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# Press molding of a Si–HDPE hybrid lens substrate and evaluation of its infrared optical properties

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ABSTRACT

A hybrid structure of single-crystal silicon (Si) and high-density polyethylene (HDPE) was developed as a new substrate for infrared lenses by using precision press molding. A thin HDPE film was used to laminate a silicon wafer and their interface was directly bonded by the silane cross-link. The HDPE film is easy to be hot-embossed to form three-dimensional surface microstructures and the silicon wafer provides a high stiffness for the hybrid substrate. The infrared (IR) optical properties of the hybrid substrate were examined by two kinds of measurements, transmittance and image sharpness. Interestingly, the transmittance measurement result shows that the IR transmittance of the hybrid substrate is higher than that of Si itself in some region of wavelength. The imaging test result shows that the hybrid substrate is capable to produce similar image quality as Si itself. These results strongly demonstrate that the developed Si–HDPE hybrid substrate is a promising alternative substrate material for IR lens.

## 1. Introduction

An infrared optical system is increasingly demanded in various applications such as oil and gas industry, military, surveillance network and many more. Infrared optical elements are normally made of expensive materials such as germanium (Ge) because of its excellent IR properties in the mid-to-far infrared region. An alternative to Ge is silicon (Si), which can also be used as an IR optical material in the far infrared region and costs less than Ge. However, machining Ge and Si into aspherical and Fresnel lenses is very expensive and time consuming because of their hard and brittle characteristics [1–4]. Machines having extremely high precision and high stiffness are required, and the machines must be used under stable environment with strict temperature control and vibration isolation. In addition, the production cost is very high because expensive single-crystal diamond tools will be worn very soon especially when machining Si [5]. These problems greatly limit the productivity and applications of high-precision IR optics. Accordingly, there is an urgent need for exploring alternative substrate materials for IR optics.

In recent years, IR polymers, such as high-density polyethylene (HDPE), are receiving extensive attentions. It has been reported that HDPE has good IR transmission in 8–14 μm region [6]. Compared with Ge and Si, HDPE is inexpensive, and easy to be shaped into complicated shapes, such as micro grooves and dimples, by various thermal manufacturing processes. However, a problem is that the IR absorbance of HDPE is higher than those of Ge and Si. For this reason, HDPE should be formed to a small thickness to obtain acceptable IR transmittance. When the HDPE substrate is thin, however, the stiffness is very low and the substrate is easy to be deflected.

In this study, a Si–HDPE hybrid substrate is proposed for producing an IR lens. The hybrid substrate combines the advantages of both materials, i.e., the high stiffness, high thermal stability and high IR transmittance of Si, and high formability of HDPE. This hybrid structure might be fabricated through thermal processes at a lower manufacturing cost compared to ultraprecision diamond turning. Moreover, HDPE has a refractive index of 1.5, which is different from that of Si (3.5) [7,8]. A combination of materials with different refractive indexes and different transmission regions might provide possibility of fabricating new multi-functional optical components [9].

For fabricating a hybrid substrate, several methods have been reported in previous researches, whereby polymer is attached onto another optical substrate. The earliest reported method used ultraviolet (UV) curable resin, in which the resin was applied on the substrate and cured using UV light [10]. This method provides strong adhesion between the two materials. Injection molding was also used to fabricate a hybrid glass-polymer lens, where the glass was inserted into the mold, and the molten polymer was injected to cover one side of the glass [11]. No adhesive agent was used for

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**Table 1**
Si material properties.

| Material properties | Value |
|---|---|
| Type | *P* |
| Doping element | Boron |
| Resistance (Ω cm) | 27 |
| Surface orientation | (1 1 1) |
| Thickness (μm) | 755 |
| Refractive index | 3.5 |
| Surface roughness ($R_a$) (nm) | 3.5 |

**Table 2**
HDPE material properties.

| Material properties | Value |
|---|---|
| Density (g/cm$^3$) | 0.955 |
| Melting point (°C) | 133 |
| Softening temperature (°C) | 125 |
| Shape | Granules |
| Grain size (mm) | Ø3 × 3.5 |
| Melt flow rate (190 °C, 21.2 N) (g/10 min) | 9 |
| Refractive index | 1.5 |

the injection molding process, and the resulting lens assembly was held by the flange of the polymer lens. Likewise, a similar method was used to fabricate a silicone-glass hybrid lens for photovoltaic application [12]. Another method is using compression molding process, where polymer is adhered to glass by heating and cooling the polymer during compression and also applying hot glue between the two substrates [13–15]. In order to improve the adhesion, a mechanical lock is designed to improve the lens material assembly by securing the assembly using strong locking devices along the adhesion [16]. A combination of glass and Si for simultaneous visible and infrared imaging has also been performed, where glass is placed at the centre of a Si lens without any adhesion [17].

In this research, a glass molding press (GMP) machine is used to form the Si–HDPE hybrid material. In GMP, the molding temperature and pressure is precisely controlled so that the shape transferability, surface quality and interface strength can be improved [18,19]. In glass molding, glass is normally formed at a high temperature (∼500 °C) above the glass transition temperature, where glass is in the softened state. In this study, as the HDPE polymer exhibits lower softening temperature (125 °C) and melting point (133 °C), the Si–HDPE hybrid structure forming is easily done in the melt state of HDPE, which is similar to that used in other applications [20]. Forming the polymer in its melt state is beneficial for complete replication of microstructures or complicated shapes to polymer without damaging the mold and the thin Si substrate. Forming Si–HDPE in the melt state also helps to create strong Si–HDPE adhesion during the press molding process.

This paper presents experimental results of fabricating Si–HDPE hybrid substrates having different HDPE thicknesses, and the evaluation results of their optical properties. The influence of polymer thicknesses on IR transmittance and IR image sharpness will be investigated systematically. Meanwhile, the effect of gap existence between the two materials on IR transmittance is also examined. The manufacturing process of the Si–HDPE hybrid structure in this research will give the potential of creating a new substrate for IR lenses in the application of night vision cameras, thermography and other IR related industries. The objective is to improve the IR transmittance and IR imaging quality and simultaneously to lower the manufacturing cost.

## 2. Experimental procedures

### 2.1. Sample materials

In the experiments, two types of materials were used. The first material is Si with 755 μm thickness in the form of a two-side polished wafer provided by Global Wafers Japan Co. Ltd. The properties of the Si material are given in Table 1. The Si wafer was then cut to the size of 15 mm × 15 mm by using a diamond pen. Cylindrical HDPE granules having a grain size of Ø3 mm × 3.5 mm, supplied by Mitsubishi Chemical Corporation, Japan, were used in the experiments. The grade of the HDPE material is LINKLON HM600A, which is a silane cross-linkable resin. The properties of the HDPE granules are given in Table 2. In the experiments of forming the hybrid structure from Si and HDPE using the GMP machine, no adhesion promoter was used because HDPE contains silane cross-linkable resin, which is capable of creating a direct bond between non-polar surfaces [21,22]. Crosslinking is a type of polymerization reaction that branches out from the main molecular chain to form a network of chemical links.

