Modeling of a Neural Electrode with MEMS Magnetic Sensor for Telemetry at Low Frequencies

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Abstract
This paper presents the design and simulation of a biomedical wireless microdevice. Most of the implantable devices require very small dimensions, requiring the use of microtechnologies to obtain the necessary size reduction. One of the most challenging devices to integrate is the antenna, required for devices using a wireless link. The proposed system uses wafer level packaging to integrate the neuro electrodes, the control electronics and the antenna, which is based on a MEMS structure to convert the incoming electromagnetic field to a voltage. It is proposed to use a cantilever, where an electroactive material is proposed as reading mechanism. Despite its implementation simplicity, this mechanism has also the potential to actuate the cantilever for possible radiation. This antenna allows the reception of signals using a carrier in the kHz range and uses only a chip area of 1.5x1.5 mm^2, and a full system volume of 5x3x1.5 mm^3.

Keywords: MEMS, magnetic sensor, Wafer-level packaging, modeling.

I. INTRODUCTION

The new biomedical devices offer the possibility of improved quality of life, as well cost savings associated with health care services.

In-body an on-body wireless biomedical wireless micro devices used for diagnostic, monitoring, and therapy, ranging from neural prosthesis to video-capsule endoscopy (VCE) systems, are emerging innovative technologies. The success of such systems relies on the use of microtechnologies, to achieve the miniaturization of several sensors and actuators, as well their integration with readout and communication electronics.

The ability to reduce sensors and actuators to a very high level, will lead to new technologies with the ability to gather biomedical data, allowing for innovative solutions in the field of health monitoring and control. Many systems under development already allow a very high degree of integration, allowing the combination of sensors and actuators, readout and control electronics, and telemetry link.

However, one open challenge is to communicate to and from a biomedical device placed inside the human body with devices outside the human body. The widely adopted solution is based on cables that pickup the signal from an inductor placed under skin. That solution is highly undesirable, since it is susceptible to electrical failure and pos-surgical complications. Antenna integration is highly desirable to overcome those problems, but also a hard task to accomplish since it requires expertise from antennas, microwaves, circuit design, and materials. Moreover, the on-chip antenna integration requires an electrically small antenna, due to wafer cost and devices size constrains [1]. The lack of antennas, small enough to be integrated with the sensing microsystem, is a difficult task to overcome because such communications must be made at relatively low frequencies, due to live tissue signal attenuation. Up to now solutions, use conventional antennas together with miniaturization techniques to achieve the smallest antennas possible. However, the size of such devices is usually limited by the antenna and is rather large.

Full integration requires the availability of very-small sub-systems that can be fitted into a single chip. Several solutions have been proposed to deliver an integrated antenna, electrodes and electronics. However, despite the miniaturization and integration that is possible to achieve, the operating frequencies at which the reduced dimensions are possible, are rather high for biomedical devices that are required to operate inside the human body, mainly due to the antenna size required. To obtain an antenna small enough, to simultaneously fit inside a microdevice and operate at low frequencies (inside the kHz-MHz range), is necessary to look for alternative ways, as discussed by [2].

In this paper, we describe one method to obtain a microsystem with all requires features, based on wafer level packaging and bulk micromachining.. Then, we present the design, modeling and simulation of the on-chip MEMS antenna.

II. SYSTEM DESIGN

A. System Integration using Wafer Level Packaging

The device fabrication under development is based on wafer level packaging (WLP) techniques. In this way, it is possible to obtain a very small microdevice, where the dimensions of the full device are only constrained by the antenna dimensions. Moreover, it is not necessary the use of, e.g., wire bonding to interconnect the antenna to the RF circuitry, since it can be bonded underneath the antenna. Application of WLP techniques [3], like adhesive wafer bonding and through-wafer electrical via formation, allows the use of different substrates together with silicon.

Fig. 1 shows an artistic view of the microdevice under development, where the final assembly of the three wafers that composed all the structure is shown. The bottom wafer, which supports the electrode-nerve interface, is a glass wafer and is bonded with an intermediate silicon wafer, which supports the CMOS electronics that establishes the interconections between the electronics and the nerve. The MEMS antenna, supported by the top wafer, is obtained using bulk micromachining.

