Paper

Conical Cavity Type Thermal Radiation Detector with Gold-Black Coating

Yoshikazu ARAKI

Saitama Institute of Technology, Department of Engineering, Faculty of Electronic Engineering

Received July 7th 2001, Accepted January 20th 2002**ABSTRACT**

The author fabricated a plain type thermal radiation detector with evaporating gold-black as the surface absorbent attached to a thermoelectric detector. The spectral responsivity of the thermal radiation detector under different evaporating conditions was investigated and the best condition for the highest degree of spectral responsivity is reported. The relative spectral responsivity of the thermal radiation detector with gold-black absorber against the thickness of the gold-black was explained with proposed plain type models. In the proposed plain type models, incident radiant energy is absorbed near the surface and transmitted through the gold-black absorber as heat. There were two kinds of the proposed plain type models, one was called the lumped constant model and the other was called the distribution constant model. Each model has two types. The best proposed model to fit the measured results was the distribution constant model 2, which contained reflection at the interface of the absorber and the PVDF pyroelectric film. To attain a very sensitive thermal radiation detector with constant spectral responsivity, which is constant within $\pm 1\%$ over a measured wavelength region, conical cavity type detectors were fabricated. Experimental samples were made to study the dependence of the effective reflectance of a conical cavity type thermal radiation detector on reflectance of the absorbent on the cone and the cone apex. The decrease in the effective reflectance for a conical cavity type was explained using a proposed conical cavity type model, which contains the first reflection, and the second repeated mutual reflections.

KEYWORDS: thermal radiation detector, absorptance, reflectance, conical cavity, model, spectral responsivity

1. Introduction

A radiation detector with constant spectral responsivity is needed as a reference standard when we measure the optical radiation energy and the spectral responsivity of a radiation detector. Until now a thermal radiation detector has been used as the reference standard of the detector. A thermal detector is one of the photo sensors, which absorbs optical radiation and transfers it to heat. Then an increase in temperature generates an electric signal through a thermoelectric or pyroelectric effect. Although the spectral responsivity of a thermal radiation detector has been considered to be dependent on spectral absorption characteristics of the receiving surface, it has not been investigated thoroughly yet.

Therefore the authors fabricated a plain type thermal radiation detector with evaporating gold-black as the surface absorbent attached to a thermoelectric detector. The spectral responsivity of the thermal radiation detector under different evaporating conditions was investigated and the best conditions for the highest degree of spectral responsivity that is constant within $\pm 1\%$ over a measured wavelength region were reported ¹⁾. The dependence of the relative spectral responsivity of a thermal radiation detector on the thickness of the gold-black layer was studied using proposed plain type models that consider absorption and reflection of incident radiant energy within the absorber ²⁾. In the proposed plain type models, incident radiant energy is absorbed near the surface and transmitted through the gold-black absorber as heat. The proposed plain type models were formulated, and the absorption and loss coefficients were estimated using the formulation and real data.

In an effort to gain more accurate proposed models, incident radiant energy was assumed to be absorbed gradually within the absorber and transmitted through it as heat. The dependence calculated using the proposed plain type models corresponded well with the experimental data.

In order to attain a high sensitive thermal radiation detector with constant spectral responsivity, conical cavity type detectors were fabricated ³⁾. The detectors were expected to increase effective absorptance through repeated mutual reflections. The dependence of the effective reflectance of a cavity type thermal radiation detector on reflectance of the absorbent on the cone and the cone apex were studied by making experimental samples. Using the samples, data concerning the correlation between the cone apex angle (90° , 60° , 45°) and the various reflectance ($0.1 \sim 0.6$) of the absorbents on the cone was obtained. The dependence of the effective reflectance of the conical cavity on the reflectance of the absorbent on the cone was formulated with the proposed conical cavity type model considering the first reflection for uniform incident energy and the second repeated mutual reflections. The proposed conical cavity type model illustrates the dependence of the effective reflectance on the reflectance of the absorbent well.

2. Sample Preparation

Two kinds of thermal radiation detectors were fabricated. One was a plain type with and the other being a conical cavity type. Both were covered with either an evaporating gold-black or various reflectance of the absorbent. A gold wire was attached to a filament and was heated and evaporated in a Nitrogen (N_2) atmosphere. The evaporated gold is then cooled by the surrounding N_2 gases into liquid state particles which become colloidal gold particles about 10 nm in diameter and adhere to one another in porous structures. Then these particles become solid metallic gold soot and demonstrate a high absorptance as incident radiation is repeatedly reflected and absorbed.

