

# Testing and Analysing of $256 \times 256$ MOS Resistor Array for IR Scene Projector

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**Abstract**—The CMOS composite film microbridge-structured resistor array is mainly used for chip design and machining; to our knowledge, there is no detailed report on the analysis of its thermo-electric characteristics and the testing of its performance. Therefore, the paper presented the structure of the chip of the resistor array developed by using semiconductor polycrystalline silicon as its main materials, the microelectronic machining (MEMS) and the anisotropic etching. It also discussed the thermal resistance, thermal conduction, transient response characteristics and emissivity of the composite film microbridge that affect the major performance of a resistor array. Finally it tested its major performances; the test results are in agreement with the thermo-electric characteristics analysis results and show that: (1) the effectiveness of pixels of the  $256 \times 256$  resistor array reaches over 99.9% and its medium-wave infrared (MWIR) apparent temperature is from 27 to  $310^\circ\text{C}$ ; (2) with respect to the response characteristics of the resistor array, the time for radiation increase is 4 ms and its time for radiation decrease is 1.6 ms; (3) its high frame rate reaches 200 Hz and its spectral radiation waveband is 2 to  $14\text{ }\mu\text{m}$ . The test results verify the correctness and effectiveness of the thermoelectric model and show that the composite film microbridge is suitable for highly dynamic electric to thermal conversion and provides an analysis method and test data for studying the thermoelectric characteristics of a microbridge-structured resistor array, thus having some engineering application values.

**Keywords**— CMOS resistor array; equivalent blackbody temperature; thermoelectric characteristic; micro-radiator; infrared scene simulation

## I. INTRODUCTION

Currently, the dynamic infrared scene projector that takes the CMOS resistor array as its core device is extensively applied to the hardware-in-the-loop simulation of infrared imaging guidance weapons. The CMOS resistor array is made primarily of polycrystalline silicon by using the bulk silicon anisotropic etching technique so as to design and machine the chip of a film microbridge and transform a digital image signal into infrared radiant energy.

The CMOS resistor array has a history of nearly 25 years and is an internationally recognized high technology in the area of infrared scene simulation. The Indigo Inc. affiliated to the St. Barbara Infrared (SBIR) Inc., the U.S. is the major

manufacturer of the internationally state-of-the-art suspension film resistor arrays used as accessories for the U.S. military equipment. The MIRAGE-series suspension film resistor array developed by the incorporation uses the single chip integration to directly build the suspension film resistor array on the silicon substrate of the machined control circuit. The film is made of low-stress silicon nitride, and the resistor made of titanium nitride. Its chip has a 1024-byte resolution; the size of its pixel is  $48\text{ }\mu\text{m}$ ; its medium-wave apparent temperature simulation scope is  $150\text{K} \sim 750\text{K}$ ; its temperature resolution is  $0.02\text{K}$ , and its frame rate is  $200\text{Hz} \sim 400\text{Hz}$ . After non-uniformity correction, the radiant non-uniformity of the resistor array is less than 1%. The incorporation has also developed the deep-hypothermal resistor array whose working temperature can reach  $50\text{K}$  and switch between  $50\text{K}$  and  $300\text{K}$ .

To further develop the CMOS resistor array, there is an urgent need for exploring the characterization of its performance parameters and the thermo-electrical characteristics of its core materials. Focusing on the development and test of the CMOS resistor array, this paper presents the design technique and structural features of its infinitesimal elements. Through the performance analysis and indicator test of the micro-radiator, the paper explains plenty of problems existing in the resistor array and their solutions and then carries out the testing of its infrared optical characteristics, thus obtaining the basic parameters and indicators for evaluating and applying the resistor array and thereby providing testing and analysis methods for its simulation and experimentation.

## II. THE STRUCTURE OF CMOS RESISTOR ARRAY'S CHIP

### A. The physical structure of a pixel

Each pixel of a  $256 \times 256$  resistor array is made up of a micro-radiator and a set of pixel control circuits, both of which are laid horizontally inside the pixel region and jointly distribute a pixel area; the design size of the pixel is  $65\mu\text{m} \times 65\mu\text{m}$ . Its structure is presented in Figure 1.

