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Some Design Considerations on the Electrode Layout of ZnO Pyroelectric Sensors

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In this study, we investigate the effect of top-electrode layout on the responsivity, which is defined as the ratio of the output voltage from the sensor to the incident radiation power, of ZnO pyroelectric sensors. Four different top-electrode layouts, namely, those of the crisscross, target, web, and full-cover types, are used to demonstrate the design concept. On the basis of the experiment, the responsivity of the sensor may be improved by opening the windows so that the ZnO layer can directly come into contact with the heat source. However, the contact windows may reduce the top-electrode area and disperse the electrode. The electrode area reduction and dispersion may degrade the responsivity of the sensor. Thus, in the layout design of the top electrode, both the contact window size of the ZnO layer and the dispersion of the top electrodes must be considered. In this study, we designed a web-type top electrode. The outer regions of this electrode possess large contact windows of the ZnO layer, whereas the inner regions possess dense top electrodes. The experiment results showed better responsivity of the sensor with the proposed web-type top electrode. The responsivity of the web type is about 4 times that of the full-cover type.

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1. Introduction

Pyroelectric sensors have been successfully used in many applications, such as pollution monitoring, hot image detector, intruder alarm, and gas analysis. They possess the advantages of being integrable with on-chip circuitry, uncooled detection, room-temperature operation, fast and wide spectral response with high sensitivity, and low cost.(1–3) Conventional pyroelectric sensors comprise a pyroelectric layer sandwiched between the top and bottom electrodes. The top side is exposed to a heat source. The dynamic response current of the pyroelectric sensor is proportional to the temperature variation rate of the pyroelectric layer.(1) A higher temperature variation rate in the pyroelectric layer leads to a higher response current of the pyroelectric sensor. The layout of the top electrode directly affects the temperature variation rate of the pyroelectric layer. A partially covered top electrode has been proved to result in a higher responsivity than that of a fully covered electrode(4) because it opens windows for the ZnO layer to directly come into contact with the heat source. However, the contact windows may reduce the top-electrode area and make the electrode dispersed. The electrode area reduction and dispersion may degrade the responsivity of the sensor. Therefore, the top-electrode layout plays an important role in the pyroelectric sensor.

ZnO is a unique material because it possesses unique properties like semiconductivity, piezoelectricity, and pyroelectricity. Thus, it is receiving much attention owing to its various applications in blue and ultraviolet light emitters, transparent conductors, solar cell windows, gas sensors, photovoltaic devices, pyroelectric imaging sensors, and surface acoustic wave devices. The pyroelectricity of ZnO is attributable to noncentro-symmetrical crystals, which have a specific polar axis along the direction of spontaneous polarization.(1,2) Given that ZnO is subjected to temperature variation, its internal polarization will produce an electric field. ZnO films are usually deposited by RF sputtering. The properties of ZnO are affected by the sputtering conditions like the composition of mixed process gases, working pressure, substrate temperature, RF power, gap between target and substrate, and postannealing temperature.(4–6)

The response of a pyroelectric sensor depends on the temperature variation rate of the ZnO layer, the temperature variation of which is directly affected by the top-electrode layout. Therefore, in this paper, we focus on investigating some design considerations and developing a better top-electrode layout. We compare four different top-electrode layouts, namely, those of the crisscross, target, web, and full-cover types. The fabrication process adopts both surface and bulk micromachinings on a silicon substrate. The ZnO layer is deposited by RF sputtering; the top and bottom electrodes are deposited by electron beam evaporation; a thermal isolation layer of silicon nitride is deposited by low-pressure chemical vapor deposition (LPCVD). The silicon substrate is etched using KOH solution to reduce heat loss through the substrate.

2. Materials and Methods

2. 1 *Sensor Design*

The present pyroelectric sensor has a sandwich structure that comprises a ZnO layer sandwiched between the top and bottom electrodes. Figure 1(a) shows the schematic diagram of the present sensor structure, whereas Fig. 1(b) shows the expanded one. The pyroelectric signal is proportional to the temperature variation rate of the ZnO layer. In other words, a higher temperature variation rate of the ZnO layer leads to a higher response current of the pyroelectric sensor. A partially covered top electrode may have a higher responsivity than a fully covered top electrode because the uncovered part of the ZnO layer is directly exposed to the heat source and thus markedly increases the heat absorption. Thus, one of the strategies is to open the heat contact windows of the ZnO layer by patterning the top-electrode layer. However, the heat contact windows of the ZnO layer may reduce the total area of the top electrode and make them more dispersed, which will degrade the signal output of the sensor. We designed and compared four different top-electrode layouts, namely, those of the crisscross, target, web, and full-cover types, as shown in Fig. 1(c). To exclude the factor of pyroelectric response current decrease due to the electrode area reduction, the total areas of the top electrodes except that of the full-cover type are made identical. In this study, we focus on investigating the effect of the top-electrode layout on the responsivity of ZnO pyroelectric sensors. The

