Influence of Strong Light on the Performance of Piezoresistive Pressure Sensor

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Title page

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ORIGINAL ARTICLE

Influence of strong light on the performance of piezoresistive pressure sensor

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Abstract: It is found that the strong light in the explosion field has great interference to the piezoresistive pressure sensor, then the shock wave data obtained by the sensor is distorted badly. To study the influence mechanism of the strong light on the piezoresistive pressure sensor, a strong light experimental platform is built. The positions of the sensor and the light source are adjusted, and the outputs of the piezoresistive pressure sensor are observed. Through microscopic simulation, the influence of different light intensities on the piezoresistive pressure sensor is analyzed. In order to reduce the influence of strong light on the performance of piezoresistive pressure sensor, we propose to add a reflective layer on the pressure surface of the sensor. The light reflection effects of different film thicknesses are analyzed through film simulation software. At the same time, the reflection effect is verified through experiments. To explain the effect of the reflective layer on the suppression of strong light, a simulation model is established, and the suppression effect of the reflective layer is verified.

Keywords: Piezoresistive pressure sensor • Strong light • Microscopic particles • Reflective layer

1 Introduction

Blast shock wave can destroy various military targets and civil buildings such as personnel, equipment, etc, which has a large range of action and strong destructive power. It occupies an important position in the design of ammunition power. Shock wave parameters are tested as the main combat technical indicators for ammunition power [1-3]. The shock wave is generally measured by a piezoresistive pressure sensor with high response frequency, high sensitivity and high accuracy [4-8]. However, the sensitive element of the piezoresistive sensor is fabricated by single crystal silicon, which is more sensitive to light. Especially, the instantaneous strong light is generated at the moment of explosion, which will produce a photosensitive effect on the sensitive element to cause the parasitic output[9-11]. At the same time, the experiment results show that the strong light generated at the moment of the explosion interferes with the ouput signals of the piezoresistive pressure sensor, which results in inaccurate shock wave measurement, then the ammunition design is affected to cause serious adverse consequences. The accurate measurement of transient pressure and the undistorted waveform description of dynamic pressure play an extremely important role in scientific experiments and design optimization demonstration [12-13]. Therefore, the influence of strong light on the pressure sensor should be reduced, which will have great practical value and broad application prospects for explosive shock wave measurement.

In recent years, many researchers have conducted researches on the interference of strong light. For example, Hongmian Du [14] has studied the rules of flash effect on the piezoresistive sensor 8530B, and achieved good results by using black paper shielding to reduce the light effect. When studying the optical effect on a piezoresistive pressure sensor, some scholars reduced the influence of the optical effect on

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the pressure measurement by shielding the sensor's sensitive surface with a foil [15]. Jianzhong Zhang added a mixed coating of silicone grease and carbon powder to the sensitive surface of the piezoresistive sensor, which can effectively eliminate light interference [16]. Some researchers have studied how to reduce the flash response in the sensor design from the perspective of the sensor designer. However, for testers, how to remove the influence of the flash response of commercialized piezoresistive sensors has become a key issue for the application of piezoresistive sensors to shock wave near-field testing[17-18].

The above scholars stayed in the experimental verification stage, and put forward various methods to prevent light interference. However, there is no relevant explanation in the microscopic field about how the strong light affects the performance of the piezoresistive pressure sensor and how the proposed suppression methods play a suppression role.

Therefore, it's necessary to explain the impact of strong light on the piezoresistive pressure sensor in the microscopic and macroscopic fields by microscopic particle simulation and experiments. And at the same time, the suppression methods will be proposed and a microscopic theoretical explanation will be made. In order to analyze the influence of strong light on the piezoresistive pressure sensor systematically, an experimental platform is set up to simulate the explosion and strong light environment is generated to observe the impact of strong light on the output signal of the sensor. Then, the changes of carriers inside the sensing chip under the light field environment are analyzed through simulation software, and the phenomenon of signal mutation from the perspective of microscopic particles is explained. Finally, the suppression methods are proposed to reduce the interference of strong light, and the related micro-particle simulation interpretation and experimental verification are carried out.

2 Strong light experiment

During the explosion, a radiant energy flow composed of ultraviolet light, visible light and infrared light is emitted to the outside world. The radiant power in the visible light region forms the phenomenon of explosive flare [19-20]. In order to simulate the strong light environment during the explosion, an experimental platform is built as shown in Figure 1, in which a 1000 W iodine tungsten lamp is a strong light source with the wavelength range of 320 nm~2500 nm, namely visible light and infrared light. The output signal of the sensor is recorded by Labview software. In this experiment, a piezoresistive pressure sensor is selected with the pressure range of 0~100 kPa to carry out the principle verification experiment, and the constant voltage of 3 V is applied to the sensor.

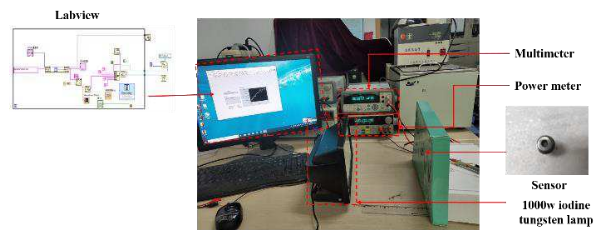

Figure 1 The experimental platform to analyze the strong light

According to the relationship between light intensity and the light source location, the light intensity at a location with different distances from the light source is changing, so the light test at different distances is an essential experiment to analyze different light intensity.

According to the relationship between light intensity I and distance R:

$$I = \frac{A}{R^x} \tag{1}$$

where, A is a constant. To determine A and x, Eq. (1) is transformed as:

$$\lg(I) = \lg(A / R^x)$$
$$\lg(I) = \lg(A) - x\lg(R)$$

It can be seen that lg(I) and lg(R) have linear relationship. The light intensities of a 1000 W iodine tungsten lamp at different distances are tested by a light intensity tester, and the relationship between light intensity and distance is calculated and fitted as follows:

$$I = \frac{1863.61}{R^{1.57}}$$

Therefore, the light intensities at different distances are shown in the following table:

Table 1 Light intensities at different distances

Distance (mm)	Light Intensity(W/cm^2)
10.00	49.65
20.00	16.67
30.00	8.81
40.00	5.60
50.00	3.94
60.00	2.96
70.00	2.32
80.00	1.88

The front pressure-bearing surface of the conventional diffused silicon piezoresistive pressure sensor is placed at different positions from the light source for illumination, and the switch is used to control the irradiation time of the light source for piezoresistive pressure sensor. Then, the voltage output signals of the piezoresistive pressure sensor are observed as shown in Figure 2 when the strong light irradiates the front side of sensing chip with 10 s at different positions from the light source. At 6 s, the switch controls the strong light to turn on, until 16 s, the strong light turns off.

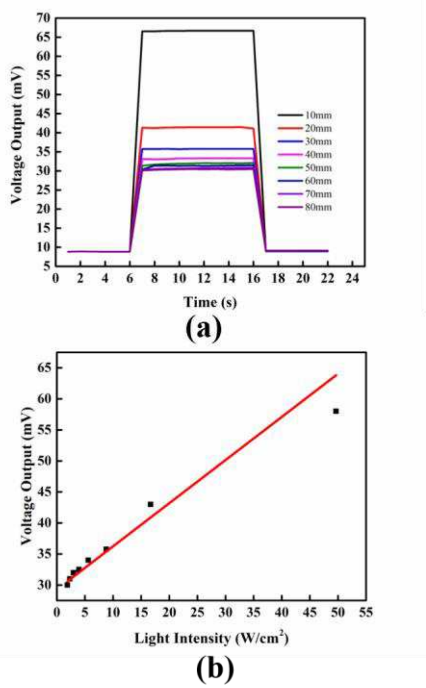

Figure 2 The voltage output signals of the piezoresistive sensor at different distances under strong light exposure with the duration of 10 s: (a) The voltage output signals of the piezoresistive sensor at different distances; (b) The voltage output signals of the piezoresistive sensor with different light intensities

It can be seen from Figure 2 (a) that the voltage output signals of the sensor due to the light irradiation gradually decreases as the illumination distance increases. Then, after sorting out the sensor output and light intensity data, we found the rule as shown in Figure 2 (b), the light intensity and the change of the sensor output are roughly linear.

When the front side of the sensing chip for the conventional diffused silicon piezoresistive pressure sensor is irradiated by the strong light, it can be seen from the above experimental results that the impact of the strong light on the output signal of the sensor is strengthened as the light intensity increases. Therefore, the conventional diffused silicon piezoresistive pressure sensor used in the explosive field is usually interfered from strong light to induce the drift of its output signal.

3 Microscopic particle simulation analysis

In order to study the piezoresistive effect on the behavior of microscopic particles under light, as shown in Figure 3 (a), a model with a size of 30×30 microns is created in Silvaco TCAD software, in which a certain concentration of boron ions is doped into N-type silicon substrate with a Gaussian distribution to form a piezoresistance area. In the piezoresistance area, different light intensities are applied to the front of the piezoresistance area, and the wavelength range is 320~2500 nm. Numerical calculations are carried out by Newton iteration method, etc., and the distributions of particles, illumination and current are analyzed.

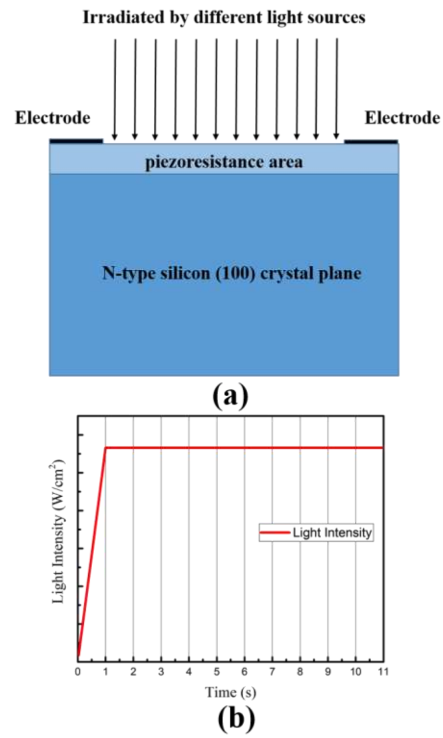

Figure 3 Simulation modeling and lighting conditions: (a) Build model; (b) Light time

In order to apply voltage to the established model, electrodes are designed on both sides, and a voltage of 3 V is applied to the piezoresistive area formed by the electrodes. The lighting, as shown in Figure 3 (b), is applied to the built model. The stable illumination time is 10 s, and the illumination intensity is the same as the experimental intensity. As shown in Figure 4, the microscopic particles and current changes caused by the light are simulated.

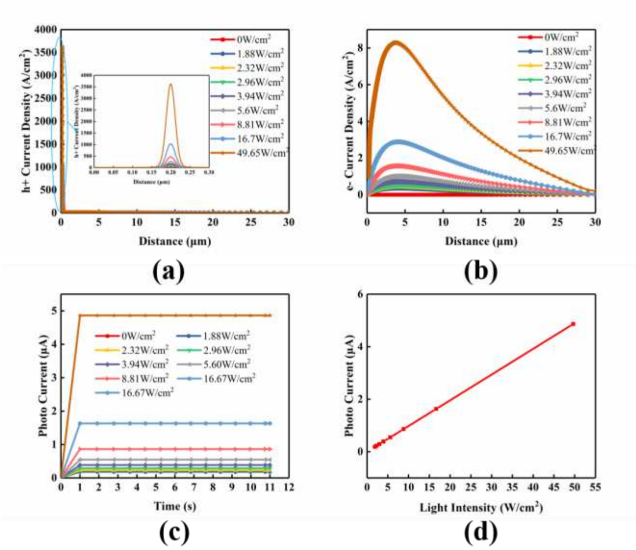

Figure 4 Changes of microscopic particles and current under different light intensities: (a) h+ current density changes; (b) e- current density changes; (c) Photo current changes; (d) Linear relationship between light intensity and photocurrent

The concentration changes of holes and electrons in the longitudinal distribution are simulated under different light intensities, as shown in Figures 4 (a) and (b). With the increase of light intensity, the concentrations of holes and electrons increase. This is because the strong light produces a certain amount of light-generated holes and electrons.

In Figure 4 (c), it can be seen that the current increases along with increasing the light intensity. And as shown in Figure 4 (d), the current has a linear relationship with light intensity, which is corresponding to the experimental result.

Because the piezoresistive area in ordinary diffused silicon can be analogous as PN junction, when the strong light irradiates the piezoresistive area and the photon energy is larger than the band gap of the PN junction in the semiconductor material, the valence electrons in the PN junction region will break free after absorbing light energy. The bondage of the valence bond becomes a free electron, and at the same time a free hole is also generated. These free electron-hole pairs generated by light are collectively called photo-generated carriers. Due to the built-in electric field, the photo-generated holes in the P-zone and the photo-generated electrons in the N-zone are blocked by the PN junction and cannot enter the junction region. Only the photo-generated electrons in the P-zone can diffuse to the junction boundary on the side of the N-zone. Holes can diffuse to the junction boundary on one side of the P-zone. At the same time, the photo-generated electron-hole pairs in the junction area are separated by the junction electric field. The electrons move to the N-zone, and the holes move to the P-zone. In the above process, the photogenerated electrons and holes are separated in the PN junction barrier region. The P and N regions obtain photo-generated positive and negative charges, respectively. The barrier height of the PN junction is reduced to form a photoelectromotive force, and the incident light energy becomes electrical energy, therefore, the current density increases.

4 Restraint methods

At present, there are few researches on strong light interference, and there are fewer related researches on anti-glare interference. According to the literatures, there are mainly two methods to prevent strong light interference. One is setting up baffles or shielding screens to prevent it. Although this method can alleviate the strong light interference to a certain extent, the addition of a baffle will affect the shock wave field, and the size of the baffle will also be determined according to the radius of the explosion product and the distance between the sensor and explosion center. Another is doing coating treatment on the sensitive surface of the sensor, so that the sensitive layer will be insulated from light, which mainly uses silicon grease mixed carbon powder as the coating. This method can effectively eliminate strong light interference, but the coating method may affect the sensitivity of the sensor, etc. In addition, the coating is manually applied, and the thickness of the coating cannot be guaranteed, and the effect of the coating cannot be guaranteed to be completely consistent.

In order to prevent the influence of strong light on the output signal of the piezoresistive pressure sensor, and guarantee the anti-interference performance consistent, a layer of high reflectivity film layer is proposed to add on the sensitive surface of the sensor to reflect most of the strong light. So that the strong light has less influence on the output signal of sensor.

According to the information currently consulted, it can be known that the more commonly used metal films with better reflectivity effect are mainly aluminum and silver [21-25], which will be verified by the simulation results with Essential Macleod software and experimental results, respectively.

4.1 Simulation for reflectivity effect

Essential Macleod software is used to simulate the reflectivity curves of aluminum and silver films with different thicknesses, as shown in Figure 5. The simulation steps are roughly as follows: first select the coated substrate, we mainly make the film on the silicon substrate, then determine the material, thickness and wavelength of the film, and finally calculate the reflectivity of the film. We have determined the optimal thicknesses of aluminum and silver films are determined with the largest simulated reflectivities at the wavelength of 320 nm~2500 nm.

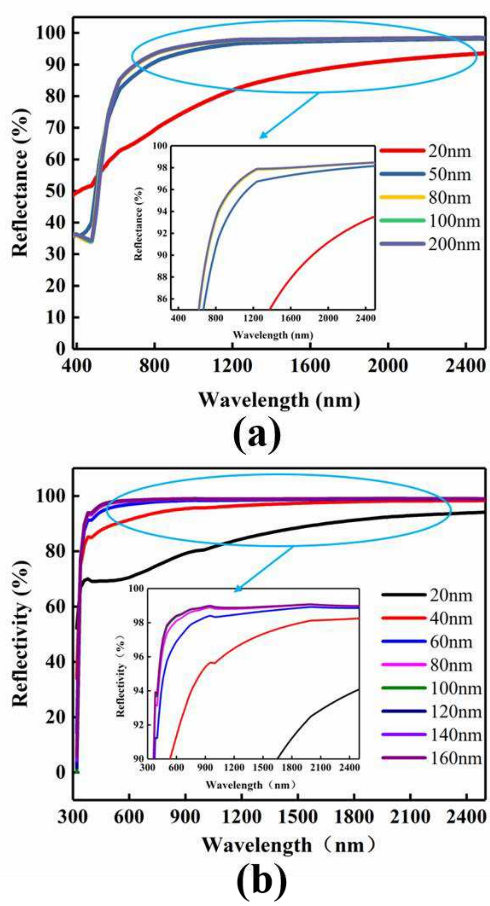

Figure 5 Simulated reflectivity curves of aluminum and silver films with different thicknesses:（a）The reflectivity curves of aluminum films with different thicknesses;（b）The reflectivity curves of different thickness silver films

In Figure 5 (a), when the thickness of aluminum film is larger than 50 nm, the reflectivities of aluminum films basically remain unchanged. In Figure 5 (b), when the thickness of silver film is larger than 100 nm, its reflectivity changes little and almost reaches the highest value. Therefore, the thickness of aluminum film can be selected as 50 nm, while the thickness of the silver film is 100 nm.

