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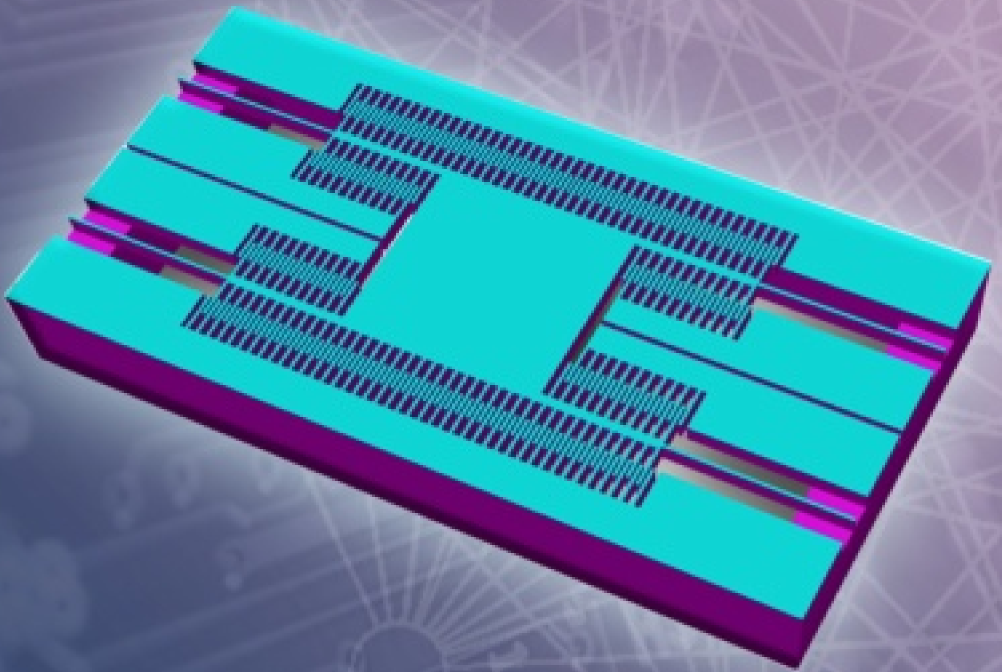

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Enhanced Performances of a Wireless System-on-Chip for MEMS Biomedical Plantar Pressure Sensor

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Abstract: This paper extends our previous work of designing a wireless data acquisition unit (DAQ) to interface Micro-electromechanical (MEMS) foot plantar pressure sensors. The designed integrated circuit (IC) is proposed for an in-shoe wireless pressure measurement system in normal daily life activities. The wireless communication transmitter is aimed to operate at 2.45 GHz industrial, scientific and medical (ISM) band. This extension paper presents the enhancement of the previous design. The newly designed chip is implemented using 180 nm complementary metal-oxide-semiconductor (CMOS) technology and displayed an improve performance compared to the original work. The chip is developed to interface MEMS sensors that has been designed, fabricated and tested. The IC had completely designed and under fabrication process. *Copyright © 2012 IFSA.*

Keywords: Foot plantar pressure, Pressure sensor, Wireless system.

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1. Introduction

In our modern living era, wireless sensing is one of the most performed measurements to enhance the quality of life. Measurement of interface pressure between the foot and shoe underpins a number of important applications. Therefore, it is important that accurate and reliable foot plantar pressure measurement system is developed. One of the earlier applications of plantar pressure was the evaluation of footwear. Lavery et al. [1] in 1997 determined the effectiveness of therapeutic and athletic shoes with and without viscoelastic insoles using the mean peak plantar pressure as the evaluation parameter. Since then there have been many works undertaken applying foot pressure measures; for example, Mueller [2] applied plantar pressure for the design of footwear for people without impairments (i.e. the general public). Other published works worth bringing up are paper by Praet and Louwerens [3] and Queen et al. [4]. Praet and Louwerens found that rocker bottom shoes are the most effective method for reducing the pressure underneath a neuropathic forefoot.