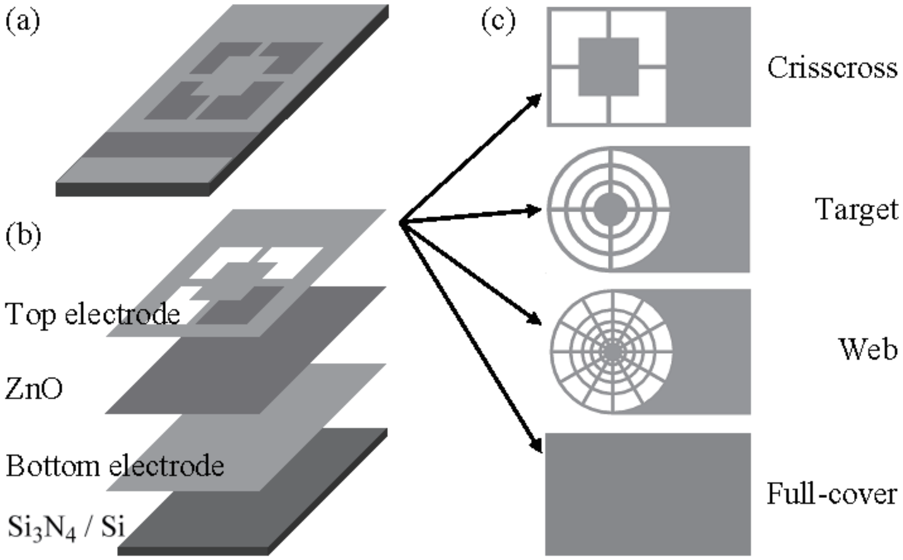

Fig. 1. Schematic diagrams of the sensor structure. (a) Assembled diagram. (b) Expanded diagram. (c) Four different top-electrode patterns.

dimensions of the top electrodes are detailed in Fig. 2. The total area of the full-cover top electrode is 14.4 mm^2, whereas those of the other three types are 9.1 mm^2.

2.2 *Fabrication Process*

The specifications of the silicon wafer are (100) p-type, both sides polished, and a resistivity range of 1–10 Ω-cm. As shown in Fig. 3(a), 1-μm-thick low-stress silicon nitride layers are deposited on both sides of the substrate by LPCVD, and then the wet-etching window at the back side is opened by reactive ion etching (RIE). The silicon nitride layer can obstruct the thermal conduction to the silicon substrate. Next, as shown in Fig. 3(b), the substrate is etched to about 50 μm thickness using 45 wt% KOH solution. The etching temperature is maintained at 75°C. The air cavity formed on the back surface can substantially reduce or block the heat loss through the substrate. Then, as shown in Fig. 3(c), the bottom electrode is deposited on the top side by electron beam evaporation and patterned by wet etching. The bottom electrode comprises a gold layer of 100 nm thickness and a chromium adhesion layer of 10 nm thickness. The next step is to deposit the ZnO layer of 600 nm thickness by RF magnetron sputtering, as shown in Fig. 3(d). A ZnO target with 99.99% purity is adopted. Prior to the film deposition, the ZnO target is presputtered for 15 min to remove any surface impurity. The chamber is pumped to a base pressure of up to 8×10^{-7} Torr before sputtering. The chamber is then

