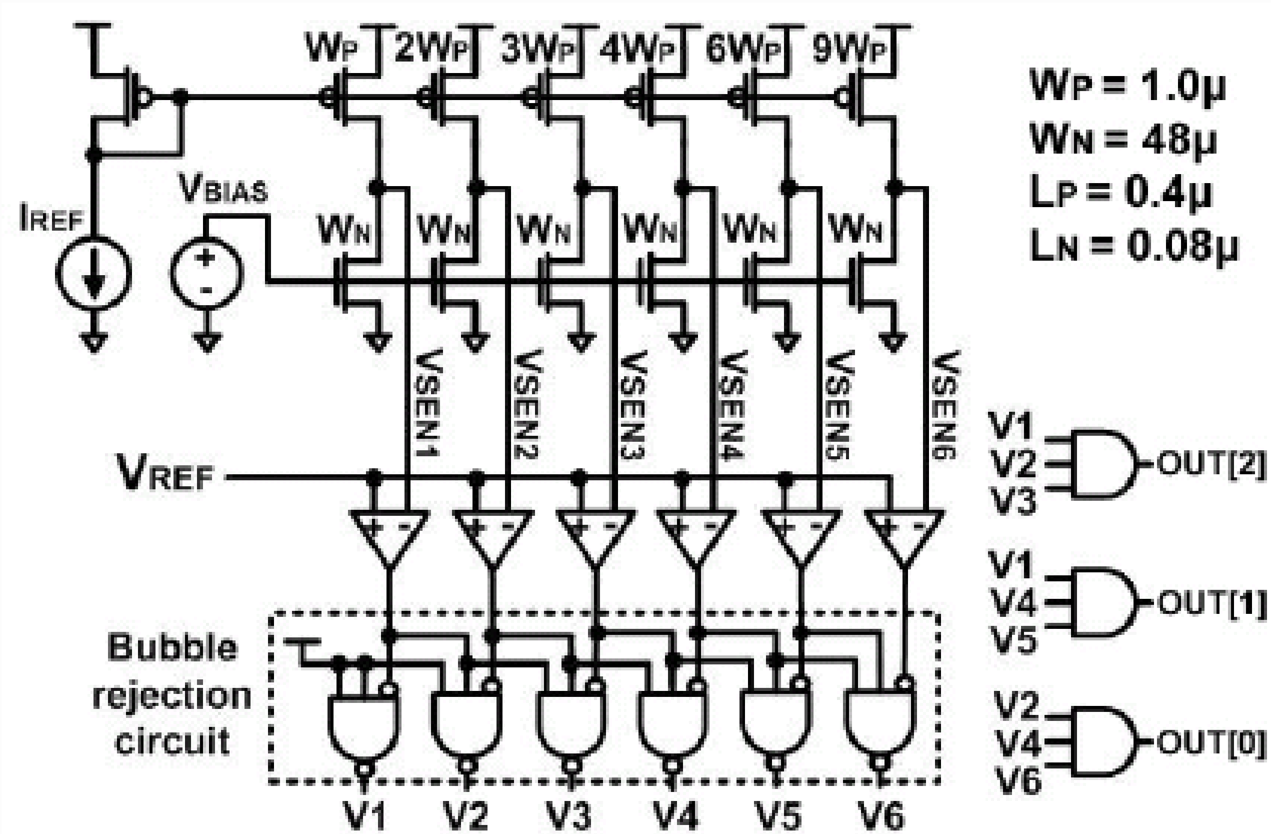
Leakage Detection Circuit





- **Sense the current of a transistor in sub-threshold**
  - **Intersection of the two curves represents the voltage output**
  - **Generate PVT tolerant I_{REF} and V_{bias}**

Multi-Channel Leakage Sensor



- **Use PMOS devices of different widths to obtain multiple channel leakage sensor**
  - **Digital signature of analog leakage variation**

