

Sacha:

Stanford Carbon Nanotube Controlled Handshaking Robot

M. Shulaker, J. Van Rethy, G. Hills, H.Y. Chen,
G. Gielen, H.-S. P. Wong, S. Mitra



Stanford University



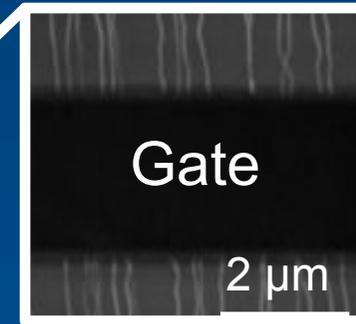
KU Leuven

Carbon Nanotube FET (CNFET)



Diameter $\sim 1.2\text{nm}$

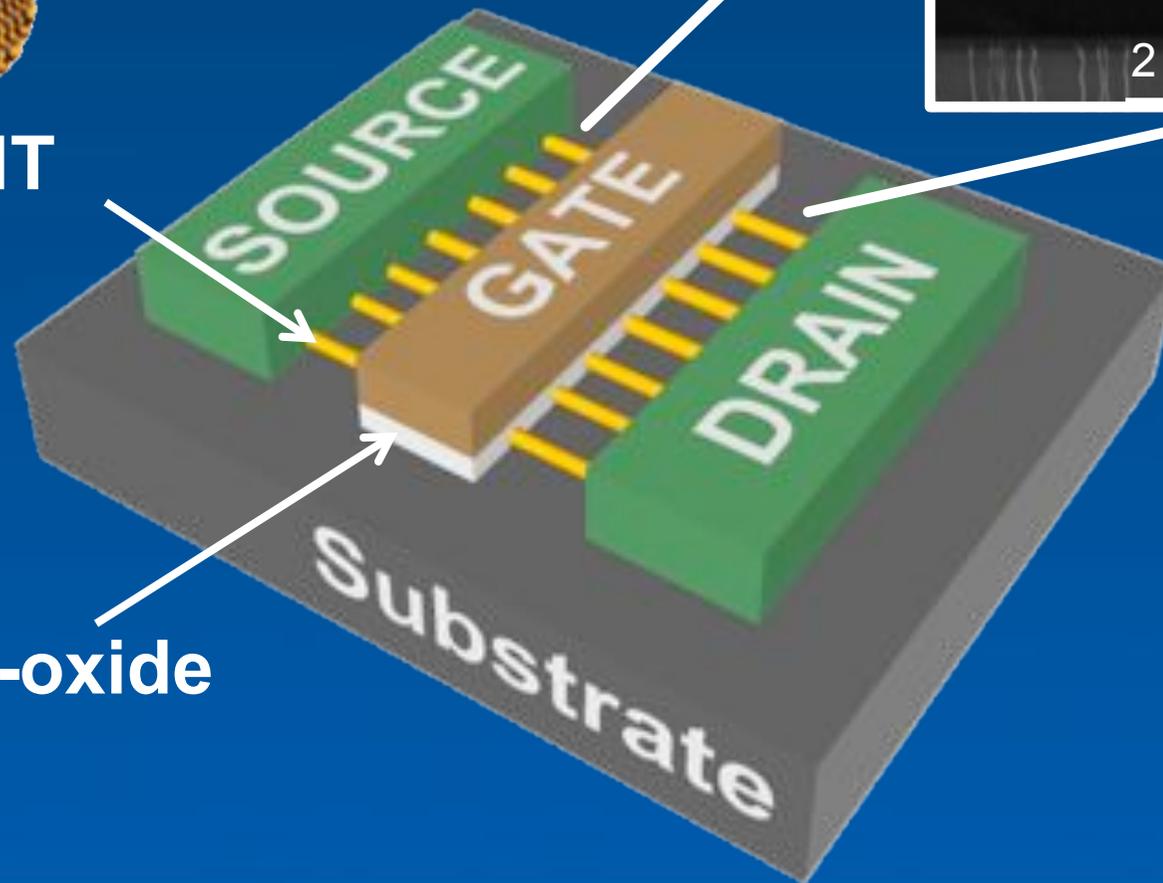
CNT



Gate

2 μm

Gate-oxide



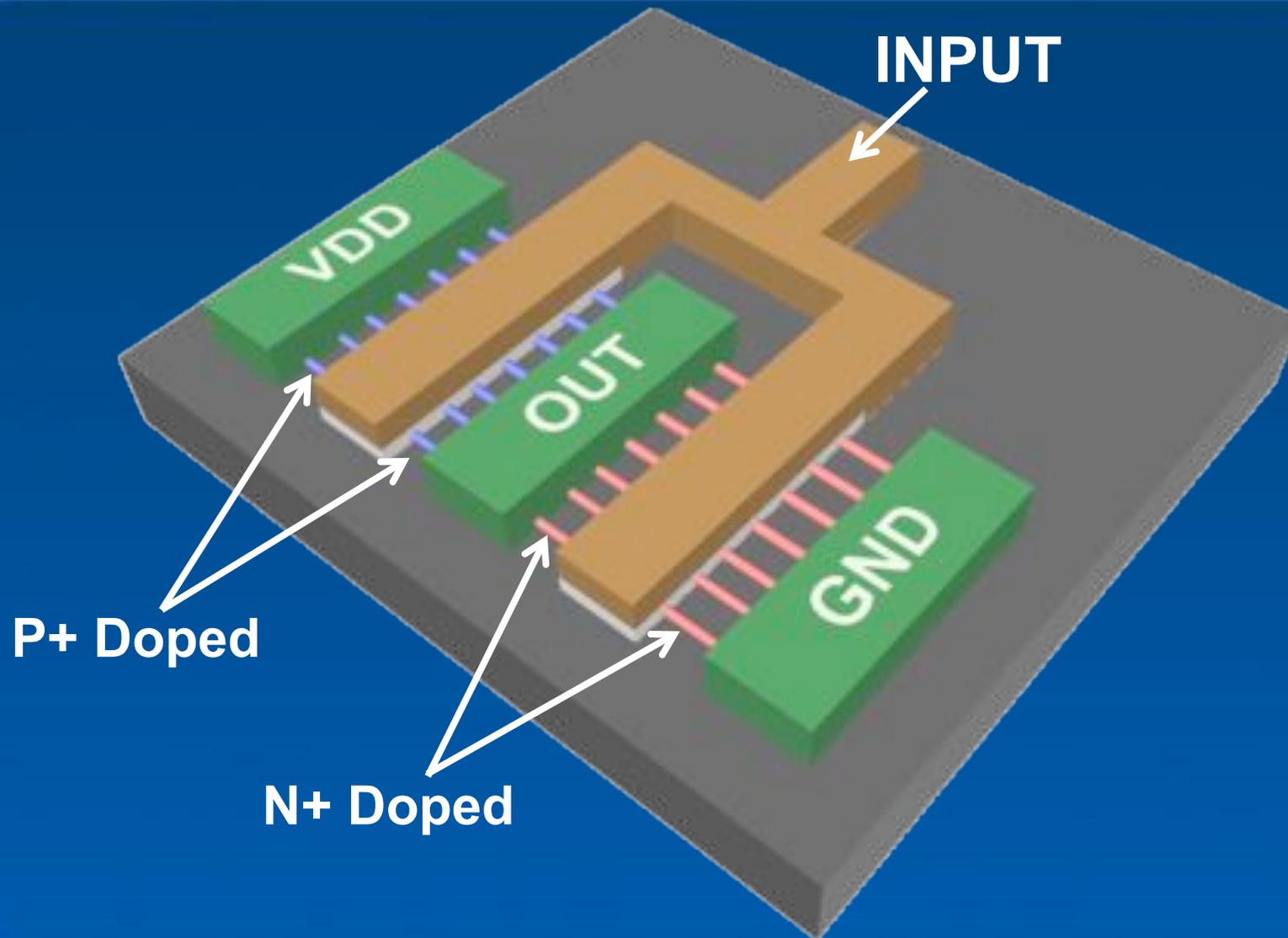
SOURCE

GATE

DRAIN

Substrate

Ideal CNFET Inverter

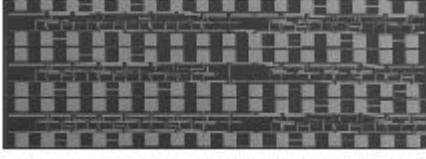


Why CNFETs?

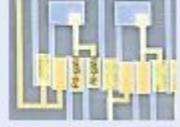
- Best I_{ON}
 - 9nm measurements [Franklin Nano Letters 12]
- 400 mV supply
 - Logic gates [Ding APL 12]
- Major energy-delay-product benefits
 - IBM Power 7 modeled [Chang IEDM 12]

Recent Progress

**First complete sub-system:
Fully digital capacitive sensor interface**



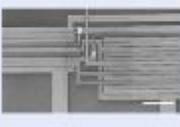
**Single-CNT
ring osc.**



**Flexible
substrate**

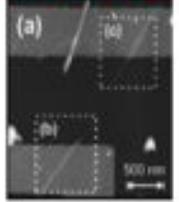


**D-latch,
half adder**

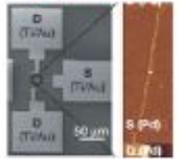


Stand-alone logic elements

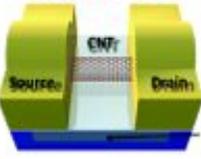
First CNFET



**Ballistic
CNFET**



**Sub-10nm
CNFET**



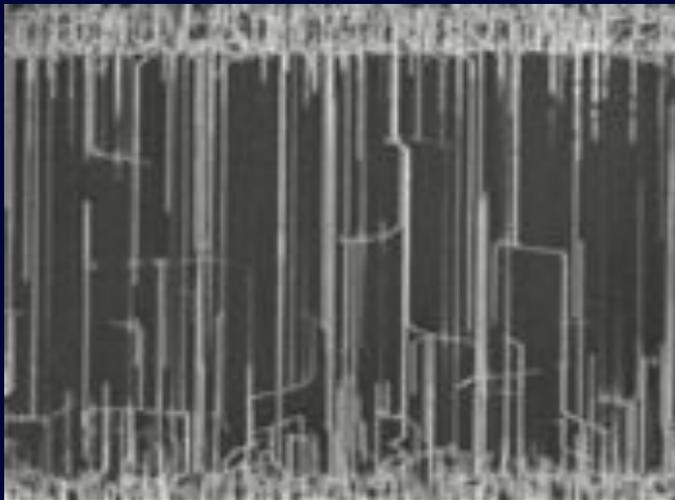
**High
performance
CNFETs**



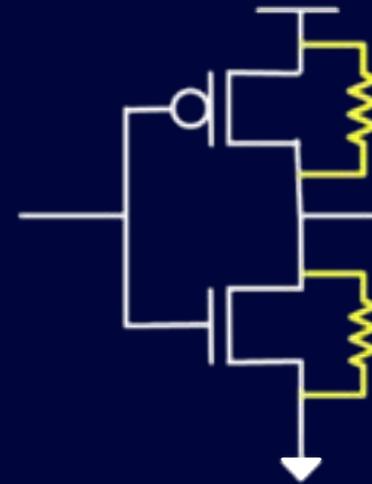
Single devices

BIG Promise, BUT Major Obstacles

Mis-positioned CNTs

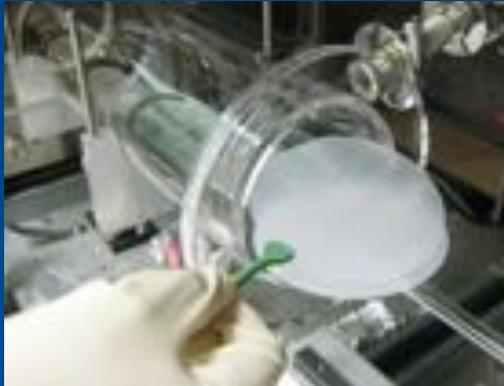


Metallic CNTs



Imperfection-immune design essential

First Wafer-Scale Aligned CNT Growth



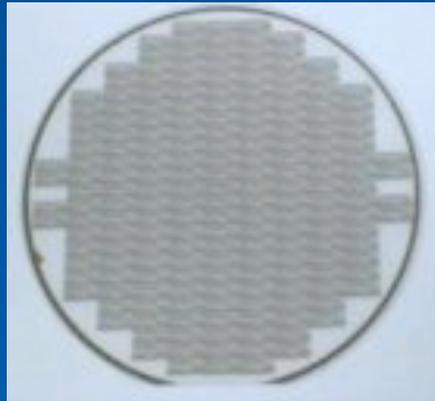
Quartz wafer
with catalyst



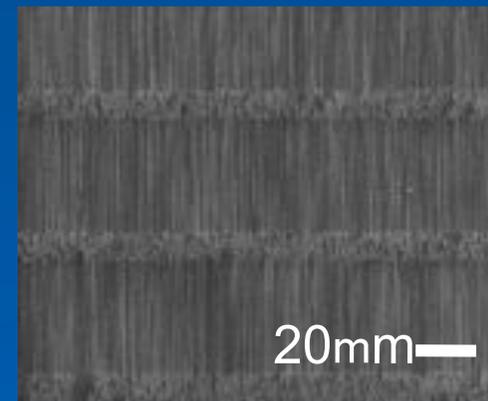
Aligned
CNT growth



Quartz wafer with CNTs



99.5% aligned CNTs

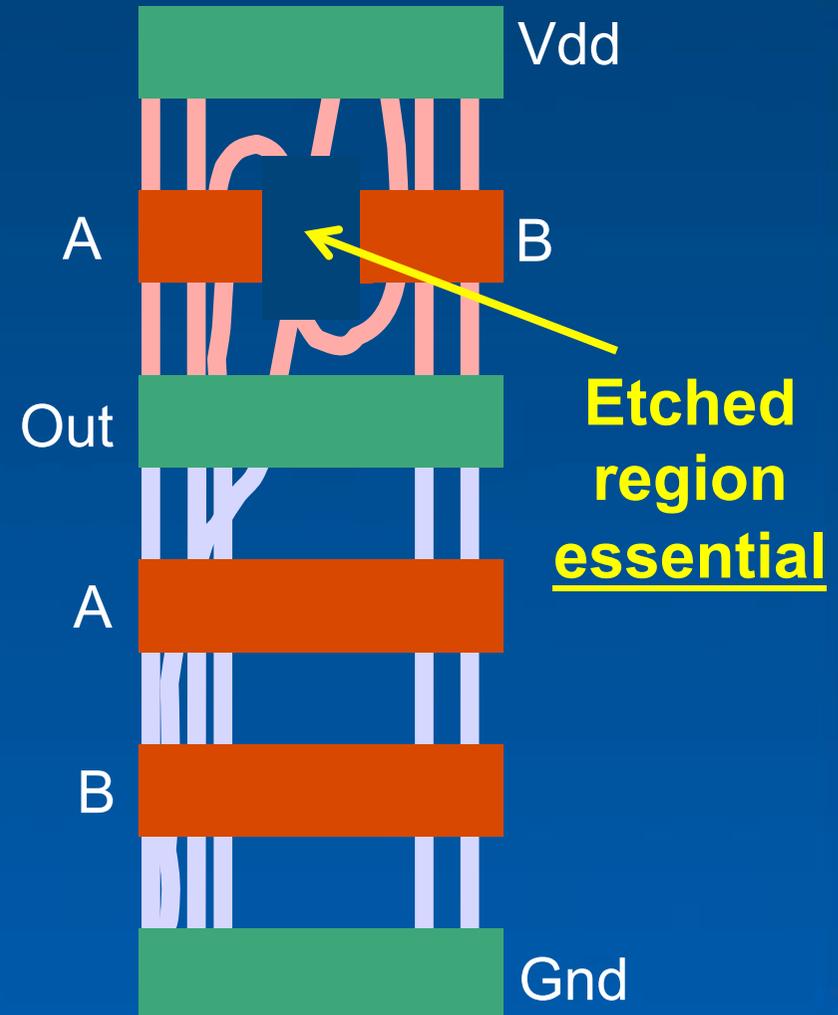


Stanford Nanofabrication Facility

Mis-positioned CNT-Immune NAND

1. Grow CNTs
2. Extended gate, contacts
3. Etch gate & CNTs
4. Dope P & N regions

- Arbitrary logic functions
 - Graph algorithms



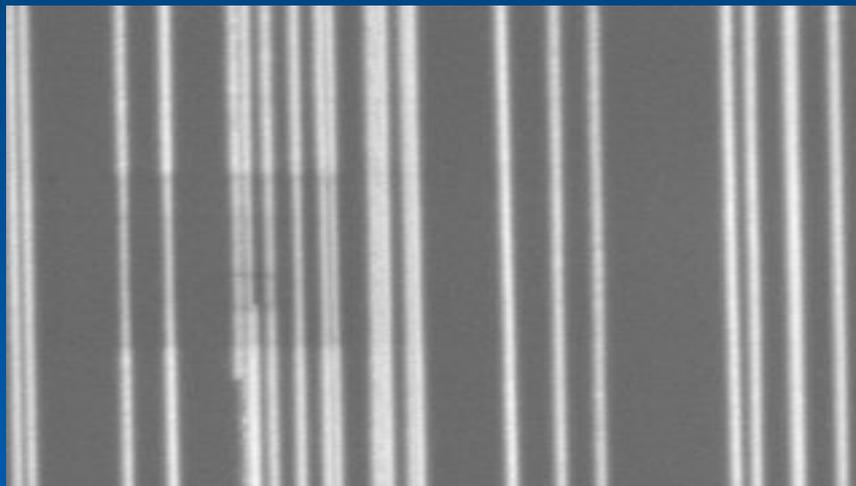
Most Importantly

- VLSI processing
 - No per-unit customization
- VLSI design flow
 - Immune CNT library

m-CNT Removal

- VLSI Metallic CNT Removal
 - Universally effective
 - All logic designs
 - VLSI processing & design flows

