# Measurement of thermal property by high speed & micro-scale IR camera

J. Morikawa and T. Hashimoto

Tokyo Institute of Technology

2-12-1, O-okayama, Meguro-ku, Tokyo 152-8552, Japan,

jmorikaw@o.cc.titech.ac.jp

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## 1. INTRODUCTION

A new method for the measurement of thermal diffusivity and thermal conductivity by use of a high-speed micro-scale infrared camera has been proposed recently[1-2]. The advantage of this technique stands on the two-dimensional visual information with the more than ten thousands pixels of focal plane arrays of IR sensitive photo sensor. This method is applicable not only to determine the value of thermal conductivity or diffusivity but also to observe the two–dimensional distribution or anisotropy of thermal property of the materials.

In this study the technique is applied to the observation of thermal resistance at the interface of the multi-layer polymer films by using a temperature wave. This is a quite new application of infrared photographs to the quantification of thermal interface with a combination of a high speed IR-FPA with a microscopic lens and a detection of phase delay by inputting a temperature wave. The two-dimensional phase lock-in technique was applied to the evaluation of phase delay at the thermal interface with a spatial resolution of 7.5μm.

In past ten years Temperature Wave Analysis (TWA)[3-5] technique has benn developed to obtain thermal diffusivity and thermal conductivity with the phase shift measurement of thermal wave in the thickness direction of thin film. When the two-dimensional IR thermography is combined with the Temperature wave technique it would lead a three dimensional measurement of thermal property. It might have a possibility for the IR thermographic technique[6-7] with the wave technology to become a general tool for the measurement of thermal property. In the framework of this principle the example of the measurement of thermal interface will be discussed in this article.

## 2. EXPERIMENTAL

Fig.1 is an experimental setup for taking the sequential thermographic photos of the specimen by IR camera with a temperature-controlled cryostat. The radiation intensity due to periodic temperature variation is recorded by an IR focal plane array (FPA). In this study InSb FPA (Phoenix, Indigo Systems, or Radiance HS, Raytheon) was used which is sensitive in 3~5μm spectral band. The array of 256x256 pixels and IR optics allows 1.9x1.9mm$^2$ specimen area giving a spatial resolution of 7.5μm/pixel with SiGe micro lens (DIOP). The frame rate varies from 60Hz to 5000Hz, corresponding to the pixel size 256x256~64x64. The time resolved IR photograph of the temperature wave on the specimen was obtained in the above conditions, and simultaneously the time profiles of temperature at all pixels are obtained. The measurement was done in a vacuum condition and a shutter speed is 1ms.

Thermal wave is generated by a.c. Joule heating on a sputtered gold resistor located at the one side of the layered film. It propagates in the thickness direction by passing through the interfaces. The generating frequency was selected considering the thermal diffusion length, 0.01Hz~10Hz. The temperature variation on the heater was controlled less than 1K.

The conversion function of intensity into absolute temperature was experimentally determined. In addition to the black point temperature on a hot stage measured with a platinum thermometer, when the emmisivity of the specimen is unknown, a thin thermocouple less than 12.5μm diameter is inserted on the front surface of specimen for the direct measurement of temperature and IR intensity. The temperature scan of heat block in the cryostat is possible in the rate of 0.5~10°C/min.

The cross section of the three layered polyimide films was prepared for the phase shift measurement as shown in Fig.2. The thickness of each layer is 125µm/75µm/125µm and the interfaces between the films were filled with a grease which has the known thermal property. On the front surface of the specimen a gold thin layer was sputtered, which was used as a heater generating a temperature wave by ac Joule heating, with a function synthesizer (NF1942), and the cross section was cut on the sputtered layer. The measurement was done in the vacuum condition and the thermal radiation from the specimen was detected by the InSb FPA cooled at 77K through the window of sapphire glass.

Table 1 is a list of a grease compound and its thermal conductivity applied to the interface.

