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

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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 1.5mm³ (0.5×1.5×2mm³) since IOPM size and capacity of the microsystem's power sources [7]. The IOPM uses a custom 1μm thin-film Li battery for this application. The IOPM harvests solar energy that enters the eye through the transparent cornea to achieve energy-autonomy. The microsystem contains an integrated solar cell, thin-film Li battery, MEMS capacitive sensor, and integrated circuits vertically assembled in a biocompatible glass housing (Fig. 17.6.1). The circuits include a wireless transceiver, capacitive to digital converter (CDC), DC-DC switched capacitor network (SCN), microcontroller (μP), and memory fabricated in 0.18μm CMOS.

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 wakeup controller (WUC) [5]. The CDC generates an IOP-dependent current by dropping VDD/2-VTH (VREF) across an impedance generated by switching the MEMS pressure sensor (GMEMS) at 50kHz. Simultaneously, a larger fixed current is generated in the same manner with the same clock and fixed capacitors (C1, C2). 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 IOP-dependent current using ΔΣ modulation to digitize IOP. The IOP-dependent current is integrated by discharging capacitor CINT. The voltage on CINT (VIN) is compared to VREF with a clocked comparator. When VIN drops below VREF, the fixed current is also integrated onto CINT, increasing VIN. The CDC achieves a pressure resolution of 0.5mmHg, which exceeds the 1mmHg 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 powered-gated, and 2.4W/bitcell SRAM 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.

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References:
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. 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. Measured results demonstrate CDC performance. The IOPM exceeds typical measurement techniques by achieving 0.5mmHg pressure resolution. 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 $10^{-6}$. IOPM power consumption is 5.3nW with the expected usage model. Energy autonomy is achieved with a 0.07mm$^2$ solar cell that supplies 80.6nW 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.