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A survey: Electronic sensors in electronic digital

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***Abstract*— an organic temperature detector is presented that consists of an organic temperature sensor and an organic complementary read-out circuit. The temperature sensor is a Wheatstone bridge composed of temperature-sensitive polymer films and metal films. The read-out circuit receives an analog temperature signal from the temperature sensor and outputs a 1-bit digital signal that reflects whether the temperature has exceeded a threshold temperature or not. For more detailed read-out, detection of the temperature range the temperature sensor is within also demonstrated using an organic 2-bit analog-to- digital converter as a read-out circuit. This paper reports a new digital readout electronics for capacitive sensors like accelerometer, gyroscopes or inclinometers. The functional principle of the readout electronics is shown by the example of the micro-machined gyroscope decoupled angular velocity detector (DAVED) developed at HSG-IMIT [Sens. Actuators A- 84 (2000) 280]. The goal of this digital concept is to minimize noise and temperature drifts caused by the analog components of the readout electronics. This is feasible, because the main part is done digitally inside a digital signal processor (DSP). Further, this new digital concept is not only used for temperature compensation or force-to-rebalance loops [Algorithm and low power digital implementation for MEMS inertial sensors, Final report 1999-2000 for MICRO Project 99-083] it is also used to readout the small capacitive changes of the sensor output.**

***Index Terms* — Temperature sensor, organic semiconductor, Analog-to-digital converter, Readout electronics for capacitive sensors; Micro-machined gyroscope; Digital readout.**

I. INTRODUCTION

Gyroscopes are used to measure the angular velocity of their “host”, a moving object, without external reference. Low cost and high precision gyroscopes find use in the fields of advanced automotive safety and comfort systems, virtual/augmented reality, people-to-people and people-to-device communication (gloves, helmets, and mobile phones), robotics (home robots and autonomous guided vehicles), and medicine (surgical instruments). Due to the large market scope, various groups are working on new designs, technologies, and readout concepts for micro-machined gyroscopes.

In 1996 HSG-IMIT filed a basic patent (issued 1998 [2]) aiming to decouple the driving and sensing mechanism. The design principle is called decoupled angular velocity detector (DAVED).The presented prototypes are based on this concept. Organic electronics are attractive candidates for the realization of next-generation flexible electronics such as flexible displays, flexible radio frequency identification (RFID) tags, and smart sensors due to their high flexibility, low weight, low temperature fabrication, and compatibility with plastic substrates [1e3]. Organic RFID tags for environmental monitoring systems have the potential to become a major commercial application for organic devices. For example, low-cost and disposable organic RFID tags with temperature sensors can be utilized for item-level tracking of the temperature environment for a variety of items that require stringent temperature

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management during transportation, such as pharmaceuticals and perishable foods. There have been several reports of organic temperature sensors where the output signal is produced in analog format [4e6]. However, it is important for smart sensing devices that the output signal is produced and processed in digital format because digital signals can be easily read in read-out systems such as RFID readers. Thus, several research groups have made efforts to fabricate analog-to-digital converters (ADCs) based on organic field-effect transistors (OFETs) [7e9]. Here, we report on two types of organic temperature detectors that consist of organic temperature-sensing circuits and organic read-out circuits with solution-processed organic p-type and n-type semiconductor thin- films. One contains an organic comparator as the read-out circuit, which produces a digital output signal to indicate whether or not the sensor temperature is higher than the threshold temperature. The other contains an organic parallel ADC that shows the temperature range the sensor temperature is within.

II. ORGANIC TEMPERATURE SENSORS

Poly(3,4ethylenedioxythiophene):poly(styrene sulfonate) (PEDOT:PSS) was used for the temperature-sensitive resistance films. PEDOT:PSS is a widely used conducting polymer for various applications such as organic photovoltaic cells, organic light- emitting diodes, antistatic coating, and sensors due to its conductivity, optical transparency, and chemical stability [10e13]. Much effort has been able to reveal the carrier transport mechanism that takes place in PEDOT:PSS thin films, and it has been reported.