## 3. COMPUTATIONAL PROCEDURE

To analyze the propagation of temperature waves in the experimental system, a one-dimensional heat conduction model is assumed. A film sample with thickness *d* is located between substrates that have known thermal properties and semi-infinite thickness. When a sine temperature wave is generated on the front surface($x=0$), it propagates in the thickness direction to be detected on the rear surface($x=d$). If the temperature wave decays to zero at an infinite position in the substrates, the temperature oscillation $T$ at $x=d$ is described as follows, by solving the one-dimensional diffusion equation:[3]

$$T(d,t) = \frac{\left\{ j_0 \exp(i\omega t)/(1+i) \right\} \exp\left\{-(i+1)kd\right\}}{\left[ (\lambda k+\lambda_s k_s)^2 - (\lambda k-\lambda_s k_s)^2 \exp\left\{-2(i+1)kd\right\} \right] / 2\lambda k} \qquad (1)$$

where $t$ is time, $j_0$ is periodical heat flux described by $j=j_0 exp(i\omega t)$, $i$ is $(-1)^{1/2}$, $\omega$ is angular frequency, $\lambda$ is thermal conductivity, and $\alpha$ is thermal diffusivity, $k$

is $(\omega/2\alpha)^{1/2}$, and subscript $s$ refers to the substrate.

If the conditions of (i) $kd>>1$ or (ii) $\lambda k \approx \lambda_s k_s$ are satisfied, eq. (1) becomes to a simple form and the phase delay is described as follows.

$$\Delta\theta = -\sqrt{\frac{\omega}{2\alpha}}\, d - \frac{\pi}{4} \qquad (2)$$

When the angular frequency is fixed, thermal diffusivity is calculated from the curvature of the relationship between $\Delta\theta$ and d in Eq. (2). To calculate the thermal diffusivity more than 12 sets of the phase vs distance plots are extracted from the pixels.

## 4. RESULTS AND DISCUSSION

Fig.3a is a thermographic photo of three layered polyimide film with a grease compound at the interface when a temperature wave 2Hz is generated on the front surface and propagates in the direction of the right side to the left side. The interfaces between the films are clearly distinguished. Fig.3d shows a waveform observed on a pixel in each layer in Fig.3a. With the increase of the distance from the heater, the phase delays and the amplitude decays. An algorithm for a phase lock-in technique, which is based on Fourier transform with a reference signal selected, is developed originally and the phase image and the amplitude image are calculated, as shown in Fig.3b and Fig.3c.

Figure 4(a) shows IR photographs of temperature wave on the cross section of the three layered polyimide films without any grease compounds at the interface, when a temperature wave of 1Hz is generated on the surface of the right side. The interfaces are clearly observed in Fig.4(a). Fig. 4(b) is the phase shift of the temperature wave calculated by the phase-lock-in technique, plotted against the distance from the heater position. At the positions of both the first and the second interfaces between the polyimide films a large dropping down of the phase is observed, that is polyimide films a large dropping down of the phase is observed, that is originated from the thermal resistance to the propagation of temperature wave in the thickness direction. In the middle layer the phase data is not a linear function of the distance. It is observed clearly that at the interface without any grease compound the phase behaves like out of the rule predicted by eq.(2). The quantity of the dropping down of the phase at the interface is an index of the thermal resistance, listed in Table2.

Figure 5 (a) shows IR photographs of temperature wave (1Hz) on the cross section of the three layered film with a grease compound A, with thermal conductivity $\lambda$=0.194W/mK, at the interface. The interfaces are clearly observed. Fig. 5(b) shows the plot of the phase shift of the temperature wave vs. the distance from the heater position of Fig.5(a). The dropping down of the phase at the interface decreases compared with the case in Fig.4(b), but a curvature of the plot of $\Delta\theta$ vs d in the third layer is not fitted to the theory.

Figure 6(a) shows IR photographs of temperature wave (1Hz) with a grease compound B, with thermal conductivity $\lambda$=0.96W/mK, at the interface. The interfaces are still clearly observed. Fig. 6(b) shows the phase plot against the distance from the heater position of Fig. 6(a). The dropping down of the phase at the interface decreases compared with the case of no grease but it shows a larger value than a grease compound A despite a larger thermal conductivity. In Fig. 6(b) the phase plot shows a linear relationship with d even in the third layer.

