17.6 A Cubic-Millimeter Energy-Autonomous Wireless Intraocular Pressure Monitor

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

University of Michigan, Ann Arbor, MI

Glaucoma is the leading cause of blindness, affecting 67 million people worldwide [1]. The disease damages the optic nerve due to elevated intraocular pressure (IOP) and can cause complete vision loss if untreated. IOP is commonly assessed using a single tonometric measurement, which provides a limited view since IOP fluctuates with circadian rhythms and physical activity. Continuous measurement can be achieved with an implanted monitor to improve treatment regimens, assess patient compliance to medication schedules, and prevent unnecessary vision loss. The most suitable implantation location is the anterior chamber of the eye, which is surgically accessible and out of the field of vision. The desired IOP monitor (IOPM) volume is limited to 1.5mm$^3$ (0.5×1.5×2mm$^3$) since IOP fluctuates with circadian rhythms and physical activity. Continuous measurement can be achieved with an implanted monitor to improve treatment regimens, assess patient compliance to medication schedules, and prevent unnecessary vision loss. The most suitable implantation location is the anterior chamber of the eye, which is surgically accessible and out of the field of vision. The desired IOP monitor (IOPM) volume is limited to 1.5mm$^3$ (0.5×1.5×2mm$^3$)

The IOPM measures IOP every 15 minutes using a MEMS capacitive pressure sensor connected to a 7μW 3.6V CDC with through-glass interconnects (Fig. 17.6.2) [4]. The measurement interval represents continuous monitoring, does not need to be exact for medical diagnosis [3], and is controlled by a slow timer in the wake-up controller (WUC) [5]. The CDC generates an IOP-dependent current by dropping VDD/2-VTH across an impedance generated by switching the MEMS pressure sensor ($\Delta V_{MEMS}$) at 50kHz. Simultaneously, a larger fixed current is generated in the same manner with the clock and fixed capacitors ($C_1$, $C_2$). Two capacitors with out-of-phase clocks are used to generate a more constant current source. This fixed current is mirrored and compared to the size of a self-healing incision, curvature of the cornea, and dilation of the pupil. Previously, a 5.4mm$^3$ (6×3×0.3mm$^3$) sensor was demonstrated with a pressure resolution of 0.5mmHg, which exceeds the 1mmHg used in the upon accurate measurement. The desired IOP monitor (IOPM) lifetime is years to converge on a suitable glaucoma treatment. However, the anterior chamber volume limits lifetime by constraining the size and capacity of the microsystem's power sources [7]. The IOPM uses a custom 1μAh thin-film Li battery from Cymbet. The lifetime is 28 days with no energy harvesting. To extend lifetime, the IOPM harvests light energy entering the eye with an integrated 0.07mm$^3$ solar cell and recharges the battery. Given the ultra-small solar cell size, energy autonomy requires average power consumption of <10μW. Processor power is reduced using subthreshold operation and delivered using an SCN with 75% efficiency (Fig. 17.6.6). The SCN uses reduced swing clocks and level converters (LCs). While IOP measurements and wireless transmissions require μWs and mWs of power, these events are short and infrequent. When CDC and radio circuits are idle, their power consumption drops to 172.8pW and 3.3nW, respectively. For the majority of its lifetime the IOPM is in a 3.65nW standby mode where mixed-signal circuits are disabled, digital logic is power-gated, and 2.4W/bit cellular RAM retains IOP instructions and data [5]. The average system power with pressure measurements every 15 minutes and daily wireless data transmissions, is 3.3nW. When sunny, the solar cells supply 80.6nW to the battery. The combination of energy harvesting and low-power operation allows the IOPM to achieve zero-net energy operation in low light. The IOPM requires 10 hours of indoor lighting or 1.5 hours of sunlight per day to achieve energy-autonomy.

Acknowledgments:
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References:
Figure 17.6.1: The IOPM contains a MEMS pressure sensor, integrated solar cell, and microbattery in a biocompatible enclosure. Its cubic-millimeter size enables implantation through a minimally invasive incision.

Figure 17.6.2: The capacitance to digital converter compares pressure-dependent and fixed currents using $\Delta\Sigma$ modulation. The design style provides independence to supply voltage and clock frequency uncertainty.

Figure 17.6.3: Measured results demonstrate CDC performance. The IOPM exceeds typical measurement techniques by achieving 0.5 mmHg pressure resolution.

Figure 17.6.4: The series-connected LC tanks: (1) enable greater frequency separation than a single tank transmitter, relaxing phase noise requirements, and (2) reduce area compared to two separate LC tanks.

Figure 17.6.5: The IOPM is activated when it receives and rectifies the wireless wake up signal. The device then transmits pressure data with a BER of less than $10^{-6}$.

Figure 17.6.6: IOPM power consumption is 5.3 nW with the expected usage model. Energy autonomy is achieved with a 0.07 mm$^2$ solar cell that supplies 80.6 nW to the battery. Battery life without recharge is 28 days.
Figure 17.6.7: Die photographs for the bottom and top chips as defined in Figure 17.6.1, both fabricated in 0.18µm CMOS.