Fabrication of the temperature sensors

The temperature sensors were fabricated using the following process. First, metal resistors and electrode patterns for organic resistors were formed on a flexible polyethylene naphtha late substrate (Teonex®, Teijin DuPont Films Japan Limited) by a photolithography technique and a subsequent lift-off process of thermally-deposited 10-nm-thick chromium and 3-nm-thick gold films. The metal resistors were covered with CYTOP fluoropolymer films (Asahi Glass Co., Ltd.), and then an aqueous solution of PEDOT:PSS (483095, Sigma-Aldrich Corporation) as organic resistors was spin- coated. The hydrophobic CYTOP® film was used to repel the solution and prevent the conductive polymer from forming unnecessary short-circuits in the metal resistors.

Sensitivity of the fabricated temperature sensors shows a photograph and a circuit schematic of the temperature sensor, which consists of a Wheatstone bridge with a PEDOT:PSS resistive film and a Cr/Au metal resistor as a reference. The role of the sensor circuit is to create an analog voltage signal that reflects the temperature.

Each voltage level of the V_p and V_n terminals emerges simply as the result of distributing V_{DD} between the corresponding PEDOT:PSS and metal resistors in series, and is proportional to V_{DD}. The room temperature resistance of the metal resistors was approximately 400 KU. As the temperature increases, V_p increases, while V_n decreases. A twofold larger temperature-induced voltage change DV (¼V_p V_n) can be obtained using the bridge circuit than that with a single pair of polymer and metal resistors.

Air-stability of the fabricated temperature sensors

Environmental stability is one of the major requirements for organic devices. It has been reported that water absorption from the atmosphere causes an increase in the resistance of PEDOT:PSS films [16,17], which must be avoided with some passivation technique. We have evaluated the air stability of the temperature- sensing ability of PEDOT:PSS thin films by heat-cycle tests in the ambient atmosphere to confirm the practicality of the water-soluble polymer as a temperature-sensing material. Three cycles of heating and cooling between 30 C and 80 C were performed on two test devices, one with a barrier layer of hydrophobic CYTOP® polymer formed by spin-coating over the PEDOT:PSS resistors and the other without a barrier layer. The output characteristics were measured every 10 C within the temperature range. In the case of the air-exposed PEDOT:PSS thin film, DV of the temperature sensor decreased after the test, which implies that the PEDOT:PSS film became more resistive, while the device with a barrier layer MEMS pressure sensors are needed for operation in many wide-temperature applications. Capacitive MEMS pressure sensors are preferred in many of the above applications due to their advantages including good reliability, accuracy and sensitivity, low temperature coefficient, low drift, and low power consumption [4,5]. Many research groups have previously reported capacitive MEMS sensors for high-temperature applications [1,2,6]. To properly operate, the MEMS pressure sensor devices require an interface electronic circuit to convert the electro-mechanical property change occurring at the sensor device due to the external applied pressure into an electrical output signal that can be easily processed, stored or transmitted. Pressure sensors are based on various electro-mechanical properties including piezoelectricity, piezo resistivity and capacitance. To improve signal to noise ratio and reduce wiring complexity, it is desirable to place the sensor interface electronics in close proximity to the sensor devices [7]. Hence, the sensor interface electronics must be capable of operating over the same temperature range as the sensors. At extreme cold and hot environments where the temperature ranges beyond −55–125 °C, the design of the sensor interface electronics is challenging and requires special design considerations. In this paper, we specifically focus on design challenges and techniques to achieve sensitive capacitance sensor interface electronics operating under high temperature conditions. CMOS based electronics currently dominate modern semiconductor industry. It has numerous advantages including low power

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consumption, low cost, and large scale integration. However, at high temperatures conventional electronics made in bulk CMOS technology suffer from many drawbacks including degradations in electron/holes mobility, reduction in MOS transistors threshold voltage, an increase of bulk junction leakage currents, and an increase in silicon intrinsic carrier density [8,9]. Increased junction leakage current at high temperatures has the most pronounced effect on bulk CMOS circuits, which can severely reduce circuit performance or, more seriously, cause circuit failure due to latch-up [10]. At temperature above 300 °C, the silicon intrinsic carrier density is comparable to the doping level, which imposes the theoretical temperature upper limit for CMOS technology [8]. The fabrication of circuits using silicon-on-insulator (SOI) technology is an effective way to address the junction leakage current problem, but the mobility and threshold drop at high temperature remains unresolved, and analog circuits in SOI technology have reduced performance due to hysteresis in the I–V characteristics of MOS transistors [8]. Silicon carbide (SiC) based electronics [11] is also promising for high temperature applications, but the materials and processing technologies are not yet maturely developed.

