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Design and Manufacturing of an In-Package Relative Humidity Sensor with Multi-Width Interdigital Electrodes Towards Enhanced Sensitivity for Characterization of Packaging Encapsulation Materials

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Abstract

This study presents a novel manufacturing process and design towards an enhanced sensitivity of an in-package relative humidity sensor. The device comprises multi-width interdigital electrodes which make oxide pillars appear during wet chemical etching in the fabrication process. Those oxide pillars appear only in wider areas while completely etched away in narrower areas providing semi-floating metal fingers. Therefore, after wafer molding, the packaging encapsulation material such as the epoxy molding compound covers larger area around the electrodes and increases the sensitivity by confining more of the electrical field lines. The results confirm the enhanced sensitivity of the proposed humidity sensor for characterization and monitoring of the aging properties of packaging encapsulation materials.

Introduction

An in-package humidity sensor, also known as an integrated humidity sensor, is important for a variety of applications where accurate measurement and control of humidity levels are crucial. Humidity, which refers to the amount of water vapor present in the air, plays a significant role in many environments, processes, and industries [1,2]. Here are some reasons why an in-package humidity sensor is important.

Quality Control: In industries such as pharmaceuticals, electronics manufacturing, and food production, maintaining specific humidity levels is crucial to ensure the quality and longevity of products. Humidity control can prevent the growth of mold, degradation of materials, and other undesirable effects that can compromise product integrity.

Health and Comfort: In indoor environments like homes, offices, and hospitals, maintaining optimal humidity levels is important for the comfort and well-being of occupants. Too much humidity can lead to mold growth and dust mites, while too little humidity can cause discomfort, dry skin, and respiratory issues.

HVAC Systems: Heating, ventilation, and air conditioning (HVAC) systems require accurate humidity measurements to optimize their performance. Proper humidity control in HVAC systems can enhance energy efficiency, prevent condensation, and maintain a comfortable indoor environment.

Weather Forecasting: Humidity is a critical parameter in weather forecasting models. Inaccurate humidity measurements can lead to flawed predictions of weather patterns and phenomena, affecting public safety and decision-making.

Agriculture: Humidity control is important in greenhouse cultivation and indoor farming. Proper humidity levels influence plant growth, disease prevention, and yield. Humidity sensors help monitor and regulate these levels.

Industrial Processes: In industrial processes such as drying, curing, and painting, precise humidity control is vital for achieving consistent product quality and process efficiency. Humidity sensors ensure that the right conditions are maintained.

Data Centers: Data centers house sensitive electronic equipment that generates heat. Managing humidity levels in these facilities is essential to prevent condensation and maintain optimal operating conditions for the equipment.

Museums and Archives: Artifacts, historical documents, and artwork are often sensitive to humidity fluctuations. Maintaining stable humidity levels helps preserve these valuable items over time.

Energy Efficiency: In energy-efficient buildings, humidity control is linked to temperature control. By managing humidity levels, HVAC systems can operate more efficiently, reducing energy consumption.

Research and Development: In scientific research and laboratory settings, precise humidity measurements are necessary for various experiments and studies, including those related to materials, chemistry, and biology.

In-package humidity sensors are important because they provide a convenient and accurate way to measure humidity levels in various applications. These sensors are designed to be compact, reliable, and capable of operating in specific environments, making them invaluable tools for maintaining the desired humidity conditions and optimizing processes across different industries and scenarios. Semiconductor devices are shrinking in size while they demand higher power dissipation. Thus, the power density levels in semiconductor devices are increasing. The packaging technologies for automotive applications are not intended for utilization in the challenging environments exceptionally when exposed to high-power densities and high humidity levels. Typically, the capacitive moisture sensors have identical micro metal fingers coated by the sensing material as shown in Fig. 1(a) [3].

In this study, a novel design with variable metal fingers is employed to enhance the sensitivity by letting more electric field lines to pass through the encapsulation layer as illustrated in Fig. 1(b).

Methodology

The sensor designed in this study is a capacitive moisture sensor. A capacitive sensor comprises interdigital electrodes spaced apart. Typically, such two electrical conductors are spaced apart by a dielectric material. In a capacitive moisture sensor, the dielectric constant of the dielectric material varies in dependence of the moisture content in the dielectric material.

Moisture absorption/desorption into the package encapsulation layer causes a change of the dielectric constant, which can be monitored precisely for reliability [4]. The interdigital electrodes are coated with epoxy molding compound (EMC) as the dielectric material between two conductors. The moisture sensor can directly measure the moisture content in the encapsulation layer, which greatly improves the measurement accuracy. Nevertheless, the interdigital electrodes in this study are designed in multiple linewidths as shown in Fig.2(a) and Fig. 2(b). With the new design, the wet chemical etching with accurate timing can etch partially free-standing support structures as described in Fig. 2(c) and Fig. 2(d) so the EMC can cover the free space.

