Sacha:

Stanford Carbon Nanotube Controlled Handshaking Robot

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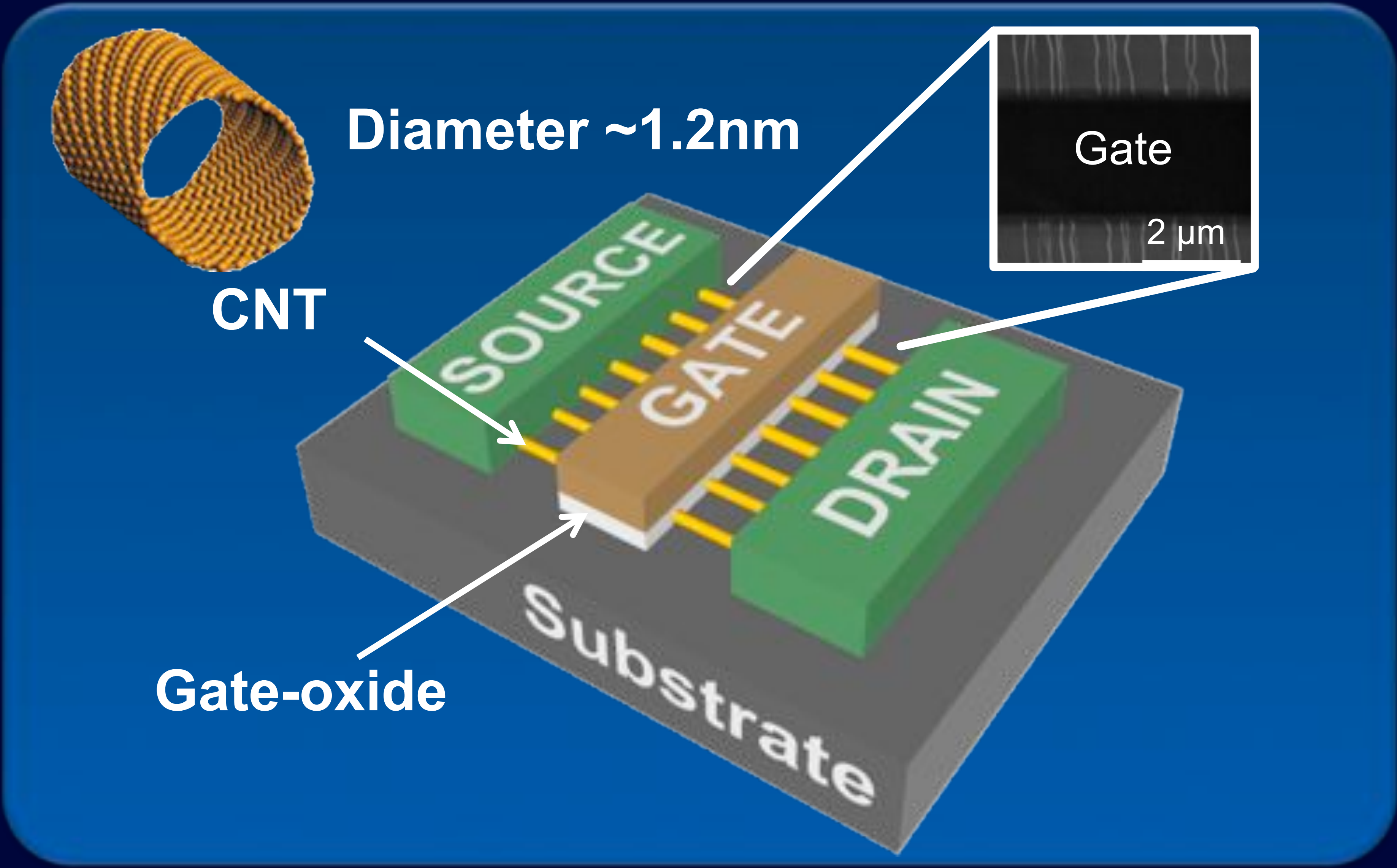
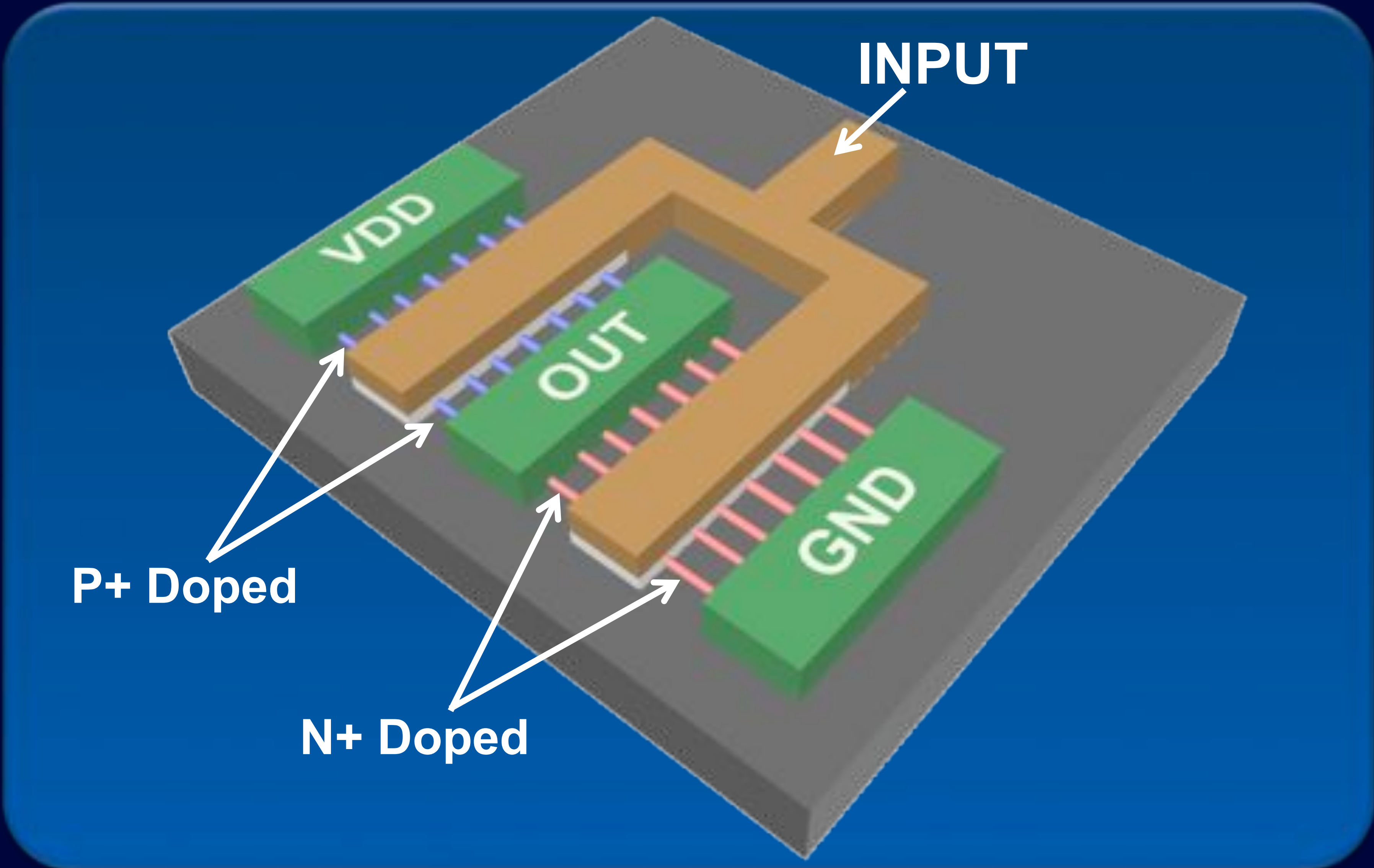
Stanford University

KU Leuven

Carbon Nanotube FET (CNFET)



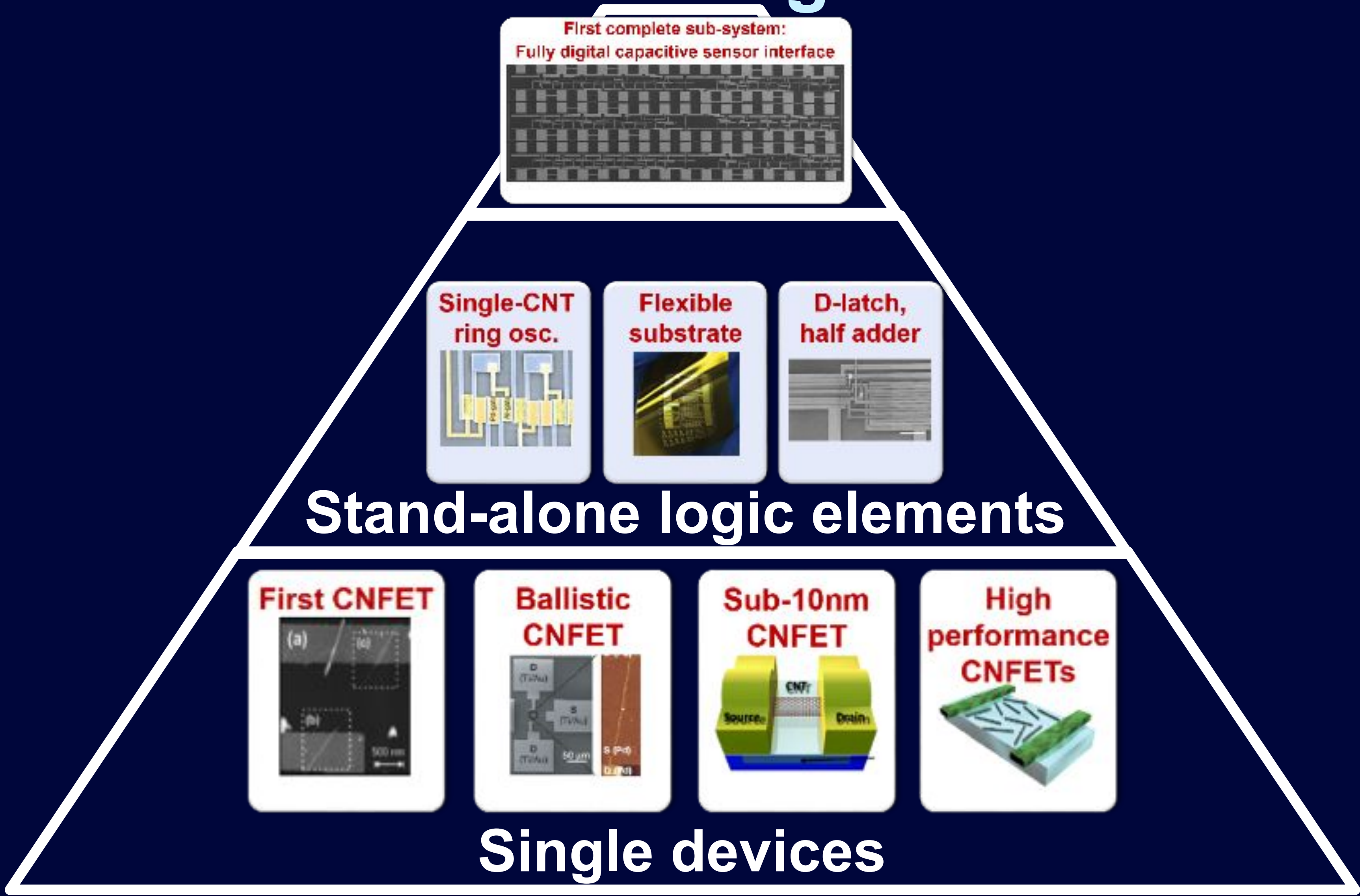
Ideal CNFET Inverter



Why CNFETs?

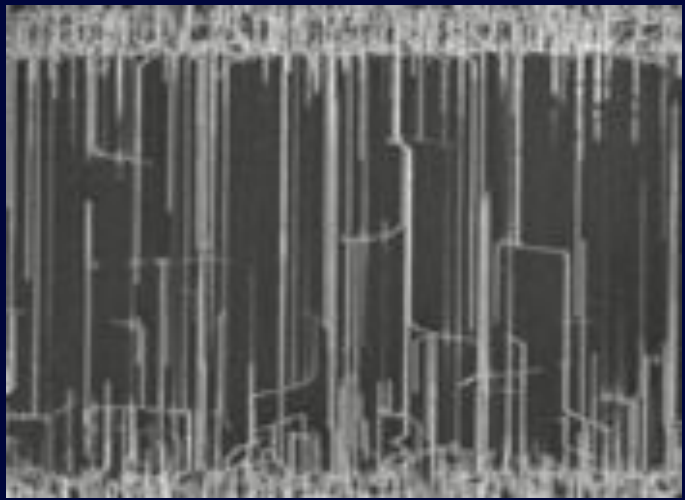
- Best I_{ON}
  - 9nm measurements [Franklin Nano Letters 12]
- 400 mV supply
  - Logic gates [Ding APL 12]
- Major energy-delay-product benefits
  - IBM Power 7 modeled [Chang IEDM 12]

