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主　論　文　の　要　旨

論文題目　**Study on CMOS LSI Systems for Solar-Cell-Powered Continuous Glucose Monitoring Contact Lenses**
(太陽光発電駆動型持続血糖モニタコンタクトレンズのための CMOS LSI システムに関する研究)

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論　文　内　容　の　要　旨

This dissertation focuses on developing next-generation smart contact lenses for continuous glucose monitoring (CGM) applications. As the number of people with diabetes increases around the world, people are desiring a non-invasive glucose monitor as a substitute for the finger-pricking method. As CMOS techniques evolve generation by generation, LSI systems are becoming more versatile, miniaturized, energy-efficient, and across-multi-discipline, making our society smarter than ever before, which makes biomolecule-based healthcare devices rushing into our daily life. As a product of interdisciplinary science and engineering, CGM contact lenses have gone through 2 generations since their birth in the 2010s., and have been advanced to be smaller, smarter, and more accurate. They are brought closer to practical applications by researchers and developers. This dissertation started with Generation 2 CGM contact lenses which can actively communicate with data receivers, and explored a new paradigm of stand-alone CGM contact lenses.

Due to the size constraints, the big challenge is the power supply for the CGM contact lenses. Some RFID-based prior studies employed wireless RF power transfer to operate the systems on a contact lens. However, an external device, such as smart glasses or a neck-type charger transmitting power at a distance of 1–15 cm, is required, which degrades the comfort and eye health of the users. In addition, wireless power transfer is lossy, incurring low energy efficiency. This research proposes to utilize solar cell-based energy harvesters to power the CGM system, which eliminates the necessity of RF power transfer. Solar power with high power density brings more possibilities and functions to CGM contact lenses. In addition, this research improves the information communication of CGM contact lenses, to make them user-friendly.

Some previous works employed potentiostat + ADC as an analog front end for CGM contact lenses. However, these sensor readout blocks are power-hungry at 0.4–0.5 µW and hard to scale down further. Recently, a new design philosophy is proposed to reduce power consumption, utilizing a combination of a biofuel cell (BFC) and a supply voltage monitor (SVM) to transduce the voltage of the BFC to a digital code. The SVM + BFC consumes nW-level power because the BFCs can leverage the power from glucose and generate a voltage/current by themselves. Then, a part of the power load is transferred from the core IC to the BFCs. In addition, BFCs can be physically scaled down to sub-mm^2 due to the evolution of new materials but potentiostats can not. Therefore, SVM + BFC can be a new solution to a miniaturized next-generation CGM system.

This dissertation overviewed three solar cell-powered BFC-input LSI systems for next-generation CGM contact lenses which are able to transmit information actively and even alert the users of hypoglycemia directly. The target of this dissertation is to demonstrate the feasibility of solar cell-powered CGM contact lenses which can achieve stand-alone operation with fewer external devices. Based on the results of these works, the design trade-offs of CGM contact lenses will be clearer to researchers and engineers.

Chapter II presents a fully-integrated LSI system for CGM contact lenses. The implemented chip in a 65 nm CMOS process contains an energy harvester, SVM, wireless transmitter, and on-chip antenna. Cooperating with a BFC generating power from glucose, it's the first attempt at introducing solar energy harvesting to a BFC-combined biosensing system for joint power supply. The major contributions of this work include 1) a fully-on-chip design of low implementation cost, with a total area of 0.413 mm^2; 2) a new paradigm demonstration that paves the way to a solar cell-powered BFC-input LSI system for stand-alone CGM contact lens; 3) 89% area reduction compared to BFC-powered biosensing system by utilizing solar cell, making the system compatible with a 0.45 mm^2 glucose BFC; 4) 3.4× increased power density of solar cell at a dim light environment (200 lx) by adopting a triple-well CMOS photodiode design which is normally available in CMOS process; 5) low power consumption of 1.58 nW which can be covered by a 0.3 mm^2 on-chip solar cell.

Chapter III proposes a solar cell-powered BFC-input biosensing system for CGM contact lenses with an off-chip antenna for long-distance wireless communication. Constrained by available power density and energy density without a battery, the previous CGM contact lens suffers from short communication distance. The new architecture solves this issue by solar cell-based energy harvesting, cooperating with a 10-nF capacitor and a 3 mm × 4 mm antenna which maximizes the radiation power to extend the communication distance. The major contributions of this work include 1) extension of wireless communication distance between CGM contact lenses and handsets up to 40 cm for the first time for a battery-less system; 2) a novel 2-D modulation combining frequency-shift-keying (FSK) and pulse interval modulation (PIM) to send the voltage information of both solar cell and BFC, which can mitigate the interference from unstable solar power; 3) improvement of voltage monitor from SVM to make it able to operate at lower supply voltage and reduce power consumption.

Chapter IV prototypes a solar cell-powered BFC-input CGM contact lens with an LED for direct hyperglycemia/hypoglycemia warning. To remove RF communication, the adoption of an LED achieves localized information display. Cooperating with localized power generation by solar cells, the system becomes fully stand-alone without any external devices. The major contributions of this work include 1) the first demonstration of a fully stand-alone RF-less CGM contact lens with localized power generation and localized information display; 2) LED driving capability for emergency cases without wireless power transfer, eliminating the necessity of glasses and data receivers, which is user-friendly for type 1 diabetes; 3) multi-stage buffer drivers to switch on the LED without level shifters or regulators, realizing 4-V voltage up-conversion for efficiency LED light emission; 4) improvement of BFC-input approach to reduce power consumption further; 5) energy harvesting at the light intensity of 800 lx which is a typical indoor ambient-light environment.

Chapter V summarizes and concludes the contributions of these LSI systems, and also discusses related works and future directions of next-generation CGM contact lenses. First, the glucose readout analog blocks still face challenges on how to optimize the trade-off between power, area, and accuracy, which is always a classic subject in the world of analog circuit design. Second, a powerful BFC is desired in CGM contact lenses to leverage the glucose in tears. Third, a new customized memory circuit for low-power low-voltage sensors is necessary to advance the intelligence of CGM contact lenses. Last but not least, the LSI systems for CGM contact lens applications can benefit from advanced CMOS process nodes, to bring us a high-power density solar cell, and a high-density memory block.