The thermoelectric element used under the test was a PVDF pyroelectric film with evaporated Al electrodes on each surface made by Kureha Chemicals. It was fixed on a plastics

Fig1 Sample configuration.

ring (outer diameter 12mm, thickness 1mm) with an epoxy type adhesive. An evaporation mask to confirm surface pattern (10mm Φ) was used as upper heat sink. This prevents the pyroelectric film from increasing in temperature during evaporation. The density and thickness of the gold-black layer was controlled by varying the amount of evaporated gold and N_2 pressure in the bell-jar.

The thickness was measured using a cross-section photograph taken with a scanning electron microscope. The density was calculated from the thickness of the film measured by subtracting the weight from the weight after evaporation of the gold-black layer.

Both a plain type and a conical cavity type detector with evaporated gold-black were used to ascertain the ideal conditions for the highest level of spectral responsivity, and to attain a high sensitive thermal radiation detector with constant spectral responsivity.

Experimental samples with various reflectance of the absorbent (gray paint) were fabricated to investigate the dependence of the effective reflectance of a cavity type thermal radiation detector on reflectance (0.1~0.6) of the absorbent on

the cone and the cone apex angles (90° , 60° , 45°).

Fig.1 shows 3 typical sample configurations. They are respectively (a) a plain type covered with gold-black, (b) a plain type experimental sample and (c) a conical cavity type experimental sample.

3. Measurement

Spectral absorptances of the sample detector (DUT: Device Under Test) were measured using the optical system shown in Fig.2. The absorptance was calculated by measuring spectral reflected radiation against incident radiation. A pressed $BaSO_4$ (Wako Chemicals) was used for a standard of a spectral reflectance. As there are two types of reflection on the radiation absorbent film of the detector (DUT), one being specular reflection and the other being averaging diffusive one, the reflective energies were integrated with the integrating sphere (120mm Φ) by using the incident monochromatic beam irradiated at 10 deg incident angle on the absorber, then measured with the photo multiplier (Hamamatsu 1438). In the integrating sphere, there were two optical paths that were set at 60 deg.

Fig2 Experimental arrangement for spectral reflectance and spectral responsivity measurement.

Separated at the center of the sphere, one was set to a standard of spectral reflectance (pressed $BaSO_4$), the other was set to a detector surface (DUT). This configuration was used for comparing both measurements by easily switching the optical paths from the standard to the DUT without detaching them. An xenon lamp (Hamamatsu L2175, 150W) was used as light source. An incident image was focused 1.5 times larger than the original on an entrance slit through a plain and concave mirror ($f=100\text{mm}$, 50mm^2). The distance between the concave mirror and the entrance slit was 240 mm. The modulation frequency of an optical chopper was 18.5 Hz.

Optical filters for protection from higher order diffractive light and stray light were changed from the UV-D33S (Toshiba, protection from stray light) within the wavelength range 320nm~380nm to the M30 (Hoya, protection from higher order diffractive light) within 390 ~ 600nm. A monochromatic radiation to radiation absorber was supplied by the Czerny-Turner type grating monochromator ($f=258\text{nm}$) with a blazed wavelength of 200nm and line density of 600lines/mm. A dispersion image of diffraction grating was focused at approximately 40 mm behind the output slit of the monochromator through a lens ($f=40\text{mm}$) just behind the output slit. A circular aperture was set there and a circular monochromatic image was focused on a radiation absorbent (DUT) in the integrating sphere with same size through a concave mirror ($f=125\text{mm}$) and two plain mirrors. Within the wavelength range 200~310nm, a measurement value was subtracted by a value of photoelectric output of the photo multiplier at 180 nm where only stray light component from scattered light was detected. Spectral responsivity was measured by using the optical measuring system shown in Fig.2. The optical measuring system for the spectral responsivity was the same as that used for spectral reflectance as far as a monochromatic radiation on radiation absorbent is concerned.