Recent Progress

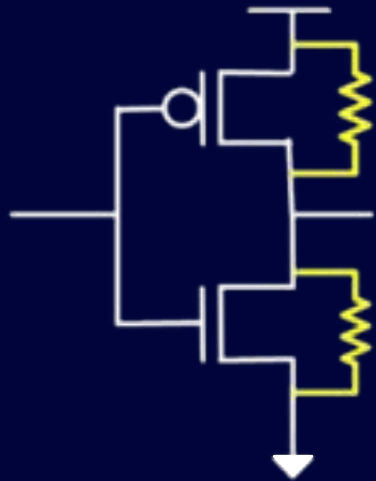


BIG Promise, BUT Major Obstacles

Mis-positioned CNTs



Metallic CNTs



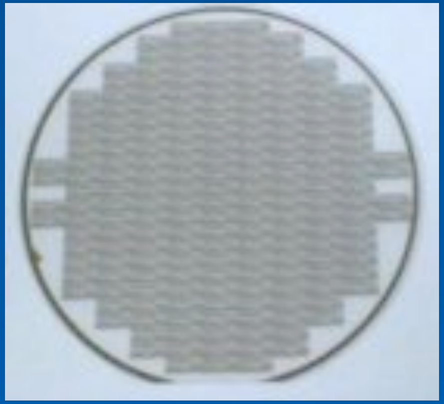
Imperfection-immune design essential

First Wafer-Scale Aligned CNT Growth

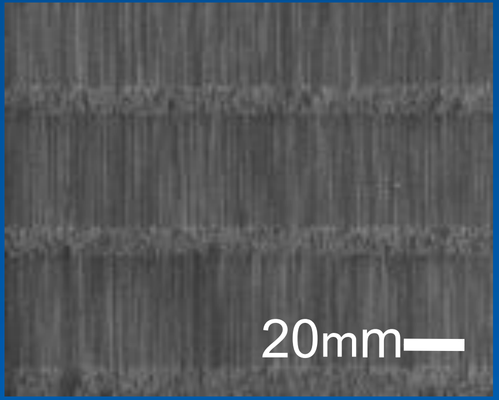
Quartz wafer
with catalyst

Aligned
CNT growth

Quartz wafer with CNTs



99.5% aligned CNTs

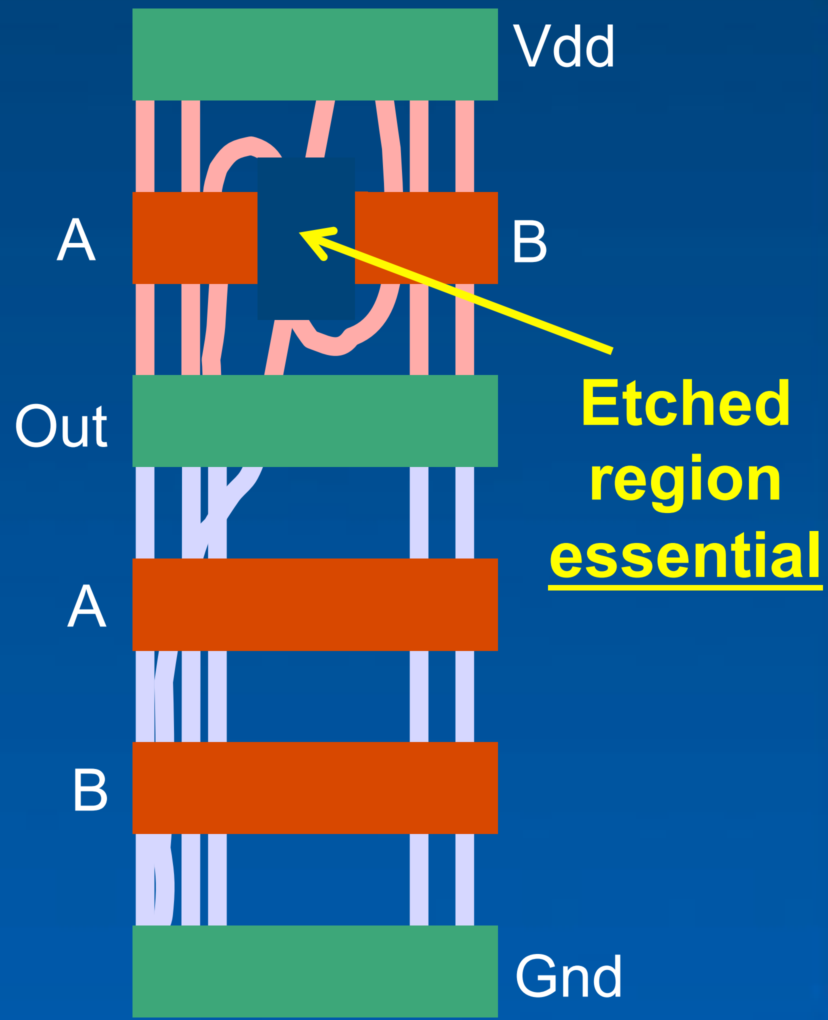


Stanford Nanofabrication Facility

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



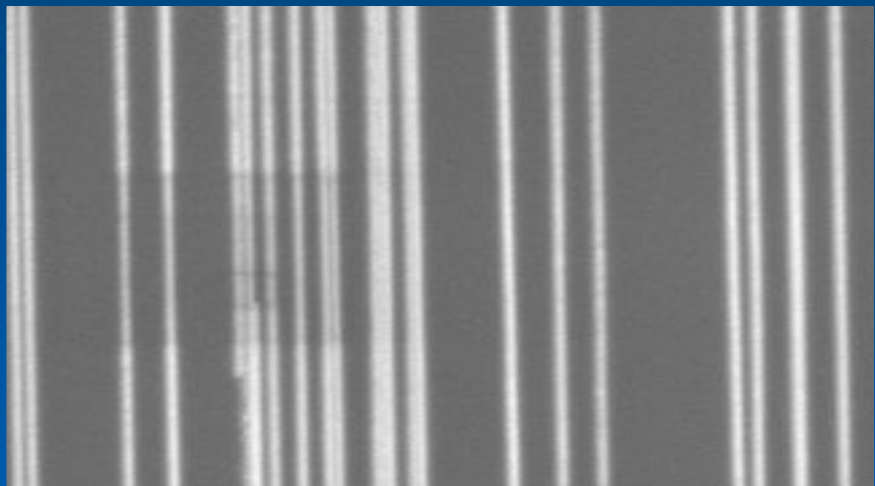
Most Importantly

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

m-CNT Removal

- **V**LSI **M**etallic CNT **R**emoval
  - Universally effective
    - All logic designs
  - VLSI processing & design flows

Chip-Scale Electrical Breakdown



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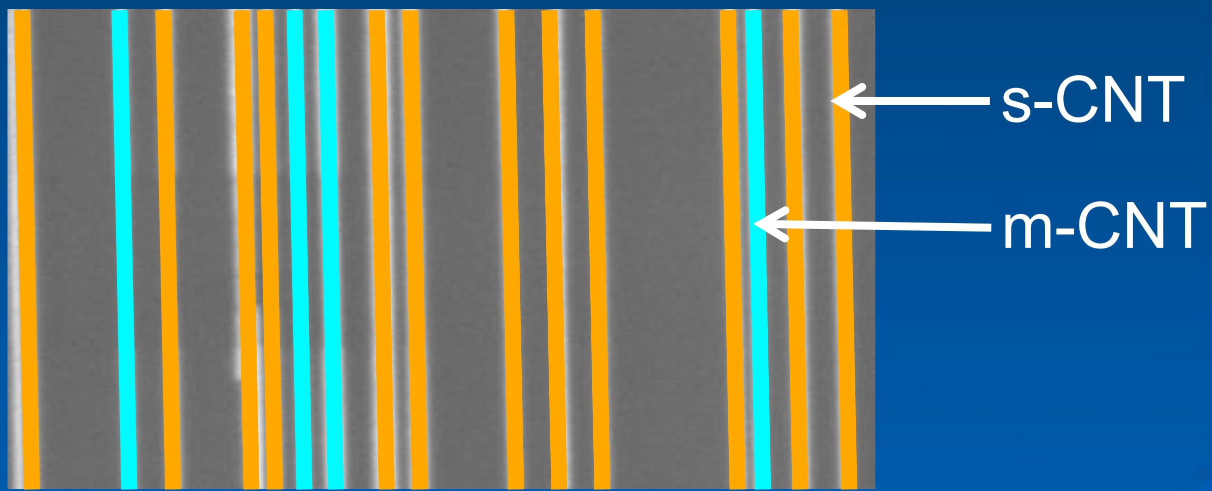

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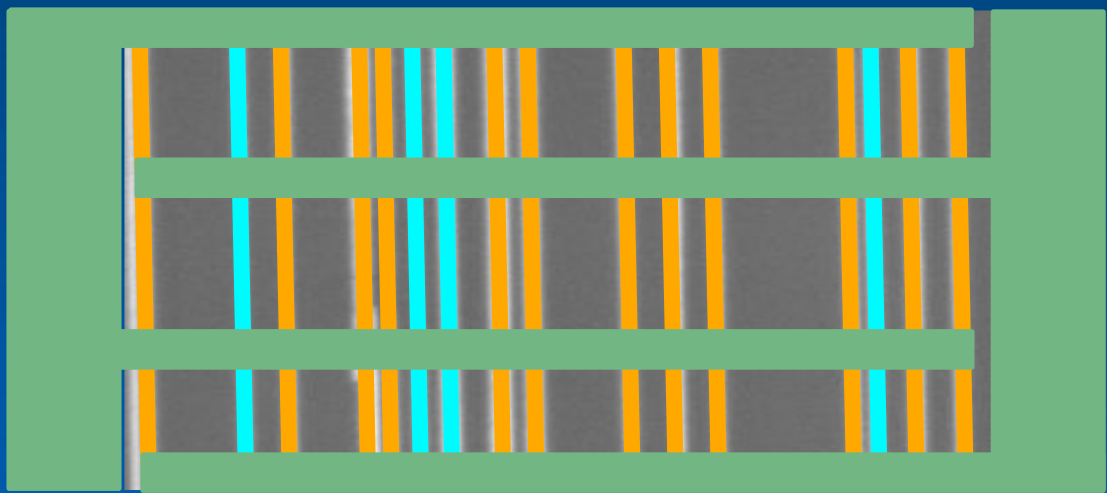
Fabricate VMR electrodes



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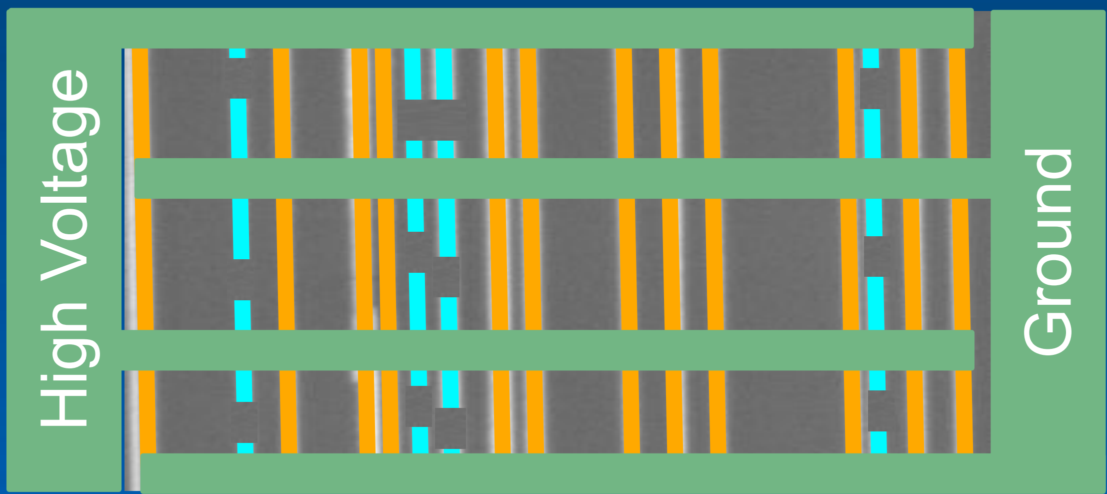
Electrical Breakdown (back-gate)



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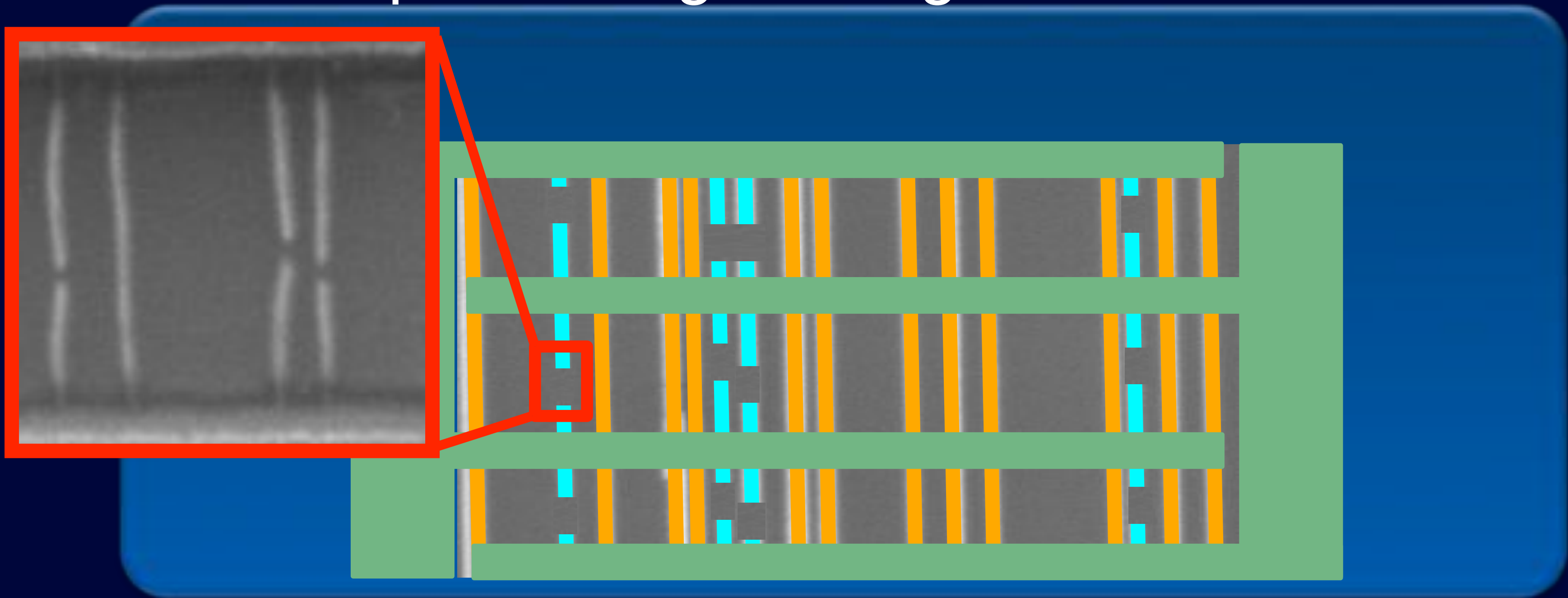

m-CNT Removal

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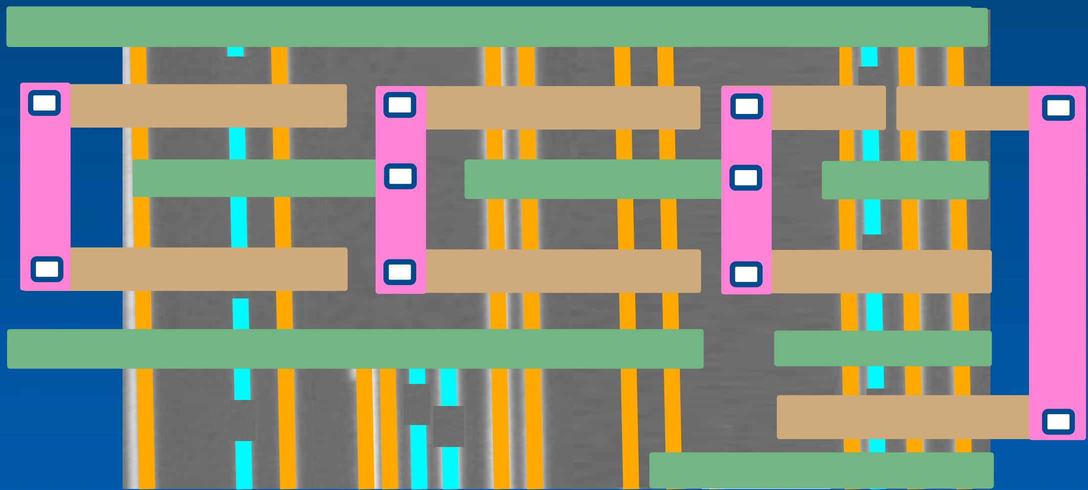
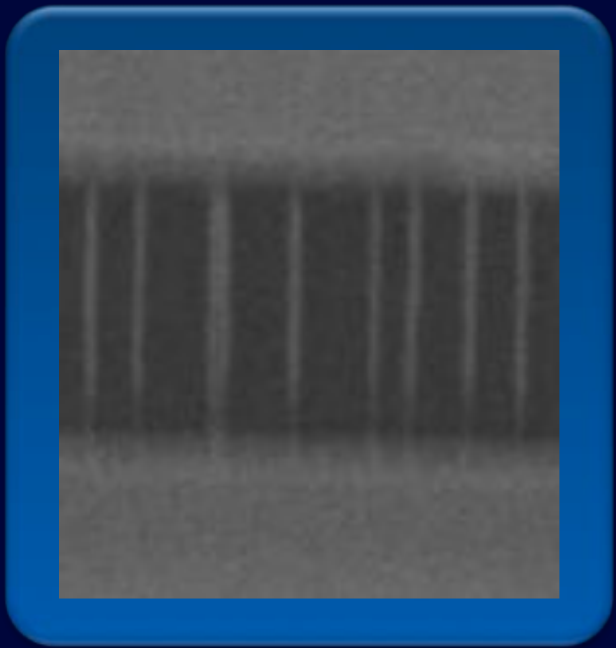
Top-gates (mis-positioned CNT-immune layout), wires



VMR Performance

m-CNT vs. s-CNT selectivity



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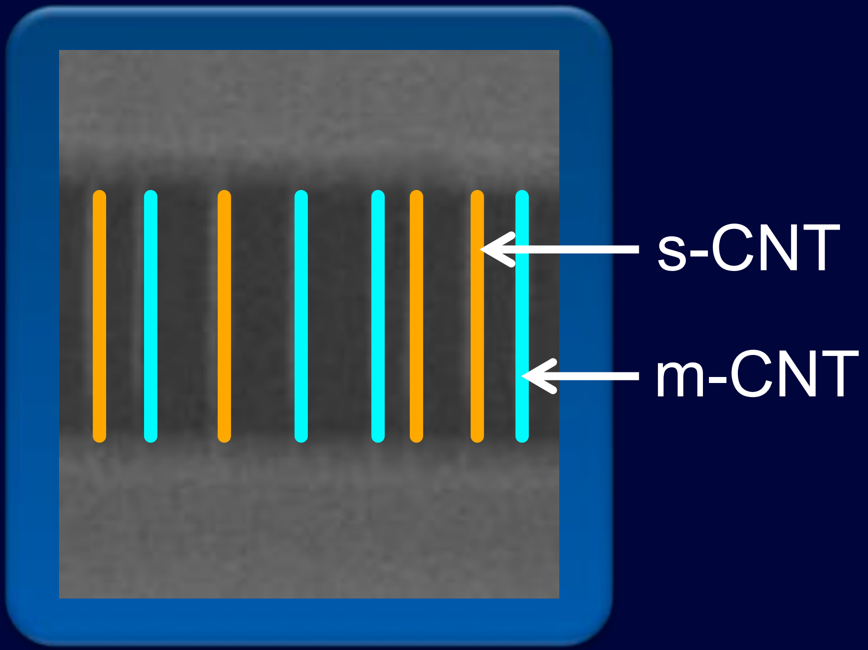