Figure 7 (a) and (b) are the IR photographs of cross sections and the phase shifts with a grease compound C, with thermal conductivity $\lambda$=0.72W/mK. The dropping down of the phase shift at the interface is shown in Table 2.

In Table 2 the grease compound reduces the phase shift at the interface, but the thermal conductivity of the grease does not show a clear relationship with it. It suggests that other factors such as the roughness of the surface, the diameter of the particles in the grease compound or the interfacial tension between the grease and the film, are also taken into account to improve the heat transfer at the interfaces.

## 5. CONCLUSION

The IR thermography by the high-speed micro scale FPA was applied to the measurement of thermal resistance in the propagation of temperature wave at the interface of multi-layered polyimide film. The dropping down of the phase shift at the interface was clearly observed and a grease compound made it decreased. The relationship between the thermal conductivity of the grease compound and the phase shift at the interface was not clear. The change of the propagation of the temperature wave at the interface was visualized quantitatively and this method is applicable to the evaluation of the thermal resistance at the interface.

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**FIGURE CAPTIONS**

Fig.1 Schematic diagram of measuring system of IR FPA system.

Fig.2 Schematic diagram of the cross section of the three layer polyimide film.

Fig.3 IR photographs of three layered polyimide film, (a) Real Image, (b)Amplitude image, (c)Phase image and (d) a waveform .at each pixel.

Fig.4 (a) IR photographs of temperature wave on the cross section of three layered polyimide films without a grease, (b) the phase shift plotted against the distance from the heater.

Fig.5 (a) IR photographs of temperature wave on the cross section of three layered polyimide films with a grease of A, (b) the phase shift plotted against the distance from the heater.

Fig.6 (a) IR photographs of temperature wave on the cross section of three layered polyimide films with a grease of B(KS613), (b) the phase shift plotted against the distance from the heater.

Fig.7 (a) IR photographs of temperature wave on the cross section of three layered polyimide films with a grease of C(SCH-30), (b) the phase shift plotted against the distance from the heater.

Table1 Thermal conductivity of a grease compound and the phase delay at the interface calculated by IR thermography.

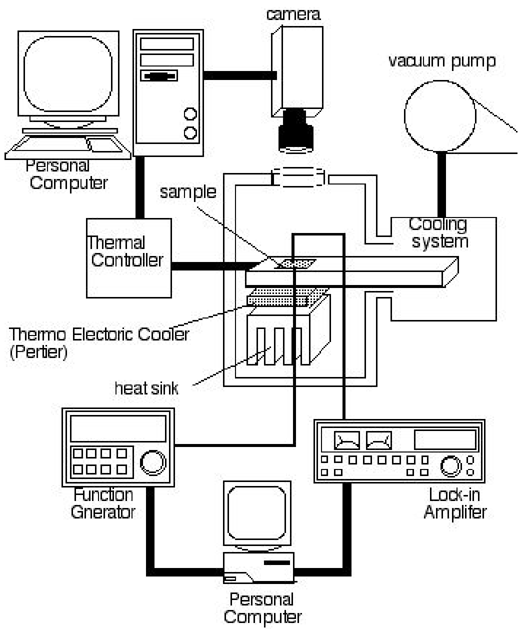



Fig.1 Schematic diagram of measuring system of IR FPA system.

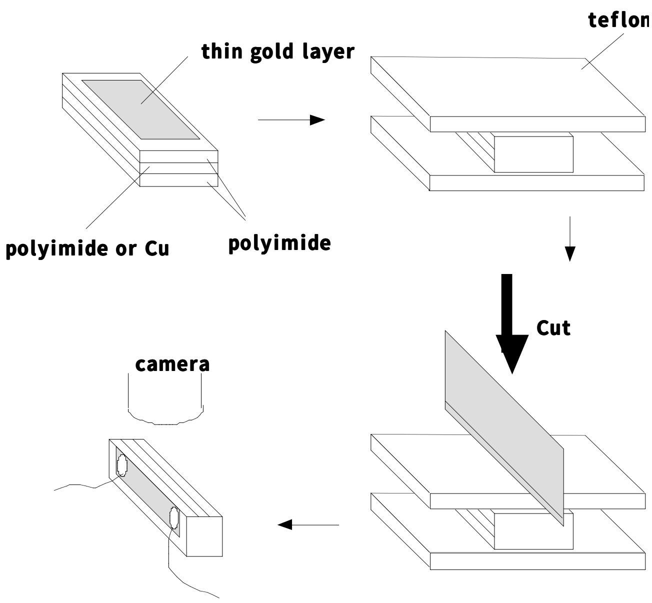



Fig.2 Schematic diagram of the cross section of the three layered polyimide films.

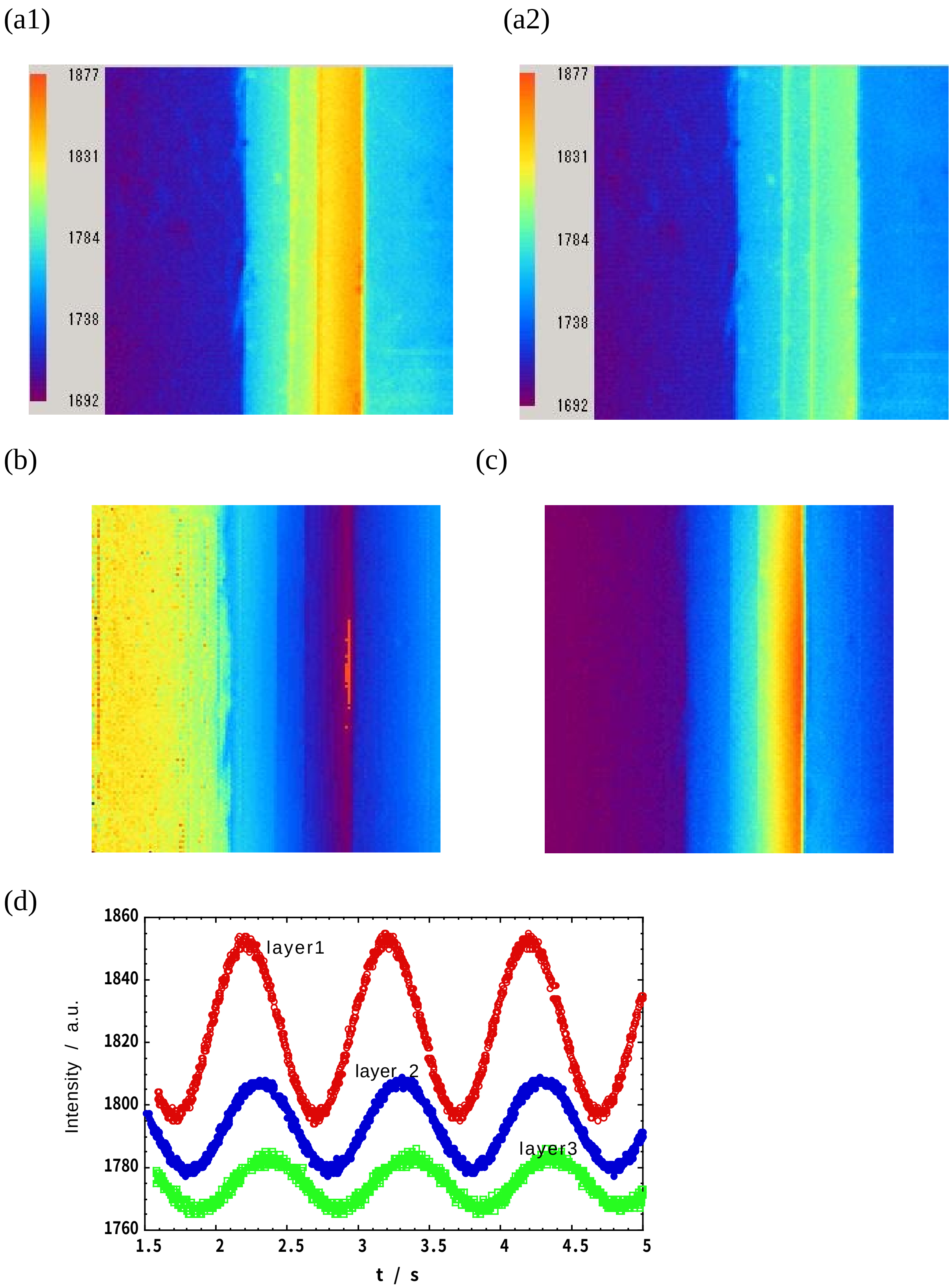
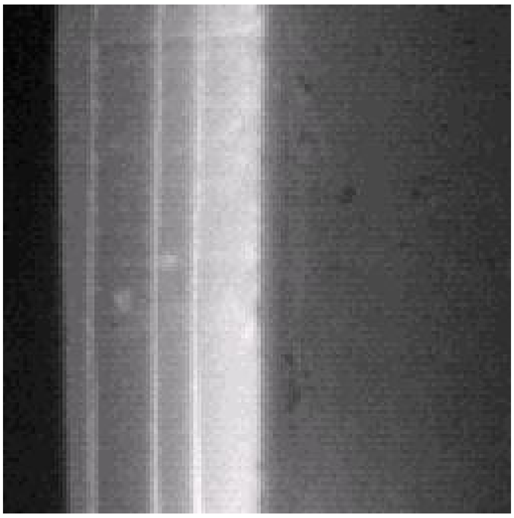