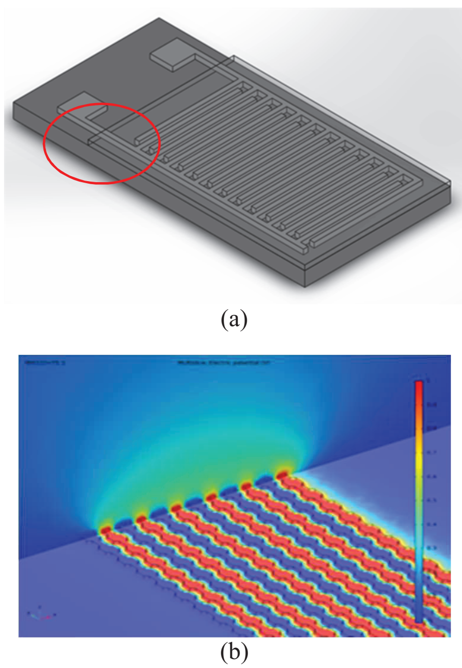

Fig. 1. (a) Traditional design of capacitive moisture sensor, (b) Novel design with variable metal fingers.

Novelty and Impact

The dependability and lifespan of electronic devices are increasingly vital due to their direct impact on device reliability. Given this perspective, it is crucial to ascertain the key factors responsible for package failure. For example, the humidity absorption, the aging properties, and RF reliability.

One aspect of this novelty relates to a capacitor comprised of electrical conductors supported by a plurality of electrically insulating support structures with plasma-enhanced chemical vapor deposited TEOS apart from one another to make maximum space for EMC to flow between the electrodes and increase the sensitivity and minimize the parasitic capacitance. This capacitor is particularly advantageous in that at least some parts of the first electrical conductor do not have an electrically insulating support layer directly below it, meaning that in those intermediate free-standing spaces, there is extra room for encapsulation material to flow between electrodes and precisely sense the properties of the molding compound.

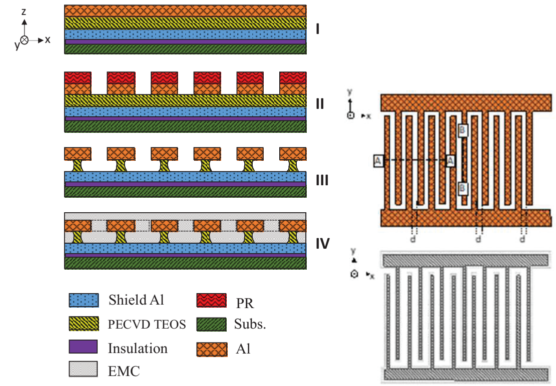

Fig. 2. The fabrication process of conventional SIDE featuring wet chemical etching (identical metal fingers with similar widths).

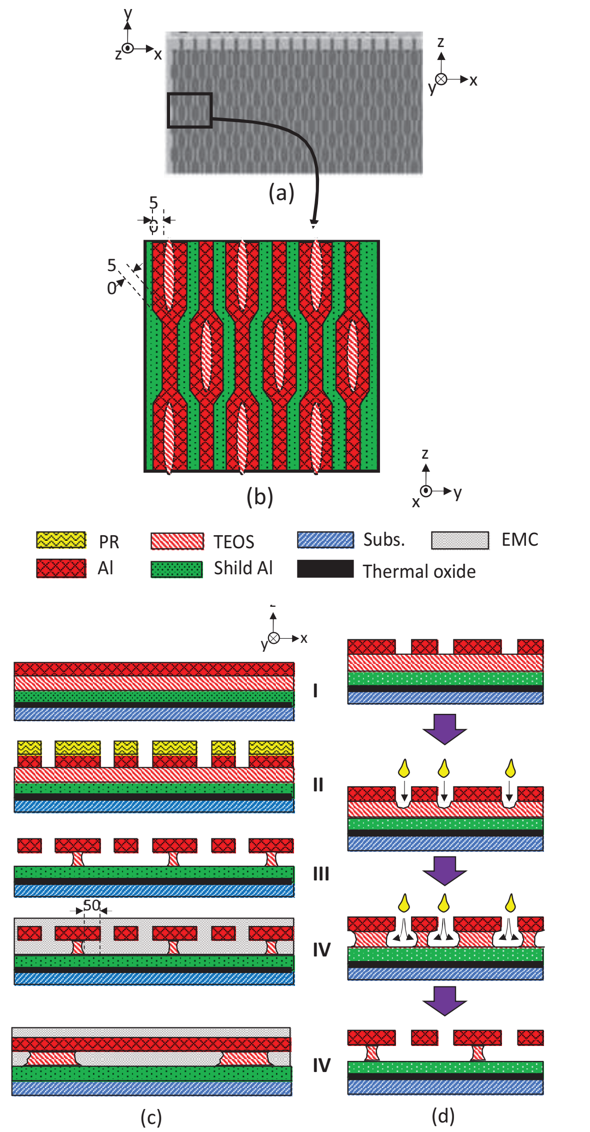

Fig. 3. (a) Capacitive sensor design, (b) Top view after oxide chemical etching, (c) Fabrication processing steps, (d) step III

