Research on Photo-Varistor Based on Lateral Bipolar Photoresistance Effect

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Abstract: At present, there has been research on the lateral bipolar photoresistance effect of various semiconductor materials, which suggests that some semiconductor materials have the potential to be used to prepare a new type of photo-varistor based on the lateral bipolar photoresistance effect. However, further research and optimization of the production process of this type of photo-varistor have not been conducted. This project conducted in-depth research on the production process of this type of photo-varistor. Firstly, I conducted a series of experiments and selected two semiconductor materials with good linearity: one was Ag/SiO2/Si P-type silicon corroded for 10 minutes, and the other was Ag/SiO2/Si N-type silicon corroded for 5 minutes. Subsequently, I solve the problem "the copper wire cannot be easily fixed" by clamping the silicon slice and copper wire between two cleaned glass sheets, so as not to affect laser irradiation and also to fix the sample. Furthermore, I use the Arduino circuit to monitor the voltage of photo-varistors sensor. This project contributes to the application and commercialization of the photo-varistor based on lateral bipolar photoresistance effect.

Keywords: lateral bipolar photoresistance effect, photo-varistor, sensor

Contents

1. The Principle of Bipolar Resistance Effect (Reference [2])

The photo controlled bipolar resistance effect is a unique phenomenon that exists in special semiconductor materials. When the laser spot moves from one electrode segment along the same line segment to another electrode segment, the resistance of the semiconductor will show a significant linear change with the position of the spot.

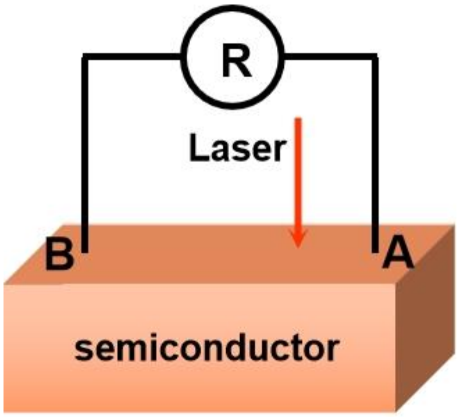


Figure 1. Schematic diagram of bipolar resistance effect, reference [2]

Under laser irradiation, the laser can excite electrons in semiconductors and have a probability of causing these electrons to transition to the metal layer, which then diffuses. At the same time, the drift electrons present in the metal layer are also moving, so the diffusion electrons on the left side of the irradiation point move in the opposite direction to the drift electrons, causing strong scattering and increasing resistance, forming a high resistance region. On the right side of the irradiation point, the diffusion electrons move in the same direction as the drift electrons, so they can maintain a small resistance. Therefore, by calculating the resistivity of each point on the left and the resistivity of each point on the right, and performing definite integration, the resistance at the corresponding position can be obtained. The resistance value of the semiconductor structure under laser irradiation is:

$$R(x) = R_0(1 + Kx) \quad (-L < x < L) \tag{1}$$

Here K is the proportion coefficient of the semiconductor structure itself, which is:

$$K = \frac{n_0 e^{-L/l}}{N_0 L} \tag{2}$$

where N_0 is the drift electron concentration, L is the distance from the midpoint to one end of the electrode, l is the electron diffusion length, and n_0 is the electron concentration at the laser irradiation site.

This also reflects that the change in resistance follows a linear trend.

2. The process and results of the research

Professor Wang Hui's laboratory at Shanghai Jiao Tong University has conducted research on the bipolar resistance effect of various semiconductor materials and mentioned that a new type of optoelectronic variable resistor can be made based on this, but further research has not been conducted on the manufacturing process of this type of optoelectronic variable resistor. This article first reproduces the bipolar resistance effect in different semiconductor materials, and based on this, identifies the most suitable material for preparing photoresists. Finally, the study of the production process of photoresists is carried out.

2.1 By testing the 14 silicon slices produced, select silicon slice samples with good linearity for the core components of the variable resistor

In order to study the influence of various semiconductor materials on their resistance effect (mainly including bare silicon, porous silicon, Ag/Si surface silver plated semiconductors, and Ag/SiO_2/Si MOS semiconductor materials), the following 14 types of silicon slices were prepared for testing, including:

（1） P-type bare silicon

（2） N-type bare silicon

（3） P-type porous silicon corroded for 5 minutes

（4） P-type porous silicon corroded for 10 minutes

（5） N-type porous silicon corroded for 5 minutes

（6） N-type porous silicon corroded for 10 minutes

（7） Ag/Si P-type corroded for 5 minutes

（8） Ag/Si N-type corroded for 5 minutes

（9） Ag/Si P-type corroded for 10 minutes

（10）Ag/Si N-type corroded for 10 minutes

（11）Ag/SiO2/Si P-type corroded for 5 minutes

（12）Ag/SiO2/Si N-type corroded for 5 minutes

（13）Ag/SiO2/Si P-type corroded for 10 minutes

（14）Ag/SiO2/Si N-type corroded for 10 minutes

It was found that three samples showed good linearity between the two poles, among which sample 13 had the best linearity, Ag/SiO_2/Si P-type silicon corroded for 10 minutes, with a sensitivity of up to 3.08K Ω per millimeter.

Two samples were damaged, and the change in resistance between the two poles of the other samples did not show a significant linear relationship, even non-linear.

2.2 Prototype of varistor samples with good linearity and high sensitivity has been produced

Two of the three samples with good linearity were selected as the core components for making a variable resistor. Then I designed other components of the variable resistor, printed them out using a 3D printer, and assembled these components with silicon slice samples for testing. We successfully produced two prototype optoelectronic variable resistor samples. One type is a smaller range and lower sensitivity variable resistor (variable resistor with Ag/SiO_2/Si P-type silicon corroded for 10 minutes, the range of 1.3331K Ω -1.95K Ω and the sensitivity of 0.4429 K Ω/mm). Another type is a high-sensitivity variable resistor with a large range (variable resistor with Ag/SiO_2/Si P-type silicon corroded for 10 minutes, the range of 133.31K Ω -149.03K Ω and the sensitivity of 8.274 K Ω/mm).

2.3 Prototype of a micro displacement monitor has been produced

Based on the prepared photo controlled variable resistor and the linearization feature of the photo-controlled resistance change, I added an analog-to-digital conversion circuit and conversion algorithm, and completed the complete displacement monitoring sensor sample using Arduino. Due to the small size of the entire device, if industrial packaging is adopted in the future, the integration level can be further improved.

3. Preparation and testing of silicon slice sample

3.1 . Preparation silicon slice sample

The first step of the experiment is to prepare the test sample, prepare porous silicon as the base material, and coat it with a metal film (Ag). The specific sample production process is as follows:

3.1.1 Cleaning semiconductor substrate materials

It is necessary to first preprocess the silicon slice, clamp the cotton with tweezers and wipe the surface of the silicon slice with acetone to remove industrial glue and some surface oxide layers. After preprocessing, formal cleaning begins.

The first step is to clean the silicon slices. The specific steps for cleaning are:

1) Preprocess the surface of silicon slices with cotton and ethanol;

2) Put the processed silicon slice into a beaker, add acetone, and perform 20 minutes of ultrasonic cleaning;

3) Pour acetone, add ethanol, and perform a 20 minutes ultrasonic cleaning.

This operation can also clean silicon slices very well, so I cleaned 14 silicon slices in this order.

