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Optimized Optomechanical Micro-Cantilever Array for Uncooled Infrared Imaging *

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We present a new substrate-free bimaterial cantilever array made of SiN and Au for an uncooled micro-optomechanical infrared imaging device. Each cantilever element has an optimized deformation magnification structure. A 160 × 160 array with a 120 µm × 120 µm pitch is fabricated and an optical readout is used to collectively measure deflections of all microcantilevers in the array. Thermal images of room-temperature objects with higher spatial resolution have been obtained and the noise-equivalent temperature difference of the fabricated focal plane arrays is given statistically and is measured to be about 270 mK.

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Infrared detection in the 8–14 µm spectral range is a significant issue in some technologically crucial problems such as environmental monitoring, satellite imaging and night-vision technique.[1,2] IR detectors can be broadly divided into cooled (photonic) detectors and uncooled (thermal) detectors. Commercialized photonic detectors require auxiliary devices cooling the detectors to about 77 K for eliminating the thermal noise of electrons, which results in high cost and excessive power consumption. In a conventional thermal IR imager, the temperature rise of each element is measured electrically, so the fabrication of focal plane arrays (FPAs) integrated with readout interconnects and electronics often involves complex high-cost processes.

In recent years, there has been an increasing interest in various microelectromechanical systems (MEMSs) based thermal imaging devices with an optical readout.[2–4] Although many of the available MEMS readout schemes can achieve extremely high sensitivity and acceptably low noise levels, optical detection offers a contactless readout of micro-cantilever thermal transducers without the need for on-chip electronics and complex wiring architectures. Several groups have succeeded in thermal imaging using optomechanical FPAs.[2–4] However, the FPA architectures developed by them are fabricated by employing sacrificial layer technique, which increases the fabrication complexity due to the sacrificial layer release difficulty and causes the structure disabled easily because of the adherence of cantilevers to the substrate. From 2002, our group has developed substrate-free bi-material FPAs for infrared imaging using an optical readout with a knife-edge filtering operation in the spectrum plane,[5,6] and obtained thermal images of a 120°C object, even though an FPA is placed in air environment.[6] Late, our group fabricated an improved FPA containing 100 × 100 elements (200 µm × 200 µm), with which we have obtained thermal images of room-temperature objects.[7,8]

To make progress toward an applicable IR imager, the sensitivity and spatial resolution of an FPA need to be improved, which means an FPA with a smaller sensor element should have a higher sensitivity. However, the system sensitivity degrades usually with the element size reduction. In order to explore the issue, in this study we develop a new substrate-free bimaterial cantilever array with a 120 µm × 120 µm pitch for an uncooled optomechanical infrared imaging device. Each element has an optimized deformation magnification structure (DMS).[7,8]. An FPA containing 160 × 160 elements was fabricated using the improved micro-fabrication technology. Compared to the previous study,

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ous works,\(^\text{[7,8]}\) the spatial resolution of the fabricated FPA is apparently improved. We also present the noise-equivalent temperature difference (NETD) in a statistical way, which is more reasonable than before.

Figure 1 illustrates a micro-cantilever element design of 120\(\mu\text{m} \times 120\mu\text{m}\). The element consists of a 1-\(\mu\text{m}\)-thick low-pressure chemical vapour deposited (LPCVD) Si\(_{N_x}\) layer and 0.2-\(\mu\text{m}\)-thick Au, having evidently different coefficients of thermal expansion (Si\(_{N_x}\): \(0.8 \times 10^{-6} \text{K}^{-1}\), Au: \(14.2 \times 10^{-6} \text{K}^{-1}\)). As shown in Fig. 1, the element consists of three-fold deformation legs and an IR absorbing area (reflector). The dimension of the reflector is 106\(\mu\text{m} \times 46\mu\text{m}\), and the folded deformation structure consists of alternately connected bi-material legs (0.2-\(\mu\text{m}\)-thick Au and 1-\(\mu\text{m}\)-thick Si\(_{N_x}\)) and unmetallized Si\(_{N_x}\) legs. Each leg is in length 106\(\mu\text{m}\) in width 3\(\mu\text{m}\). In a pitch of 120\(\mu\text{m} \times 120\mu\text{m}\), to maximize the thermal deformation of the element induced by a certain temperature rise of an IR source, the fold number of DMS is optimized (three-fold). The element is symmetrically supported on a 10-\(\mu\text{m}\)-wide frame. Figure 2 shows a micrograph of a portion of the fabricated 160 \(\times\) 160 FPA.

