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Design Study of a Wireless Pressure Sensor for Medical Application

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Abstract:

This work provides crucial contributions for an implantable wireless sensor proposed for epidural or subdural brain pressure monitoring. We designed a pressure sensor based on SAW (surface acoustic wave) reflective delay lines on a diaphragm. FEM simulations were used to optimize the sensitivity, size and mechanical stability of the device. We have chosen a design that allows maximizing the sensor effect, while simultaneously providing temperature compensation. A production process for SAW membrane sensors on lithiumniobate was developed. It integrates different methods for the production of thin membranes like ultra sound drilling and laser processing as well as the protection of the sensitive SAW structures. We fabricated prototypes that demonstrated encouraging behavior in wired and wireless measurements in a pressure chamber.

Key words: SAW, surface acoustic wave, pressure sensor, intracranial pressure monitoring

Introduction

Pressure and strain monitoring is widely used in human medicine. The pressure values of more than 100 different locations are used for diagnostics and treatment in fields like cardiology, gastroenterology, urology, orthopedy and many others. Some of these measurements can be done by the use of removable catheters, or noninvasive investigations, while others require surgery to place the measuring device. In this case implantable wireless sensors have big advantages compared to wired sensors since the sensor data can be transmitted from inside the body without restraints for the patient. The clinical observation of the intracranial pressure (ICP) is critical for the treatment of head injuries and brain diseases, to give an example. Some patients with hydrocephalus, idiopathic intracranial hypertension or head injury frequently require a repeated investigation of the brain pressure over a period of months or even years [1-3]. These patients could profit dramatically from a sensor system that is permanently installed and can be read out through the scalp without the use of a cable or the requirement of a surgery to access the sensor data. Even in intensive care, where no mobility of the patient is required, the wireless system is advantageous. A wired or catheter like system increases the risk for infection by preventing the wound from closing. In comparison a wireless readout allows the wound to heal and thus minimizes the infection risk.

This work describes design concepts and experimental studies for an implantable sensor proposed for epidural or subdural intracranial pressure monitoring based on SAW (surface acoustic wave) devices. Such devices are since long known for their wireless and completely passive temperature or pressure measurement capability [4-6]. They are therefore qualified candidates for such implantable physical sensors. Most investigations of SAW pressure sensors have been done on quartz based devices [7-12] But even when using other materials the studies are nevertheless limited to relative low frequencies of about 400 MHz [15, 16]. For the present application, where the size of the SAW device and the antenna are to be minimized, as the sensor has to be placed under the scalp; the operating frequency should be maximized. Hence we have chosen to construct and investigate a membrane sensor based on a SAW delay line principal, working in the ISM band 2.45 GHz.

Concept

The idea is to use a reflective SAW delay line with a thin diaphragm as pressure sensor [7, 8, 17]. In our design the sensor housing has the shape of a mushroom. The thinner cylinder houses the SAW sensor and allows the pressure to act on the backside of the membrane. The antenna is placed on the cap and is connected to the IDT (Inter Digital

Transducer) on the front side by wire bonds. The maximum diameter of the device should not exceed 2 cm, which is, according to our investigations, sufficient for a short range antenna working at 2.45 GHz. To place the device in the head a hole of some millimeters diameter has to be drilled into the cranial bone and the thinner part of the sensor is inserted. The antenna, which needs more space than the sensor, stays outside the bone under the scalp. This allows for a moderate invasive surgery. Furthermore the readout distance of the system increases as the high frequency radiation needs not to transit bone.

We have chosen lithiumniobate as piezoelectric substrate since it permits operating the devices in the highest ISM band reachable for SAW devices with optical lithography, at 2.45 GHz [18]. The sensor effect of the SAW pressure sensor originates from the stress or strain, along the propagation path. It modifies the propagation velocity and, hence, the round trip delay time of the transmitted wave. This can be measured using an FMCW reader at a rate of 100 Hz [19, 20]. For brain pressure monitoring a pressure ranging from -20 mmHg to 300 mmHg should be detected. These small values require the construction of a very thin diaphragm to obtain the required accuracy In addition, a phase analysis is required to obtain the necessary resolution in time []. The reflectors of the delay line have to be placed exactly to ensure a maximum sensor effect in combination with an accurate temperature compensation of the SAW device. In the current design we are using a uniform IDT on the YZ Rayleigh wave cut of lithiumniobate and four reflectors with different reflecting strengths to compensate for the propagation losses. Two of the reflectors are positioned on the membrane, where the effect of the stress reaches a maximum, whereas two other reflectors are used for the compensation of the delay time changes due to temperature.