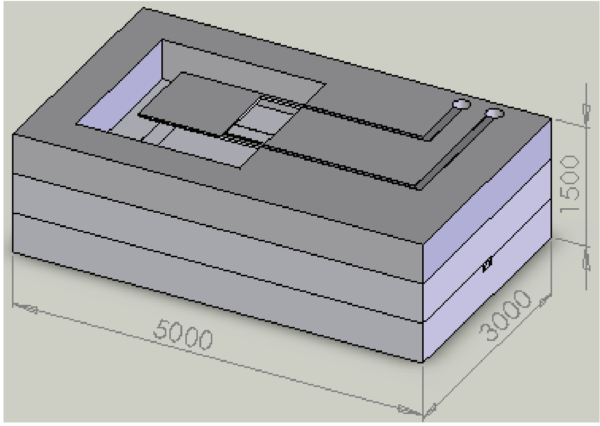

Figure 1: Global artistic view of the wireless biomedical microdevice (All dimensions are in µm)

This integration solution offers potential of low cost, low profile and simplified assembly. We evaluate this on the integration of neuro electrodes with microelectronics and antennas.

As starting material, one AF-45, 100 mm diameter and 500 µm thick glass wafer was used. After that two silicon 500 µm thick wafers are bonded on top of the wafer containing the electrodes. They are adhesively bonded, using ~5-7 µm thick BCB (benzocyclobutene) layer as the adhesive. In Fig. 2 it is represented the glass wafer, where the nerve is shown (white) as well the 3 grey platinum contacts fabricated on it [4].

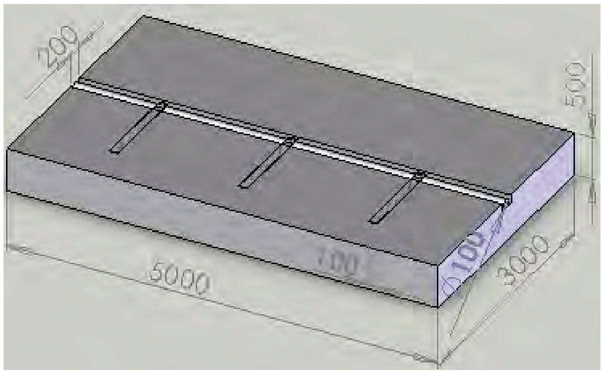

Figure 2: Full system bottom wafer showing the connection between the nerve and the platinum electrodes. All dimensions are in µm.

Above the electrode glass wafer, a silicon wafer is bonded and, used to design all the readout and control microelectronics. The physical contact with the nerve, is made with vias through the second wafer. Those vias may be obtained by DRIE (Deep Reactive-Ion Etching) and then sputtered with aluminum. Finally, the top wafer is represented in Fig. 3. This layer supports all the required MEMS technology required to implement the wireless link communication. In this work, a simple cantilever will be evaluated as a possible candidate to operate as a MEMS receiving antenna.

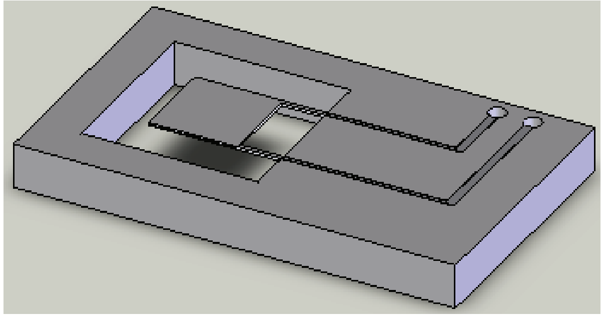

Figure 3: Silicon top wafer with MEMS antenna.

B. MEMS Antenna Integration

The basic principle of micromachined cantilevers offers an interesting possibility to measure a variety of physical parameters. One of the most basic MEMS antennas we can design is a U-shaped cantilever (Fig. 4) where the cantilever model is represented together with the bulk substrate. To operate as an antenna, the cantilever is designed to measure the magnetic field component from the electromagnetic wave, using the Lorentz force on the current carrying lead. The proposed sensing mechanism is based on a piezoelectric material, like PVDF. This material will produce a voltage proportional to the cantilever deflection. That voltage may then be used as input for a differential amplifier. This solution can be easily integrated with the MEMS structure and has the potential for low power consumption. Moreover, piezoelectric actuation can be used as the actuation mechanism for MEMS micro-radiators.