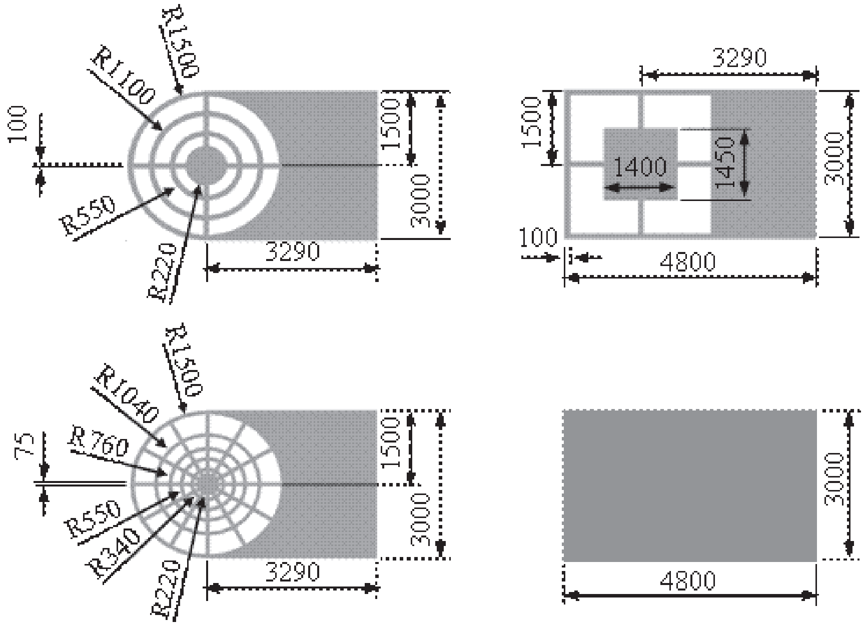

Fig. 2. Top-electrode dimensions in micrometer.

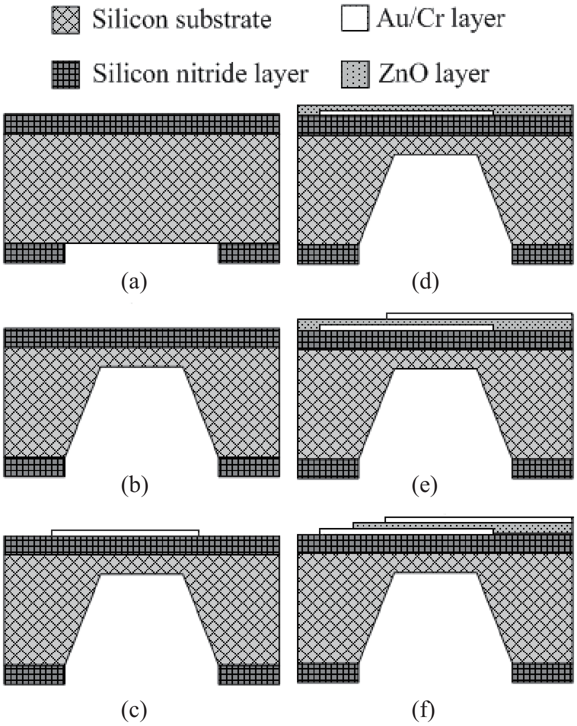

Fig. 3. Process flow of the ZnO pyroelectric sensor. (a) Deposit Si_3N_4 layers on both sides of the substrate by LPCVD and open the wet-etching window by RIE. (b) Etch the substrate to form an air cavity to reduce or block the heat loss through the substrate. (c) Deposit the bottom electrode by electron beam evaporation and then pattern by wet etching. (d) Deposit the ZnO layer by RF magnetron sputtering. (e) Deposit the top electrode by electron beam evaporation and pattern by lift-off. (f) Pattern the ZnO layer by wet etching to open the bonding pad of the bottom electrode.

filled with a mixture of argon and oxygen at a ratio of 5:3. The RF power is maintained at 120 W. The chamber pressure is 2 mTorr during deposition. The substrate is heated to 200°C during deposition, which can help improve the ZnO film quality. Then, the top electrode is deposited on the ZnO layer, as shown in Fig. 3(e). The composition and deposition of the top electrode are similar to those of the bottom electrode, except that the top electrode is patterned by the lift-off method, which is detailed in the authors' previous paper.(5) Finally, as shown in Fig. 3(f), the wet etchant, comprising $CH_3COOH:H_3PO_4:H_2O = 1:1:10$, is used to pattern the ZnO layer to open the bonding pad of the bottom electrode. The finished ZnO pyroelectric sensors with different top electrodes are shown in Fig. 4.

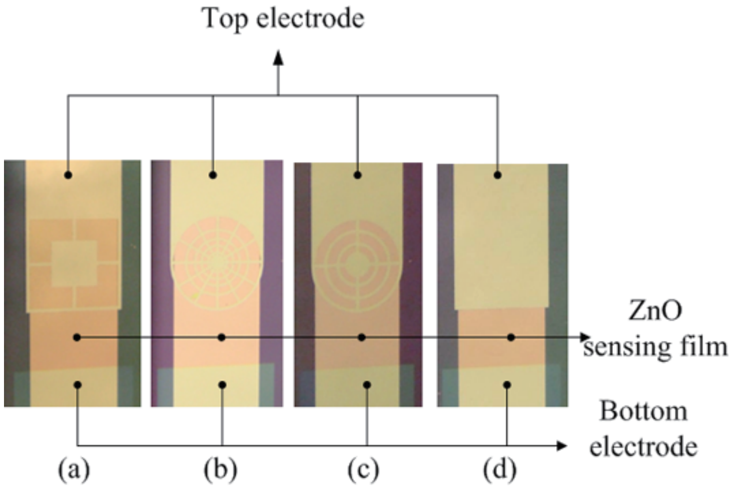

Fig. 4. Top view of fabricated ZnO pyroelectric sensors with different top electrodes. (a) Crisscross type. (b) Web type. (c) Target type. (d) Full-cover type.