While foot health is usually taken for granted, human being only appreciate it when it is too late. For example, it is estimated diabetes mellitus to cost over $1 billion per year worth of medical expenses in the United State alone [5]. Diabetes is now considered an epidemic and the number of patients is expected to increase from 171 million in 2000 to 366 million in 2030 [6]. Obviously, the total global expanse due to this is much more worrisome during the current global financial crisis. In addition, foot ulcer among the elderly is increasing at an alarming rate, and the risk is further increased by pathologies such as Alzheimer’s disease, congestive heart failure, chronic obstructive pulmonary disease, cerebral vascular accident, diabetes mellitus, deep venous thrombosis, hip fracture, hip surgery, limb paralysis, lower limb oedema, malignancy, malnutrition, osteoporosis, Parkinson’s disease, rheumatoid arthritis, and urinary tract infection [7-9].

The improvement in balance is important both in sports and biomedical applications. Notable mentions for sports application are soccer balance training [10-12] and forefoot loading during running [13-15]. While for biomedical and healthcare areas, it can relate to the gait instability in the elderly community. Therefore, foot plantar pressure information can be used for improvement of balance among the elderly [16, 17]. Based on the above discussion, it could be said that it is crucial to devise techniques capable of accurately and efficiently measuring foot pressure in normal daily life for general purposes application or specific ones.

There are few currently available commercial foot-pressure sensors; however, these sensors are not completely satisfying the requirement of various biomedical application. The plantar pressure systems available in the market or in research laboratories vary in sensor configuration to meet different application needs. In response to the needs of such sensors, the research group in Victoria University had successfully design, fabricated and tested a miniature foot pressure sensor based on MEMS technology that can be inserted in the insole of a shoe as reported in [18].

There is a growing need for biomedical wireless sensor systems, which can simultaneously acquire biomedical signals from a patient and transmit the signals wirelessly to a remote location for further data analysis. Compared to wired systems, wireless bio-signal recording devices provide a number of benefits: data collection out of laboratories, freedom and higher patient mobility in daily routine. These systems entail severe technical challenges, such as the robustness of the wireless link and the need of a suitable data transmission band, coupled to low-power dissipation and small size for in-shoe application devices.

This paper directed towards the enhancement of the previously published work in [19]. This paper also focuses on the silicon implementation of a wireless DAQ-IC for foot plantar pressure sensors. The IC is designed to interface the fabricated MEMS pressure sensor and to be implemented together with the sensor in the insole of a shoe. The paper is divided into 6 sections. Part 2 describes the system architecture. The circuit design will be discussed in section 3. While, part 4 presents simulation and testing result and finally, section 5 draws the conclusion.

2. System Architecture

The ability to integrate complete sensor systems into a very small device is of growing importance. Recent years have seen the development of microsensor technology, system on chip design, wireless technology and ubiquitous computing. When assembled into a complex microsystem the technologies become powerful tools in medical diagnostics, environmental monitoring and personal connectivity. In this paper we describe the architecture of a silicon chip that has all the attributes required of a microsystem for use in biomedical and sport applications. Fig. 1 shows the block diagram of the implemented DAQ system-on-chip, designed to demonstrate the functionality of a System-on-Chip (SoC) as a wireless interface to foot plantar pressure sensor. The presented circuit consists of Comparator, Successive Approximation Register (SAR), Digital to Analog Converter (DAC), Parallel in Serial out (PISO) Register, Voltage-Controlled Oscillator (VCO) and a digital controller. In this paper a digital controller block is designed to synchronise the timing of each building blocks, minimize the input/output (I/O) of the IC and to add flexibility of controlling the whole system. The analog signal from the MEMS pressure sensor is digitalise by the 8-bit SAR-ADC then data is serialise by a PISO register which is then modulated by an FSK modulator. Finally, the digitized signal is sent to a 2.4 GHz binary FSK wireless transmitter based on direct modulation of a ring Voltage-Controlled Oscillator (VCO), enabling a 5-Mbit/s data rate.

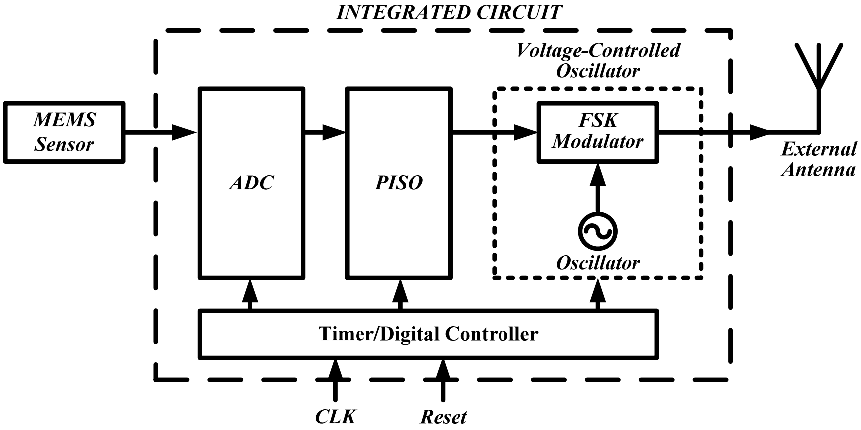

Fig. 1. Block Diagram of System Design.