Provided with enough thick gold-black, dependence of responsivity of thermal detector with gold-black as a

Fig.3 Relative spectral responsivity of thermal radiation detector with gold-black absorber against thickness of the gold-black.

radiation absorbent on wavelength was reported to be negligible. Blevin reported that more than $3\mu\text{m}$ thick under 1 torr N_2 and $10\mu\text{m}$ thick under 2 torr N_2 was necessary.⁴⁾

Therefore the authors fabricated the detector with $40\mu\text{m}$ gold-black under 1.5 torr N_2 as a radiation absorbent for a standard of spectral responsivity. A photo current of the photo multiplier was converted to a voltage signal by the current-voltage transform amplifier (time constant 2ms, R_f (feedback resistance)=1M Ω) and measured by a lock-in amplifier (time constant 1.0 s) synchronized with a modulation frequency of the chopper. Measurements were done as follows. Each measurement was done five times at a certain wavelength scanned each 10 nm within 1 sec. An average value of the five measurements was calculated. The whole measurement by scanning wavelengths mentioned above was done three times after detaching the DUT from the optical path (integrating sphere) and setting it again.

4. Results and Discussion

Fig.3 shows the responsivity of the thermal radiation detector with gold-black absorbent against the thickness of the gold-black. The thickness of the gold-black was varied with the number of gold evaporation to avoid change in density. 19mg gold was evaporated at one time. Fig.3 illustrates that the highest responsivity is attained with about $11\mu\text{m}$ gold-black, and that the thinner the layer of gold-black is, the greater the dependence of responsivity on wavelength is for gold-black layer thickness thinner than $8\mu\text{m}$. Dependence of the relative spectral responsivity of the thermal radiation detector with gold-black absorber on thickness of the gold-black layer was considered by using the proposed plain type model and taking absorption and reflection of incident energy within the gold-black absorber into consideration. In the proposed plain type model, incident energy is absorbed near the surface and transmitted through the gold-black absorber as heat. This model is called the lumped constant model. Fig.4 shows schematic diagram of the lumped constant model. There are two kinds of the models, one does not consider reflection on the thermal detector surface (lumped constant model 1) while the other does. (lumped constant model 2)

Fig.4 Schematic diagram of the lumped constant model

Measured reflectance r_m is supposed to consist of the component 1 (r_s) which reflects on the surface ($x=0$) and the component 2 which transmits through an absorber reflects on the other surface ($x=s$) then transmits through the surface ($x=0$).

The components 1 and 2 are written r_s and $(1-r_s)\exp(-2k \cdot s)$ respectively at a fixed wavelength λ . Then $r_m = r_s + (1-r_s)\exp(-2k \cdot s)$ and the equation is rewritten as

$$\ln(r_m \cdot r_s / (1-r_s)) = 2k \cdot s \quad (1)$$

Here r_s is nearly equal to r_m in case of large s . The value of r_m at $s=40 \mu\text{m}$ is taken as that of r_s .

A plot of $\ln(r_m \cdot r_s / (1-r_s))$ vs. s was accomplished by using measurement values. The values of the absorption coefficient were estimated using the slopes of the lines that show Eq.(1). Almost the same values of $k=0.3$ were for the wavelength of 400 and 500 nm.

The condition $d\rho(s)/ds=0$ leads to $s=(1/k)\ln(1+kt)$ and the maximum value of $\rho(s)$ was obtained at a value of the s where $\rho(s)$ is the effective generated heat energy. The value of the s where the maximum $\rho(s)$ is attained is $11 \mu\text{m}$ and a loss coefficient ϵ was calculated to be $0.0015 \mu\text{m}$.

The proposed plain type models were formulated and the absorption and loss coefficients were estimated by using the formulation and the experimental data. In order to get more accurate models, incident energy was supposed to be absorbed gradually within gold-black absorber and transmitted through gold-black absorber from there as heat. This model is called the distribution constant model. There are two kinds of this model, one which does not consider reflection on the thermal detector surface (distribution constant model 1) while the other does. (distribution constant model 2)

Fig.5 Calculation for relative spectral responsivity of thermal radiation detector with gold-black absorber against thickness of the gold-black.

Fig.6. Relation between reflectance of the sample coated with gray paint and degree of decrease in reflectance.

