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A Highly Sensitive Capacitive-Type Humidity Sensor Using Customized Polyimide Film without Hydrophobic Elements

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In this paper, we report the design, fabrication and measurement results of a highly sensitive capacitive-type humidity sensor using a customized polyimide film without hydrophobic elements for evaluating the hermeticity of micropackages. For higher sensitivity, a customized polyimide film as a moisture-absorbing layer is applied instead of using general polyimide films for microelectronic applications. The polyimide film is obtained by synthesizing polyamic acid composed of m-pyromellitic dianhydride, phenylenediamine and dimethylacetamide followed by thermal polymerization. An assembly of the humidity sensor and a micropackage which is realized with localized heating and bonding with a polysilicon heater is also fabricated to verify packaging compatibility. Characteristics of the sensor which include sensitivity, hysteresis and stability are measured. The measurement results show a percent normalized capacitance change of 37.45/%RH, hysteresis of 0.77% over a range from 10 to 90%RH and stability of 0.25% maximum drift from the average value at 50%RH for 120 min. According to these results, it is expected that the proposed humidity sensor can be applied to evaluate the hermeticity of micropackages.

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1. Introduction

As the demand for successful hermetic packaging increases, a tool to evaluate hermeticity of micropackages has become important.(1) In the issue of hermeticity in micropackaging, the failures are mainly due to contaminants such as moisture and gases, which results in various problems such as air damping or the squeeze-film effect. Since moisture has higher permeability than typical gases, it is effective in detecting the incoming amount of moisture for evaluating the hermeticity of micropackages. Humidity sensors can be mainly classified into three types. One is a conductive type using ceramics,(2,3) another is a capacitive type using polymeric films(4–9) and the other is a surface acoustic wave (SAW) type.(10) Although a conductive-type humidity sensor is quite sensitive to moisture, its characteristics largely depend on temperature and are seriously degraded by contaminants. For a capacitive-type humidity sensor, a thinner moisture-absorbing layer(4) is advantageous for high sensitivity, but there are constraints on the uniformity of the thin moisture-sensing layer, polyimide in this case. The normalized percent capacitance change (NPCC) can effectively yield information on sensitivity and is defined by eq. (1).(7)

$$NPCC = \frac{C_\mathrm{f} - C_\mathrm{i}}{C_\mathrm{i}} \times \frac{1}{\Delta RH} \times 100 \tag{1}$$

Here, NPCC is normalized percent capacitance change, C_i and C_f are capacitance at the initial and final states, and ΔRH is relative humidity change. The large change in the dielectric constant of a moisture-sensing layer according to relative humidity change is a crucial factor for a large normalized percent capacitance change. Generally, most commercial polyimides for electronic application include hydrophobic elements to make the dielectric constant stable against moisture changes and to ensure a low dielectric constant preventing cross talk.(11,12) These kinds of polyimide films are not suitable for a highly sensitive humidity sensor application. In this research, a capacitive-type humidity sensor using a customized polyimide film synthesized with m-pyromellitic dianhydride (m-PMDA), phenylenediamine (PDA) and dimethylacetamide (DMAc) is proposed to enhance the characteristic, particularly sensitivity. It is not easy to say that there is an affirmative value of sensitivity for evaluating the hermeticity of a micropackage. If a micropackage is in an ambient environment, relative humidity when it is exposed to such environment might be changed rather abruptly. For early detection of the failure of a micropackage, it is important to analyze the sensor characteristics for the low level of relative humidity. Most of the previous humidity sensors proposed by other studies give us measured sensitivity data from 20%RH. For the proposed humidity sensor, sensitivity was measured from 10%RH. Thus, the proposed humidity sensor integrated in a micropackage can be considered a device which is capable of earlier detecting failure of hermeticity. The proposed humidity sensor is integrated in a micropackage using localized heating and bonding method to verify the packaging compatibility of the proposed humidity sensor.

2. Design and Fabrication

2.1 *Material selection and synthesis*

Polyimide has been widely used in the microelectronics industry, for example, for interlayer dielectrics and packaging materials, where low dielectric constant and its insensitivity to moisture are important features. As one of the methods to enhance these characteristics, 17 group elements, particularly fluorine, are included in a dianhydride or a diamine. This results in the decrease in the dielectric constant due to the small dipole, the low polarizability of the CF bond and the increment of free volume.(11,12) Since these fluorinated polyimide films are not suitable for a highly sensitive humidity sensor, polyamic acid (PAA) was synthesized by the reaction of the diamine of m-PDA with the dianhydride of PMDA containing no fluorine element, in an aprotic solvent of DMAc. The good water sorption behavior of the polyimide film composed of those monomers has been verified in previous studies.(13,14) The PAA synthesis starts with the addition of 2.16 g of m-PDA to 47.4 g of DMAc. PMDA of 218.3 g is added to the solution at a constant temperature of 25°C and a stirring speed of 300 rpm. After obtaining the polyimide precursor, it is spin-coated on a silicon wafer and thermally or chemically polymerized. Through these processes, a moisture-sensing layer, the polyimide film, is obtained. The synthesis sequence of the PAA and the polyimide film is shown in Fig. 1.