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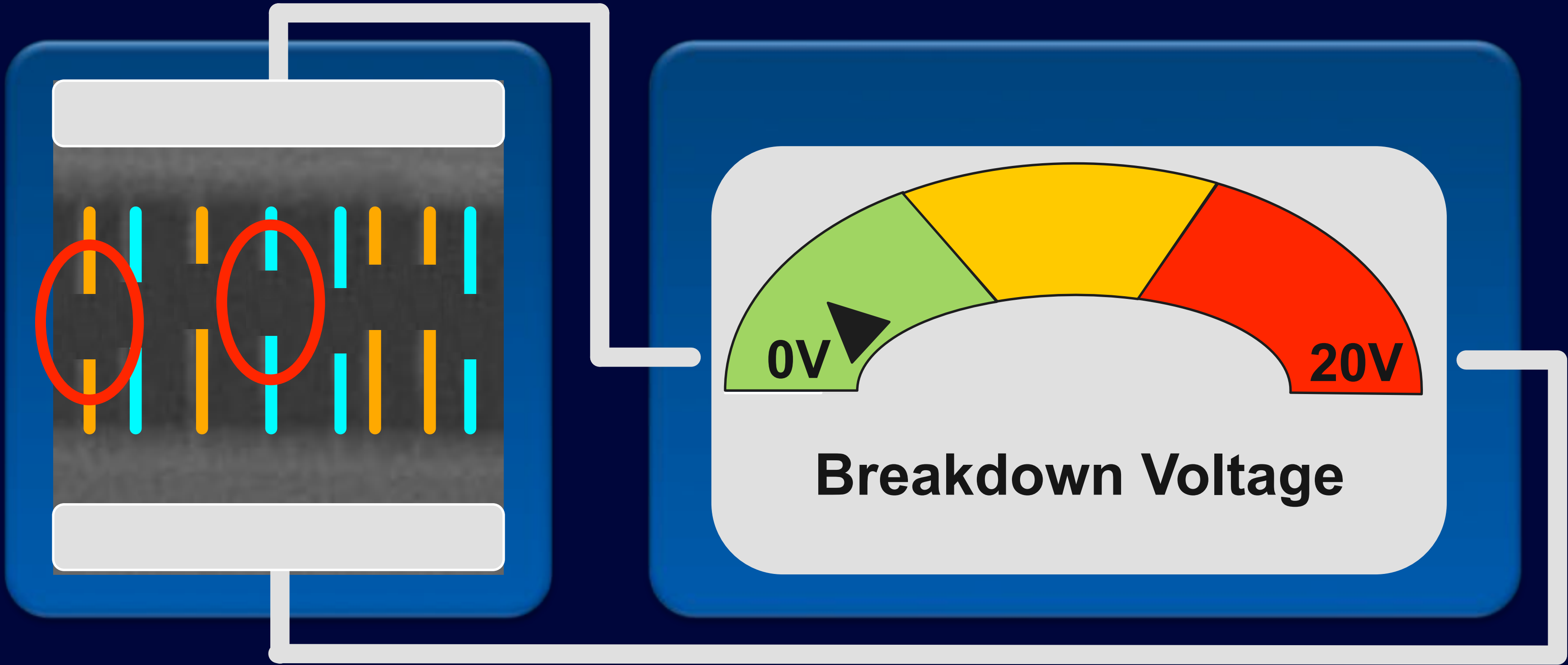

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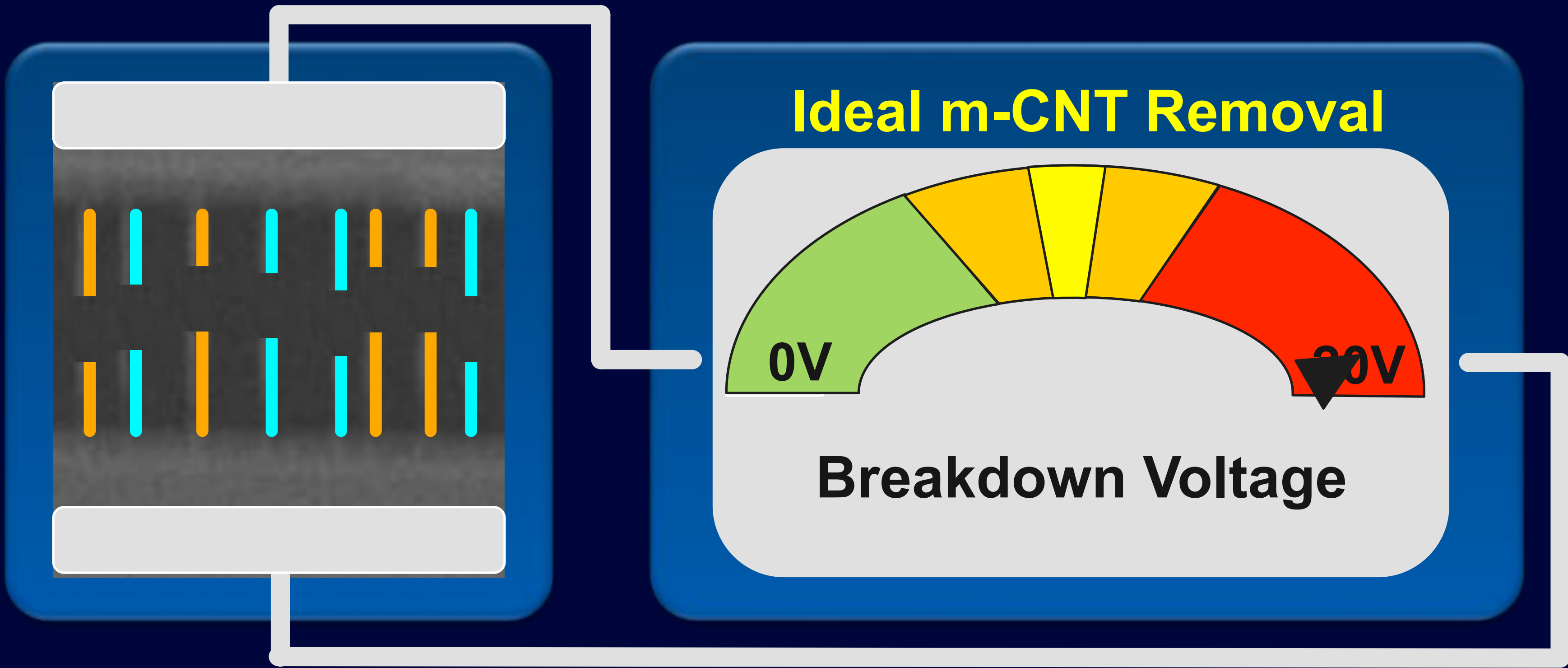
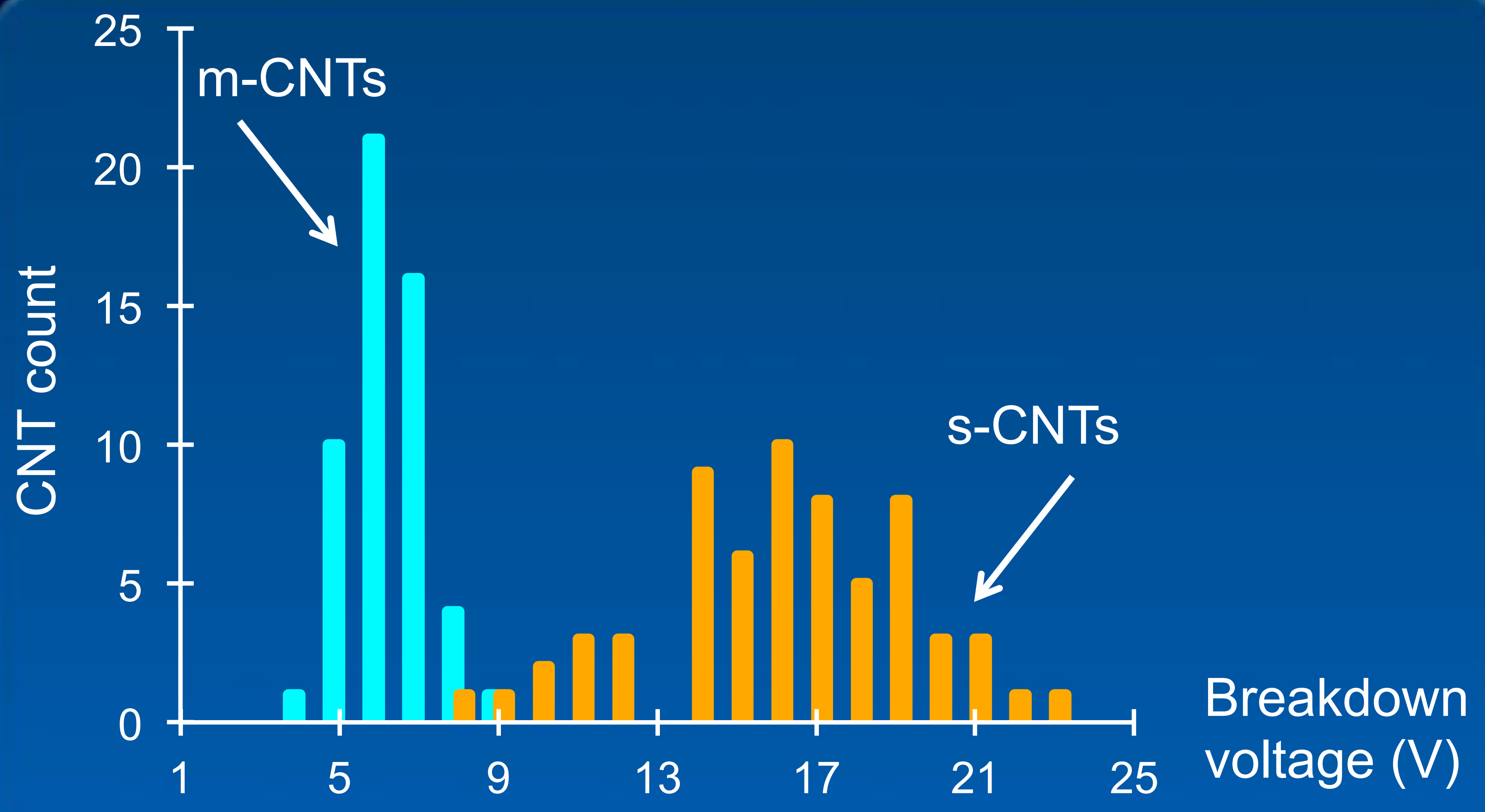


VMR Performance

Experimental Distribution



VMR Performance

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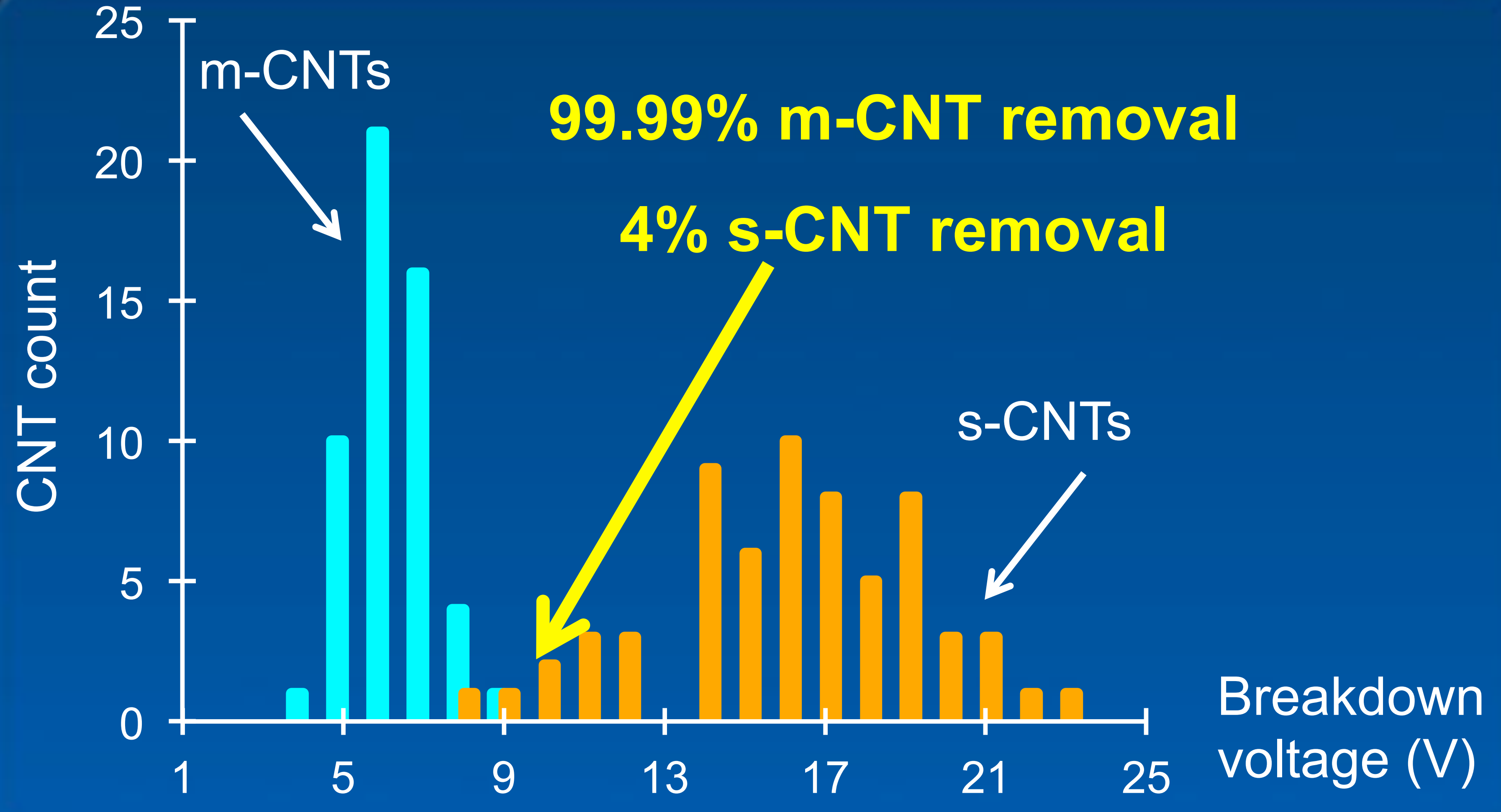
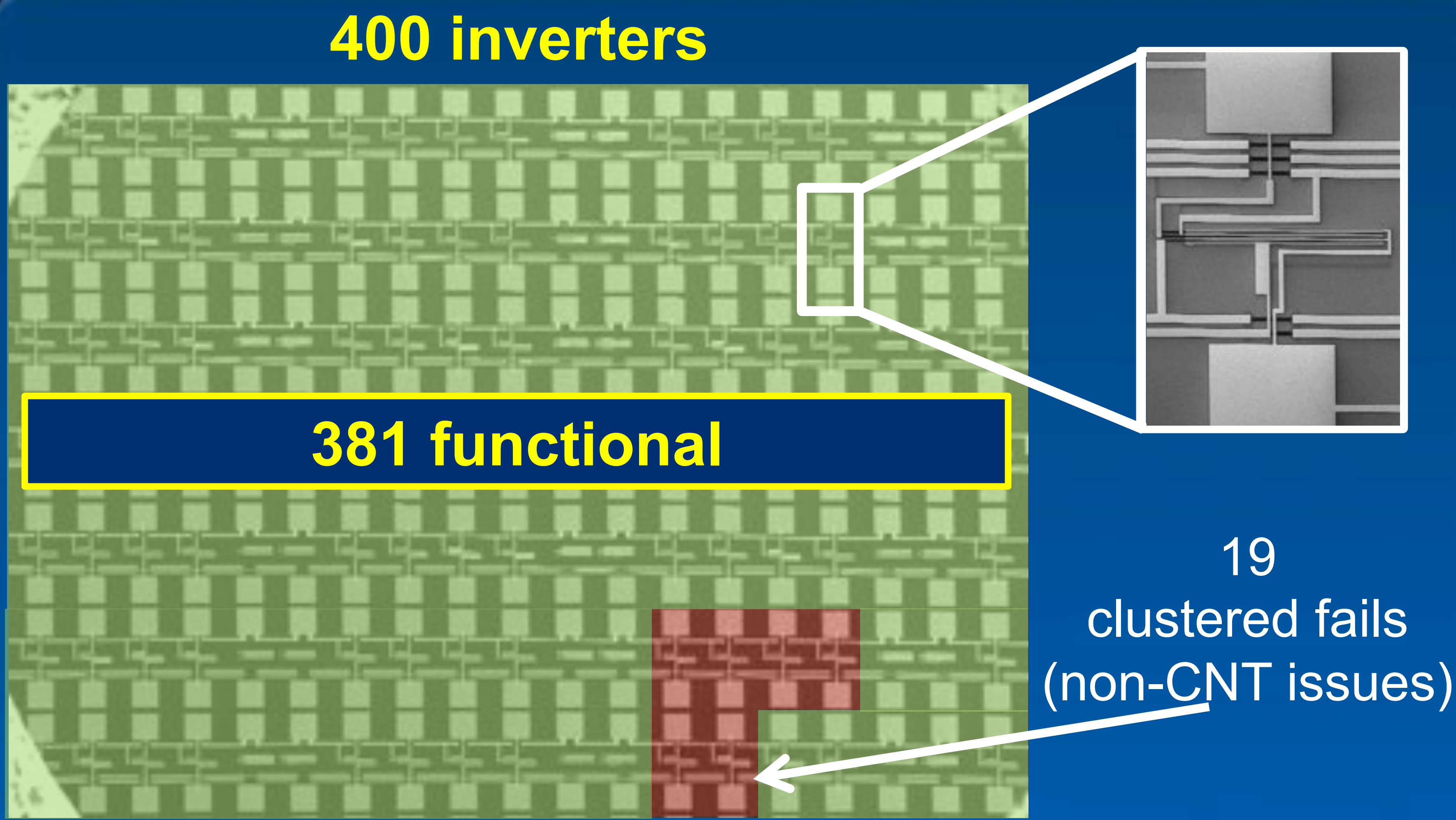


