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A Chip Integrity Monitor for Evaluating Long-term Encapsulation Performance Within Active Flexible Implants

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Abstract—One key obstacle in employing silicon integrated circuits in flexible implants is ensuring a long-term operation of the chip within the wet corrosive environment of the body. For this reason, throughout the years, various biocompatible insulating materials have been proposed, yet, evaluating their long-term encapsulation performance on representative silicon samples still remains to be the main challenge. For this aim, in this work, a sensitive platform is introduced that can track the integrity of the chip against water and ion ingress. This platform is developed to be used for long-term monitoring of chip integrity and study of encapsulation layers in wet environments. The platform comprises a sensing array and a measurement engine and operates by tracking the changes in the inter-layer dielectric resistance within the chip. The proposed system uses a novel charge/discharge-based time-mode resistance sensor that can be implemented using simple yet highly robust circuitry. The sensor array is implemented together with the measurement engine in a standard 0.18/μm 6-metal CMOS process. For chip validation, dry and wet measurements in saline are presented in this paper.

Index Terms—Chip integrity, flexible implants, encapsulation, charge-discharge, time-mode operation, monitoring, reliability.

I. INTRODUCTION

For years, active medical implants have relied on titanium cases for protecting the inside components against the fluidic environment of the body. Despite their long-term reliability, these implants end up having large volumes, are heavy, and unlike biological tissue, are stiff and rigid. For this reason, a great deal of research has been dedicated to replacing the bulky titanium cases with flexible polymers and thin-film coating layers [1], [2]. Recently, these efforts have been further endorsed by the new field of bioelectronic medicine, in which small, flexible, and lightweight implants are needed for targeting the delicate nerve structures within the body [3]. In previous work, we have shown an active electrode array for epidural spinal cord stimulation in which silicone rubber was used for the packaging of the miniature integrated circuits (ICs) [4]. In [5], a millimeter scale wireless peripheral nerve stimulator has been reported where parylene, as a thin biocompatible polymer, has been used for the final packaging of the chip and the piezoelectric crystal. Such approaches add a thin biocompatible polymer, has been used for the final packaging of the chip and the piezoelectric crystal. Such approaches add

In wet ionic environments, failure of electronics can occur due to water molecule and ion ingress through the protective layers (due to imperfections, defects, pinholes, etc), first causing parameter changes in the passive (capacitance/resistance) and active (MOS transistor) components, and later causing shorts and/or hard opens [1], [6], [7]. For polymer encapsulated single-chip implants, the ingress of water and ions could initiate from the top passivation and/or the edges of the chip (Fig. 1). Given the micro/sub-micrometer scale of components inside the chip, even tiny amounts of water or ions could lead to performance loss or total device failure [1], [7]. For this reason, a sensitive on-chip platform is needed to evaluate the long-term encapsulation performance of the coating materials in wet ionic environments. In [8] the advantages of an in situ sensing system was highlighted and a circuit was proposed to detect water infiltration from the edges of the silicon die.

In this work we present the implementation of an in situ sensing array that can detect leakage pathways through the top and edges of the chip and track the propagation of the leakage in realtime. The employed sensing method is based on tracking the resistance change in the inter-layer dielectrics (ILD) between successive metal layers in the chip. The platform can track the resistance change throughout the 234x23 sensor array and at different depths of the chip. Time-mode operation [9] is used, where a pulse-width carries the measurement information, and time measurements are used to detect the changes in the ILD with a tuneable measurement range and measurement accuracy.

The organization of this paper is as follows: the top-level overview of the proposed time-mode resistance measurement system and measurement concept is introduced in Sec.II. The design of the sensor pixel is presented in Sec.III. Chip implementation and measurement results are given in Sec.IV, and finally, conclusions are drawn in Sec.V.

II. RESISTANCE MEASUREMENT SYSTEM

A. System Level Implementation

The proposed whole-chip measurement system is implemented as a sensor pixel array as shown in Fig. 2. The array consists of 234 rows and 23 columns. To measure each pixel’s value, a fully-digital measurement engine that can automatically check all the cells for integrity and degradation within the SiO2 ILD is implemented. Row enable enables a row of pixels for sensing,
and Row read enables the output of the chosen row’s pixels. Then all columns are read by the measurement engine (Column read) and further processed.