The research group in Victoria University had developed and tested a MEMS sensors that has many good characteristic; small in size (3 mm × 3mm × 1.5mm), has high-pressure range measurement capability (maximum 3 GPa), excellent linearity both at low and high pressure sensing and negligible hysteresis. The tested pressure performance of the MEMS sensor is shown in Fig. 2. The fabricated sensors is depict in Fig. 3.

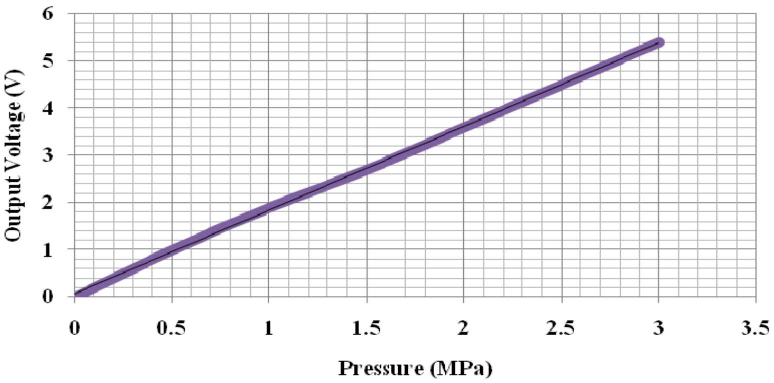

Fig. 2. Graph Demonstrating Highly Linear Output Voltage vs. Pressure Relationship.

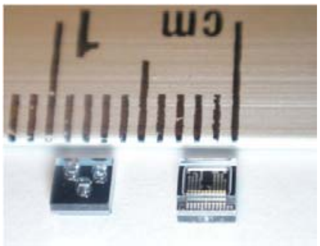

Fig. 3. The Fabricated Sensor.

3. Circuit Design

The signal processing devices in biomedical application typically require low voltage, low noise analog interfaces which places a high demand for very low power consumption ADC [20]. Successive Approximation Register (SAR) ADC architecture is best suited for low power and small area application. The SAR-ADC allows for high performance, low power ADCs to be packaged in small form factors for today's advanced biomedical applications. Fig. 4 shows the block diagram of the proposed 8-bit SAR-ADC. The main building block of the device consists of a comparator, a SAR and a charge-redistribution digital to analog converter (DAC).

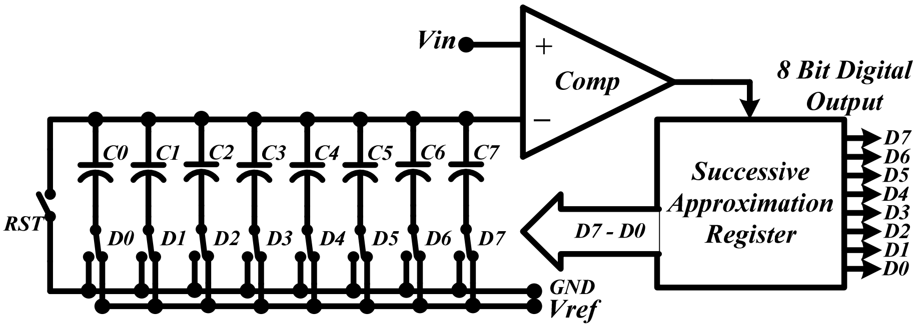

Fig. 4. Block Diagram of the Designed 8-bit SAR-ADC.

For the comparator we adopted a latched CMOS comparator circuit. The latched comparator consist of CMOS latch and S-R latch circuit. The newly adopted comparator demonstrates minimum offset error at 500 MSps sampling speed and power consumption of 148.4 µW compare to earlier design of 125 MSps sampling speed and 1.77 mW of power consumption.

