PhD Defense Presentation

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2108 Engineering Building

Compact, low-power microelectronic instrumentation for wearable electrochemical sensor arrays in health hazard monitoring

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Biological and chemical hazards threaten human health and are of growing world concern. Addressing this threat requires monitoring hazards in real time while profiling local environments that are unique to individuals. Wearable sensors offer the potential to monitor local exposure of individual users while enabling distribution across a global scale. However, achieving this goal is challenged by the lack of autonomous high performance sensors with the power and size features required for wearable implementation. Wearable sensors need sensing techniques having high-performance in power, sensitivity, and selectivity for biological and chemical hazards within a small volume. The autonomous operation of wearable sensors demands electronics to intelligently analyze, store, and transmit the data and generate alerts, within the strict constraints of power, sensitivity and size. Electrochemical sensors have many characteristics that meet the challenging performance requirements of wearable sensors. However, the instrumentation circuits for electrochemical sensors are too heavy, bulky, expensive and consume too much power for wearable applications. Modern complementary metal–oxide–semiconductor (CMOS) technology provides an ultra-small, low-cost, low-power and high-performance microelectronics solution for wearable sensors. This dissertation investigates CMOS circuit design for wearable electrochemical sensor arrays in health hazard monitoring. Multiple electrochemical modes (amperometric and impedance) provide orthogonal data to sensor array algorithms to improve sensor sensitivity and selectivity. A unique multi-mode resource-sharing instrumentation circuit was developed to integrate amperometric and impedance sensing abilities, and share electronics components among recording channels, with reduced size, cost, and power. A wearable sensor array operating many electrochemical sensors in tandem can measure multiple hazardous targets in a wide range of concentrations. To address the wide dynamic range of such a sensor array, a new CMOS amperometric circuit that combines digital modulation of input currents and a semi-synchronous incremental ΣΔ ADC was developed. The new circuit simultaneously achieves a combination of wide dynamic range (164 dB), high sensitivity (100 fA), high power efficiency (241 µW) and compact size (50 readout channels on a 3×3 mm² chip) that is not available in any existing instrumentation circuits. While the circuits above addressed key challenges in gas sensors,
electrochemical biosensors offer a different set of challenges. In particular, miniaturized biosensors based on nanopore interfaces, including ion channel proteins, after great potential for high-throughput biological study and wearable biosensing. However, they require electrochemical instrumentation circuits that are not only compact, low power, and highly sensitive but also are high bandwidth, fast enough to observe less than millisecond biological responses. To address this need, a shared-segment interleaved amperometric readout circuit was developed, and measurement results show it has superior performance in terms of power and area compared to other known current sensing circuits for the same biological targets. This circuit achieves 7.2 pA_{rms} noise in a 11.5 kHz bandwidth, over 90 nA bidirectional input current range with only 21 µW power consumption, and ultra-compact size, allowing over 400 channels to be integrated on a single chip. The combined results of this research overcome many challenges for the development of wearable electrochemical sensor array in health hazard monitoring applications.

PUBLICATIONS

Journal papers

Conference papers:


Pre-PhD publications—journal papers:


Pre-PhD publications—conference papers:
