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Thermopile IR Detector Integrated with Wavelength Selective Filter Stable against Temperature and Incident Angle Change

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1. Introduction

Backgrounds

Recently, there are growing needs for simple and convenient methods to detect or measure the amount of substances. Detections using light, especially mid-infrared (MIR) spectrum, are attractive for their robust and long term stable natures. MIR spectrum gives the selective detection based on the uniqueness of the absorption spectrum which each substance have. Possible application fields for the sensor extend from home appliances (e.g., fire alarm, heating, ventilation, and air conditioning (HVAC) systems) to industrial and medical instruments (e.g., air pollution monitoring, capnography). For further acceptance from the market, the sensor is expected to be small in size and stable against environmental changes. IR detectors for detecting MIR regions play the essential role of measuring the amount of molecules of interest, based on the absorption. Thermal IR detectors are promising candidates since they can operate at room temperature and have relatively broad spectral responses over wide range of wavelengths, which cover many specific peaks of substances. The spectral response of the detectors is characterized as flat [1]. In order to measure a specific molecule of interest, the detectors are usually equipped with dielectric multilayer bandpass filters (BPFs).

Desirable specifications for further downsizing

Most of the commercially available detectors are equipped with one or more BPF(s), hermetically encapsulated in a metal package, like a TO can, which is usually several millimeters in its dimensions. The BPF generally have incident angle and polarization dependences. [2]. Size of an optical cell dominates the dimensions of a sensor module, while longer optical path length gives more degree of freedom to the specifications, such as measurement range and accuracy, of the sensor. The sensor module available on the market today is about 5cm × 5cm in size. For automobile devices, as an example, less than 1/2 of the size is expected. For further downsizing of the sensor, multiple reflections inside the optical cell are effective to resolve the discrepancy between smaller optical cell and longer optical paths. Smaller detector dimensions and the detector's insensitivity to conditions of incident light may contribute in more flexible optical cell design.

Issues for realizing accurate sensors

Temperature affects the passband of BPFs [2]. Onoda *et al.* pointed out the major factors which triggers the center wavelength shift [3]. When the layered material expands, changing its thickness, the passband shifts towards the longer wavelength. One of the methods to compensate the temperature dependence is to choose the substrate material which has a larger thermal expansion coefficient than that of the film materials [4]. The expansion of the substrate works for thinning the film layer. For MIR region, one example is CaF_2 which is characterized with its large thermal expansion and small temperature coefficient of refractive index [5]. However, due to its brittleness and low thermal conductivity, dicing processes of CaF_2 based BPFs seems to have some difficulties. Up until today, most commercially available detectors equipped with multilayer BPFs still rely on Si or Ge substrate materials. So, the large temperature dependence still exists.

In this study, we propose a MIR detector integrated with wavelength selective filter. The center wavelength is stabilized compared with the commercially available thermopile detector with BPFs.

2. Detector Design and Fabrications

The operating principle of the thermal detector is based on the temperature increase of a certain area of the detector and its conversion to electrical signal. For thermopiles, the increase is converted to the voltage by Seebeck effect. The responsivity $\Re_v$ of the thermopile detector is generally given by

$$\Re_v(\lambda) = \frac{\Delta V}{\phi_e} = \frac{n \cdot S \cdot \varepsilon(\lambda)}{K}(1 - \exp(\frac{K}{C} \cdot t)) \quad (1)$$

where n is the number of thermocouples connected in series, S is Seebeck coefficient, C is heat capacity of the absorber, K is thermal conductance between the absorber and the heat sink, ϕ_e is the incident IR power, $\varepsilon(\lambda)$ is emissivity of the absorber. Eq. (1) shows that certain degree of wavelength selectivity can be integrated by selecting an absorber which has the spectral emissivity with acute peak at desired wavelength.

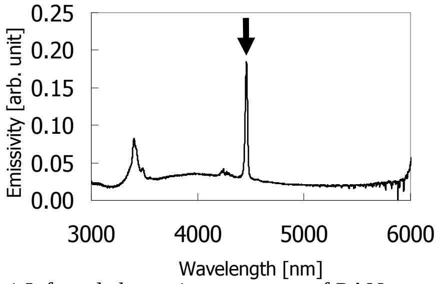

Fig. 1 Infrared absorption spectrum of PAN

In this study, polyacrylonitrile (PAN) is used as the absorber material. PAN has acute peak at λ_{peak}=4458nm with FWHM of 25nm, as shown in Fig. 1. $\varepsilon(\lambda)$ will be larger compared to other wavelengths. The absorption is induced by the stretching of C≡N bond, which has relatively small temperature dependence on the center wavelength shift, as reported on previous study [6]. The spectral responsivity of the fabricated detector is expected to show stable center wavelength against temperature change.