### 2.2. Hybrid structure design

The structure of a Si–HDPE hybrid structure test piece is schematically shown in Fig. 1. To improve the adhesion strength between the two materials, a mechanical lock was designed at the edge of the Si substrate, leaving an effective lens area of 13 mm × 13 mm after subtracting 1 mm for locking. In this way, the fragile Si substrate is fully protected by HDPE from external forces and shocks, and at the same time, the flatness of the HDPE film can be maintained strongly by the Si substrate.

### 2.3. Press molding machine and molds

Fig. 2 illustrates the process of fabricating a Si–HDPE hybrid substrate using GMP. During the process, a Si substrate was placed inside the mold impression, followed by the HDPE granules. The lower mold was then raised up towards the upper mold and the heating took place by using circular infrared lamps. The compression process started when the temperature reached the melting point of HDPE and both the lower and the upper molds would be completely closed. During the compression, HDPE would fill up the impression and laminate the Si substrate. The molds were then cooled down and the resulting hybrid substrate was removed from the lower mold surface.

The Si–HDPE hybrid structure forming was conducted by using an ultraprecision glass molding machine, Toshiba GMP211 (Toshiba Machine Co. Ltd., Japan), which was originally designed to form glass lenses. The molding chamber is covered by a transparent silica glass tube, inside which Nitrogen gas is purged during molding to prevent oxidation at high temperature. The highest heating temperature of the machine is 800 °C, which is monitored by a thermocouple within ±1 °C measurement accuracy. The pressing force of the machine ranges from 0.2 kN to 20 kN with a resolution of 0.98 N. The upper mold is remained stationery, while the lower

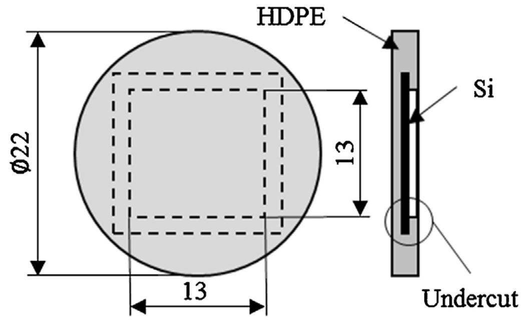

**Fig. 1.** An example of Si–HDPE hybrid structure design.

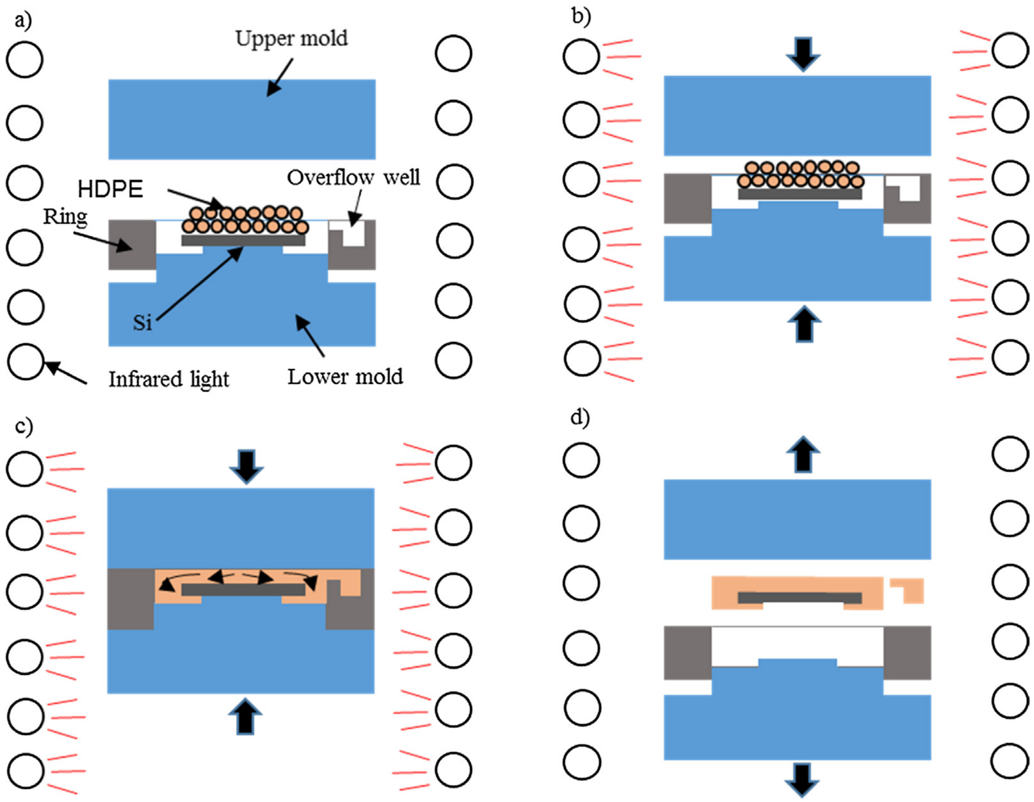

**Fig. 2.** Schematic diagram of press molding process: (a) material setup, (b) heating, (c) pressing, and (d) cooling and specimen removal.

mold controlled by an AC servomotor with a movement resolution of 0.1 μm.

The upper mold used in this study was shaped by using a universal lathe from an aluminium cylinder to a diameter of Ø40 mm and a height of 20 mm, and the top surface of the mold was then flattened/micro-structured by using an ultraprecision lathe, NanoForm X (Ametech Precitech Inc., USA). The machine was equipped with an air bearing spindle and a single crystalline diamond tool with a nose radius of 250 μm. The final mold surface had a mirror finish, with surface roughness of 7.8 nm $R_a$.

The lower mold is composed of a group of elements, as schematically shown in Fig. 3, to form a flexible cavity to control the shape of the HDPE material and create the mechanical lock. The cavity formed by a circular ring has a diameter of Ø22 mm, the depth of which was automatically adjusted by a spring supporting the ring, depending on the HDPE thickness. A stop bolt was used to prevent the circular ring from coming out from the mold. A photograph of the molds is shown in Fig. 4.