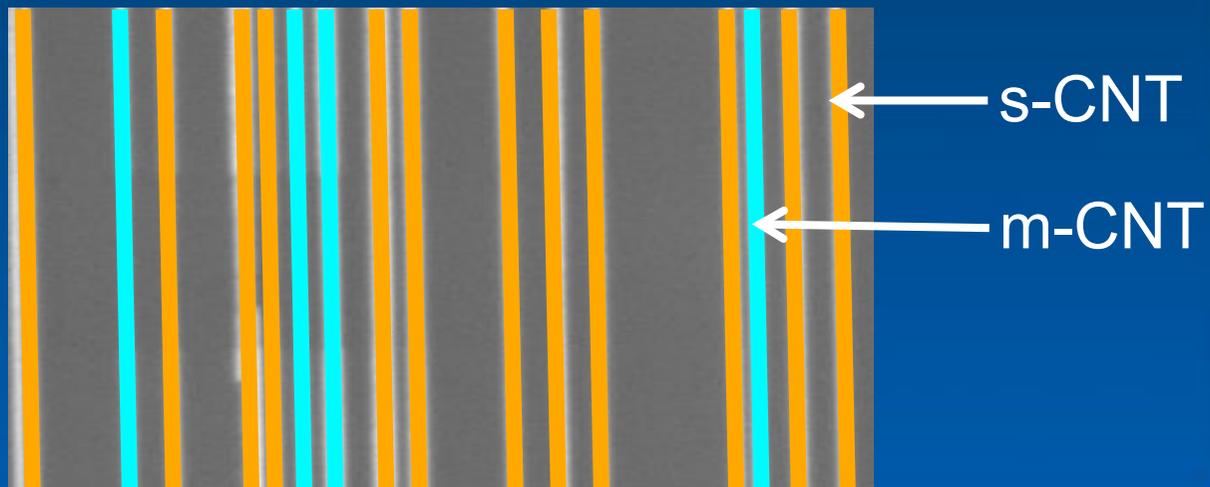
Chip-Scale Electrical Breakdown



m-CNT Removal

- VLSI Metallic CNT Removal
 - Universally effective
 - All logic designs
 - VLSI processing & design flows

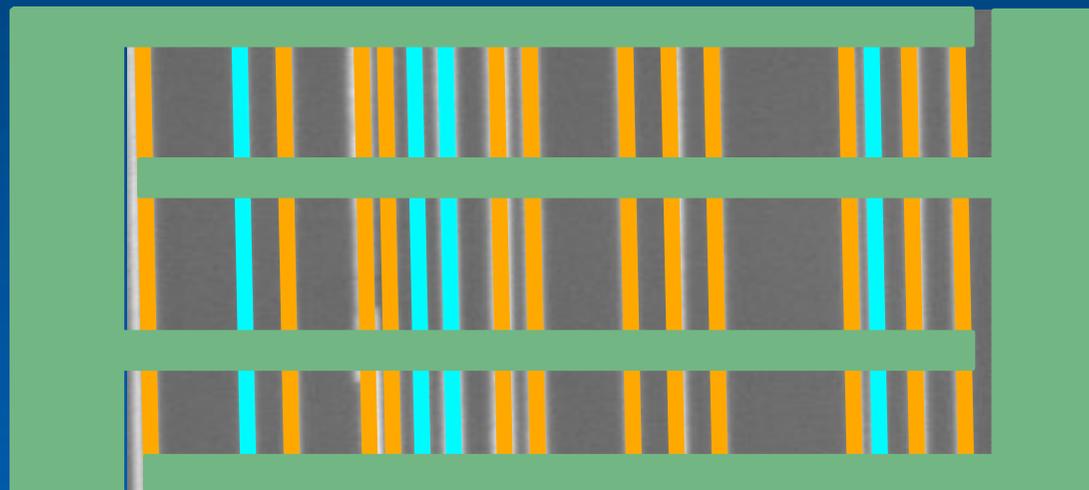
Chip-Scale Electrical Breakdown



m-CNT Removal

- VLSI Metallic CNT Removal
 - Universally effective
 - All logic designs
 - VLSI processing & design flows

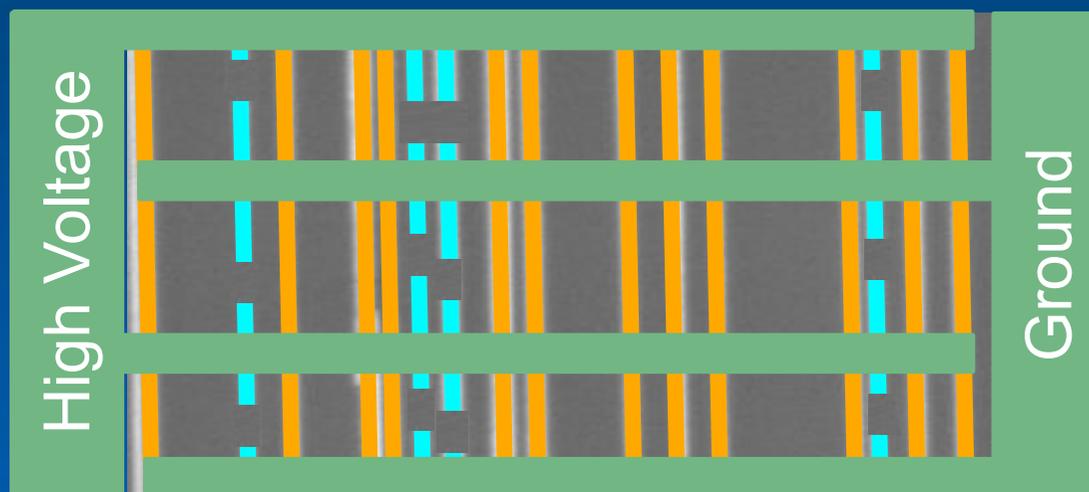
Fabricate VMR electrodes



m-CNT Removal

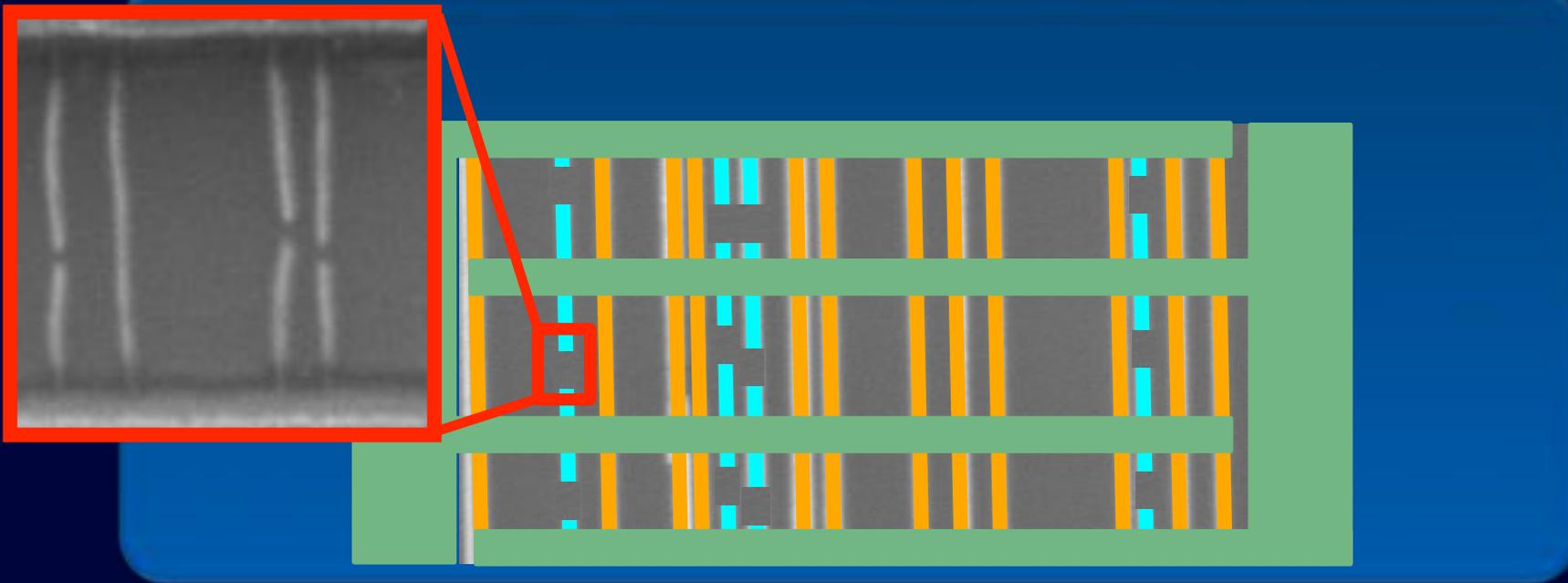
- VLSI Metallic CNT Removal
 - Universally effective
 - All logic designs
 - VLSI processing & design flows

Electrical Breakdown (back-gate)



m-CNT Removal

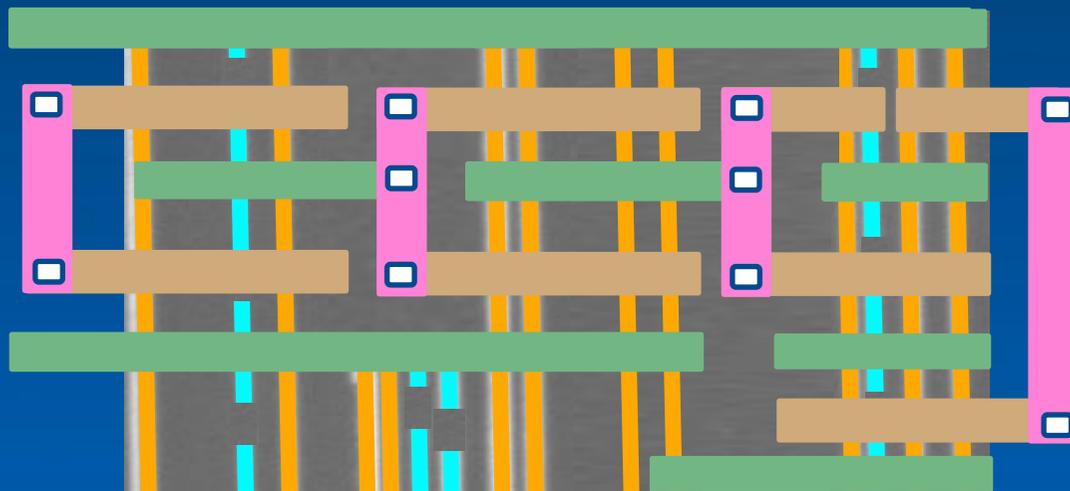
- VLSI Metallic CNT Removal
 - Universally effective
 - All logic designs
 - VLSI processing & design flows



m-CNT Removal

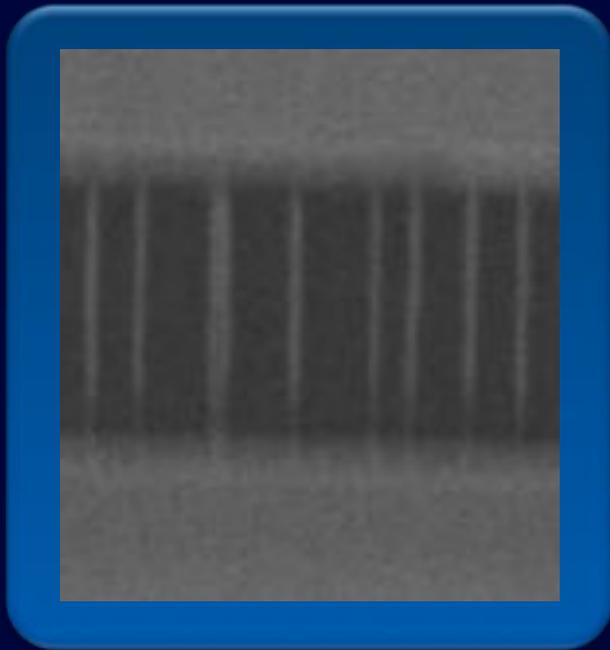
- VLSI Metallic CNT Removal
 - Universally effective
 - All logic designs
 - VLSI processing & design flows

