WIRELESS PASSIVE SENSOR FOR MEASURING ECG AND OTHER BIOPOTENTIALS IN IMPEDANCE LOADED SAW TECHNOLOGY

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Abstract: A remotely requestable, passive, short-range sensor network for measuring biopotentials is presented. The sensor system is able to simultaneously monitor six leads, and it can be used for Holter-electrocardiogram (ECG) and other biopotential monitoring, or in industrial applications. The sensors are based on a surface acoustic wave (SAW) delay line with voltage-dependent impedance loading on a reflector interdigital transducer (IDT). The impedance to the IDT is introduced by a high-frequency LC-load-circuit. The load circuit impedance is varied by the capacitance of a varactor, which is dependent on the heart potential. The acquired sensor signal is the phase and amplitude modulation caused by the impedance changes in this load circuit. High resolution is achieved by developing a programmable MNOS-capacitor with a thin dielectric oxide and an epitaxial layer with extremely low doping, to achieve high capacitance tuning at zero-voltage region, as well as by developing a high-Q microinductor by thick metal electroplating. The circuit is constructed planar, and miniaturization is achieved by using Flip-Chip technology. Simultaneous monitoring of multiple leads is realized by time-division-multiplexing of signals from different sensor. The sensor response has been evaluated with a cable connection, and the sensor function manifested with a wireless link.

Introduction

The health care system in Western Countries is currently based on the healing of existing diseases. This system is expensive, and the costs could be decreased by developing preventive methods. Cardiovascular diseases are the main cause of death within the population in the age of 44-64 years, and the second most frequent cause of death of people between 24 and 44 years. In Germany alone, about 300 000 people suffer annually from a heart attack. An early recognition of possible attack symptoms and warning the patient or the physician about it would enable them to take preventive action to avoid the attack. This would reduce the risk of irreparable damage to the organs or even death.

To lower the number of heart attacks, preventive methods must be improved. Monitoring risk groups, such as people recently having had a bypass or pacemaker implantation surgery, is the most obvious way to achieve results. The continuous monitoring should be performed in real time because the threat of an attack often requires urgent action.

Long term recording of ECG is a standard procedure in current cardiac medicine, but the devices are not capable of performing real-time analysis due to restrictions in size and energy consumption of the recorder. Further, the devices are uncomfortable for the patients limiting their mobility, because the chest-electrodes are connected via cables to the recording unit, which must be worn on the body during all of the daily activities and sleep. If these cables between the electrodes and the recording unit were replaced by a radio link, the patient comfort would be increased.

In recent years there has been research for solving the problems of wireless data transmission [1, 2, 3] and for improving the signal evaluation [4, 5, 6]. The objective of our project is the development and evaluation of a telemetric diagnosis-network for continuous real-time monitoring of risk-patients for up to a few weeks using SAW transponder sensors. The goal is to achieve increased sensor wearing comfort by replacing the traditional wiring with a radio link [7]. The network consists of three levels, as shown in Figure 1. The sensor is responsible for data acquisition at the patient. It is interrogated by a RF-impulse sent from a portable reader/recorder unit [8], which is to remain in immediate vicinity such as pocket or nightstand of the patient. The data collected and pre-processed at the reader unit will be sent to a stationary analysis unit where the diagnostics takes place. The link between the reader unit and the analysis unit is flexible, using for example blue tooth in home-care setting, or GSM link in ambulatory situations. In this paper we focus on the conception and development of the sensor for data-acquisition, marked with a circle in Figure 1.

Passive and wireless SAW reflectors have been realized as sensors for various mechanical [9], physical [10, 11], and chemical [12, 13] parameters, but to our knowledge this is the first system under development specifically for medical applications and for measuring potentials. The SAW technology makes it possible to realize a miniaturized, wireless, and passive biopotential monitoring system, which is capable of performing the same and more functions as a conventional Holter-equipment with an increased patient comfort. The sensors can be placed directly on the electrodes, which leads to miniaturization and to reduction of the total amount of cables to a minimum.