Circuit Robustness



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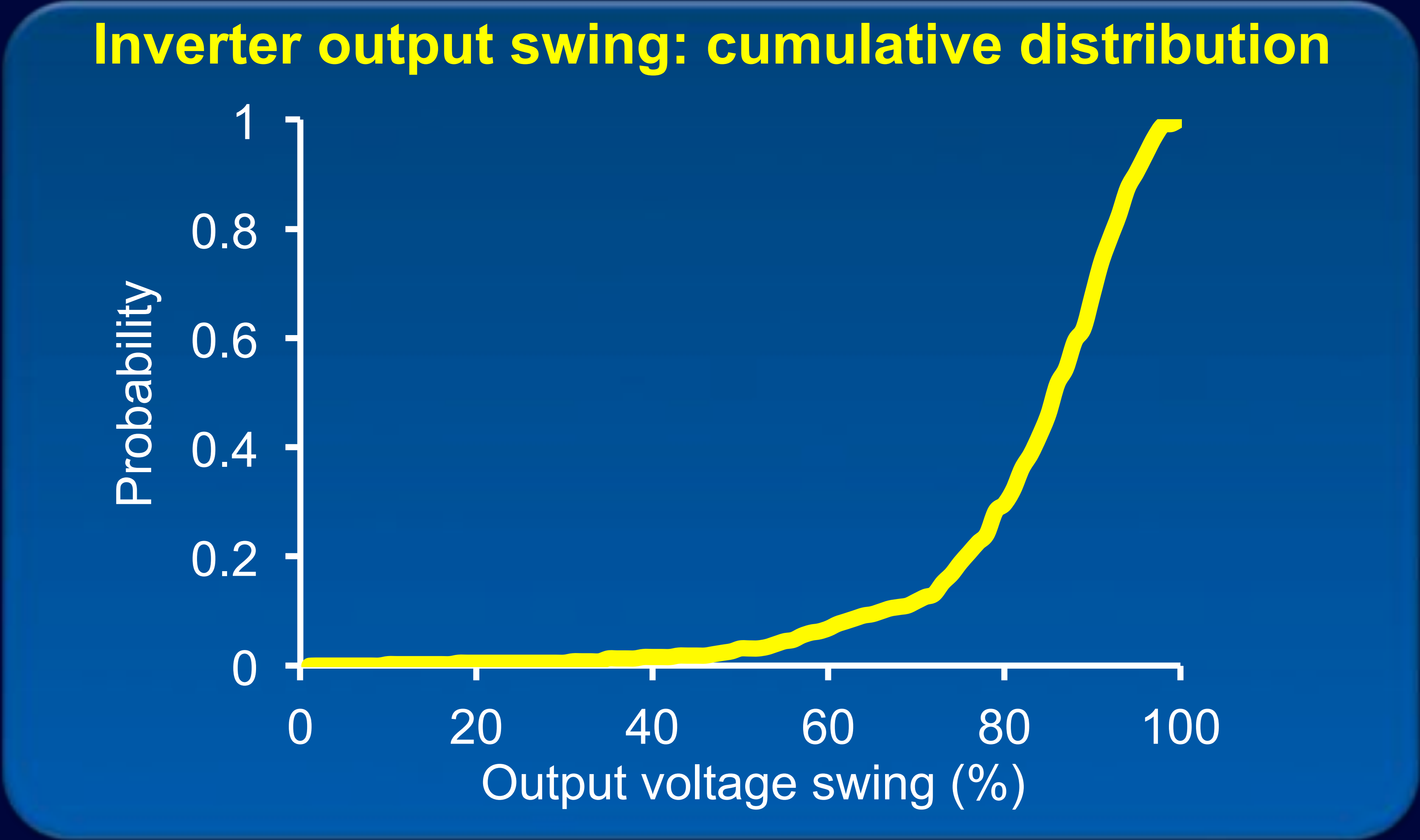
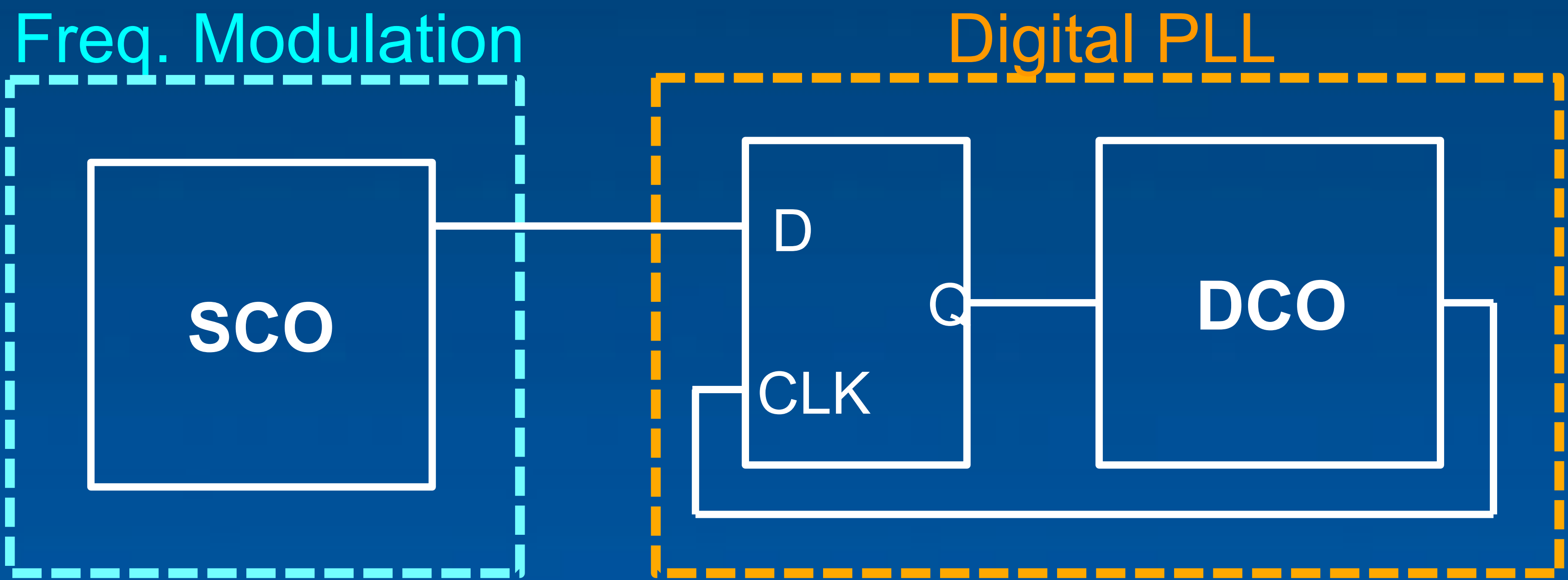


