A Cubic-Millimeter Energy-Autonomous Wireless Intraocular Pressure Monitor

Gregory Chen, Hassan Ghaed, Razi-ul Haque, Michael Wieckowski, Yejoong Kim, Gyouho Kim, David Fick, Daeyeon Kim, Mingoo Seok, Kensall Wise, David Blaauw, Dennis Sylvester

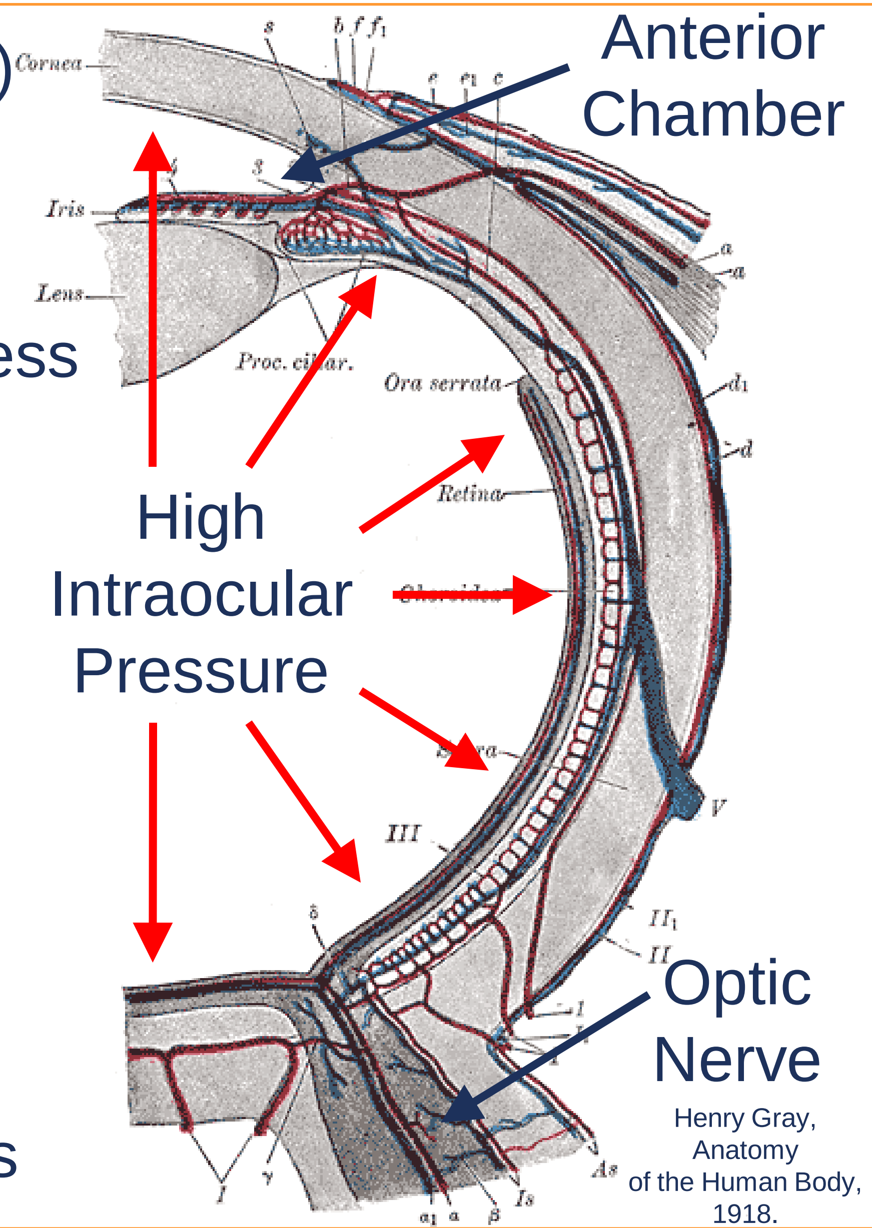
grgkchen@umich.edu

Department of EECS
University of Michigan, Ann Arbor

Glaucoma

- High intraocular pressure (IOP)
- Causes optic nerve damage
- Affects 1/100 people globally
- #1 cause of irreversible blindness

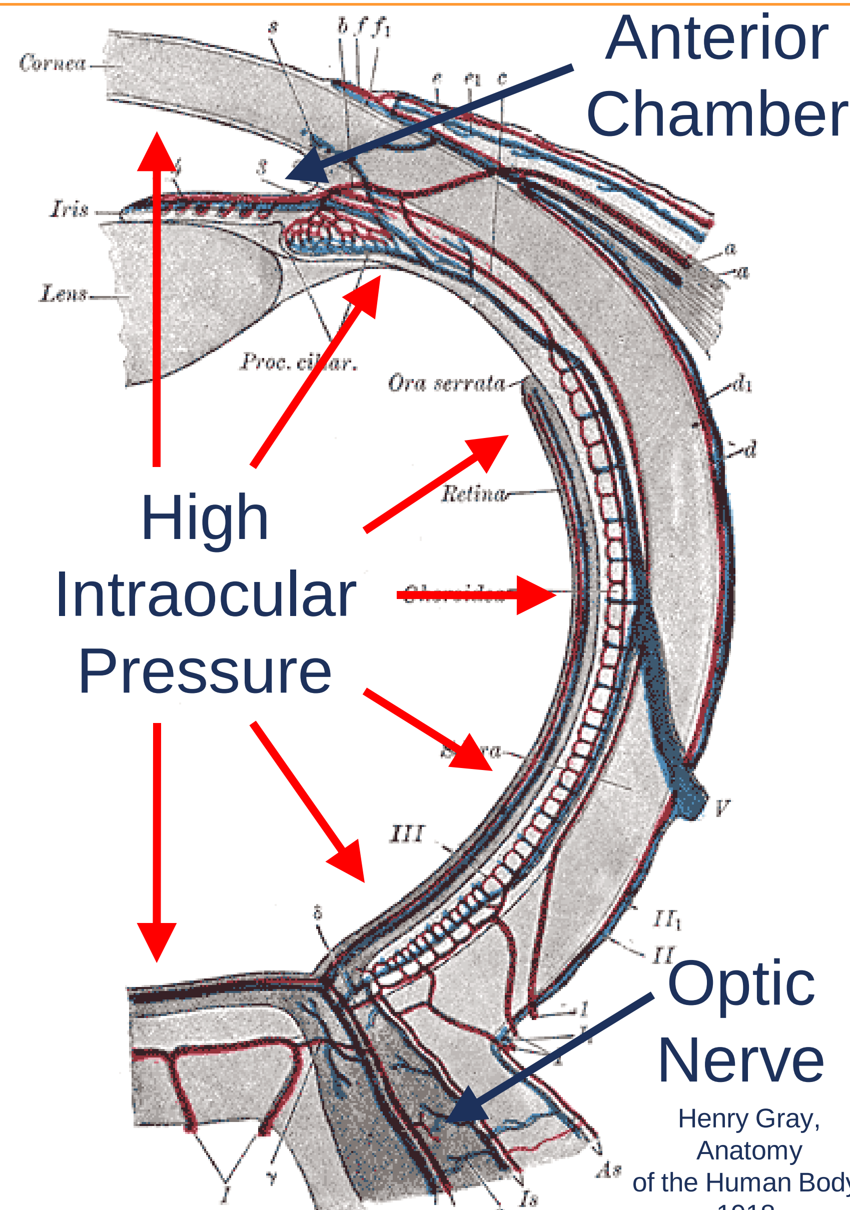
- Treatment
  - Eye drops or oral medication
  - Surgery
  - Discrete IOP measurements
- Challenges
  - Infrequent pressure recordings
  - Eye pressure fluctuates
  - Slow assessment of treatments



Henry Gray, Anatomy of the Human Body, 1918.

Continuous IOP Monitoring

- Faster feedback to doctors
  - Assess efficacy of treatments
  - Check patient compliance
  - Study disease mechanisms
- Previous work
  - Contact lens with strain gauge measures eye deformation
  - Implanted microsystem with pressure sensor and 27 mm antenna
  - Inductively powered



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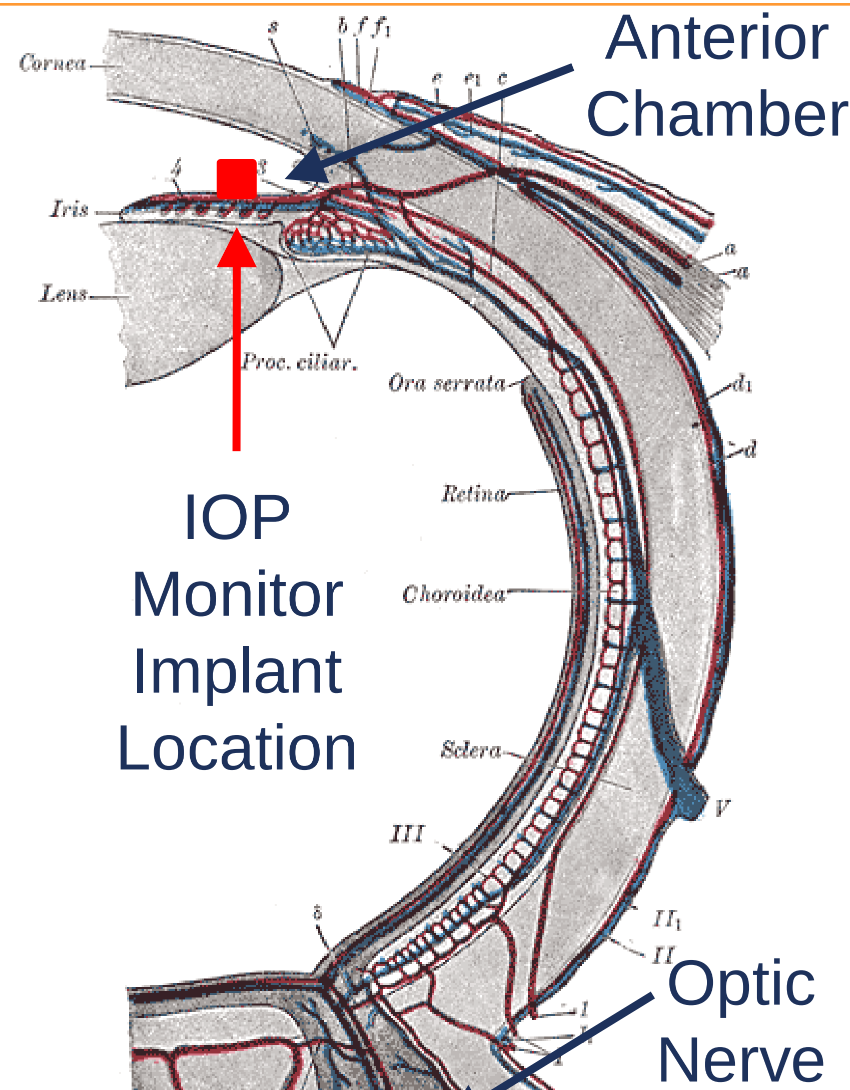
Continuous IOP Monitoring

- Implantation constraints
  - Implanted in anterior chamber
  - Self-healing “cataract” incision
  - Immobilized implant
  - No sutures
  - **Cubic-millimeter size**
- Energy constraints
  - Low patient intervention
  - Self-powered microsystem
  - **Multi-year lifetime**



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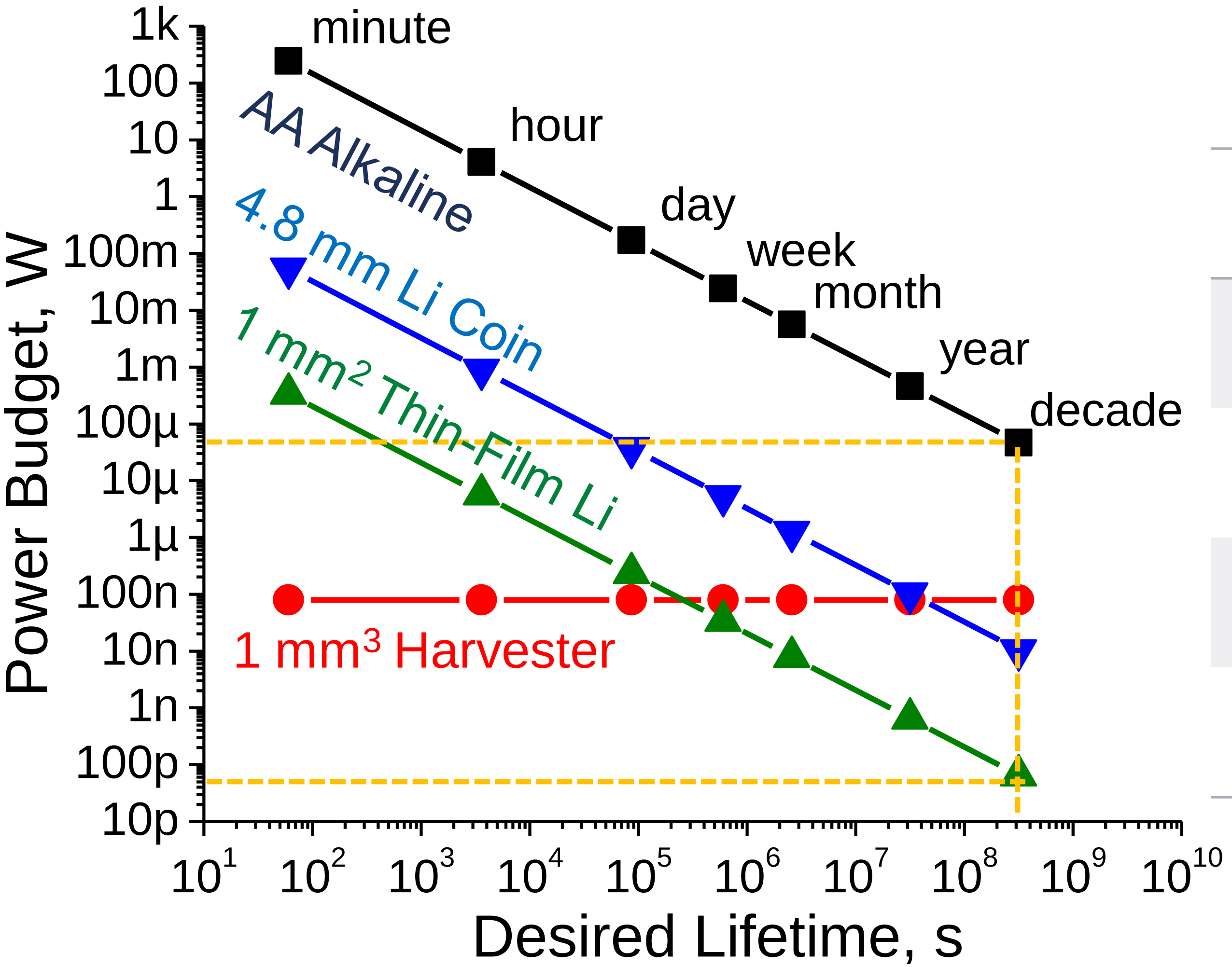
Power Budget Challenges

