HIGH SPATIAL, TEMPORAL AND TEMPERATURE RESOLUTION THERMAL IMAGING METHOD USING EU(TTA)3 TEMPERATURE SENSITIVE PAINT

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Abstract: This paper reports a novel non-contact thermal imaging method with high spatial, temporal and temperature resolution for Power MEMS applications. This method uses a temperature sensitive paint (TSP) with europium (III) thenoyltrifluoroacetone (Eu(TTA)$_3$). The fluorescence of Eu(TTA)$_3$ was excited by a short pulsed UV light, and a temporal resolution as high as 0.2 ms was achieved under normal CCD camera observation. Also, a spatial resolution of ca. 13 μm and a temperature resolution of ca. ± 0.2 °C were demonstrated.

Keywords: Temperature sensitive paint, Non-contact thermal imaging

INTRODUCTION

Microscale thermal imaging is important for the evaluation of the microdevices such as LSI and MEMS. Because the heat capacity of the microdevices is quite small, a non-contact thermal sensing method is required. An infrared thermography is used for this purpose. The thermograph converts an incident radiation power into the electric signal, but the incident power strongly depends on an emissivity of the object surface. The emissivity correction is usually performed for precise temperature measurement. In many cases, however, both temperature and emissivity are unknown parameters, and thus precise temperature measurement by thermography is difficult. In addition, high temporal resolution is often required because of small thermal time constant. A thermograph such as a bolometer is too slow to measure such a high speed phenomenon.

A temperature sensitive paint (TSP) is one of the candidates for high speed non-contact microscale thermal imaging. The intensity and lifetime of fluorescence from the TSP are influenced by the temperature. The lifetime of fluorescence is as short as 0.2–0.6 ms [1, 2], which promises a high temporal resolution. Both intensity and lifetime of fluorescence can be used for thermal measurement. If a normal CCD or CMOS camera is used, the former is convenient to use, because such a camera is too slow to observe the lifetime. Kolodner *et al.* used a microscope for high spatial resolution [3] and reported that the temperature resolution was as low as 0.01 °C, while the temporal resolution was not so high. Nagai *et al.* reported a high speed thermal imaging system using a high speed camera [4]. They reported that the temporal resolution was as fast as 1 ms. However, a high cost of the camera diminishes an opportunity to apply this system for wide variety of applications. Therefore, we developed a flash exciting method using a normal CCD camera. Compared with the high speed camera observation method, our approach is advantageous from cost and sensitivity points of view.

PRINCIPLE OF THE MEASUREMENT

Figure 1 shows the principle of the measurement. In this study, a thin film heater is used as a test device to measure. When the heater turns on, the temperature of the test device behaves as a first order lag system. A 0.2 ms pulse of UV light flushes after a time interval Δ*t*, and a momentary fluorescent image, *I*(*x*, *y*), where *x* and *y* are the address of the pixel, is captured using the CCD camera. By changing Δ*t* stepwise, a movie of the high speed thermal phenomenon is obtained.

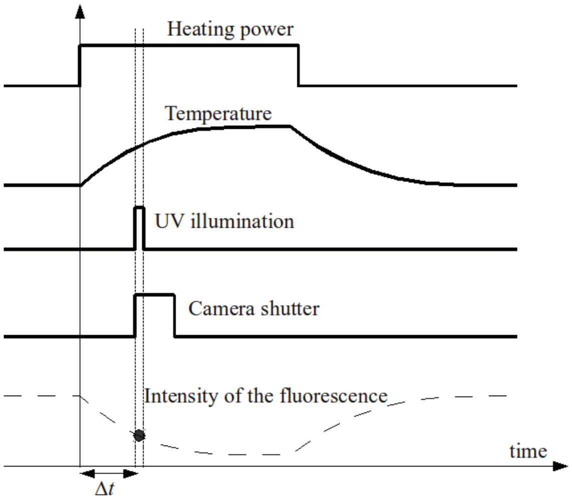

Fig. 1: The principle of the measurement using UV flash method.

CHARACTERISTICS OF THE TSP

We used Eu(TTA)$_3$ as a fluorescent material of the TSP, in which polyvinylbutyral (PVB) was used as a matrix. A methylethylketone (MEK) was used as a solvent of the TSP. The TSP consisted of 0.090 g PVB, 0.033 g Eu(TTA)$_3$ and 1.0 mL MEK. The prepared TSP was spin-deposited on the test device. Figure 2 shows the measurement setup. The temperature of the test device was controlled by a hotplate underneath it. The temperature of the sample was measured by a thermocouple glued on it. The fluorescence was captured by the CCD camera.