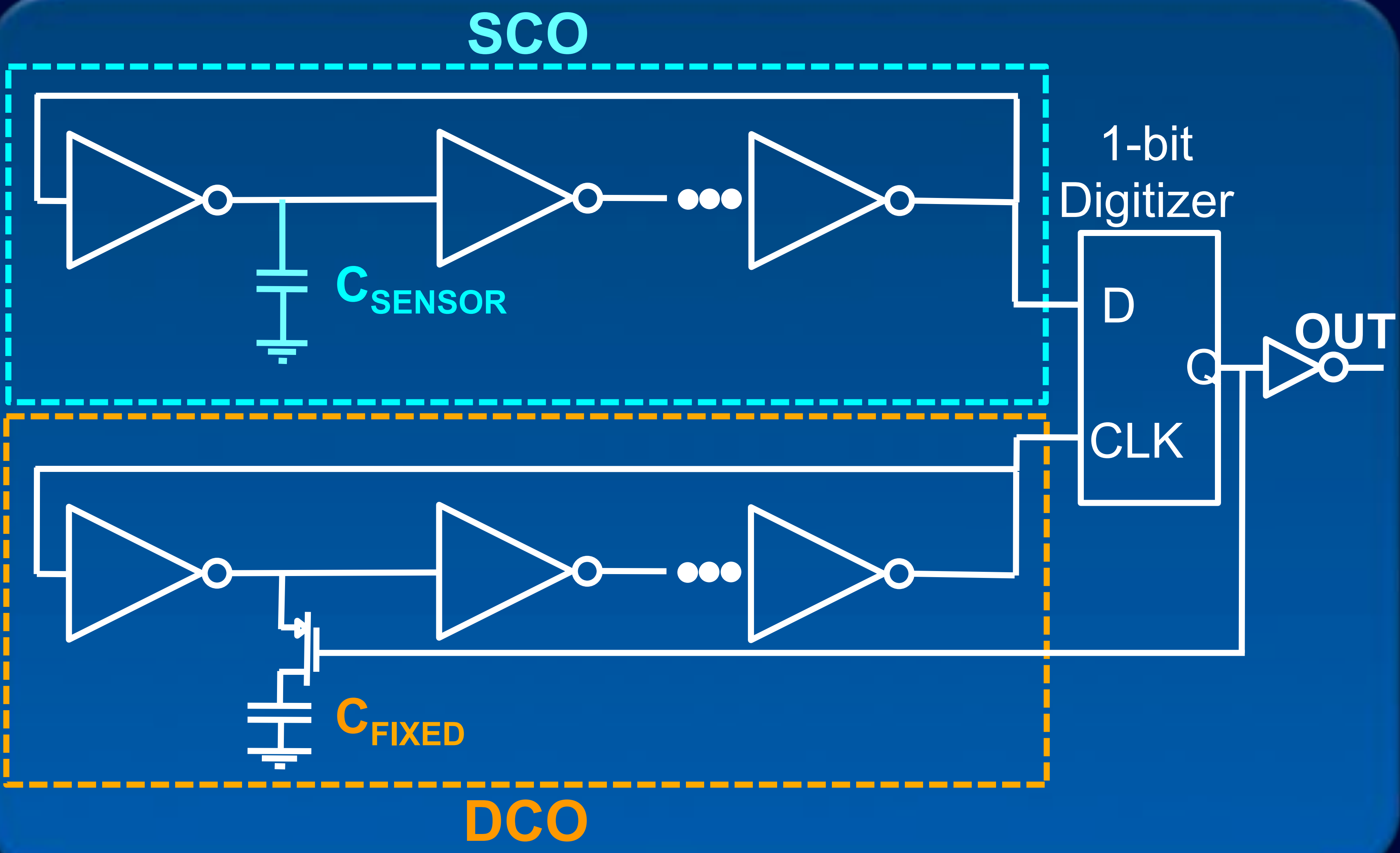
Complete Sub-System

Complete Capacitive Sensor Interface

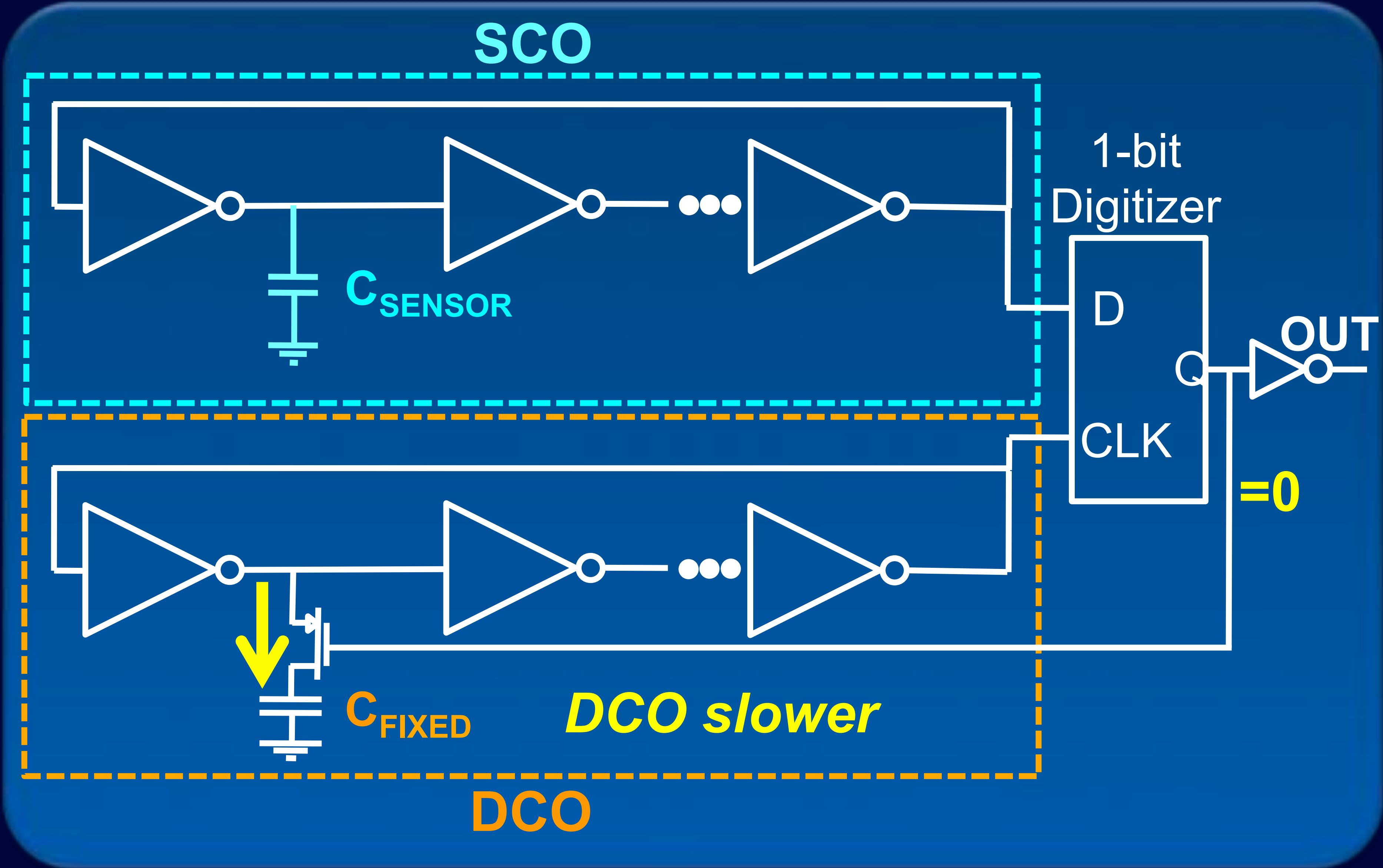


SCO = Sensor-controlled oscillator
DCO = Digitally-controlled oscillator

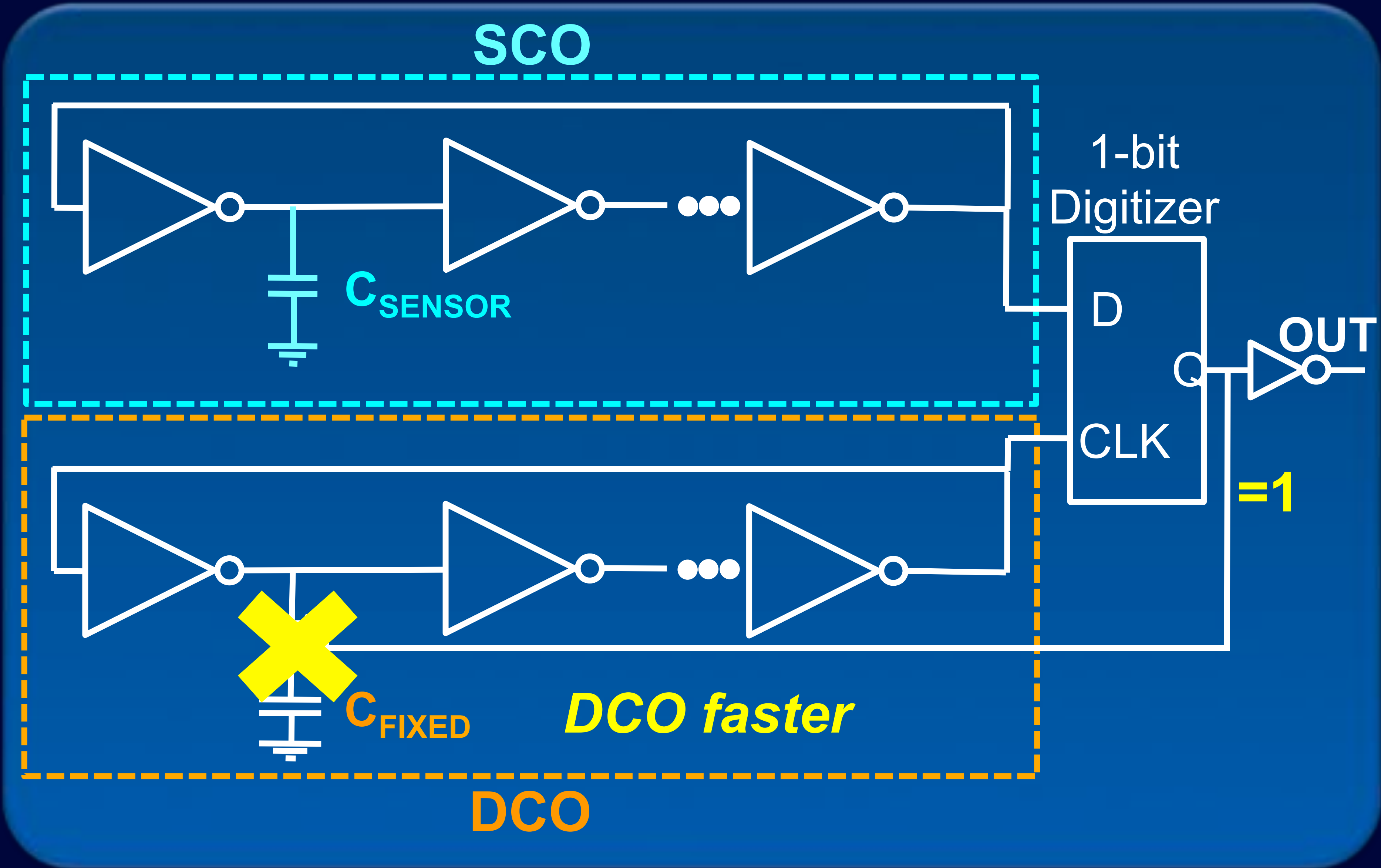
Capacitive Sensor Interface



Circuit Operation

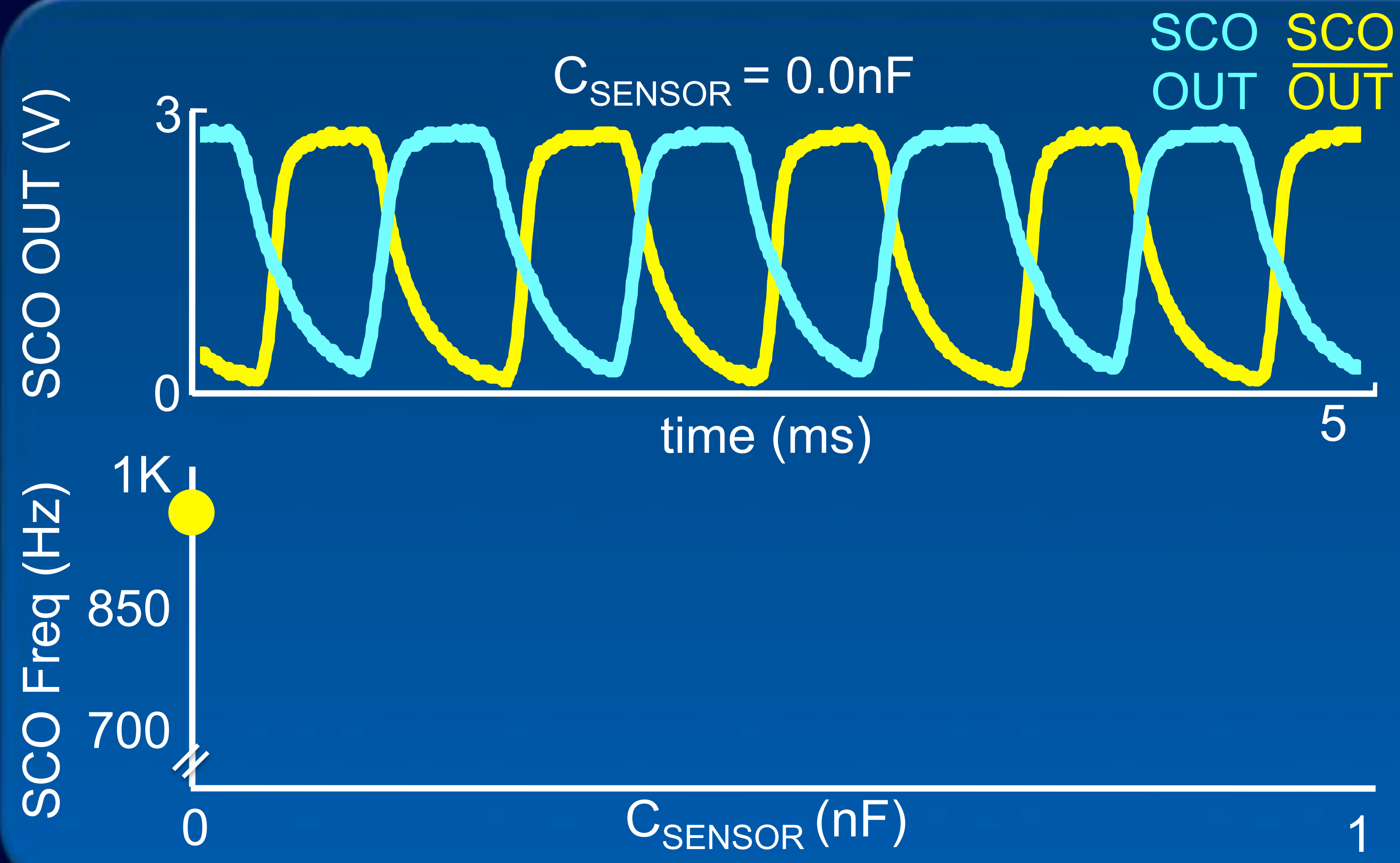


Circuit Operation



Ring Oscillator Performance

SCO vs. C_{SENSOR}



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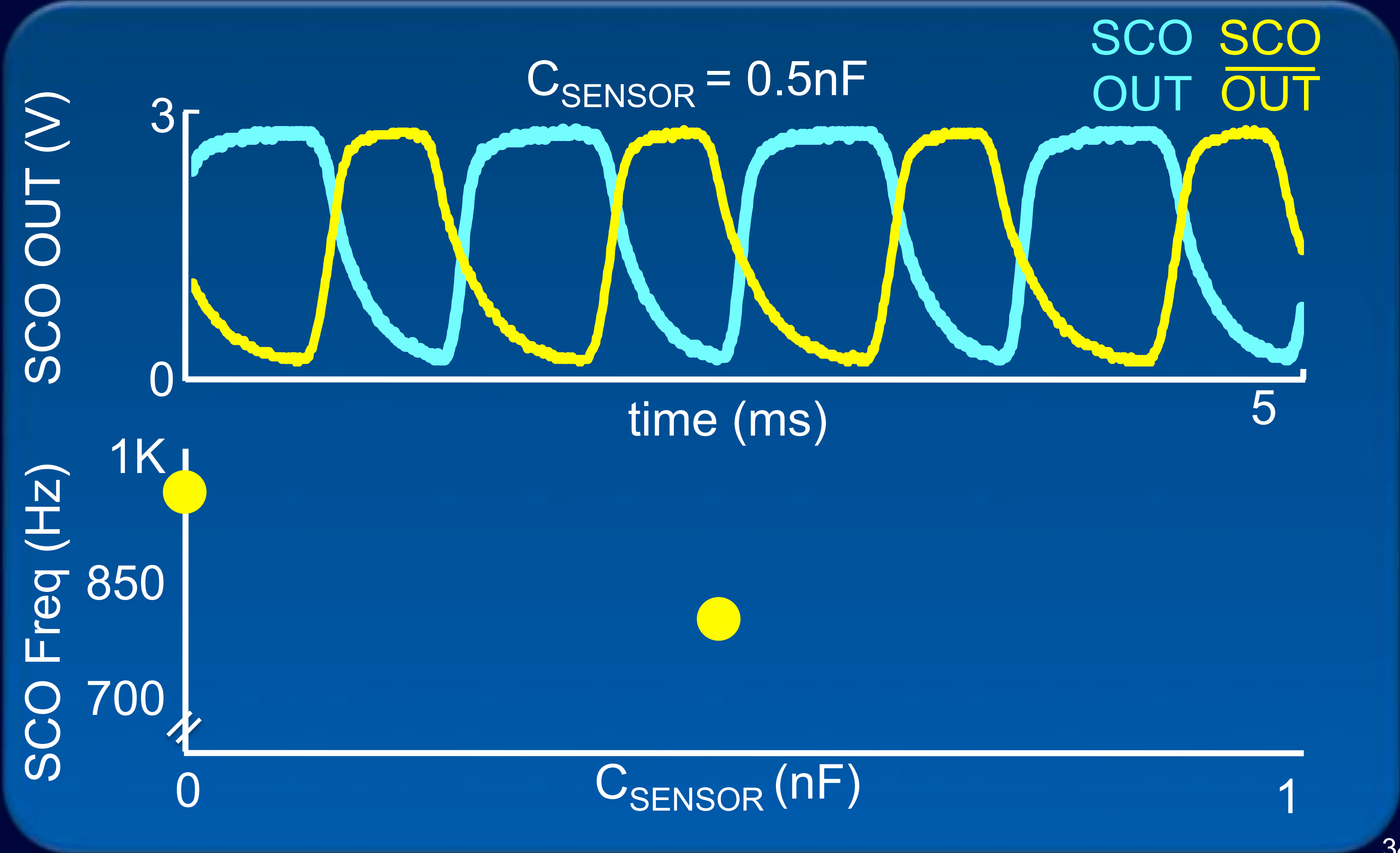

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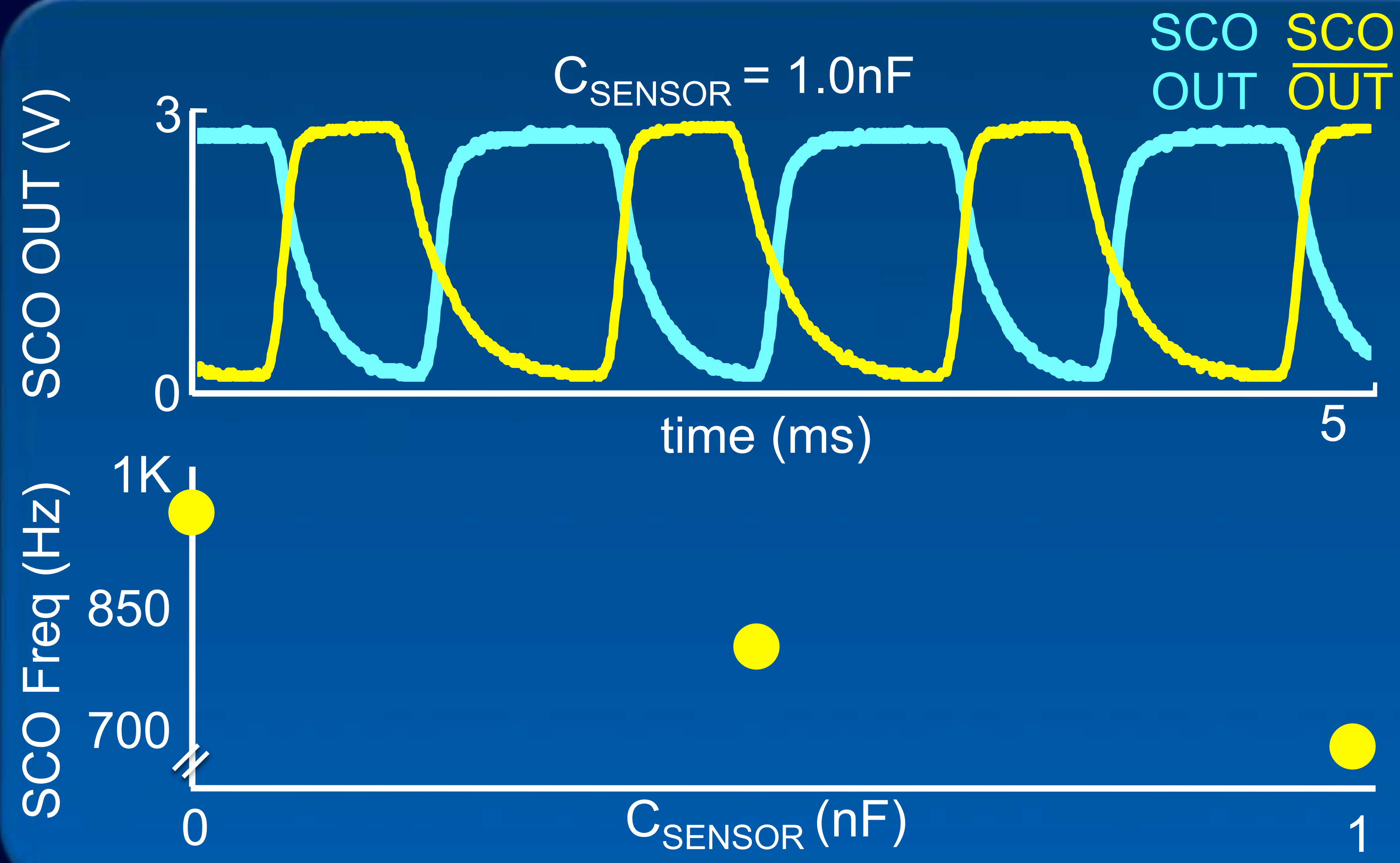
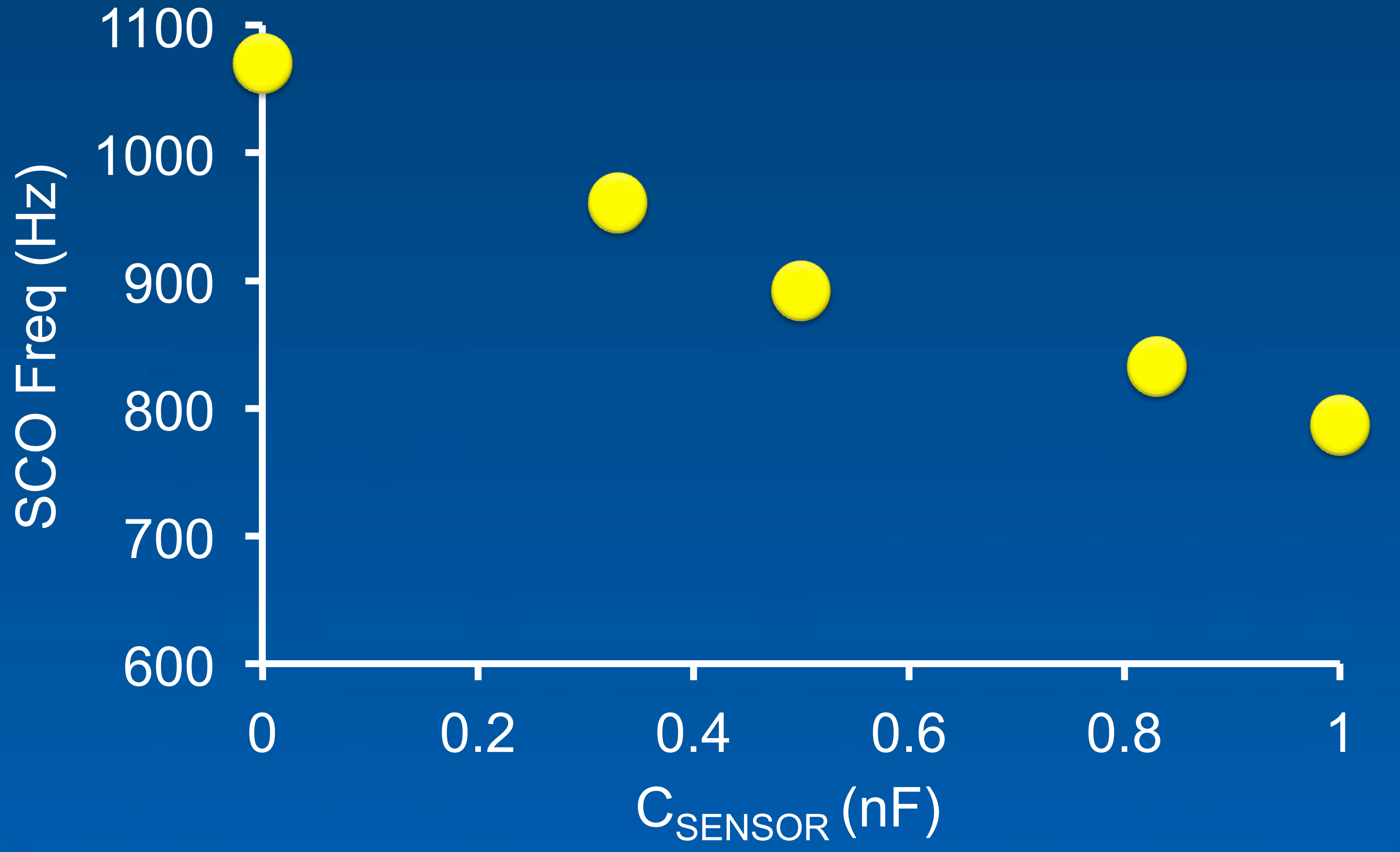