A serial-in, serial-out architecture is used to minimize the number of bonding pads (6 in total) to ease the handling of the device during testing in wet environments. The clock (CLK) and reset (RST) signals together with the data-input port (dataIn) are used for controlling the measurement engine externally, and the output is sent off-chip through dataOut. As it will be shown in Sec.IV-A, it is possible to change both the accuracy and maximum resistance measurement capability of the system by changing the clock frequency, hence adapting the system for different measurement conditions.

B. Measurement principle

The proposed measurement method employed in each pixel is based on charging a node, leaving that node floating to discharge and measuring the discharge time. A simple model of the method is shown in Fig. 3(a). In the figure, \( n_1 \) is the node that is charged and then left floating when the switch opens, \( R_{ox} \) is the resistance of the ILD oxide, representing the irregularities in the oxide structure that is intended to be monitored, \( C_{ox} \) is the oxide capacitance between the floating node and the ground plane, and \( R_{shunt} \) represents all the other shunt resistance elements connected to \( n_1 \). As the model in Fig. 3(a) shows, a familiar parallel RC circuit is created once the switch opens. The charge on the capacitor will discharge through the resistors as shown in Fig. 3(b). The voltage at \( n_1 \) is VDD just before the switch opens, and after the switch opens, at time \( t \), it is given by

\[
V_{n_1}(t) = VDD \cdot e^{-t/RC_{eq}}
\]

where \( RC_{eq} = R_{ox}/R_{shunt} \) and \( C_{eq} \) is the combination of all the capacitances to ground at node \( n_1 \). By measuring the time it takes for node \( n_1 \) to be discharged to a specific value, in our case VDD/2, the RC time constant between \( n_1 \) and ground may be measured with a very high accuracy. For a target discharge threshold of VDD/2, the discharge time and the RC time constant at \( n_1 \) are given by

\[
T_{discharge} = \ln(2) \cdot R_{eq}C_{eq}
\]

\[
R_{eq}C_{eq} = T_{discharge}/\ln(2)
\]

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T_{discharge} = \ln(2) \cdot R_{eq}C_{eq}
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\]
Moreover, we expect the discharge time of \( n_1 \) in the resistance is higher than the increase in the capacitance. For this aim, if we monitor a lower discharge time count, we can conclude that the reduction of the capacitance of the layer. In such a case, if we monitor a multiple changes but mainly: i) the conductance of the ILD leakage of MN1. However, as the chip integrity is breached and the 3-state buffer, the gate leakage through the latch, and the gate elements: the current leakage path through MP1 and output of the 3-state buffer, the gate leakage through the latch, and the gate leakage of MN1. It is assumed that in the presence of water or ions in the ILD layer, the dominant discharge path for \( n_1 \) will be through the ILD oxide. Therefore, we use the variation in the discharge time of node \( n_1 \) to track the changes in the resistance and capacitance of the SiO\(_2\) layer between any two metal layers that act as our sensing plates (Fig. 5). Finally, we convert the time it takes \( n_1 \) to discharge to VDD/2 to a time count and calculate the measured resistance using this time count.

In the absence of water molecules and ions in the ILD SiO\(_2\) layer between two successive metals, the resistance of the ILD will be very high (in the order of 10\(^{15}\) ohms). At this point, the dominating resistance at node \( n_1 \) will be mainly from the gate leakage of MN1. However, as the chip integrity is breached and water molecules and ions penetrate the ILD layers, there will be multiple changes but mainly: i) the conductance of the ILD SiO\(_2\) that has been breached will increase (i.e., the resistance will reduce), and ii) due to the presence of water molecules and ions, the dielectric constant of the SiO\(_2\) will increase, hence increasing the capacitance of the layer. In such a case, if we monitor a lower discharge time count, we can conclude that the reduction in the resistance is higher than the increase in the capacitance. Moreover, we expect the discharge time of \( n_1 \) to be reduced in proportion to the reduced resistance (representing the amount of ions and molecules in the oxide).