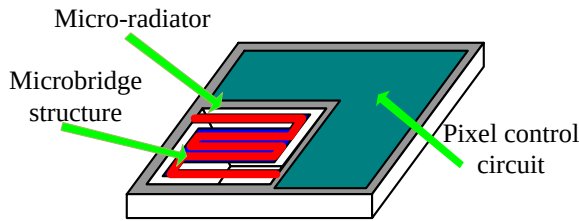


**Figure 1.** The resistor array's pixel plane structure bridge frame

The micro-radiator and the pixel control circuit are machined into shape with one pass. After the chip is made in a factory, it can release and suspend the micro-radiator directly through using the bulk silicon MEMS technique. The chip-making technique is simple, and the past experience shows that the yield of the micro-radiator can reach as high as above 99.8%. Under the precondition that the pixel area is certain, the sacrifice of the duty ratio of the micro-radiator to a certain degree can increase its response speed and ensure that its frame rate is more than 200Hz.

### B. The structure of a micro-radiator

A 256×256 resistor array's micro-radiator is designed to have multi-layer composite film and in-built with a polycrystalline silicon heater. After the composite film is formed, the silicon substrate below it is hollowed by using the bulk silicon MEMS technique; thus, the composite film becomes a suspended bridge structure. The micro-radiator is designed to have a double-leg support as shown by Figure 2. The design size of the bridge frame is  $30\mu\text{m} \times 30\mu\text{m}$ ; the design width of the bridge leg is  $4\mu\text{m}$ , and its design length is  $30\mu\text{m}$ ; the bridge floor is rectangular and its design size is  $14\mu\text{m} \times 26\mu\text{m}$ . The design resistor of the polycrystalline silicon heater is about  $2K\Omega$  and reaches about  $5K\Omega$  at a high temperature. The duty ratio of the whole micro-radiator (including its bridge leg) inside a pixel is 14.3%.

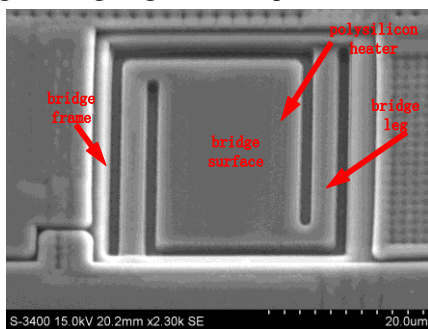


**Figure 2.** The model of a 256 × 256 resistor array's micro-radiator

The finite element model analysis and the black body radiation integral calculation results show that when the heating power is 1.5 mW, the average actual temperature of the micro-radiator can reach about 670°C. Then, the average equivalent blackbody temperature of the resistor array can reach 301°C; its radiant energy rise time is around 2.7 ms; its radiant energy fall time is about 0.6 ms; both are less than 5

ms, fully meeting the requirement that the frame rate should be 200Hz.

Figure 3 gives the photo of a manufactured 6-inch 256×256 resistor array and the partially amplified photo of a released resistor array. Because its size is large, a single chip reaches 20×20 mm and only 28 chips can be placed on one wafer.

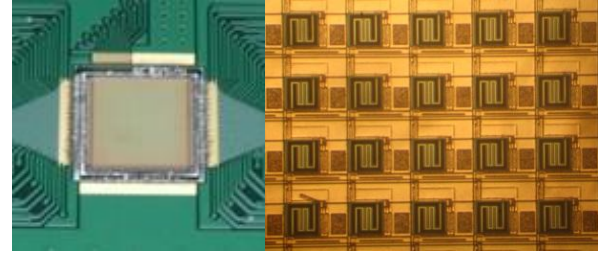


**Figure 3.** The photo of 256×256 resistor array's chip and the partially amplified photo after its release

## III. ANALYSING THE THERMOELECTRIC CHARACTERISTICS OF A RESISTOR ARRAY'S MICRO-RADIATOR

The micro-radiator is the core for a resistor array to convert its electrical energy into thermal radiant energy. For the resistor array to simulate a dynamic and high-temperature infrared target, the micro-radiator should meet the following requirements: ① it must be able to withstand the transient high-and-low-temperature impact; ② it must have comparatively high conversion efficiency; ③ it must have sufficiently quick thermal response. According to the above requirements, the paper analyses the basic thermoelectric characteristics of the polycrystalline silicon inlaid inside the micro-radiator.