Fig.3 IR photographs of three layered polyimide film, (a1,a2) Real Image, (b)Phase image, (c)Amplitude image and (d) a waveform of temperature wave.

(a)



(b)

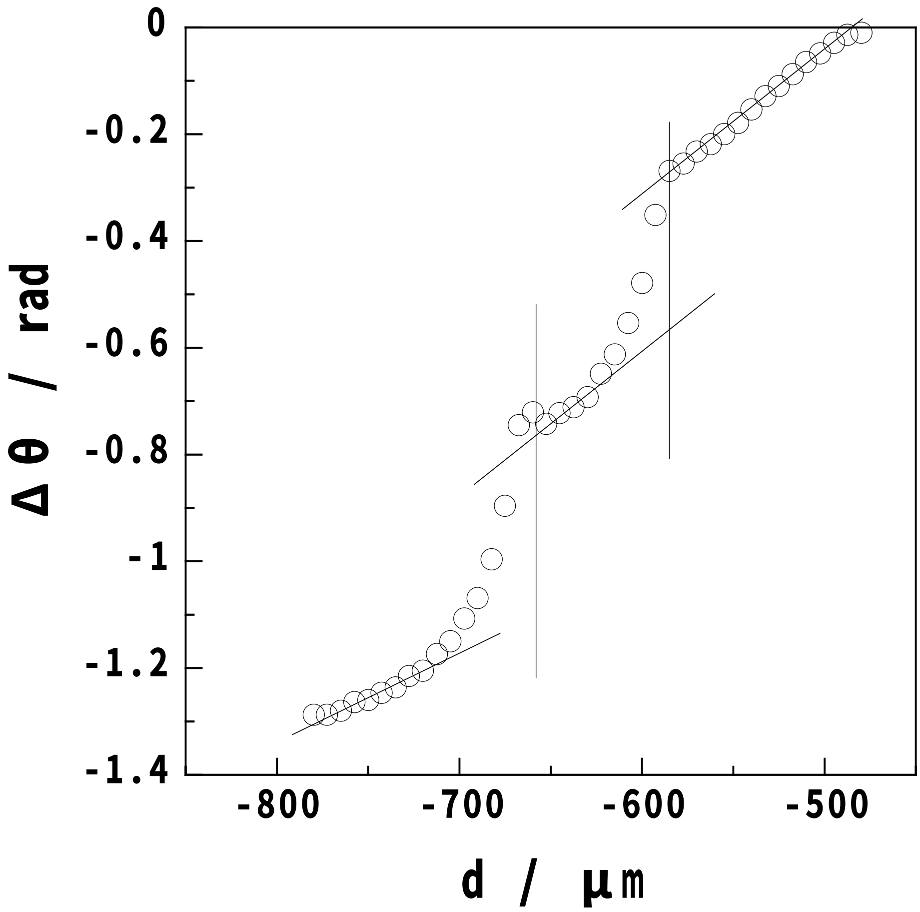
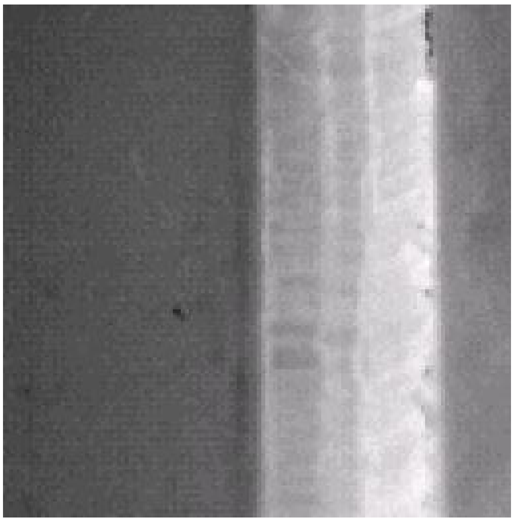