III. PRINCIPLE OF OPERATION

The principle of DAVED is described in more detail with the example of the so-called RR-structure. RR indicates, the sensor features, two rotary oscillation modes. The entire movable structure (printed gray) is driven to a rotary oscillation around the z-axis by comb drives (primary mode). When the device is turned around the x-axis, Coriolis forces arise, which cause an oscillation around the y-axis (secondary mode). It is detected by substrate electrodes and yields the output signal. In this out of plane direction, the high stiffness of the inner beam suspension effectively suppresses an oscillation of the inner wheel. Only the outer rectangular structure, which is decoupled from the inner wheel by torsional springs, can follow the Coriolis forces. In this concept, decoupling means, that the primary oscillator (the inner wheel) has (ideally) only one degree of freedom relative to the substrate. The secondary oscillator has the same one and one additional degree of freedom. Thus, the secondary oscillation does not influence the driving mechanism and parasitic effects of the comb drives like levitation can be suppressed effectively.

An amplitude modulation technique similar to the readout of the surface micro-machined accelerometer presented by Analog Devices Inc. [3] is used to detect these small changes. The principle of this technique is schematically shown. To measure the two oscillations of a CVG two different carrier signals in the range of some hundred kHz are applied [1]. Besides the demodulation with the carrier signals the readout of gyroscopes involves many additional complex functions like phase sensitive detection of the driven and detection oscillation, usually two control loops to keep the driven oscillation stable and force to rebalance loops of the secondary oscillation.

Realizing these tasks with analog components results in the following difficulties:

Each component yields additional noise and especially temperature drift;

The development of the control loops is extremely time-consuming; and

the integration of advanced features like self-test, self-calibration and other adaptive functions is hardly possible or not at all feasible.

To avoid these drawbacks a digital approach was realized. Thereby, the number of analog components should be reduced to minimum and the signal should be digitized directly after the first amplification stage.

According to Shannon's theorem [4]: (an analog signal with a bandwidth of f_A must be sampled at a rate of $f_s > 2 \times f_A$) and Nyquist's criteria [5]: (if $f_s < 2 \times f_A$, then aliasing will occur) a sample rate of at least the double carrier frequency would be required. Since the resulting high processing rate in the range of 1 MHz would exceed the performance of available DSPs, an under sampling technique is exploited. This technique is a known, e.g. from telecommunication technology. The envelope of the time continuous, amplitude modulated carrier signal represents the information of the signal. Two under sampled signals with two different divider frequencies (under sampling frequency) are shown. Only the one with the integer submultiple divider (1/3) reconstructs the information signal correctly.

The amplitude modulated signal corresponds to the output of the differential condenser. Because of the oscillation of the mechanical sensor structure the carrier signals are modulated sinusoidal. To realize the carrier signal and the trigger signal with the integer submultiple frequency a timer with a frequency divider is used.

The trigger signal controls the analog-to-digital converter (ADC) with sample and hold (S&H) module. This readout electronics can be used for each type of capacitive sensor to detect the small changes of the sensor output.

With the described setup, the analog parts of the electronics are reduced to a minimum.

IV. REALIZATION

The new readout concept to evaluate the sensor output signal is realized in digital electronics, except for the first low noise preamplifier and the analog high pass filter. The block diagram contains all basic elements, the MEMS-structure (gyroscope, colored dark gray), the digital part (DSP, colored gray) and the analog parts.

The gyroscope supplies an amplitude modulated signal, which will be amplified, filtered and then digitized by the ADCs.

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The signal processing of the digital part is realized with two separate channels, the so-called primary and secondary path. The primary path is used to generate the driving voltage for the gyroscope. This part consists of a phase and an amplitude control loop, realized with PI-controllers to accommodate the amplitude and frequency changes due to variation of damping and modulus of elasticity over temperature (primary closed loop).