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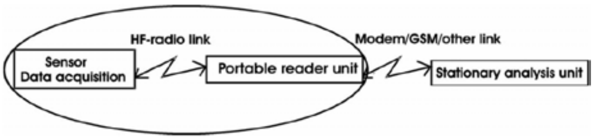

Figure 1: ECG-monitoring system with sensor, portable reader, and stationary central analysis unit

Materials and Methods

The sensor consists of a SAW delay line, a receiving/transmitting antenna, an LC load circuit, and electrodes attached to the patients chest, as illustrated in Figure 2. The sensor effect relies on the variation of the complex impedance Z_{load} of the load circuit, which, next to the electrodes, is contacted to the reflecting IDT on the SAW-device. Z_{load} is varied by the measured heart potential U through the capacitance of C(U) the varactor. The inductor L tunes the circuit to the operating frequency of the system.

The sensor is operated with pulse radar technology. To interrogate the sensor a short high-frequency read impulse is sent out from the portable reader unit. The signal is captured by the antenna connected to the Antenna-IDT, where it is converted to an acoustic signal having the original frequency, but the velocity about 10^{-5}th that of a radio signal. This signal then travels as a surface acoustic wave through the delay line to the reflector and to the load-IDT. At the reflector, part of the signal is reflected and delivers a reference-value used for calibrating the signal path. The rest of the signal travels to the load-IDT, where it is modulated as a result of the sensor function. At the instant of measurement the heart-potential has a certain value U, which determines the capacitance C(U) of the varactor diode. The impedance $Z_{load}(C(U))$ of the load circuit thus depends on the C(U), and causes the amplitude and phase of the signal to be modulated [11]. The scattering parameter S_{11} of the reflected signal can be estimated by formula (1), which is derived from the P-matrix formalism,

$$S_{11}(Z_{load}) = \frac{P_{13}^2}{P_{33} + \dfrac{1}{Z_{load}(C(U)) + Z_{match}}}, \qquad (1)$$

where P_{13} is the electroacoustic coupling factor of the IDT and P_{33} is the electrical admittance, and Z_{match} is the impedance component of the matching element L in Figure 2. The phase and amplitude modulated signal is then reflected at the load IDT and travels the reverse path back to the reader unit, where the evaluation electronics calculates the desired physical values.

The resolution of the system is critical because of the extremely low voltages of the ECG and other biopotentials. An ECG-signal is in the range of a few millivolts and less, and thus causes only small changes in the load-circuit impedance. It must still be employed to produce a measurable signal.

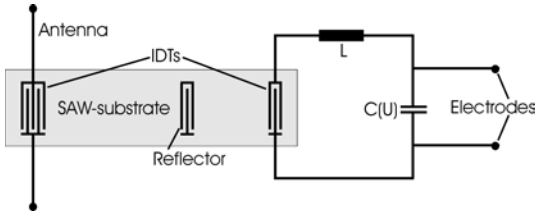

Figure 2: Design principle of the heart-potential sensor

The change of impedance of the load circuit, and thus the resolution of the signal, is limited by the capacitance ratio of the used varactor diode. Also, close attention must be paid to the high quality factor of the load circuit. The system sensitivity can further be increased by evaluating the phase modulation of the sensor-response. This way better signal-to-noise ratio (SNR) can be achieved. This requires accurate matching of the resonant circuit to the driving frequency of the SAW-device.

A total set of three leads is usually required to obtain useful data of the heart function in a standard ambulatory Holter-monitoring, and 12 leads are used to get the full dataset. Our system can simultaneously monitor up to six leads. The reflector and the measurement IDT on each sensor are placed on the SAW-chip surface with a fixed increasing offset distance resulting in a time multiplexed system response.

Figure 3a shows the response of a single sensor. The partial wave reflected at the reflector can be seen in the time domain as a peak at 1.4 μs. The peak at 2.4 μs is the wave reflected at the load-IDT at a certain Z(load). Peaks caused by multiple reflections at the reflector and IDTs follow the two main peaks. Figure 3b combines the signals from all six sensors. It illustrates the importance of the reference peak. The response of different sensors varies according to the attenuation in the transmission path, so that for example the sensor number 2 has a higher attenuation than sensor 1 due to different location on the body.

