A novel opto-mechanical uncooled infrared detector

Binbin Jiao a, Chaobo Li a, Dapeng Chen a,*, Tianchun Ye a, Shali Shi a, Yi Ou a, Lijun Dong a, Qingchuan Zhang b, Zheying Guo b, Fengliang Dong b, Zhengyu Miao b

a Micro-processing and Nano-technology Department, Institute of Microelectronics, Chinese Academy of Sciences, Beijing 100029, China
b Key Laboratory of Mechanical Behavior and Design of Materials, University of Science and Technology of China, Hefei 230027, China

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Abstract

This paper presents a novel opto-mechanical uncooled infrared detector that has successfully been fabricated. The detector is composed of a bi-material micro-cantilever array released from the Si substrate, whose reflector retains its shape even with changes in temperature. In comparison with the generally used sacrificial layer cantilever, the loss of incident IR energy caused by the reflection from and absorption by the silicon substrate is eliminated in this substrate-free structure. Moreover, the freestanding structure of the detector makes it easy to fabricate. The revised reflector in this structure has no distortion during its activity that keeps the sensitivity of the detector from being passivated. We present an infrared (IR) image of a person’s hand to demonstrate the ability of the structure to create images. The performance test showed that the noise-equivalent temperature difference of the imaging system can reach about 175 mK.

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1. Introduction

In recent years, significant attention has been paid to uncooled infrared (IR) detectors for their wide applications in both military and civil fields, such as remote sensing, night vision and navigation [1–3].

Nowadays, due to the progress of micro-electromechanical system (MEMS) fabrication technology, a method which uses an optical readout system to measure the cantilever of the detector inclination angles caused by an absorbing infrared radiation is becoming more common [4–7]. This kind of detector is built up with arrays of bi-material micro-cantilever without any extra high responsivity readout circuits so the detector is low cost and easily fabricated.

Previous works have shown several types of optical-readable detectors. Mao et al. [4], and Zhao et al. [5] reported detectors with Si substrates, using different optical readout parts, in 1999 and 2002 respectively. Ishizuya et al. [6,7] created a cancelling structure sensor with a pixel array of 160 × 120 in 2003. These detectors employed sacrificial layer structures with about 2–3 μm between the substrate and the micro-cantilever to form the functional components. This is the main cause of prohibiting more than 40% of the incident IR energy from reaching the detecting arrays. Furthermore the small distance between the active components and the Si substrate often gets to conglutination in the releasing process which is the prime cause of sensor invalidation.

To eliminate the IR loss due to the reflection and absorption by the substrate, a novel substrate-free detector has been developed. This structure has no silicon substrate under the active parts which makes it a good candidate for...
a higher efficiency incident IR flux absorber with less heat losses than the sacrificial layer structure. The revised reflector in the detector has almost no distortion when activated that can keep the sensitivity of detector from being passivated. With the optical readout system [8], thermal images of the human body have been obtained successfully at room temperature. The noise-equivalent temperature difference (NETD) of the imaging system is estimated to be about 175 mK.

2. Design

2.1. Working principle

The complete IR imaging system is shown in Fig. 1. The system is composed of a series of lenses and a focal plane array (FPA), in which the FPA is the core of the system, and is sealed in a vacuum chamber to prevent dissipation of heat. Visible light that comes from the LED through the pinhole becomes parallel via a collimating lens. Subsequently the parallel light is reflected by the pixels of the FPA and then passes through a transforming lens. These reflected diffracting rays synthesize the spectra of the cantilever array on the rear focal plane of the transforming lens. When the incident IR flux is absorbed by a pixel, the pixel’s temperature rises, and then causes a small deflection of the bi-material cantilevers because of the mismatch of thermal expansion coefficients (TEC) between the two materials. Consequently the changes in the reflected visible light intensity distribution are collected and analyzed by a CCD through the knife-edge filter placed in the focal plane of transforming lens. Thus, the optical information is converted to a grey level change in the CCD and imaged.