### 2.4. Molding conditions

During press molding the hybrid structure, it is important to eliminate any gap between the two materials after press molding as the gap would affect light transmission according to the Snell's law. Light reflection can be characterized by the following equation:

$$n_1 \sin\theta_1 = n_2 \sin\theta_2 \qquad (1)$$

where $n_1$ and $n_2$ are the refractive indexes of materials 1 and 2, while $\theta_1$ and $\theta_2$ are the incident and refraction angles, respectively. Leaving a gap between Si and HDPE will cause light variance in the hybrid structure. Thus, it affects the image quality of the

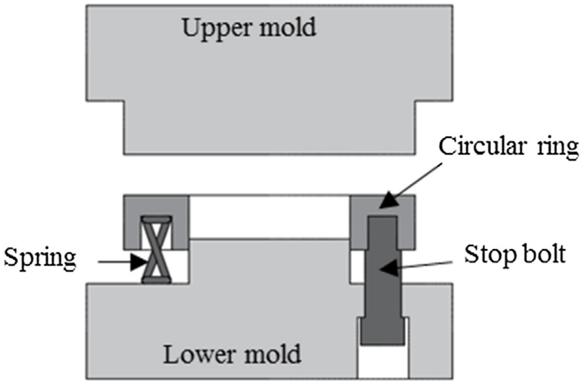

**Fig. 3.** Schematic diagram of upper and lower mold structure.

**Fig. 4.** Photographs of fabricated aluminium molds.

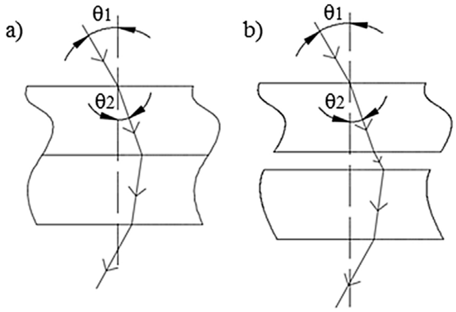

**Fig. 5.** Light diversion in a hybrid structure (a) without gap, and (b) with gap.

resulting lens. The effect of light travelling through the hybrid structure without/with a gap is shown in Fig. 5. Fig. 5(a) shows no light diversion between the two substrates whereas Fig. 5(b) shows light diversion when there is a gap. The focal point of the two-material structure will be different due to the presence of the gap. Therefore, it is extremely important to precisely control the pressing force and heating time to eliminate possible gaps between Si and HDPE.

In this study, the thermal cycle used for making the Si–HDPE hybrid structure is shown in Fig. 6, and the experimental steps are described as follows.

(1) The Si substrate was placed into the cavity, followed by the measured volume of HDPE granules. The molding chamber was then closed.
(2) The lower mold was moved towards the fixed upper mold, leaving a gap of 2 mm between the two molds. Nitrogen gas was purged into the chamber for 20 s to prevent mold oxidation.
(3) The molds and the specimen were heated from the room temperature to 140 °C by an IR lamp heater at a heating rate of 99 °C/s.
(4) The temperature was maintained for 70 s and followed by the molding press at a minimum compression force of 0.2 kN.
(5) While compression continuing, nitrogen gas was purged into the chamber again for cooling the mold to 80 °C at a rate of 99 °C/s. The cooling rate here is important to prevent shear deformation at the substrate interface which affects the adhesion strength.
(6) The mold was opened and the molded hybrid substrate was discharged for further cooling at room temperature.

### 2.5. IR transmittance measurement

IR transmittance measurement was conducted to verify the IR transmittance and absorbance of the hybrid Si–HDPE structure for different HDPE thicknesses. The IR value of the Si substrate only was also measured for comparison. The IR measurement was done using a Bruker Fourier Transform Infrared (FTIR) Spectrometer that is capable of measuring at a wavelength range from 2.5 to 25 μm. The sample was placed between the IR source and the IR detector of the FTIR instrument. When measuring the hybrid substrate, the HDPE side was placed facing the IR source while the Si side facing the detector. The reason for this orientation is because micro lens shapes will be formed on the HDPE side and it is important to find out the IR characteristics of the hybrid substrate at this orientation.

### 2.6. IR imaging test

IR images were captured using the Therm-App smartphone thermal camera (Opgal Optronic Industries Ltd.) with 384 × 288 pixel resolution. The spectrum of the camera is for the long wave IR region from 7 to 14 μm and supplied with a 19 mm focal length germanium lens. The camera was connected to an android smartphone for operating the camera and processing the images. The setup for image capturing is shown in Fig. 7.

In order to capture the images of objects with different materials and thicknesses, a cover with a Ø12 mm hole was placed in front of the camera lens. The Si–HDPE hybrid substrates were then placed at the hole, and the grayscale image was captured at a distance of 340 mm. The object used for imaging was a fan blade shape chart printed in black and white on a piece of paper. The size of the chart is 100 mm × 120 mm and composed of small and big fan shapes to evaluate the sharpness of the image. The small fan section was to evaluate the smaller images while big fan section for larger images.