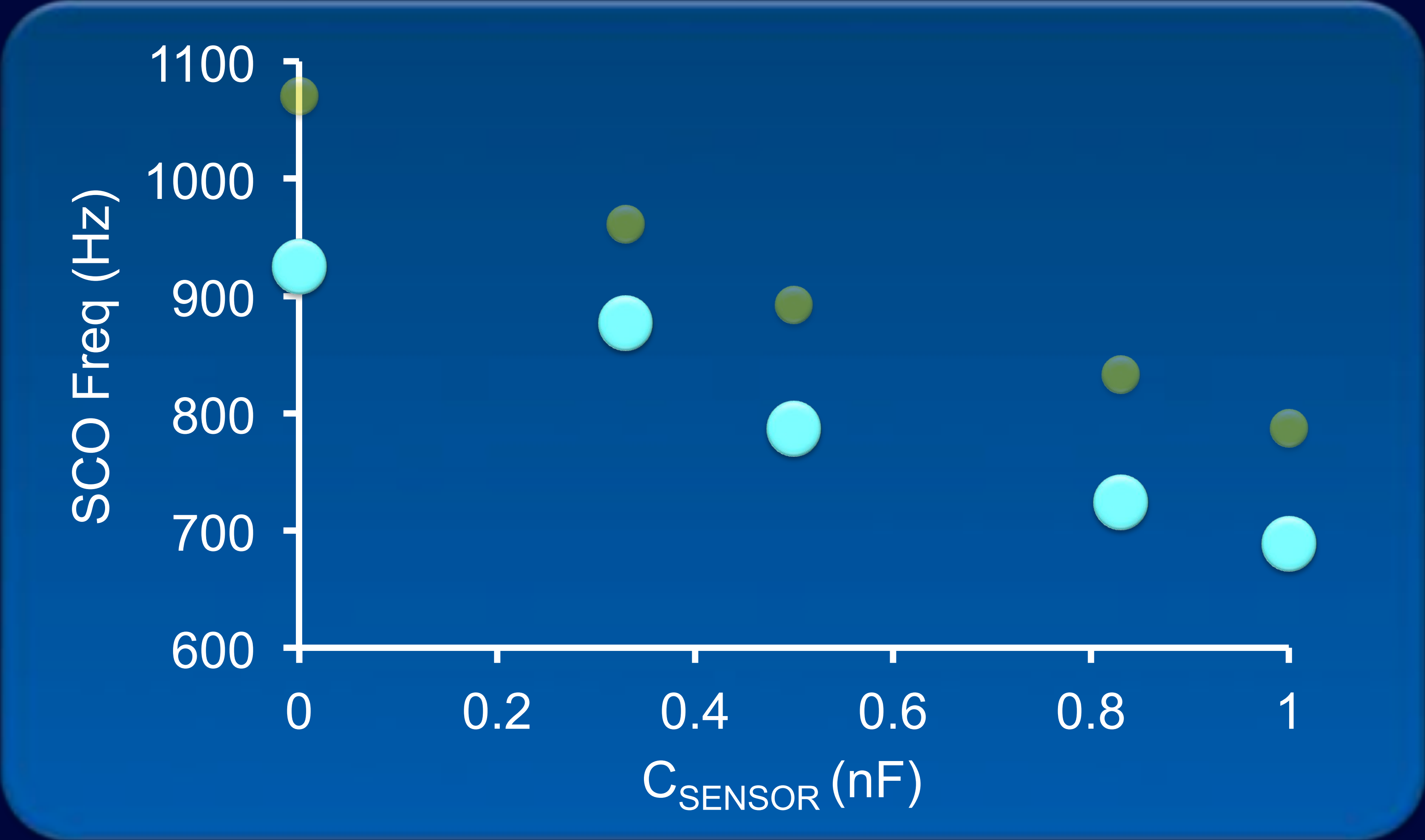
Ring Oscillator Performance

Multiple SCOs



Ring Oscillator Performance

Multiple SCOs



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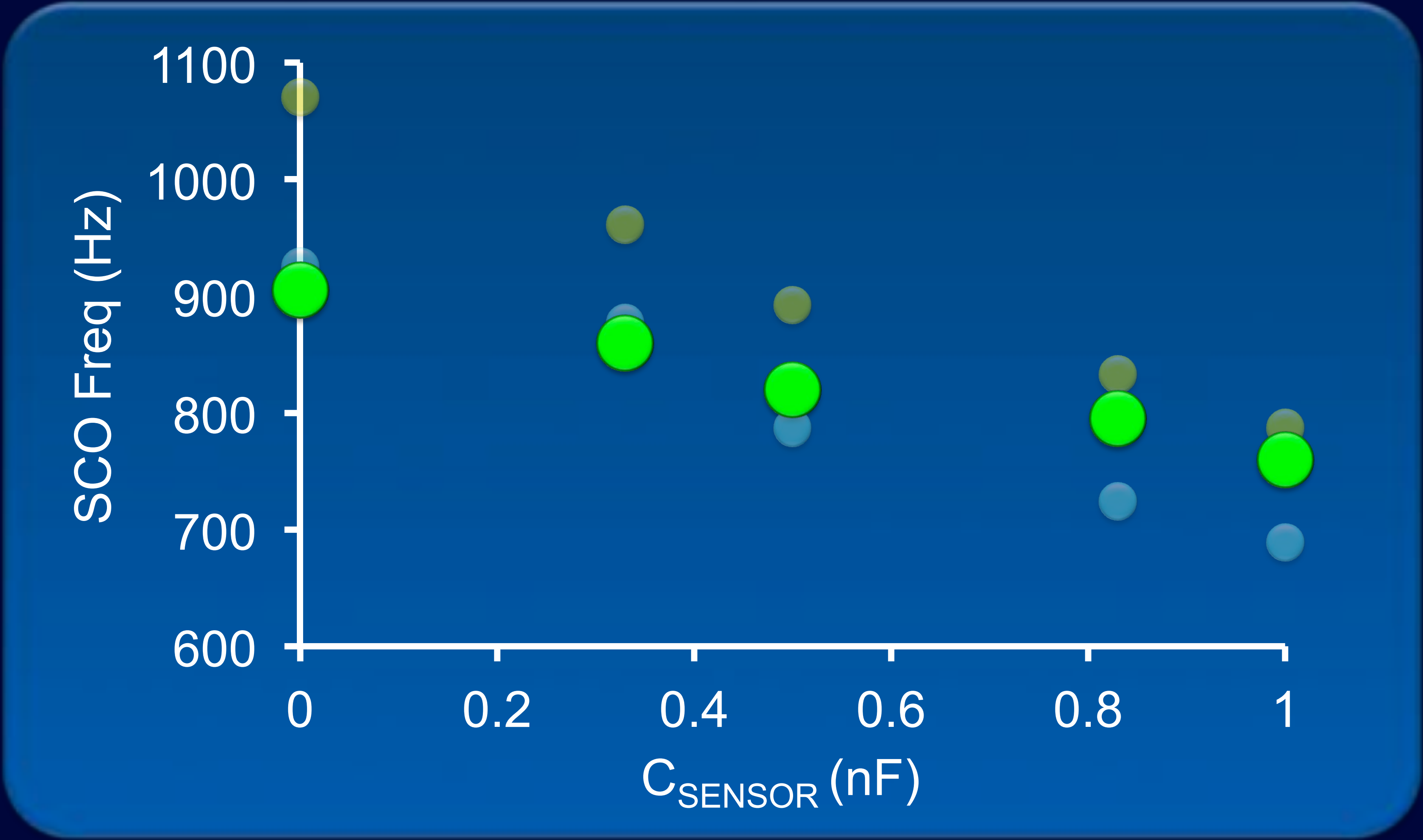

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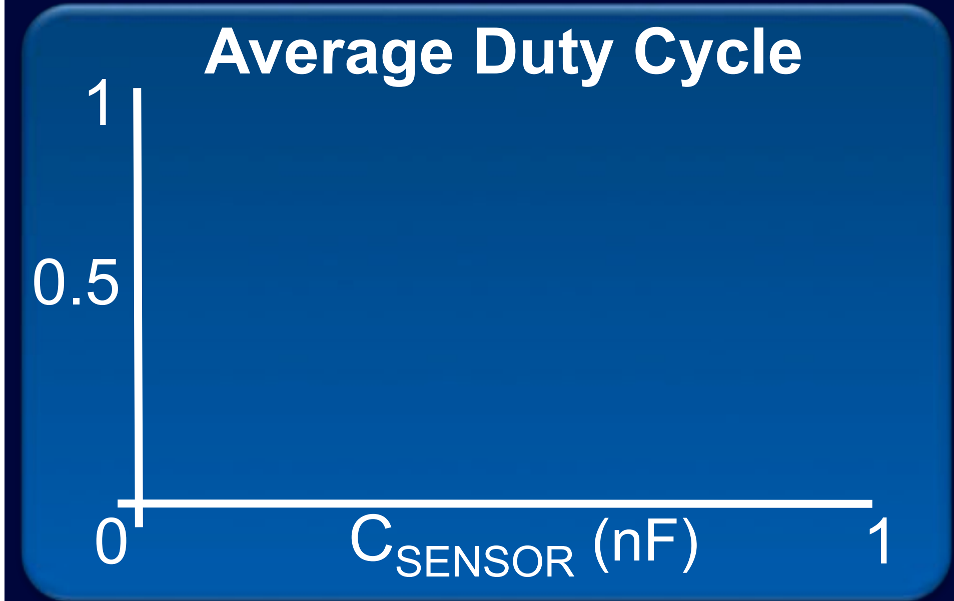

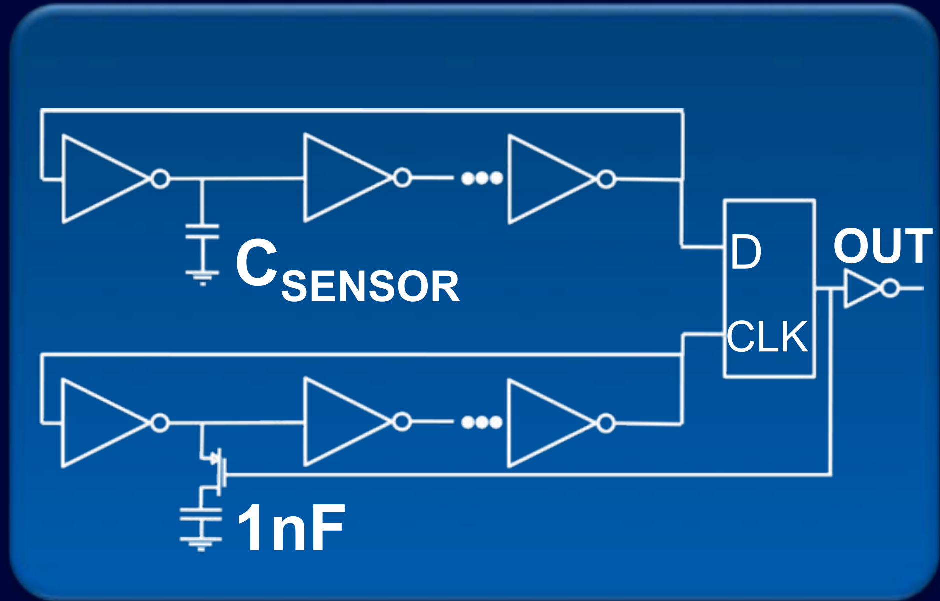

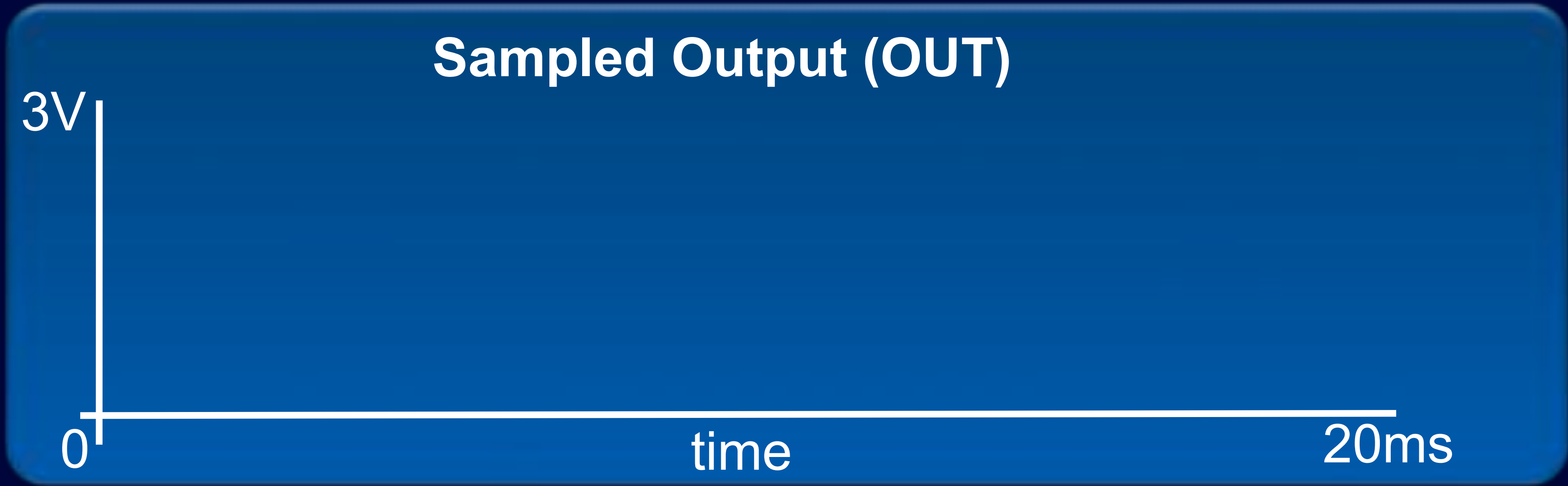

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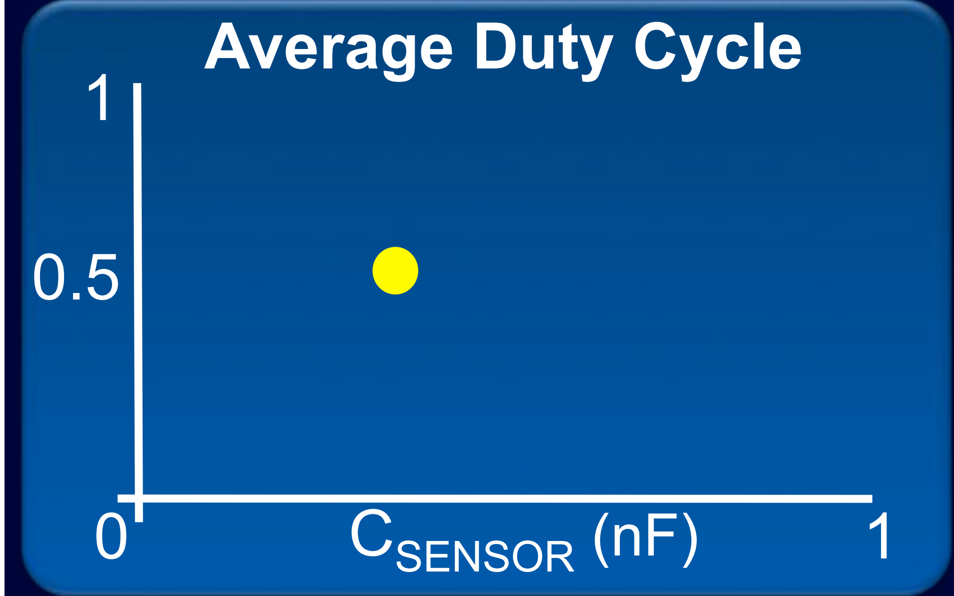