Figure 3 shows the temperature dependency of the fluorescence from the TSP prepared by us. The fluorescence of Eu(TTA)$_3$ had negative temperature coefficient of intensity (TCI), which is well knows as thermal quenching [5]. The TCI, *S*, was ca. –2.3 %/K, which is consistent with the previous reported values (–1.23 to –5 %/K) [1, 3].

THERMAL IMAGING SYSTEM

Experimental setup

Figure 4 shows the experimental setup. A 355 nm UV LED was used as an excitation light source. The fluorescence of which the peak wavelength is 612 nm was observed by the CCD camera (Sentech, STC-TB33USB) through the optical band-pass filter.

In this study, two types of thin film heaters were used as observation objects, one of which was a thin film heater deposited on a bulk substrate, the other was a self-suspended thin film. Figure 5 shows the structure of the test devices. There were two heaters on a bulk type test device, as shown in fig. 5(a), one of which was used as a temperature sensor for calibration. A self-suspended thin film type test device consisted of a parylene thin film, a Pt thin film heater and the TSP, as shown in fig. 5(b). A heating signal generator and a delayed pulse generator, which controlled the flush timing of the UV LED and the shutter timing of the CCD camera, were implemented by a micro controller (Microchip, PIC18F2550).

Thermal imaging result

Figure 6 shows the experimental result of the bulk type test device, and inset (a) is the captured fluorescent image without heating. Although the temperature of the device was uniform (= T_0), the intensity of fluorescence, $I_0(x, y)$, was not uniform because of the difference of the reflectivity underneath the TSP. Thus, the thermal image, $T(x, y)$, is calculated as

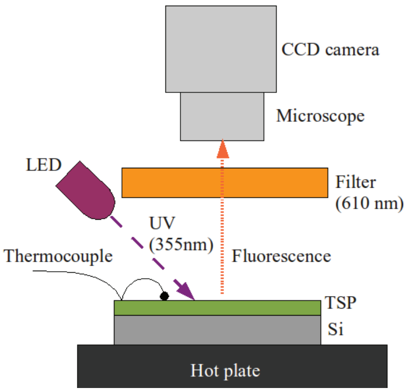

Fig. 2: The experimental setup for TCI measurement.

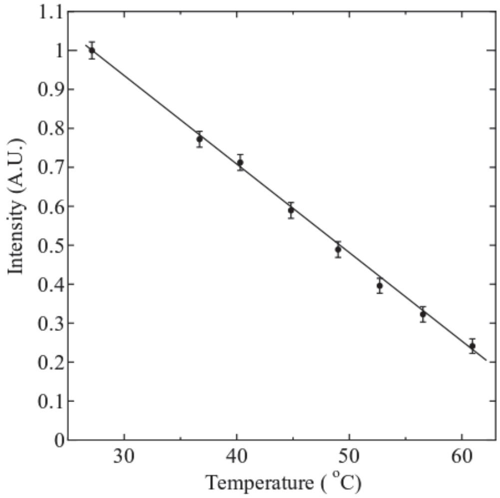

Fig. 3: The temperature dependency of fluorescence from the TSP.

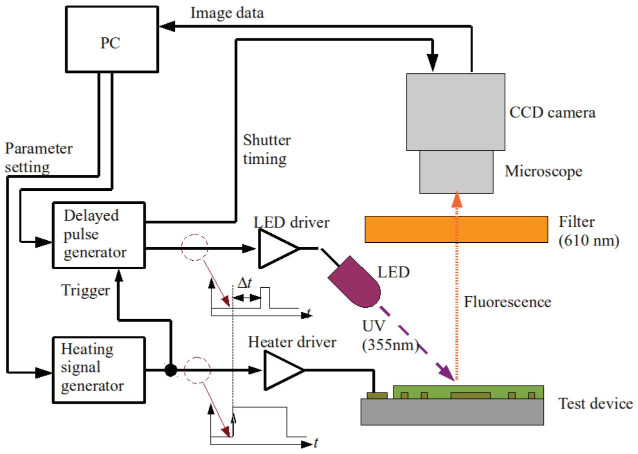

Fig. 4: The experimental setup for thermal imaging.