C. Kim et. al. VLSI 2004

Improving Signal to Noise Ratio

- An oscillator with large number of stages

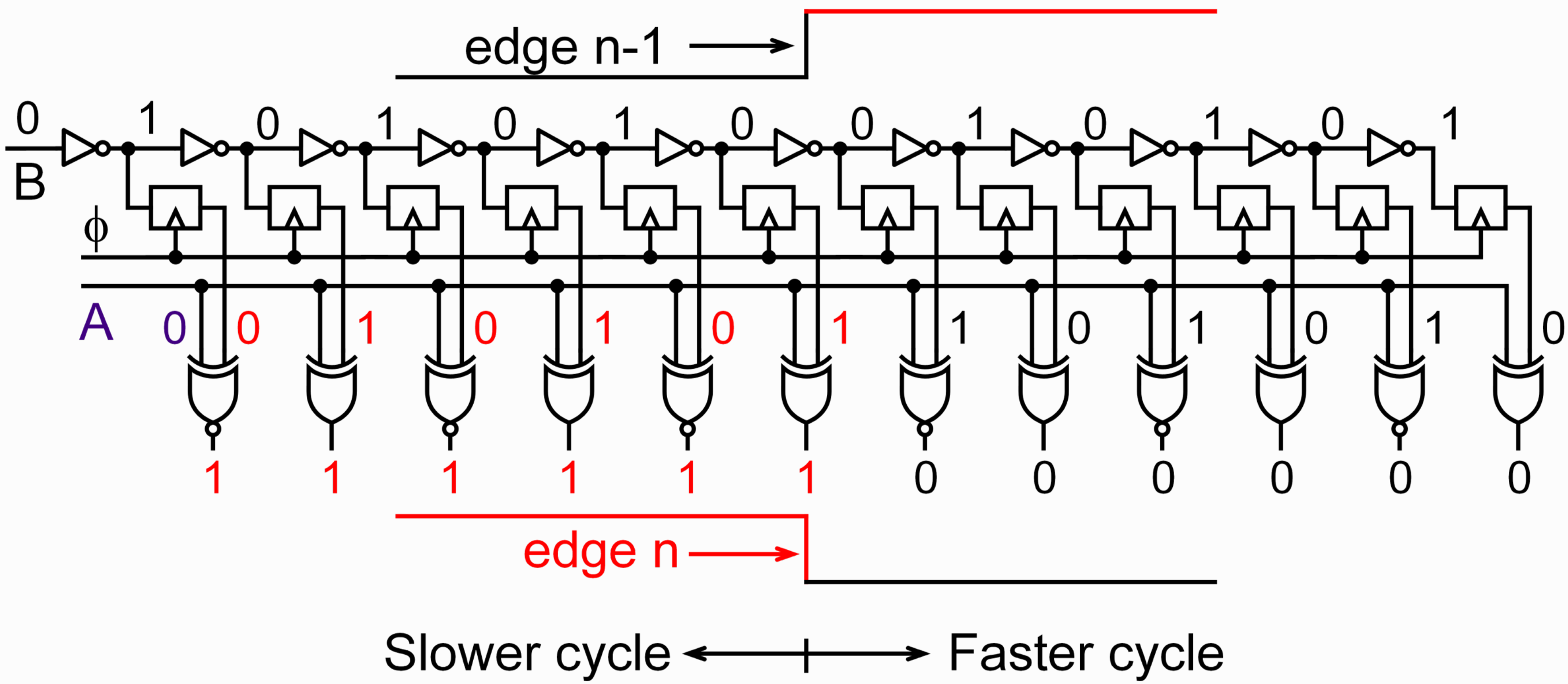
a) Helps differentiate variation by device type