The secondary path is used to demodulate the angular rate signal and converting into an equivalent voltage/current or bit-combination. After band pass filtering, the under sampled signal is demodulated with a driving voltage out of phase of 90°. The filtered result is directly proportional to the angular rate and is now available as analog (digital-to-analog converter, DAC) or digital output (RS232-interface).

The secondary closed-loop (force to rebalance loop), for further reduction of the temperature drift of the secondary oscillator is not implemented yet.

In this concept the carrier signals and the trigger signals for the ADCs are generated from the system clock of the

DSP. If the frequency of the system clock drifts over temperature the derived frequencies change with the same amount and no additional source of error exists.

V. Circuit Architecture

The procedure shows the schematic implementation of a basic CMOS CDC circuit previously implemented by other research groups [26,27]. The circuit uses a simple oversampled architecture where negative feedback is used to control the input branch to keep the integrator output, V_o, oscillating around analog ground, V_{AG}. Its working principle is similar to a conventional sigma–delta analog-to-digital converter (ADC), except that it has no internal digital-to-analog converter (DAC) and separate input and reference voltages [26]. In operation, assuming output y is "1", when 1 is high, C_1 is disconnected from the input reference voltage, V_{ref}, and C_2 is discharged. The integrator output, V_o, remains unchanged since no charge is transferred to the integrating capacitor, C_f. At the next clock phase, 2 becomes high, a positive charge of $C_2 V_{ref}$ is delivered into C_f via C_2, causing V_o to decrease by $C_2 V_{ref}$ $/C_f$. This operation continues until V_o is smaller than V_{AG} and now y becomes "0". Then, during the time when 1 is high, C_1 is charged to V_{ref}. Next, when 2 is high, a negative charge of $-C_1 V_{ref}$ is delivered into C_f via C_1, causing The above circuit structure can be used in applications where C_1 and C_2 may be both constant capacitors (e.g., in the case of matching on-chip CMOS capacitors for ADC and DAC applications), or they may be time-varying capacitances and $C_1 + C_2$ is relatively constant (e.g., in the applications of capacitive accelerometers or pressure sensors) [27]. In a typical capacitive MEMS sensor readout scenario, C_1 is the reference capacitor while C_2 is the sensor capacitor to be measured. The circuit is susceptible to various non-ideal effects, including finite operational amplifier gain, operational amplifier offset, thermal noise, 1/f noise, clock-feed through noise, charge injection, and bulk junction leak- age currents. Wang et al. [27] proposed an improved CDC circuit as that can significantly reduce sensitivity to the abovementioned non-ideal effects. The novelty of our work deals with extending the performance of the improved CDC circuit to operate over the wide temperature range from −55 °C to 225 °C and integrating the CDC circuit with a MEMS capacitive MEMS pressure sensor.

The performance of the integrator is critical since it is used to realize the noise-shaping transfer function. Ideally, the operational amplifier of the integrator should have infinite gain and zero offset voltage. Finite operational amplifier and nonzero offset voltage can cause errors in the transfer function of the first stage integrator and increase quantization noise at low frequencies. The thermal noise can be effectively attenuated using large input capacitors. The 1/f noise and clock-feed through noise are prevailing at low frequencies. Since the signal of capacitive sensors is usually located at low frequencies, these low frequency noises must be reduced to achieve accurate measurement.

Correlated double sampling (CDS) technique is used to cancel low frequency noises. It can also increase the effective operational amplifier gain and decrease its input offset voltage. Two holding capacitors C_{h1} and C_{h2} are used to store and subtract the virtual-ground voltage (caused by low frequency noises, and finite gain and offset of the operational amplifier) during the y = 0 and y = 1 clock phases, respectively [27]. Using CDS technique, the effective value of the operational amplifier offset becomes V_{os}/A, and the effective operational amplifier gain becomes nearly A^2 (V_{os} is the Op-Amp offset and A is the operational amplifier open loop gain) [29,30]. The values of C_{h1} and C_{h2} do not significantly influence the accuracy of the operation, as they are only used to store and cancel the offset voltages. The first order modulator requires a very high sampling ratio to get high resolution. However, a higher order structure can be used to achieve the same resolution with a smaller oversampling ratio. Here, a second order structure is chosen because its structure is simpler and more stable, as compared with even higher order structures. A second order sigma–delta modulator is formed by adding a second integrating stage. The second order modulation is guaranteed by making $C_3 = 2C_4$ [28]. The other capacitors are carefully chosen so that they make the modulator stable and the operational amplifiers of the integrators are working in their linear range.