Top-gates (mis-positioned CNT-immune layout), wires



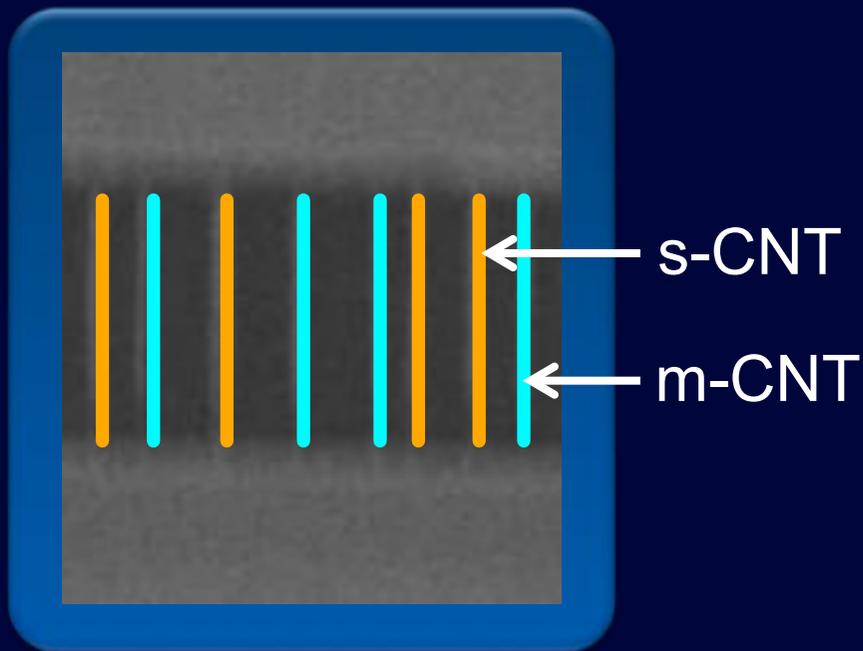
VMR Performance

m-CNT vs. s-CNT selectivity



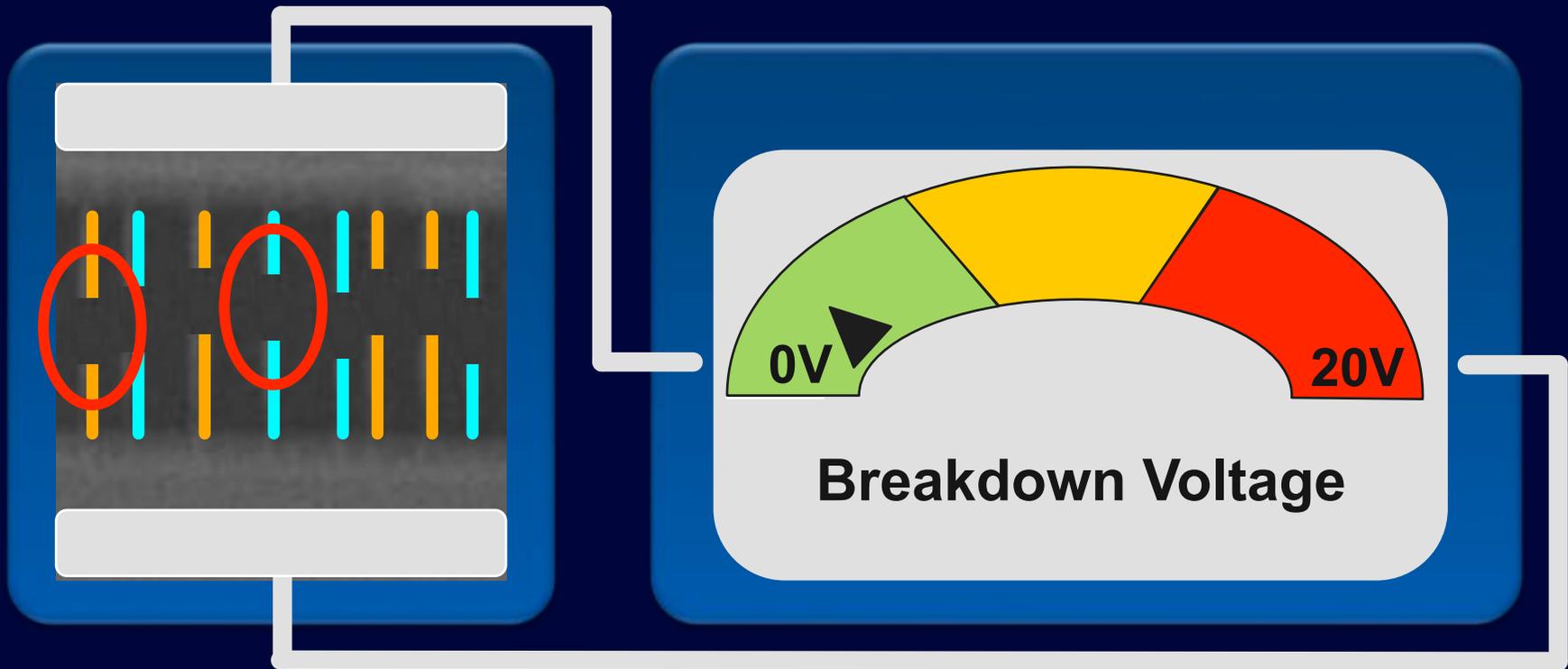
VMR Performance

m-CNT vs. s-CNT selectivity



VMR Performance

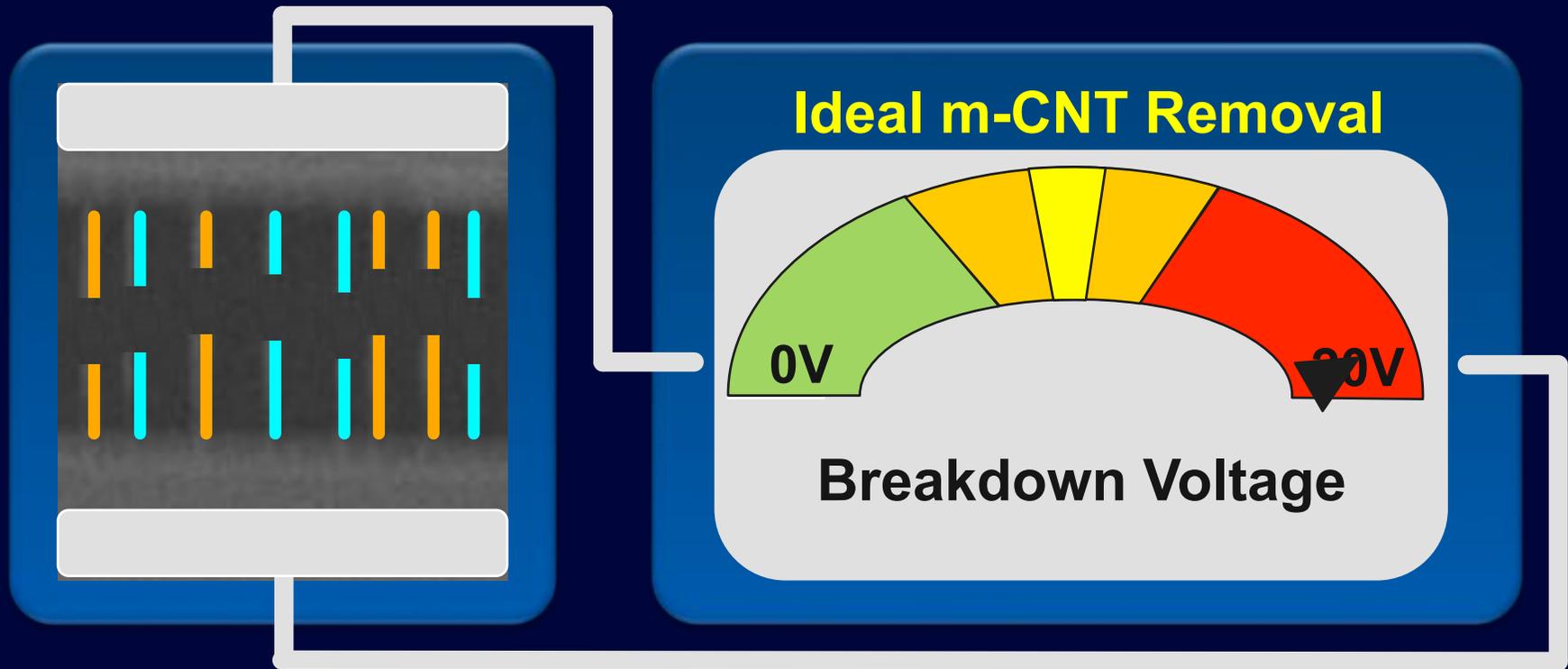
m-CNT vs. s-CNT selectivity



Exceeds Breakdown Voltage!

