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

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

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

Power Budget Challenges

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

<table>
<thead>
<tr>
<th>Battery</th>
<th>Peak Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>AA Alkaline</td>
<td>1.5 W</td>
</tr>
<tr>
<td>4.8 mm Li Coin</td>
<td>600 µW</td>
</tr>
<tr>
<td>1 mm² Thin-Film Li</td>
<td>40 µW</td>
</tr>
<tr>
<td>1 mm³ Harvester</td>
<td>80 nW</td>
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</tbody>
</table>
1.5 mm³ 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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- Measure IOP every 15 minutes
- Interval set with 31 pW leakage-based oscillator in Bottom Wakeup Controller (WUC)
IOP Monitor Usage Model

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- Extract and store medical data
  - μP wakes up from power-gated standby mode and stores data in 2.4 fW/bit SRAM
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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
- 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 $C_{INT}$
Voltage on integration capacitor \((V_{\text{INT}})\) is compared with reference \((V_{\text{DD}}/2)\)

- Fixed current is disabled when \(V_{\text{INT}}\) is higher than \(V_{\text{DD}}/2\)
Duty cycle of comparator output ($\Sigma\Delta_{OUT}$) is proportional to pressure

10,000:1 decimation filter is used to digitize $\Sigma\Delta_{OUT}$
- $\Sigma\Delta$ 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.

- 10^{-6} bit error rate at a transmit distance of 10cm.
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 $V_{\text{SOLAR}}$ 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 mm² solar cell
- 0.18 μm CMOS
- 5% solar efficiency
- Removed nitride and silicide

- Cymbet thin-film Li battery
- 1 mm² custom size
- 1μAh capacity
- 40μW peak power
- 0.32 mm² 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

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<tr>
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<th>Time/Day</th>
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<tr>
<td>CDC</td>
<td>7.0 µW</td>
<td>19.2 sec</td>
<td>134.8 µJ</td>
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<tr>
<td>Transceiver</td>
<td>47.0 mW</td>
<td>134.4 µsec</td>
<td>6.3 µJ</td>
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<td>SCVR</td>
<td>116.9 nW</td>
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<tr>
<td>(\mu P \text{ @ 100 kHz})</td>
<td>90.0 nW</td>
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<td>1.7 µJ</td>
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<tr>
<td>CDC</td>
<td>172.8 pW</td>
<td>24 hours</td>
<td>14.9 µJ</td>
<td></td>
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<tr>
<td>Transceiver</td>
<td>3.3 nW</td>
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<td>285.1 µJ</td>
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<td>15.1 µJ</td>
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<tr>
<td>(4\text{kb SRAM})</td>
<td>9.8 pW</td>
<td>24 hours</td>
<td>846.7 nJ</td>
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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

80 nW recharge power delivered to battery
Bell’s Law

100x decrease in volume every decade
Thank you