Fig.4 (a) IR photographs of temperature wave on the cross section of three layered polyimide films without a grease, (b) the phase shift plotted against the distance from the heater.

(a)



(b)

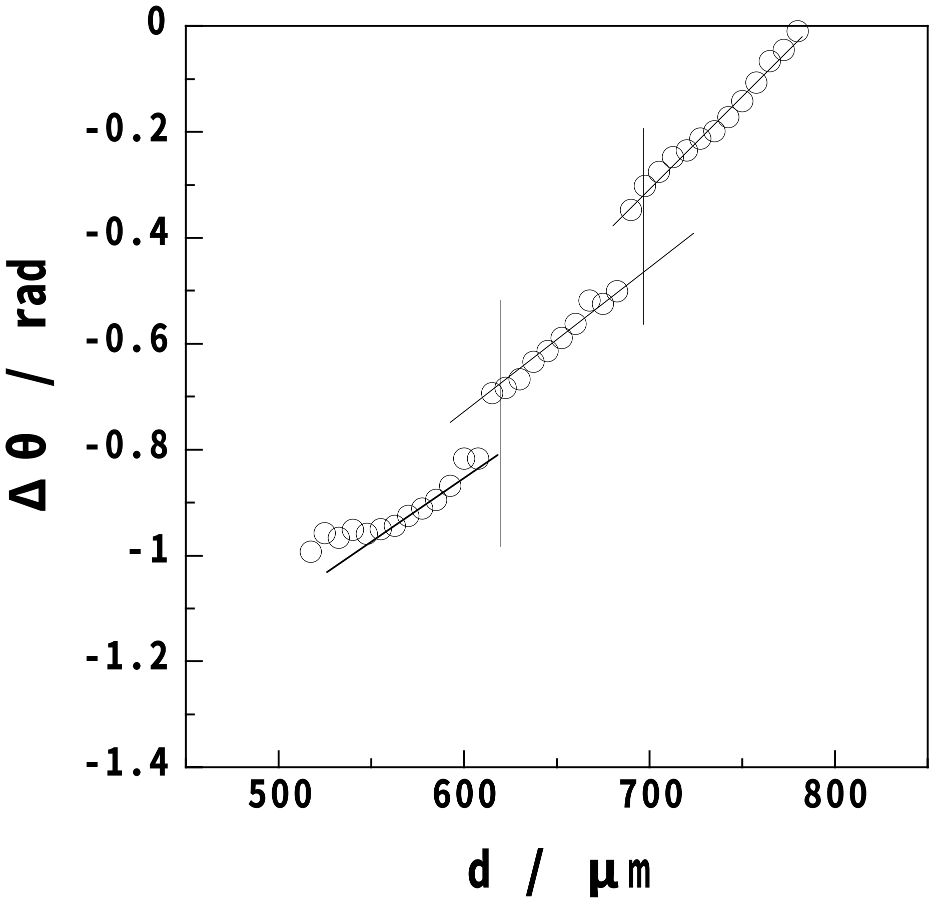
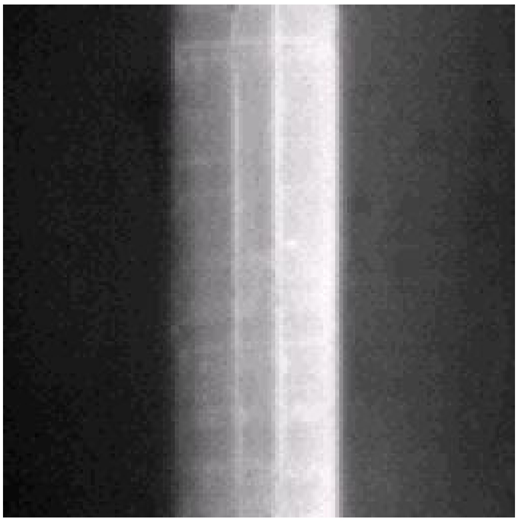