b) Averages out the effect of local variation

c) Requires fewer division stages before readout

d) Shouldn't be used for a VCO operation

Time-to-Digital Conversion Using an Edge Detector

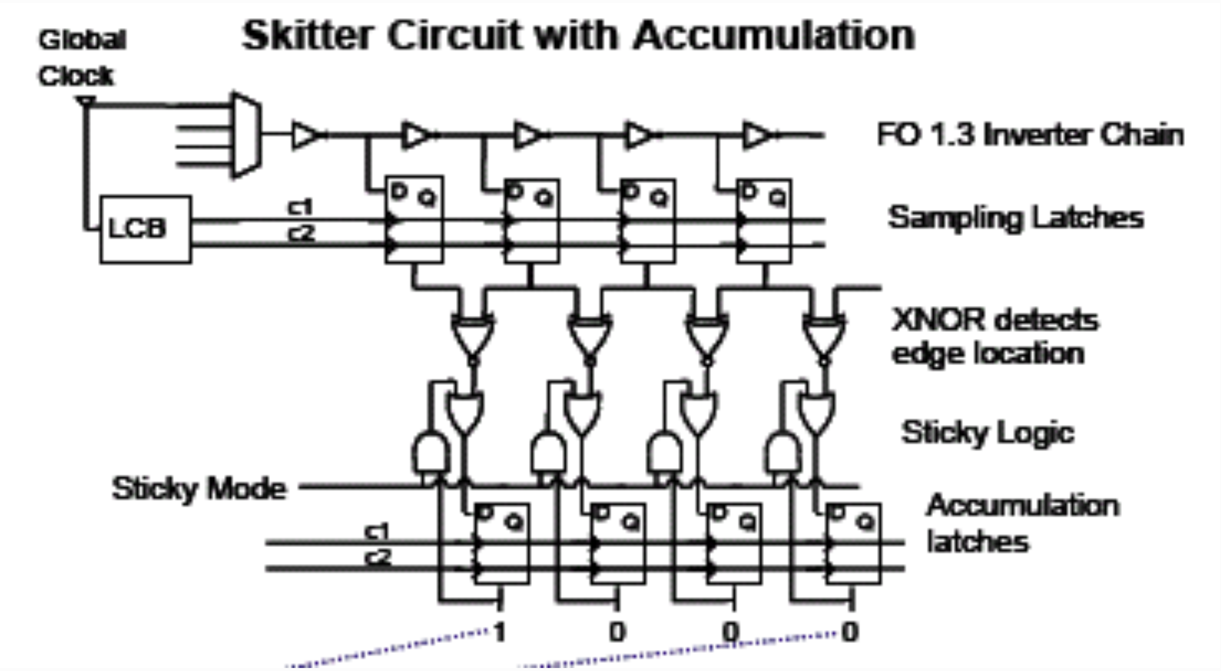


- **Edge movement due to**
  - **Changes in clock cycle**
  - **Changes in path delay**