2.2 *Device design and fabrication*

The capacitive-type sensor with the size from 0.96×0.96 mm^2 to 9.6×9.6 mm^2 has been designed and fabricated with approximately 50%, 60% and 70% effective areas. Figure 2 shows the fabrication sequences and the optical photograph of fabricated humidity sensor. The fabrication starts with a silicon wafer passivated with 5000-Å-thick silicon dioxide. Subsequently, a 3000-Å-thick Au bottom electrode is formed on an adhesion layer of 200-Å-thick Cr. A dielectric layer is spin-coated and cured with three-step thermal polymerization of the PAA. The polymerization step is started at 50°C for 4 h in a vacuum oven for rapid removal of the solvent, the second step is performed at 250°C for 90 min for gradual polymerization, and the last step is performed for perfect polymerization at 300°C for 1 h in an atmospheric drying oven. The thinner moisture-absorbing layer is advantageous for sensitivity of a humidity sensor. However, as the polyimide film thickness decreases, it is

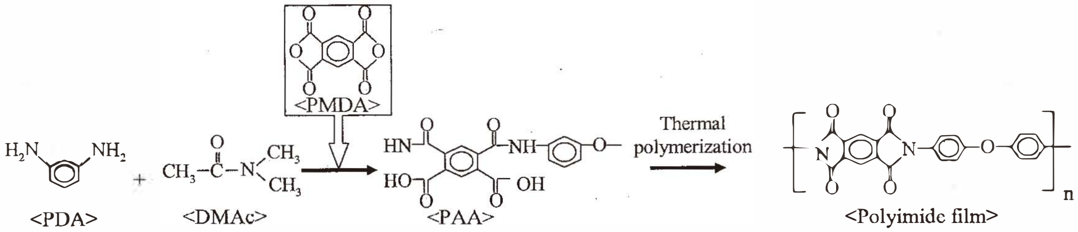
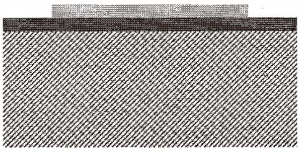
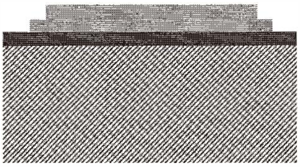


Fig. 1. Polyimide film synthesis sequence used for the capacitive-type humidity sensor.

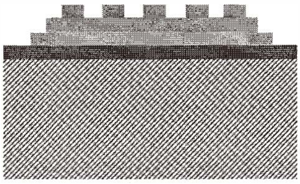
(a) Passivation by 5000-Å-thick SiO_2



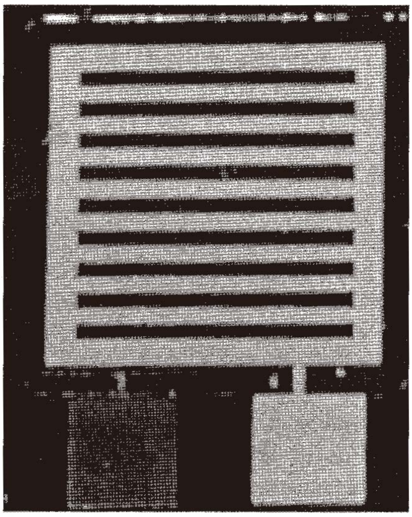
(b) Bottom electrode deposition and patterning



(c) Polyimide spin coating and patterning



(d) Top electrode deposition and patterning



(A) (B)

Fig. 2. Fabrication steps and optical photograph of the humidity sensor. (A) Simplified fabrication sequence. (B) Fabricated humidity sensor.

increasingly difficult to maintain film uniformity. Furthermore, pores may be introduced during thermal polymerization steps because of particles such as dust or air that are trapped in polyamic acid. The polyimide film with thickness of 1.0–1.2 μm is obtained and patterned by reactive ion etching. The last fabrication step is the upper electrode formation of 1-μm-thick Al film at 50°C. Alongside the fabrication of the humidity sensor, a micropackage using localized heating and bonding with a polysilicon heater and aluminum solder has also been fabricated to verify packaging compatibility. Figure 3 shows the fabrication steps for the package. The fabrication starts with deposition and patterning

(a) Insulation by 1-μm-thick SiO_2

(e) Polyamic acid spincoating and curing

(b) Doped polysilicon formation for bottom electrode

(f) Top electrode deposition and patterning

(c) SiO_2 deposition and patterning

(g) Al solder line formation on $SiO_2/Si_3N_4/SiO_2$ layer

(d) Polysilicon micro heater line formation

(h) Encapsulation by localized heating and bonding

Fig. 3. Integration sequence of the humidity sensor in a micropackage.