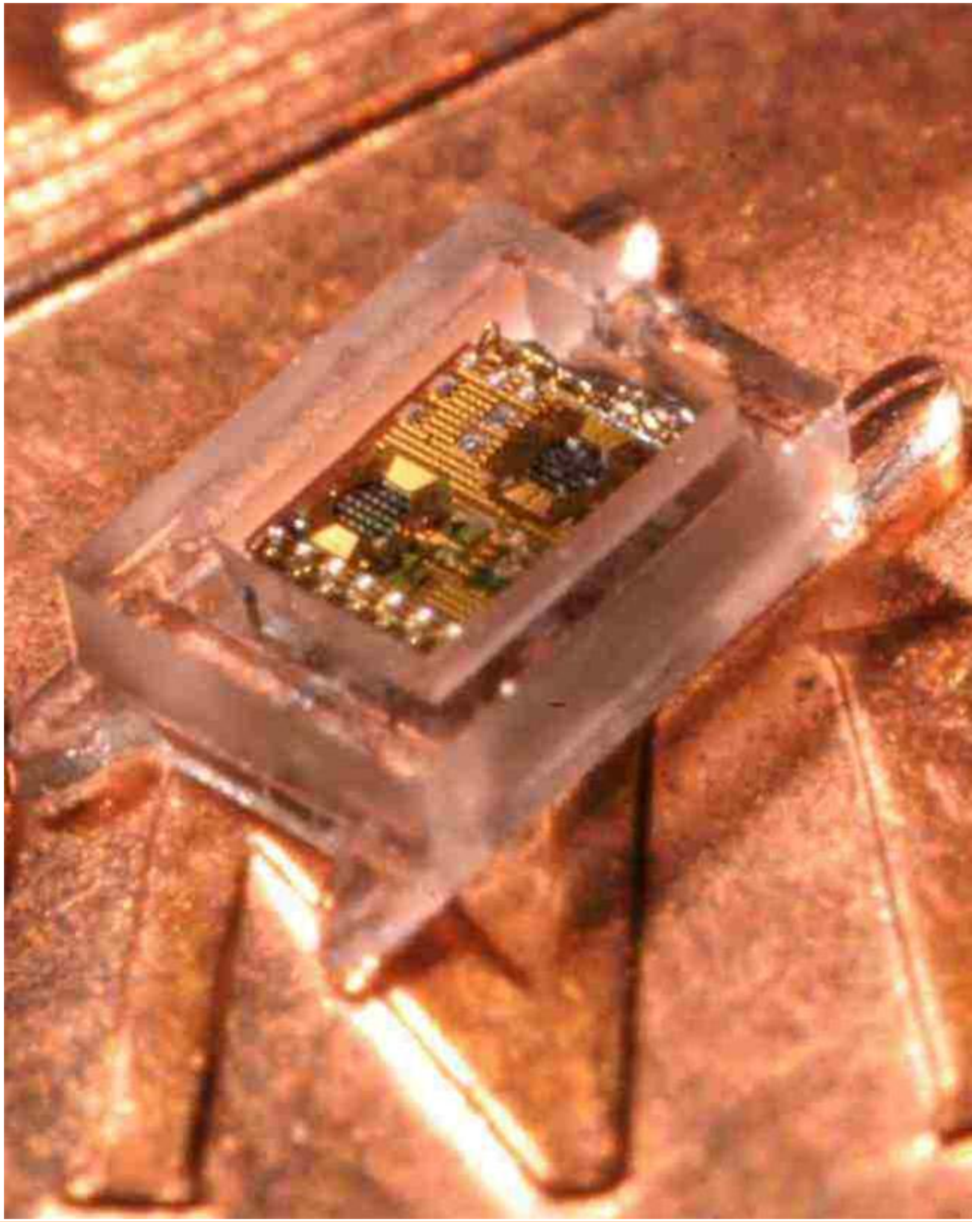


Battery	**Peak Power**
AA Alkaline	1.5 W
4.8 mm Li Coin	600 µW
1 mm^2 Thin-Film Li	40 µW
1 mm^3 Harvester	80 nW

Microsystem volume constraints heavily limit power source capabilities and load circuit power consumption

1.5 mm^3 Intraocular Pressure Monitor

- Continuous IOP monitoring
- Wireless communication
- Energy-autonomy
- Device components
  - Solar cell
  - Wireless transceiver
  - Cap to digital converter
  - Processor and memory
  - Power delivery
  - Thin-film Li battery
  - MEMS capacitive sensor
  - Biocompatible housing



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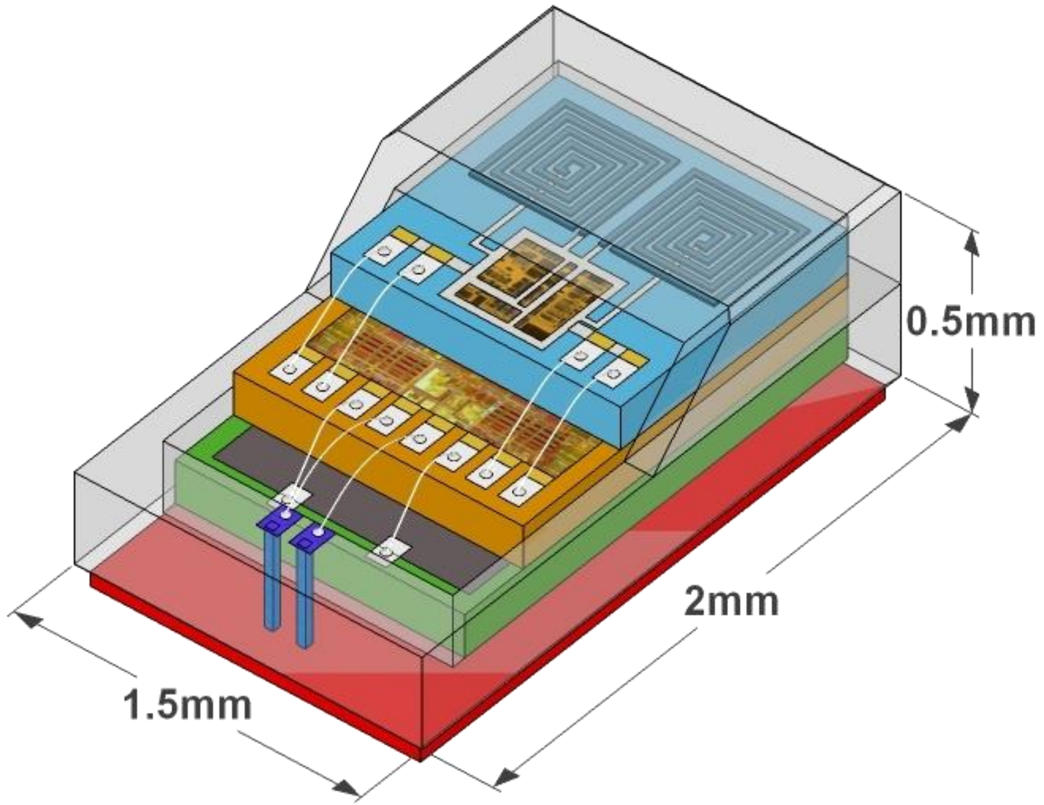
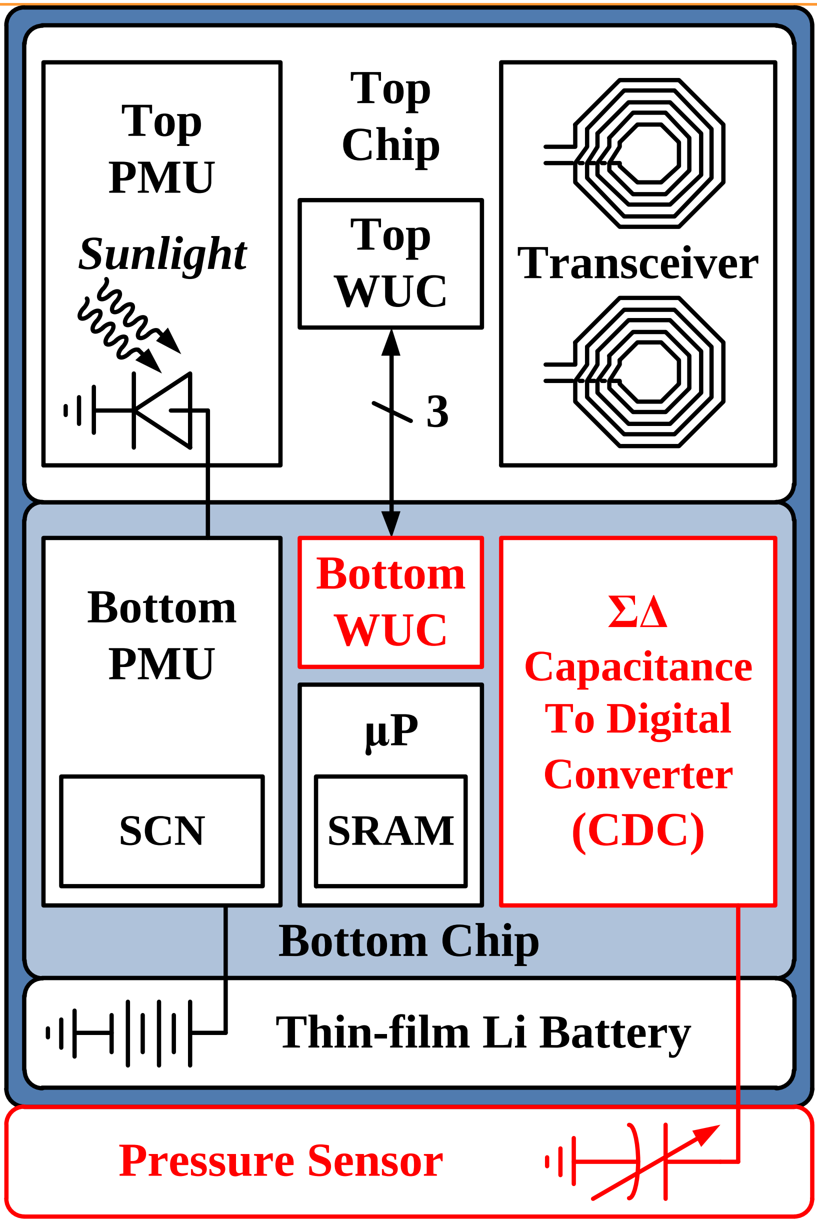


IOP Monitor Usage Model



- Measure IOP every 15 minutes
  - Interval set with 31 pW leakage-based oscillator in Bottom Wakeup Controller (WUC)

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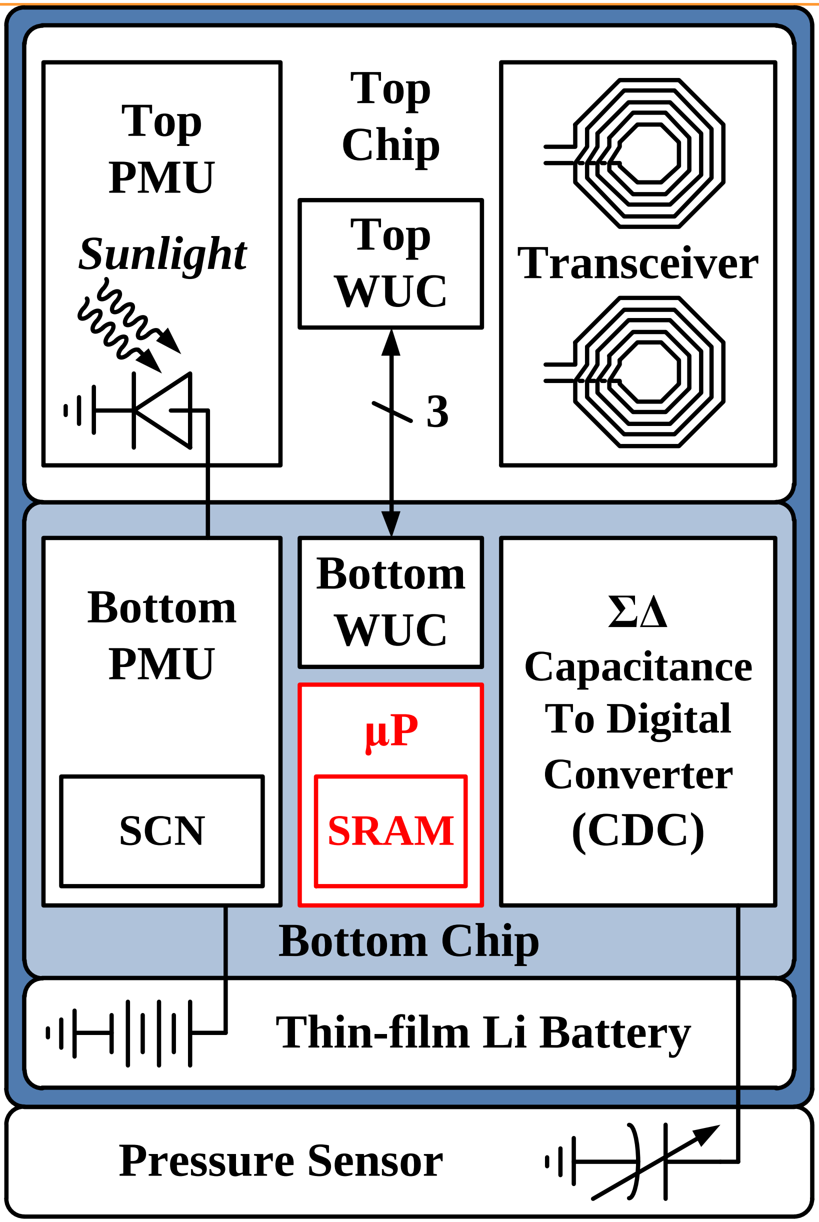