VI. Comparator

The comparator is implemented using a regenerative comparator followed by a static latch [32]. Two cascaded pre-amplifiers are placed before the regenerative

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comparator to amplify the voltage difference at the input to a large level to achieve high precision. The preamplifiers are also biased by the constant-g_m biasing circuit so that its gain and bandwidth can be maintained over a wide temperature range. Simulation results show that the comparator has resolution better than 0.1 mV with a 10 MHz clock at 125 °C.

The noise and offset voltage of the comparator will increase at high temperature. Since the comparator is located after the second integrator, its noise and offset are shaped the same way as the quantization noise and attenuated by the large DC gain of the first and second integrators. So, the circuit performance is generally insensitive to noise and offset of the comparator.

The other components are transmission gates used as switches and digital blocks including a D flip–flop, a non-overlapping two- phase clock generator, some 2-input NAND gates and inverters to generate the control signals. The transmission gates are built using parallel NMOS and PMOS transistors. At high temperatures, the junction leakage current of NMOS transistor is much larger than that of PMOS transistor, causing a net temperature-dependent leakage current to drain charge from the sample/hold node [8]. Minimum size NMOS transistors are used in transmission gates to reduce the junction leakage current. PMOS transistors are sized such that $(W/L)_p = (n / p)(W/L)_n$ to improve the linearity of the switch turn-on resistance. The digital blocks are implemented without special design considerations as standard CMOS digital circuits have been demonstrated operational at temperature around 300 °C [33].

VII. Simulation results

The circuit level simulation is done in Cadence using all of the circuit blocks discussed. For a typical MEMS capacitive sensor, its steady-state capacitance is on the order of few pico-Farads, and the capacitance change during operation is from several tens to few hundred femto-Fards. In the simulation, the sensor reference capacitance C1 is set to 5pF, and the sensor capacitance C2 is set to 5.2pF, as a reasonable representation for a MEMS capacitive pressure sensor. The following other parameters are used in the simulation: Cf1 = 4C1, Ch1 = Ch2 = C3 = Cf2 = 2pF, C4 = 1pF, Vref = 0.2 V, and clock frequency is 1 MHz. At every clock cycle a data point of y is generated, so the number of data means the number of clock cycles needed to make the estimation. For example, the number of data is 500 means 500 data points are acquired. The acquired data points are passed through a window with the same length of the data to obtain the value. The window used here acts as a digital low-pass filter.

A. Resolution

The basic functions to improve the performance have been implemented and the feasibility especially regarding sufficient DSP performance [6] and synchronization of the two necessary readout paths has been proved.

Since most of the signal processing is done digitally, noise mainly caused by analog components is minimized. First measurements (test board), of non-linearity (0.39%) and noise (rms: 0.21 °/s) in the measurement range of ±200°/s are presented.

Customized development can be done in a very short time, because the hardware is comparatively simple and the development is focused mainly on the software. Control loops, self-test, self-diagnostic and self-calibration routines can be implemented faster and complex calculations which are not possible with analog electronics can be performed to improve the system.

VIII. Conclusion

A CMOS CDC circuit for MEMS capacitive pressure sensors is designed, fabricated and tested for the wide temperature range from −20 °C to 225 °C. The circuit is implemented using the IBM 0.13 m CMOS process technology which incorporates a 2.5 V power supply. Simulation results show that the circuit has better than 0.03% accuracy between −55 °C to 225 °C. Experimental results show that it has good temperature stability, resolution better than 1.44fF, and accuracy better than 2.4% between −20 °C to 225 °C. The circuit is tested with a commercial capacitive MEMS pressure sensor and shows stable response over the wide temperature range. The performance of this circuit could be further improved with a fully differential architecture.

Common advantages of the new digital readout compared to analog principle are:

- Lower noise;
- Lower temperature drift;
- Fast customized development; and
- Simplified sensor fusion (e.g. gyroscope + inclinometer) [7].

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