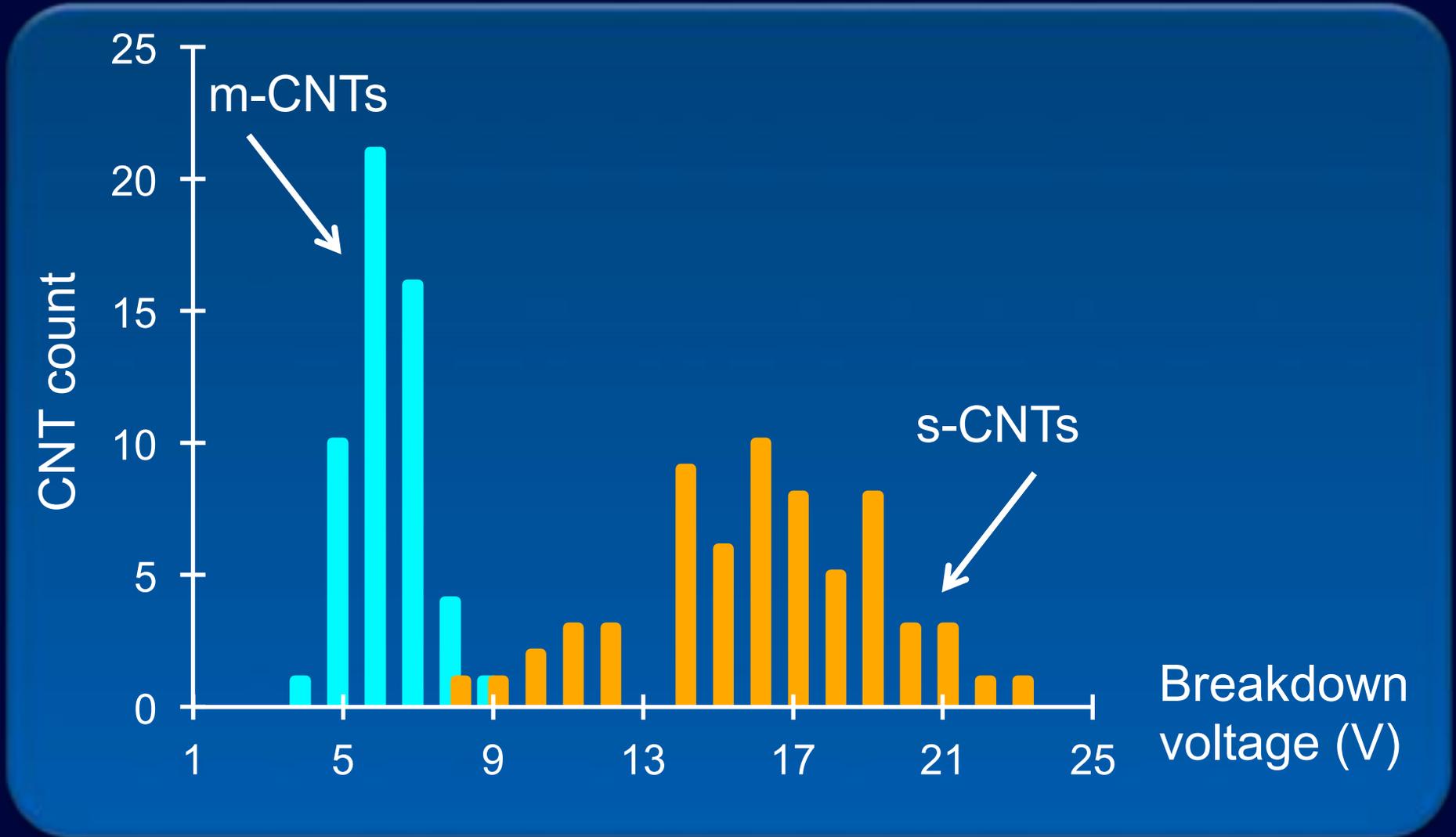
VMR Performance

m-CNT vs. s-CNT selectivity



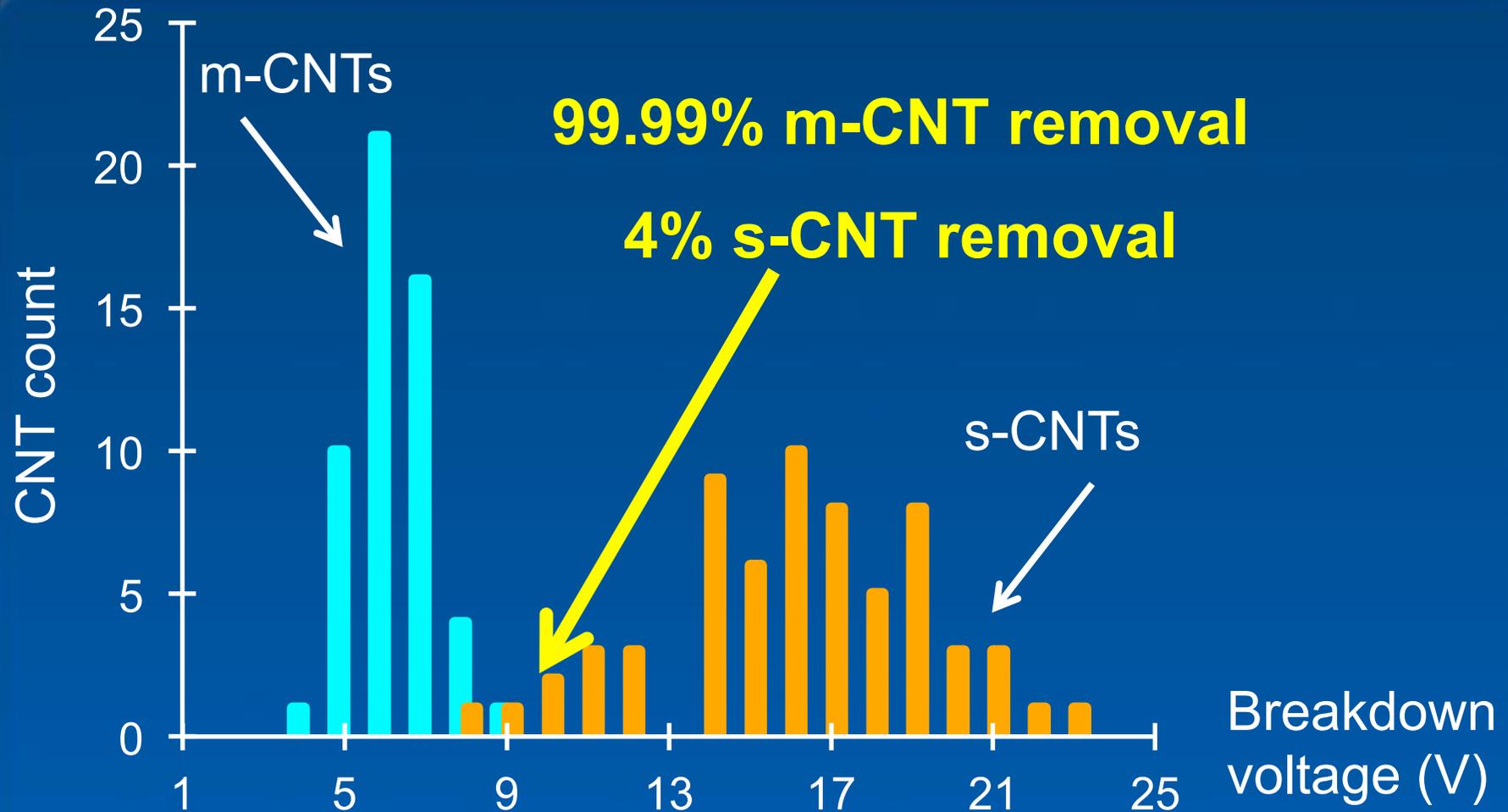
VMR Performance

Experimental Distribution



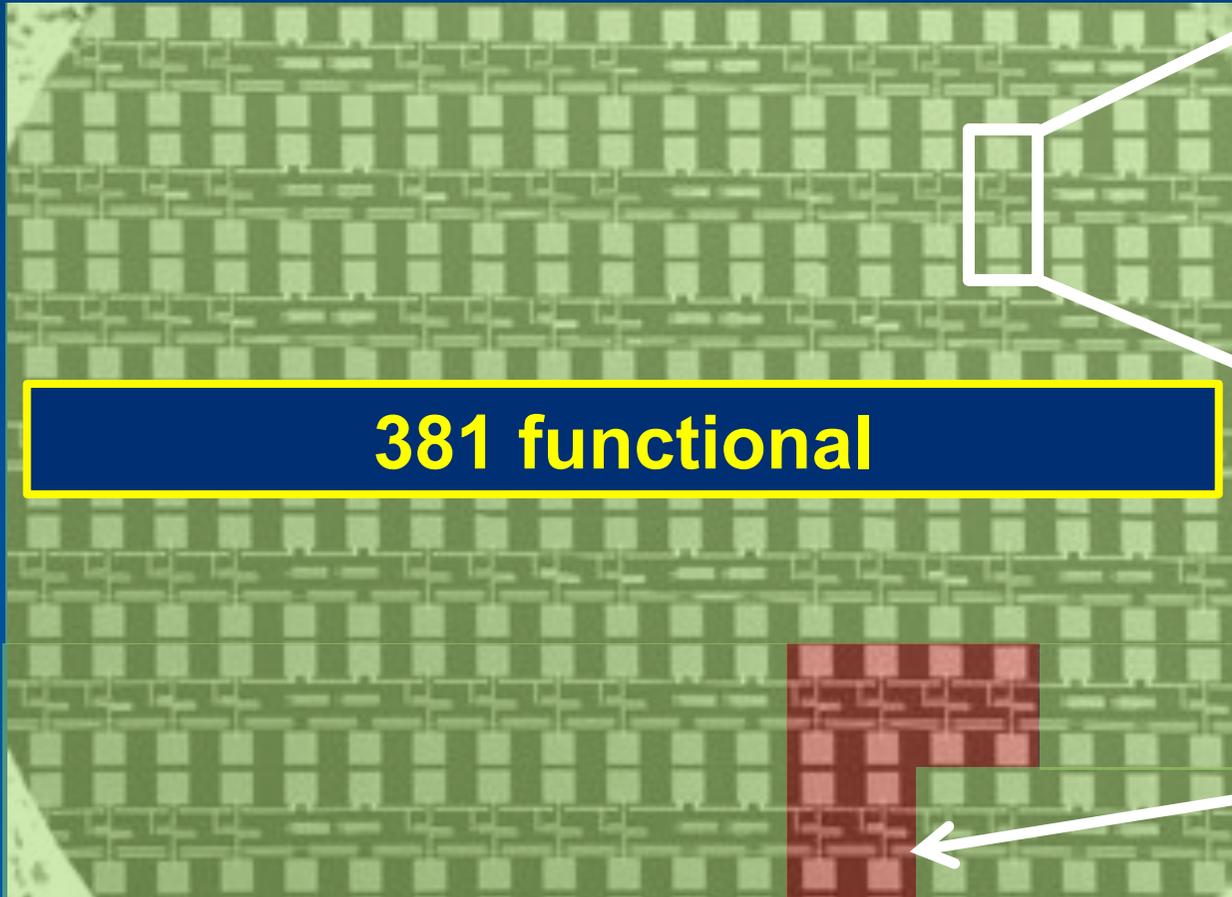
VMR Performance

Experimental Distribution



Circuit Robustness

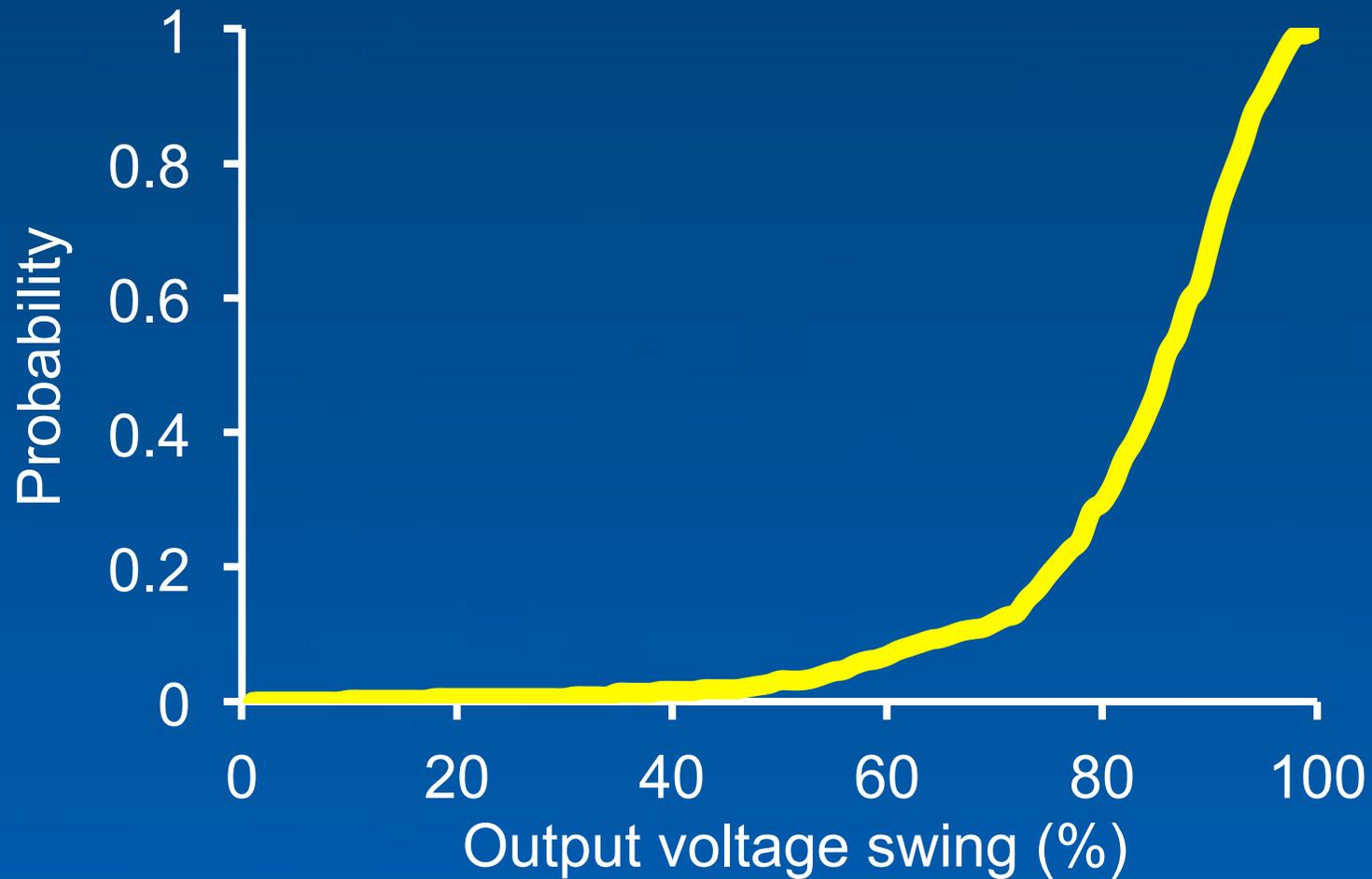
400 inverters



19
clustered fails
(non-CNT issues)

Circuit Robustness

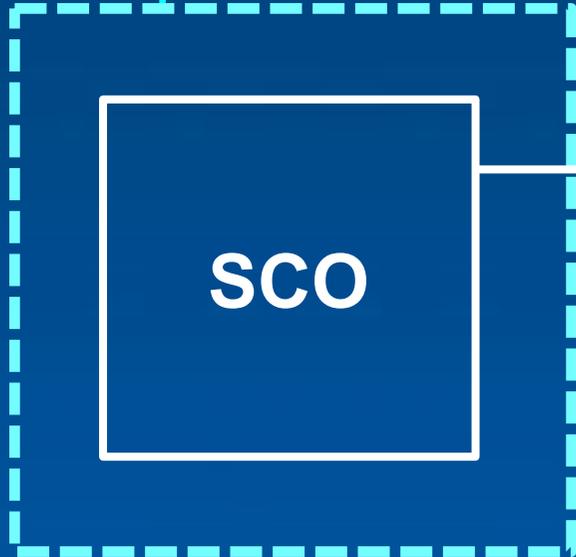
Inverter output swing: cumulative distribution