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  - µP wakes up from power-gated standby mode and stores data in 2.4 fW/bit SRAM

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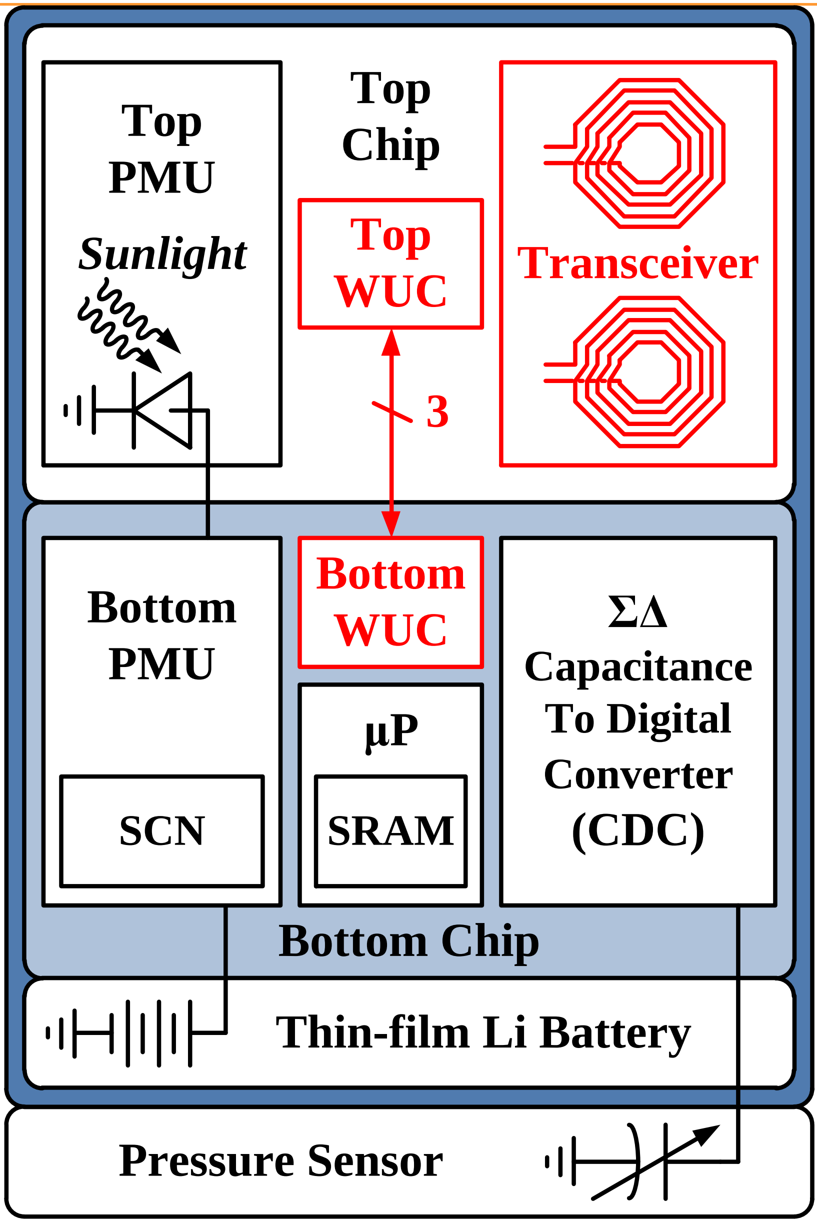

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- Extract and store medical data
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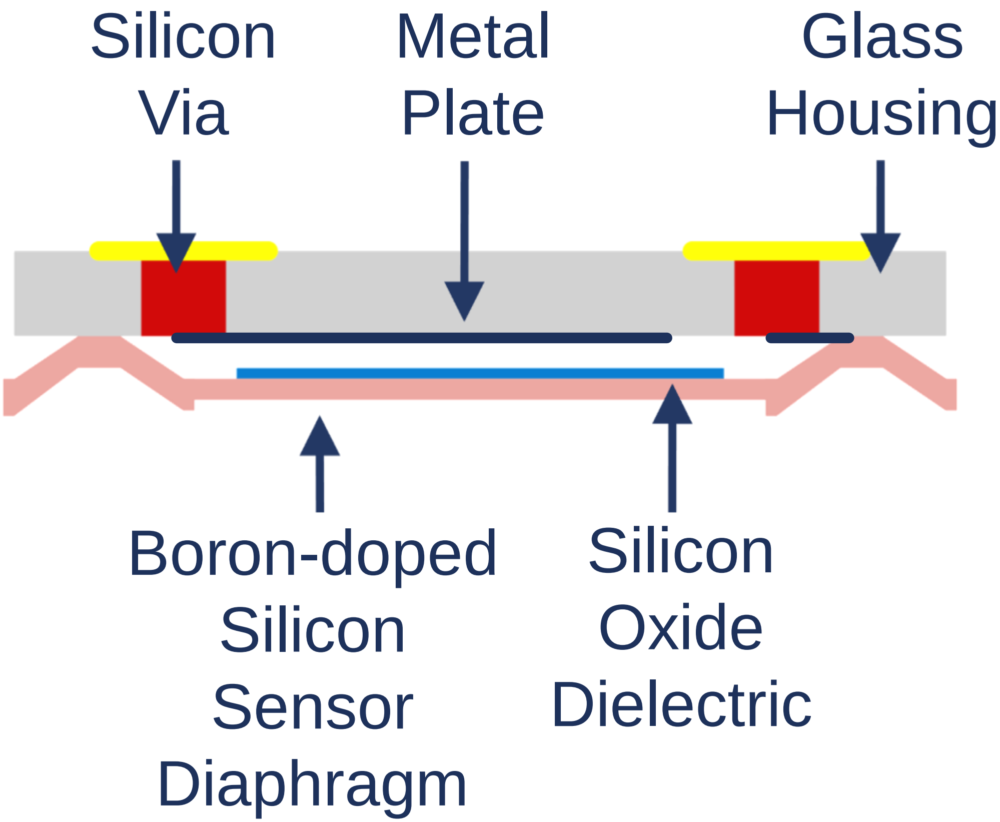
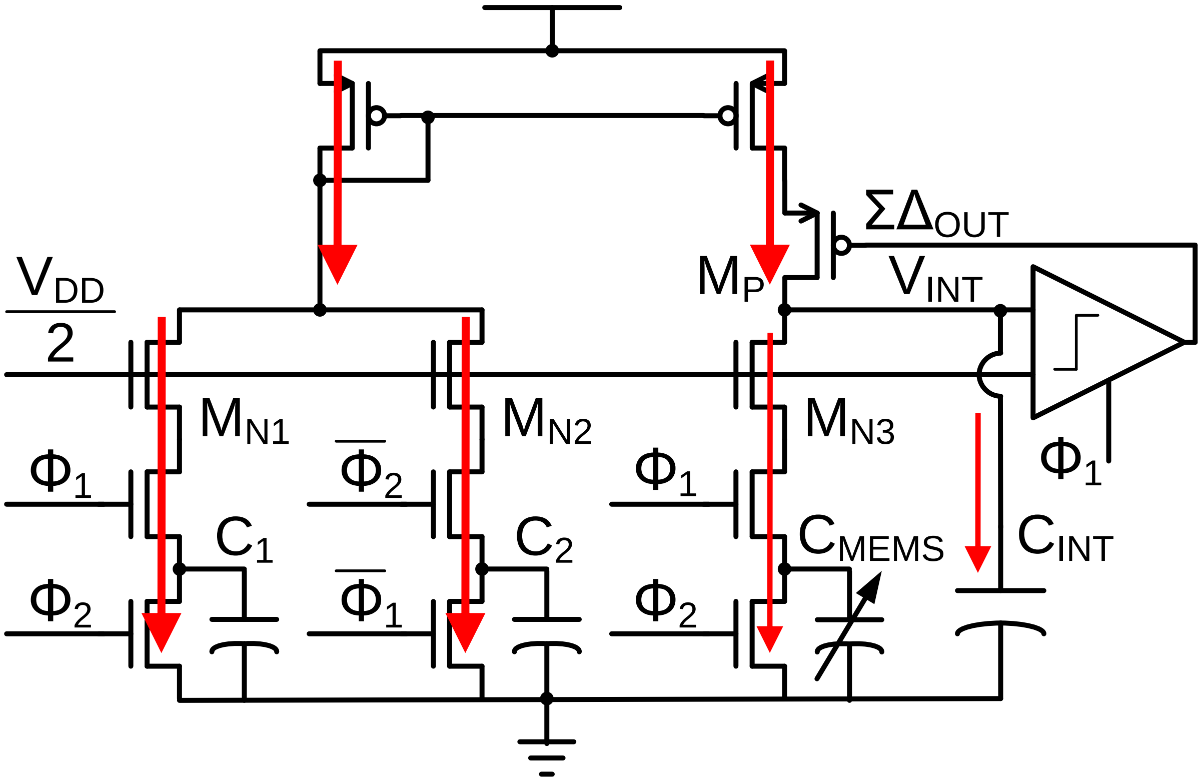
- Wirelessly read device as needed
  - Wirelessly queried
  - Transmits data to PC
  - 0.1 µs pulse and local V_{DD} to meet peak power constraint

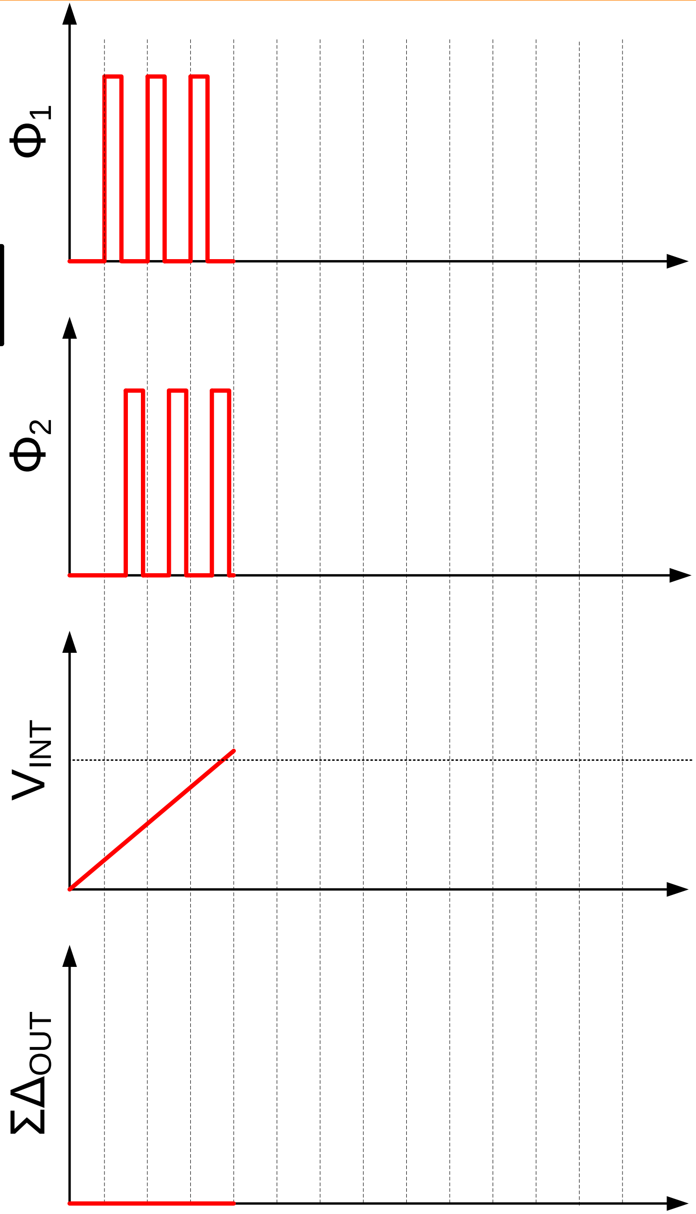
Capacitive Pressure Sensor



- Contact mode operation with oxide between capacitor plates
- Capacitor area, not distance between plates, changes
- 26 fF/mmHg sensitivity and high linearity