### IV. Chip Implementation and Measurement Results

A prototype system containing the sensor array and the measurement engine core is implemented in a 0.18\(\mu\)m standard CMOS process. Fig. 7(a) shows the implemented chip together with the polydimethylsiloxane (PDMS) covering the pads and wire bonds. For proof of concept, in this paper, all the dry and wet measurements are done with bare dies where the top passivation is the only insulating layer. For this aim, PDMS is only applied over the pads and wire bonds leaving the sensor array fully exposed. Chip area including the bonding pads is 1.1 mm x 1.1 mm. The sensor array consists of 5382 sensor pixels, with varying metal sensor plate structures, as explained previously. The size of each pixel is 3.92 \(\mu\)m by 29.68 \(\mu\)m, hence giving the same resolutions in the y and x directions, respectively.

Figure 7. (a) Chip photo showing the sensor array, measurement engine, and polydimethylsiloxane (PDMS) covered bonding wires. (b) Measurement set-up showing the custom designed PCB used for both dry and wet measurements. (c) SEM image illustrating the intentional scratched passivation surface of the chip. Pixels with M6-M5 sensor plates are marked.

#### A. Dry measurements

To verify the correct operation of the system and determine the measurement capabilities, the first measurements are done in dry conditions. For each chip, dry measurement results are also used as a reference for comparing to wet measurements. The external clock frequency for the measurement engine is adjustable from 75 MHz down to 125 kHz. The clock frequency will allow for measurement of the discharge time with differing accuracy and maximum resistance limits. For example, for a clock frequency of 50 MHz, the minimum discharge time-step that can be measured is 20 ns. Using Eq. (3), and an average value of 241 F for \( C_{eq} \), it can be calculated that the minimum measurable resistance change is 1.2 M\(\Omega\). Any changes greater than 1.2 M\(\Omega\) will be captured by the system as a reduction in the discharge counter, with a maximum measurable value of 1.26 T\(\Omega\). To increase the

![Figure 6. Timing of the measurement pixel operation.](image)

![Figure 7.](image)

![Figure 8.](image)
measurement range, the external clock can be reduced to a lower frequency, e.g., 125 kHz, where the maximum measurable resistance becomes 0.504 peta-ohm \([0.504 \cdot 10^{15} \Omega]\). During our measurements we found out that a 125 kHz clock is sufficient to set the upper range of the measurement, as resistance values higher than 0.504 peta-ohm in the ILD oxide are not measurable due to the shunt current leakage paths \(R_{\text{shunt}}\) in each pixel. The shunt current leakage path in each pixel is dominated by the gate-leakage of the MOSCAP transistor, and our measurements are in agreement with our expected gate-leakage calculations and the results that have been previously published \([10]\). To measure all the pixels with a 125 kHz clock, approximately 12.5 hours is needed. Results of such a measurement are presented in Fig. 8, showing the measurement capabilities of the implemented platform.

B. Wet measurements

Wet measurements were performed to verify the capabilities of the implemented platform in tracking water/ion ingress through the ILD stacks. Our earlier wet experiments after two weeks of continuous soaking in saline showed no changes in the array when compared to dry measurements. This suggests the good insulating properties of the chip passivation provided by the foundry. Therefore, in this paper, to test the functionality of the proposed circuit in a controlled environment, three scratches were intentionally introduced on the chip passivation surface using an ultrasonic cutter. This would allow faster propagation of water/ions in the chip ILD layer. A SEM image of one such scratch is shown in Fig. 7(c).

After scratching the surface of the chip, measurements under different conditions were made. First, a dry measurement of the chip was done. Fig. 9 shows the results of this measurement where the scratched areas on the chip are seen as lighter colour pixels compared to the rest of the array. The lighter colours indicate a faster discharge time and could be due to an introduced damage in the top metal when scratching the passivation surface. In these measurements a clock of 50 MHz was chosen to increase the accuracy of the measurement as explained previously. Second, we tested the chip in a phosphate-buffered saline (PBS) solution with a pH of 7.4. The solution was kept on the sensor array using an ultrasonic cutter. This would allow faster propagation of water/ions showing how water/ion ingress through the scratched area can change the resistance in neighboring pixels.

V. CONCLUSIONS

A fully integrated, standard-CMOS, chip integrity moni-
tor has been presented. The implemented chip utilizes novel charge/discharge-based, time-mode pixels that monitor the changes in the sensing element’s oxide through ultra-high resistance measurements. The sensor array is implemented together with a digital measurement engine that continuously monitors the sensor readings. The system can measure resistance values up to 0.5 peta-ohm, with controllable measurement steps that can be as low as 1.2 MΩ.

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