2.2. Structure design

The goal of a FPA design is to enhance the pixel’s mechanical response to maximize the grey level change of the CCD for a given IR flux while restraining the pixel to a predetermined size. To optimize the performance of the FPA, several parameters, such as cantilever materials, absorption design and thermo-mechanical properties, must be considered.

2.2.1. Selection of materials

The selection of materials for bi-material cantilever should meet the following basic criteria: (1) one of the materials must efficiently absorb IR in the range of 8–14 μm, and the other a good reflector in the visible spectrum for optical readout; (2) the two materials must have a large mismatch in TEC; (3) at least one material’s thermal conductivity must be low; (4) the films of the materials must have low residual stress. Additionally, the materials must be compatible with micro-fabrication processes and should possess good chemical inertness. The two materials used in this paper for bi-material cantilever are low-pressure chemical vapor deposited (LPCVD) low-stress SiNx and Au. Table 1 lists the physical properties of some of the optional materials used for bi-material cantilever arrays. The comparison shows that low-stress SiNx and Au have the desirable large mismatch in TEC. Fig. 2 shows the real (η) and imaginary (κ) parts of the refractive index of SiNₓ indicating the absorption peak is in the 8–14 μm spectral range which is suitable for the requirement of detection. In addition, low-stress SiNₓ also has low thermal conductivity, which is significant for thermal isolation.

2.2.2. IR absorption design

Generally, a sacrificial layer structure is adopted in which each active component is separately fixed on the substrate through anchors. Thus, the incident IR flux must first get through the Si substrate and then be absorbed by the cantilever. The light propagating through medium can be expressed as

\[ E = x_0 \cdot E_0 \cdot e^{i\omega t} \left( \frac{N - i\kappa}{N + i\kappa} \right) \]

where \( N = \eta - i\kappa \), \( \eta \) is the refractive index, \( \kappa \) is the extinction coefficient, \( \omega \) is the wave’s frequency, and \( C \) is the speed of light in a vacuum. The reflection coefficient \( R \) for the boundary between silicon and air is given by

\[ R = \frac{(\eta_1 - \eta_2)^2 + \kappa_2^2}{(\eta_1 + \eta_2)^2 + \kappa_2^2} \]

where \( \eta_1, \eta_2, \kappa_1, \kappa_2 \) are the refractive index and extinction coefficient for Si and vacuum. For silicon, \( \kappa \) is several orders of magnitude smaller than \( \eta \) and can be ignored for the calculation of refractive coefficient.
Fig. 3 shows the transmission and reflection of the wave occurring simultaneously after the infrared radiation strikes the surface of the silicon substrate. The transmitted IR produced transmission and reflection at both of the interfaces. For wavelengths in the range 8–14 μm, $g_1$ and $g_2$ are about 3.418 and 1, therefore the reflected IR energy is about 46% which shows that only 54% of the incident IR can reach the cantilever due to the existence of the Si substrate. Moreover, the absorption of the Si substrate was not taken into account because $k_1$ is very small.

To reduce the IR energy loss, we developed a novel substrate-free cantilever which is fixed on the surface rather than on the silicon substrate. The silicon which is directly under the cantilever has been eliminated during the fabrication process. Fig. 4 shows a schematic diagram of the substrate-free structure. Because of no IR reflection, the substrate-free cantilever has a higher effective incident IR flux than the sacrificial layer cantilever with the same IR absorbing material. For the interface between SiNx ($\eta = 1$, $\kappa = 1$) and vacuum ($\eta = 1$, $\kappa = 0$), we can obtain $R = 0.2$. This means 80% of the IR radiation spreads in the SiNx. The attenuation function of the IR energy in SiNx is

$$|E^2| = S \cdot E_0^2 = E_0^2 \cdot e^{-\frac{2\pi}{\lambda}Z}$$

where $E_0$ is the initialization incidence energy, $S = e^{-\frac{2\pi}{\lambda}Z}$ is the decay factor, and $Z$ is the incidence length. The incidence length $Z$ is about 1 μm.