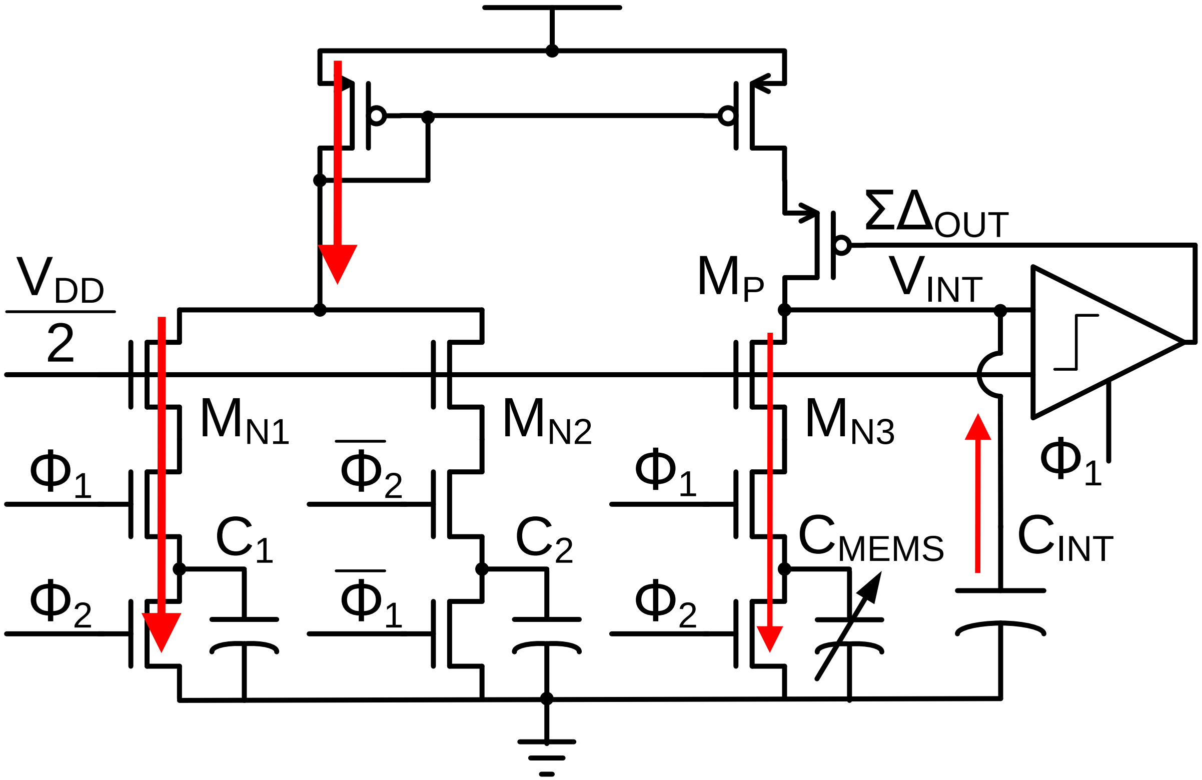
ΣΔ Capacitance to Digital Converter

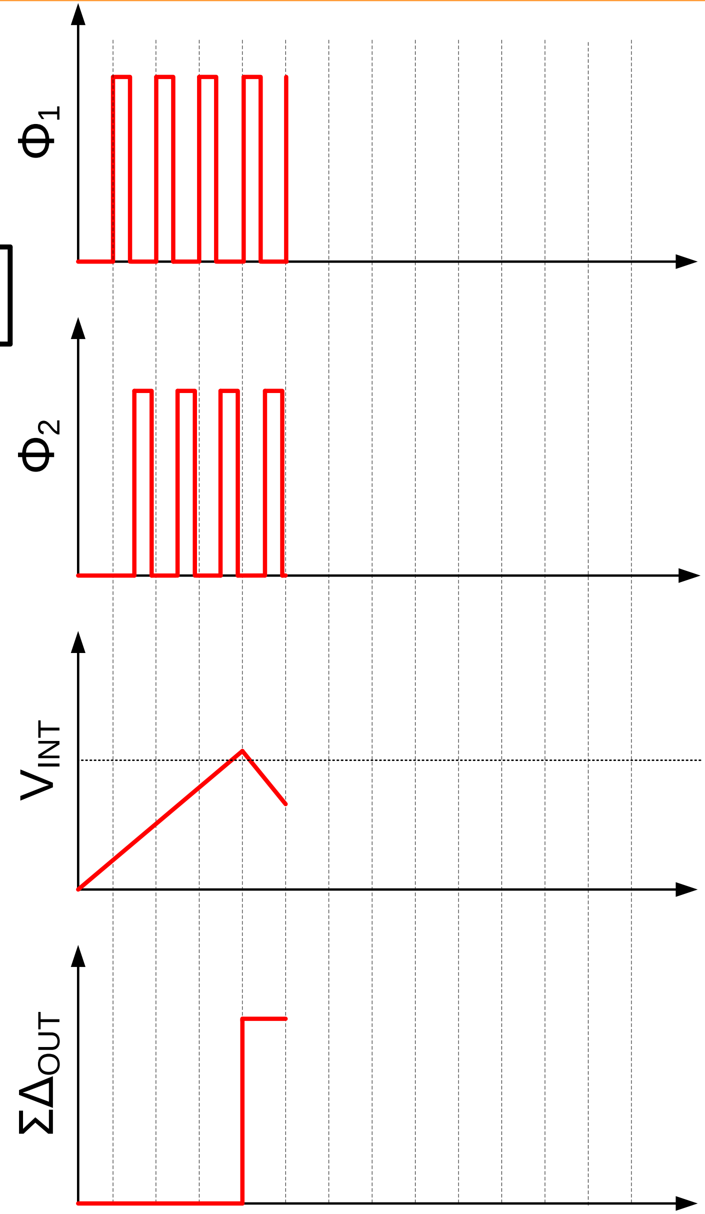




- Pressure sensor (C_{MEMS}) is switched to make a pressure-sensitive current sink
- MIM capacitors (C_1, C_2) generate a larger fixed current source
- Currents charge/discharge C_{INT}

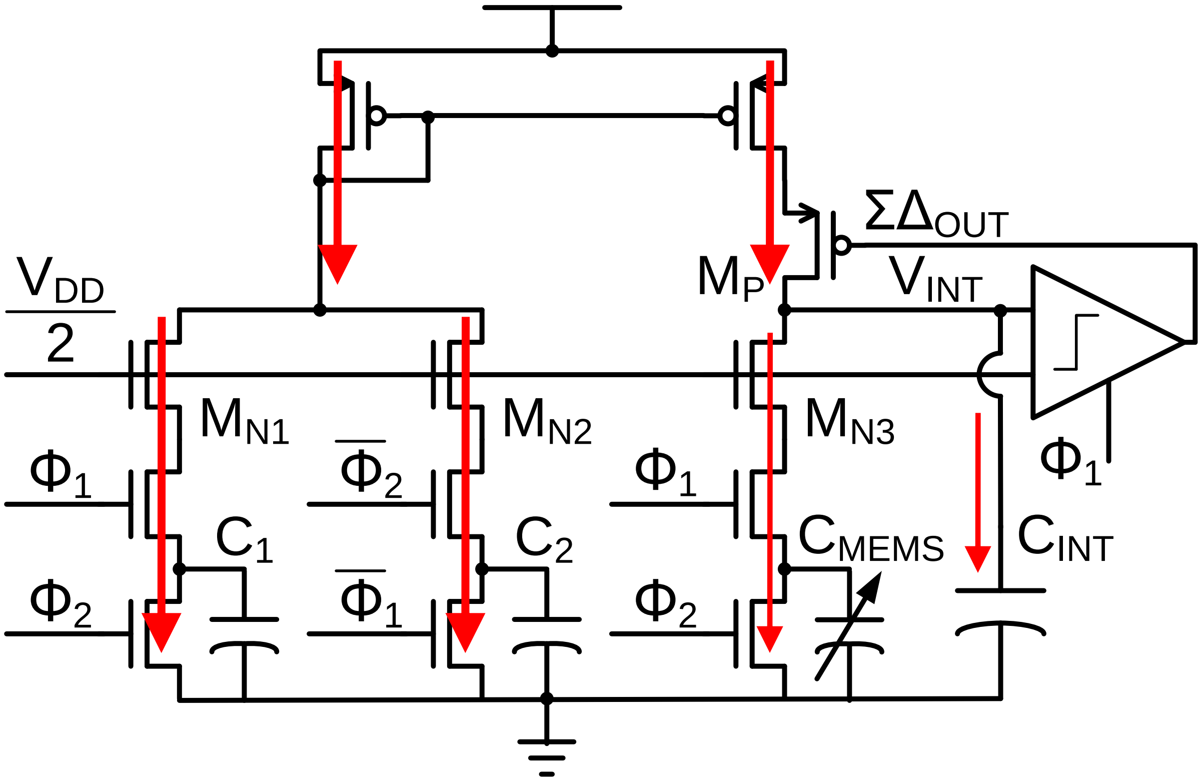
ΣΔ Capacitance to Digital Converter

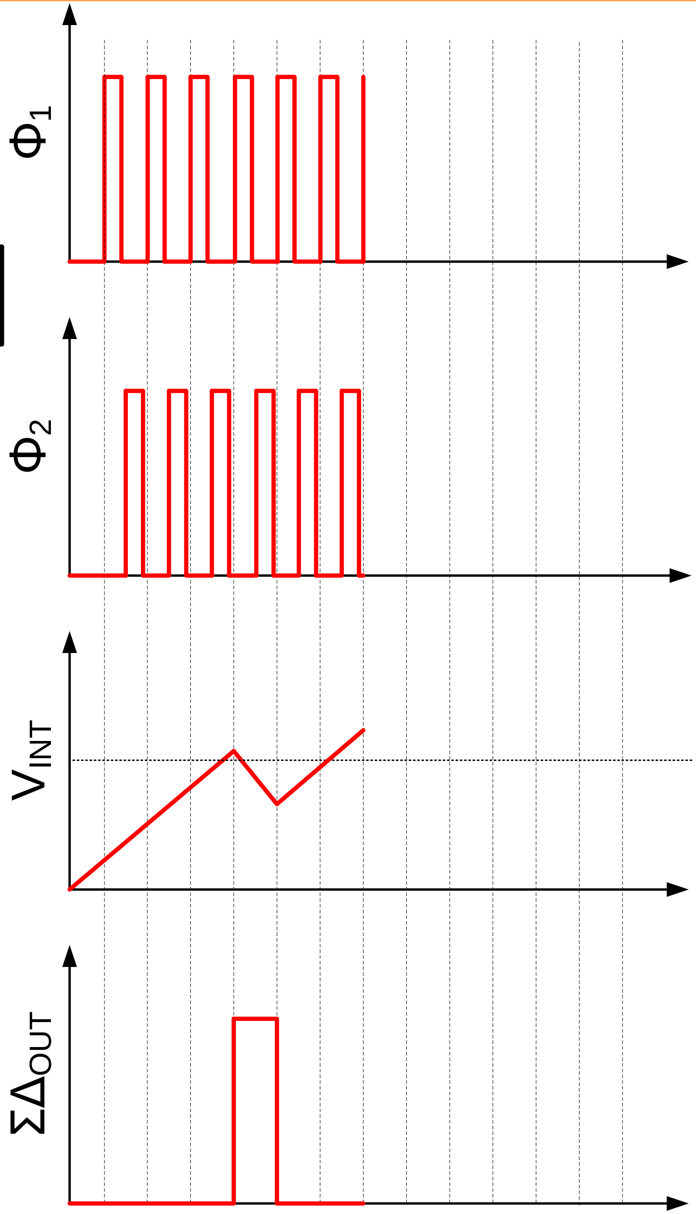




- Voltage on integration capacitor (V_{INT}) is compared with reference ($V_{DD}/2$)
- Fixed current is disabled when V_{INT} is higher than $V_{DD}/2$