Results and Discussion

Fig. 3 (d) illustrates that the EMC covers the majority of the electrical field lines which increases the sensitivity of the sensor. The new design, featuring wet chemical etching of the oxide sacrificial layer, contains oxide pillars supporting the metal fingers where it has wider linewidth. However, in narrower areas there is no support underneath as shown in Fig. 3 (c). The conventional shielded interdigital electrodes including identical metal fingers with similar widths are illustrated in Fig. 2 [4]. Comparing to this previously designed RH sensor with calibration results reported in table I [4], the new multi-width interdigital electrodes make further space for EMC to flow between the metal fingers.

The novel fabrication approach maximizes the electrical field lines to pass through the EMC and enhances the sensitivity. The proposed design also alleviates the trade-off between sensitivity and response time of the capacitive sensor.

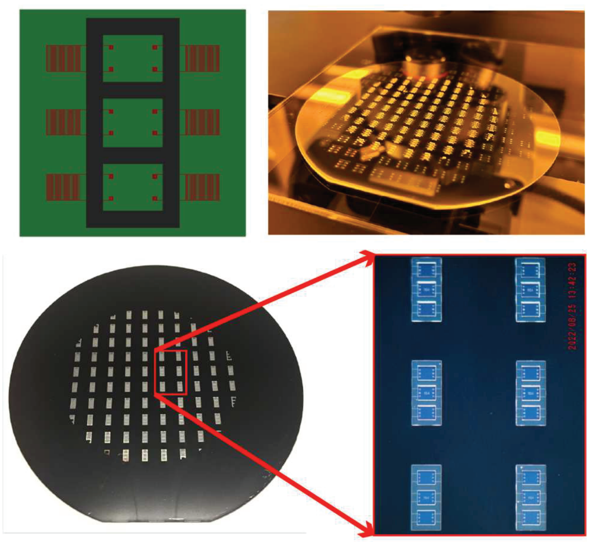

Fig. 4. The design layout, the fab-out wafer with TPVs, and the wafer after molding.

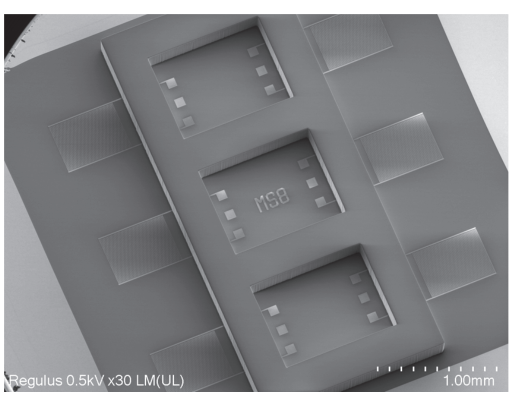

Fig. 5. The SEM imaging of the humidity sensor chip.

Table 1. Sensor Calibration Results

	MS1	MS2	MS3
Capacitance before molding (pF)	1.54	0.98	3.6
Capacitance after molding (pF)	5.85	3.95	14.5
Conductance before molding Ω^{-1}	1.25 e-10	1.57 e-10	1.18 e-10
Conductance after molding Ω^{-1}	4.25 e-9	2.5 e-9	2.11 e-9
Sensor Size (μm²)	480 x 620	480 x 620	480 x 620
Die Size (mm²)	6 x 6	6 x 6	6 x 6
Sensors per die	6	6	6

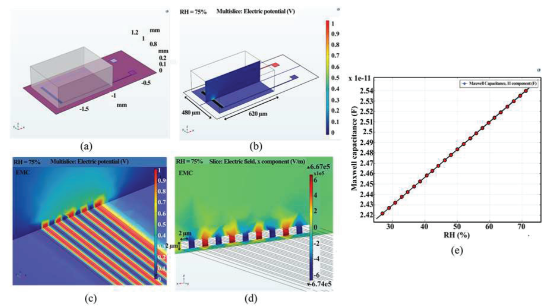

Fig. 6. The simulated results of previously designed SIDE in [4]

Conclusions

The proposed manufacturing process creates an in-package relative humidity sensor which is capable of in-situ reliability monitoring of the EMC or other encapsulation layers. The proposed design featuring multi-width interdigital electrodes enhances the sensitivity compared to [4] in which identical-width fingers were utilized. This feature in combination with wet chemical etching of the oxide sacrificial layer make a novel sensor developed for better in-situ characterization of packaging encapsulation materials.

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