The SAR is essential to control the switches of the DAC and the comparator based on successive approximation algorithm. The circuit consists of an 8-bit shift register and an array of D flip-flop (DFF). It is designed to reads the output of the comparator and controls the switches of the DAC. Nine clock cycles required to complete one conversion. The first cycle is to reset all DFF and at the same time avoid the residual charge of the DAC and charge injection of the switches during the conversion.

The DAC in this design is based on a binary-weighted switched capacitor array without op-amp shown Fig. 4. The array switches are controlled by the signal generated from the SAR. Each switches connecting to the GND is implemented by a simple nMOS and a single pMOS is used for V_{ref}. In this design we utilize a metal-insulator-metal (MIM) capacitor which show minimum parasitic effect compared to capacitor employed earlier, MOS capacitor. This characteristic demonstrates better precision in post layout, where it is crucial to achieve accurate reading of the analog signal from the MEMS sensor. The capacitor array should be kept as small as possible to save power dissipation.

Since the main objective of this system is to design a miniature device with low power consumption, single transmitter is used which requires that the output of the ADC should be serial rather than parallel. Therefore, the PISO is included to make the ADC serial. Which consequently, using a single VCO is sufficient for the system. The PISO circuit consist of 8 DFF and combinational logics. The designed SAR-ADC has been implemented in Cadence IC6 using 180 nm technology. The ADC consumes a total power of 584.5 µW at an operating speed of 12.5 MSps. Table 1 summarize and compare the performance of the new implemented ADC with the previous design.

Table 1. Performance of the Design SAR-ADC.

Parameter	Previous Design	This Design
Resolution	8-bit	8-bit
Power Consumption	16.19 mW	584.5 µW
Technology	350 nm CMOS	180 nm CMOS
DNL	± 0.5 LSB	± 0.5 LSB
INL	± 0.5 LSB	± 0.5 LSB
Core Supply Voltage	3.3 V	1.8 V

Usually, a VCO is an integral element of any wireless transceiver and other communication systems. Whereas, ring oscillator is one of the common component with wide tuning topologies to be used as a VCO or a phase lock loop (PLL). In this system, a ring oscillator based VCO controlled by the output of the ADC is used as a direct frequency modulation (FM) modulator. This is considered as the smallest integrated transmitter. In this design, the VCO acts as the carrier generator and modulator.

It is a known fact that a ring oscillator has a wide tuning range and utilizes minimum space compared to LC oscillator. In our current design the tuning range of the VCO is between 1.07 GHz and 3.68 GHz for the input of 0.7 V and 1.8 V respectively. This parameter is too wide to be implemented in our design. In this system, we aim to uses the lower industrial, scientific and medical (ISM) band of frequency of 2.45 GHz. Due to this nature we design a unique controlling circuit at the input of the VCO. The controlling circuit has two main functions. The first function is to control the frequency oscillation. So when the output of the serial ADC is low the frequency oscillates at 2.4 GHz and when the signal is high, 2.5 GHz frequency is measured at the output of the VCO. This is the requirement of the communication protocol of 2.45 GHz ISM band. Hence, the VCO will act as frequency-shift keying (FSK) modulator with mid-band frequency of 2.45 GHz. The second function of the controlling circuit is to differentiate from one set of data from the serial ADC to the next set of data. Thus, making the user at the receiver end of this system easily distinguish the signal data for demodulation purposes. Fig. 5 depicts the simplified FSK modulator block uses in our system. Table 2 summarizes the performance of the implemented FSK modulator.

Table 2. Performance of the Design FSK Modulator.

Device Performance	Previous Design	This Design
Technology	350 nm CMOS	180 nm CMOS
Supply Voltage	3.3 V	1.8 V
Center Frequency	2.45 GHz	2.45 GHz
Tuning Range	63 %	55 %
Voltage Swing	2 V	1 V
Power Consumption	1.13 mW	419.2 µW