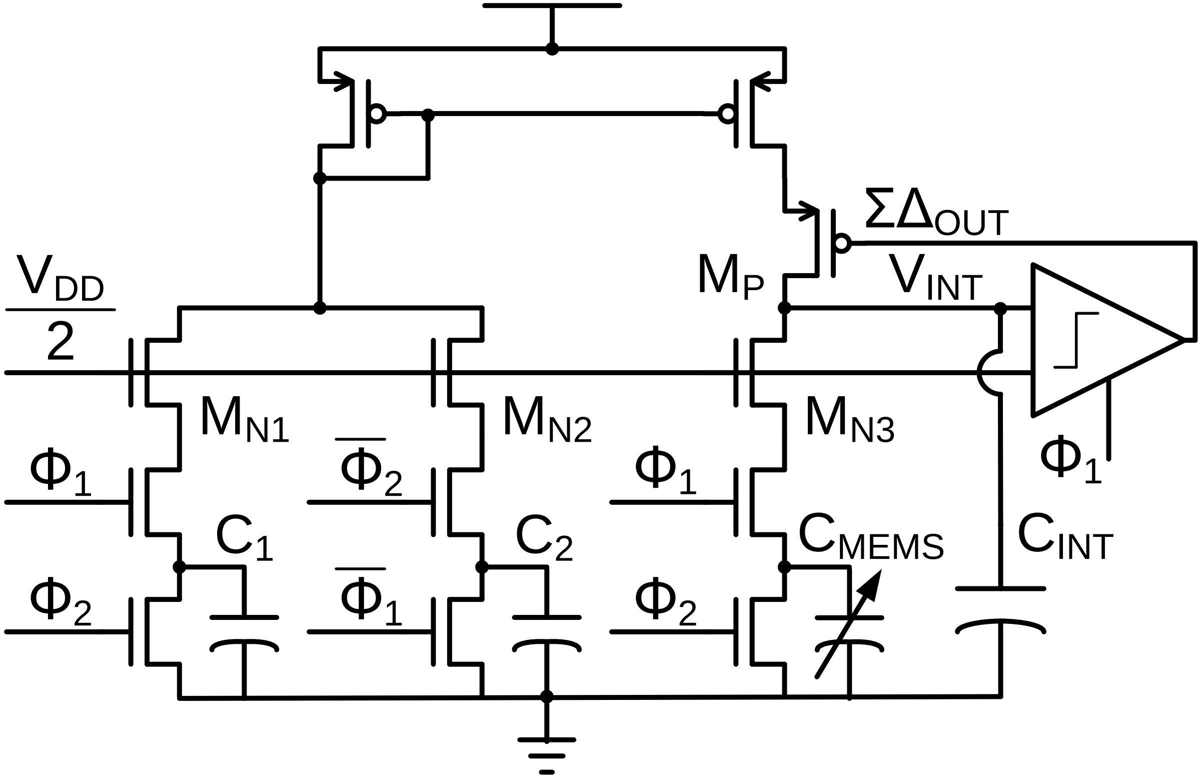
ΣΔ Capacitance to Digital Converter

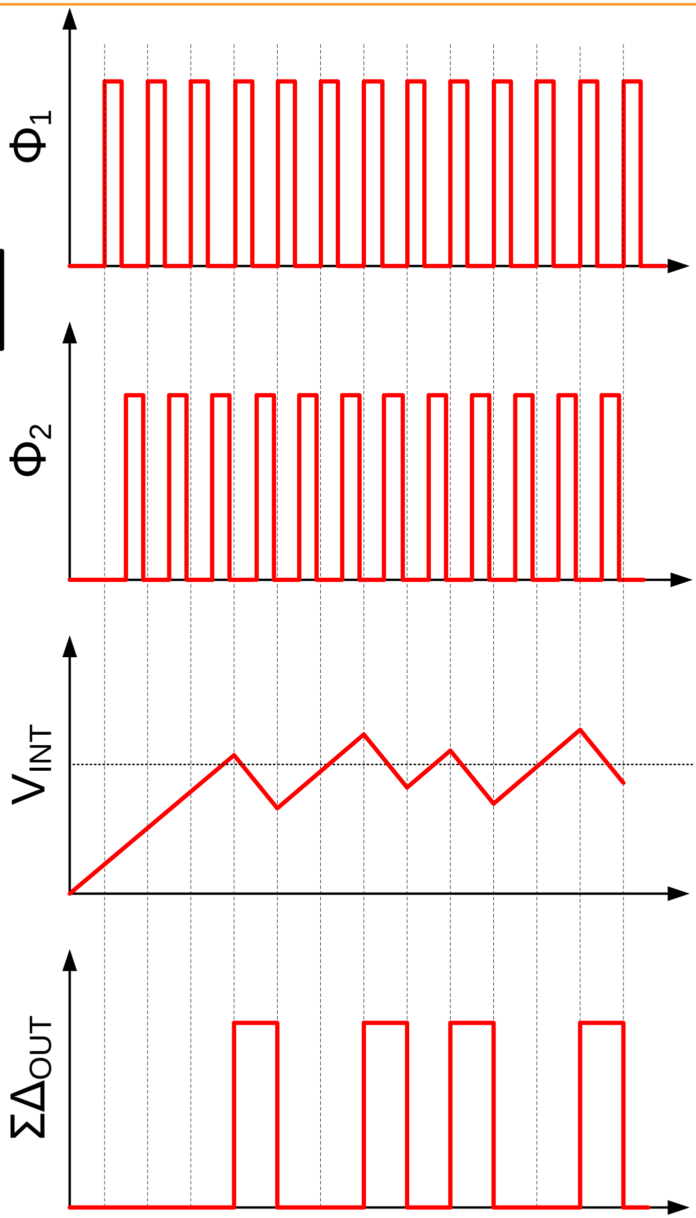




- Duty cycle of comparator output ($\Sigma\Delta_{OUT}$) is proportional to pressure
- 10,000:1 decimation filter is used to digitize $\Sigma\Delta_{OUT}$

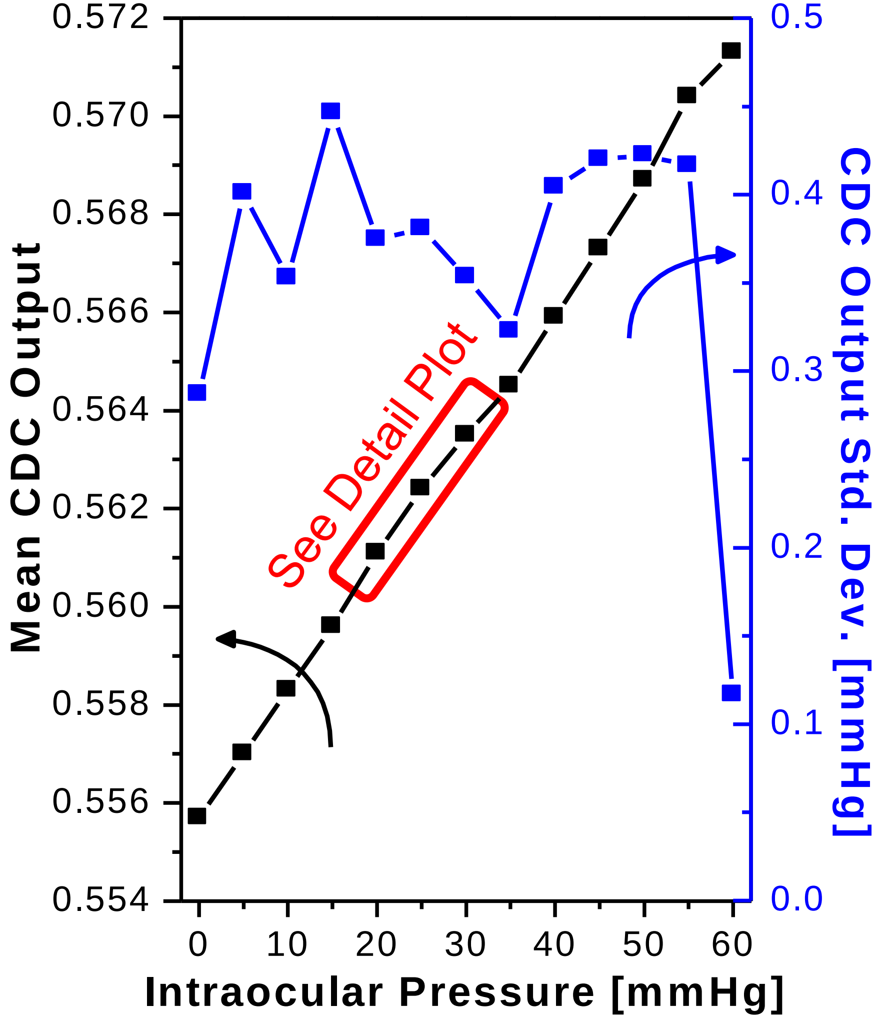
ΣΔ Capacitance to Digital Converter

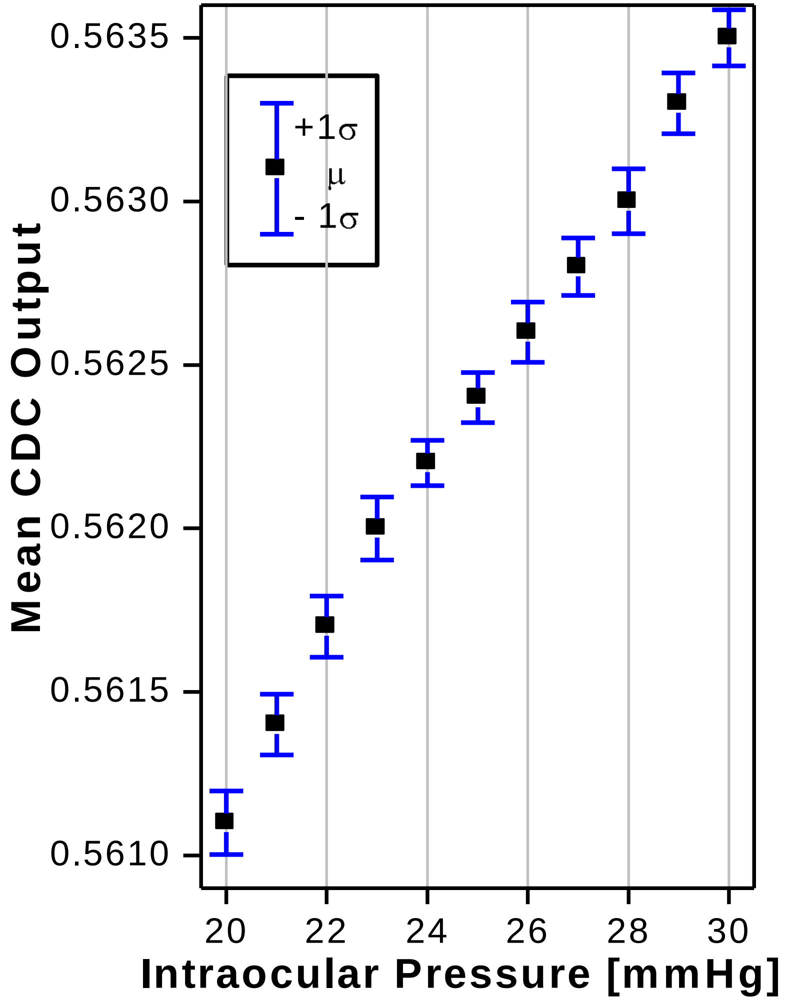




- ΣΔ modulator averages out temporal and quantization noise
- Compares ratio of currents for lower sensitivity to clock, voltage

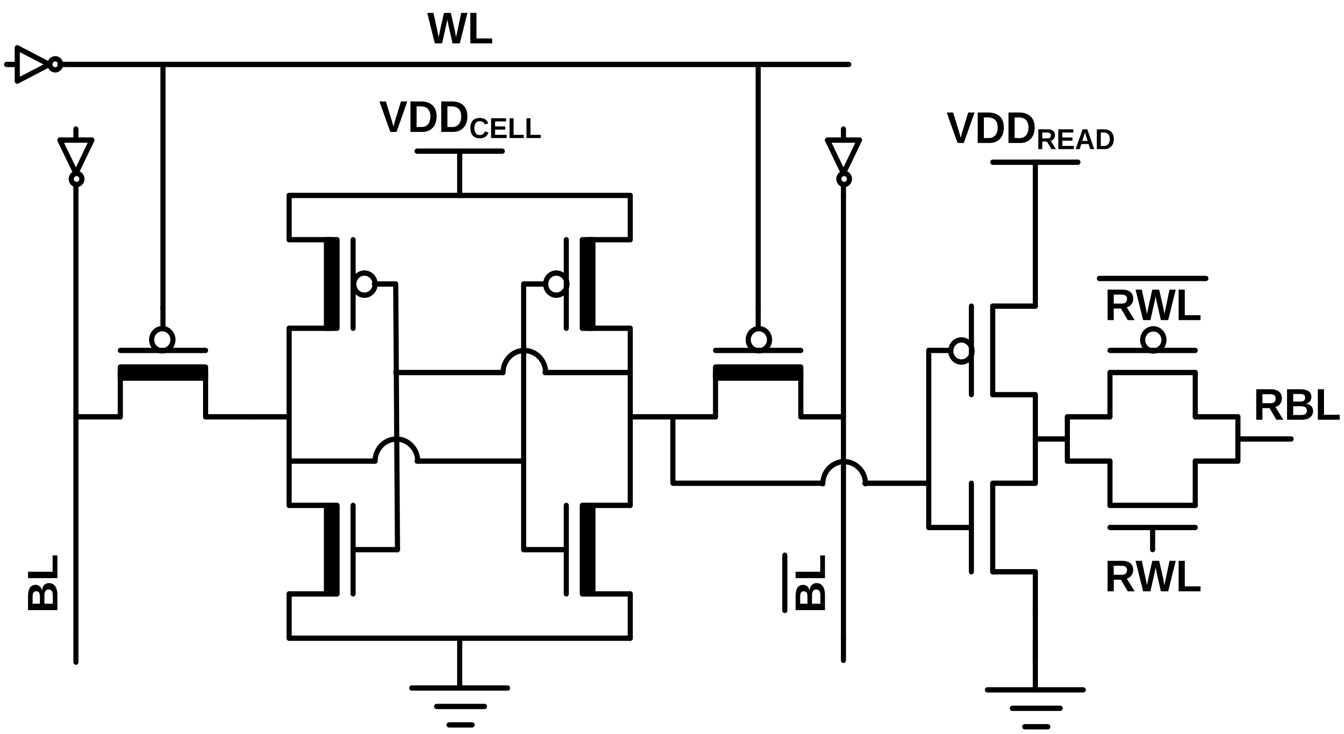
Capacitance to Digital Results





- DNL = 0.31 LSB, INL = 1.54 LSB
- 0.5 mmHg pressure resolution is 2x better than tonometry