Dependence of the relative spectral responsivity of thermal radiation detector with gold-black absorber on thickness of the gold-black layer was calculated and compared with the experimental data and shown in Fig.5. It is shown that the proposed plain type models favorably illustrate the results well.

Both a plain and conical cavity type experimental samples covered with gray paint are used to investigate an effectiveness of repeated mutual reflections on the conical cavity surface. The spectral reflectance of the sample coated with gray paint is measured with both plain type and conical cavity type samples.

Fig.6 shows the relation between reflectance of the sample coated with gray paint and the degree of decrease in reflectance by repeated reflections on conical cavity surface.

Here K_c defines the ratio of the reflectance(ρ_c) of conical cavity type sample to that (ρ) of plain type for the same cone apex. Fig.7 shows schematic explanation for calculating effective reflectance through repeated mutual reflections.

Fig.7 Model for calculating effective reflectance through repeated mutual reflections.

It was shown that cavity type detectors decrease effective reflectance through repeated mutual reflections. The dependence of the effective reflectance of the conical cavity on the reflectance of the absorbent on the cone was formulated with a proposed conical cavity model. The proposed conical cavity model introduces the following assumptions.

- (1) Reflection satisfies $\cos\theta$ law. (uniform diffusion)
- (2) Total reflection consists of sum of the first reflection for uniform incident and the second repeated mutual reflections.
- (3) The ratio of incident energy to reflected energy escapes from the circular aperture is constant R_s for the second and following steps.

The ratio of reflectance $R_{17}(90^\circ)$ of the conical cavity type to that of the plain type through the first reflection was calculated to be 0.54 for the cone apex 90° by using the conical cavity model. $R_{17}(60^\circ)$ and $R_{17}(45^\circ)$ are also calculated to be 0.29 and 0.18 respectively.

Reflections and absorption were repeated using the following processes. The escape reflection energy through the circular aperture at the first reflection was written as $\rho_o R_{17}$. Therefore the remaining light $\rho_o(1-R_{17})$ irradiated to the inner side of a conical cavity.

Then a certain amount of the light $R_{17}\rho_o(1-R_{17})$ was emitted through the circular aperture at the second reflection. The total amount of emitting light was written as R_{17} . As the ratio of R_{17} to ρ_o is defined as K_c ,

$$K_c = R_{17} + R_{17}\rho_o(1-R_{17}) / (1-\rho_o(1-R_s)).$$

K_c shows a degree of decrease in reflectance for a conical cavity type compared with a plain type. R_{17} and R_s were estimated by using measured and calculated values.

The calculated results of K_c are shown in Fig.6 along with the measured ones. The figure shows that the effective reflectance for the conical cavity type depends on the reflectance of the absorbent well.

5. Conclusion

The relation between the spectral responsivity of radiation and a N_2 pressure (from 0.5 torr to 3.0 torr) in the evaporation of gold was investigated and optimum conditions of the N_2 pressure for gold evaporation are shown as 1.5 torr. It was also shown that the detector with 11 μ m gold-black evaporated in 1.5 torr showed little dependence of spectral characteristics on wavelength within the wavelengths range 200-600nm: $\pm 1\%$, and a high responsivity.

The relative spectral responsivity of the thermal radiation detector with gold-black absorber against the thickness of the gold-black was explained with the proposed plain type models.

In the proposed plain type models, incident radiant energy is absorbed near the surface and transmitted through the gold-black absorber as heat. There were two kinds of the proposed plain type models, one was called the lumped constant model and the other was called the distribution constant model. The best model to fit the measured results was the distribution constant model 2 which contained reflection at the interface of the absorber and the PVDF pyroelectric film.

To attain a very sensitive thermal radiation detector with constant spectral responsivity, conical cavity type detectors were fabricated. Experimental samples were made to study the dependence of the effective reflectance of a conical cavity type thermal radiation detector on reflectance of the absorbent on the cone and the cone apex. The decrease in the effective reflectance for a conical cavity type was explained using the proposed conical cavity model which contains the first reflection and the second repeated mutual reflections. The degree of decrease in reflectance (K_c) for a conical cavity type was formulated and examined with experimental results. It was shown that the formulation of the correlation between the reflectance (ρ_o) of the paint on the cone and K_c with various cone apex angles (90° , 60° , 45°) explained the measured data with a fair degree of accuracy.

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