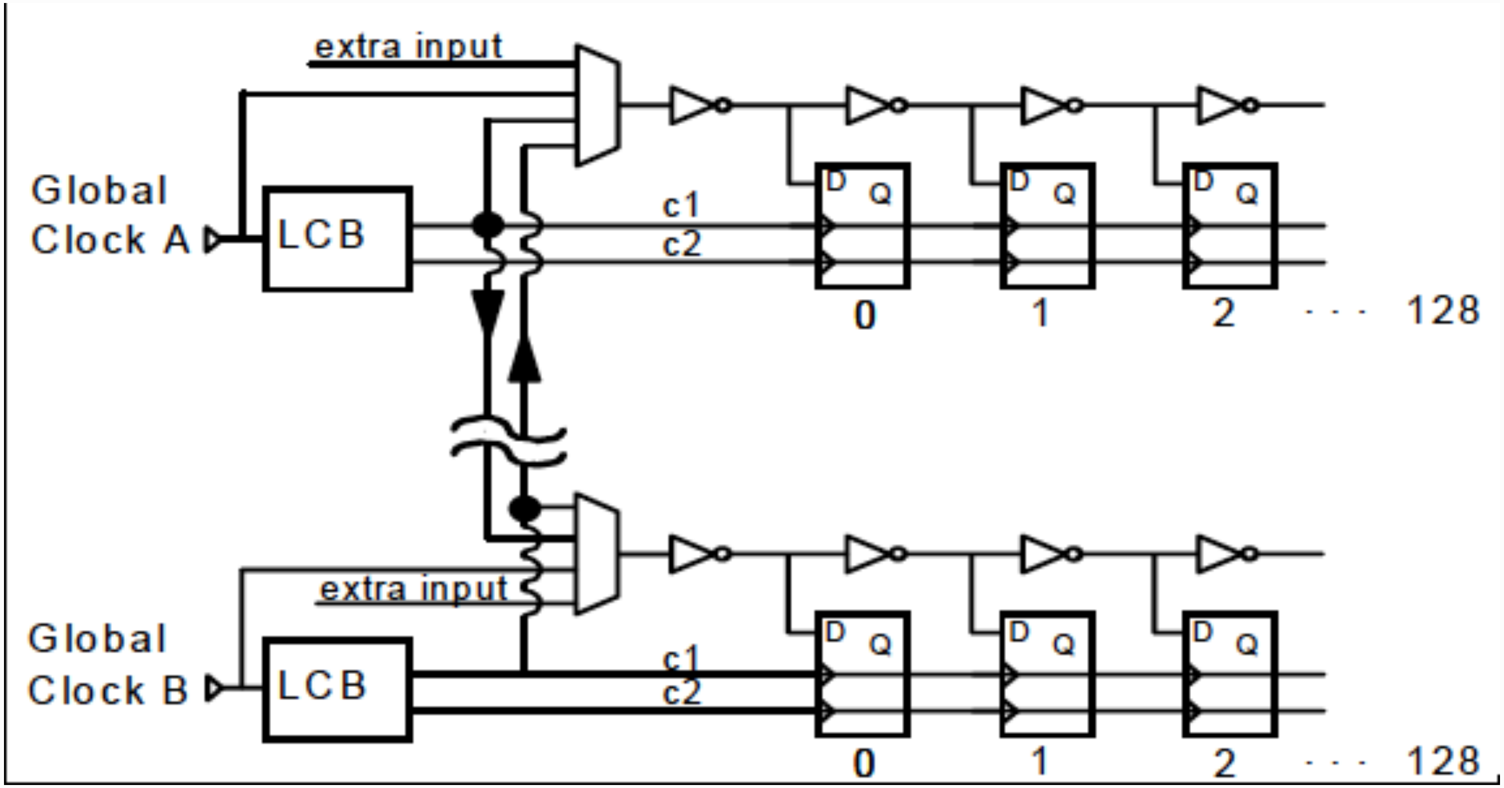
A. Drake et. al. ISSCC 2007

Skitter (Skew + jITTER) Circuit

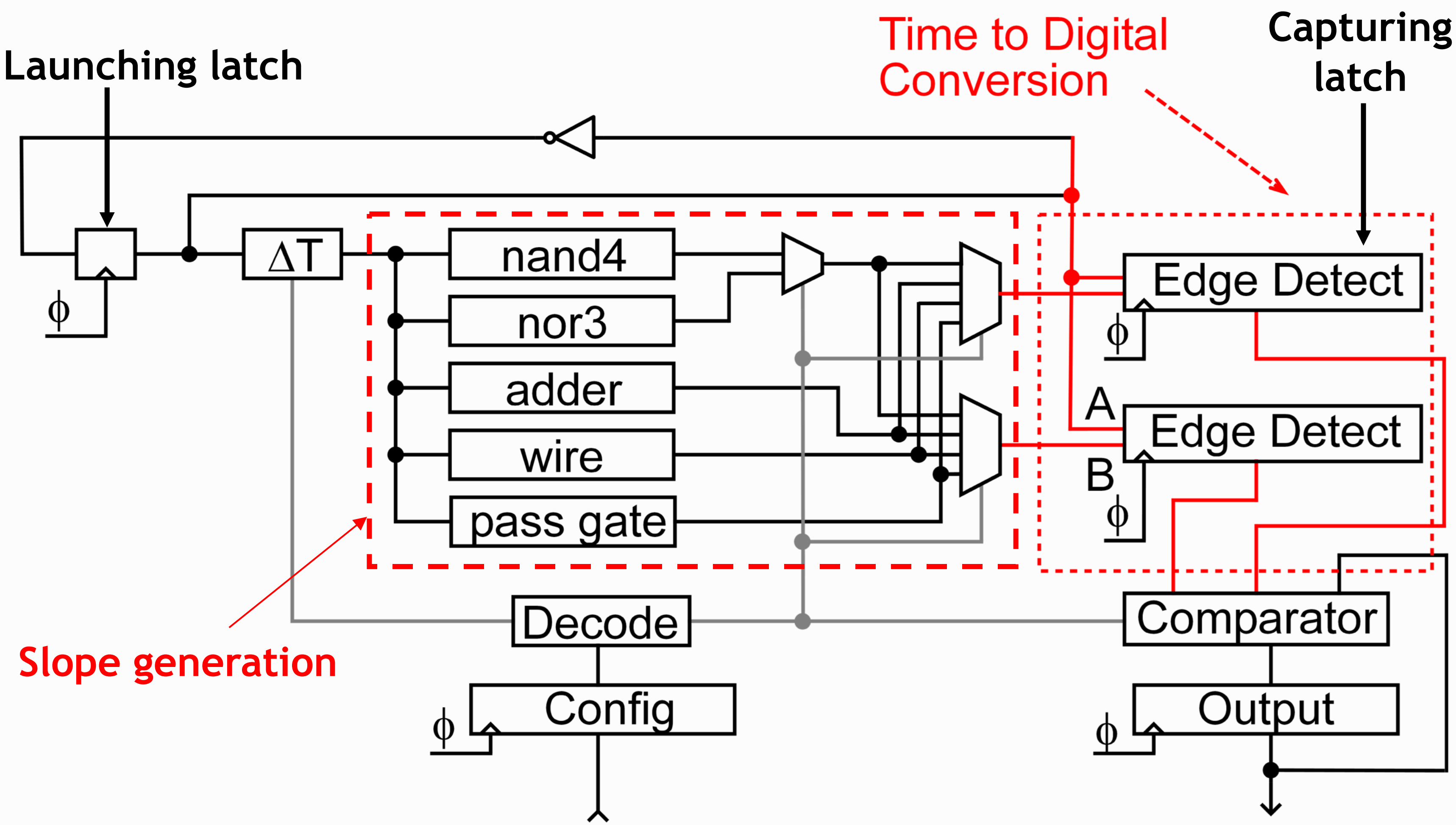
- Measure timing uncertainties from all sources
- Track skew between different regions (also environmental effects)
- During debug, detect supply voltage droops, detect failure mechanism
- Complete digital readout through scan-chains
- Cycle-Cycle variation, Best-Worst case detection



Skitter (Skew + jITTER) Circuit



Delay based Sensing - Critical Path Monitor (CPM)



A. Drake et. al. ISSCC 2007