$$T(x,y)-T_0=S^{-1}\left(\frac{I(x,y)}{I_0(x,y)}-1\right) . \qquad (1)$$

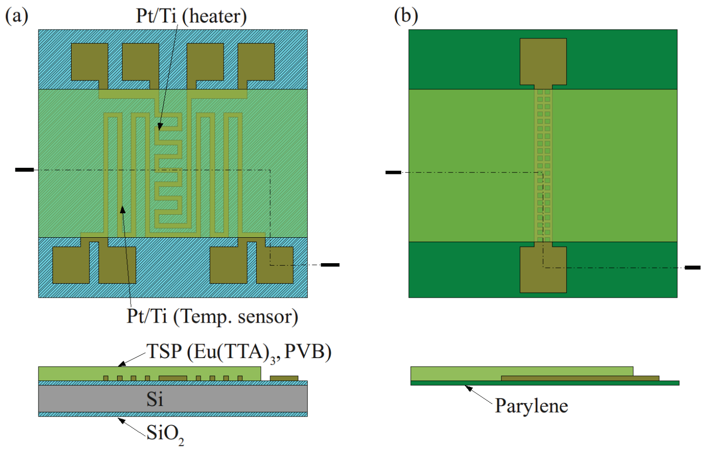

Fig. 5: Test devices. (a) Two heaters are fabricated on the Si substrate. One of them is used as a reference temperature sensor. (b) A thin film heater is on a parylene thermal isolation membrane.

Figures 6(b) to (f) show the thermal images obtained using eq. (1). Dashed rectangle in the figures indicates the heating region. Figure 6(b) is a thermal image corresponds to the fig. 6(a), i.e. the temperature of the sample was uniform. A heating pulse with a duration of 50 ms started at $t = 0$ ms. The temperature of the heater rose within the heating period (Figs. 6(b) to (e)). The thermal diffusion process was successfully observed within the cooling period, which started at $t = 50$ ms (Figs. 6(e) to (f)). Figure 7 shows the thermal response at several points of the test device. As expected, a temperature on the heater (solid circles and triangles in Fig. 7) behaved as a first order lag system. On the other hand, the temperature response was delayed at the points away from the heater because of the finite thermal propagation velocity. The temperature resolution was as good as ± 0.2 °C.

Figure 8 shows the temperature distribution of the self-suspended thin film type test device. Heating pulse width was 20 ms. As found in Figs. 8 (a) to (d), hot spots were clearly observed, and their time response by thermal diffusion in the cooling period was successfully tracked. The hot spots were generated due to cracks in the flexible thin film heater shown in Fig. 9.

DISCUSSION

A pixel of the captured image corresponds to an area of 13 × 13 μm^2, i.e. the spatial resolution is 13 μm. The spatial resolution can be enhanced up to diffraction limit with an appropriate high magnification optical system. In this system, the CCD camera has a 8 bit resolution, which results in the temperature resolution as low as 0.17 °C. The obtained temperature fluctuation (± 0.2 °C) was same order of magnitude. A higher resolution camera

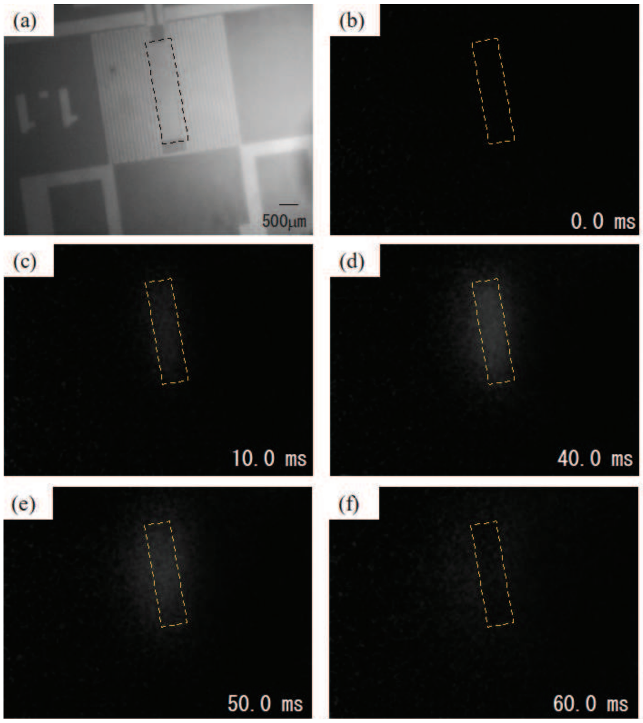

Fig. 6: (a) A captured fluorescent image without heating and (b) a thermal image obtained using eq. (1). Thermal images within a (b)-(e) heating period and a (f) cooling period. Dashed rectangle indicates the heating region.