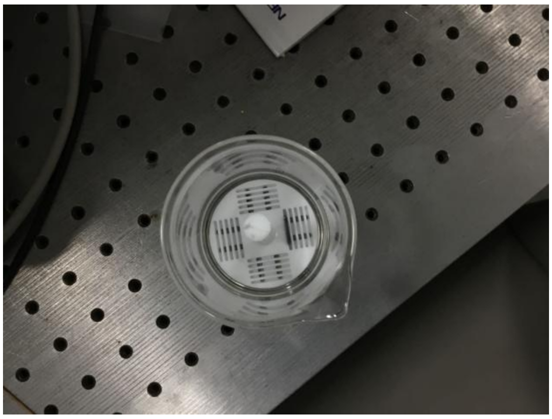


Figure 2: Silicon slices placed in ethanol

3.1.2 Corrosion of semiconductor surfaces

Figure 3. Corrosion device for producing porous silicon

After cleaning, it is a corrosion process on the semiconductor surface. Different from previous references, this time the reagents will be prepared first. The reagent consists of 4g ammonium fluoride, 30mL plasma water, 80mL ethanol, and 70mL phosphoric acid. Firstly, take out the ammonium fluoride from the freezer and use a spoon to remove the solid ammonium fluoride. Then, add 30mL of plasma water for dissolution (adding plasma water can effectively accelerate the dissolution rate). After dissolution, add ethanol for dissolution, and then add phosphoric acid for dissolution. Once fully dissolved, a colorless test reagent is prepared.

Next, during the preparation process, I need to pour the reagent into the tank shown in Figure 3. Insert a graphite sheet at one end and connect the wire to serve as the cathode. On the other end, use a metal clip with wires to clamp the semiconductor sample and insert 1/3 of the sample into the reagent as the anode. This step aims to corrode the surface of silicon slices and create porous silicon structures through the ionization process. During the ionization process, I was able to control the output voltage. In this experiment, the current was controlled at 0.1A by adjusting the voltage, and two types of silicon slices were successfully made, one for corrosion for 5 minutes and the other for corrosion for 10 minutes. Interestingly, I have observed that P-type silicon typically takes longer to achieve a current output of 0.1A, while N-type silicon typically excites a current output of 0.1A when a voltage is just applied. This discovery is very eye-catching and may be related to material properties.

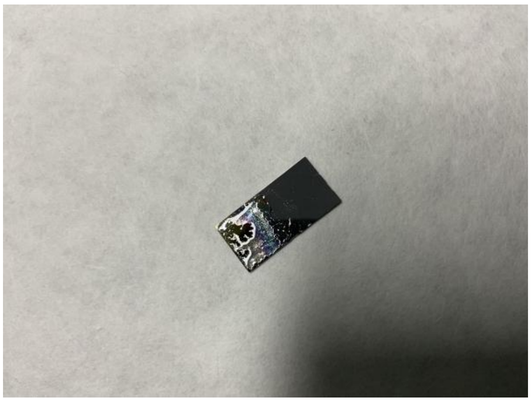


Figure 4: Semiconductor silicon slices that have not been blown dry after corrosion

3.1.3 Coating using magnetron sputtering technology

The following coating adopts DC magnetron sputtering, which is currently one of the more advanced technologies for depositing metal thin films on semiconductor surfaces. This technology has multiple advantages, including low surface temperature of the base, high film production efficiency, and uniform film thickness. The main coating principle is to accelerate the movement of metal raw material argon cations towards the target material through inert gas cations, bombarding the target material at the negative electrode, and causing the atoms of the target material to fly out of its surface under high-speed collision, forming sputtering. The coating steps are as follows:

Power on:

(1) Turn on the main power supply.

(2) Turn on the power to the water pump.

(3) Turn on the mechanical pump and low vacuum gauge.

(4) Slowly open V6 and close it after the pressure drops to 20pa.

(5) Turn on the solenoid valve and turn on the molecular pump.

(6) Open the gate valve.

Sputtering:

(1) Close the ionization gauge.

(2) Open the intake valves (V4, V5).

(3) When the pressure reaches 9 * 10-4pa, close the gate valve.

(4) Open the pressure reducing valve at the bottle and then turn on the volumetric flow meter.

(5) Adjust the gate valve to maintain a constant air pressure of 0.7pa.

(6) Turn on the DC power supply for sputtering.

(7) Rotate the corresponding position between the substrate and the target material to control the time.

The distance between the shell of the target and the target material is 2-3mm, and it must not be in contact, otherwise there will be a short circuit.

Molecular pump start-up sequence: First, turn on the on/off button, reset the FUNC DATA button to zero, and then press the START button.

Detailed steps for sputtering:

After the pressure drops to 5 * 10-4pa, close the pressure reducing valve at the gas cylinder.

Power supply to gas flow meters.

Turn off the high vacuum gauge and open the argon intake valve.

Set the gas flow meter to the degassing (cleaning) position.

After the pressure drops to 10-1pa, turn on the high vacuum gauge.

After the pressure drops to 10-4pa, turn the gas flow meter to the closed position (close the high vacuum gauge).

Adjust the pressure reducing valve of the gas cylinder (0.1-0.15Mpa).

Set the gas flow meter to the valve control position and adjust the flow rate (10-13).

Close the gate valve to a certain extent.

In addition, it is necessary to control the sputtering time. In this experiment, the sputtering time for Ag thin film was 8 seconds, while the sputtering time for SiO2 oxide layer was about one minute. These are empirical values obtained from consulting with other members of the laboratory. Finally, during the sputtering process, the target is moved through a computer program for sputtering.

In this project, 14 semiconductor silicon slices were prepared. The first step was to clean silicon slices 1 to 14, with samples 1 and 2 used as reference standards. The 2nd Step, perform a 5 or 10 minutes corrosion operation on a total of 12 silicon slices from No. 3 to No. 14. The 3rd Step, coat a total of 8 silicon slices from No. 7 to No. 14 with different metal films.

So, the 14 semiconductors with different structures listed earlier were prepared.

3.2 Testing the Resistance Effect of Semiconductor Samples

After preparing all 14 semiconductor structures, I began to build a device to measure the bipolar resistance effect of these 14 silicon slices. Use a specific wavelength of laser to test the effect of different powers on the sensitivity of a sample. The experimental method is as follows: move the laser on a precision slide and record the changes in electron diffusion length and resistance of each sample.

The experimental operation first requires connecting the semiconductor sample to an electrode, and here I choose to use indium for the operation. Cut a small piece of indium dot on the existing indium wire, use a toothpick to stick the indium dot onto the semiconductor sample, and keep the distance between the two indium dots not far. Then scrape the conductive copper wire on the head and press it onto the indium point. Afterwards, cut off two pieces of indium dots and press them onto the copper wire, which is equivalent to clamping two copper wires and making two electrodes. Finally, connect the copper wire to the circuit of the multimeter for measuring resistance, and the measurement operation can be completed, as shown in Figure 5.

A B

Laser

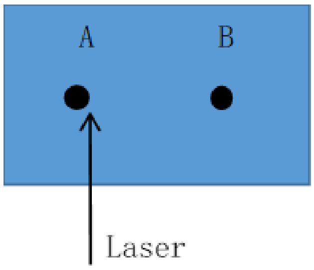


Figure 5. Diagram of the testing

Here, the blue rectangle represents the semiconductor sample, the arrow represents the laser beam, and the two dots represent the two electrodes respectively. The laser moves from A to B on the AB line segment and records the value of the resistance change.