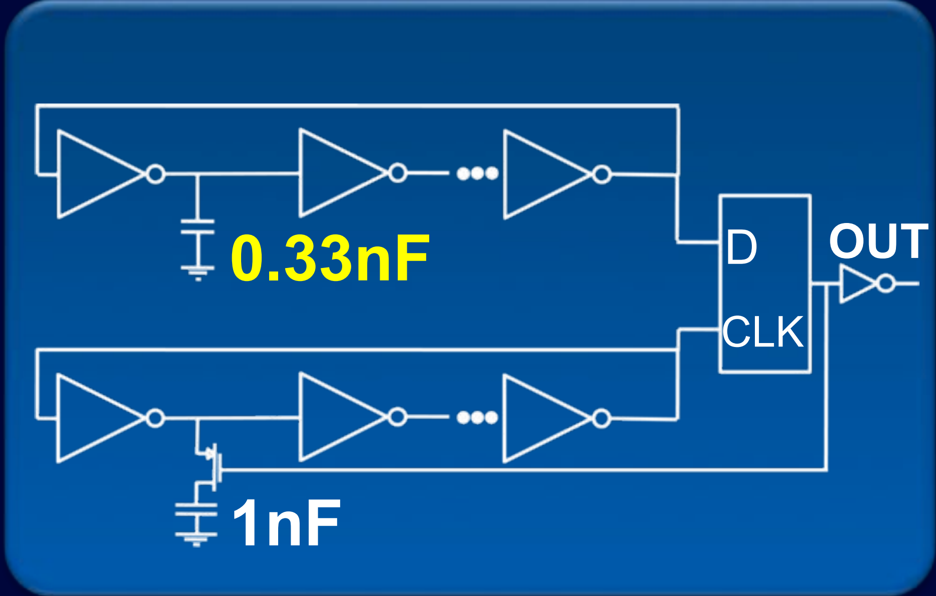

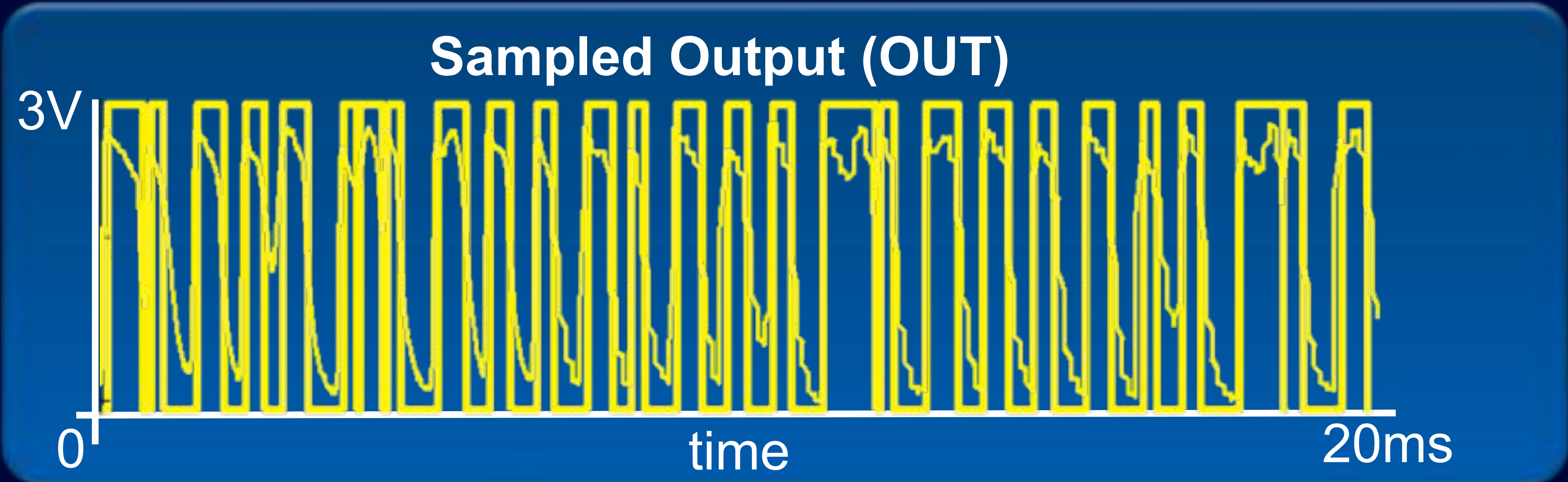

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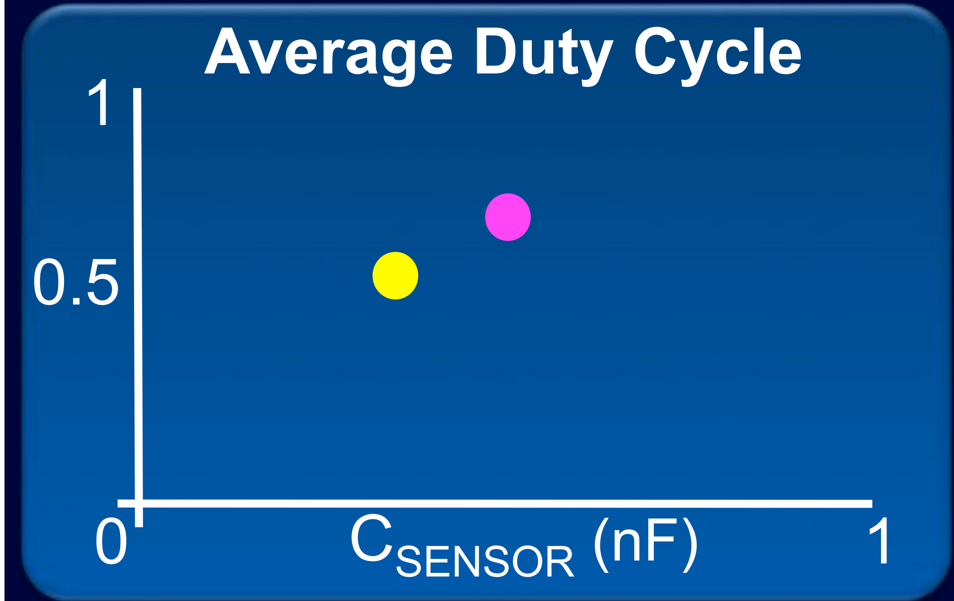

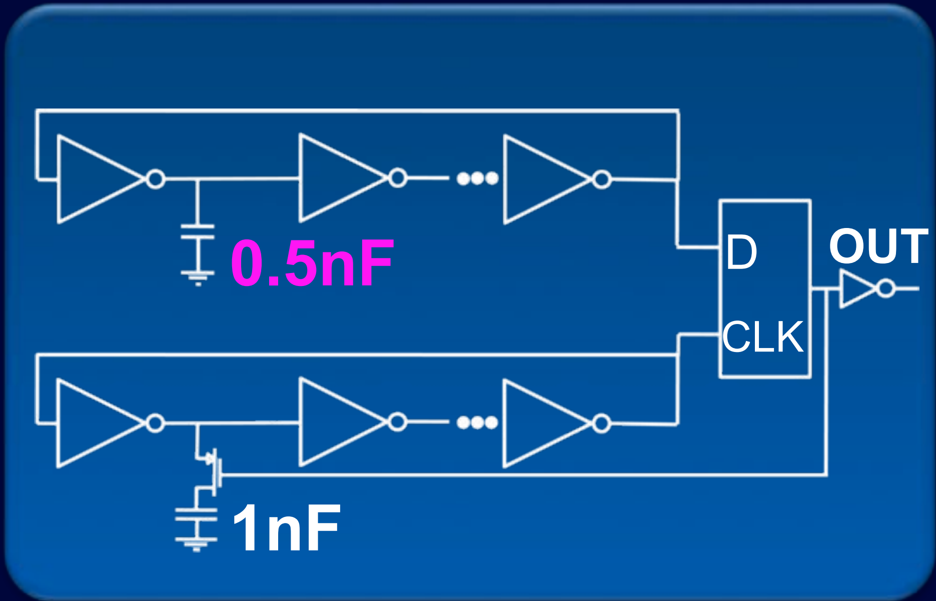

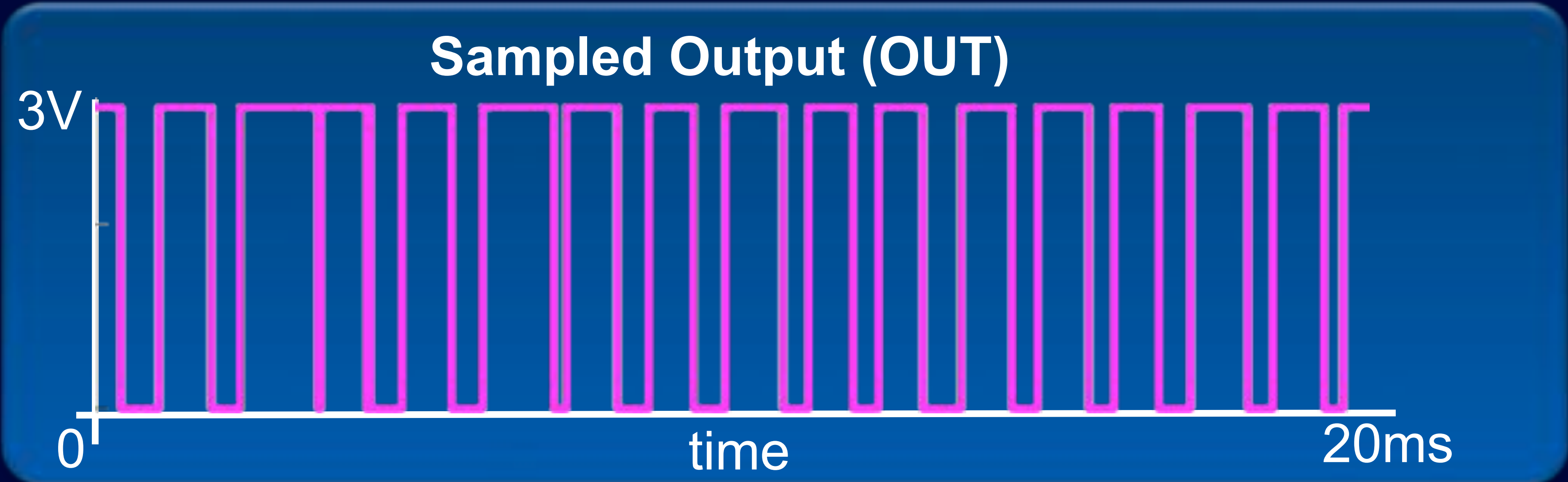

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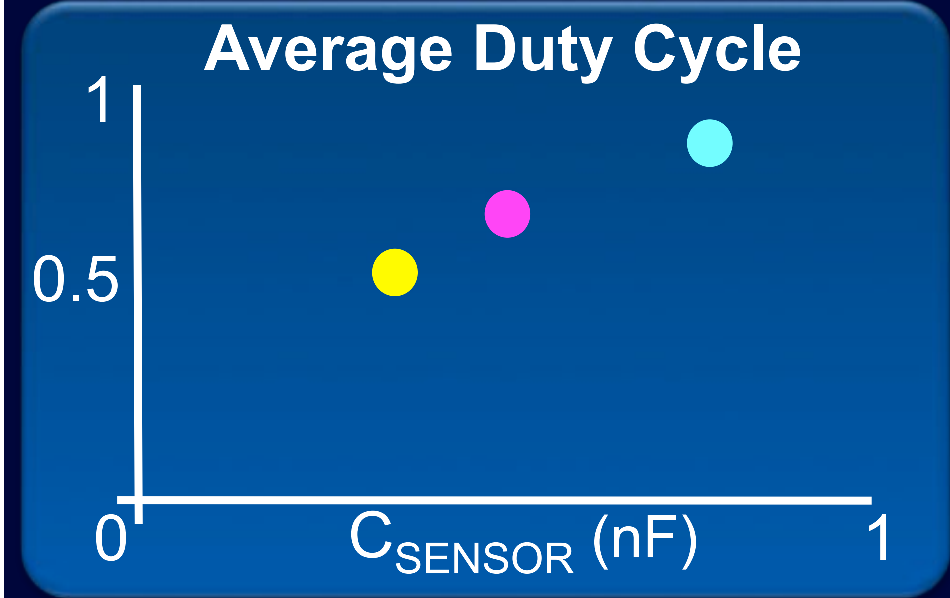