### A. The temperature characteristic of a polycrystalline silicon resistor

The temperature characteristics of the polycrystalline silicon resistor are rather complicated owing to the existence of carrier trap, dross regulation and crystal regeneration; therefore, it is extremely difficult to establish the physical model of its temperature characteristics. The paper uses the micro-radiator's experimental structure to directly test the resistance temperature characteristics of polycrystalline silicon from the room temperature to the high-temperature region of 1000K, thus obtaining the characteristic data of the variation of resistance with temperature within an operating temperature range. The formula for describing the fitted curve is given in (1) and that for describing the temperature coefficient of resistance (TCR) and the temperature is given in (2) :

$$R = 1.03196 + 0.00112T + 8.212 \times 10^{-7} T^2 \quad (1)$$

$$TCR = 0.00108 + 7.76252 \times 10^{-7} T \quad (2)$$

Where  $T$  denotes temperature, and the formulae show that the polycrystalline silicon has positive TCR, which itself increases with increasing temperature.

### B. The temperature characteristics of heat transfer coefficients

There exists a temperature gradient inside a solid body; the passage of energy-flux density  $Q$  through the solid body can be described as:

$$Q = -k \frac{dT}{dx} \quad (3)$$

In the equation,  $k$  is the heat transfer coefficient of the solid body. The heat of a solid body transfers mainly through lattice vibration and free electrons. The heat transfer coefficient can be expressed as:

$$k = \frac{1}{3} C_e v_e l_e + \frac{1}{3} C_p v_p l_p \quad (4)$$

Where  $C_e$  and  $C_p$  are the contributions of an electron and a phonon respectively to the volumetric heat capacity; and  $v_e$  and  $v_p$  are the motion velocities of an electron and a phonon respectively; and  $l_e$  and  $l_p$  are the mean free paths of an electron and a phonon respectively. The temperature characteristics of the heat transfer coefficient of polycrystalline silicon are shown in Figure 4, which shows that its heat transfer coefficient decreases with increasing temperature. Consequently, the heat transfer performance is desirable at the low-temperature section, but it decreases at the high-temperature section.

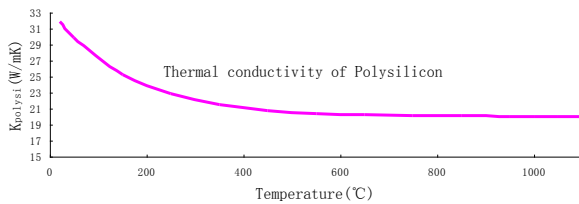


Figure 4. The curve that indicates the heat transfer coefficient of polycrystalline silicon varies with temperature

### C. Transient thermal response analysis

The transient thermal response analysis is for the sake of predicting the response speed of the resistor array and the approximate impact of pressure on the response speed. The 1.5V voltage is loaded into the model in the mode of step signal, obtaining the transient temperature field distribution of the microbridge under the step voltage. The checking of the temperature response at a certain point of the microbridge's central zone can determine the response speed of the resistor array. The pressure in the cases of 105Pa and 0.1Pa respectively was calculated; the calculation results, given in Figure 5, show that in the case of low pressure, the time for temperature rise (10% to 90%) is 1.3 ms and that in the case of normal pressure, the time is reduced to 0.9 ms. It is predicted that when the gas pressure is between 105 Pa and 0.1 Pa, the response time should be between 0.9 ms and 1.3 ms. The calculation results show that the response speed of the resistor array is very fast; this is mainly because the heat transfer coefficients of thermo-electric pile polycrystalline silicon strip and aluminum strip are rather big. Even if the gas pressure is quite low, the hot end of the thermo-electric pile is still able to effectively transfer heat to its lining foundation, thereby rapidly establishing thermal balance.