The overall device is shown in Figure 6：

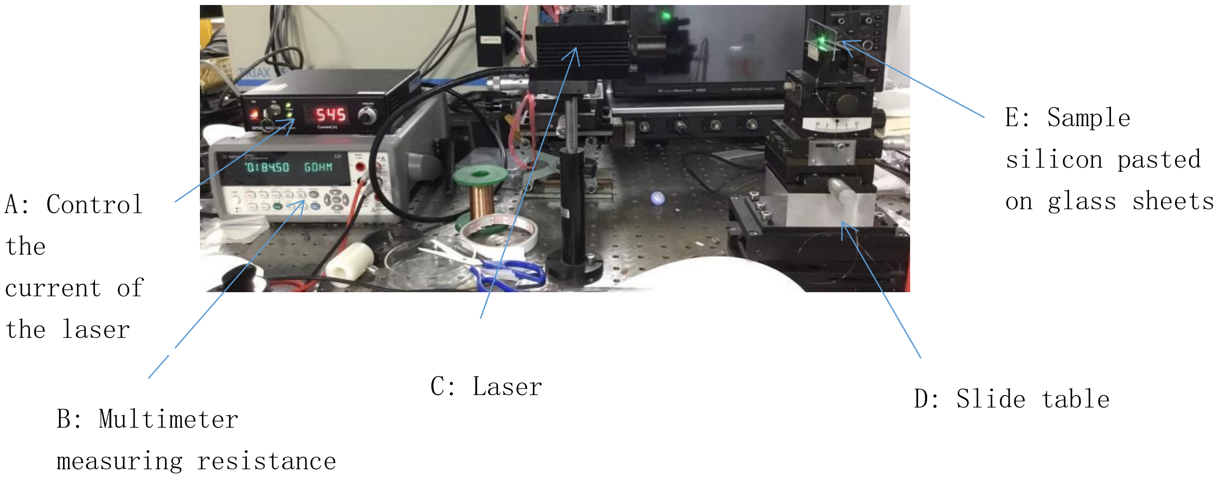


Figure 6. Experimental equipment

Next, I provided a brief overview of some materials that have obtained special patterns, and the main patterns and conclusions drawn from them are mainly analyzed in the ninth group of experiments. Finally, I summarized all the tests in the table.

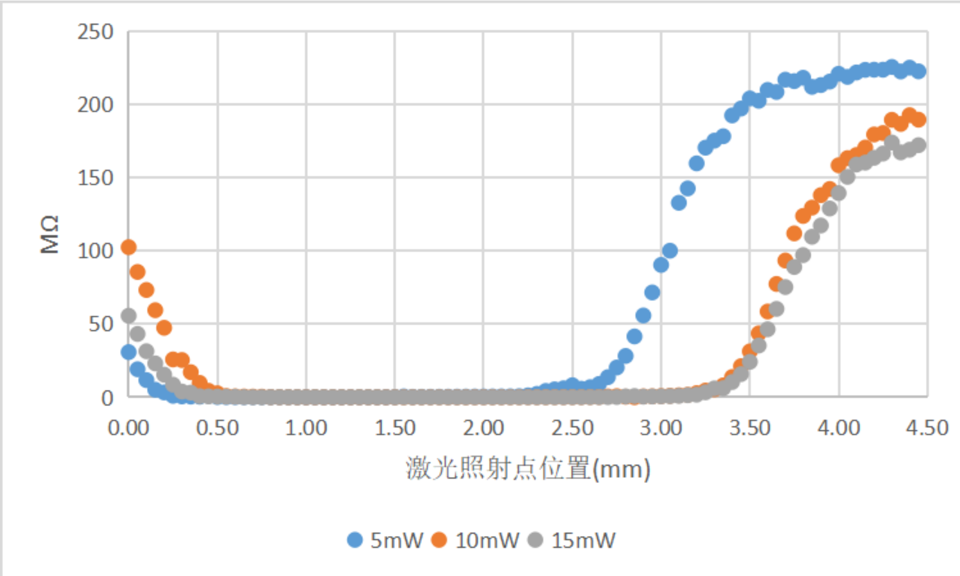
3.2.1 Test Case 1

Time: December 9, 2021, 16:30-21:00 PM

Number: Sample 4 (Porous P-type silicon corroded for 10 minutes)

Electrode position: 0.5mm to 2.5mm.

Purpose: To measure the effect of different laser powers on resistance sensitivity under the same material, the measured data are as follows:



From the experimental results, it can be seen that the resistance change caused by the displacement of the laser between the two electrodes is not significant. This is likely due to the large distance between the two electrodes, which did not meet the requirement of being much smaller than the electron diffusion length. Based on Yu Chongqi's paper[2], as the laser power increases, the sensitivity also increases accordingly, but after reaching a certain level (about 10mW), the sensitivity change is not significant. Therefore, in order to reduce the impact of laser power on the test results, the laser power used in subsequent tests of this study was 15mW.

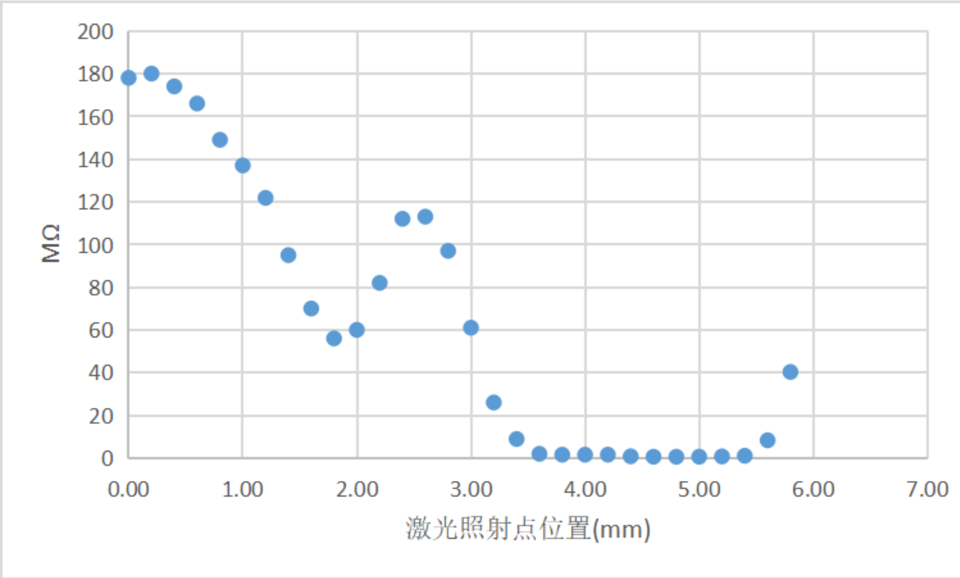
3.2.2 Test Case 2

Time: December 9, 2021, 16:30-21:00 PM

Number: Sample 1 (P-type bare silicon)

Electrode positions: 0.8mm and 3.2mm.

Purpose: To measure the bipolar resistance effect of this structure. Obtain the following data:



This experiment found that the resistance increases linearly with the displacement of the irradiation point in the middle, which does not conform to the linear situation. **This situation has not been mentioned in previous papers.**

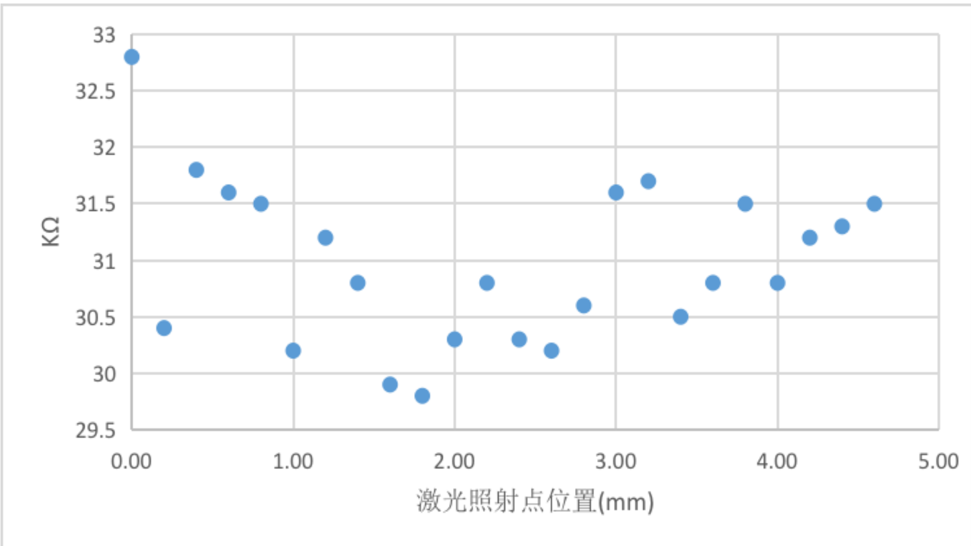
3.2.3 Test Case 3

Time: December 9, 2021, 16:30-21:00 PM

Number: Sample 2 (N-type bare silicon)

Electrode positions: 1mm and 3mm.