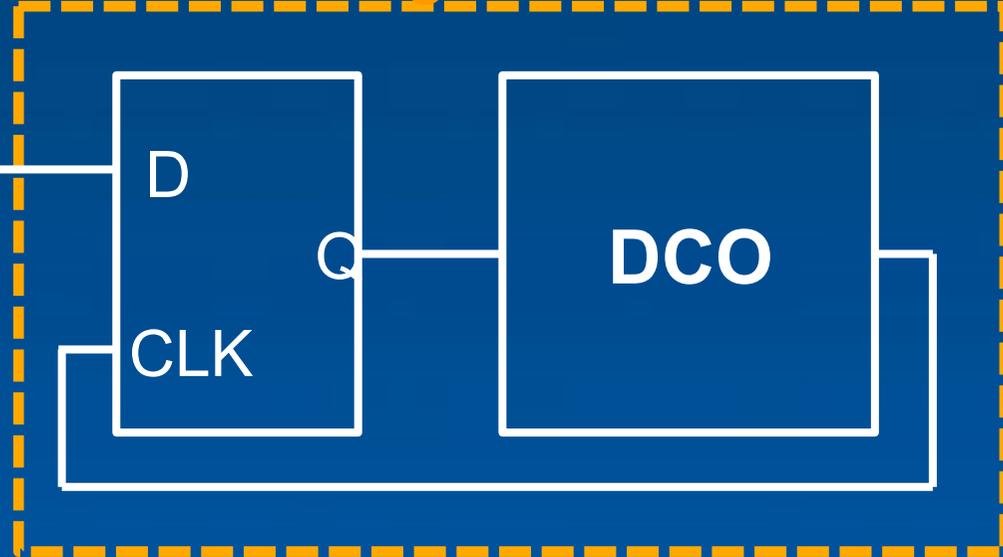
Complete Sub-System

Complete Capacitive Sensor Interface

Freq. Modulation



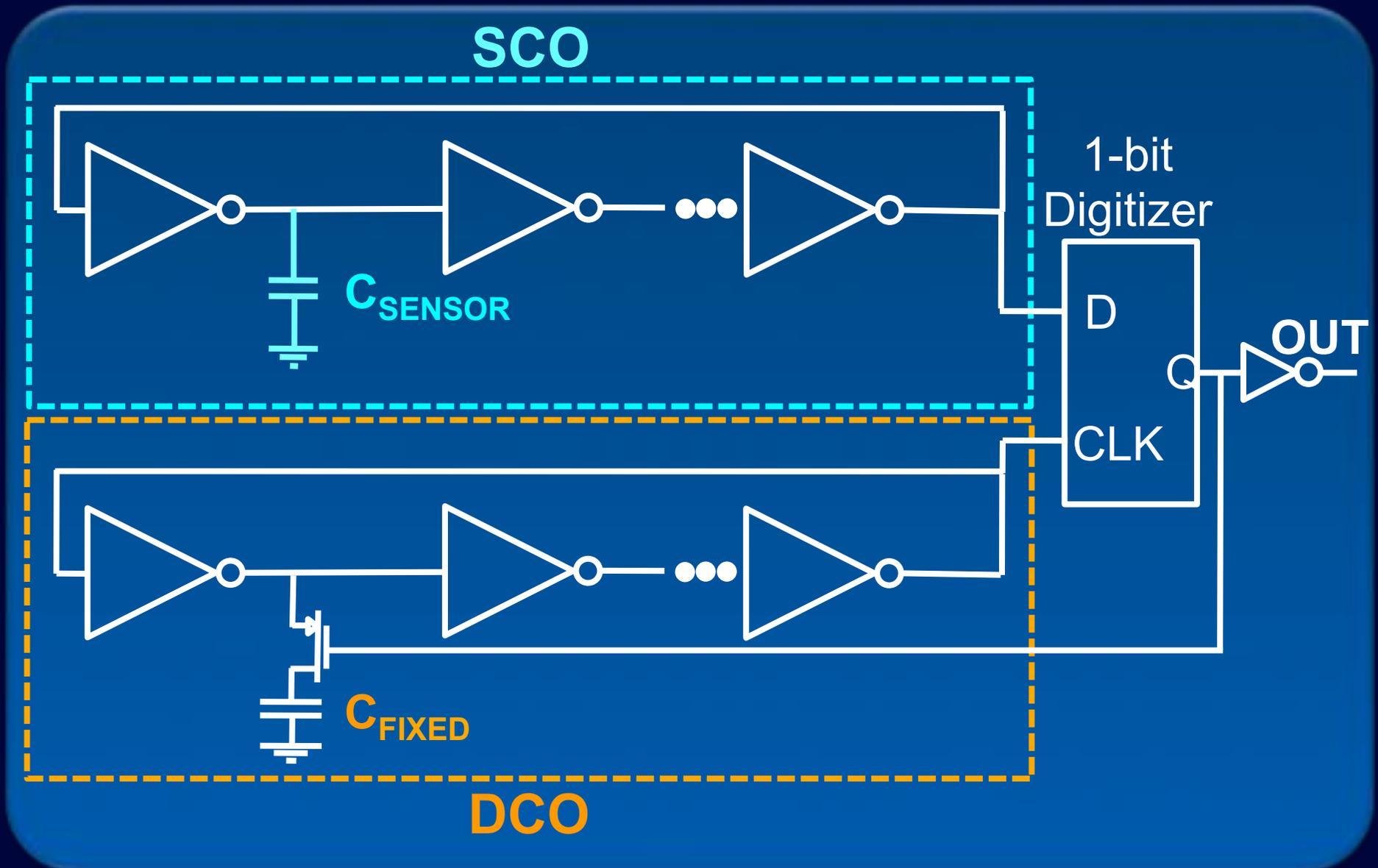
Digital PLL



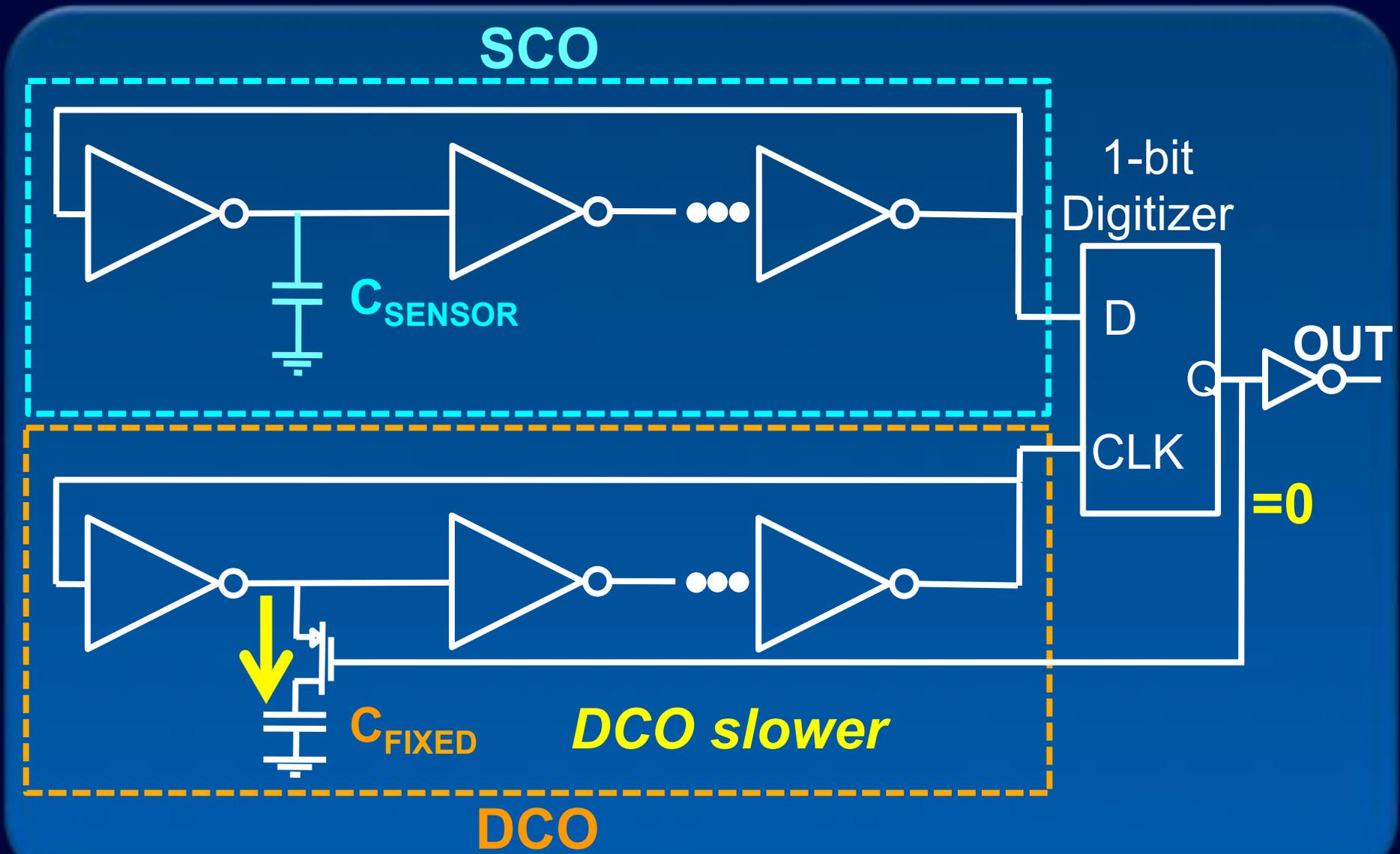
SCO = Sensor-controlled oscillator

DCO = Digitally-controlled oscillator

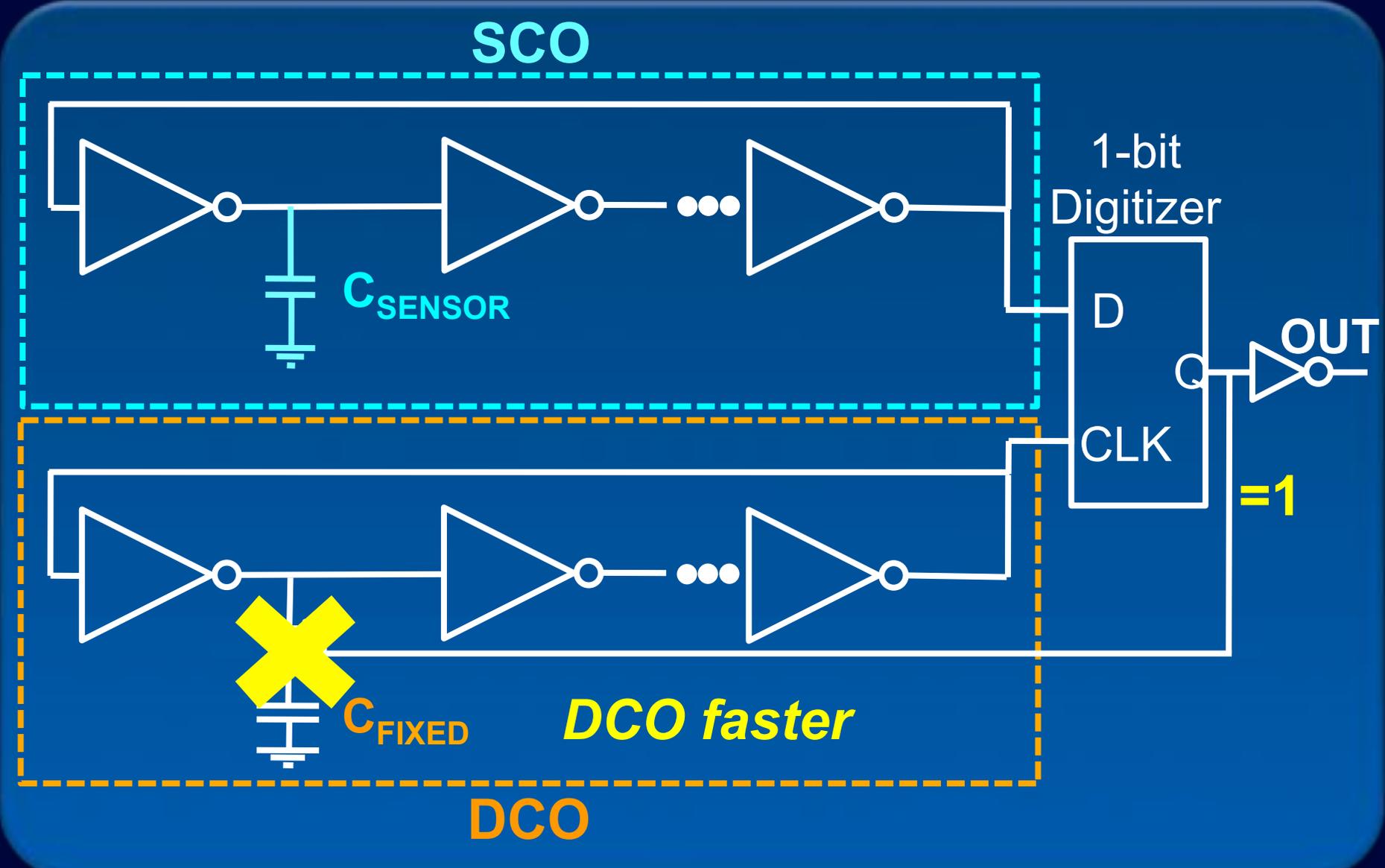
Capacitive Sensor Interface



Circuit Operation

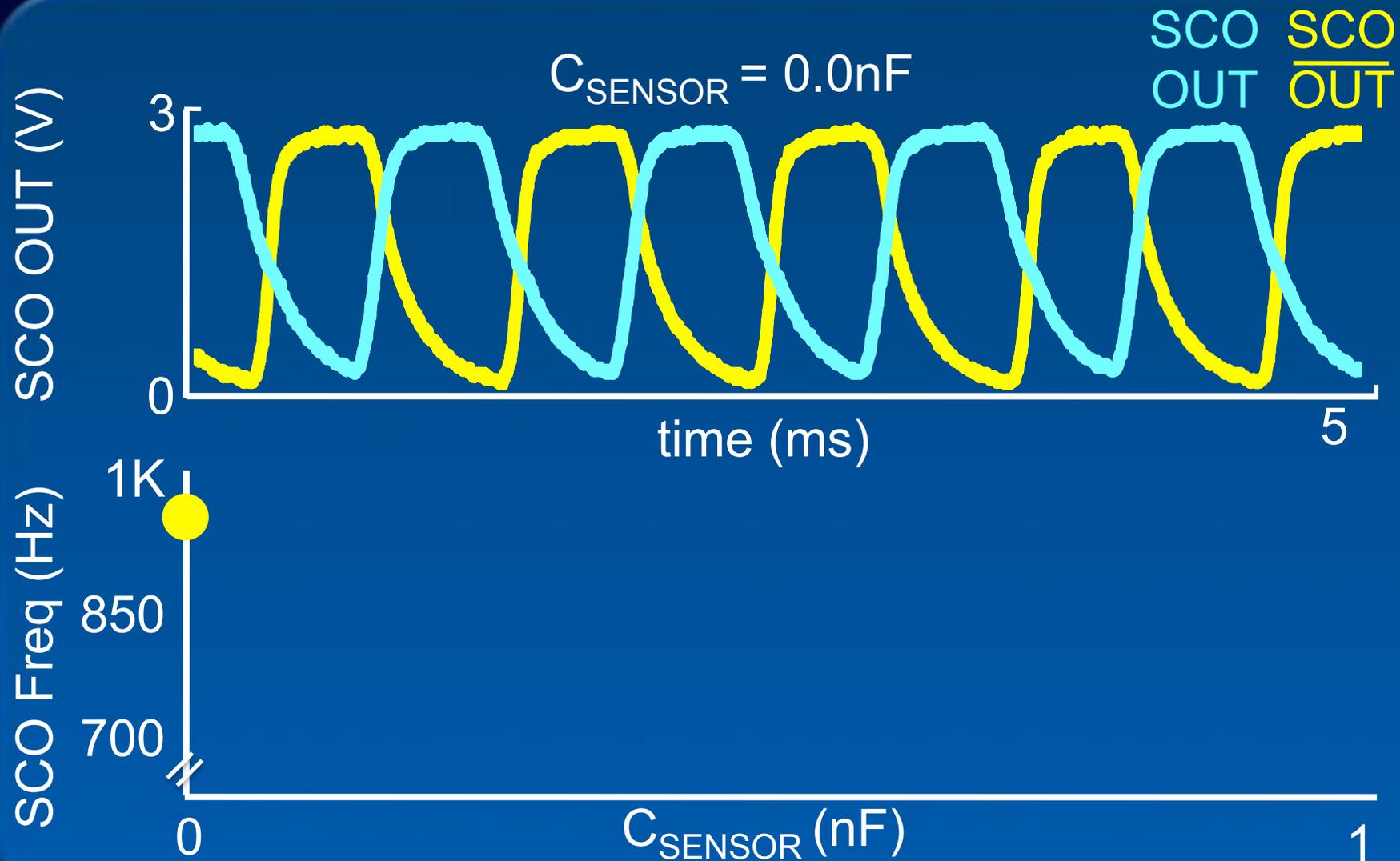


Circuit Operation



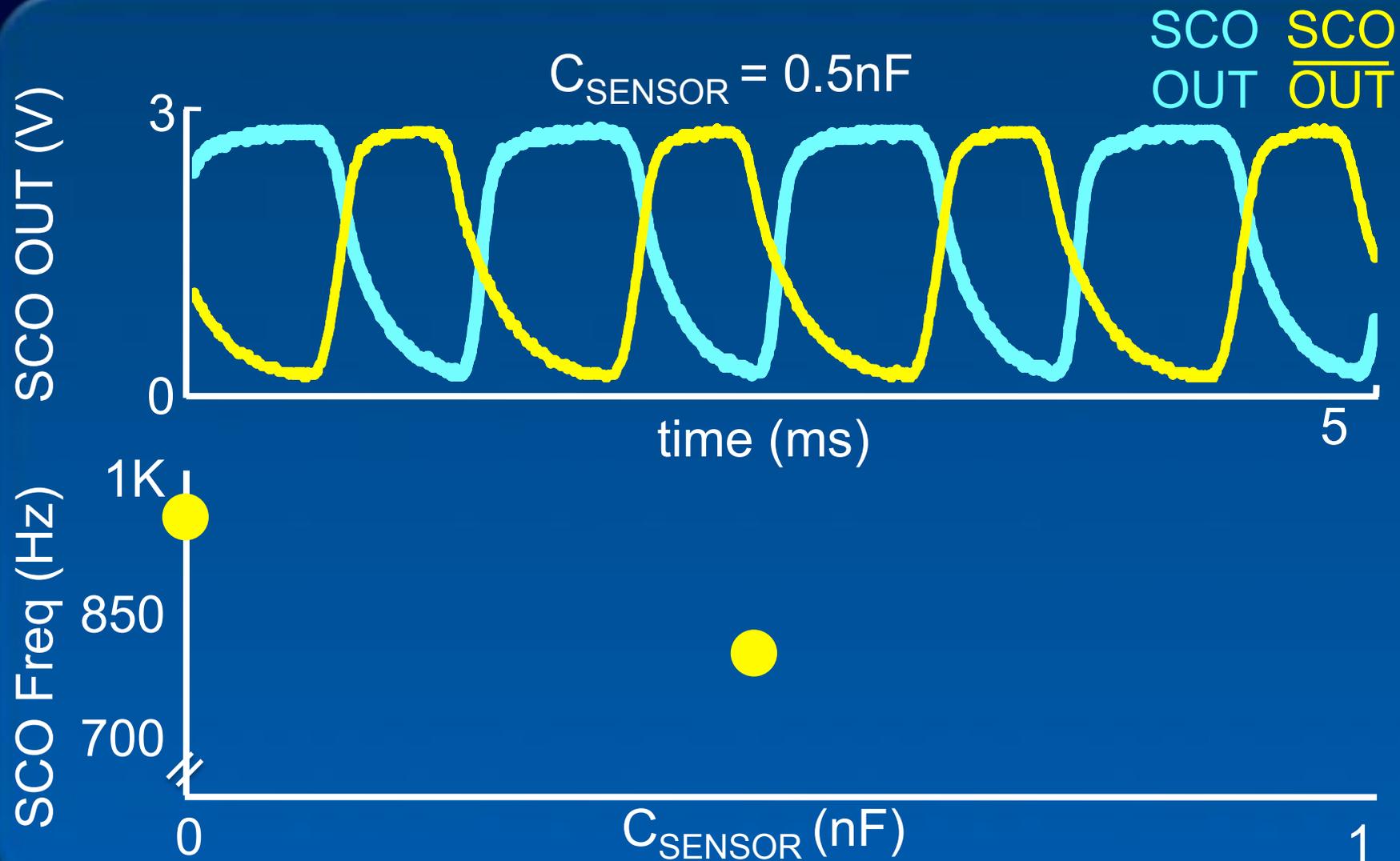
Ring Oscillator Performance