Fig. 2. Micrograph of a portion of the fabricated FPA.

The optical readout of the present thermal imaging device with the fabricated FPA has been described in detail in the previous works.\(^\text{[5,6]}\) In experiments, the FPA is sealed in a vacuum chamber (about 0.1 Pa) to reduce the effects of convection and conduction of air, as well as to eliminate the random vibration noise of cantilever elements caused by air-molecule collision.

NETD of the fabricated FPA can be estimated according to \(\text{NETD} = I_{\text{noise}}/(\Delta I/\Delta T_S)\), where \(I_{\text{noise}}\) is the grey level of system noise, \(\Delta I/\Delta T_S\) represents the system grey response to the temperature rise of an IR source. To characterize the NETD, firstly, an experiment measuring the system noise was performed using the fabricated FPA at the background temperature of 25℃. In the experiment, 300 background images were serially captured and the grey fluctuations for the CCD pixels that correspond to the reflector images are statistically calculated. The mean noise fluctuation, 8 grey levels, can be regarded as the system noises reasonably. Secondly, another experiment of obtaining the system grey response \(\Delta I/\Delta T_S\) was performed using a temperature controllable IR source with the control precision of 0.01℃. Thirty frames of thermal images were captured at each temperature from 26℃ to 50℃ by step of 3℃. The grey response

![Image of IR source and one of its thermal images in the grey response measurement experiment. (a) IR source, (b) a thermal image of the source, (c) and (d) enlarged sections of the thermal image.]

![Image of histogram of the grey responses of the 33 \(\times\) 33 cantilever elements whose images compose the thermal image of the source.]

of each cantilever element can be calculated by the grey level response to the temperature change. Figure 3 shows the IR source and its thermal image. The thermal image (b) of the source (a) contains images of 33 \(\times\) 33 cantilever elements, and (c) and (d) are enlarged sections of (b). Every bright spot in (b) and (c) is an image of a reflector. For each element image, such as the one surrounded by dashed line in Fig. 3(d), which consists of 4 \(\times\) 4 CCD pixels, 16 (4 \(\times\) 4) responses
of pixels can be obtained. A reasonable consideration is that the maximum of the 16 responses is taken as the element’s response. Figure 4 shows a histogram of the grey responses of the 33 × 33 cantilever elements. The responses range from 9 to 60 grey levels per degree Kelvin due to nonuniformity in elements. When the nonuniformity is improved, the responses can be more concentrated. The system sensitivity (ΔI/ΔTs) can be obtained by averaging the measured responses, which is calculated to be about 30 grey levels per degree Kelvin. Therefore, the experimental NETD was estimated to be about 270 mK.

![Figure 5. IR imaging results using an f/0.8 IR lens and a 12-bit CCD. (a) Thermal image of a man, (b) man’s waving right hand. The cloth wrinkles, hair and the collar can be distinguished from the IR images.](image)

Figure 5 demonstrates the thermal images with an f/0.8 IR lens and a 12-bit CCD at the background temperature around 25°C. In Fig. 5(a), we present an IR image of a man wearing glasses at the distance of about 2 m away and in Fig. 5(b) displays the man’s waving right hand. It is easy from Fig. 5 to distinguish the glasses, clothes wrinkles, hair and the collar. The spatial resolution has been evidently improved, compared with the previous works.[7,8] There appears to be some hollows without elements, which have failed in the fabrication process.

In summary, an uncooled IR imager based on an optimized optomechanical micro-cantilever FPA is presented. With the optimized 160 × 160 FPA, the average system grey response to the temperature rise of an IR source is measured to be 30 grey level/K, and accordingly, NETD is about 270 mK. Our analysis shows that NETD of the fabricated FPA would be improved if the optical readout with less noise is used. Thermal images of room-temperature objects with higher spatial resolution have been obtained.

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