Fig.5 (a) IR photographs of temperature wave on the cross section of three layered polyimide films with a grease of A, (b) the phase shift plotted against the distance from the heater.

(a)



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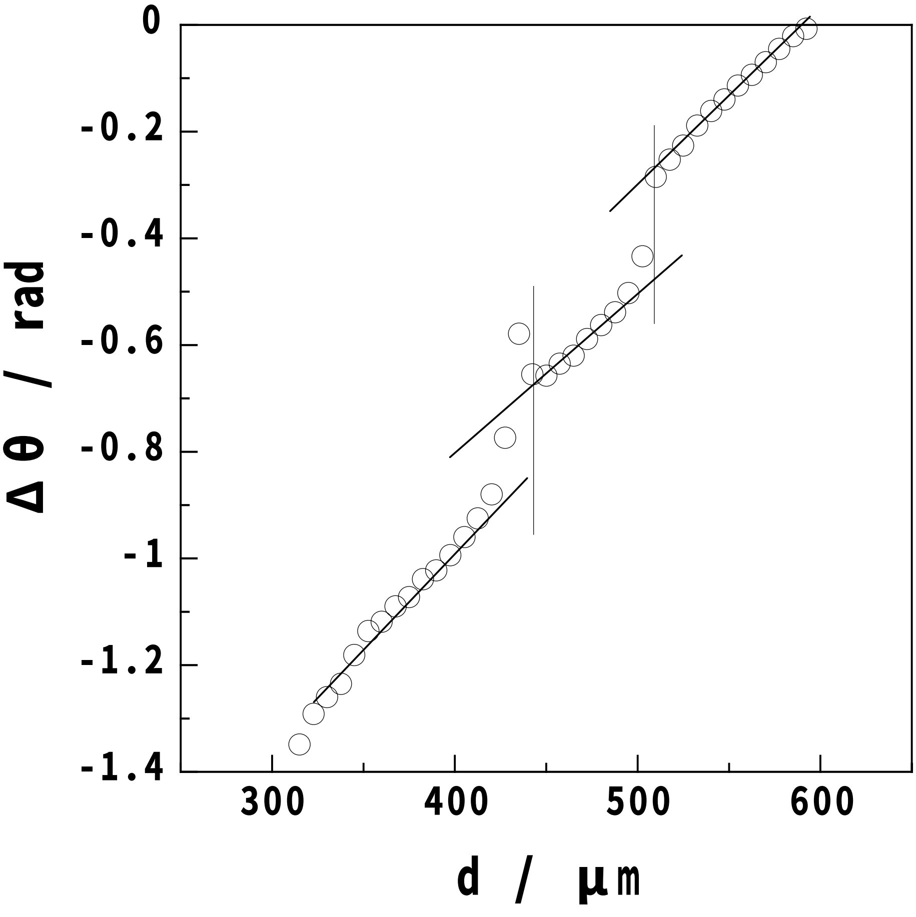
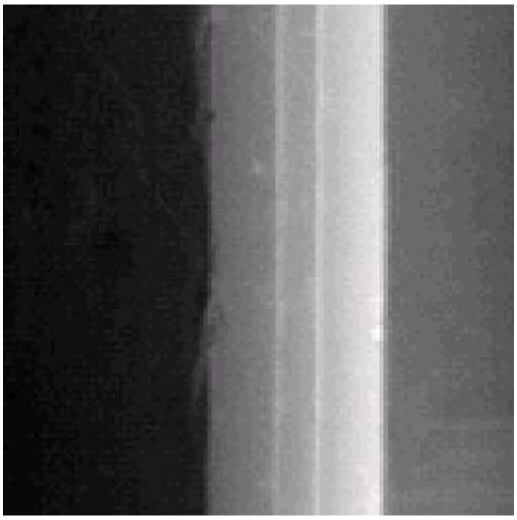



Fig.6 (a) IR photographs of temperature wave on the cross section of three layered polyimide films with a grease of B, (b) the phase shift plotted against the distance from the heater.