In the actual fabrication process for sensing chip, there are several metal leads on the surface of sensing chip. Therefore, in order to achieve the purpose of insulation, a layer of silicon dioxide is usually sputtered on the surface of sensing chip beneath the metallic films. The reflectivity changes of 50 nm aluminum film and 100 nm silver film are simulated under SiO_2 insulating layers with different thicknesses, as shown in Figure 6. The SiO_2 insulating layer with different thickness has little effect on the reflectivities of aluminum film or silver film. Based on the principle of minimal influence on the sensor performance, the thickness of silicon dioxide insulating layer is selected as 20 nm.

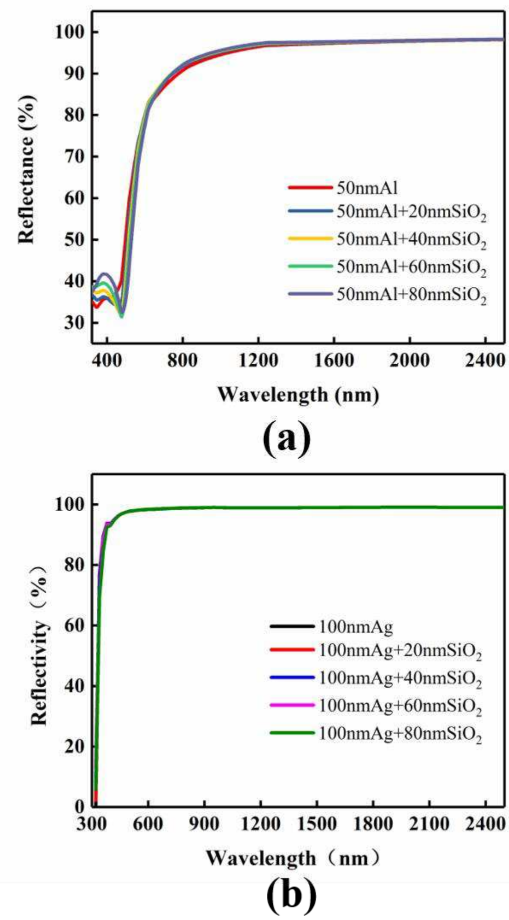

Figure 6 The influence of silicon dioxide insulating layer with different thicknesses on the reflectivity of metallic films:（a）Influence of the insulating layer with different thickness on the reflectivity of aluminum film;（b）Influence of the insulating layer with different thickness on the of silver film

The aluminum and silver films are easily oxidized in the air, which affects their reflection effect, so they need to be protected. For this reason, another SiO_2 layer is fabricated by sputtering technology on the aluminum or silver films to protect them. Then, the protective SiO_2 layers with different thicknesses are simulated to analyze their influence on the reflectivities of the composite films, as shown in Figure 7.

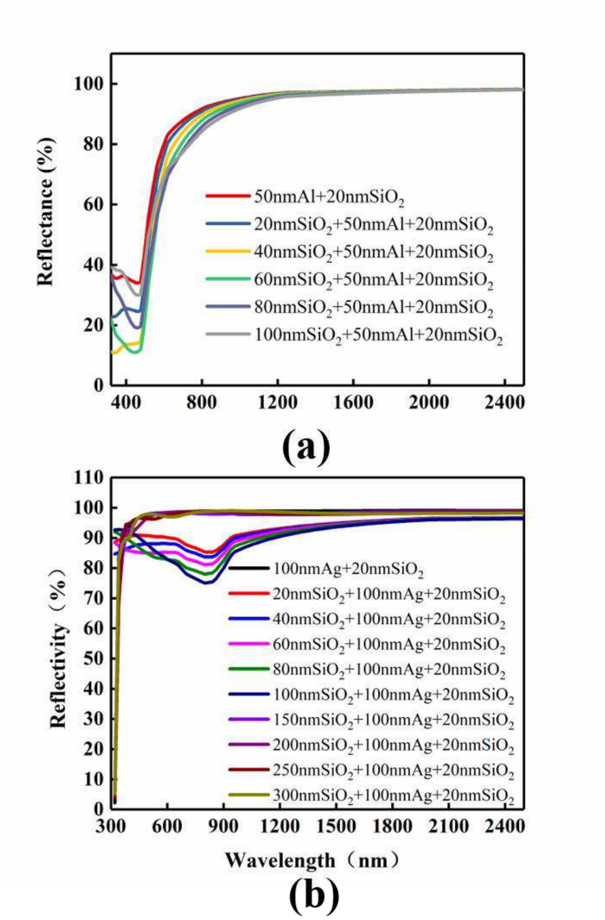

Figure 7 The influence of protective SiO_2 layers with different thicknesses on the reflectivities of composite films: (a) Aluminum film; (b) Silver film