Fig. 2 shows a fabricated detector. The size of the thermopile sensor used is 2mm × 2mm and consist of 64 thermocouples in total. The central part of the sensor is a diaphragm, fabricated by anisotropic etching of silicon. The thermopile, comprised of platinum and highly doped p-type silicon, has hot junctions on the diaphragm and cold junctions on the substrate which act as a heat sink. The absorber material is formed onto the diaphragm and the hot junctions. PAN on the diaphragm is designed to convert the incident IR light at λ_{peak} efficiently to heat. A solution of the absorber material is prepared and dispensed using a manipulator. The PAN bump with ~8μm in thickness is obtained. The volume increase of the detector is 0.14%.

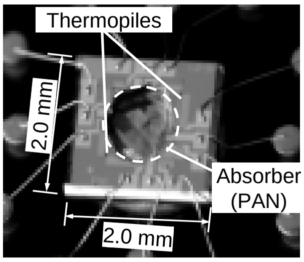

Fig. 2 Fabricated thermopile detector with PAN bump as a wavelength-selective absorber material.

3. Results and Discussions

MIR Spectroscopic Characteristic of the detector

Fig. 3 shows spectral responses from detectors with PAN (close circles) and without PAN (open circles) on the diaphragm. At λ=4450nm the detector with PAN has a peak output of +0.25μV or +35% increase from baseline. The peak showed a good correlation with the intrinsic emissivity of PAN.

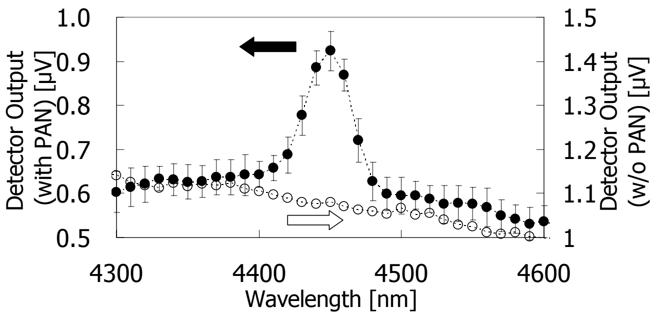

Fig. 3 Spectral responses of the fabricated detector with PAN (close circles) and without PAN (open circles)

Temperature stability of the center wavelengths

Fig. 4 shows temperature stability of the center wavelength (TSCW) for the fabricated detector and a detector with BPF on Si substrate. The temperature is raised up to 80°C, which is generally an upper limit for automobile electronic devices. The close circle data of the fabricated detector are obtained by FTIR, since the detector shows small shift that the resolution of the monochromater can not detect the shift. The temperature sensitivities of dielectric multilayer BPF and PAN absorber are 0.83 and 0.038 nm/°C, respectively. The fabricated detector performed better stability of the center wavelength. FWHM of ROIs for many gases are 80-270 nm. The dielectric multilayer has the risk of passband to deviate from ROI. In contrast, the detector with PAN absorber shows only +2.5nm shift, which is well inside ROI.

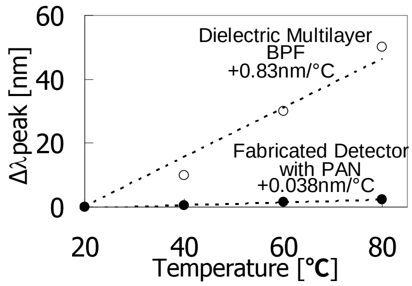

Fig. 4 The center wavelength shifts due to temperature change for the detector with dielectric multilayer BPF (open circles) and the fabricated detector (close circles)

4. Conclusions

A new method to integrate wavelength selective filter into the thermopile detector using absorbance spectrum of a polymer material is introduced. The fabricated detector shows ~0.25μV or 35% increase from baseline at λ_{peak} of the absorber. TSCW of the fabricated detector over the temperature range from ~20°C to 80°C is +0.038%/°C. The detector is expected to have no angular dependence. These features will contribute to the downsizing of the sensors. Improvements on dispensing processes of the absorber may contribute to the further increase to the peak output.

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