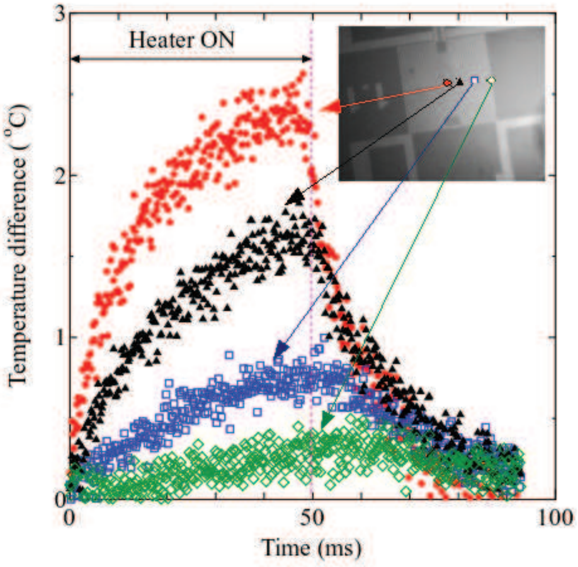

Fig. 7: The temperature response of several points of the sample. Measurement points are indicated on the inset picture.

enables more precise measurement, e.g. a 12 bit resolution camera may provide a temperature resolution as low as 0.01 °C.

The temporal resolution of the system is decided by the pulse width of the UV flash. The maximum resolution is limited by the response time and the lifetime of fluorescence (ca. 0.2–0.6 ms)[1, 2]. The obtained temporal resolution was 0.2 ms, which is almost as high as the theoretical maximum temporal resolution.

This TSP can be easily removed by an organic solvent such as ethanol, which does not damage the observation object. This thermal imaging system only needs the TSP easy to prepare and a few optical elements, and thus it is easy to apply to wide variety of Power MEMS applications.

CONCLUSION

We demonstrated a novel high spatial, temporal and temperature resolution non-contact thermal imaging system using Eu(TTA)$_3$ temperature sensitive paint (TSP). The LED flashing method enabled the high temporal resolution with a normal CCD camera. The intensity of fluorescence from the TSP was able to be successfully modulated by the temperature of a test device. The sensitivity of the TSP was ca. –2.3 %/°C. The obtained spatial, temporal and temperature resolutions of the thermal imaging system were ca. 13 µm, 0.2 ms and ± 0.2 °C, respectively.

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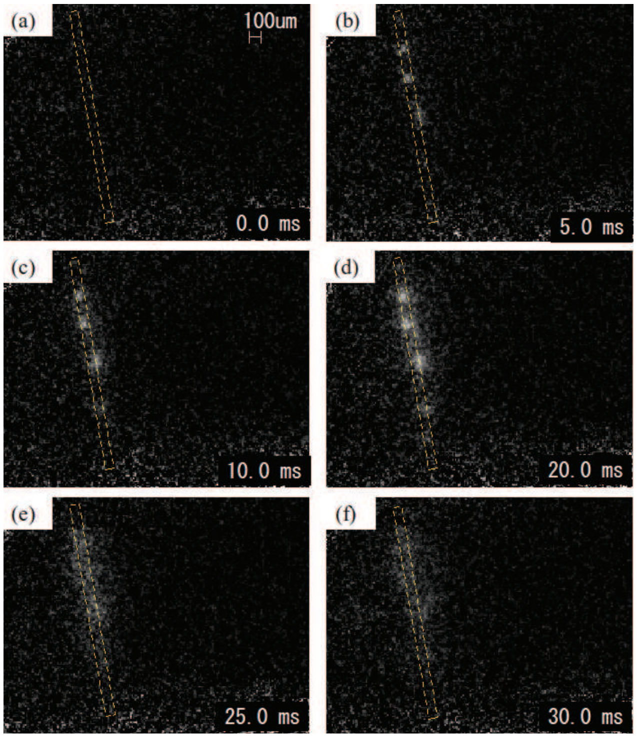

Fig. 8: Thermal images of the self-suspended thin film test device. Dashed rectangle indicates the area of the heater. Some hot spots are observed during the (a)-(d) heating period and dissipate to the surroundings during the (e),(f) cooling period.

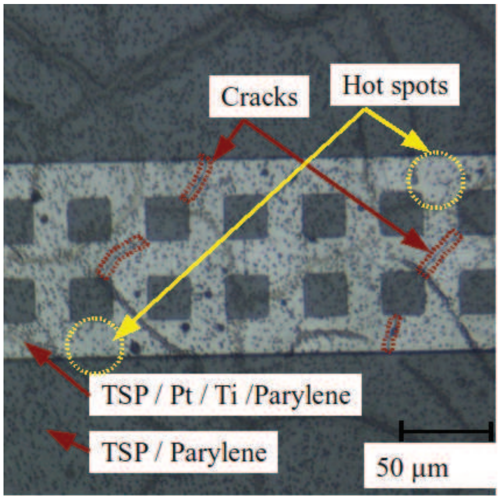

Fig. 9: Cracks on the thin film heater.