2.3 *Signal Measurement*

A responsivity measurement system (Fig. 5), similar to that shown in the authors' previous paper,(5) is used to evaluate the performance of the present ZnO pyroelectric sensors. The radiation source is a calibrated He-Ne laser of 633 nm wavelength and 1 mW maximum power. The power spectrum of the laser is also measured using a power meter by Fourier transform infrared (FTIR) spectroscopy. The laser beam is chopped at a modulated frequency (ω). The modulated beam is split into two beams by a prism. The two beams have the same power; one is reflected on a photodiode as the reference, and the other is defocused such that the beam spot can cover the entire region of the patterned top electrode of the ZnO pyroelectric sensor. The photodiode is used simply for visual reference on the oscilloscope. The output voltage of the sensor is amplified using an SR560 low-noise voltage amplifier. Both the output signals of the sensor and photodiode are recorded and displayed using a digital oscilloscope.

3. Results and Discussion

When ZnO is subjected to a temperature variation, its internal polarization will produce an electrical field, which induces a response voltage between the top and bottom electrodes. The responsivity is proportional to the temperature variation rate of the ZnO layer. No temperature variation in the ZnO layer results in no internal polarization change, and thus no response voltage. Therefore, to obtain a temperature variation in the ZnO layer, the laser beam must be chopped at a modulated frequency because it is a

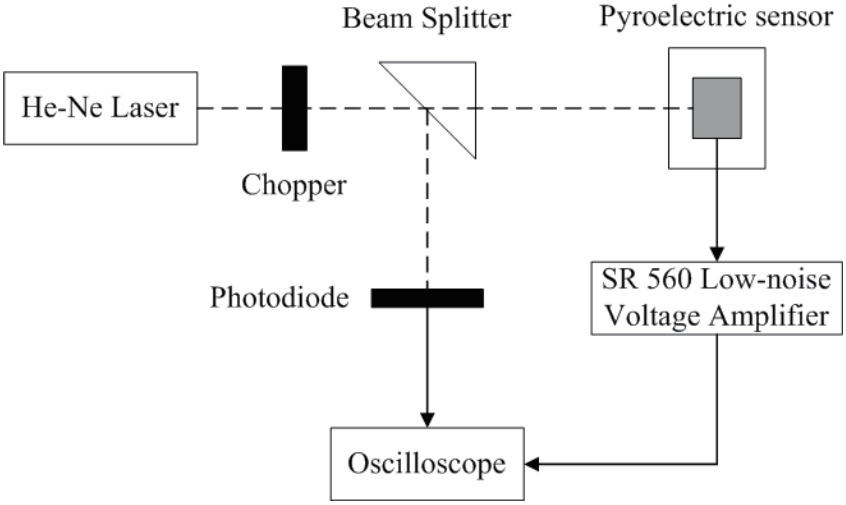

Fig. 5. Schematic diagram of the responsivity measurement experiment.