5000-Å-thick doped polysilicon which is used as the bottom electrode and interconnection line for the humidity sensor on 1-μm-thick silicon dioxide. A 1-μm-thick doped polysilicon microheater line is formed for heating and melting Al solder. The polyimide layer and top electrode for the humidity sensor are defined by the same method mentioned above. Subsequently, 2-μm-thick Al layer is used for the solder material which is defined on the $SiO_2/Si_3N_4/SiO_2$ insulation layer. Localized heating and bonding is carried out by applying voltage to the doped polysilicon microheater line which melts Al solder. Pyrex is used for encapsulation of the micropackage. Figure 4 shows the fabricated package.

3. Measurement and Results

Sensitivity, hysteresis and stability have been tested inside an environmental chamber (WEISS WK1^{340}) with a RLC meter (HP4274A) at 100 kHz. The schematic setup for measuring the characteristics of the fabricated humidity sensor is shown in Fig. 5. The

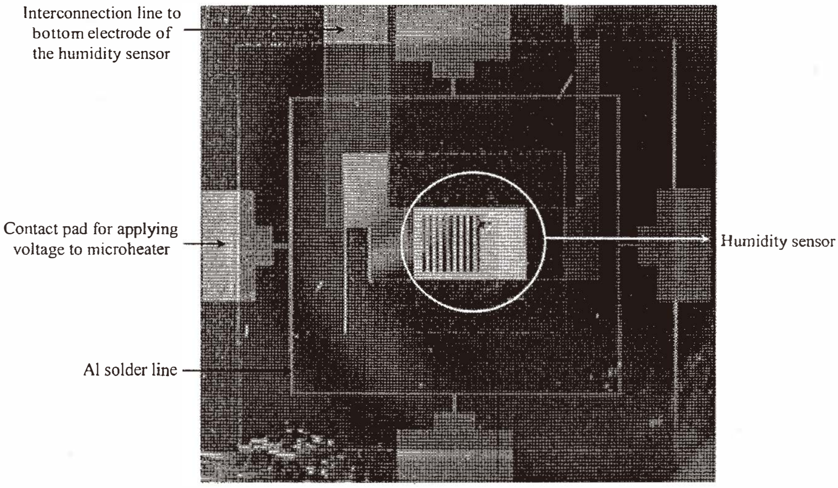


Fig. 4. Optical photograph of the integrated humidity sensor in a micropackage.

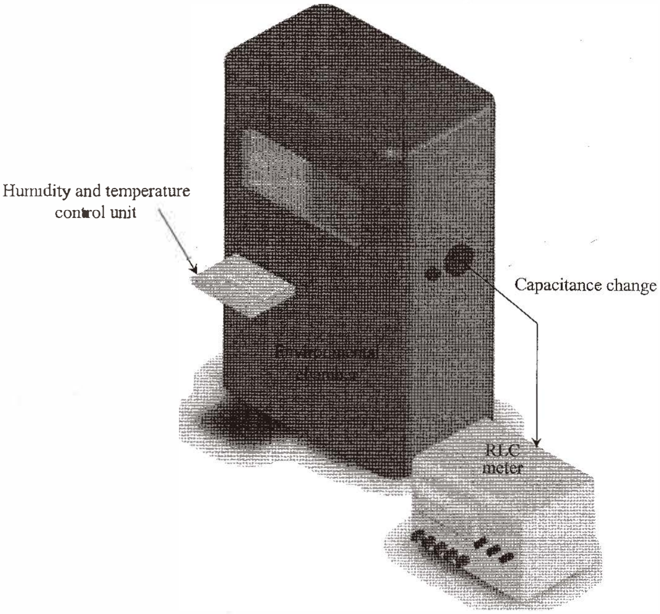
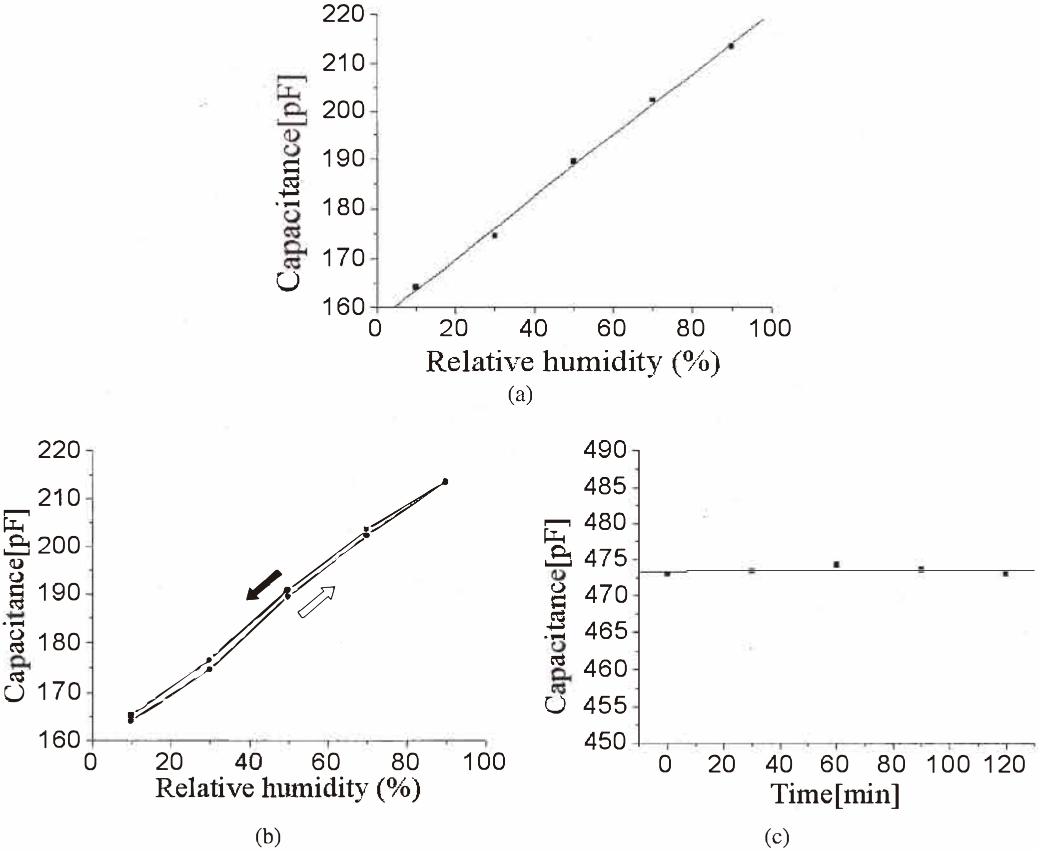


