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Dual luminescent arrays sensor fabricated by inkjet-printing of pressure- and temperature-sensitive paints

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ABSTRACT

A novel dual luminescent sensor, which consists of discrete dot arrays of pressure- and temperature-sensitive paints (PSP and TSP), has been developed for a precise pressure measurement on a solid surface. The sensor arrays were well-ordered by inkjet-printing of PSP and TSP solutions. Since pressure- and temperature-sensitive luminophores are isolated from each other, the dual luminescent arrays sensor avoids the interaction between the two luminophores that has been one of the major issues of conventional dual luminescent sensors. It is an advantage of the dual-array sensor that an optimal solvent and an optimal binding material can be used for each luminophore. In this study, a 2-propanol solution of PtTFPP and a toluene solution of ZnS–AgInS_2 (ZAIS) nano-particles were employed as PSP and TSP solutions, respectively. The newly developed dual-array sensor could prevent the interaction between PtTFPP and ZAIS that was observed in the mixture sensor of these luminophores, and had comparable pressure and temperature sensitivities with conventional PSP or TSP. Moreover, the pressure distribution on the surface with a non-uniform temperature distribution was successfully measured by the dual-array sensor.

1. Introduction

The pressure-sensitive paint (PSP) measurement technique has been studied for several decades [1,2]. PSP is a pressure sensor based on oxygen quenching of a luminescence from luminophore in the paint; the luminescence intensity varies with a variation in oxygen concentration or pressure. In general, the luminescence intensity also decreases with an increase in temperature. Therefore, it is required to correct the temperature effect on the PSP results for precise pressure measurements.

Non-intrusive temperature sensors such as an IR camera and temperature-sensitive paint (TSP) have attempted to be utilized for the temperature correction of the PSP result. However, the use of an IR camera makes the measurement system complicated [3], and also has other issues such as a low spatial resolution of an IR camera and radiation from other surrounding heat sources. On the other hand, most of the apparatuses for the TSP measurement are the same as those for the PSP measurement. The temperature correction for a symmetric model was carried out by coating PSP and TSP on the starboard- and port-side of the model surface [4,5]. Dual luminescent sensors using PSP and TSP, such as a mixture sensor [6–10] and a multi-layer sensor [11,12], have been proposed for the application to general asymmetric flow fields. A mixture sensor is applied to a model surface by simply coating a mixture solution of PSP and TSP. However, some luminophores were reported to change properties when mixed with other luminophores, e.g. degradation of photostability under an illumination [9,10], and reduction in a luminescence lifetime [6]. These are caused as a result of the interaction between the pressure- and temperature-sensitive luminophores such as energy transfers from the pressure-sensitive luminophore to the temperature-sensitive luminophore and vice versa [6,13]. Some studies proposed isolating the pressure- and temperature-sensitive luminophores from each other to avoid the interaction by encapsulating the luminophores [6–8]. The method imposes a restriction on the selectivity of materials; all materials have to dissolve in one solvent. A multi-layer sensor was fabricated by coating a PSP layer on a TSP layer with a medium layer added between the PSP and TSP layers to prevent the interaction between the pressure- and temperature-sensitive luminophores [12]. It should be noted that a low heat conductivity of polymers of the layers induces a considerably large temperature gradient in the layer-thickness direction (the normal direction to the surface). Nagai et al. [14] experimentally showed that a measurement error of TSP increased with the thickness of the layer. Egami et al. [15]

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reported that polymer coatings enlarged temperature variation on a model surface. These results suggest that a multi-layer sensor is not preferable as a dual luminescent sensor.

We have developed a novel dual luminescent sensor to overcome the difficulties with the above conventional methods. The dual luminescent sensor is composed of tiny discrete dot arrays of PSP and TSP (see Fig. 1) fabricated by means of inkjet-printing. The static properties of the dual luminescent arrays sensor (the emission spectrum and the pressure and temperature sensitivities) were investigated. Then, the capability of the dual-array sensor was examined by applying it to a pressure measurement on a surface with non-uniform temperature distribution.

2. Dual luminescent arrays sensor

2.1. Features

The dual-array sensor is comprised discrete dot arrays of PSP and TSP; respective dots are painted in a staggered arrangement as shown in Fig. 1. Since the pressure- and temperature-sensitive luminophores are isolated from each other, the interaction between pressure- and temperature-sensitive luminophores is prevented. Moreover, a solvent and a binding material, which generally affect on properties of the paints [16,17], can be independently adopted for each luminophore. On the other hand, both the luminophores are regarded as uniformly coated in the captured luminescence image, when the sizes of the dots are adjusted to be enough small compared with the pixel size of the captured image (e.g. by capturing the image far enough from the sensor, or by adjusting the size of the dots and the distance between the dots). This maintains a high spatial resolution, which is one of great advantages of the PSP and TSP measurements, and the sensor is applicable to asymmetric flow fields. Thus, the dual-array sensor has a lot of advantages.