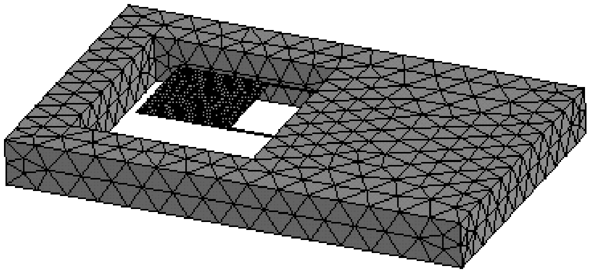

Figure 4: Geometry and mesh of an electrically small antenna based on a MEMS device.

The U-shaped cantilever under analysis detects only magnetic field components that are parallel to the arms of the cantilever. The Lorentz-force acting on a lead is used to bend the micromachined cantilever. Deflections, which are small compared to the length of the cantilever, will be a directly proportional to the applied force. To reach the highest possible sensitivity it is advisable to use a resonant mechanism, where the carrier frequency of the magnetic field is the same as the eigenfrequency of the elastic structure. Due to the high quality factors of Si structures, which are at least several hundred, this is an efficient way to enhance the sensitivity.

C. Antenna Design

The mechanical displacement can be converted into a voltage using an optical, capacitive, or piezoelectric transducer. The most attractive options are capacitive and piezoelectric. These solutions can be easily integrated with the MEMS structure and have the potential for low power consumption. Since the desirable displacement depends on structure dimensions and material properties, electrostatic actuation can be used as the actuation mechanism for MEMS micro-antennas. However, if large displacements are required, or if the MEMS structure area becomes too small for capacitive detection, the use of a piezoelectric material can be the solution, since it can act both as sensor and actuator. Moreover, the operation is only voltage based, leading to low power driving operation. Furthermore, it produces a voltage in response to a deflection, leading to simple readout electronics.

The proposed MEMS structure was engineered to have the desired electrical and geometrical properties, as well the requirements to be used in a post-process module compatible with integrated circuit (IC) fabrication.

Fig. 5 shows the 3D FEM (finite element method) model being used to analyze the receiving properties for a cantilever operating as an antenna. FEM modeling is a very powerful technique to predict the interaction between different domains (electrical, mechanical, and electromagnetic).

D. Neuro Electrodes Antenna Integration

The signal is carried till the nerve using aluminum paths. However the use of an aluminum contact is not a solution to connect the path with the nerve. The chosen connecting material was the grey platinum. In terms of micromachining process it was done covering the 4 µm aluminum layer with 1 µm of grey platinum. It is a demand this interface is biocompatible and has properly characteristics. In order to achieve this aim the original aluminum was covered by grey platinum only in the electrode-nerve interface [4].

E. RF Link Modeling

As it was stated before the physical interaction with the cantilever is assured by the Lorentz force. This is possible due to a current distribution on the aluminum layer just above the silicon which is assumed of being about 100 mA. If there is an external magnetic field which interacts with this current it represents a mechanism of interaction. From the interaction between an external magnetic field and a current distribution on the cantilever arise the possibility of modulate its displacement.

The mechanism of interaction could be described by the Lorentz force expression which is given by:

$$\vec{F}_L = (\vec{B} \times \vec{I})L \qquad (1)$$

III. SIMULATION AND RESULTS

The antenna was submitted to an equal distributed pressure in the whole bulk area. This mechanical strain was used to simulate the effect of the Lorentz force on the antenna. The result that came out from this simulation is the displacement of the structure which will be used to evaluate what is the voltage produced by the Polyvinylidene fluoride (PVDF) layer. PVDF is an electro-active material, meaning it produces an electrical voltage when submitted to a strain. This voltage will be them measured using readout electronics placed on the silicon wafer which is used in the middle layer.

A. Antenna Modeling

The numerical method known as the Finite Element Method (FEM) [6] was used to understand how the proposed structure behaves in response to a specific pressure input, as well to the material properties and MEMS device dimensions [2].