(a)



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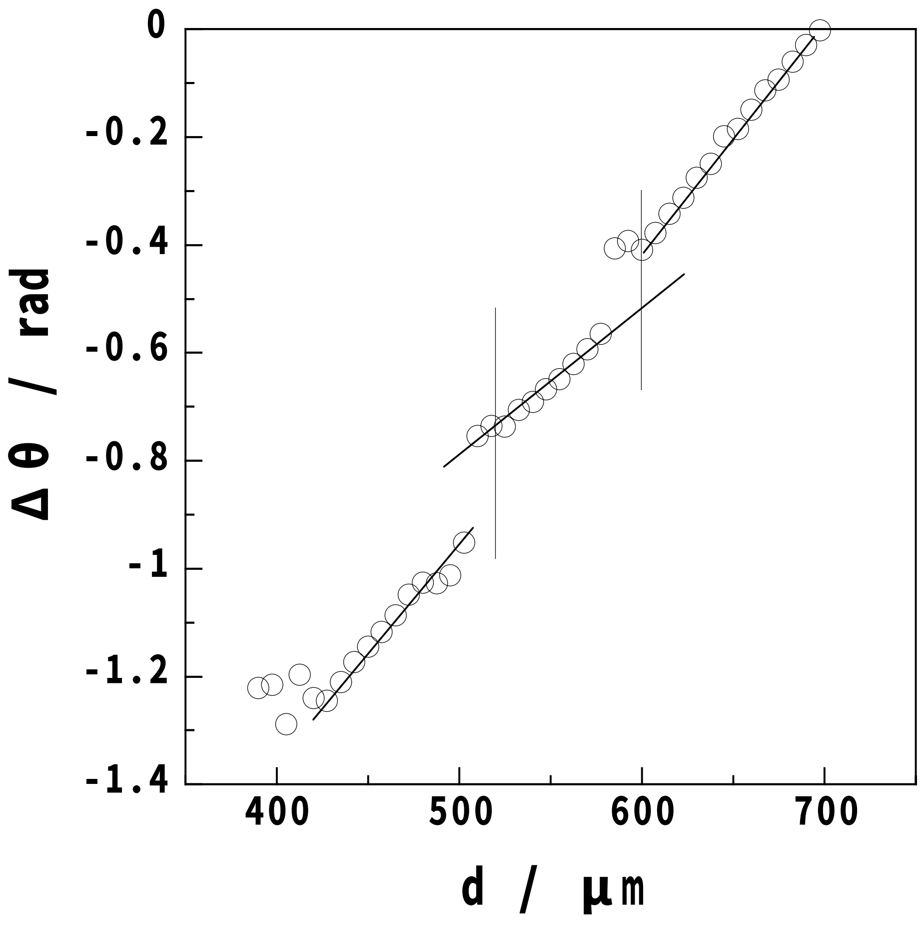


Fig.7 (a) IR photographs of temperature wave on the cross section of three layered polyimide films with a grease of C, (b) the phase shift plotted against the distance from the heater.

Table 1 Thermal conductivity of grease compound.

| Grease compound | Thermal conductivity W / mK | Thermal diffusivity $m^2/s$ |
|---|---|---|
| A | 0.194 | $1.03x10^{-7}$ |
| B | 0.96 | $4.83x10^{-7}$ |
| C | 0.72 | |

Table 2 Phase delay of a temperature wave (1Hz) at the interface.

| Grease compound | $\Delta\theta_{interface}$ / rad |
|---|---|
| no grease | 0.642 |
| A | 0.276 |
| B | 0.387 |
| C | 0.243 |