A Capacitance Level Sensor Design and Sensor Signal Enhancement

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Abstract—This paper introduces a novel fringe field capacitive sensor. To enhance the sensor signal, various sensor electrode design strategies and a surface modification method are introduced, discussed and compared. The sensors are characterized by both simulations and experiments. The experiment results demonstrate the sensor capability of water level measuring. In addition, fringing field sensor of the field strength across the target by the dielectric strength can be used to measure the dielectric constant or component of a solution. The experiment results show that nitrogen plasma surface modification can improve the sensitivity from 69pF/mm to 97pF/mm.

Keywords: Fringing electric field, capacitance sensor, atmospheric-pressure plasma, level sensor.

I. INTRODUCTION

Capacitive sensors are capable of measuring various physical parameters. They are widely used in industrial, biomedical, and instrumental electronic devices, such as proximity sensors, pressure sensors, accelerometers, displacement sensors, water level sensors, torque sensors, etc[1-5]. In general, capacitive sensors consist of two parallel electrodes and dielectric material, when the electrode overlapping area, distance, or dielectric constant is affected by temperature, humidity or stress, one can take advantage on the changing of capacitance to measure these physic parameters. The widely used applications include hygrometer, manometer accelerometers, and etc... Capacitive sensor is different from other types of sensors, such as resistive, electromagnetic, or stress sensors, it provides non-contact and low energy consumption measurement[1]. Most of the capacitive sensors have fringing filed effect, based on the consideration of linearity and sensitivity; people utilize less fringing field effect to detect external physical parameters. The first fringing effect capacitive sensor consists of two electrodes placed in the middle insulator[6]. This simple electrode design provides highly sensitive fringing field measurement capability.

When the device operates at high frequency, fringing field capacitance have non-negligible influence to circuit, in terms of signal process, succession of other scholars developed employed micro-fabrication process to manufacture fringing capacitive sensors[7, 8]. If the overlapping area between two electrodes is reduced, it will reduce parallel capacitance; conversely, increasing the edge length and the side area of electrodes, one can improve fringing field effect and sensitivity. The design improvement process of fringing field sensor relies on a good understanding of the physics principles, numerical simulation tools or analytical methods [9, 10]. In general, design variables include the geometry and the material properties of electrodes [11]. In order to enhance sensor sensitivity, this paper also investigates the influence of hydrophilicity of the electrode surface on capacitive measurement. An atmospheric-pressure nitrogen-plasma surface treatment method has been introduced for electrode surface modification. This method is widely adopted by many industries for surface cleaning and modification [12-14].

In following sections, the electrode geometry design, simulation analysis, fabrication, measurement results, and a related application to level sensing are presented.

II. DESIGN AND SIMULATION

The optimal design of a fringe filed capacitive sensor depends on the meshed electrode pore size and electrode thickness being considered. For the determination of the pore size and density, a numerical simulation include all these variables, has to be studied. A two dimensional COMSOL simulation results suggest that increasing the effective edge length of these electrodes can promote fringing field effect. For a given electrode area, increasing the fractal dimension can actually extend the effective electrode edge length of electrodes to enhance the fringing field effects.

![Figure 1. Schematic diagram of various electrode designs](image-url)
As shown in Fig. 1 (a-f), six electrode number arrangements, 1, 2, 4, 8, 16, and 32, respectively are simulated.

In the two-dimensional simulation, the total length of the top electrode is held at 40μm, the dielectric thickness is 0.3μm, the total length of the bottom electrode is 70μm. To increase the number of electrodes in a finite design space, it can effectively enhance the fringing field capacitance. The simulation result is shown in Fig. 2.

![Capacitance vs Number of Electrodes](image)

**Figure 2.** Different kinds of electrode designs and their capacitances.

Based on the outcomes from simulation results, to verify this design approach, two different kinds of pore sizes and densities for capacitive sensor are designed and fabricated, which provide two effective electrode edge lengths to enhance the fringing capacitance. The capacitance sensor parameters are listed in Table 1. The master pore width of sensor Type I and sensor Type II are 80μm and 150μm, respectively.