Purpose: To measure the bipolar resistance effect of this structure. Obtain the following data:



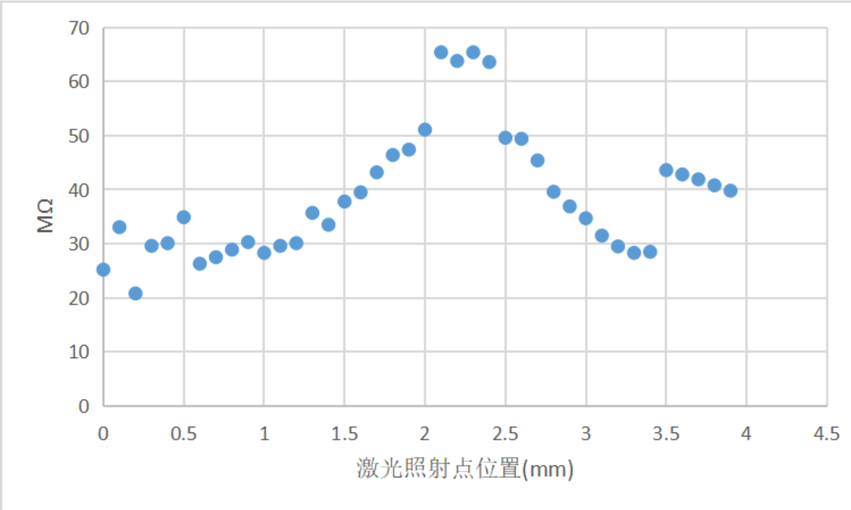
3.2.4 Test Case 4

Time: December 9, 2021, 16:30-21:00 PM

Number: Sample 7 (P-type silicon of Ag/Si corroded for 5 minutes)

Electrode positions: 1.5mm and 3mm.

Purpose: To measure the bipolar resistance effect of this structure. Obtain the following data:

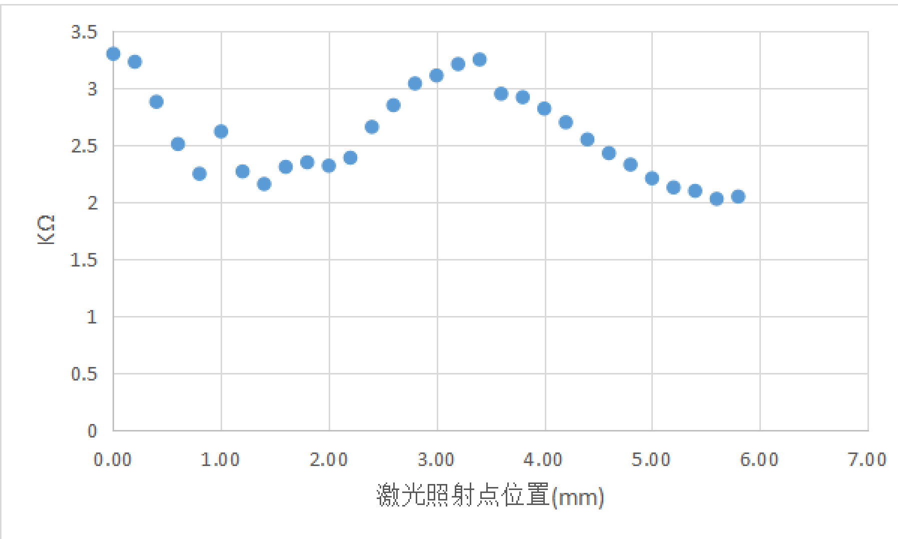


3.2.5Test Case 5

Time: December 9, 2021, 16:30-21:00 PM

Number: Sample 8 (N-type silicon of Ag/Si corroded for 5 minutes)

Electrode positions: 2mm and 3.5mm.

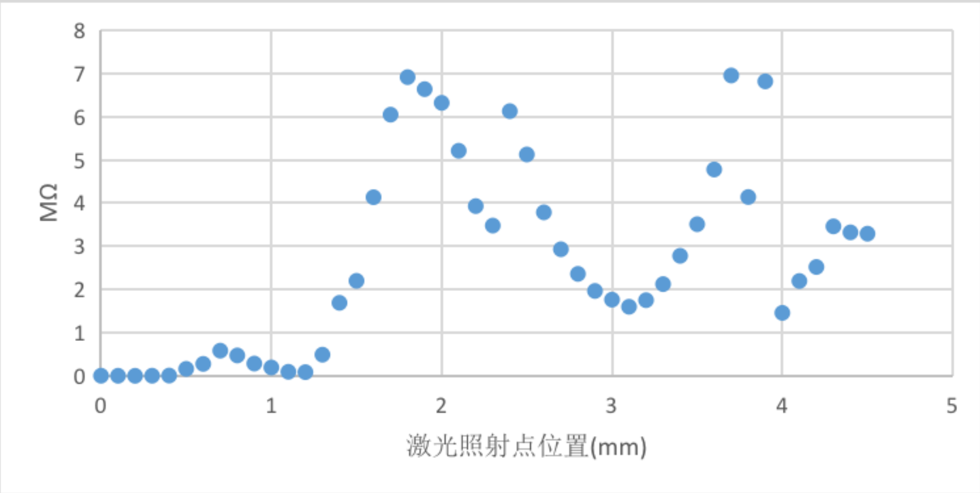


3.2.6 Test Case 6

Time: December 10, 2021, 4:00 PM -20:00 PM

Number: Sample 9 (P-type silicon of Ag/Si corroded for 10 minutes)

Electrode positions: 1.3mm and 3mm.



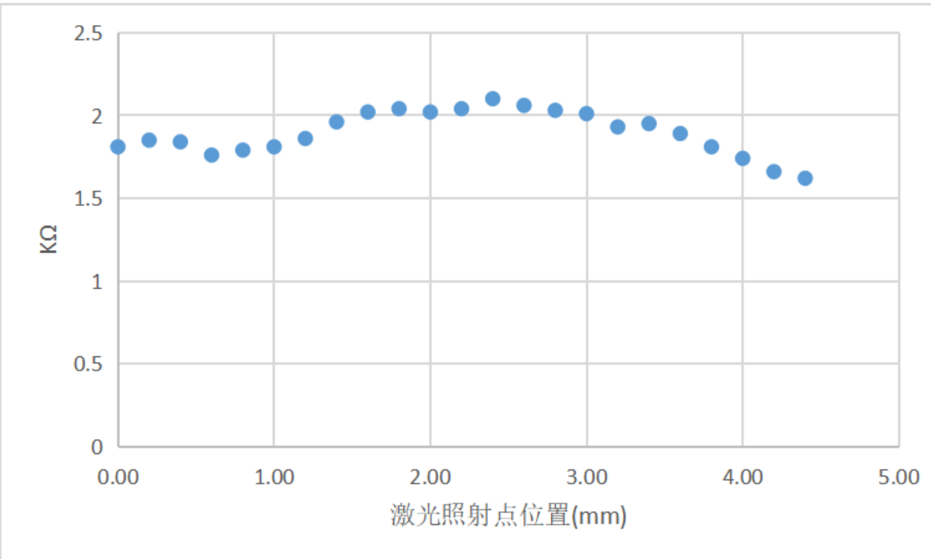
3.2.7 Test Case 7

Time: December 10, 2021, 4:00 PM -20:00 PM

Number: Sample 10 (N-type silicon of Ag/Si corroded for 10 minutes)

Electrode position: Place the electrodes at 0mm and 2mm positions.