In Figure 7 (a), when the thickness of protective SiO_2 layers is 20 nm, the influence on the reflectivity of aluminum composite film is minimal. Finally, the optimized reflective composite film is determined with 20 nm insulating SiO_2 layer, 50 nm aluminum film and 20 nm protective SiO_2 layer.

As shown in Figure 7 (b), the thickness of the protective SiO_2 layer in the composite film with 100 nm silver film is determined as 200 nm according to the simulated maximum reflectivity. Therefore, another reflective optimized composite film is finally determined and consists of 20 nm insulating SiO_2 layer, 100 nm silver film and 200 nm protective SiO_2 layer.

4.2 Experimental Verification

According to the simulation results about the reflectivities of composite films, aluminum films are fabricated separately by sputtering technology with the thicknesses of 20 nm, 50 nm, 80 nm, 100 nm, and 200 nm, and silver films are also fabricated separately by the same technology with the thicknesses of 50 nm, 100 nm, 150 nm, and 200 nm. The reflectivities of the sputtered films are measured with an ultraviolet-visible spectrophotometer with the type of UV-3600. According to the detection capability of the equipment, the wavelength range is set to 220 nm-1800 nm, and the final test results are shown in Figures 8 and 9.

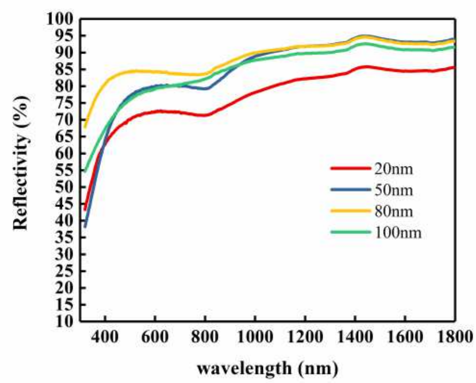

Figure 8 The tested reflectivities of aluminum films

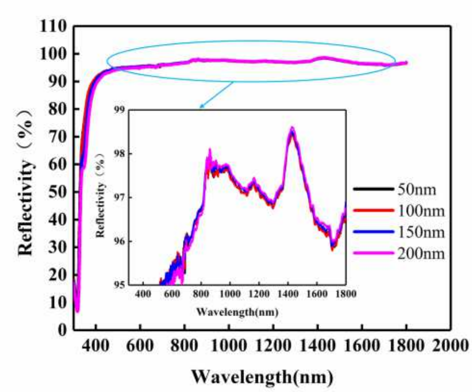

Figure 9 The tested reflectivities of silver films

In Figure 8, the reflectivity of aluminum film is not greatly improved when its thickness is larger than 50 nm, so the thickness of aluminum film can be selected as 50 nm. As shown in Figure 9, when the thickness of silver film is larger than 100 nm, its reflectivity has small change. Therefore, the thickness of silver film is selected as 100 nm. The above experimental results agree well with the simulation results.

The reflectivities of composite films consisted of insulating SiO_2 layer, aluminum or silver film and protective SiO_2 layer with different thicknesses are also tested by ultraviolet-visible spectrophotometer. The experimental results are shown in Figure 10. The overall reflectivity of the composite film with silver film is higher than that of the composite film with aluminum film, and the protective SiO_2 layer has little effect on the reflectivity. So, the composite film with silver film is finally chosen as the reflective layer.