In this paper a 1.2 μm thick SiNx cantilever is employed, so that it can completely absorb the IR energy that has been incident on the film. It means that the substrate-free cantilevers can absorb 80% of the incident IR energy. On the other hand the sacrificial layer cantilevers in the previous works [3,4,6,7] could only absorb 54% of the entire IR energy. By comparing the two types of cantilevers discussed above we can conclude that the substrate-free one is more effective.

### 2.2.3. Thermo-mechanical design

The bi-material cantilever legs tend to bend due to change in the temperature of the structure which is caused by the mismatch in the TEC of the two different materials. To maximize the angle of deflection $\theta$ of the reflector, the fold method and an interval gild have been introduced into the pixel design. Fig. 5 shows the thermal deflection principle; where I(a) and 2(a) are non-metal-coated leg serving as the thermal isolation portions while I(b) and 2(b) are metal-coated legs serving as the thermal deflecting legs. When the incident IR radiation is absorbed by the pixel, the thermal deflecting legs produced bending effect. If there is only one leg in the pixel, the bending angle is $\theta_1$ and if there are twofold legs, the bending angle becomes

![Table 1](image)

<table>
<thead>
<tr>
<th></th>
<th>Density $\rho \times 10^{-3}$ kg/m³</th>
<th>Young’s modulus $E$ (GPa)</th>
<th>Thermal conductivity $K$ (W/(m K))</th>
<th>Expansion coefficient $\alpha \times 10^{-6}$ K⁻¹</th>
<th>Heat capacity $C_0$ (J/(kg K))</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiNx</td>
<td>2.40</td>
<td>180</td>
<td>5.5 ± 0.5</td>
<td>0.8</td>
<td>691</td>
</tr>
<tr>
<td>Au</td>
<td>19.3</td>
<td>73</td>
<td>296</td>
<td>14.2</td>
<td>129</td>
</tr>
<tr>
<td>Al</td>
<td>2.7</td>
<td>80</td>
<td>238</td>
<td>23.6</td>
<td>908</td>
</tr>
</tbody>
</table>

Fig. 2. Real ($\eta$) and imaginary ($\kappa$) parts of the refractive index of a LPCVD SiNₓ.

Fig. 3. The structure with Si substrate IR reflection and transmission sketch map.

Fig. 4. Proposed structure’s IR reflection and transmission sketch map.

Fig. 3. The structure with Si substrate IR reflection and transmission sketch map.
For fold method, the bending angle would be \( \theta_1 + \theta_2 + \theta_3 + \cdots \). In our design, threefold legs are selected for fabrication reasons. We can demonstrate that with the change in the temperature, the reflector will tend to bend and the deformation can be expressed as

\[
\theta(x) = 6(x_1 - x_2) \cdot \left( \frac{d_1 + d_2}{d_1^2 k} \right) \Delta T \cdot x
\]

where \( (x_1 - x_2) \) is the thermal expansion coefficient difference of Au and SiNx, the \( K \) structure parameter is given as \( K = 4 + 6n + 4n^2 + \frac{\phi n^3}{1/\phi n} \), \( n \) is the thickness ratio of Au and SiNx films \( (n = d_1/d_2) \), and \( \phi \) is the Young’s modulus ratio of Au and SiNx \( (\phi = E_1/E_2) \).

Deformation of the reflector is not desirable because it spreads the spectrum of the reflector and is a cause of passivation of the sensitivity of the readout system [9]. So, if we make the Au film on reflector and deformation cantilever in the same step and have the same thickness, there will be a conflict. The deformation cantilever needs a maximum deformation at a certain temperature changes but the reflector needs a minimum. Therefore to minimize this conflict, we made the thickness of Au film on the reflector different from the Au film on the deforming cantilever. In our design 250 Å Au film is chosen for readout light reflector. This selection of this thickness made a reduction in the deformation to an acceptable range which in turn kept the reflected spectrum narrow enough for high sensitivity.

### 2.2.4. Structure

After consideration of all the above points we have designed a structure as shown in the following figures.