Purpose: To measure the bipolar resistance effect of this structure. Obtain the following data:



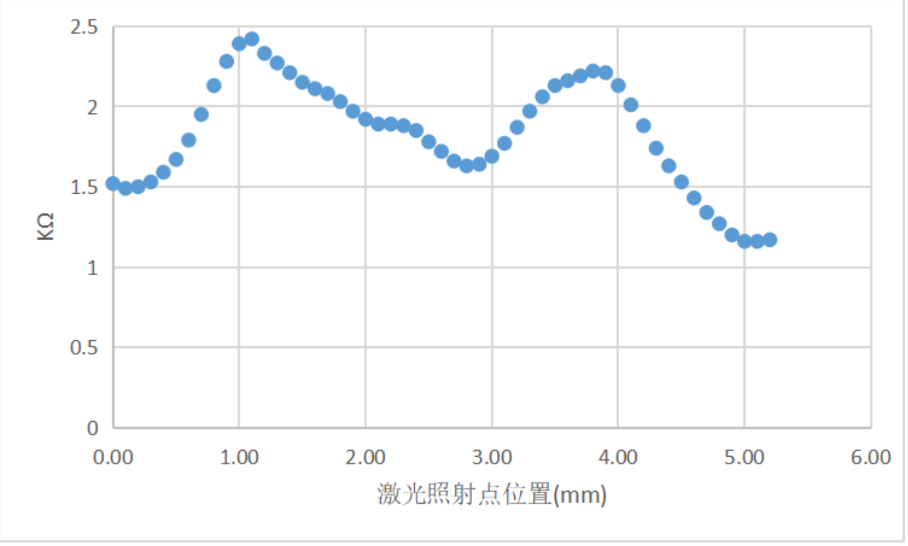
3.2.8 Test Case 8

Time: December 10, 2021, 4:00 PM -20:00 PM

Number: Sample 12 (N-type Ag/SiO2/Si)

Electrode positions: 1mm and 2.8mm.

Purpose: To measure the bipolar resistance effect of this MOS structure. Obtain the following data:



In this MOS structure, a strong linear variation was observed between the two electrodes. However, it is interesting to note that there is a small portion of nonlinear region between 2.1mm and 2.3mm in the middle, which is likely caused by a larger electrode distance of 1.8mm. The remaining parts follow the same pattern as obtained from reference [2].

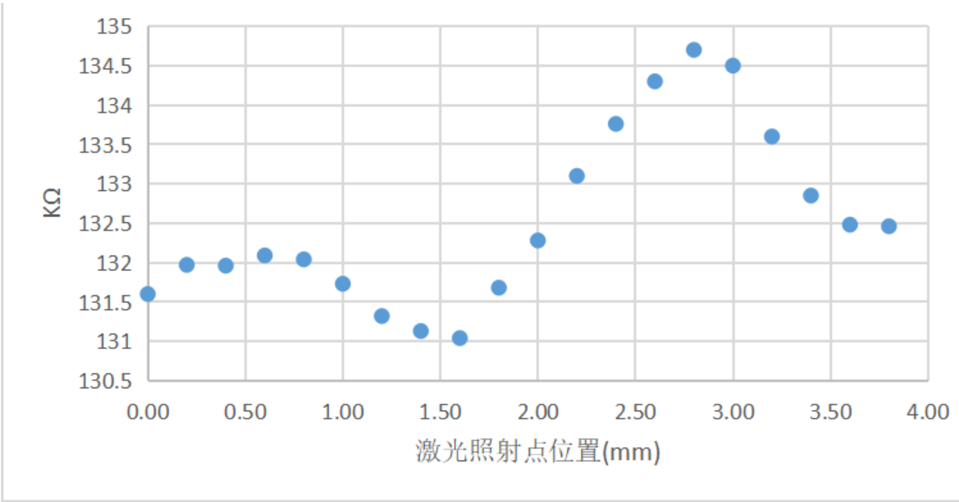
3.2.9 Test Case 9

Time: December 10, 2021, 4:00 PM -20:00 PM

Number: Sample 13 (Ag/SiO2/Si P-type silicon corroded for 10 minutes)

Electrode position: The electrodes are installed at 1.5mm and 2.8mm positions.

Purpose: To measure the bipolar resistance effect of this MOS structure. Obtain the following data:



Analysis: In the P-type silicon structure of Ag/SiO2/Si corroded for 10 minutes, strong linearity was found, and its sensitivity was also higher than that of the Ag/SiO2/Si N-type silicon structure corroded for 10 minutes. The strong linearity of MOS structures is likely due to their longer diffusion length, so as shown in formula (2), the resistance change at an electrode distance of about 1.5mm-2mm can be better approximated as linear compared to other structures. However, due to the smaller diffusion length of other structures, the diffusion of charge carriers to another electrode causes nonlinear resistance changes. Secondly, this experiment shows that the variation of N-type bare silicon is smaller than that of P-type silicon, and there is no linear relationship, which is also an issue not discussed in the references.

There is contamination on the surface of samples 11 and 14 due to improper experimental operations, and some of the surface coatings are damaged, so no measurements were taken.

3.2.10 Trend analysis and summary

Test No.	Sample No.	Electrode position	Analysis
1	Sample 4 P-type porous silicon corroded for 10 minutes	0.5mm, 2.5mm	The resistance change caused by the displacement of the laser between the two electrodes is not significant. This may be due to the large distance between the two electrodes, which did not meet the requirement of being much smaller than the electron diffusion length. From the results, it cannot be distinguished which power has the greatest sensitivity change on semiconductor samples.

2	Sample 1 P-type bare silicon	0.8mm, 3.2mm	This experiment found that the resistance increases linearly with the displacement of the irradiation point in the middle, which does not conform to the linear situation. This situation has not been mentioned in previous published papers.
3	Sample 2 N-type bare silicon	1mm, 3mm	This experiment found that the variation of this N-type bare silicon is minimal and has no linear relationship, presenting an overall nonlinear region. This may be because the position of the silicon slice during measurement is a bit crooked, so the path of the laser does not match the line segment formed by the two electrodes, or it may be because in bare silicon, the bipolar resistance effect itself is not strong.
4	Sample 7 Ag/Si P-type corroded for 5 minutes	1.5mm, 3mm	There is no basic coherent linear trend here, but rather a linear increase followed by a non-linear zone before a linear decrease. Although it basically conforms to a linear relationship, it does not show a trend of continuous increase or decrease. In summary, this time there was an intention to reduce the distance between the two electrodes, but there was still no linear relationship, possibly because the distance between the two electrodes was still too large.
5	Sample 8 Ag/Si N-type corroded for 5 minutes	2mm, 3.5mm	Although the distance between the two electrodes was not reduced, a basically linear increasing line can still be observed.
6	Sample 9 Ag/Si P-type corroded for 10 minutes	1.3mm, 3mm	This time, after the initial linear growth, it showed a non-linear region similar to Ag/Si silicon slices, followed by a linear decrease.
7	Sample 10 Ag/Si N-type corroded for 10 minutes	0mm, 2mm	Although there is a certain linear upward trend in resistance, the overall resistance does not change much.
8	Sample 12 Ag/SiO_2/Si N-type corroded for 5 minutes	1mm, 2.8mm	In this metal oxide semiconductor structure, a strong linear variation was observed between the two electrodes. However, it is interesting to note that there is a small portion of nonlinear region between 2.1mm and 2.3mm in the middle, which is likely caused by a larger electrode distance of 1.8mm.
9	Sample 13 Ag/SiO_2/Si P-type corroded for 10 minutes	1.5mm, 2.8mm	In the P-type silicon structure of Ag/SiO2/Si corroded for 10 minutes, strong linearity was found, and its sensitivity was also higher than that of the Ag/SiO2/Si N-type silicon structure corroded for 10 minutes.