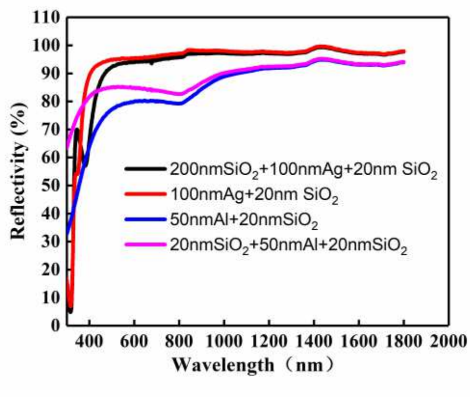

Figure 10 Reflectivity curves of composite films with different layers

The anti-glare light interference effect of the reflective composite film is simulated with the microscopic particles by Silvaco TCAD, and the model as shown in Figure 11 (a). The reflectivity of composite film consisted of 200 nm protective SiO_2 layer, 100 nm silver film and 20 nm insulating SiO_2 layer is simulated. A light intensity of 48.65A/cm^2 is applied to the built model and a model without a reflective layer is used for comparison. The simulation results are shown in Figure 11(b)-(d). Based on the simulation results under the same light intensity, when a reflective layer is added to the piezoresistive area in the build model, the current, hole concentration, and electron concentration are greatly reduced compared with the model without the reflective layer. Therefore, the reflective layer plays a great role to reduce the effect of the strong light on the performance of the piezoresistive sensor.

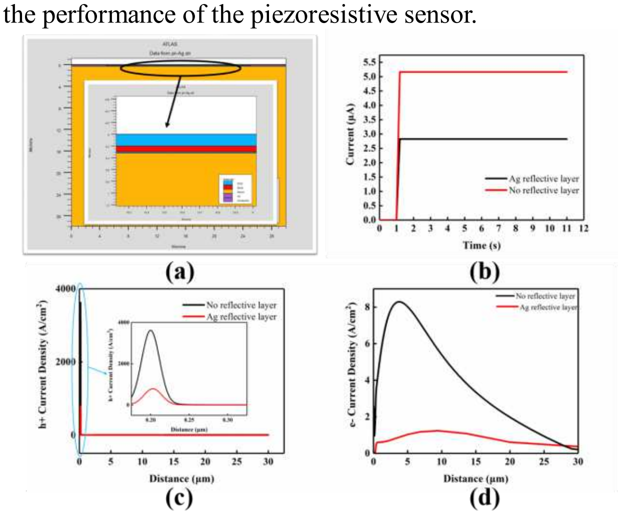

Figure 11 Reflective layer simulation: (a) Reflective composite film model; (b) Current changes; (c) e- current density changes; (d) h+ current density changes

5 Conclusions

(1) In this paper, an experimental platform is built to simulate the explosion field, and the influence of strong light on the output of the piezoresistive pressure sensor is analyzed. The results show that strong light does have large interference at the output of the piezoresistive pressure sensor. The experimental results show that the interference to the output of the piezoresistive pressure sensor gradually increases with the intensity of light field. The experimental data show that sensor output is proportional to light intensity.
(2) In order to explain how strong light interferes with the output of the piezoresistive pressure sensor, the model of the piezoresistive pressure sensor is established through Silvaco TCAD software, and different intensities of strong light are applied to it, and the changes in its internal current are analyzed. Simulation results show that with the internal current of the piezoresistive continues to increase with the light field intensity, which makes the output of the pressure sensor increase. The simulation data show that the piezoresistive current is also proportional to light intensity.
(3) In order to solve the problem of strong light interference to the piezoresistive pressure sensor, a method of adding a reflective layer on the front of the sensor is proposed. Through simulations and experiments, the thicknesses of the metal reflective layer and the insulating layer are determined. The reflection effect of the reflective composite layer has also been experimentally verified. In order to explain its suppression effect and principle, the changes of internal current, hole concentration, electron concentration under strong light are analyzed by simulation, which proves that the reflective composite layer has a positive effect on suppressing the interference of strong light.

6 Declaration

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Availability of data and materials

The datasets supporting the conclusions of this article are included within the article.

Authors' contributions

The author' contributions are as follows: Xiang-Huang Han, Yao Chen, Mi-Mi Huang, were in charge of the whole trial; Mi-Mi Huang, Li-Bo Zhao, Zu-Tang Wu, Xiao-Zhang Wang and Jiu-Hong Wang reviewed and edited the manuscript; Ming-Zhi Yu and Yong-Lu Wang assisted with sampling and laboratory analyses; Ping Yang, and Zhuang-De Jiang assisted with the manuscript checking; All authors read and approved the fnal manuscript

Competing interests

The authors declare no competing financial interests.

Consent for publication

Not applicable

Ethics approval and consent to participate

Not applicable

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