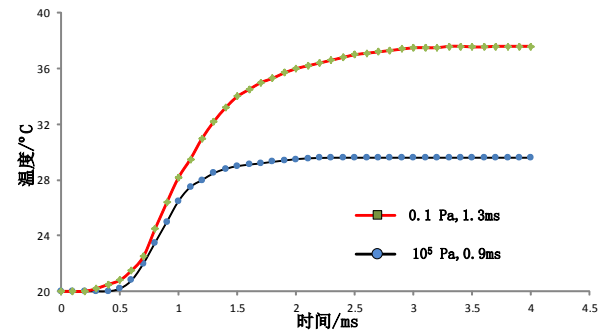


Figure 5. The transient response curve of a microbridge

### D. The micro-radiator's surface emissivity analysis

To evaluate the spectral radiance characteristics of the micro-radiator processed with CMOS technology, it is necessary to analyse a stereotyped micro-radiator's surface emissivity.

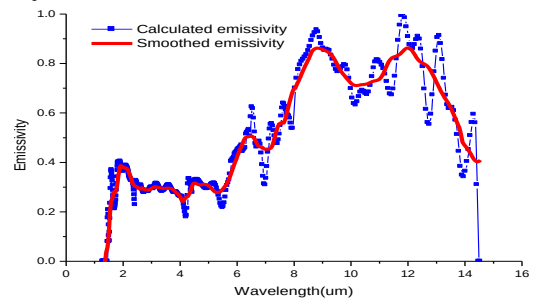


Figure 6. The distribution of micro-radiator surface radiation that varies with wavelengths as estimated with the peak wavelength comparison method

Figure 6 gives the distribution variation of the surface emissivity with wavelength, which is calculated through comparing black body data with micro-radiator data. The smoothed trend line shows that the average emissivity of the micro-radiator is about 0.3 at the waveband from 3 to 5  $\mu\text{m}$  and about 0.75 at the waveband from 8 to 12  $\mu\text{m}$ . Because the peak wavelength of the micro-radiator under test is located at around 3.3  $\mu\text{m}$ , the average emissivity from 3 to 5  $\mu\text{m}$  should be rather accurate, while that from 8 to 12  $\mu\text{m}$  may have rather big errors.

## IV. TESTS

The micro-radiator's thermo-electric characteristic analysis results are used to test and discuss the CMOS resistor array's apparent characteristics. The test items include the equivalent blackbody temperature test, the micro-radiator's response characteristics test and the radiation spectrum characteristic test because they reflect temperature characteristics.

### A. The maximal equivalent blackbody temperature

The 256-pixel MOS resistor array uses the microbridge resistance as its micro-radiator; the microbridge resistance has thermal insulation from the ambient environment, forming a film microbridge's cavity structure, whose duty ratio is 14.3%. Although the brightness of the micro-bridge fibril is quite high and its temperature can reach even about 1000K, the

equivalent surface radiation temperature is rather low because of the low duty ratio. The maximal equivalent blackbody temperature reflects the physical temperature of the micro-radiator, its duty ratio and emissivity.

The maximal equivalent blackbody temperature is tested with the SC7000 medium-wave thermal imager at the test waveband of 3 to 5  $\mu\text{m}$ . The pixel ratio between the resistor array and the thermal imager should be larger than 4:1 so as to ensure that the latter under-sample the former, thereby truly revealing the average radiation effect of the former's pixels. In the test, the miniature square image is illuminated with the maximal control voltage and the thermal imager is used to test the pixels inside the square and the time average equivalent blackbody temperature. Table 1 gives the test results of the maximal medium-wave infrared apparent temperature of the 256 $\times$ 256 resistor array under effective control voltage and limit control voltage. The test results are in agreement with the thermo-electric characteristic analysis model and show that the resistor array of the microbridge has satisfactory temperature characteristics and can simulate highly dynamic temperature characteristics. Table 1 gives the maximal MWIR apparent temperature of the 256 $\times$ 256 resistor array.

**TABLE 1.** THE MAXIMAL MWIR APPARENT TEMPERATURE OF THE 256 $\times$ 256 RESISTIVE ARRAY

| control voltage                          | effective control voltage 10/v | limit control voltage  |
|------------------------------------------|--------------------------------|------------------------|
| Maximal equivalent blackbody temperature | 27 $^{\circ}\text{C}$          | 310 $^{\circ}\text{C}$ |

### B. Time for radiation increase/decrease

The maximal frame rate of the resistor array is primarily concerned with the work mode of its image-refreshing circuit and the thermal response time of the micro-radiator. The optimization of the structure and control mode of the image-refreshing circuit can remarkably reduce or even basically eradicate the impact of refresh time on the frame rate which, at this time, is determined mainly by the thermal response time of the micro-radiator, namely the time for radiation increase and decrease. The maximal frame rate of the resistor array, the impact on which had been eradicated, equals to the reciprocal of the peak value among the time for radiation increase and the time for radiation decrease, not the reciprocal of the sum among them as it is usually understood. This is because pixels always change directly from the initial state of the previous frame to the new state of the next frame, there being no cooling reset in between.