The knowledge of the mechanical limit of the substrate as well as the dependency of the propagation velocity on the applied stress is mandatory to determine the optimal position of the reflectors. Theoretical calculations of the strain dependency of SAWs require the knowledge of third order elastic constants, are elaborate and, usually, include geometric boundary conditions. To avoid this, we used a combination of experimental investigations and simulations to determine the strain sensitivity of the lithiumniobate substrate [21]. We have chosen the well-defined and simple geometry of a bending beam to apply a well-defined force on a SAW delay line made on lithiumniobate. By varying the force, measuring the changes of the delay times for different loads and correlating the experimental results with the calculated stress or strain values on the propagation path we could derive the sensitivity of $7.7\ 10^{-12}\ Pa^{-1}$ for the YZ cut of lithiumniobate.

We obtained the stress and strain distribution of the device for different geometrical configurations by simulation and used them to optimize the sensor effect while simultaneously ensuring the maximum applied stress on the membrane to stay below the crack limit.

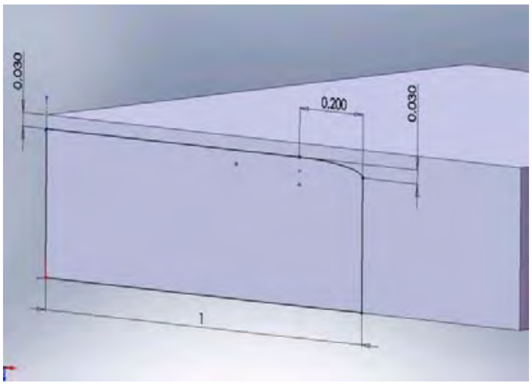

Fig. 1. Geometry used for the stress simulation of the diaphragm: radius 1 mm, thickness of membrane 30 µm, semi axis of elliptical transition 200 µm, substrate thickness 300 µm.

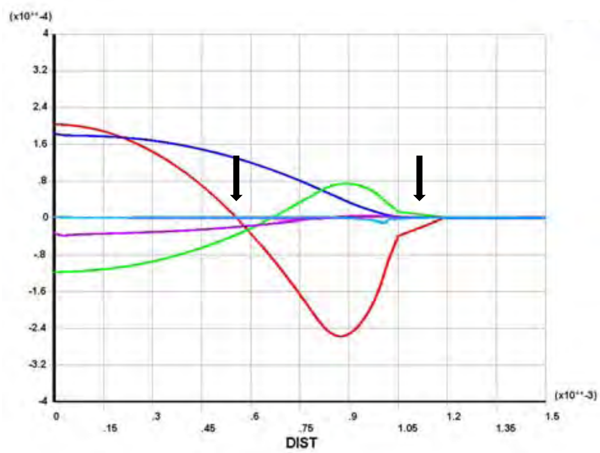

Fig. 2. Strain contribution of the membrane sensor according to the geometry given in Fig.1. Strain contributions along the propagation path of the SAW device. Zero is the center of the membrane, radius is 1 mm. Strains: ε_x (red), ε_y (blue) and ε_z (green). The reflector positions for maximum sensitivity are indicated by arrows.

Fig. 1 shows the geometry used for the stress-strain simulations and Fig. 2 shows the obtained strain components in x-, y- and z-direction on the diaphragm along the radius of the membrane. The zero crossing of the x-component of strain is essential. By placing the propagation path of the delay line along the

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diameter of the membrane and the reflectors on the two crossing points, a differential method can be used to maximize the sensor effect and annihilate the temperature dependency.

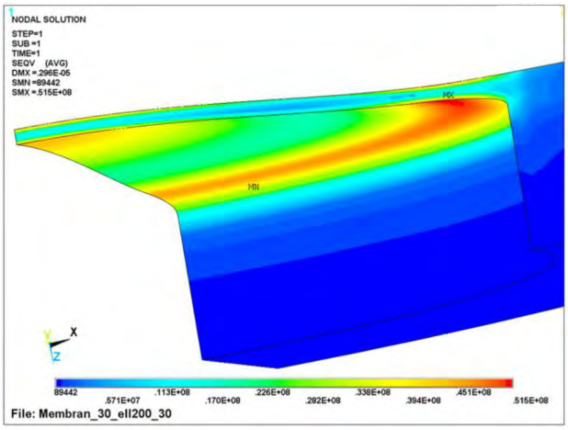

Fig. 3. Von Mises equivalent stress for a diaphragm with elliptical transition geometry

An example for the reflector positions for a design with three reflectors and optimized for sensitivity is shown in Fig. 2. The sensitivity of the sensor increases with the area beneath the stress curve along the propagation path. Of course, the sensitivity is related to the propagation length and, hence, to the diameter of the membrane and to the maximum strain. Table 1 gives some descriptive key values that allow the comparison of different geometries. The simulation shows, that an elliptical fillet provides a higher sensitivity then a circular one at a comparable stress level.