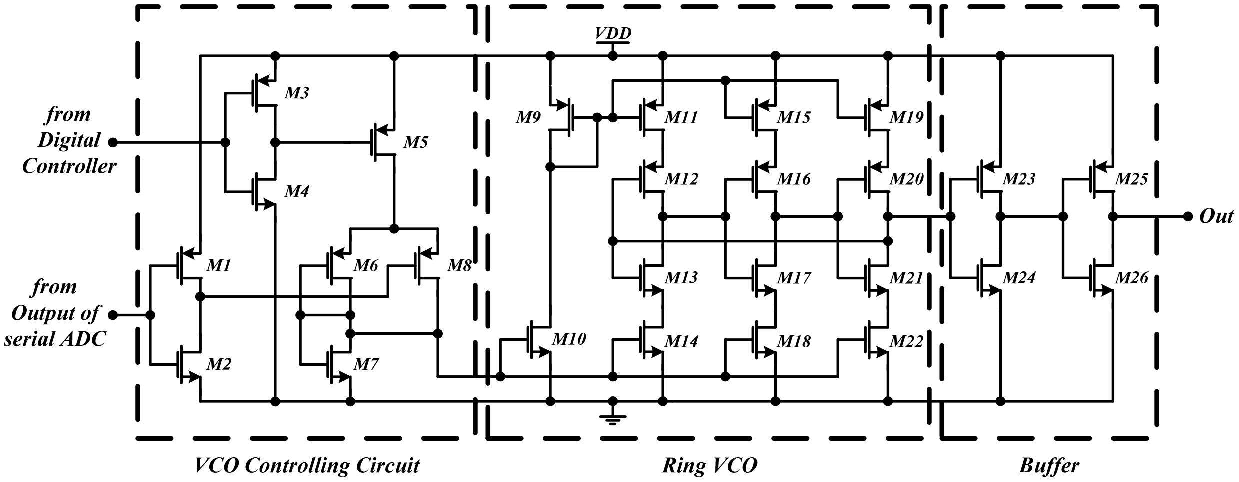

Fig. 5. Schematic Diagram of the FSK Modulator.

4. Simulation Result

The proposed single chip wireless DAQ-IC for foot plantar pressure sensor has been designed and tested in Cadence (EDA) tools using 180 nm CMOS process and at current time is in the process of chip fabrication. The circuit design was implemented using Cadence Virtuoso Schematic Editor while chip layout was implemented using Cadence Virtuoso Layout Suite XL. For the post layout simulation purposes Cadence Virtuoso Analog Design Environment was utilized. The final layout including the pads of the chips size is about 0.64 mm^2 as shown in Fig. 6 compared to earlier design of 1 mm^2. The padding positions are based on the probe to test with test bed available in Victoria University. The top padding is for the radio frequency (RF) probe, on the right are for the analog I/O 9 pin-7 BNC DC probe and at the bottom are dedicated for the digital I/O 5 pin-4 BNC probe.

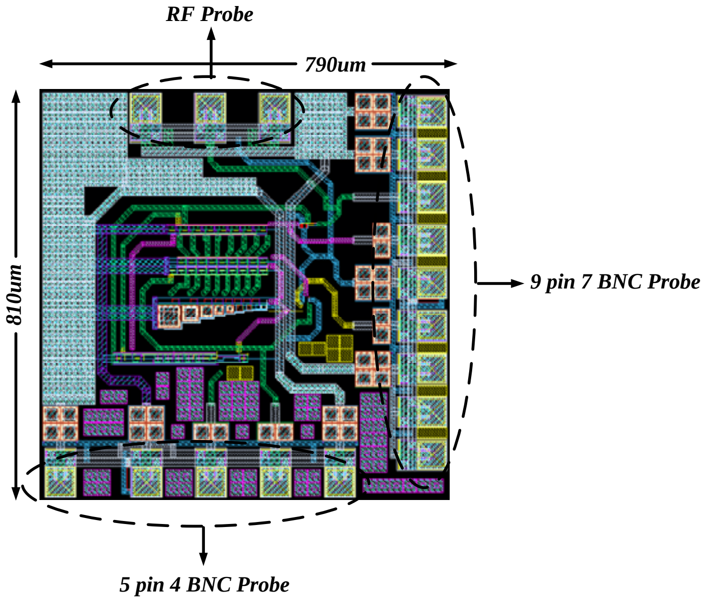

Fig. 6. Final design layout with padding to test with test bed.

The post layout of each building block had been simulated to verify its functionality, performance capability, sizing and power consumption. The overall system shows that, the system works as their intended design. Table 3 summarizes the performance of the implemented wireless system using the proposed architecture. The overall system consumes just a mere 1mW of power at operating speed of 12.5 MSps.