Fig. 5. Schematic setup for measuring characteristics of fabricated humidity sensor.

device used for sensitivity and hysteresis measurement is of 2.8×2.8 mm^2 size with 71.3% effective electrode area and an approximately 1-μm-thick polyimide film. Stability has been measured for the device whose size was 4.8×4.8 mm^2 with 71.3% effective electrode area and 1.1-μm-thick polyimide film. Figure 6 shows measured characteristics. Measurement results show that the proposed humidity sensor has good sensitivity, hysteresis and stability; in particular, the hysteresis and stability are better than those of sensors developed by other groups.$^{(4–9)}$

3.1 *Sensitivity*

The measurement has been performed from 10% to 90% relative humidity with 20% increment at a constant temperature of 40°C. At each relative humidity level, the capacitance was recorded for 30 min. The sensitivity is defined using eq. (1) and is the ratio



(a)

(b)

(c)

Fig. 6. Measurement results for the fabricated humidity sensor. (a) Sensitivity, (b) Hysteresis, and (c) Stability.

of the capacitance change to the reference capacitance over a specific relative humidity range, 10%–90% in this case. The percent normalized capacitance change was 37.45/%RH and the deviation from the linear fitted line was 0.46% as shown in Fig. 6(a).

3.2 *Hysteresis*

It is important that a humidity sensor has a small deviation from the first measured capacitance over repetitive uses of the humidity sensor. Thus, the test was performed by changing %RH from 10% to 90% and from 90% to 10% consecutively with increment and decrement of 20%RH at 40°C. The result shows the measured hysteresis of 0.77%, as presented in Fig. 6(b).

3.3 *Stability*

This characteristic was measured at 50%RH for 120 min and data acquisition was performed every 30 min. Figure 6(c) shows that the average value is 0.08% and the maximum drift is 0.25%. The drift might be mainly due to that of the humidity level controlled by the environmental chamber.

4. Conclusion

A packaging-compatible capacitive-type humidity sensor has been proposed and fabricated using 'polymer/metal multilayer processing techniques.' To achieve high sensitivity to moisture change, the sensing layer is selected and synthesized by the reaction of m-PDA, PMDA and DMAc which has no hydrophobic elements instead of using a general polyimide film for general microelectronic applications. The fabricated capacitive-type humidity sensor shows the normalized percent capacitance change of 37.45/%RH, hysteresis of 0.77% and stability less than 1%. Along with the humidity sensor, a micropackage containing the humidity sensor has been fabricated by the localized heating and bonding method using polysilicon heater to verify fabrication compatibility. According to these results, it is expected that the developed humidity sensing scheme can be applied to evaluate the hermeticity of a micropackage containing various MEMS structures.

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