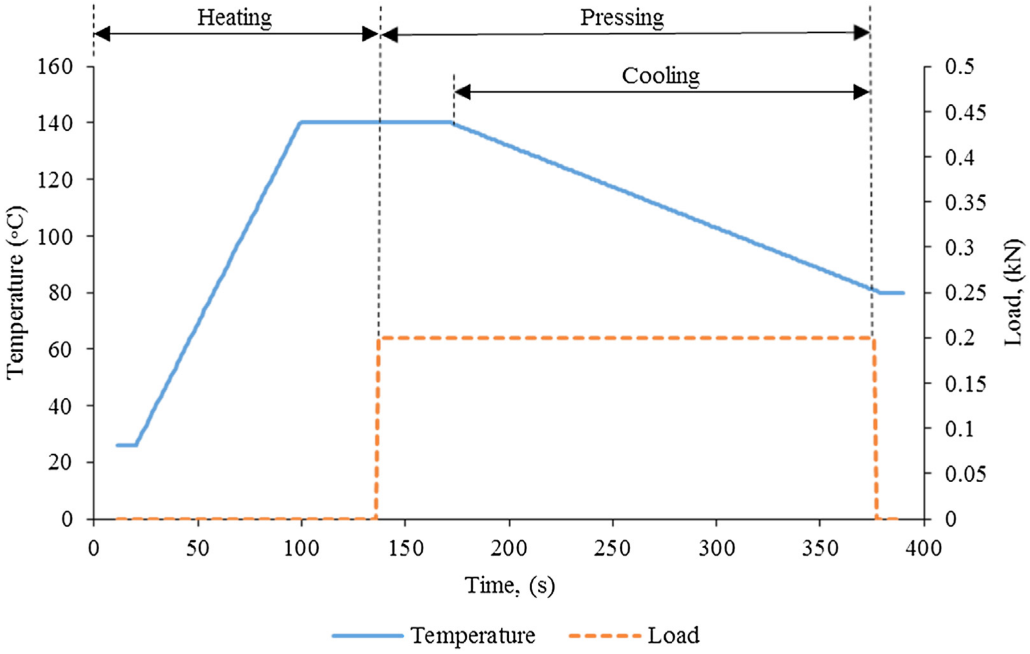

**Fig. 6.** Process parameters for hybrid structure molding press.

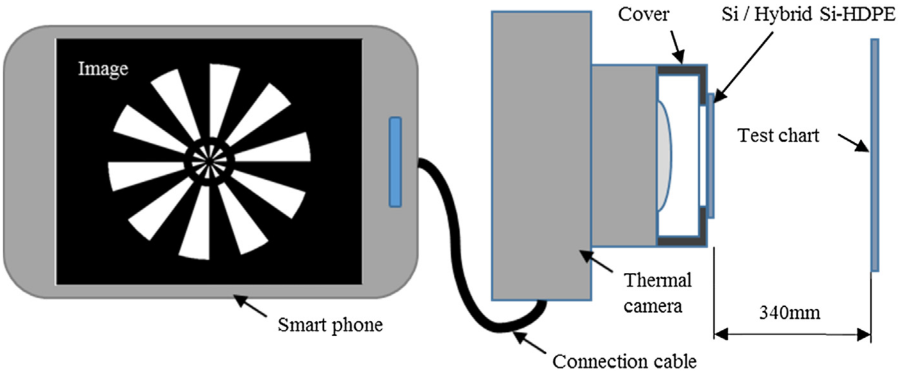

**Fig. 7.** Camera setup with image chart for optical performance evaluation.

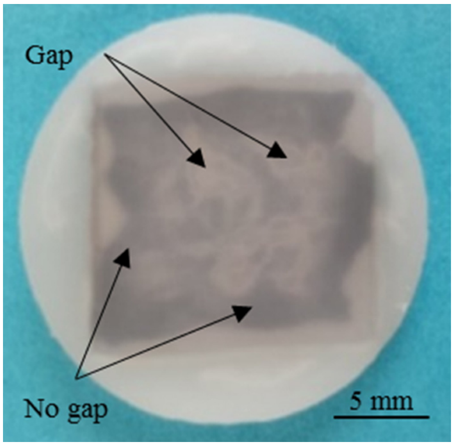

**Fig. 8.** Photograph of the Si–HDPE hybrid substrate under melting temperature of 133 °C.

The captured images were then analysed using the ImageJ software to measure the edge sharpness of each image.

## 3. Results and discussion

### 3.1. Hybrid substrate press molding

A number of press molding tests were performed under various conditions to produce Si–HDPE hybrid substrates with different thicknesses. We found that at the nominal melting temperature (133 °C), HDPE was not able to stick on the Si substrate firmly. Fig. 8 shows a photograph of a hybrid substrate pressed at 133 °C after being heated for 70 s. It is clear that gaps occurred in many regions because interface bonding was not strongly created between HDPE and Si under this condition. For this reason, the molding temperature are set to 140 °C, slightly above the nominal melting temperature, and strong crosslinking bonding between the two substrate interfaces were confirmed.

In order to prevent degradation of HPDE property, the heating time should be set as short as possible. In the present molding test, we found that a heating time of 70 s was the best. If shorter heating times, such as 50 and 60 s, were used, the HPDE did not fully melt and affected substrate adhesion. An insufficient heating time also affect the polymer flow during molding, leading to incomplete filling of the mold cavity and flow marks. Photographs in Fig. 9 shows the effect of heating time on the adhesion and polymer flow. Fig. 9(a) shows flow marks and interface gaps were formed by the incomplete mixture of HDPE granules when the heating time was 50 s. The flow marks reduced and interface gaps were eliminated when the heating time increased by 10 s, as shown in Fig. 9(b). The flow marks were completely eliminated as shown in Fig. 9(c) when the heating time was set to 70 s.

Under optimal press molding conditions, the silane crosslinkable HDPE resin was able to create strong bonding between the two materials and left no gap at their interface. The mechanical lock designed at the edge of the Si substrate was proved to be very useful to hold and protect the Si substrate. As an example, two finished Si–HDPE hybrid substrates after molding press are shown in Fig. 10. No gaps and no flow marks are seen, demonstrating the HDPE has been uniformly and strongly adhered to the Si substrate.

To examine the interface between the two materials, a press molded Si–HDPE sample was cut by a slicing machine to make a cross section which was observed by a scanning electron microscope (SEM). Fig. 11 shows the cross-sectional SEM photographs of the sample taken at different locations. For either of the photographs, no gap is seen between the two materials, demonstrating that the hybrid substrates was strongly bonded during the molding press.

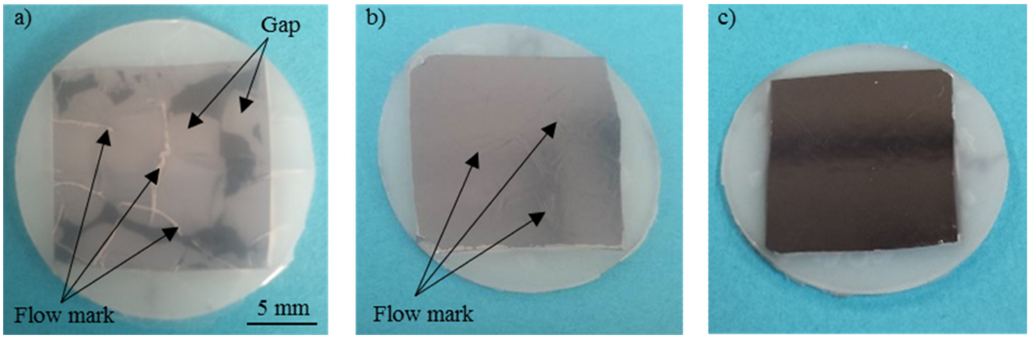

**Fig. 9.** Photographs of the Si–HDPE hybrid substrates pressed under different heating time: (a) 50 s, (b) 60 s, and (c) 70 s.