2.2. Materials and sensor fabrication

Platinum tetrakis(pentafluorophenyl)porphyrin (PtTFPP) was employed as a pressure-sensitive luminophore because of its high pressure sensitivity around an atmospheric pressure. The absorption and emission spectra of PtTFPP have peaks around 395 nm and 650 nm, respectively [2,18,19]. We focused on ZnS–$AgInS_2$ (ZAIS) nano-particles [20,21] as a temperature-sensitive luminophore. ZAIS is one of quantum dots and has following notable features: (i) tunable peak wavelength of the luminescence from 530 nm to 750 nm by varying the composition x in the precursor, $(AgIn)_xZn_{2(1-x)}(S_2CN(C_2H_5)_2)_4$, (ii) high quantum yield from 20% to 80%, and (iii) broad absorption spectrum from UV light to visible light. We adopted ZAIS (x = 0.4) (hereinafter referred to as simply "ZAIS"), whose luminescence peak is at 530 nm. ZAIS was prepared according to the procedure described in the literature [20]. PtTFPP and ZAIS can be excited with a single light source, because both luminophores commonly have absorption bands around 400 nm. The luminescence can be easily separated from each other with optical filters, because PtTFPP and ZAIS luminescence have almost no spectral overlap. A commercial-available thin-layer chromatography (TLC) aluminum plate (Silica gel 60, Merck) was adopted as a binding material for both luminophores.

The dual-array sensor was fabricated by inkjet-printing of solutions of PtTFPP and ZAIS. The solution of PtTFPP was prepared by dissolving the luminophore in a 2-propanol at a concentration of 0.15 mg/mL. ZAIS obtained from the precursor of 50 mg was dissolved in a toluene of 15 mL. Note that different solvents were used for each luminophore here due to following reasons: (i) ZAIS cannot dissolve in a 2-propanol, and (ii) although PtTFPP can dissolve in both toluene and 2-propanol, luminescence intensity of the 2-propanol solution is obviously (more than fifteen times) higher than that of the toluene solution when the solutions are applied to the TLC plate. Therefore, we adopted a 2-propanol for PtTFPP and a toluene for ZAIS; this is an advantage of the dual-array sensor as mentioned in Section 2.1. The solutions were printed on the TLC plate with two inkjet nozzles with the diameter of 100 μm (IJHB-1000, Micro Jet). Dot patterns of PtTFPP and ZAIS were formed by moving the TLC plate with an XY-stage. The solutions were ejected drop by drop for smaller dot size, and the process was repeated ten times; ten droplets in total were printed at each dot. The diameter of the painted dots was about 0.3 mm; thus the center-to-center distances of the respective dots were set to 0.6 mm in order not to spatially overlap with neighboring dots.

2.3. Luminescence images

The prepared dual-array sensor coupon was illuminated by an LED unit with a central wavelength of 395 nm (LEDH294-395, Hamamatsu Photonics). Close-up luminescence images of the dual-array sensor are shown in Fig. 2. The luminescence image of Fig. 2(a) was captured by a color camera with a long-pass filter of 480 nm (SCF-50S-48Y, Sigma Koki) in order to simultaneously observe both the red luminescence of PtTFPP and the green luminescence of ZAIS. Fig. 2(a) shows that the PtTFPP and ZAIS arrays are spatially isolated from each other. The luminescence images of Fig. 2(b) and (c) were captured by a monochrome camera with a band-pass filter of 690 ± 60 nm (PB0144, Asahi Spectra) and that of

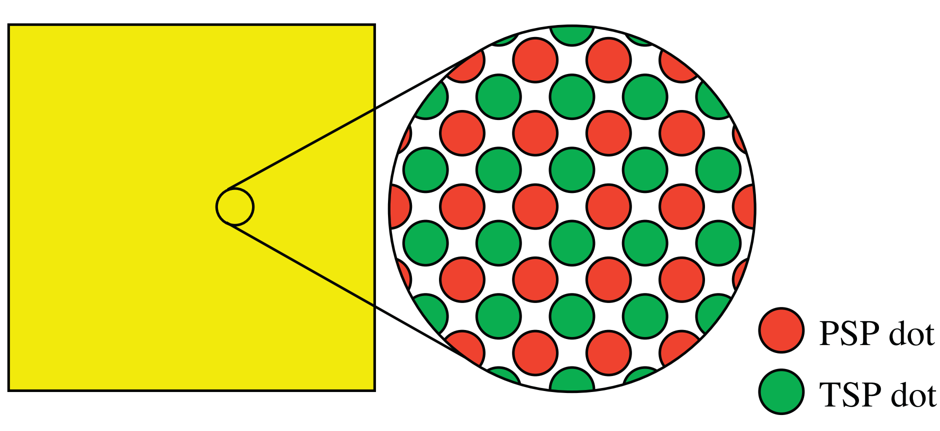

Fig. 1. Dual luminescent arrays sensor.