Tab. 1: Comparison of different diaphragm geometries for radius=2 mm, and a fillet of A, C) 300 µm radius, B) elliptical 200 µm x 30 µm

	thickness of membrane	**deflection at 1 bar**	**maximum strain in x-direction**	**position of inflection points relative to center**	**max. principal stress on top of membrane**	**max. principal stress on transition on the backside**
	[µm]	[µm]	$x10^{-4}$	[µm]	[MPa]	[MPa]
A	30	1.45	1.4	470	34.8	42.1
B	30	2.95	2.1	560	49.4	55.2
C	50	0.40	0.6	500	14.1	16.3

For an ideal sensor delay line sensor design two reflectors have to be positioned at crossing points of the x-component of strain. The distance of these two reflectors determines the propagation path used for sensing. For a simple compensation of temperature effects an additional delay path of the same length has to be realized. This second path is not affected by pressure and is used for a differential measurement. Provided, that there is no temperature gradient on the device, this delay line can be positioned anywhere on the die. In a uniform IDT the SAW wave is emitted symmetrically to both sides. For the optimization of the signal and hence the reading range of the device it would be preferable to position the compensation path on the opposite side of the IDT. We haven't used this option, because it would require a much longer device. Instead, we have realized two geometries. One simply uses an additional reflector behind the pair used for pressure measurement (Fig.2). Another design uses one additional reflector on each side of the central pair separated by half of the central distance. A sketch of the design is shown in Fig.4. The die has a thickness of 300 µm; the radius of the membrane is 2 mm.

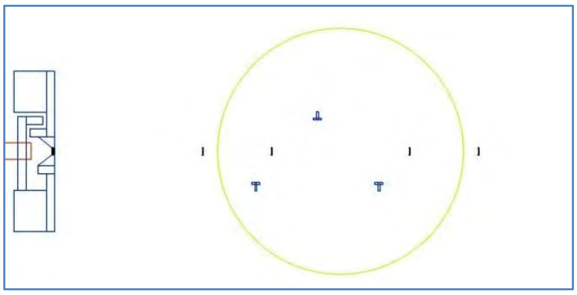

Fig. 4. Placement of the delay line relative to the diaphragm. The IDT is on the left, the inner two reflectors are used for pressure measurement the outer ones for compensation.

Experimental

As described in the design (Fig. 1, 3), the blind hole for the diaphragm has to be produced with very steep flanks, and ideally with an elliptical transition geometry.

Fig. 5. Picture of a membrane in lithiumniobate. It is made by ultrasonic drilling

Such geometry can hardly be realized by any etching process, especially as the etching rate for lithiumniobate is extremely low. In search of a production process, that provides this feature and which furthermore is compatible with the lithography process used for the fabrication of delay lines, we have used a combination of ultrasound drilling and laser structuring. A fluor-krypton Excimer laser was used to smoothen the backside of the membrane. Fig. 4 shows the diaphragm after the drilling process using a suspension of 10 µm. With this process a membrane thickness of 70- 80 µm can be obtained with a roughness of about 1 µm.

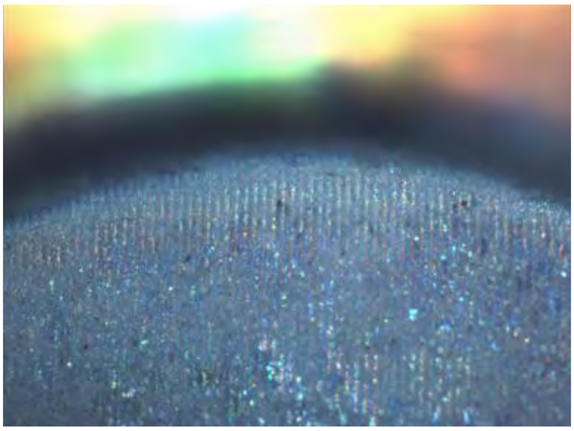

Fig. 6. Part of the membrane after smoothing with an Excimer laser

Fig. 7. Picture of a broken membrane, seen from the side, to demonstrate the fillet radius of 140 µm.

By applying laser ablation the membrane could be smoothed and thinned further. The membranes were processed in line scans of 20 µm, applying a wavelength of 248 nm and pulse duration of 23 ns. In this second processing step we achieved a membrane thickness of about 50 µm with a roughness of 300 nm. The resulting radius of the fillet is approximately 140 µm.

We fabricated several samples. They were tested by applying different pressure values on the backside of the membrane. We measured the S-parameters of the devices connected to a NWA (NetWork Analyzer). The data was analyzed in time domain using phase analysis of the signal peaks. Fig. 8 shows a typical time domain response of a delay line with four reflectors.