Varactor Diode: The capacitor functions as the detuning element of the load circuit, where the capacitance is changed by the heart-potential. The capacitor must have a steep capacitance-voltage curve about the zero-voltage region, as well as a high Q-factor. Regular varactors do not fulfil the steepness requirement. Instead, Schottky-diodes have CV-characteristic closer to the desired and are therefore better suitable for the ECG-sensor. In the further measurements of is work a Schottky-diode model MGR704 (Micrometrics, Inc., NH, USA) was used.

In order to further improve the sensor performance, we have also developed another type of varactor with MOS technology. Also an MOS-capacitor can be designed to posses both the steep CV-curve and a high Q-factor. The capacitance of the MOS-diode is determined by the serial connection of the oxide capacitance and the capacitance of the space-charge region. The minimum capacitance depends on the thickness of the oxide, since in the accumulation region the differential capacitance of the semiconductor is very high, and the total capacitance is

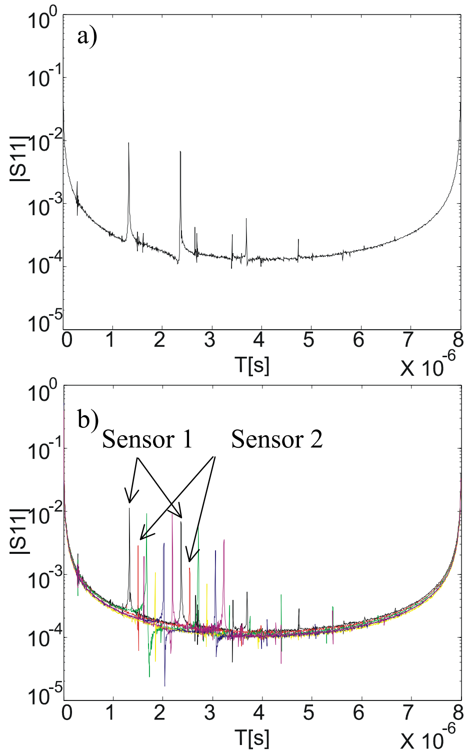

Figure 3: a) Response of single sensor and b) combined response of 6 different sensors

therefore at its maximum. As the voltage increases, a depletion region is formed at the semiconductor surface, and the total capacitance decreases. The minimum achievable capacitance is then determined by the doping density.

Because it is very challenging to produce the MOS-diodes with the correct threshold voltage, they have been replaced by MNOS structures, Figure 4, where the capacitance can be programmed very accurately simply by applying a bias voltage for a defined period of time. This procedure introduces charge-carriers at the nitride-oxide interface which result in a shift of the threshold voltage to the desired value.

Inductor: The load circuit must be tuned to the driving frequency of the SAW-transponder in order to maximize the phase modulation of the signal. The inductor acts as a matching unit to the load circuit. To achieve the required resolution with the system, a very high Q-factor of the inductance is required, as the quality of the resonant circuit is limited by the quality of the inductor. A new high-Q planar microcoil by UV-LIGA process has been developed for this purpose. By constructing high structures with the desired geometry, the series resistance of the coil can be reduced. The dielectric losses are minimized by using glass or highly doped silicon as substrate material. The stray capacitances are further minimized by optimizing the geometry of the inductor.

The manufacture of the microinductors comprises six steps, which are shown in Figure 5. Thin layers of tungsten and gold were deposited on the substrate for electrical connection. A 50 µm thick layer of photoresist was spread on the substrate, and patterned by