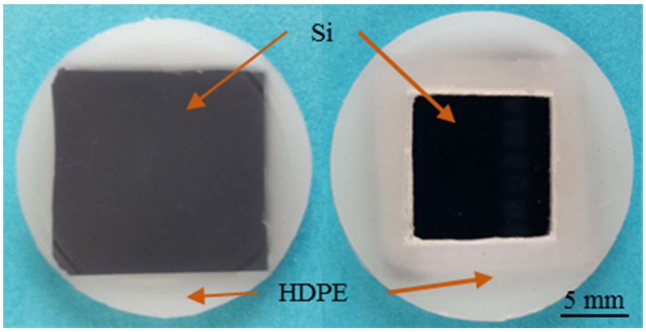

**Fig. 10.** Photograph of two pressed HDPE–Si substrates, showing different sides.

### 3.2. IR transmittance evaluation

The hybrid substrates with four different thicknesses of HDPE, 50, 55, 65, and 115 μm on Si substrates with the same thickness (755 μm) were then measured by using FTIR to investigate the effect of HDPE thickness on IR transmittance and absorbance. For comparison, a Si substrate without HDPE was also measured.

Fig. 12 shows the transmittance of the hybrid substrates at a range of wavenumbers from 700 to 1400 cm$^{-1}$ (wavelength from 7 to 14 μm) with comparison with those of Si and HDPE individually. It is seen that as a general trend, the IR transmittance was reduced as the thickness of HDPE increased. When the HDPE thickness was increased to 115 μm, the IR transmittance was lower in almost all the wavenumber region compared to that of the Si substrate. Thus, a successively thick HDPE film is not suitable for use in this case. In addition, the transmittance of the Si–HDPE hybrid substrate is especially lower than that of Si in the regions of 710–740 cm$^{-1}$ and 1070–1130 cm$^{-1}$. However, interestingly, we found that for thinner HDPE films (50 and 65 μm), the hybrid substrate has higher IR transmittance than that of the Si substrate in some specific wavenumber regions, such as 830–1070 cm$^{-1}$ and 1130–1340 cm$^{-1}$. This means the possibility that by laminating Si with a thin layer of HDPE polymer, the IR transmittance can be further improved. This phenomenon might be due to that the HDPE layer itself reduced the reflection of light at substrate surface, like an anti-reflection film [23]. The reason why the IR transmittance of the hybrid structure is especially higher in regions 830–1070 cm$^{-1}$ and 1130–1340 cm$^{-1}$ is that the IR transmittance of HDPE itself is higher in those regions than other regions, as shown in Fig. 12. Though the total IR transmittance of the Si–HDPE hybrid substrate is lower than that of HDPE only, the shape of IR transmittance curve is basically maintained.

The absorbance of the hybrid substrates recorded at the same wavenumber region as the IR transmittance tests was plotted in Fig. 13. It is seen that the IR absorbance level increased when the