Table 2

<table>
<thead>
<tr>
<th>Pixel area ((\mu m^2))</th>
<th>Infrared absorption (reflection) pad area, (A_{pad}) ((\mu m^2))</th>
<th>Cantilever length, (L_{leg}) ((\mu m))</th>
<th>Cantilever width, (d) ((\mu m))</th>
<th>SiNx thickness, (h_2) ((\mu m))</th>
<th>Au thickness, (h_1) ((\mu m))</th>
</tr>
</thead>
<tbody>
<tr>
<td>120 \times 120</td>
<td>110 \times 63</td>
<td>2619</td>
<td>2</td>
<td>1.2</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Fig. 6 shows the top view of the pixel. The pixel is \(120 \times 120 \mu m^2\). A bi-material shell in the middle is serving as a reflecting mirror and IR absorber. A SiNx beam and Au coated SiNx cantilevers are alternatively located at both sides of the shell making up the deforming cantilever and the isolation cantilever. Fig. 7 shows the cross-sectional view of the structure. SiNx is used as an IR absorbing material, while a very thin Au film is used as the reflector of the detecting light. The Au film on the deforming cantilever is thick which maximizes its deformation. Table 2 shows the design parameters for the microstructure of the FPA.

### 3. Micro-fabrication

The device is a stencil cantilever structure that does not use a sacrificial layer releasing process. The freestanding stencil bi-material cantilever is fabricated using both surface micro-machining and silicon bulk wet etching. The process for creating a bi-material freestanding stencil cantilever is presented in the following section.

The micro-fabrication process is shown schematically in Fig. 8. The main steps of micro-fabrication process are as follows: (1) low-pressure chemical vapor deposited (LPCVD) low-stress SiNx onto the Si wafer [10]; (2) defining the window for the bulk silicon wet etching on the backside; (3) photolithography of the cantilever on the front side and dry etching of SiNx to form three-dimensional cantilevers; (4) evaporation of Au on the reflector;
(5) evaporation of Au on the deformation cantilever; and (6) KOH wet etching mainly from the wafer backside to fabricate the freestanding stencil bi-material cantilever structure.

Based on this series of processes given above, a large array with $160 \times 160$ pixels was obtained successfully. Fig. 9 shows a scanning electron microscope (SEM) photo of a part of the FPA.

Comparing with the structure of a sacrificial layer releasing process, the proposed structure as well as the process of fabricating the detector is much easier and more reliable.

### 4. Imaging experiment results and discussion

In the experiment an f/0.7 IR lens and a 12-bit CCD camera were used and the FPA containing $160 \times 160$ pixels was sealed in a vacuum chamber ($\sim 0.015$ Pa). The thermal image of a person’s hand at home temperature was obtained which is shown in Fig. 10.

To define the performance of the infrared imaging system, the noise-equivalent temperature difference (NETD) is introduced. NETD is the equivalent temperature change in an IR source that can be detected with a signal-to-noise ratio of unity. It is expressed as

$$\text{NETD} = \frac{I_{\text{noise}}}{\Delta I/\Delta T_s}.$$  \hspace{1cm} (5)

where $I_{\text{noise}}$ is the grey level of the total noise and $\Delta I/\Delta T_s$ is the thermal response sensitivity of the system and defined as the grey level change when there is unit temperature change of the IR object.

In our experiment, $I_{\text{noise}}$ was measured by pick 40 thermal pictures with no IR objects and the histogram was obtained. The histogram related to the noises is shown in Fig. 11. From the histogram, it clear that more than 90% of grey noises are lower than eight grey levels. Therefore the eight was selected as the $I_{\text{noise}}$ for our system. To assess the $\Delta I/\Delta T_s$, a black dyed hotplate (see the inset of Fig. 12a) was used as an IR object. A series of thermal images was collected at different temperatures. Fig. 12b demonstrates the curve of the hotplate’s image grey levels at the position of five selected FPA elements (see Fig. 12a) versus the hotplate’s temperatures. It can be seen that the average value of $\Delta I/\Delta T_s$ of the IR detector can reach 45.76 grey/K. Considering the $I_{\text{noise}}$ as eight, the NETD of the IR imaging system can be approximately 175 mK.