From the above test results, I found a good linear relationship in the resistance between the two electrodes in samples 8, 12, and 13.

In the future, I will use the three samples obtained above that meet the sensitivity requirements as basic components to make a variable resistor.

4. Making semiconductor variable resistance devices

4.1 Production process

In order to create a portable small variable resistor, I have decided not to use the multifunctional, bulky, and expensive laser in the laboratory. On the contrary, I purchased a batch of small lasers with the same wavelength as those used in the laboratory, with a head diameter of only 1 centimeter and a length of 2.6 centimeters. At the same time, I also purchased a small precision slide to streamline the equipment. The use of these small devices aims to improve portability, reduce costs, and enable me to conduct experiments in smaller spaces.

In order to connect the slide and semiconductor samples, I designed the following 3D print and used a 3D printer to complete the production. This device is 63mm long, 50mm wide, and 43mm high. As shown in Figure 7:

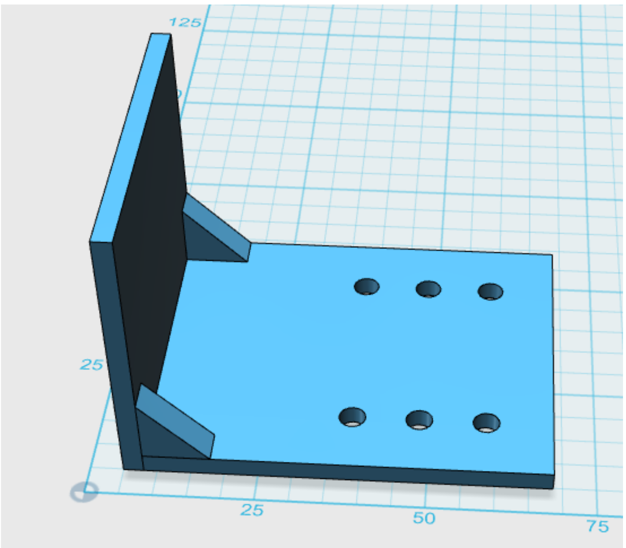


Figure 7. 3D model of the stand

In order to connect the slide and laser, I also designed another 3D print, which is 40mm long, 30mm wide, and 3mm thick, as shown in Figure 8:

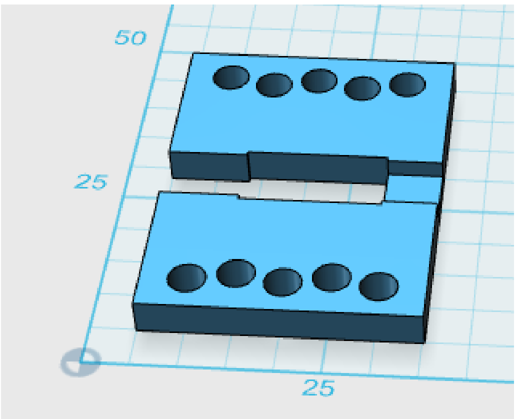


Figure 8. 3D model of laser mounted board

During the production process, a problem was encountered, which was how to fix the silicon slice. Due to the fragility of silicon slices and their inability to be exposed to air for extended periods of time, as well as the need for careful use of tweezers for movement, and the fact that copper wires clamped with indium dots are prone to detachment, I need to find ways to stabilize the silicon slices and copper wires. My solution is to clamp the silicon slice and copper wire between two cleaned glass pieces, which will not affect the laser irradiation and can also fix the sample. When operating, first place a sample on a glass sheet, clamp the copper wire with indium dots, and then use tape to fix the copper wire to ensure that it does not fall off during the operation. Then cover the sample with a second piece of glass and stick the two pieces of glass with glue (note that the glue will not come into contact with the semiconductor). As shown in Figure 9:

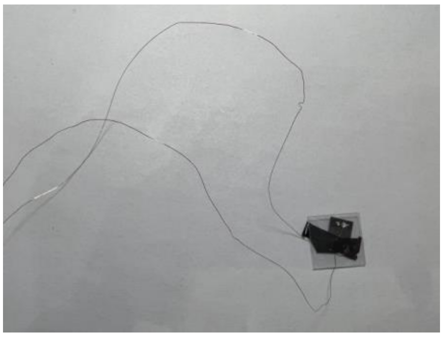


Figure 9. a silicon slice fixed with glass sheets

This plan is only a sample plan. After consulting the information, I believe that industrial packaging with glass windows can be used in the future, which can not only make it sturdier but also further reduce its volume.

By connecting the above components together, the complete prototype of the semiconductor variable resistor device is completed, as shown in Figure 10:

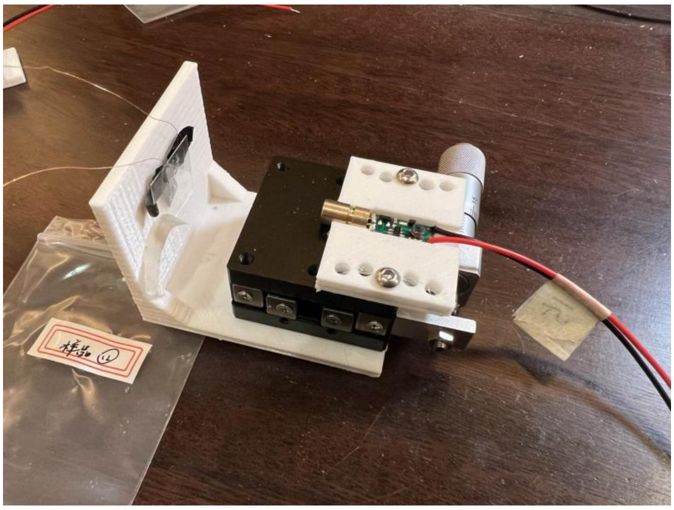


Figure 10. Prototype of Semiconductor Rheostat

4.2 Testing of Rheostats

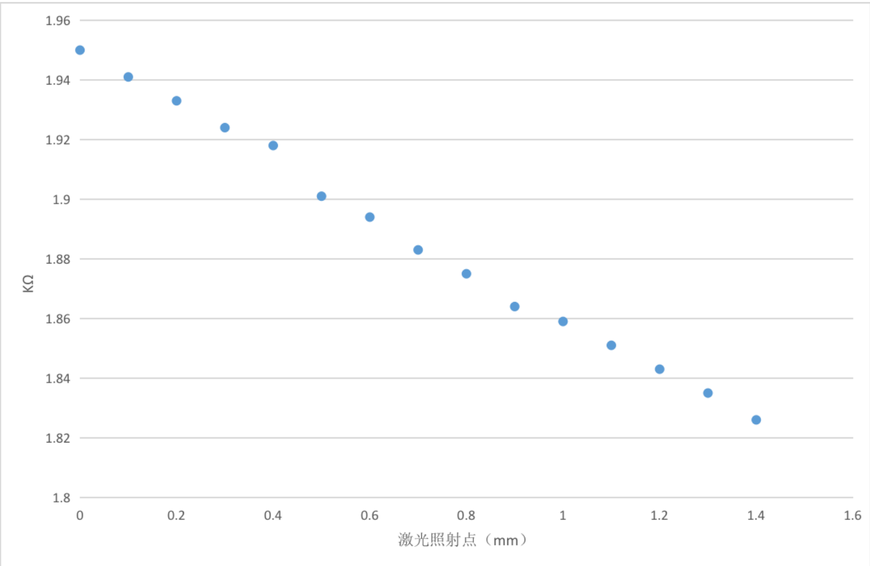
After testing sample 12 and sample 13 separately, two types of varistors with different ranges and sensitivities were produced, one with lower sensitivity for a smaller range and the other with higher sensitivity for a larger range.