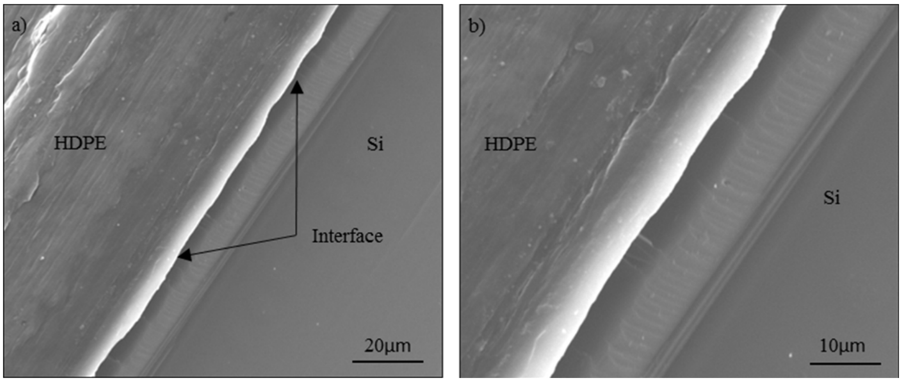

**Fig. 11.** Cross-sectional SEM images of the interface of a hybrid substrate.

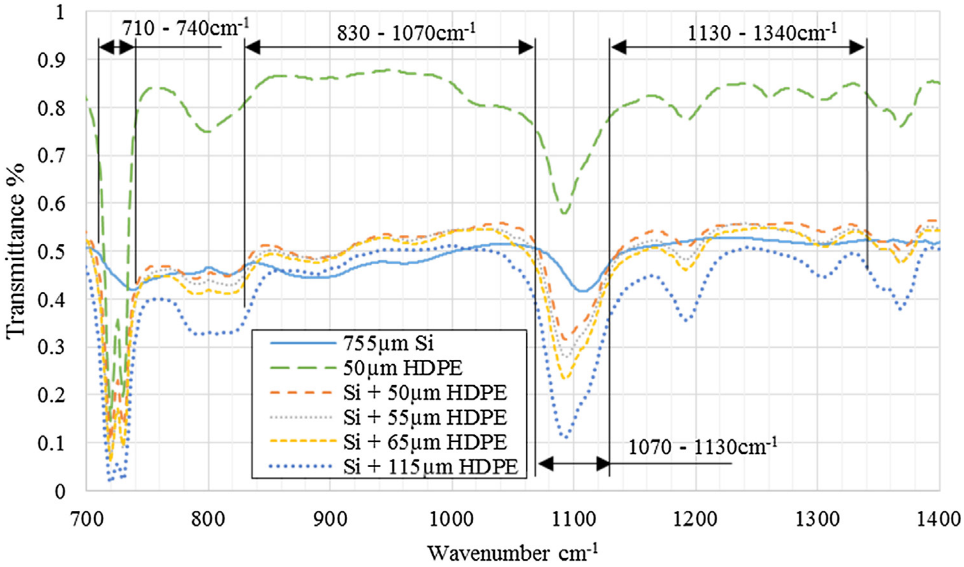

**Fig. 12.** IR Transmittance of Si, HDPE, and Si–HDPE hybrid substrates with various HDPE thickness.

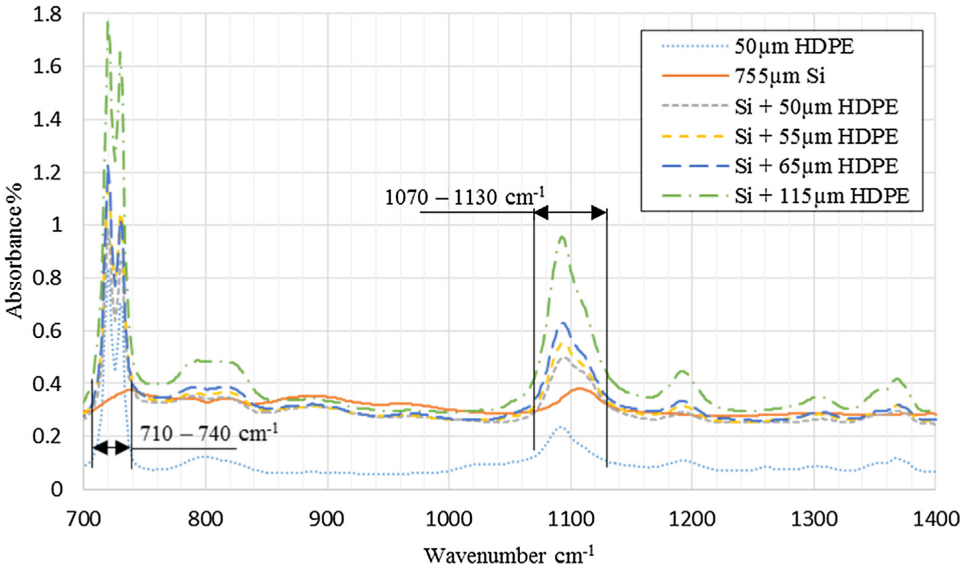

**Fig. 13.** IR absorbance of Si, HDPE, and Si–HDPE hybrid substrates with various HDPE thickness.

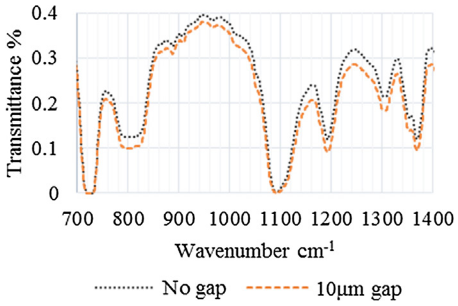

**Fig. 14.** Effect of interface gap on IR transmittance of a hybrid substrate.

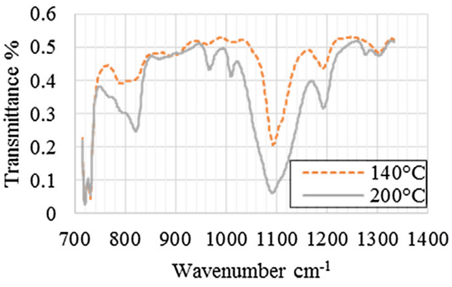

**Fig. 15.** Effect of molding temperature on the IR transmittance.

transmittance decreased for thick HDPE, and a small thickness of HDPE results in the IR absorbance to reach the tolerance level. The IR absorbance of the hybrid substrate is at par with Si itself when the HDPE thickness is 50 and 65 µm.

For evaluating the influence of the interface gap between the two materials on the IR transmittance, a measurement was done and the results were presented in Fig. 14. The sample used in the measurement has a HDPE layer thickness of 330 µm on the Si substrate and the gap width between them was 10 µm. In Fig. 14,

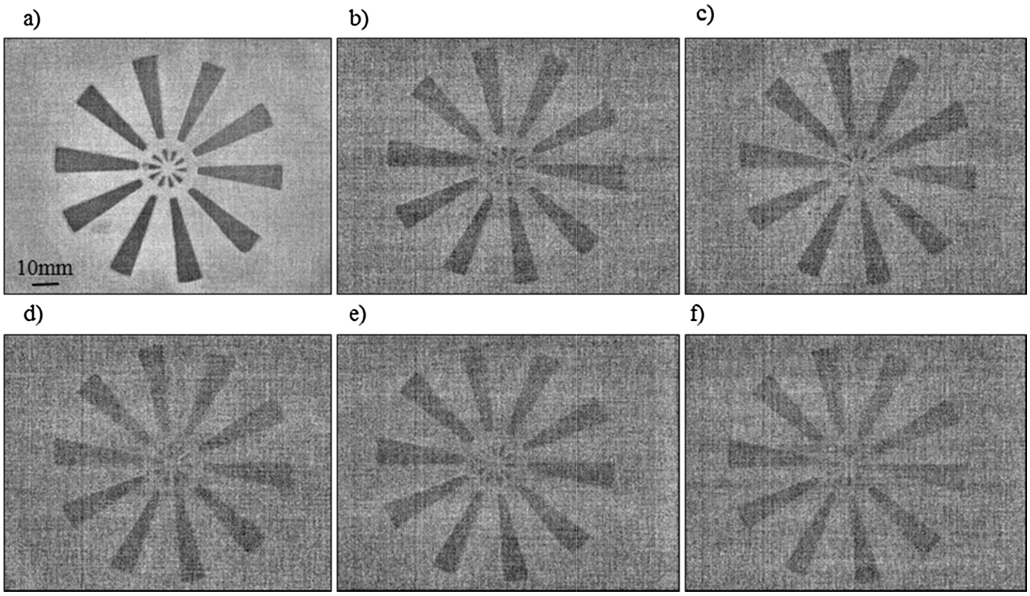

**Fig. 16.** (a) IR image without filter and images for different substrates: (b) 755 µm Si, (c) 50 µm HDPE + 755 µm Si, (d) 65 µm HDPE + 755 µm Si, (d) 75 µm HDPE + 755 mm Si, and (f) 155 µm HDPE + 755 µm Si.

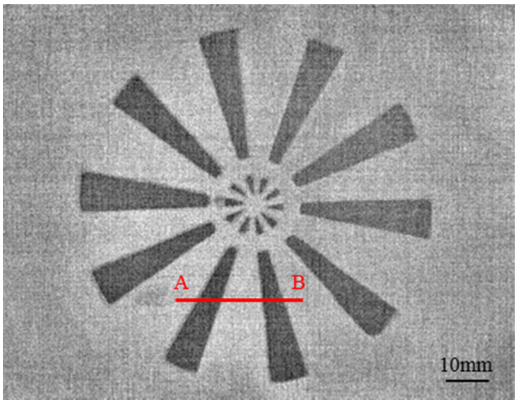

**Fig. 17.** Image cross section for edge sharpness measurement.

there is a significant loss of transmittance in all regions due to light diversion at the gap. This result agrees well with the Snell's law as mentioned in Section 2.4. The results show again the importance of fabricating the hybrid substrate without leaving any gap to prevent the losses of IR transmittance.

Temperature is another important factor in polymer forming, as a high temperature will degrade the polymer property and affect the IR transmittance. To examine the effect of molding temperature on the IR transmittance, two Si–HDPE hybrid substrates molded at 140 and 200 °C, respectively, were used for evaluation. Fig. 15 shows the effect of temperature on IR performance. Here, the thickness of HDPE was 60 μm. It is clear that the IR transmittance was reduced significantly due to the degradation of the polymer at 200 °C. Therefore, it is important to use lower molding temperature for a shorter period of time to prevent the HDPE polymer from degradation during the press molding of the hybrid substrates.