Although current results are not comparable with pyroelectric detectors or thermopiles detectors, it has tremen-
dous potential for improvement. Such improvement can be made in two ways: by decreasing the noise and by increasing the FPA’s sensitivity.

4.1. Noise

4.1.1. Noise from readout system

The readout system can cause two types of noise: one due to the dark current of the CCD, and the other by instability of illumination. In our experiment, the CCD used was 12-bit (s/n: 70 dB). The dark current can be a cause of producing at most one grey level noise. Our illumination was achieved by a simple constant source that was composed of an operational amplifier and an audion. Therefore in the readout system the main noise source of noise is the constant source. Testing the CCD with the illumination shows that it can cause five grey levels of noise.

4.1.2. Noise from other sources

There are many other sources that can possibly add more noise such as thermodynamic fluctuation noise, vibration noise, and noise caused by temperature instability. The noise caused by the thermodynamic fluctuation noise and vibration noise are very small and can be ignored [4]. In the experiment no thermostatic equipment was used and the whole system was placed in an ordinary room. Therefore, the noise caused by temperature instability could not be uncontrolled and it has been proved that this kind of noise is the overriding noise in an opto-mechanical based IR detector [5]. As our system, the thermal–mechanical sensitivity is 0.012 rad/K and the readout sensitivity ($\Delta I/\Delta \theta$) is $0.6 \times 10^5$ grey/deg [9] which shows that only 10 mK fluctuates in room temperature can introduce seven grey level noises.

The above discussion shows that the noise level can be reduced greatly by using more stable constant source and thermostatic equipment.

4.2. FPA sensitivity

Increasing the FPA’s sensitivity is another method of improving the performance. The two choices are to decrease the thickness of SiNx film and to use Al film to substitute for the Au film in bi-material cantilever.

The influenced of bi-material cantilever thickness on the sensitivity of FPA is shown in Fig. 13. The figure shows that thinner is much better and there is an optimized thickness between the Au film and SiNx film for the certain thickness of cantilever. But if the thickness of SiNx gets below 1 μm the part of the IR energy will be reflected consequently at the interface of the Au and SiNx. Therefore the optimization plans are to deposit thicker SiNx film for the absorber and thinner film for the legs or employing a resonant cavity [5] with a $\lambda/4$ gap to increase the IR absorption efficiency.

As it is known by Table 1 that Al film has better parameters for composing the bi-material cantilever. Therefore if the protection problem of Al film in the Si substrate releas-
ing process can be solved, the sensitivity of our FPA can be increased to a great extent.

In short the employment of better peripheral equipment and advancement in the fabrication progress can increase in the performance of the IR imaging system.

5. Conclusion

In this paper we have presented the design, fabrication and performance of an uncooled IR detector having $160 \times 160$ pixels. The detector is a bi-material micro-cantilever array released from the Si substrate whose reflector can retain its shape with temperature changes. In comparison with the generally used sacrificial layer structures, the substrate-free cantilevers have higher effective heat flux because of the elimination of the reflection from the substrate. In addition it has no conglutination invalidation problem and the revised reflector is thus able to reduce the readout sensitivity passivation to an acceptable range. The pixel size is $120 \times 120 \ \mu \text{m}^2$.

A thermal image of a person’s hand was obtained in the imaging experiment and the profile was clearly identified. The imaging results showed the detector has the capability of detecting objects at about room temperature. The NETD of this system was estimated at about 175 mK. It is to be noted that the experiment was conducted without any thermostatic equipment and highly constant readout illumination.

In the future a constant temperature ring and a highly constant readout illumination will be introduced in the system design to reduce most noise. Enhancing the sensitivity of the FPA is another way to improve the performance of system. This can be obtained by decreasing the total thickness of the cantilever and optimizing the thickness ratio of Au and SiN$_x$. Moreover, replacement of the Au film with an Al film in the bi-material cantilever can further improve the performance.

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References