4.2.1 A smaller range and lower sensitivity variable resistor (with Sample 12)

Test data:

Laser point position	**Resistance value (KΩ)**
0	1.95
0.1	1.941
0.2	1.933
0.3	1.924

0.4	1.918
0.5	1.901
0.6	1.894
0.7	1.883
0.8	1.875
0.9	1.864
1	1.859
1.1	1.851
1.2	1.843
1.3	1.835
1.4	1.826

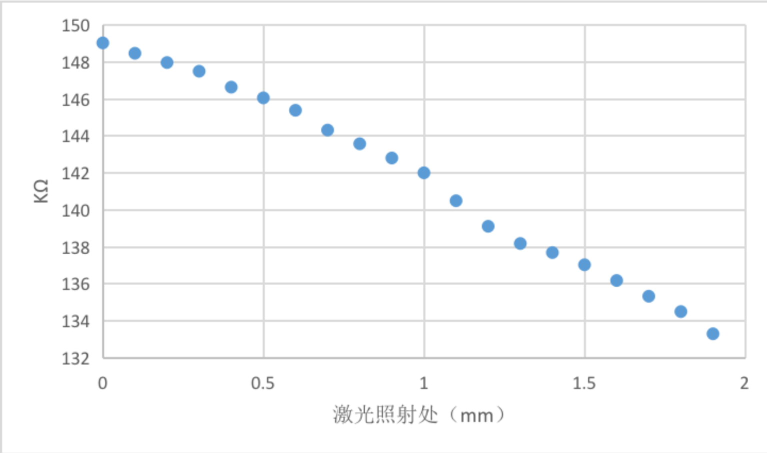


In order to improve the linearity, I reduced the distance between the two electrodes. As shown in the above test results, the linearity is indeed good, and some nonlinear regions that were originally present have now disappeared. The two electrode positions used here are 0mm and 1.4mm respectively. The resistance range of this Ag/SiO2/Si P-type silicon structure corroded for 10 minutes is 1.33K Ω -1.95K Ω, with a sensitivity of 0.44K Ω/mm.

4.2.2 A large range and high sensitivity variable resistor (with Sample 13)

Test Data:

Laser point position	Resistance value (KΩ)
0	149.03
0.1	148.47
0.2	147.97
0.3	147.5
0.4	146.64
0.5	146.06
0.6	145.39
0.7	144.32
0.8	143.58
0.9	142.81
1	142.01
1.1	140.5
1.2	139.12
1.3	138.19
1.4	137.7
1.5	137.04
1.6	136.19
1.7	135.34
1.8	134.51
1.9	133.31



The two electrodes of the Ag/SiO2/Si P-type silicon structure, which were corroded for 10 minutes, were located at 0mm and 1.9mm, respectively. The resistance range was 133.31K Ω -149.03K Ω, and the sensitivity was 8.27K Ω/mm.

From the experimental results, it can be seen that the glass cover plate of the device does not affect the power of laser irradiation and has no effect on the bipolar resistance effect of the sample.

5. Application - displacement monitoring sensor based on a new semiconductor optoelectronic variable resistor

Based on the high sensitivity of the laser point irradiation position and the linear variation characteristics of the large range, this optoelectronic variable resistor can be applied to the monitoring of small displacement and made into a sensor for small displacement monitoring. It can be used as a detection of physical size differences, and thus widely applied in tolerance quality monitoring of precision devices; It can also be used as a monitoring device for mechanical displacement and applied in various fields where small displacements are caused by stress, mechanical vibration, and other factors.

I plan to add an analog-to-digital conversion circuit to further automatically control displacement.

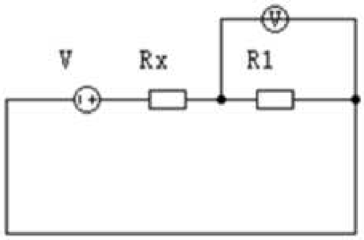


Figure 11. Resistance voltage divider circuit diagram

where V represents the total voltage, while Rx here is the resistance value of the photoelectric variable resistor that I need to obtain, and R1 is a set resistance value. By measuring the voltage value of R1, the resistance value of Rx can be obtained. The expression is:

$$\mathrm{Rx} = \frac{\mathrm{R1(V-V1)}}{\mathrm{V1}} \tag{3}$$

The resistance value of the optoelectronic variable resistor based on this production is high, which can be read using the analog pins in Arduino, and the cost is very low. Calculate the relative displacement of the output laser point based on the slope parameters of the semiconductor variable resistance device calibrated by the previous experimental instrument.

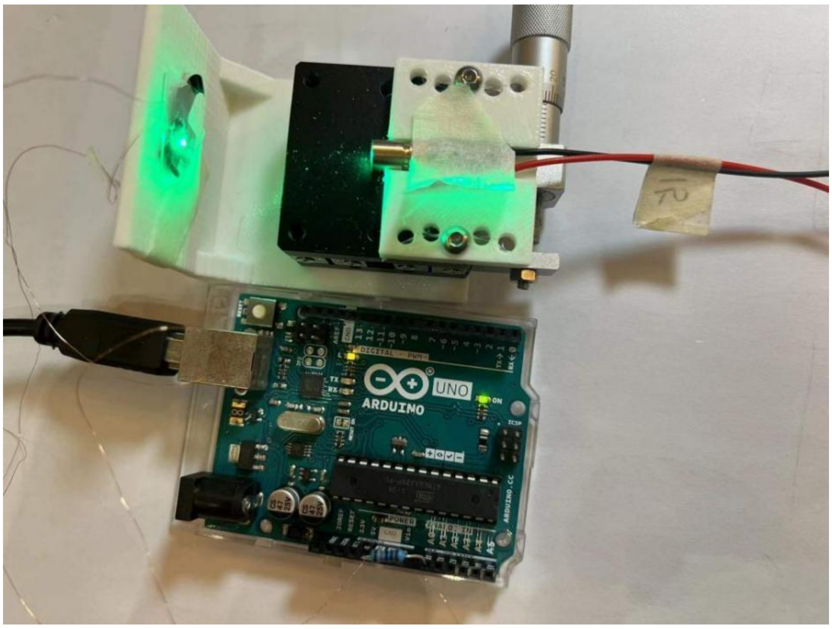


Figure 12. Using Arduino as signal monitoring

Sample 13 (Ag/SiO2/Si P-type silicon structure corroded for 10 minutes) was used in this experiment. The optimal line was drawn from the linear data in 5.5.2, and the expression for resistance is:

$$R(x) = -8.273684x + 149.03 \ \ (0 \leq x \leq 1.9) \tag{4}$$

Where x represents displacement in mm, and R (x) represents resistance in K Ω.