### 3.3. Image quality evaluation

Fig. 16 shows 384 × 288 pixel images captured using a thermal camera for the Si–HDPE hybrid substrates with different film thicknesses. As a reference, Fig. 16(a) shows the grayscale image of the chart captured without any filter. When a 755 μm thick Si substrate was placed in front of the camera, the image becomes darker and the contrast of the image is lower, as shown in Fig. 16(b). This is caused by the reduced IR transmittance due to the Si substrate. In this case, the small fan shape is still identifiable at the centre of the chart along with the bigger fan shape. The image of the hybrid substrate with 50 μm thick HDPE in Fig. 16(c) shows almost no difference with that in Fig. 16(b). Compared to Fig. 16(b), the shape of the small fan in Fig. 16(c) is shown more clearly, demonstrating the IR transmittance and image quality of the hybrid lens was improved. This agree well with the results of IR transmittance in Fig. 12, i.e., a thin layer of HDPE applied to Si improve transmittance of the IR light. Fig. 16(d) shows the image when the HDPE thickness was increased to 65 μm. The image becomes dull and blur, where the small fan profile starts to lose its shape. This is due to the increase of the IR light absorption with the increase of HDPE thickness. Fig. 16(e) and (f) are results obtained when the HDPE thickness was 75 μm and 155 μm, respectively. The image of the chart becomes duller, where the small fan shape is hard to identify.

From these results, a strong dependence of image quality on the HDPE thickness is confirmed. To provide a clear image, the hybrid lens requires the HDPE film thinner than 100 μm. Under the present

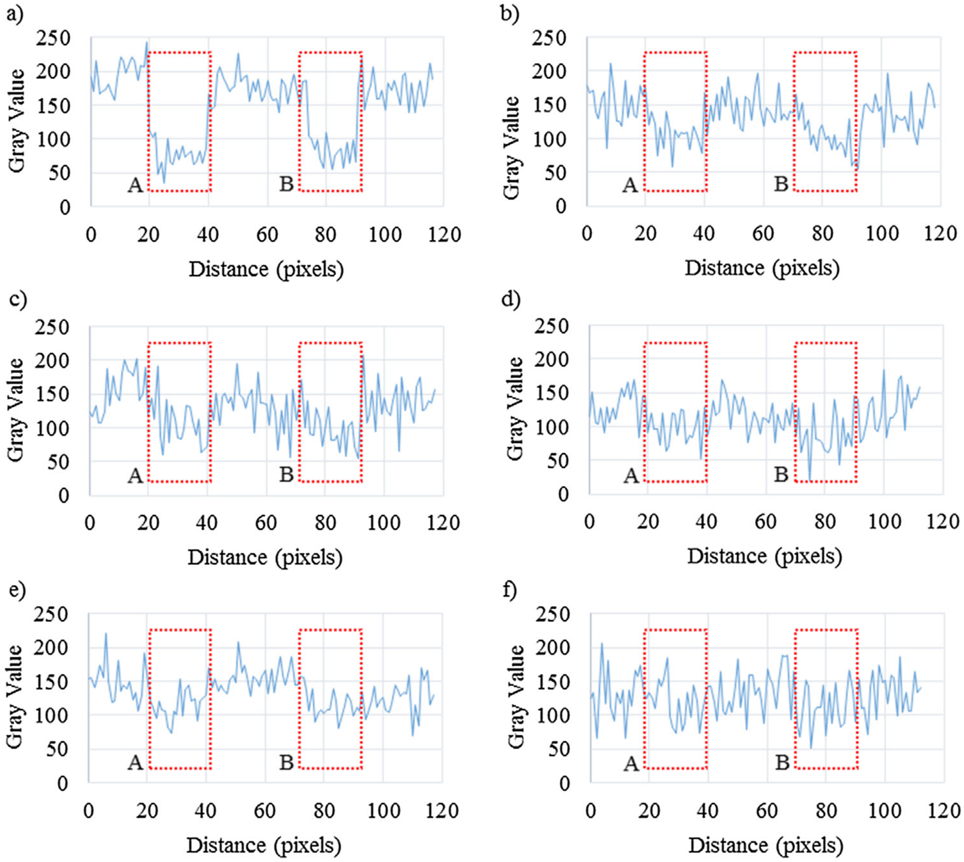

**Fig. 18.** Image edge sharpness measurement: (a) without filter, (b) 755 μm Si, (c) 50 μm HDPE + 755 μm Si, (d) 65 μm HDPE + 755 μm Si, (e) 75 μm HDPE + 755 μm Si, (f) 155 μm HDPE + 755 μm Si.

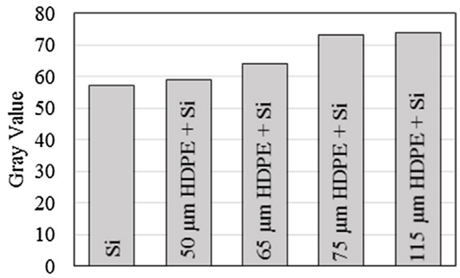

**Fig. 19.** HDPE thickness effect on the image gray value.

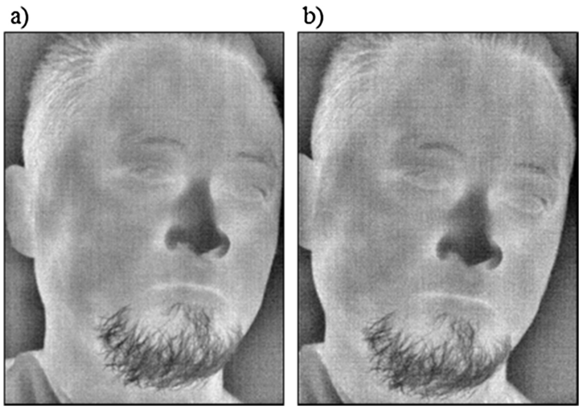

**Fig. 20.** Night mode images obtained by different lens substrates: (a) 755 µm Si, and (b) 50 µm HDPE + 755 µm Si.

experimental conditions, a HDPE thickness of ∼50 µm has been found to be suitable for the hybrid lens.

### 3.4. Image sharpness evaluation

The ImageJ software was used to analyse the grayscale image obtained from the thermal camera by differentiating the gray value and the pixels of the image, as presented in Fig. 16. In the analysis, darker pixels will result in lower gray value. The distance between the image chart and the thermal camera was set to 340 mm by assuming that all the images have the same light illumination. Cross sections of the images were made in areas indicated by line A-B in Fig. 17, and then the grey values were plotted in Fig. 18.