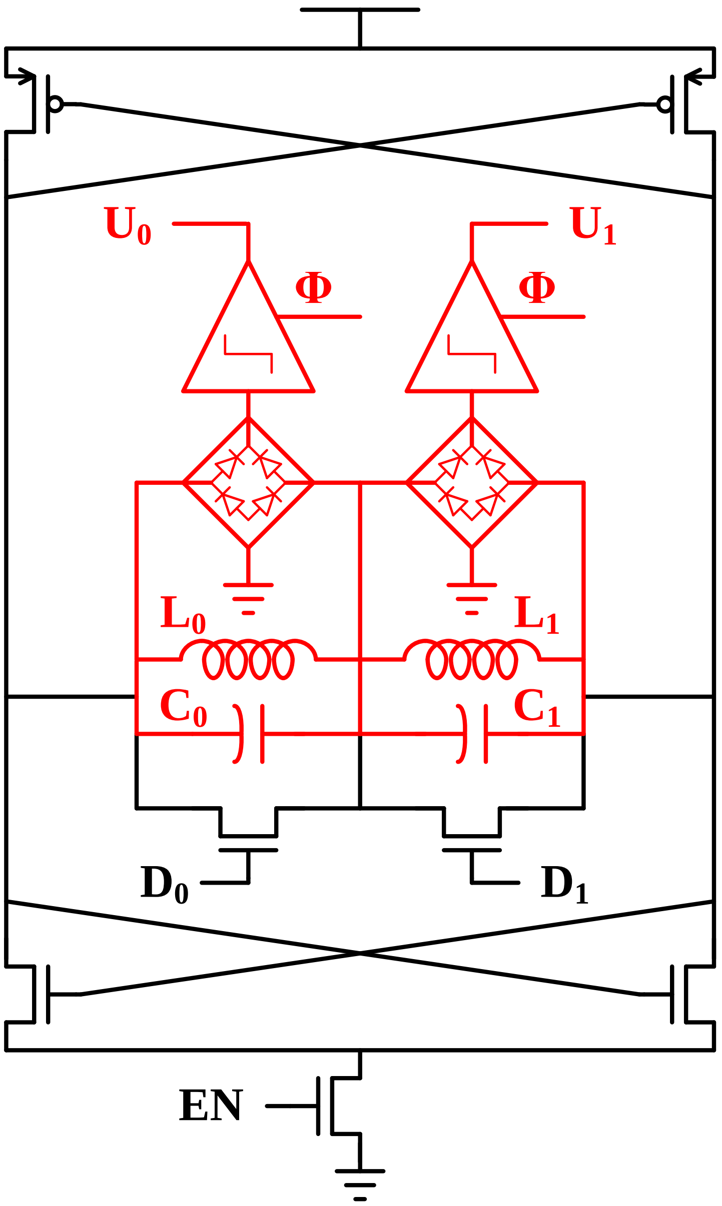
Processor and SRAM



- CDC completion signal wakes up 8-bit processor
- Reads IOP data from memory-mapped location
- Performs DSP, such as detection of dangerously high IOP
- Stores data into a 4 kb, 2.4 fW/bitcell SRAM
- Coordinates communication with wireless transceiver

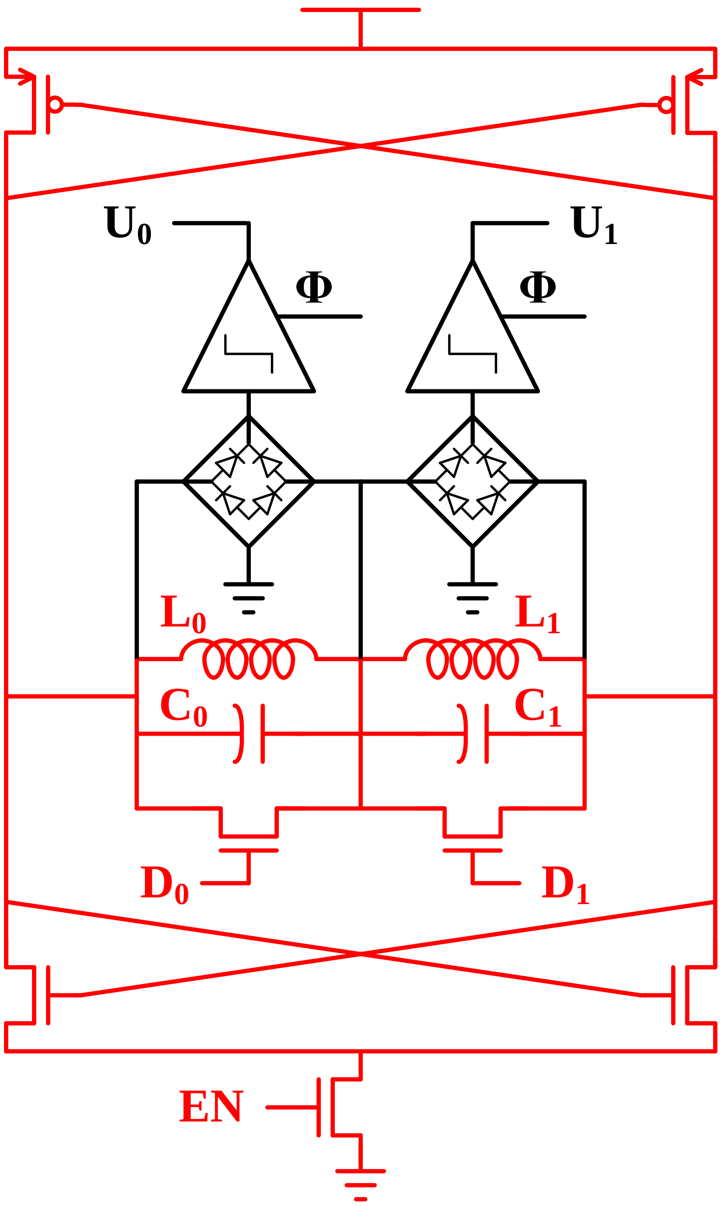
Wireless Receiver

- Fully-integrated transceiver (TRx)
  - FSK within ISM bands
  - Tones at 433 MHz, 900 MHz
- Dual-resonator LC tanks
  - Lower false positive rate than two separate LC tanks
- 4-stage full-bridge rectifiers
  - 20 mV output with 1 W device placed 4 mm over eyelid
- Comparators generate full-range wakeup/programming signals
  - Clocked with 50 Hz 31 pW leakage-based oscillator

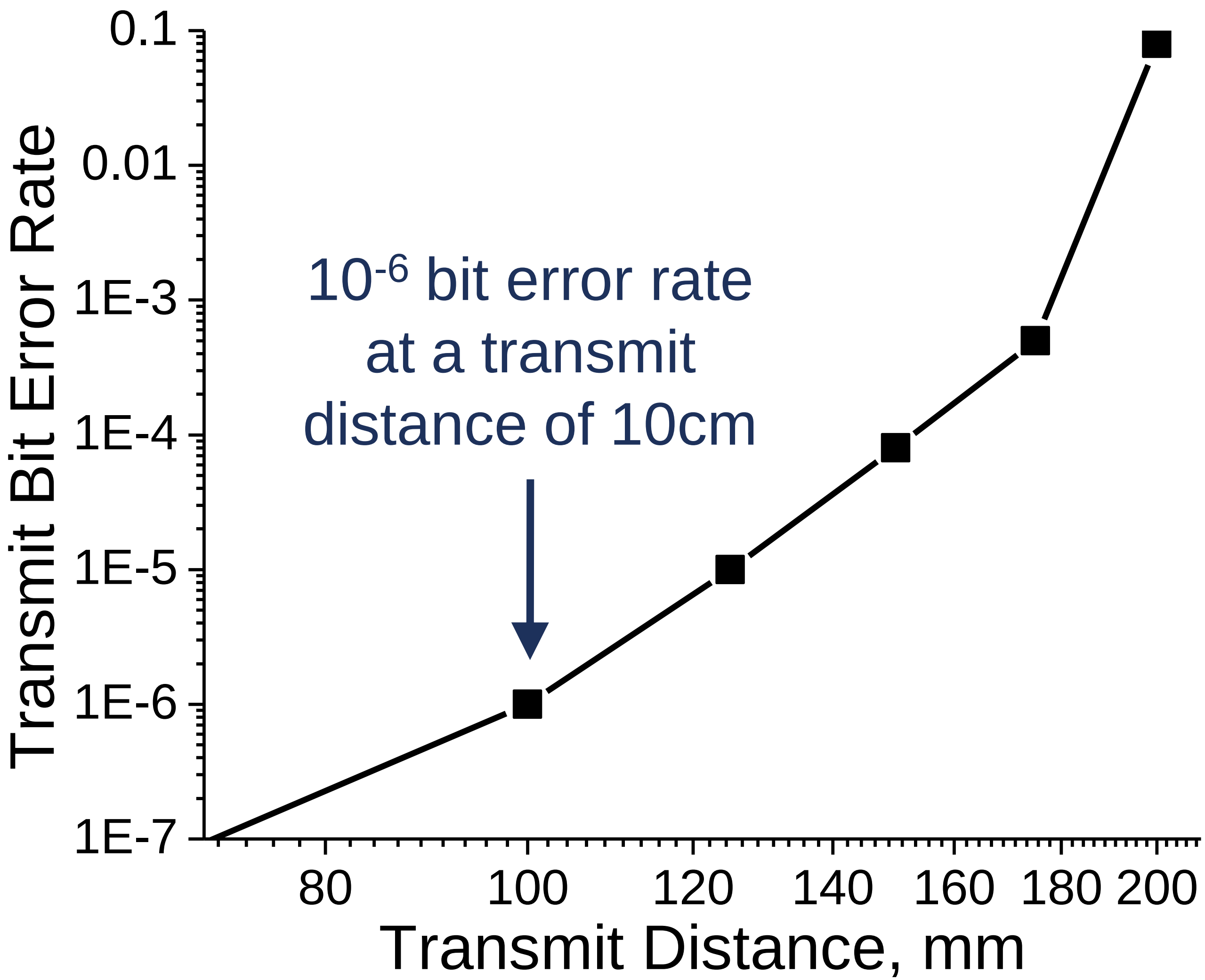


Wireless Transmitter

- Architecture combines local oscillator and power amplifier
  - Fewer inductors and lower area
  - Inductors must be large to radiate maximum power
  - Lower Q than typical LOs
- High quality factor dual-resonator
  - Higher frequency separation than single-tank with varactor
  - Tolerates larger phase noise
  - Smaller than two separate tanks
  - One tank shorted based on value of transmitted bit



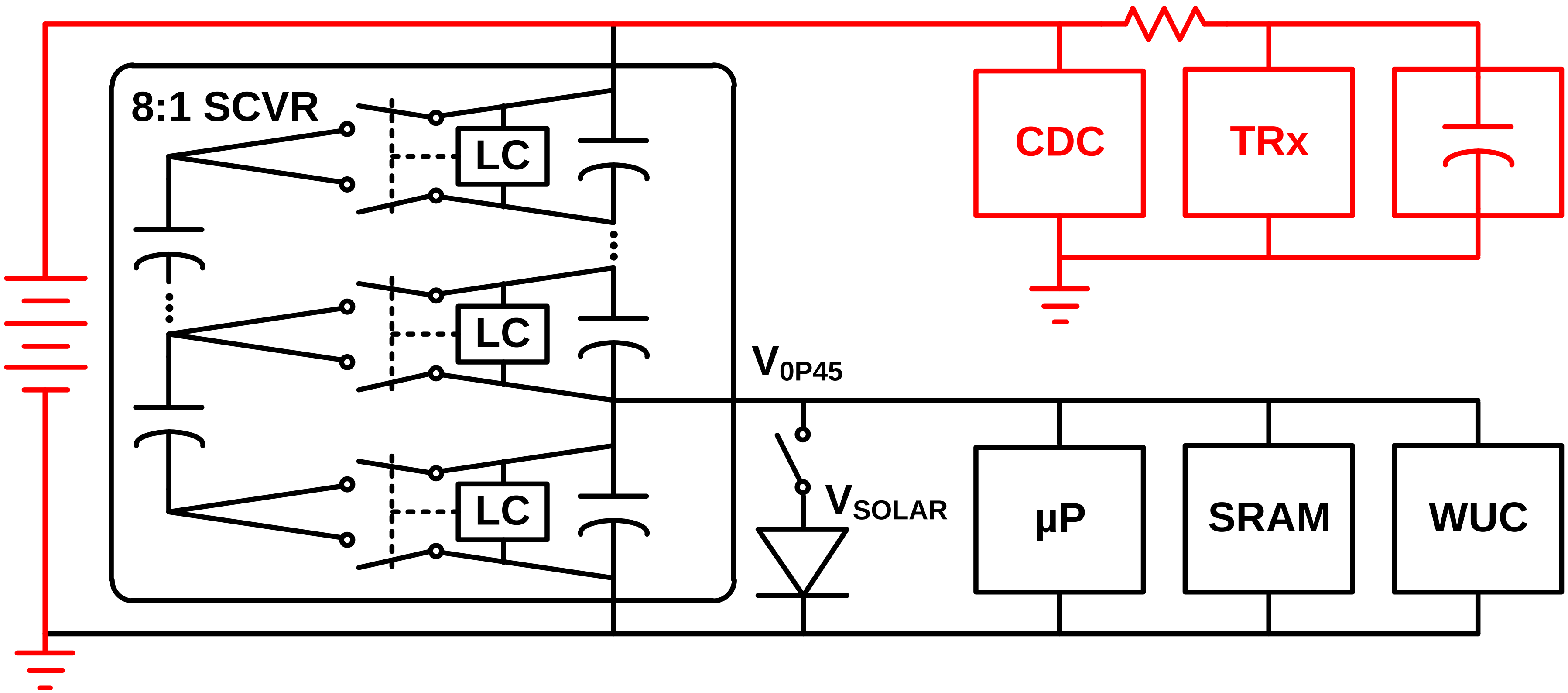
Transmitter Results



- Transmit media is 0.5 mm saline and air to represent the aqueous humor and distance between eye and external device

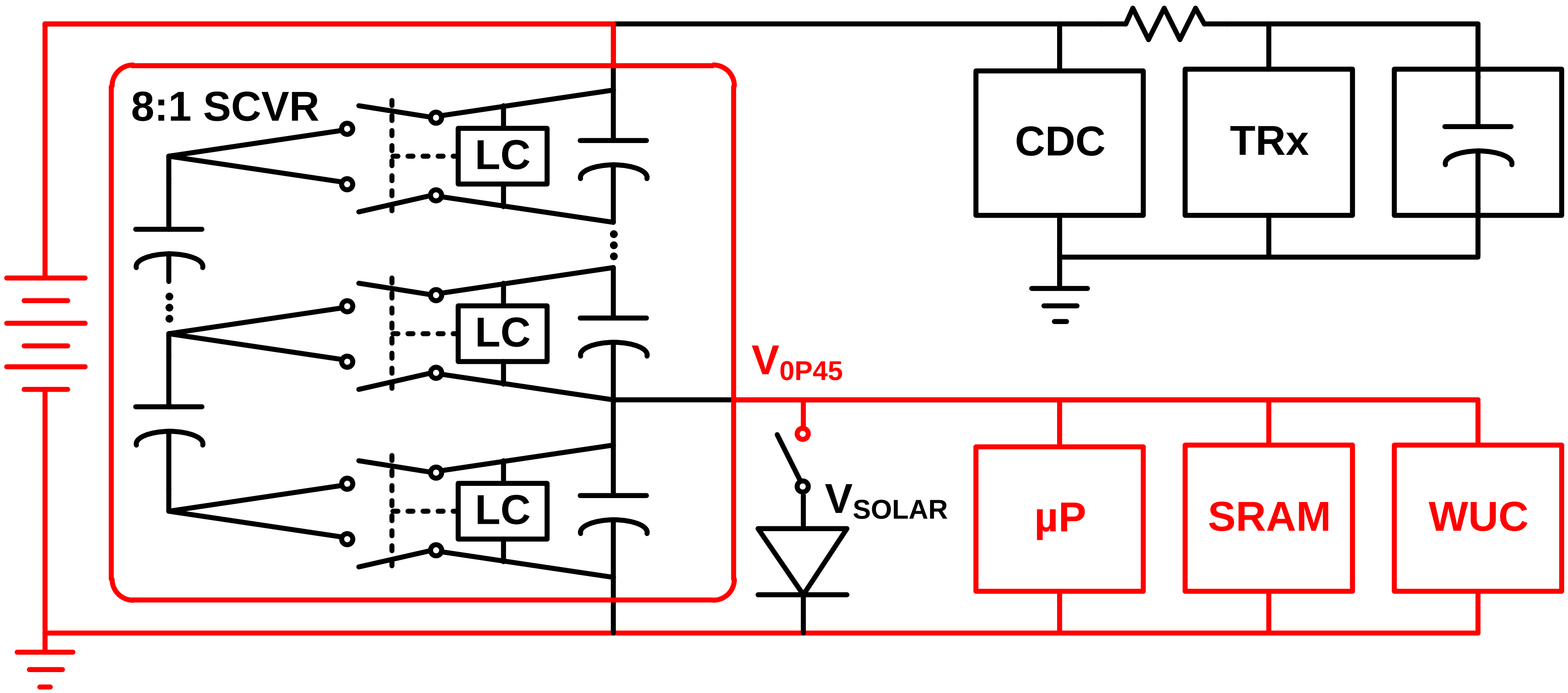
Power Delivery and Management

- Battery powers CDC and wireless TRx
- Isolated local TRx power supply prevents catastrophic V_{DD} drop
- CDC and TRx designed with high-V_{TH} thick-t_{OX} IO devices and no bias currents for low leakage during standby mode



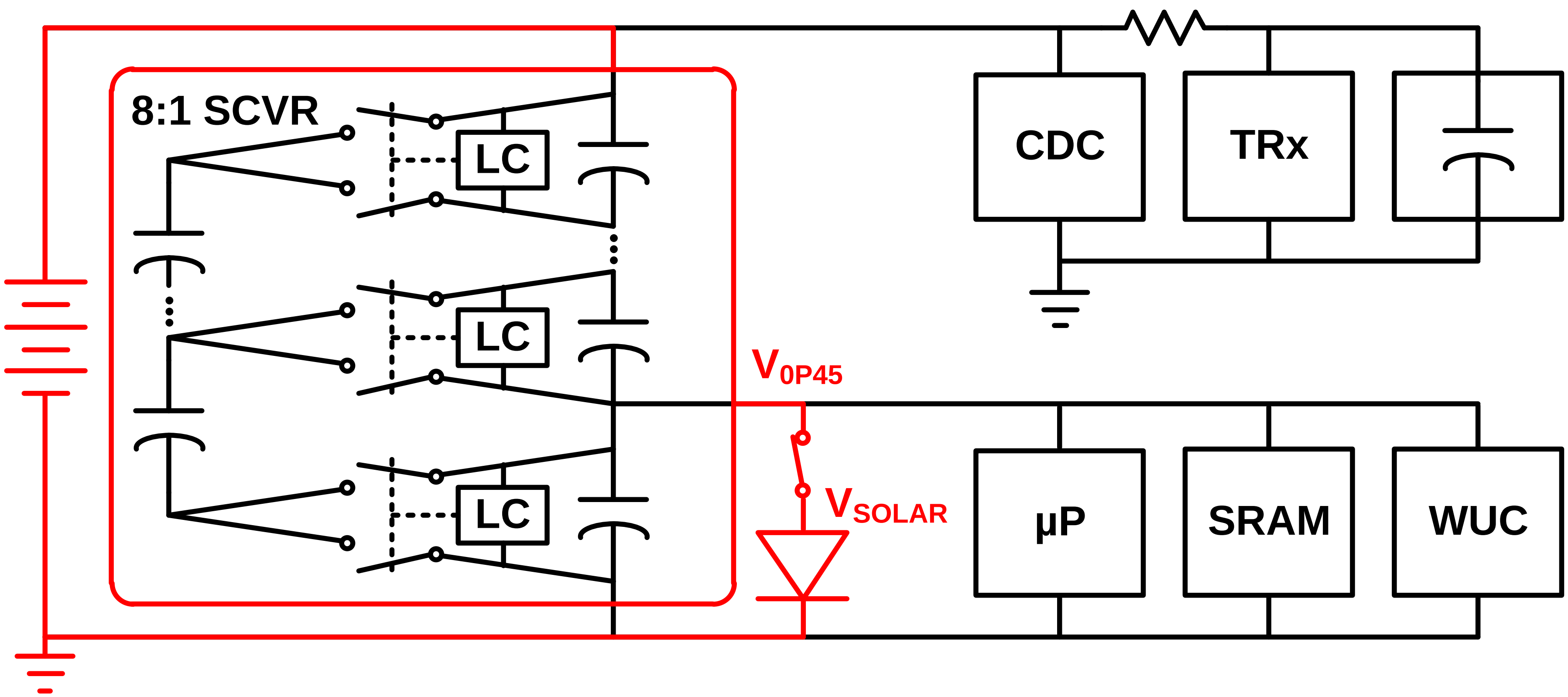
Power Delivery and Management

- 8:1 Switch Cap Voltage Regulator (SCVR) delivers 0.45 V
- µP is power gated in standby mode and uses logic devices
- SRAM and WUC use IO devices for low standby leakage
- SCVR clock is reduced to 50 Hz clock in standby mode

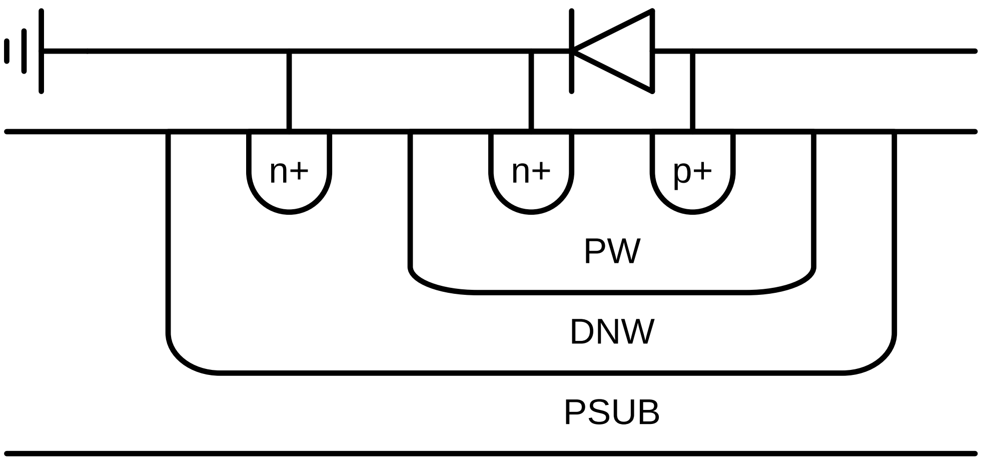


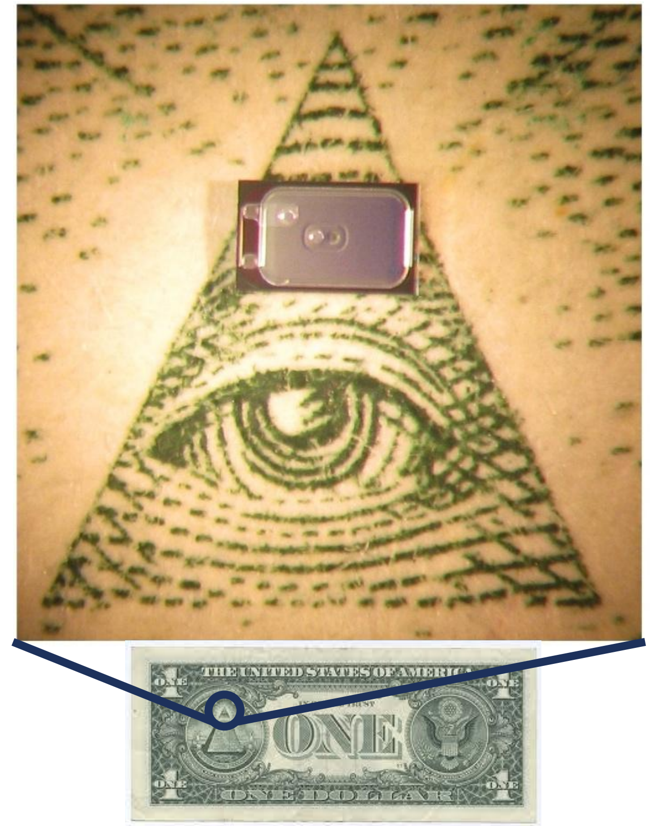
Power Delivery and Management

- Solar cell connected when open circuit V_{SOLAR} exceeds V_{0P45}
  - Check voltage on solar cell with small replica
  - Compare using clocked variable offset comparator
- SCN up-converts solar energy to recharge the battery



Power Sources

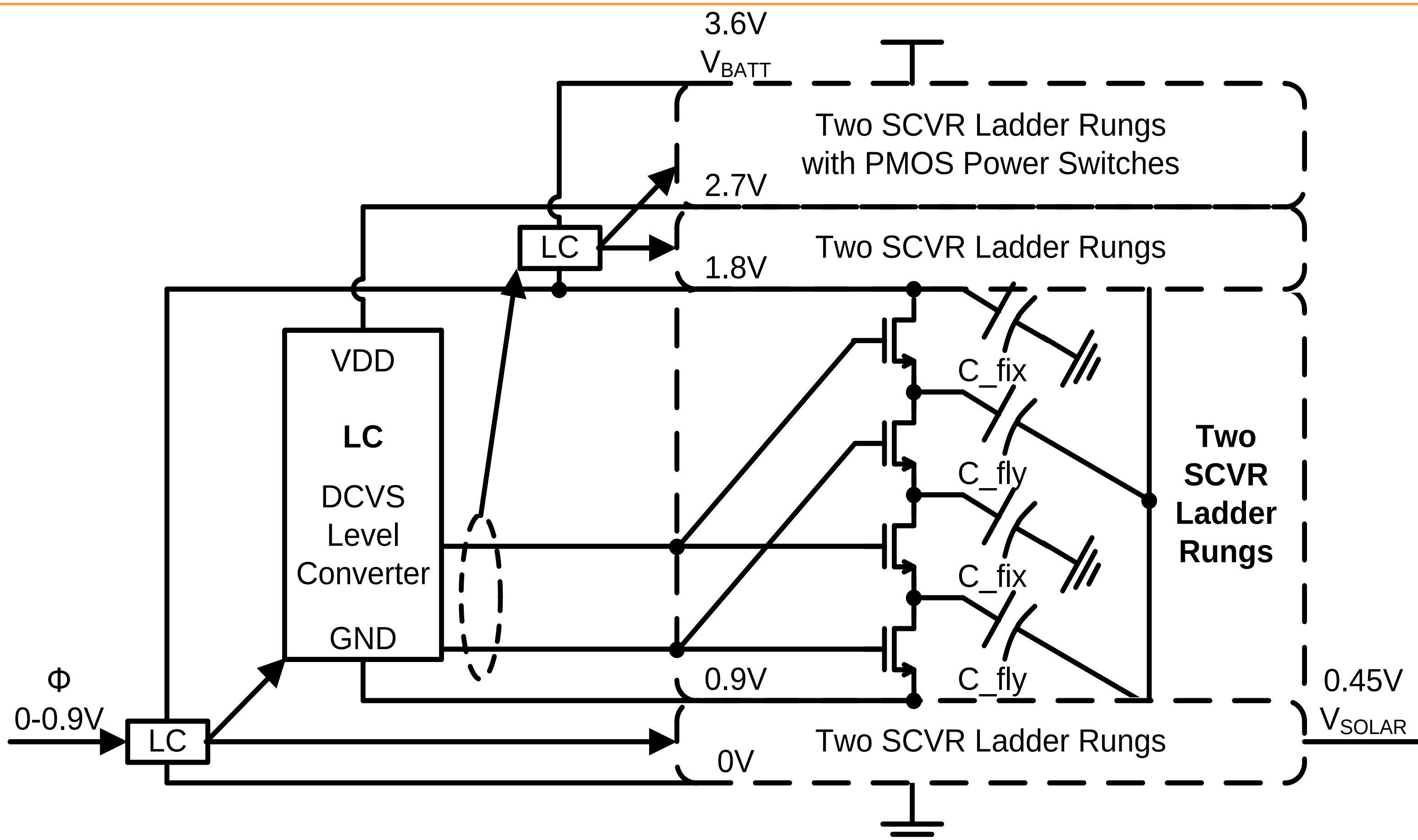




- 0.07 mm^2 solar cell
- 0.18 µm CMOS
- 5% solar efficiency
- Removed nitride and silicide