Expression for displacement:

$$x = \frac{(R-149.03)}{-8.273684} \ \ (133.31 \leq R \leq 149.03) \tag{5}$$

The code of resistorx() running in Arduino is as follows (calculate the current resistance value of the semiconductor variable resistor based on the measured voltage value):

```
double resistorx(double R1, int V1){
double Rx=0;
if(V1!=0){
Rx = (1023-V1)*R1/V1;
}
return Rx;
}
```

The function resistor2position() calculates the displacement based on the resistance value.

```
double resistor2position(double y){
double x=0;
double a =-8.273684;
double b = 149.03;
x = (y-b)/a;
return x;
}
```

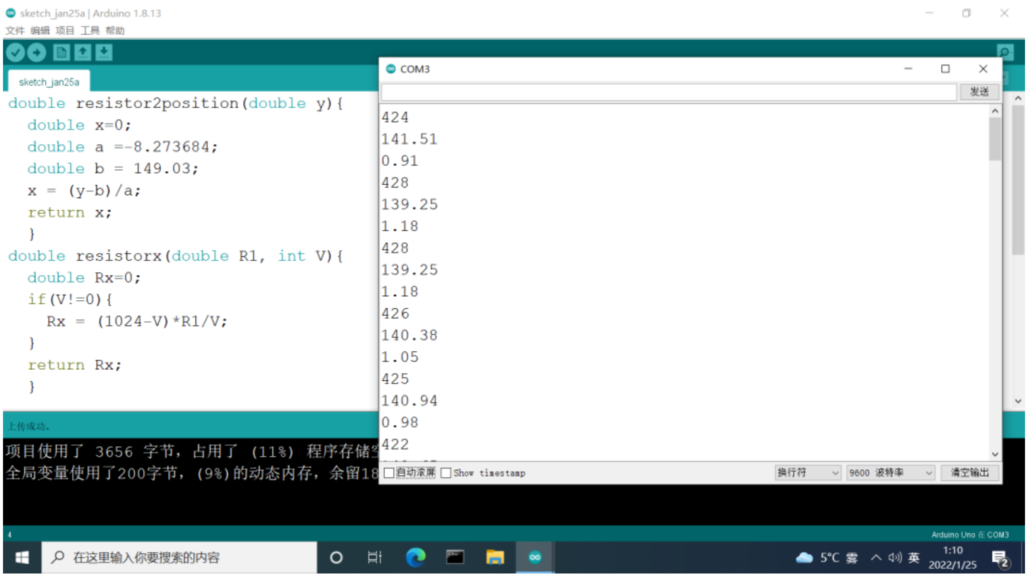
The total voltage I have chosen in this circuit is 5V, and in Arduino, 1023 represents 5V voltage. The input parameters R1 and V also correspond to the formula.

In the loop loop of Arduino, use analogRead() to read the input measurement voltage, and then call the first two functions to calculate the displacement change. The displacement data provided is in millimeters.

```
void setup() {
  //Open the serial port connection between the Arduino board and the computer, and initialize the baud rate with a default of 9600
  Serial.begin(9600);
}

void loop() {
  // put your main code here, to run repeatedly:
  int sValue = analogRead(A0);
  Serial.println(sValue);
  Serial.println(resistorx(100,sValue));
  Serial.println(resistor2position(resistorx(100,sValue)));
  delay(1000);
}
```

There are three rows of test data for each group. The first row shows the voltage measured by the voltmeter, which is not measured in volts, but the corresponding value obtained by Arduino after dividing the 5V voltage into 1023 parts. The second line represents the calculated resistance value of Rx, while the third line represents the corresponding displacement.



from the serial output of Arduino, the following data can be obtained:

The analog value corresponding to the voltage	**Rx (K Ω) Calculated resistance value**	**Corresponding displacement (mm)**
424	141.51	0.91
428	139.25	1.18
428	139.25	1.18
426	140.38	1.05
425	140.94	0.98

Furthermore, I can omit the slide and change the laser point through the deformation of the structural shell, thus achieving the desired monitoring displacement (deformation). At the same time, the Arduino Mini Pro can be used, making the entire device very compact, with a length, width, and height of only 68mm * 28mm * 33mm.

The final monitoring device is shown in Figure 13:

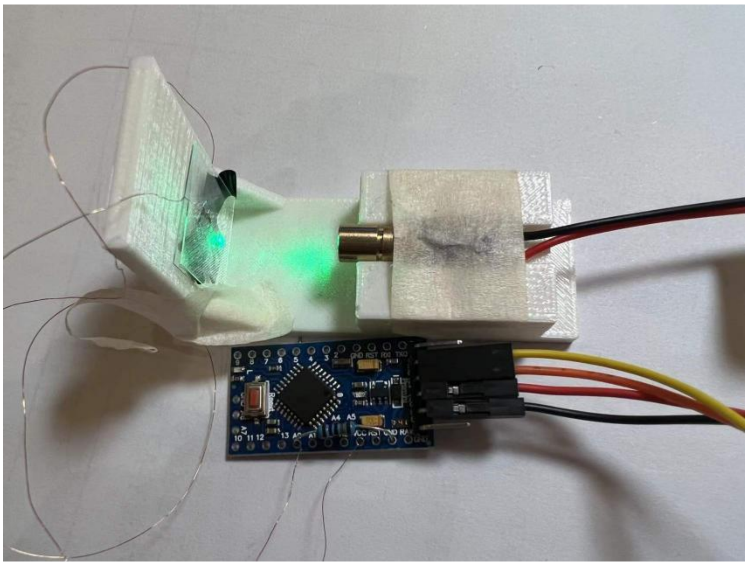


Figure 13. Miniaturized displacement monitoring sensor

6. Reflection on relevant issues and further research

6.1 Some details are not handled perfectly

The linearity of some samples is not good enough, which may be related to my improper handling of some details during the experimental process. There are mainly the following aspects:

(1) Because I chose to clip the copper wire through a toothpick between two small indium dots, which cannot avoid some errors. For example, during the process of pasting indium dots, sometimes the indium dots may be made too large. In this way, because the distance between the two electrodes itself is about 1mm, sometimes the two indium dots can cause too few areas in the middle of the electrodes. That is to say, although I hope to control the electrode distance to about 1mm, in reality, the gap area in the middle can sometimes be very small, which to some extent creates the formation of nonlinear regions.

(2) The laser I used in this experiment did not use a lens combination for focusing, and when the distance between the two electrodes is too small, it often causes the irradiation point to cover two indium points, which leads to a certain degree of decrease in measurement accuracy, resulting in a decrease in linearity.

(3) During the process of placing samples for measurement, sometimes the two electrodes and the plane where the laser moves are not in the same horizontal plane, which means that the samples are sometimes placed diagonally, which to some extent leads to the formation of nonlinear regions.

I will improve these issues in future experiments.

6.2 More experiments are needed

At present, for the production of silicon slice samples, it is impossible to determine the specified range and sensitivity with certainty, and each time it needs to be measured through experiments. In the future, I plan to conduct detailed experimental operations to make the range of resistance changes exhibited by the bipolar resistance effect of the semiconductor structure controllable. These detailed experiments will include:

(1) Test the influence of different film thicknesses on the resistance effect;

(2) Change the pore size of porous silicon to adjust the substrate resistance and test its corresponding resistance effect;

(3) Test the effect of different temperatures on resistance;

(4) Test the effect of different laser powers on resistance effect;

(5) Increase the lens and further adjust the size of the irradiated laser spot to be as small as possible to further improve linearity.

It can be expected that after the above experimental data is obtained, a series of silicon slices with good linearity and high sensitivity can be optimized, and the related linearity and sensitivity can be controlled, providing a basis for future large-scale production.

6.3 Analysis of newly discovered phenomena

When testing bare silicon and sample 4, it was found that the resistance in the middle region of the two electrodes remained basically unchanged, while there was a certain linear pattern when the light spot moved outward from the two electrodes. This is a question worth analyzing and will also be the topic of my next research.。

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