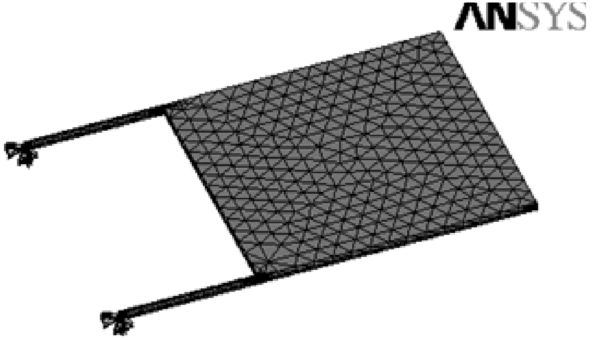

Fig. 5 FEM modeling of MEMS antenna.

B. Detection Method

The cantilever includes three different layers. The upper layer represents the PVDF. As an eletroactive material, we know that it produces a voltage in response to a mechanical stress. The upcoming study is to evaluate how much displacement, the minimum, we need to obtain enough voltage at PVDF layer terminals, so it can be detected by the readout electronics. Up to know, it is known that a displacement in the order of nanometers is enough to produce voltage amplitudes in the range of mV.

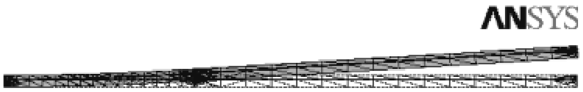

Figure 6: Non-stressed structure at white, non-bended lines. After applying pressure the structure bend and it is represented at blue.

C. Cantilever Layers Properties

As mentioned earlier, the cantilever, which works as a MEMS antenna, has 3 different layers. The bottom one is silicon nitride, the intermediate is aluminum and the top layer is PVDF. To obtain the present results 3 different material properties were essential, the Young's modulus, Poisson ratio and mass density. Table 1 shows the parameters used for simulation.

Table 1 – Material properties used in FEM simulation
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	Young's modulus (GPa)	Poisson ratio	mass density (Kg/m^3)
Silicon	150	0.27	2329
Aluminum	70	0.35	2700
PVDF (Polyvinylidene Fluoride)	2	0.3	1770

D. Analysis

Fig. 6 shows results obtained with the implemented model. According to Fig. 5, the cantilever is attached to the bulk wafer by two beams. For numerical simulation it is enough to ensure that the extremity of each beam, which supports the body of the cantilever, does not have freedom to move. This is represented in Fig. 5 by the blue arrows. The red lines on the body of the cantilever are representing the equally distributed pressure on it. The value required for this pressure will depend on how much displacement we have to cause in the cantilever to have the desired voltage at the PVDF layer terminals. And this will define the minimum magnetic field we are able to measure. For now we use the value of 5 N/m^2, what we think is perfectly reasonable.

Both, displaced structure by the applied pressure and the original structure are represented in Fig. 6. The displaced structure after applying pressure is represented by the blue and bended one. The dotted structure is the original one, before applying the pressure.

At left, it is represented the static extremities of the beams and at right it can be noted the maximum displacement of the body of the cantilever which was around 5 µm. It was performed a modal analysis in order to discover what is the fundamental resonant frequency of this structure which is around 810 Hz.

Based on equation 1, if there is a magnetic induction (B) of about few mT and considering a cantilever current of 100 mA, together with a beam length of 0.5 mm, it leads to a Lorentz force of 5µN. In this way, if it is demanding a detection of a magnetic induction in the order of nT, the Lorentz force must be also six orders of magnitude below. It can be extrapolated that, to measure a magnetic induction in the order of nT, the applied pressure on the cantilever's body must be in the order of pN. The importance of achieving a capacity for measure a magnetic induction in these orders of magnitude (nT) arise from the comparison with other similar devices, [5].

IV. CONCLUSIONS

This paper presents a solution to obtain a fully integrated microdevice with electrodes, CMOS electronics, and antenna. It shows how to design, model and simulate the behavior of a magnetic sensor for telemetry at low frequency.

The antenna concept and integration is based on MEMS techniques, which enables the integration of new materials with the standard silicon processing steps, as well the fabrication of complex three-dimensional structures, in an economically acceptable way.

It was analyzed the use of an electroactive sensing mechanism to translate the MEMS antenna deflection onto an electrical voltage. With this detection device, it is expected to measure the magnetic flux in the order of nT.

Moreover, the proposed solution was based on standard processing microtechnologies, as well on CMOS microelectronics.

V. REFERENCES

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