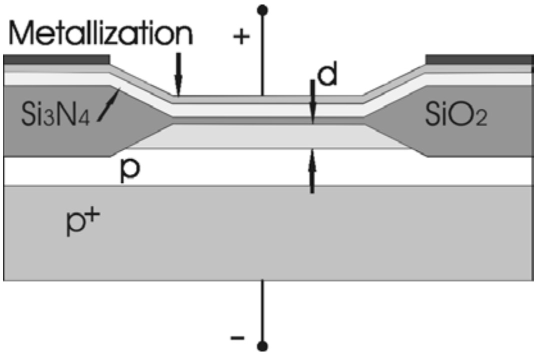

Figure 4: Schematic presentation of developed MNOS-diode

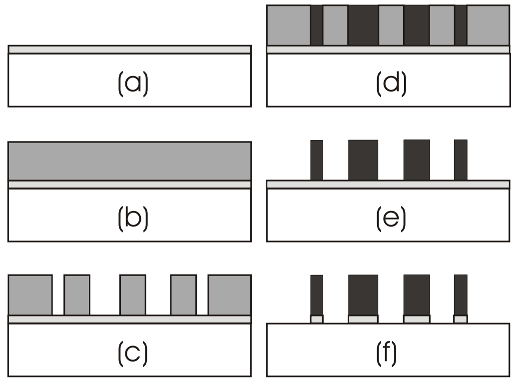

Figure 5: Microinductor manufacturing process. White: substrate, black: copper, light gray: tungsten, gold, and dark gray: photoresist

photolithography to form a negative of the coil structure. Copper was electroplated into the structure to form the coil, and finally the resist and the thin metallization layer were removed.

Assembly: Building an LC-resonant circuit at 2,4 GHz requires special attention to be paid on parasitic effects. The component values are very small in the range of a few picoFarads and nanoHenries. We have built the complete sensor planar in order to minimize the parasitic effects and to maximize the signal-to-noise ratio.

The varactors are available in a chip-size package with dimensions of about W350 x L350 x H150 μm^3. They were attached on the substrate with a silver-filled adhesive because of the ease of the procedure as compared to reflow-soldering. The additional advantage of adhesive bonding is that the whole system can be assembled lead-free to be compatible with the EU-directions regarding lead-free electronics.

The matching circuit, conductors and the antenna are constructed in a single lithography step, and further miniaturization is achieved by replacing the standard SAW-contacting technology with bond-wires by using Flip-Chip technology, as shown in Figures 6 and 7. This is necessary, because in the sensor very small inductances and manufacturing tolerances are required, and at the high frequencies the bond wires would significantly contribute to the total inductance of the circuit.

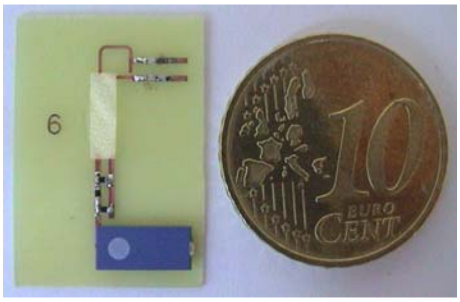

Figure 6: Prototype of ECG sensor

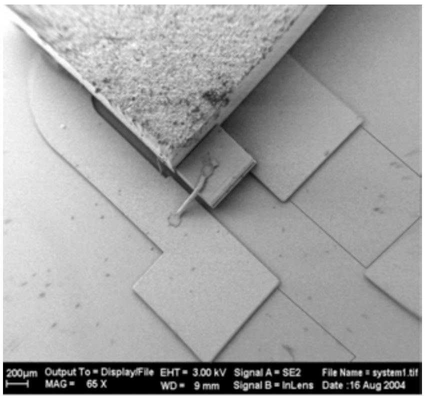

Figure 7: Detail of ECG-sensor

Results

The C-V-characteristic of the Schottky diode used in the experiments, as well as that of the first prototype of the developed MNOS-diode are shown in Figure 8. It can be seen that an improvement in the properties has been achieved with the self-developed capacitor.

The manufactured microinductors have smooth and vertical sidewalls. Figure 9 shows the photoresist before the electroplating of copper, and Figure 10 the finished copper coil. The inductance and quality factor of the coils were measured to be 6,5 nH and 70 at 2,45 GHz. The simulated self resonant frequency of the coils is at 8 GHz.

The SAW-chips have been specially designed for these ECG-sensor and manufactured with a modified standard process. They have been characterized for time-response as shown previously, as well as for the impedance behavior. The maximum phase dynamic of the devices was investigated by connecting a variable impedance to the load-IDT.