SCO vs. C_{SENSOR}



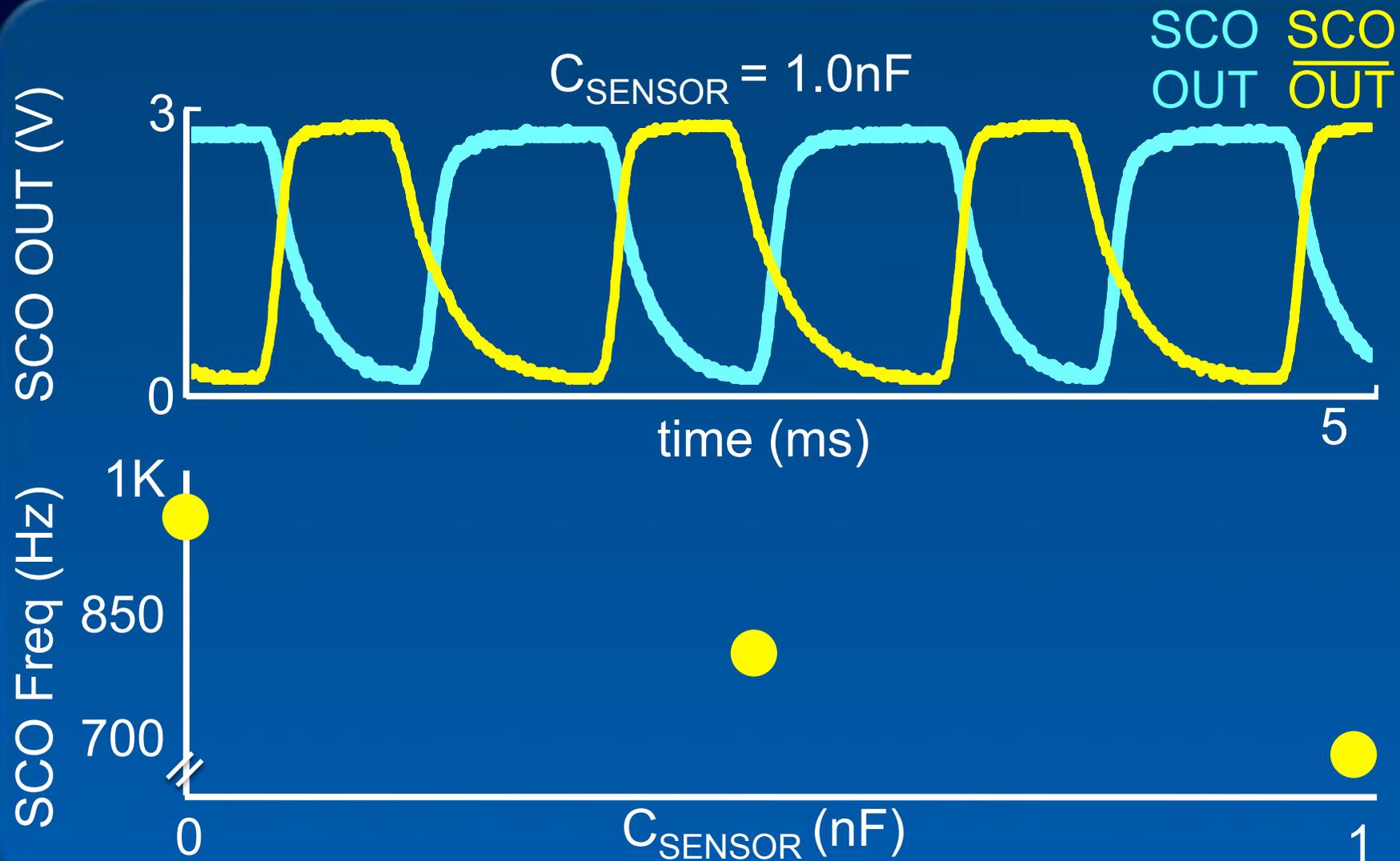
Ring Oscillator Performance

SCO vs. C_{SENSOR}



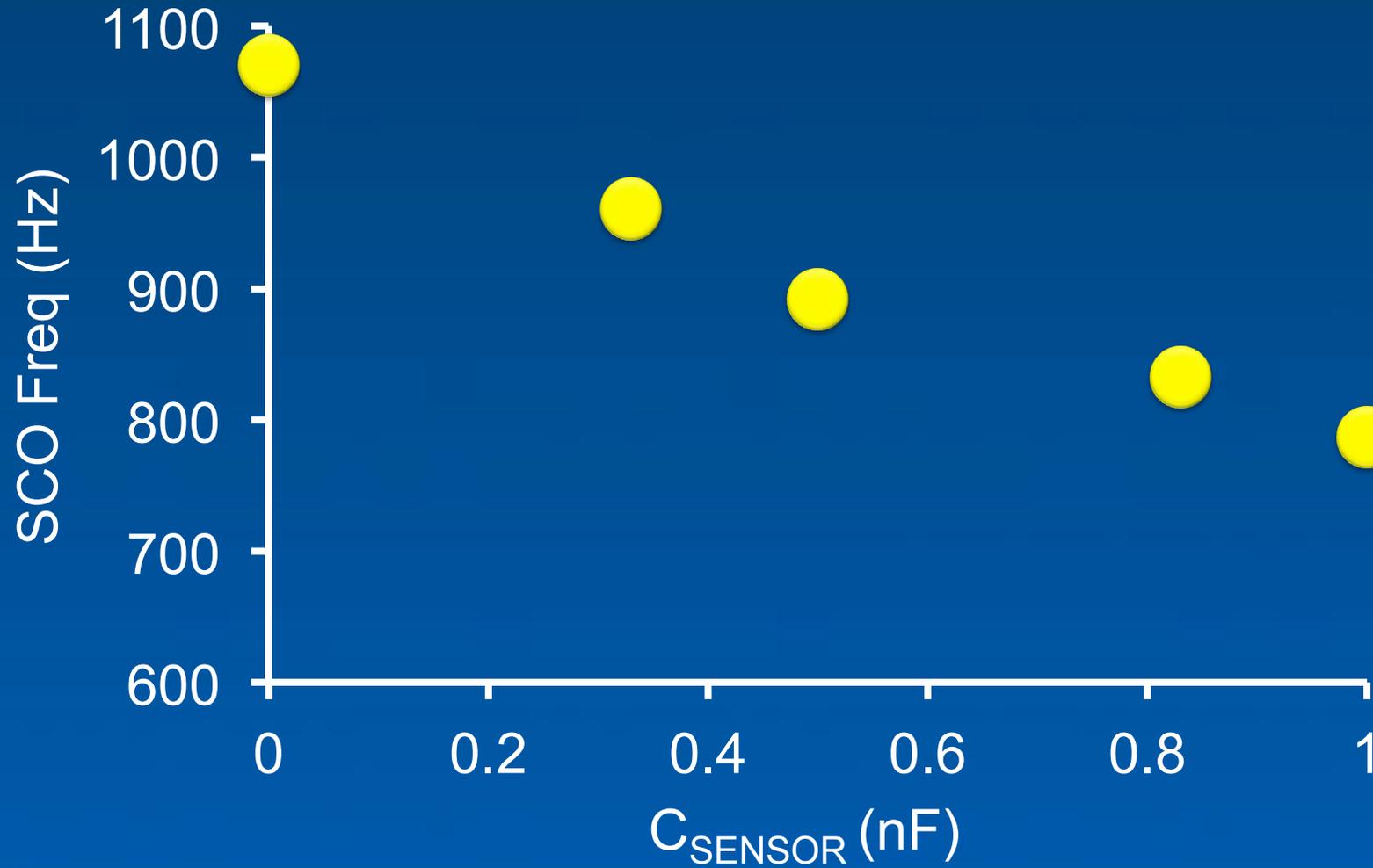
Ring Oscillator Performance

SCO vs. C_{SENSOR}



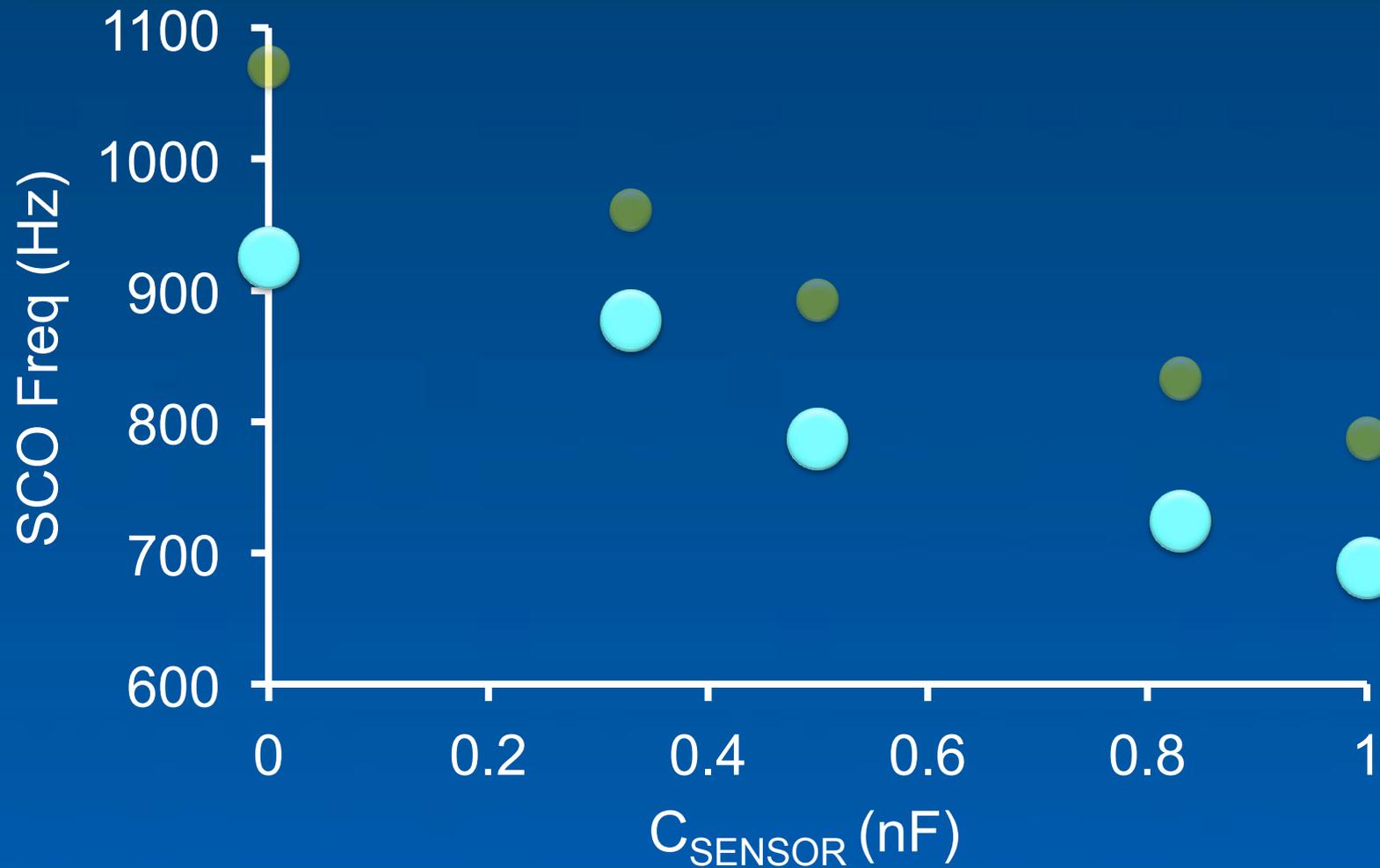
Ring Oscillator Performance

Multiple SCOs



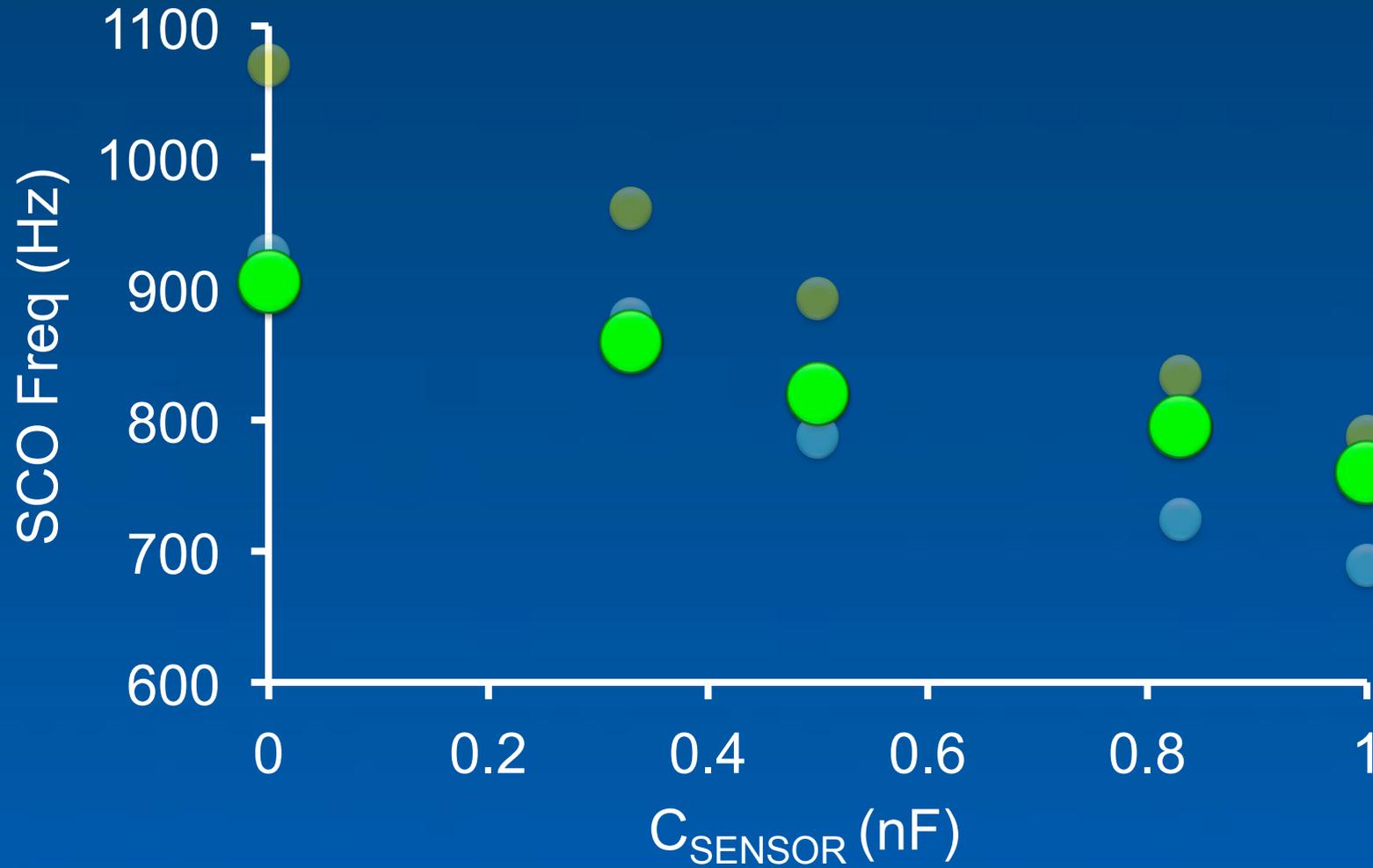
Ring Oscillator Performance

Multiple SCOs



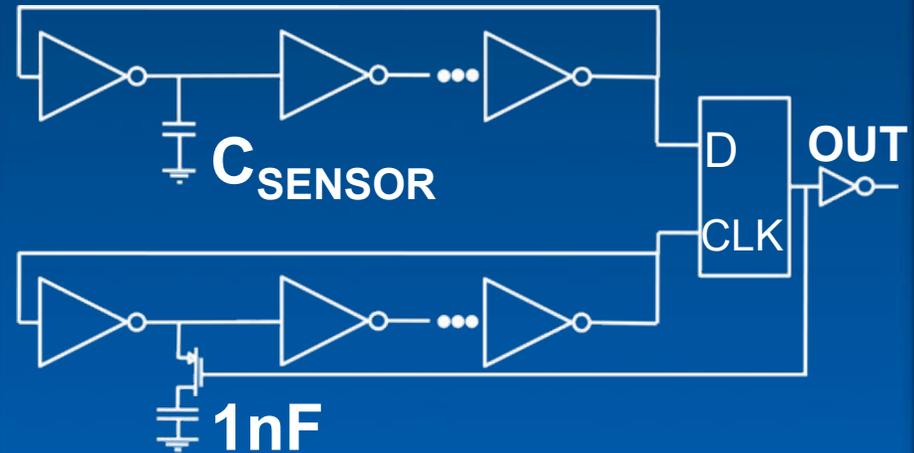
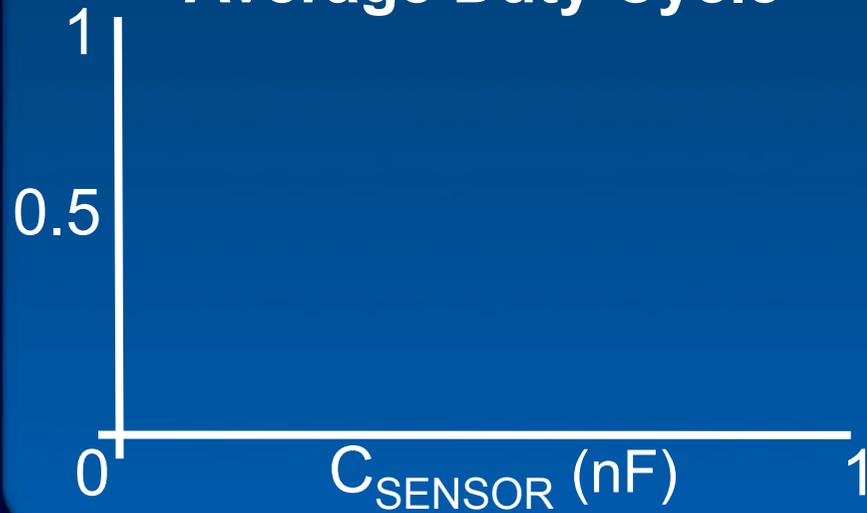
Ring Oscillator Performance