Table 3. Performance of the Design System.

Parameter	Previous Design	This Design
Max Data Rate	1.25 Mbit/s	5 Mbit/s
Power Consumption	19.53 mW	1.05 mW
Type of Modulation	Frequency-shift keying (FSK)	Frequency-shift keying (FSK)
Center Frequency	2.45 GHz	2.45 GHz
Technology	350 nm CMOS	180 nm CMOS
Core Supply Voltage	3.3 V	1.8 V
Chip Size with Pads	1 mm^2	0.64 mm^2

5. Conclusions

This paper demonstrated a portable, lightweight, and wearable in-shoes pressure sensor system that featured MEMS pressure sensor and a miniaturized DAQ with wireless capability. The main goal of the design and development of wearable and wireless foot plantar pressure system is to maximize their wearability, unconstrained mobility, usability and reliability in daily life environments. In this paper, the design and implementation of a wireless System-on-Chip for MEMS biomedical sensor was presented for use in foot plantar pressure sensors. After introducing the target application and resulting design constraints, the actual DAQ-IC design was detailed. A power consumption of 1.05 mW was achieved using charge redistribution successive approximation architecture as the DAQ and a ring VCO as the FSK modulator. The total chip size including pads is about 0.64 mm^2. Analysis of the full sensor node power consumption showed that this wireless DAQ is sufficient for the intended system operations.

Simulation results are encouraging and show that the system is feasible for converting the sensor signals to digital signals, hence translate it to its frequency representation and ready for transmitting. Once the chip is realize, the next step is to measure the characteristic of the designed chip, compare with the simulation result and run experiment in real life situation.

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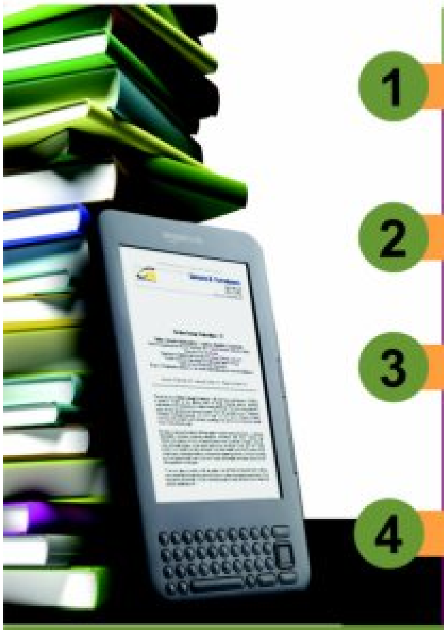

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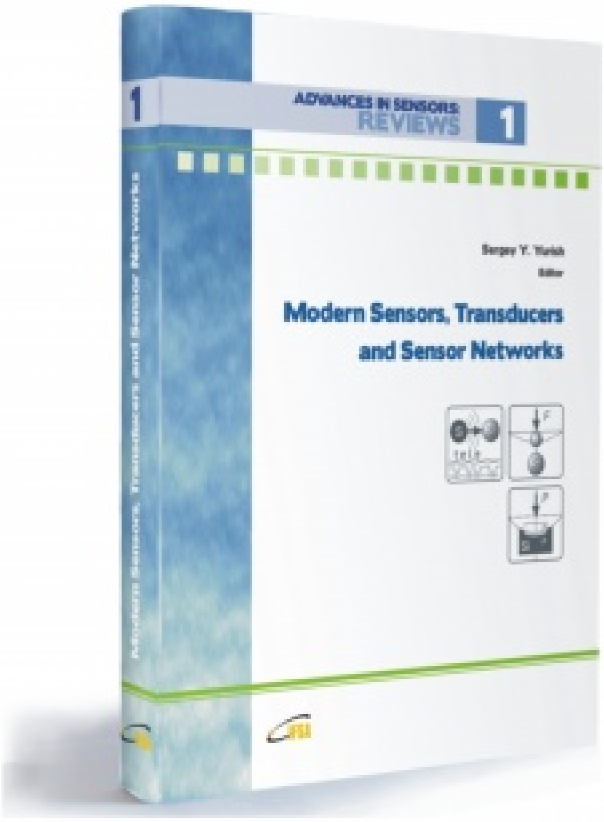
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