The measurement curve in Figure 11 reveals a maximum amplitude dynamic of 20 dB. At the resonant frequency the attenuation of the reflected signal is at its minimum, as depicted in formula 1. Similarly, the phase modulation was measured by on-off switching the load-IDT by opening and closing the short circuit between its poles. The maximum phase dynamic achieved was close to 100°.

The sensor response was evaluated with a cable link to the scanning unit. Phase modulation of the sensor response was evaluated by applying the potential to the

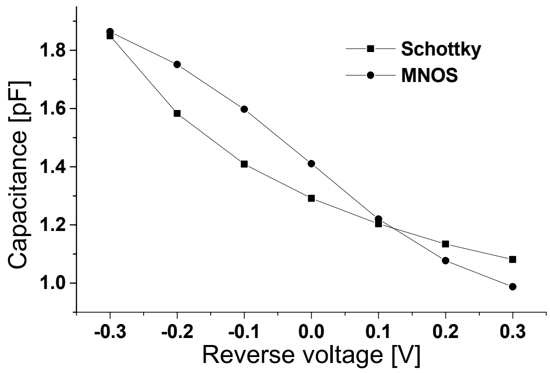

Figure 8: CV-characteristic of the Schottky-diode and the developed MNOS-diode

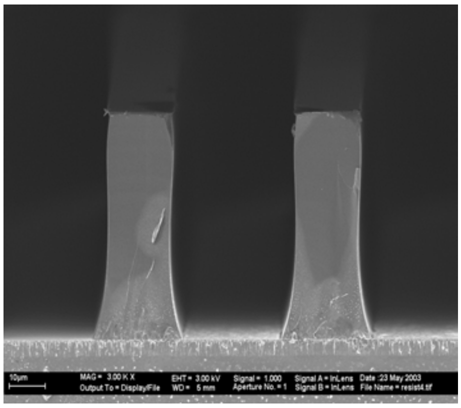

Figure 9: Negative resist structure of microcoil

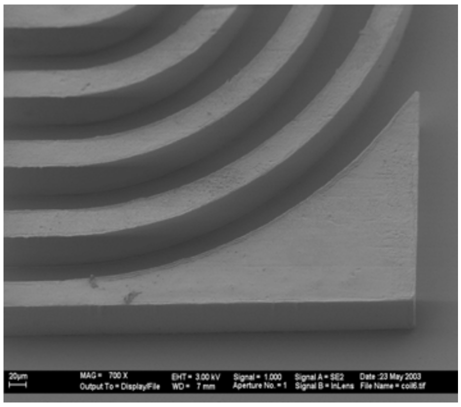

Figure 10: Copper electroplated microcoil

varactor with a laboratory voltage source. Maximum dynamic of 45° was measured in a voltage region of 6 volts. The working principle was also demonstrated with a wireless radio-link, and, presently, the maximum read distance achieved was 5 cm.

Discussion

The functioning of a wireless passive ECG sensor based on surface acoustic wave transponder technology has been demonstrated. The sensor is not yet capable of sensing millivolt potentials required in the biopotential applications, but instead a laboratory voltage source has

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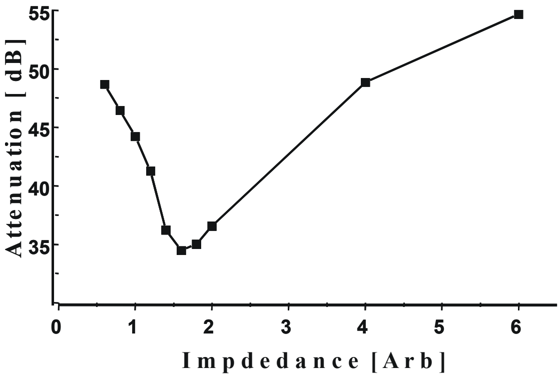

Figure 11: Amplitude response of SAW chip

been used in the measurements. The sensitivity of the sensor can be increased by improving the electrical matching of the antenna to the transceiver IDT, as well as increasing the power of the reader unit of the system. Mainly, anyhow, improvements in the sensor behavior are expected to be achieved by further improving the MNOS diode characteristic. This topic presently being pursued.

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