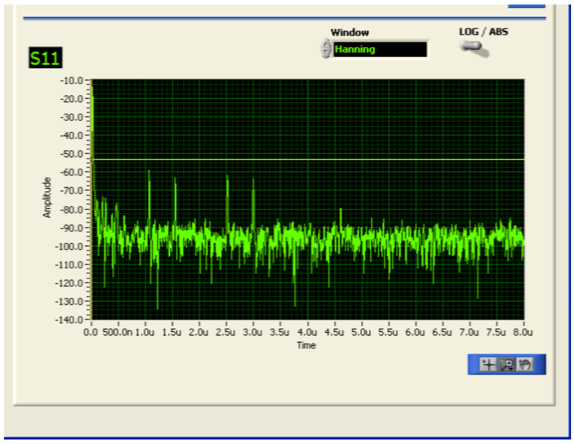

Fig. 8. Typical time domain signal for a reflective delay line.

The sensitivity of the sensor is given by the change of the phase due to pressure. In Fig.9 the results are shown for different combinations of reflectors. The blue and green curves correspond to the delay lines that are not affected by pressure and which are used for compensation, whereas the red and black ones show the increasing phase due to pressure.

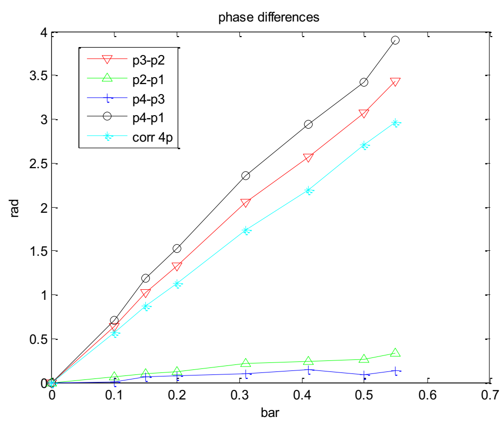

Fig. 9. Phaseshift as measured versus pressure for different combinations of reflector signals

By comparing different reflector geometries we obtained the most stable sensor behavior for the four reflector design (Fig.4). In Fig. 10 the sensitivity is shown for this design.

Results

By investigating the devices in a pressure chamber we observed a variance of about 0.02 rad and a crack limit of 2.4 bar. Inside the sensor housing the lid works as a mechanical stop for the membrane to prevent breaking.

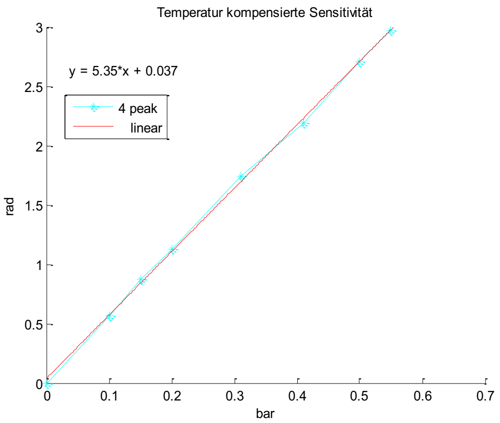

Fig. 10. Calculated sensitivity of ~ 5 rad/ bar

Besides the investigations with the NWA we used an FMCW reader equipped with a polar receiving antenna of 9 dBi for wireless readings. For a first test, commercially available helical antennas were used on the sensor side. With these antennas the reading distance was about 20 cm in air.

This range is much smaller than the signals we usually measure with SAW devices of similar performance [19, 20]. The reason is the missing matching of the SAW device with the housing and the antenna.

Tab.2 gives an overview on the experimental sensor parameters.

Sensor	
Temperature Range	body temperature ± 2°C
Measuring Range for phase	2 π
Temperature Compensation	yes
Crack limit	2.4 bar
Sensitivity	< 5 rad/ bar, tuneable by size of membrane
Variance	0.02 rad, 1% of crack limit
Size including housing	5× 3× 10 mm^3
Reading range with helical antenna in air	20 cm

Tab.2: Sensor parameters

Outlook and Conclusions

As the performance of the reading has clearly to be improved, we are presently working on the development of an antenna operating in the human body at 2.45 GHz. Furthermore, we work on the optimization of the housing in terms of electrical matching. First results were obtained with simulations using the human body model from ANSYS. The simulations indicate that an antenna of reasonable size and reading distance can be realized. To compare the theoretical results with experiments we are currently establishing an experimental test environment based on salt solutions. This is necessary as the tests cannot be performed in-situ for the destined application, of course.

Although the readout antenna is still under development it can be concluded from the measured parameters, that membrane pressure sensors based on SAW technology have a high potential as implantable sensors in medical applications.

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