Multiple SCOs

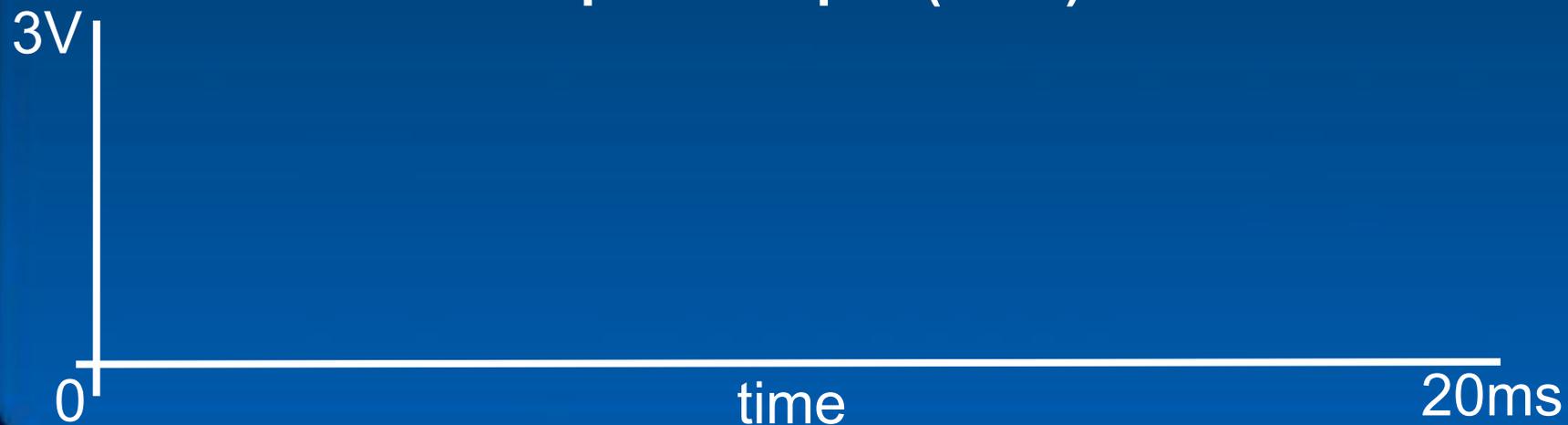


Ring Oscillator Performance

Average Duty Cycle

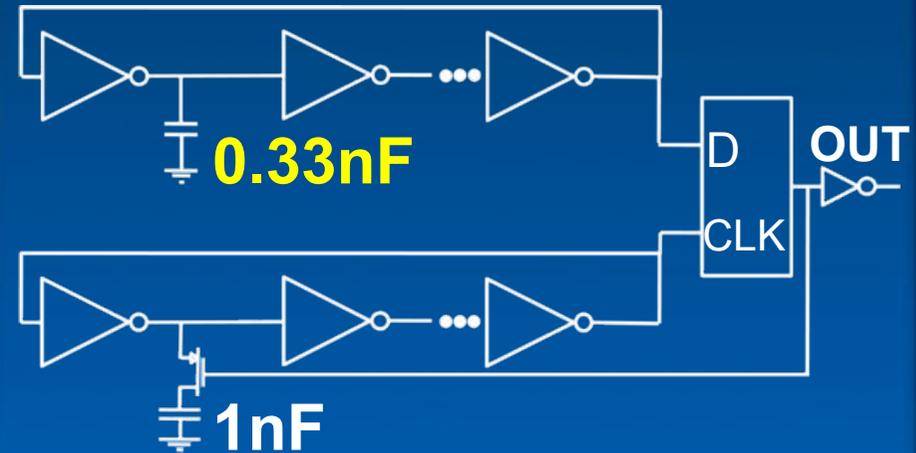
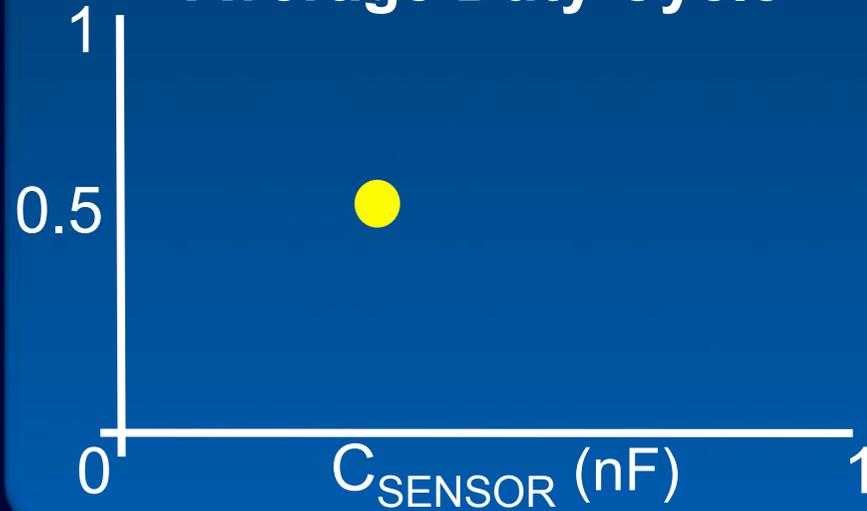


Sampled Output (OUT)

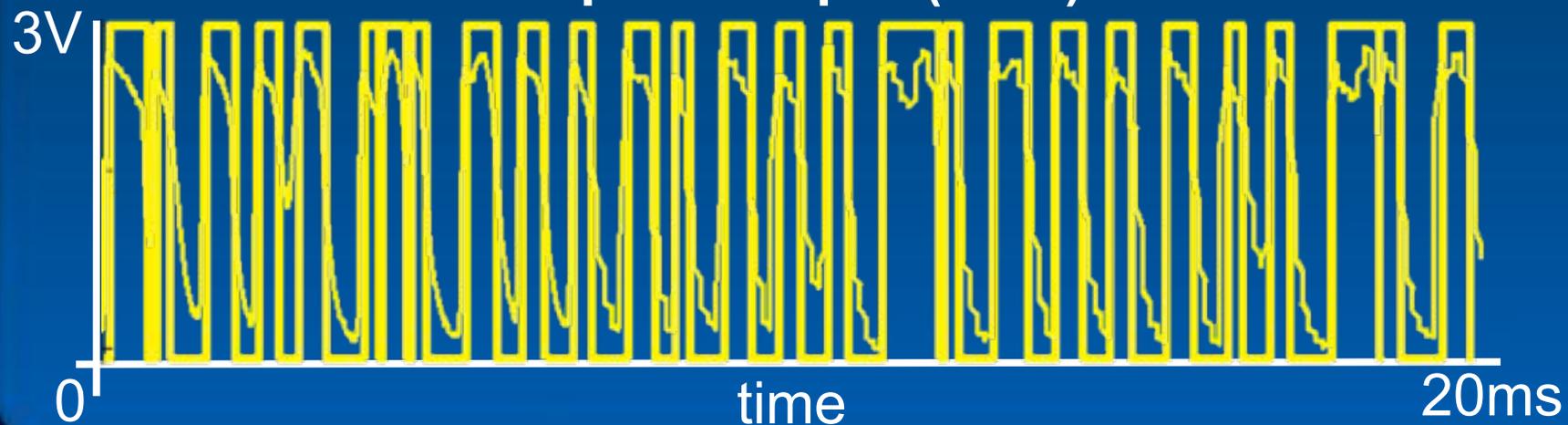


Ring Oscillator Performance

Average Duty Cycle

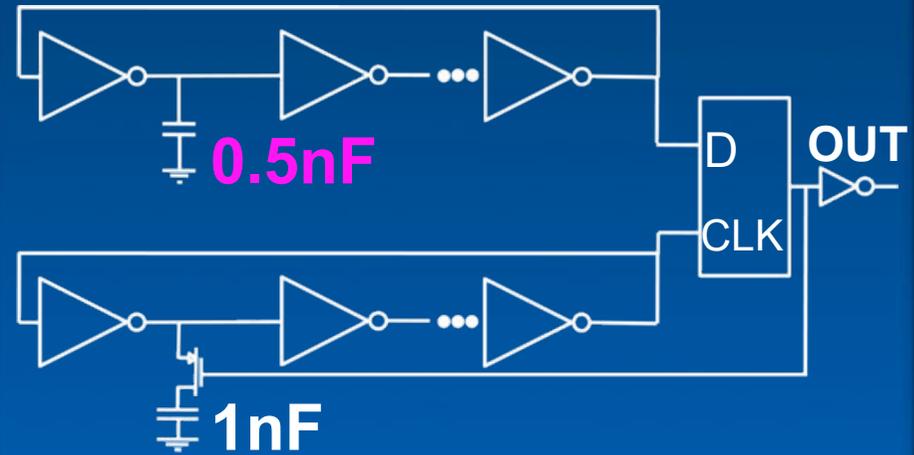
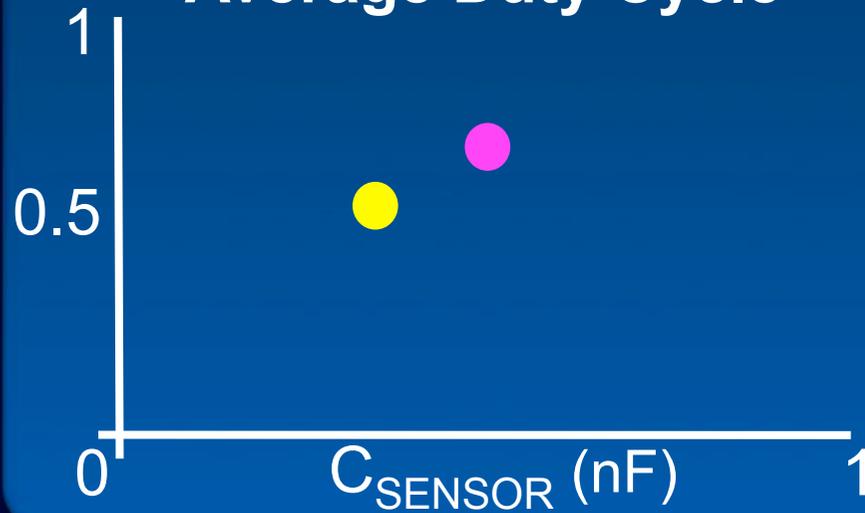


Sampled Output (OUT)

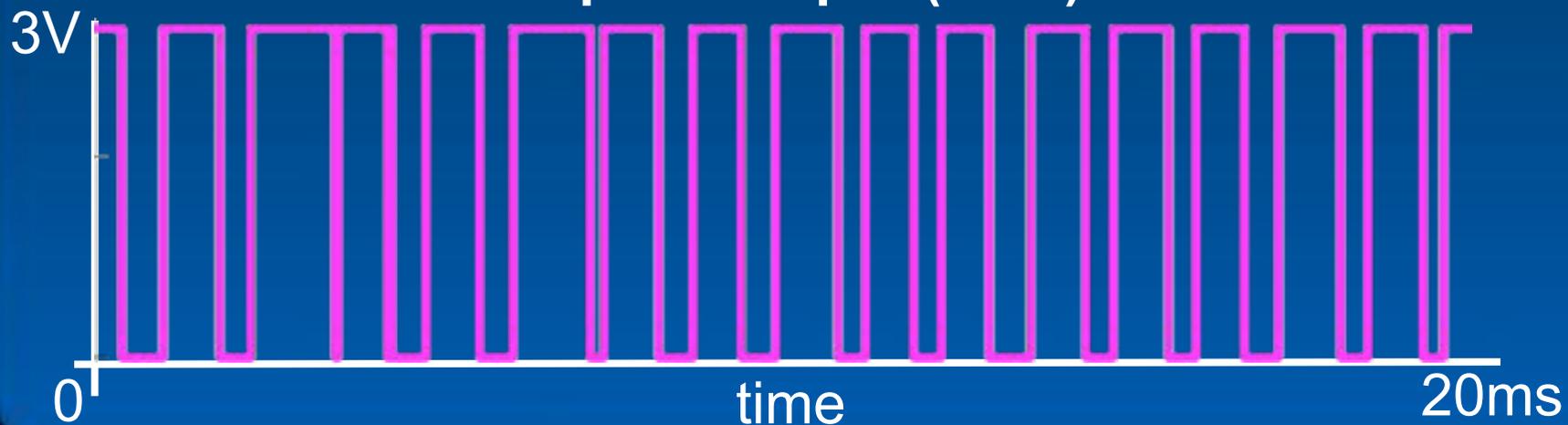


Ring Oscillator Performance

Average Duty Cycle

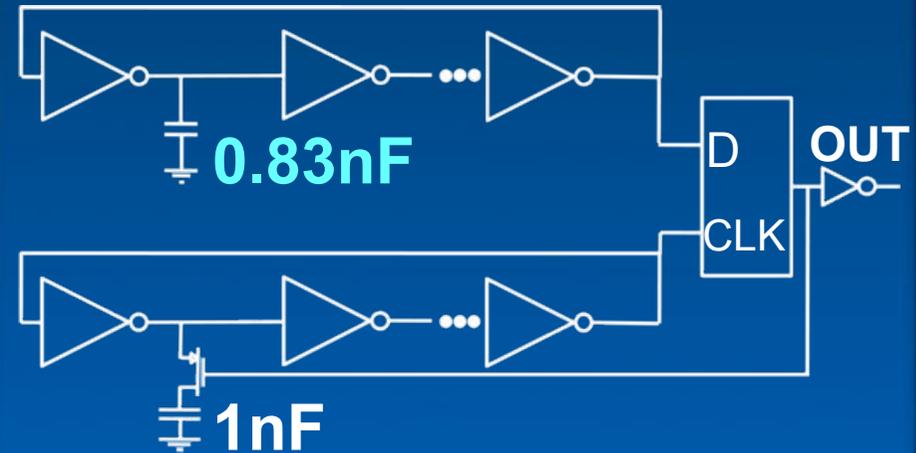
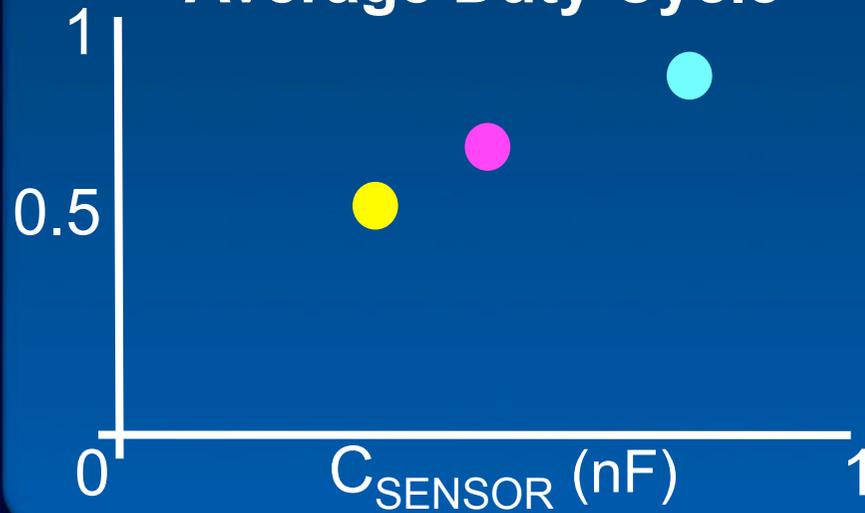


Sampled Output (OUT)

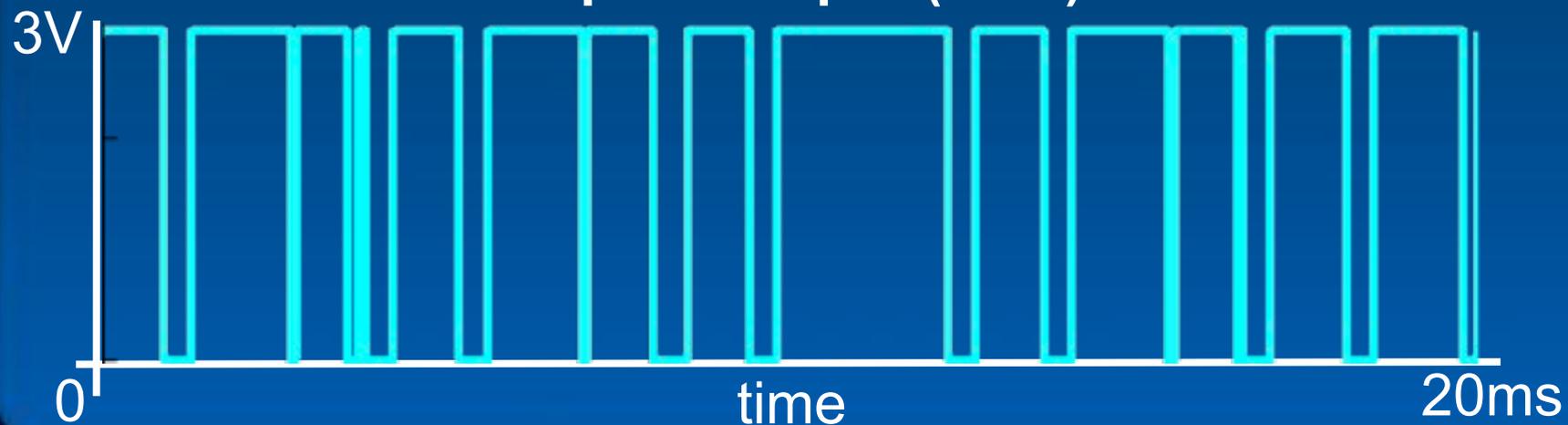


Ring Oscillator Performance

Average Duty Cycle

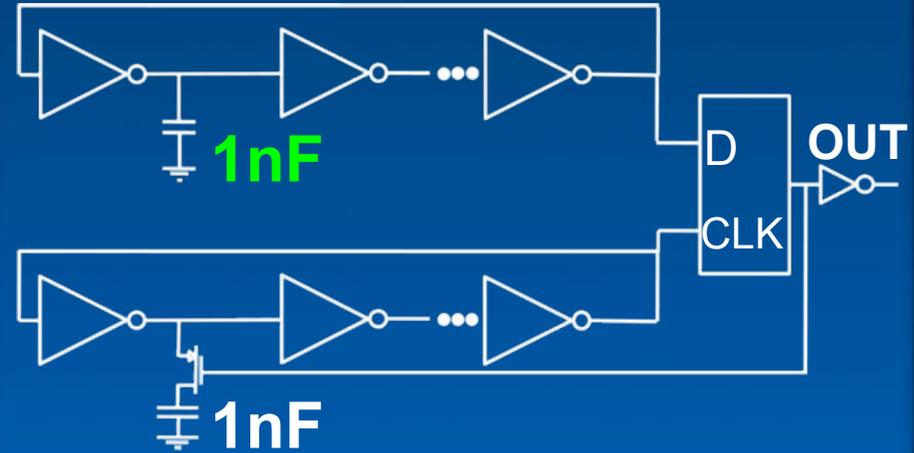
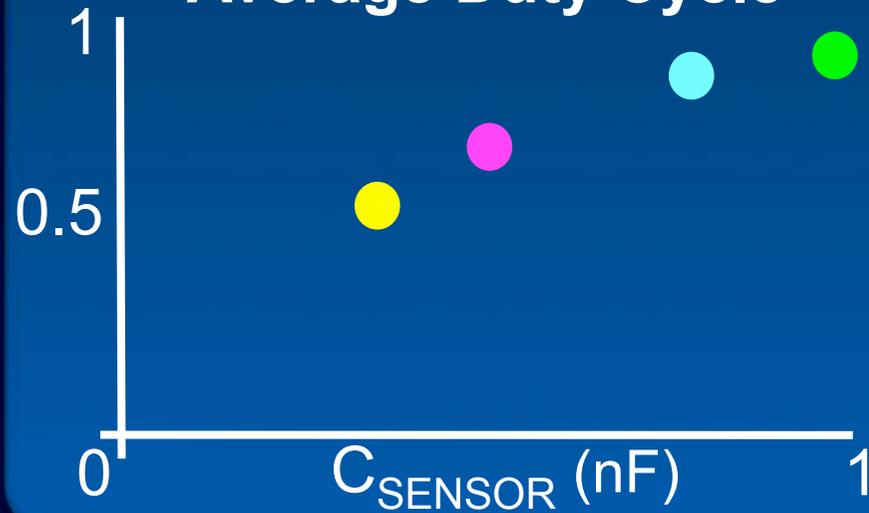


Sampled Output (OUT)

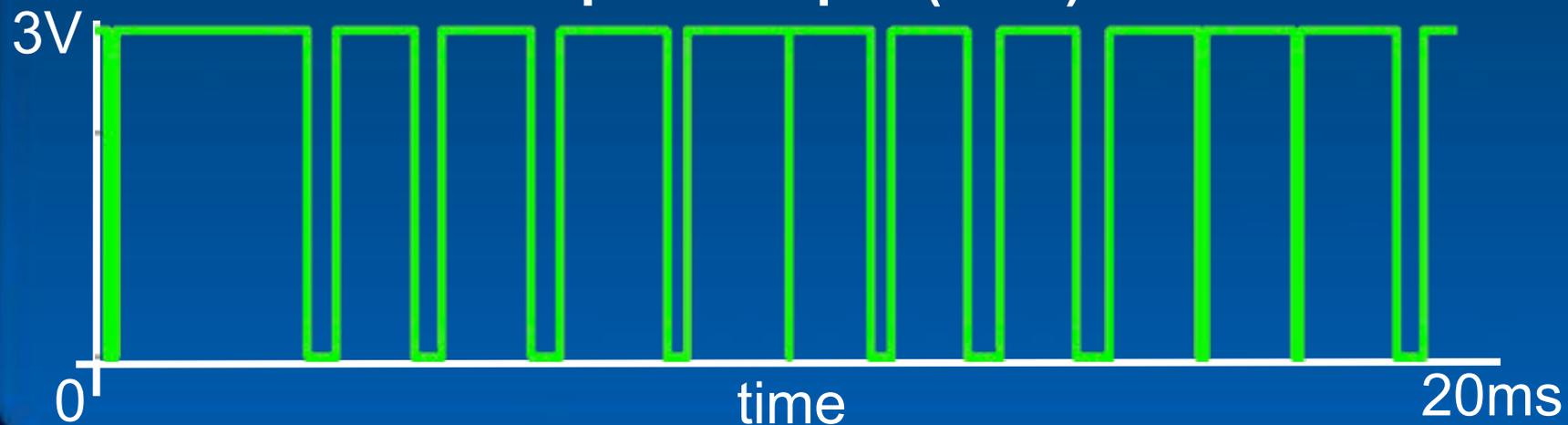


Ring Oscillator Performance

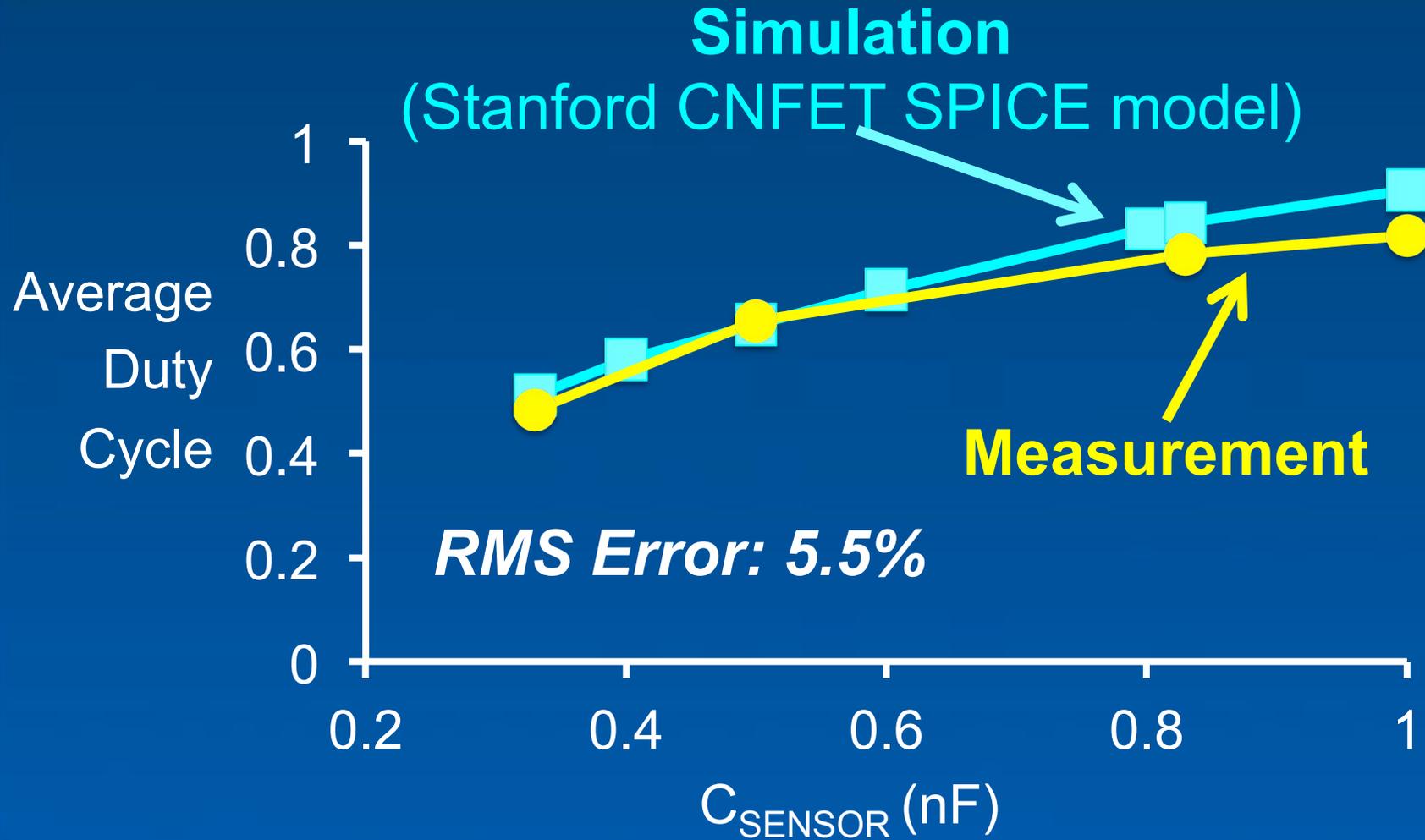
Average Duty Cycle



Sampled Output (OUT)

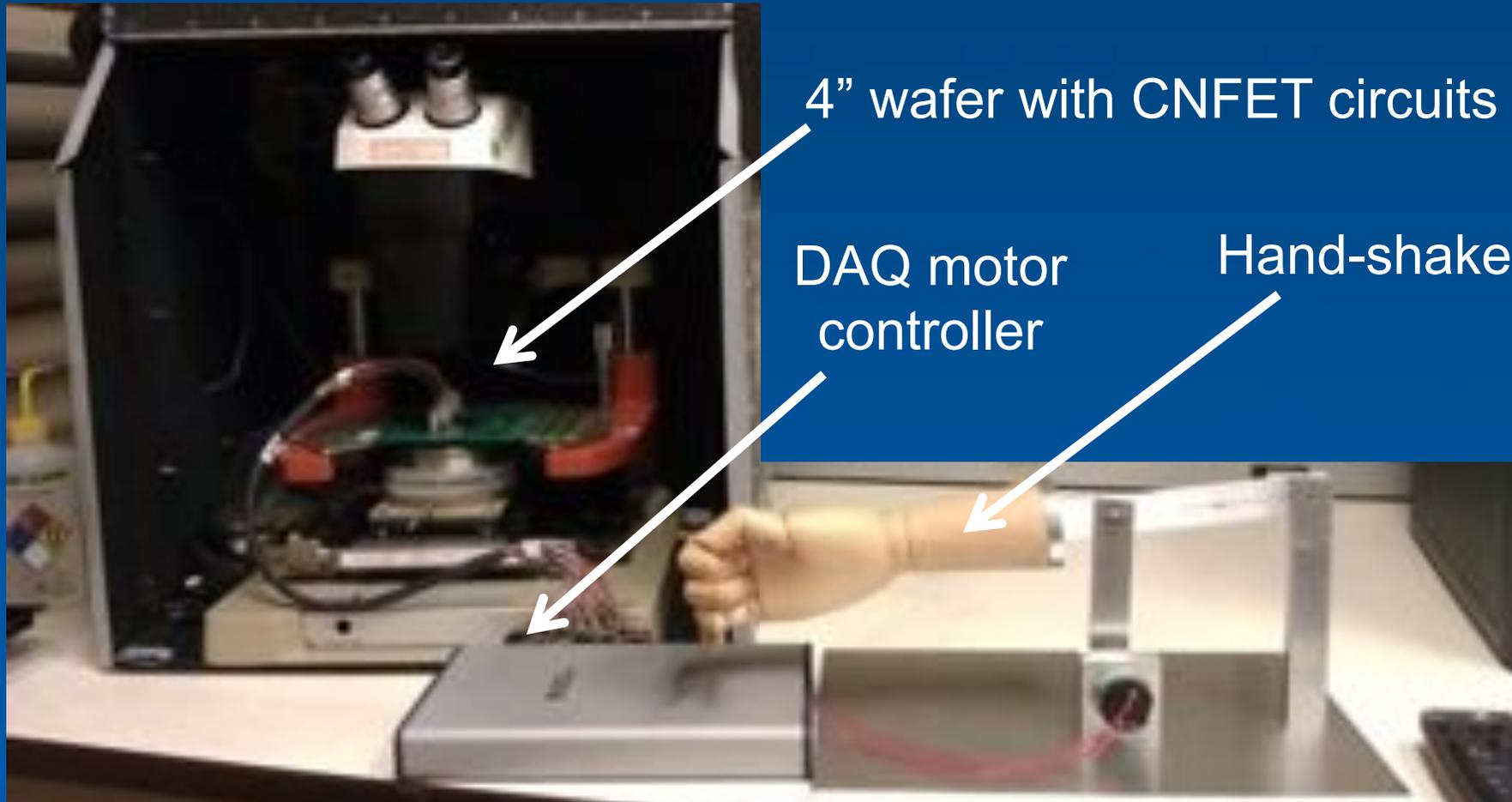


Sensor Interface Results



Sensor Interface Demonstration

Sacha: Stanford Carbon Nanotube Controlled Hand-shaker



Moving Forward

- High energy efficiency
 - CNT density
 - CNT contact resistance
 - CNT doping
- CNT variations: unique opportunities
 - CNFET correlation by layout

Conclusion

- **First demonstration**
 - sub-system built entirely using CNFETs
- **Enabled by**
 - Imperfection immune design
 - Robust CNFET processing
 - Fully digital