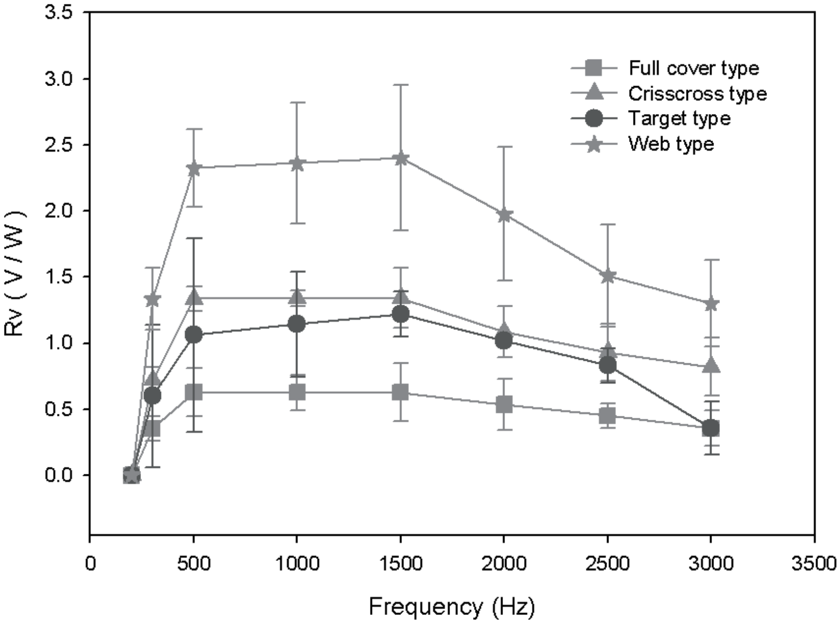

Fig. 6. Voltage responsivities of ZnO pyroelectric sensors with various top-electrode patterns.

continuous and stable heat source. As shown in Fig. 6, the responsivity increases rapidly with increasing modulated frequency until 500 Hz. This is due to the increase in the temperature variation rate of the ZnO layer. However, as the frequency goes beyond 1500 Hz, the responsivity decreases with increasing modulated frequency. This is due to the fact that the response time of the sensor cannot catch the variation speed of the incident heat source. The response time of a pyroelectric sensor is related to a number of factors, such as material, thermal capacity, thickness, environment, substrate, structural design, thermal isolation layer, heat receptor, electrode layout, pyroelectric coefficient, absorption coefficient, and fabrication method. From the reciprocal of the modulated frequency, one knows that the minimum response time of the present sensor is about 0.67 ms.

Figure 6 shows the voltage responsivities (*Rv*) of the present ZnO pyroelectric sensors with four different top-electrode layouts. There are 6 samples for each top-electrode layout. *Rv* is defined as the ratio of the output voltage of the sensor to the input power of the incident heat source. All the four types show the highest *Rv* in the frequency band between 500 and 1500 Hz. The full-cover type has the lowest *Rv* among the four types. This is because the radiation absorption of the ZnO layer is seriously obstructed by the full-cover top electrode. At identical total top electrode areas, which are the same as the total area of the ZnO layer directly exposed to the heat source, the web type shows a higher *Rv* than the other two partially covered types, namely, crisscross and target types. This phenomenon is attributed to the fact that the top electrodes of the latter two types are more dispersed than those of the web type, although the total top-electrode areas of these three types are identical. A larger piecewise area of the exposed ZnO layer leads to better heat absorption but, also, to more dispersed top electrodes. Thus, in the design of the top electrode, both the piecewise area of the exposed ZnO layer and the dispersion of top electrodes must be considered. This is why we designed a web-type top electrode. The outer regions of this electrode possess a large piecewise area of the exposed ZnO layer, whereas the inner regions possess a low dispersion of top electrodes. The *Rv* of the web type is about 4 times that of the full-cover type and 2 times that of the crisscross and target types. The results of the experimental measurement agree with our design concept mentioned in Materials and Methods.

4. Conclusions

In this research, we propose some design considerations on the layout of top electrodes for ZnO pyroelectric sensors. The top-electrode layout affects the responsivity of the sensor significantly because it directly affects the heat absorption of the ZnO layer as well as the impedance of the sensor. The partially covered top electrode has the advantage of open windows for the ZnO layer to directly come into contact with the heat source, which can promote the responsivity of the sensor because of the high temperature variation rate of the ZnO layer. However, the disadvantage is that the contact windows reduce the top-electrode area and disperse the electrode, which can degrade the responsivity of the sensor. In conclusion, a larger contact window of the ZnO layer leads to better heat absorption but, also, to more dispersed top electrodes. Thus, in the design of the top electrode, the contact window size of the ZnO layer and the dispersion of top electrodes must be considered. In this paper, we designed a web-type top electrode. The outer regions of the web type possess a large contact window of the ZnO layer, whereas the inner regions possess a low dispersion of top electrodes. From the experiment results, better responsivity of the sensor with the proposed web-type top electrode is confirmed.

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References

1 R. W. Whatmore: Rep. Prog. Phys. **49** (1986) 1335.
2 S. G. Porter: Ferroelectrics **33** (1980) 193.
3 C. C. Chang and C.S. Tang: Sens. Actuators, A **65** (1998) 171.
4 C. S. Wei, Y. Y. Lin, Y. C. Hu, C. W. Wu, C. K. Shih, C. T. Huang and S. H. Chang: Sens. Actuators, A **128** (2006) 18.
5 C. C. Hsiao, K. Y. Huang and Y. C. Hu: Sensors **8** (2008) 185.
6 J. S. Ko, W. Liu and W. Zhu: Sens. Actuators, A **93** (2001) 117.