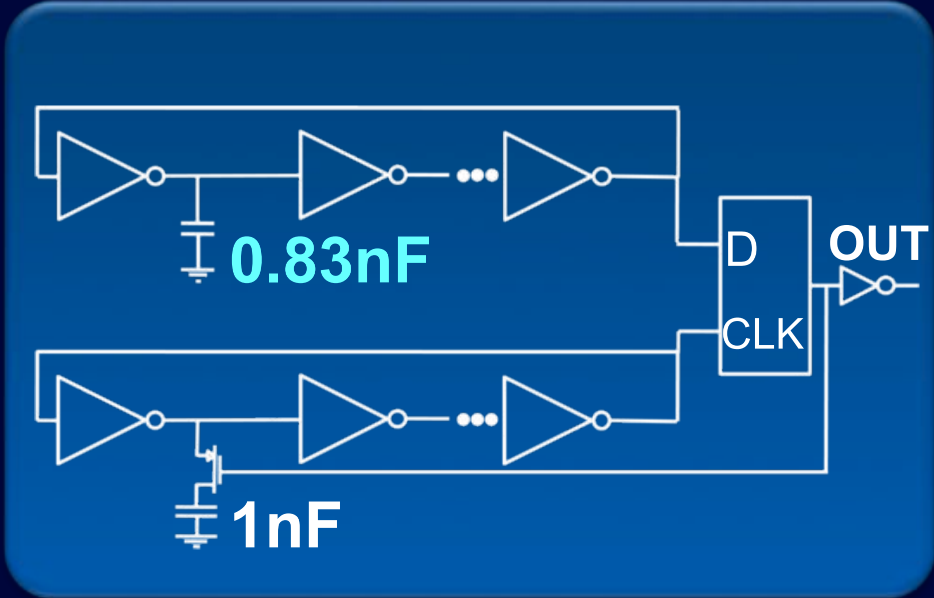

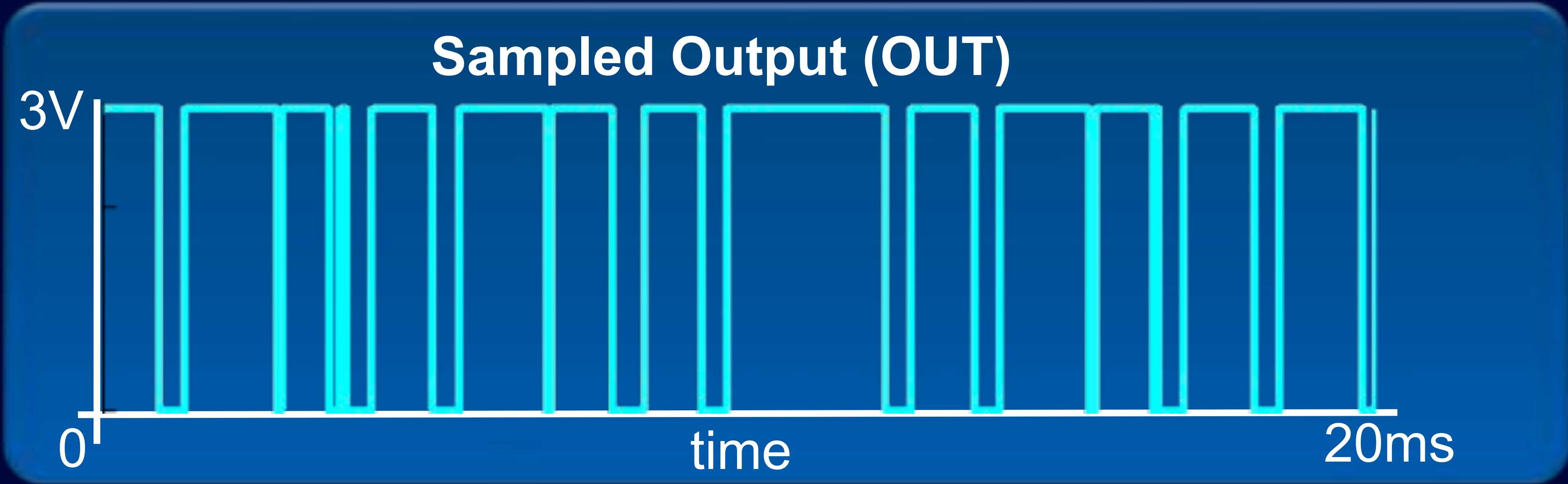

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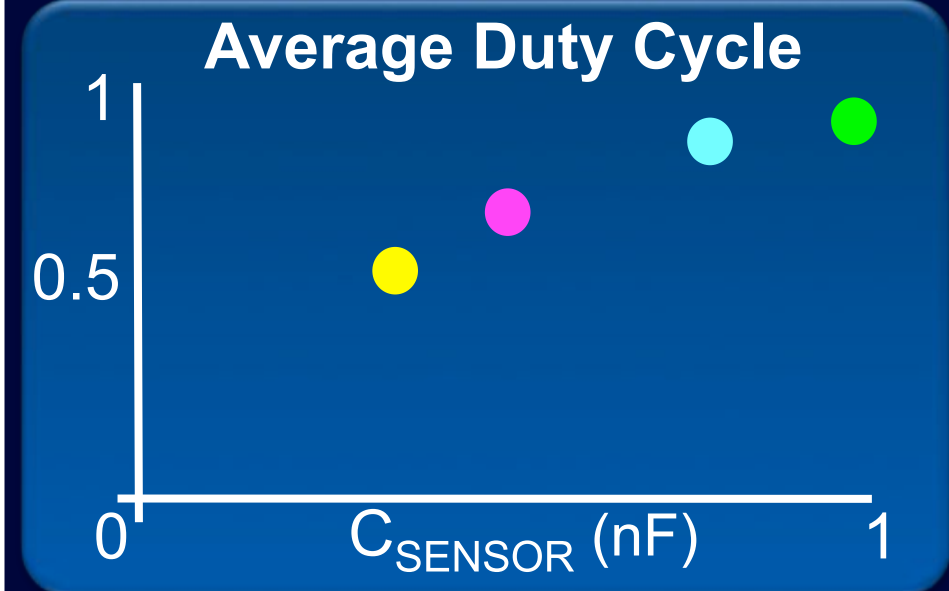
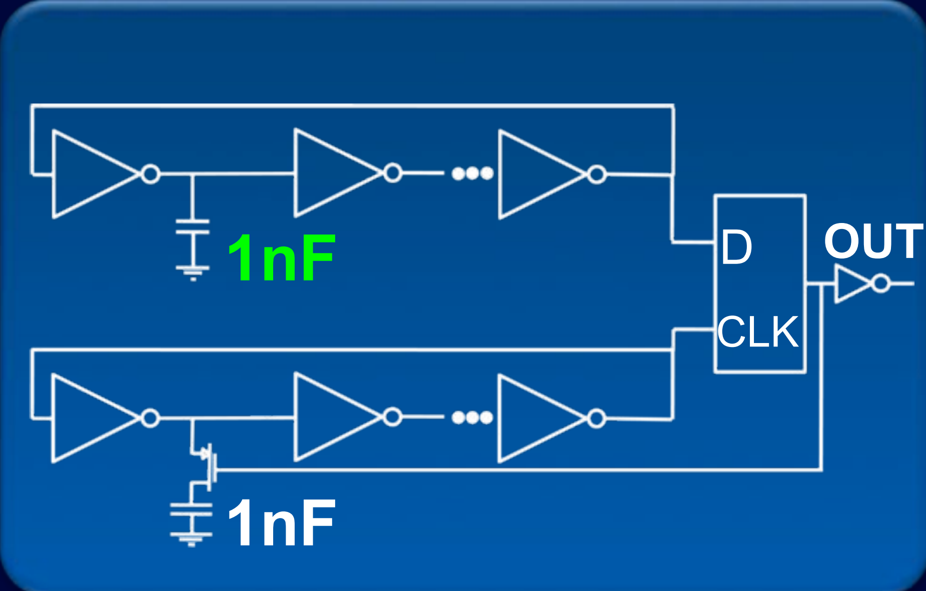
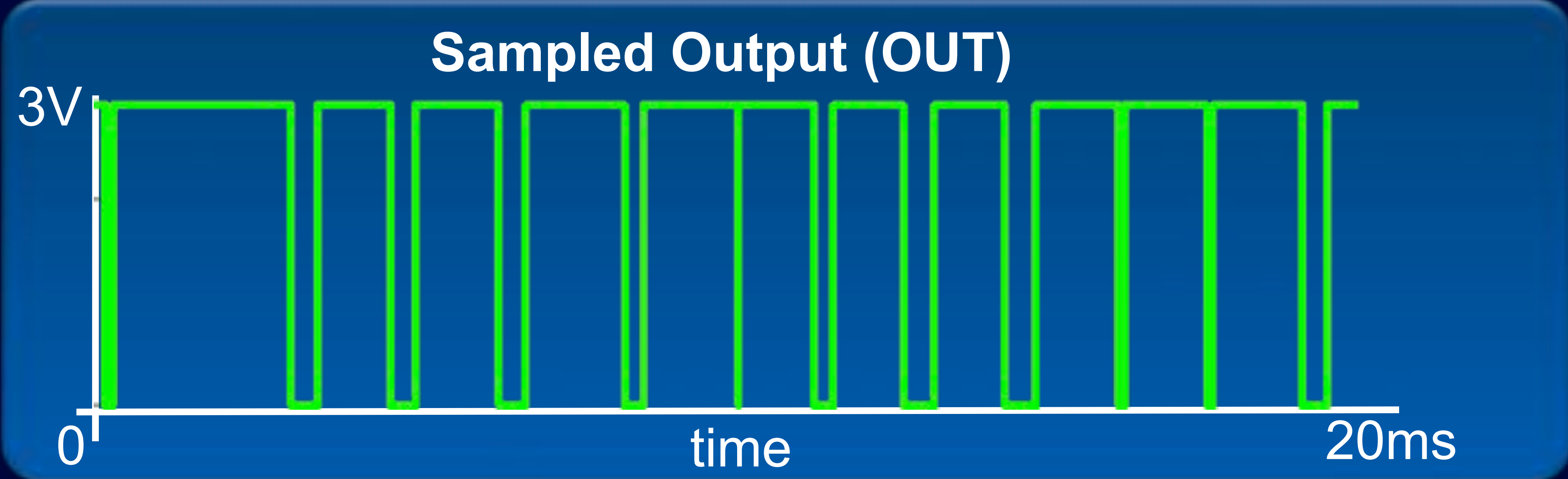
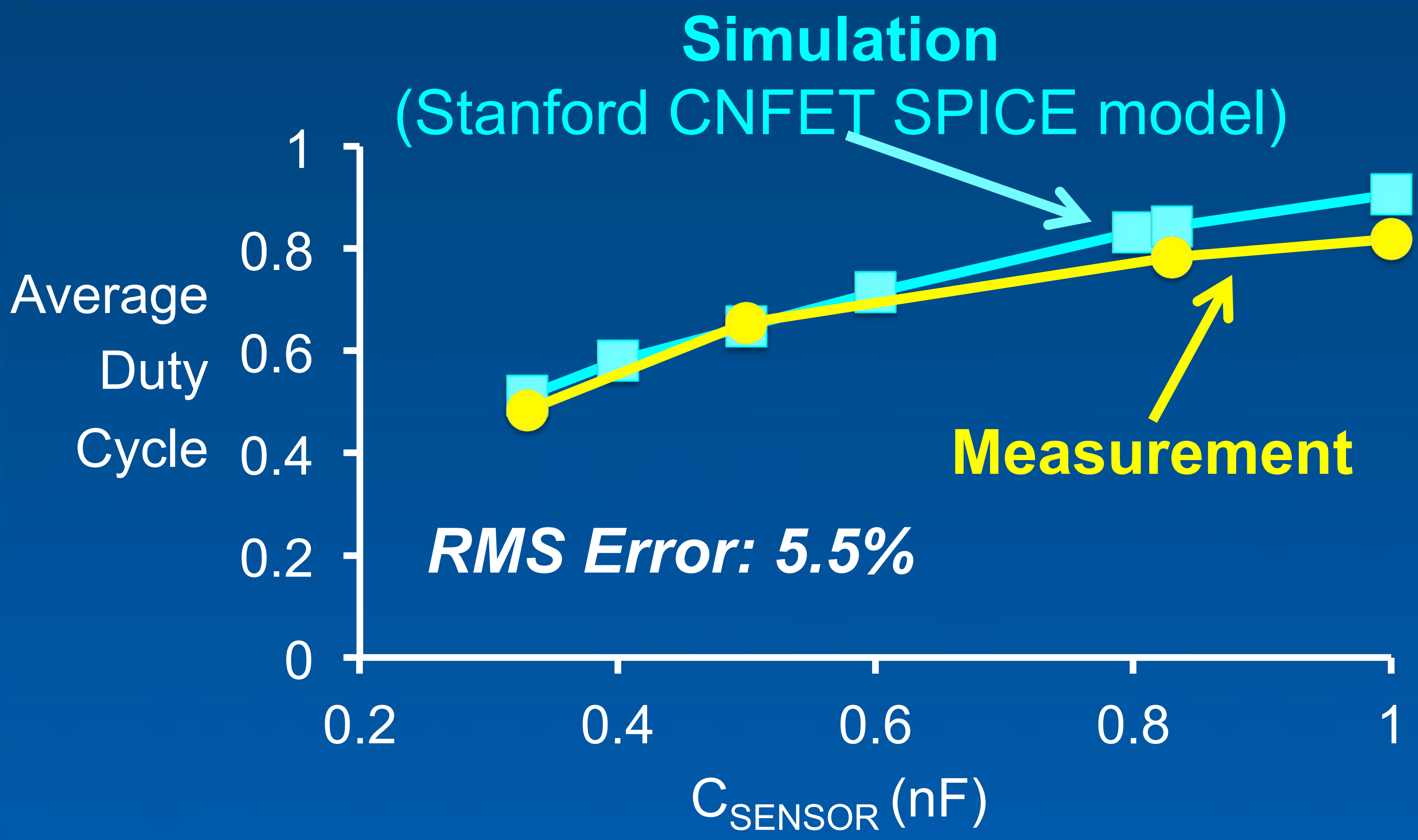




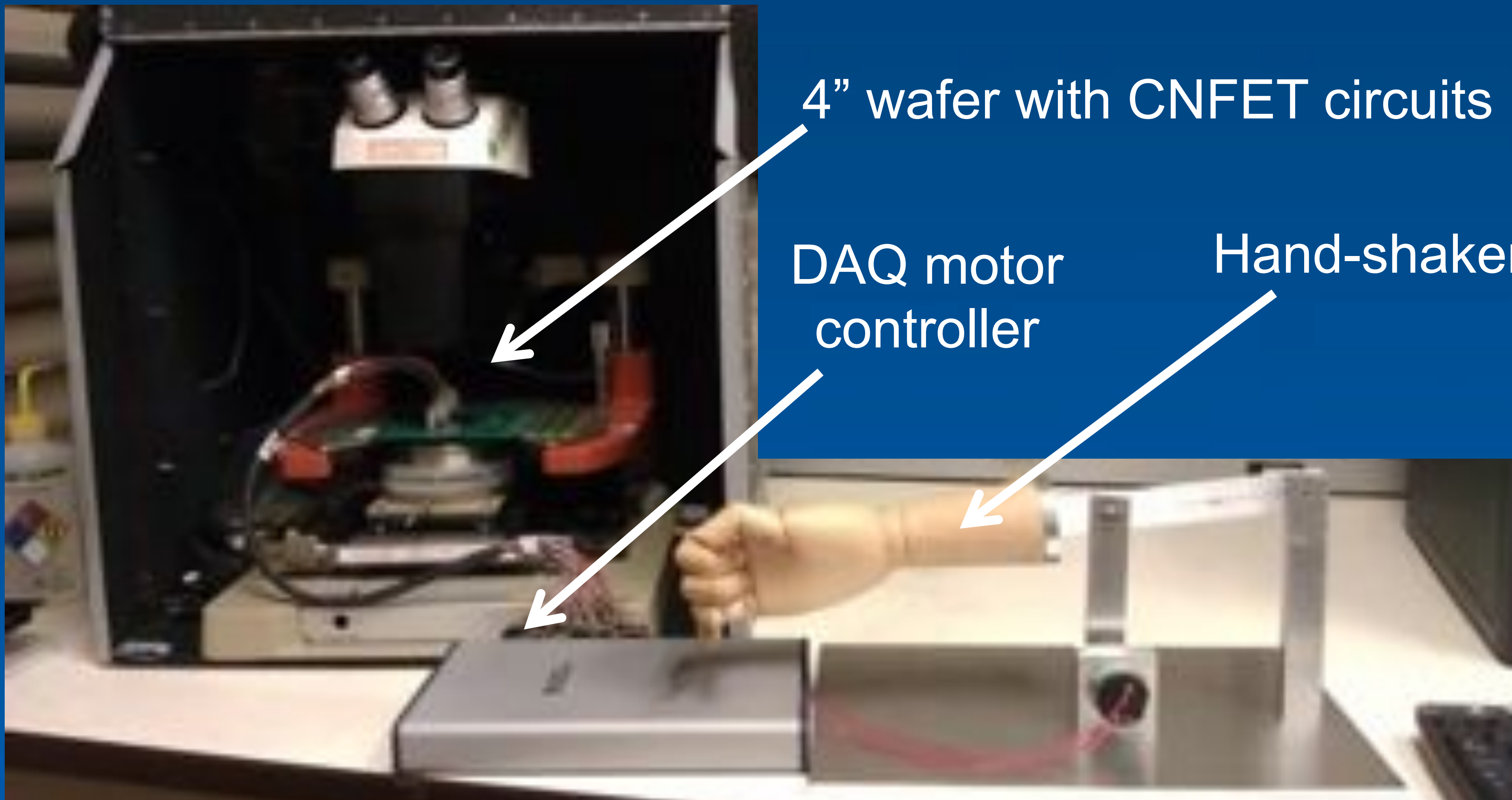


Sensor Interface Results



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