<table>
<thead>
<tr>
<th>Specifications of the Capacitance Level Sensor</th>
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<tbody>
<tr>
<td><strong>Type I</strong></td>
</tr>
<tr>
<td>Wafer thickness</td>
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<tr>
<td>Silicon lattice direction</td>
</tr>
<tr>
<td>Resistance</td>
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<td>Doping element</td>
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<tr>
<td>Aluminum thickness</td>
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<td>Oxide thickness</td>
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<tr>
<td>Master pore size</td>
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<tr>
<td>Internal hole width</td>
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<tr>
<td>Internal small pore density</td>
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<tr>
<td>Area size</td>
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<td>Edge length</td>
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![Type I: 80μm master pores with internal small 10μm mesh holes](image)

**Figure 3.** A schematic diagram of two different capacitive sensor designs.

III. FABRICATION AND experimentation

A. Fabrication

This paper utilized surface microfabrication process to manufacture meshed capacitive sensor, as shown in Fig. 4. Capacitor plates spillover the arc-shaped fringing field line from high potential states to low potential states. Due to electric field lines intend to focus at the edge of a conductive electrode, therefore, multi-mesh electrodes can increase the fringing field effect of within a given design area.
The process started with a cleaned and heavily boron doped 4 inch p-type single crystal silicon wafer. The silicon substrate was functional as a ground electrode. A 0.3μm thick thermal growth oxide was served as a dielectric layer for capacitive sensing. A 0.3μm thick aluminum layer was also evaporated on the top of the silicon dioxide wafers to make the top electrode. A 2μm photoresist (PR) layer was spin-coated and exposure mesh pattern on the photoresist to define the sacrifice layer, and then utilized aluminum etchant solution to form the fringe sensing electrode. The process consisted of only one masking step. The fabrication steps with corresponding substrate cross-sections in the device process sequence are illustrated in Fig. 5. After post process, the wafer will be section to chip and etch contact windows to connecting electrode.

B. Experiment

Our experiment results in Fig. 6 demonstrated that the top electrode with 80μm pore yields more than 60% capacitance enhancement than the electrode with 150μm pore which was very close to the theoretic estimation and finite element analysis.

An atmospheric-pressure nitrogen-plasma surface treatment were introduced to improve the electrode wettability and the water contact angle are reduced from 77.1° to 12.1°, as show in Fig. 7. The sensor surface wettability would increase the immersive area, and it can contribute to the enhancement of fringe filed capacitance at nanoscale.

After N₂ plasma treatment of the electrode surface would be more hydrophilic, it employed 150μm pore electrodes for plasma treatment, and utilized deionize water to test capacitance under different liquid level. The sensor with N₂ plasma treatment demonstrates 38%~ 59% enhancements than the sensor without. It also improves the sensor sensitivity from 69pF/mm to 97pF/mm. The fringe field level sensor is capable of measuring the water level, as shown in Fig. 8.
Moreover, compared with two different kinds of pore structures capacitive sensor at different ratios of deionize water and IPA mixture. In this experiment, the 80 μm pore electrode has better sensitivity than 150 μm pore electrode for liquid composition sensing, as shown in Fig. 9.

![Graph showing capacitance change with liquid level](image)

Figure 9. Compare the different proportions of DI water and IPA solution

**IV. CONCLUSION**

This paper presents a novel fringe field capacitive sensor with surface process technology using high-density mesh electrode structure to enhance fringing field effect. The atmospheric-pressure nitrogen-plasma surface treatment can increase the original capacitance of 38%–59%, and sensor sensitivity from 69 pF/mm to 97 pF/mm. The experiment results demonstrate the sensor capable of water level measuring.

**ACKNOWLEDGMENT**

This work was supported by the National Science Council, NSC-98-2221-E-018-012-MY2 and Ministry of Education Advisory Office Grant, Taiwan, R.O.C.

**REFERENCES**