As shown in Fig. 18(a), if no filter is used, a sharp step is clearly identified at the edge of image. The step height became smaller when a Si substrate (Fig. 18(b)) and Si–HDPE hybrid lenses (Fig. 18(c–f)) were placed in front of the camera. A dark image produces more noise, and the noise level depends on the thickness of the HDPE. When a 50 µm thick HDPE was added to the Si substrate to form the hybrid lens (Fig. 18(c)), the image edge sharpness is similar to that of the Si substrate only (Fig. 18(b)). For a very thick HDPE film (115 µm), the edge of the image is hard to identify, as shown in Fig. 18(f). To summarize, the gray value of each Si–HDPE image cross section is plotted in Fig. 19. A clear relationship between the gray value and HDPE thickness is identified, i.e., the gray value increased with the increase of HDPE thickness laminating Si.

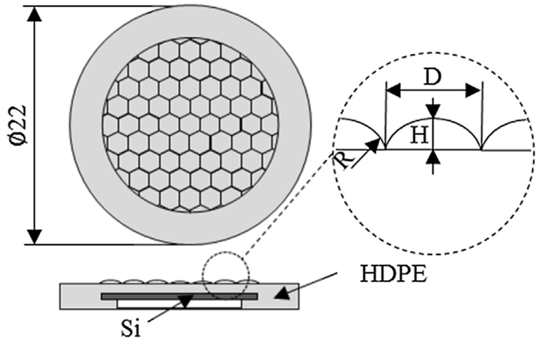

**Fig. 21.** Design of a Si–HDPE hybrid plano convex lens array.

### 3.5. Night mode imaging

The grayscale image of a human face was captured using the night mode at the distance of 1 m to show the ability of the hybrid substrate as the material for the night vision infrared lens. Fig. 20(a) shows the image captured when the thermal camera was filtered by the 755 µm thick Si substrate, whereas Fig. 20(b) shows the image filtered by a hybrid substrate with 50 µm thick HDPE. There is no obvious difference between the two images.

### 3.6. Micro lens array forming

Finally, a trial was conducted to form micro lens arrays on the HDPE film of the hybrid substrate to confirm the possibility to fabricate micro-structured IR optics. The lens design is schematically shown in Fig. 21, and details are given in Table 3. A plano convex lens array with lens curvature radius (*R*) 10 mm, diameter (*D*) 2 mm, and sag height (*H*) 46 µm was formed on a HDPE laminated Si substrate. Fig. 22(a) illustrates a photograph of such a lens array formed on the hybrid substrate, and Fig. 22(b) presents the three-dimensional measurement results of the lenses. The lens sag height

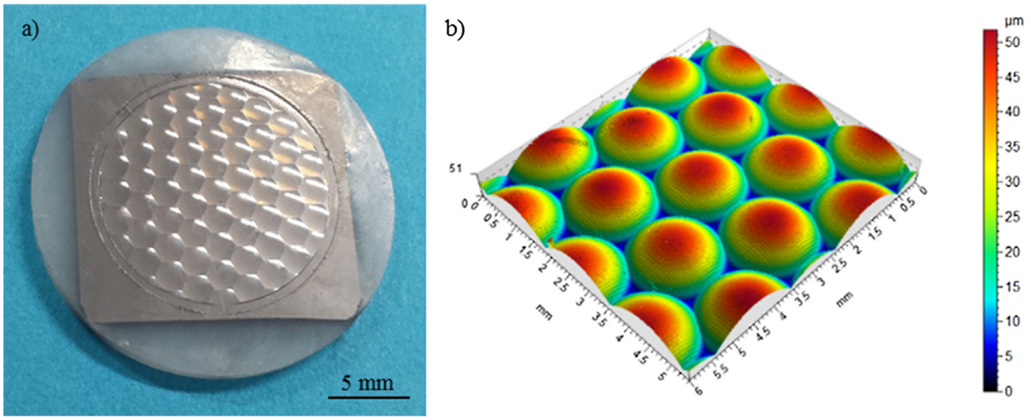

**Fig. 22.** (a) Photograph and (b) three-dimensional topography of a Si–HDPE hybrid substrate where plano-convex lens array were formed.

**Table 3**
Plano-convex lens array design parameters.

| Parameters | Value |
|---|---|
| Lens radius ($R$) (mm) | 10 |
| Lens pitch (mm) | 1.73 |
| Lens height ($H$) (μm) | 46 |
| Lens diameter ($D$) (mm) | 2 |
| Total number of lens | 61 |

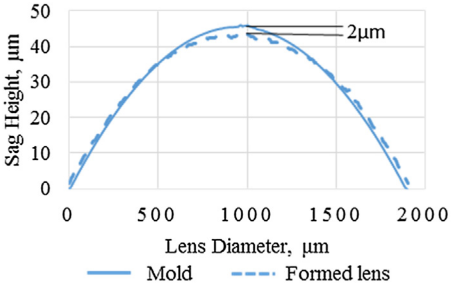

**Fig. 23.** Comparison of cross-sectional shape between the mold and the formed lens.

was then measured and compared with that of the mold, as shown in Fig. 23. A 2 μm difference of the lens sag height was formed, which might be due to the polymer shrinkage during cooling.

The results from the present study have preliminarily demonstrated the possibility to fabricate freeform micro lenses on the Si–HDPE hybrid substrate for future IR optical systems. Further investigation will be conducted in this study to improve the optical design and the form accuracy of the micro lenses by compensating the polymer shrinkage. Beside HDPE, other IR polymers will also be attempted to realize new IR systems for various wavelength ranges.

## 4. Conclusions

Si–HDPE hybrid lens substrates have been manufactured using press molding method, and the IR optical properties of the fabricated substrates were evaluated. The following conclusions are obtained:

1. Fabrication of Si–HDPE hybrid substrates has been successfully performed by using press molding method. A set of molds were designed and fabricated, which enables high-precision forming of Si–HDPE hybrid structures with mechanical locks.
2. The effects of some key factors in the press molding process, such as molding temperature and heating time, were investigated. It is possible to create strong adhesion of the two materials without leaving interface gaps.
3. The Si–HDPE hybrid substrate has higher IR transmittance in wavenumber regions of 830–1070 $\text{cm}^{-1}$ and 1130–1340 $\text{cm}^{-1}$ than that of Si substrate only. This interesting phenomenon might be a result of that the HDPE itself acts as an anti-reflection coating for the Si substrate.
4. A successively thick HDPE laminating will reduce the image sharpness and IR transmittance. A Si substrate laminated with ~50 μm thick HDPE is able to produce the same image quality as that of Si only and improved the IR transmittance.
5. The fabricated Si–HDPE hybrid lens substrates are useable for night mode IR imaging with satisfactory image quality. The possibility of forming micro lens arrays on the hybrid substrate has been demonstrated.

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