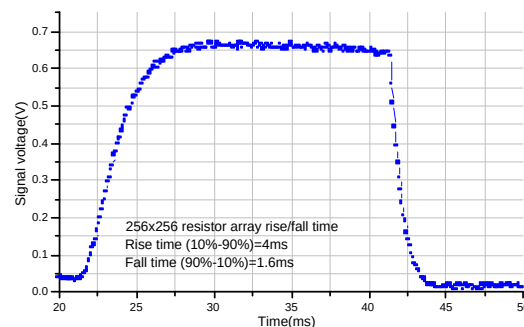


**Figure 7.** Time response characteristics of the 256 $\times$ 256 resistive array.

Figure 7 gives the time response characteristics of the pixel radiation recorded by an MWIR seeker when the middle row of pixels of the 256 $\times$ 256 resistor array is working in the mode of flickering in light and dark, showing that the time for radiation increase of the resistor arrays of both types is apparently longer than their time for radiation decrease, their time for radiation increase being less than 5 ms. This indicates that the maximal frame rate of both types of the resistor array can reach over 200Hz; this is in agreement with the transient thermal response analysis results, showing that the resistor array of microbridge structure has transient response characteristics.

### C. Testing spectral radiation characteristics

The resistor array's spectral distribution is tested with the multiband spectroradiometer, with the resistor array remaining in the bright state. Voltage control is used to measure the radiation spectra of the resistor array whose control characteristics are  $V_s=2.8, 3.3$  and  $3.8\text{V}$  respectively, as shown in Figure 8.

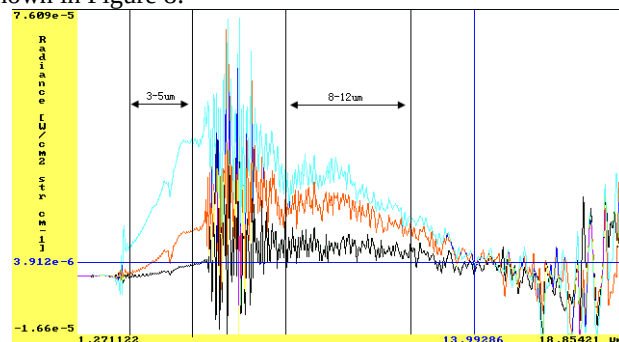


**Figure 8.** The spectral radiation curve of the resistor array

The equivalent blackbody temperature corresponding to the control voltage of 3.3V is 400.2K. Taking into consideration the radiation temperature, the response of seeker, the geometric shape of bridge floor and the transmittance of window, the calculation result on emissivity is 0.384 and 0.071. The test results show that the spectral curve thus tested is in agreement with the surface emissivity curve of the micro-radiator.

## V. CONCLUSIONS

The paper presents the structure and thermo-electric characteristics of the chip of a home-made and second-

generation  $256 \times 256$  resistor array of high frame rate and tests its apparent thermo-electric characteristics. The test results: the effectiveness of a pixel reaches above 99.9%; the MWIR apparent temperature is from 27 to 310 °C; the maximal frame rate is 200 Hz; the time for radiation increase is 4 ms; the time for radiation decrease is 1.6 ms; the average emissivity of medium-wave spectral radiation is up to 0.3. The comparison of the microbridge's thermo-electric characteristic analysis results with its test results verifies the correctness, rationality and effectiveness of the thermoelectric characteristic model. The test results show that the composite film microbridge is suitable for highly dynamic electric to thermal conversion, that its response characteristics and spectral characteristic both reach high levels and that it can meet the requirements for infrared scene simulation.

As the core chip of an infrared scene projector, the resistor array plays a pivotal role in the test, performance evaluation and dynamic simulation of an infrared imaging guidance system and a forward-looking infrared system. This study has certain engineering application values and provides an analysis method and test data for subsequent research and development.

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