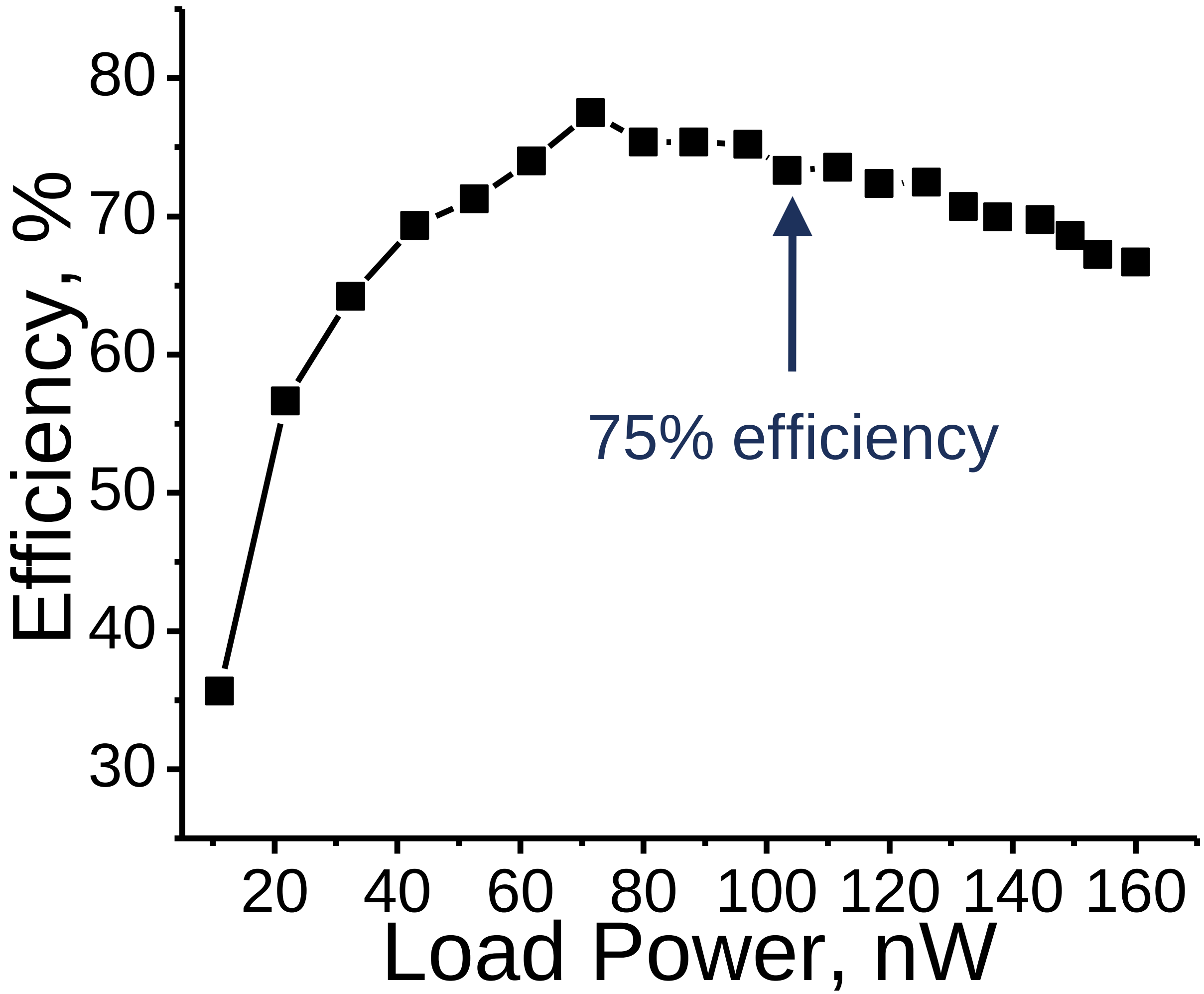
- Cymbet thin-film Li battery
- 1 mm^2 custom size
- 1µAh capacity
- 40µW peak power

8:1 Ladder SCVR



- 0.32 mm^2 with 35 pF MOS fixed caps, 45 pF MIM flying caps
- Minimum-sized IO device switches for low standby leakage
- 1.8 V clocks with level converters reduce switching overhead

SCVR Measurements



- 75% efficiency with 100 nW processor load in active mode
- 40% efficiency with 72 pW load in standby mode

IOP Monitor Power Consumption

- Measure IOP every 15 minutes with 10k:1 decimation filter
- DSP with 10k processor cycles @ 100 kHz per measurement
- Daily wireless transmission of 1344b raw IOP data

Active Mode	**Power**	**Time/Day**	**Energy/Day**
CDC	7.0 µW	19.2 sec	**134.8 µJ**
Transceiver	47.0 mW	134.4 µsec	**6.3 µJ**
SCVR	116.9 nW	19.2 sec	**2.2 µJ**
• µP @ 100 kHz	90.0 nW	19.2 sec	**1.7 µJ**
Standby Mode	**Power**	**Time/Day**	**Energy/Day**
CDC	172.8 pW	24 hours	**14.9 µJ**
Transceiver	3.3 nW	24 hours	**285.1 µJ**
SCVR	174.8 pW	24 hours	**15.1 µJ**
• 4kb SRAM	9.8 pW	24 hours	**846.7 nJ**
• WUC	62.0 pW	24 hours	**5.2 µJ**

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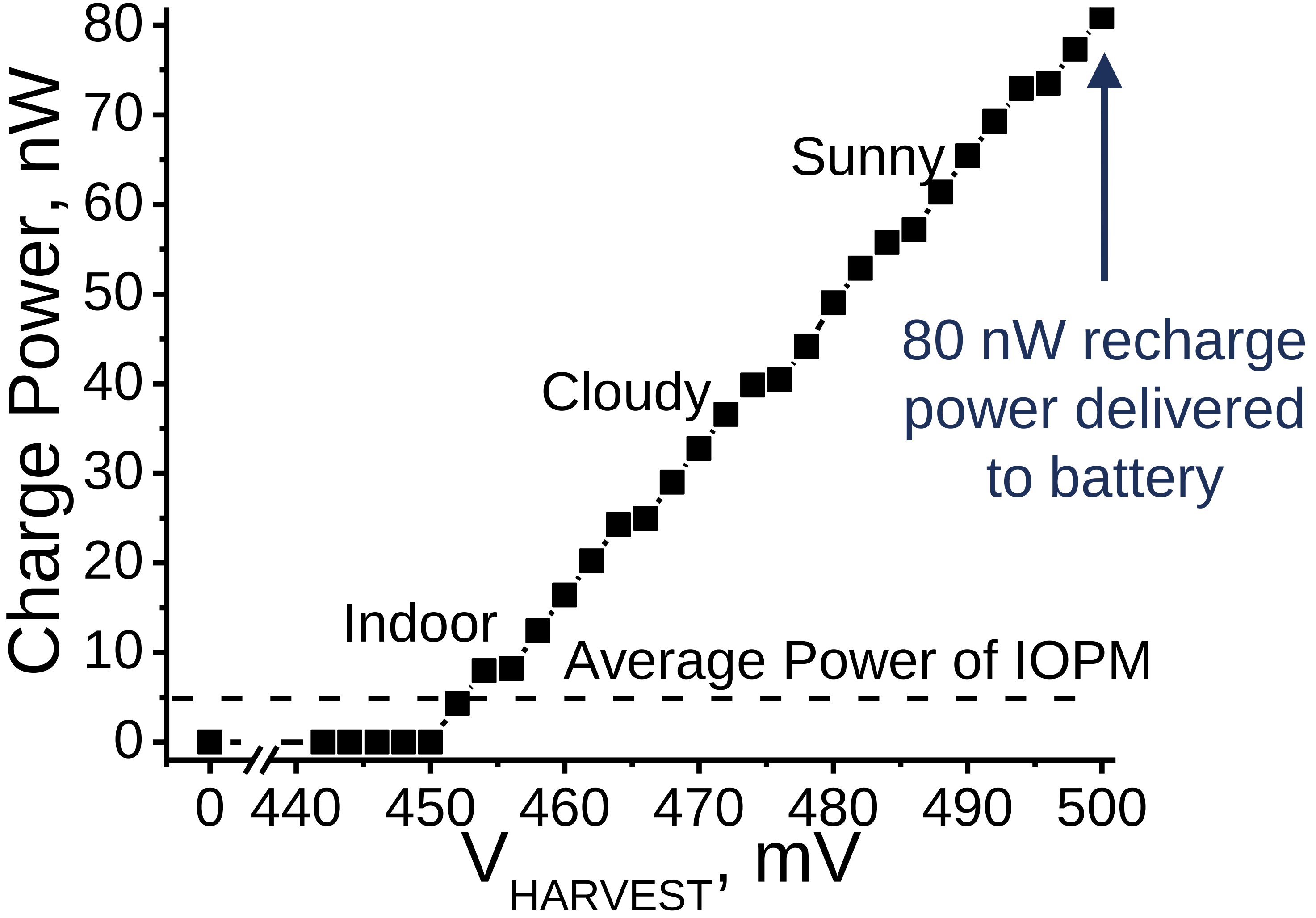
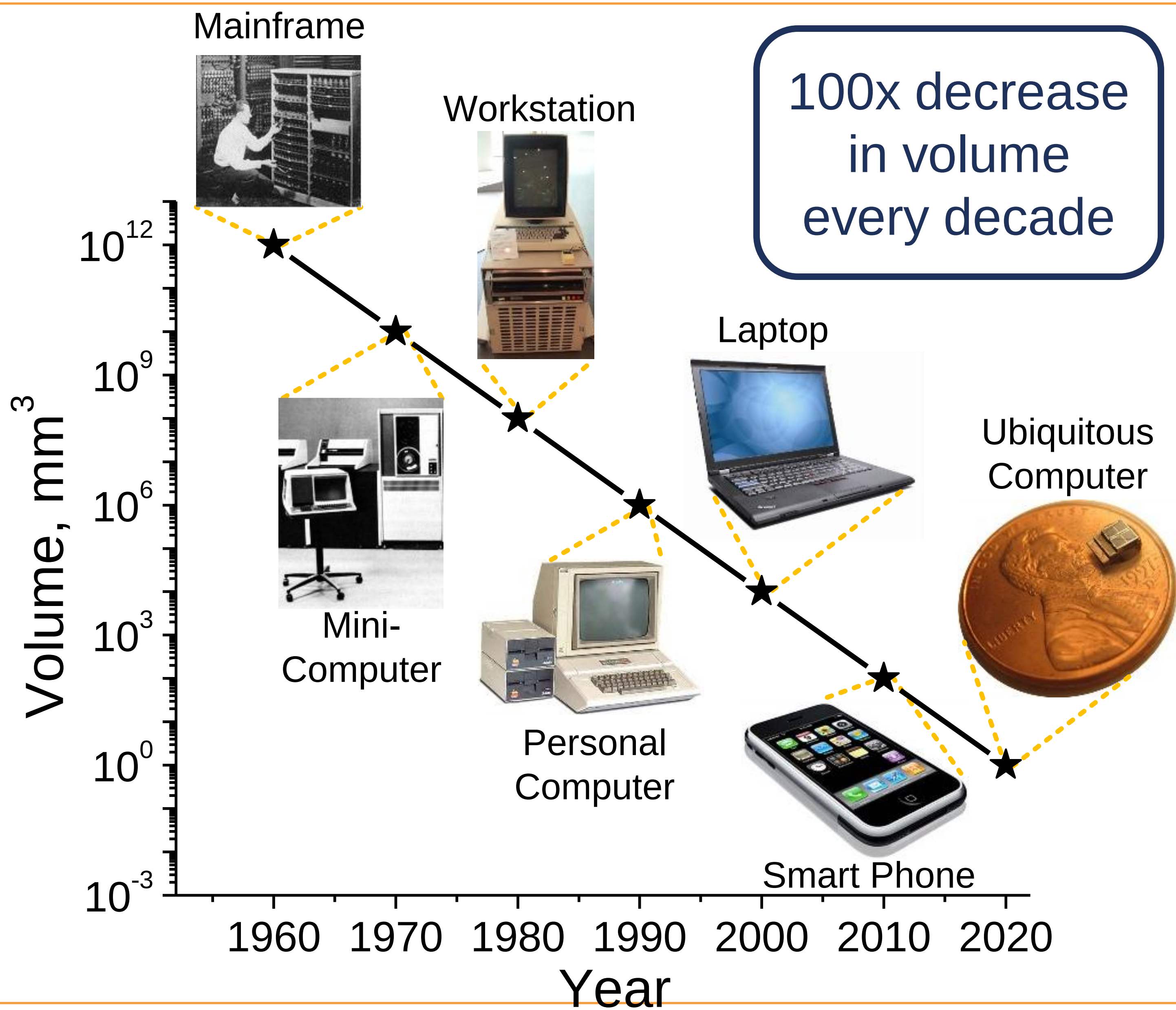
5.3 nW average power -> 28 day lifetime with no harvesting

PMU Measurements



- Energy autonomous operation with 1.5 hours of sunlight or 10 hours of indoor lighting per day

Bell's Law



100x decrease in volume every decade

Thank you