Improvement of low-temperature sensing realized with a superlattice infrared photodetector

C. C. Chen, M. C. Hsu, W. H. Hsieh and C.H. Kuan *

Department of Electrical Engineering, National Taiwan University

1, Roosevelt Rd. Sec.4, Taipei, Taiwan, R.O.C. 10617

ABSTRACT

It's found that the temperature accuracy (ΔT), measured by the photocurrent ratio of two linearly independent spectral responses, depends on two factors. One is the dissimilarity of the spectral responses determined primarily by the separation of the long and short wavelength peaks, and is not related with their responsivity magnitude. The other is dominated by the smaller S/N between the two measured photocurrents. The dissimilarity can be improved by moving the short wavelength peak to an even shorter one. However, this decreases the signal magnitude measured by the shorter wavelength peak at low target temperature, and results in the degradation of the S/N and ΔT . Therefore, a superlattice structure with absorption peaks at $6.7\mu\text{m}$ and $9.7\mu\text{m}$ is designed, and the wavelength separation is less than the conventional two-color QWIP. The spectral response of the detector is voltage-tunable through a current blocking layer that acts as an energy filter for the photo-excited carriers. The measured peak detectivity of this detector is $3.7 \times 10^9 \text{cmHz}^{0.5}/\text{W}$ ($9.7\mu\text{m}$) at -0.5V and $2.2 \times 10^{10} \text{cmHz}^{0.5}/\text{W}$ ($6.7\mu\text{m}$) at -0.1V at 45K . Our detector is capable of measuring target temperatures ranging from 300K to 1200K and higher. The estimated ΔT is 0.8K for 300K target, and 0.17K for 1200K target.

Keywords: Superlattice infrared Photodetector, temperature sensing, temperature accuracy, multi-color infrared photodetector

1. INTRODUCTION

The need of multi-color infrared photodetector arises from various applications including probing the temperature of an object. One method to measure the target temperature with two-color infrared photodetector is through the definition of a quantity, the photocurrent ratio, which is a function of the target temperature only.¹ This approach had been investigated in 1995,² and the two-color infrared photodetector is constructed by stacking two quantum well structures with different peak responsivities at $4.5\mu\text{m}$ and $8.8\mu\text{m}$ respectively. In this paper, we review the photocurrent ratio method in detail and derive an equation for temperature accuracy to understand the factors that affect the temperature accuracy. With this equation, we design a superlattice structure that had been used as an infrared detector in the mid and long wavelength region,^{3,4,5} and this structure improves the temperature accuracy at low target temperature. In addition, the spectral response is voltage-tunable by the introduction of a current blocking layer as an energy filter for the photo-excited carriers in the second miniband of the superlattice structure.

This paper is organized as follow. Section 1 is a brief introduction and section 2 reviews the photocurrent ratio method for temperature sensing and the temperature accuracy. The design principles and sample description of the two-color superlattice infrared photodetector will be shown in section 3. In section 4, we will present the characterizations of the superlattice infrared photodetector. Finally, the performance and application of the two-color superlattice infrared photodetector in temperature sensing are demonstrated in section 5, and then follows the conclusion.

2. TEMPERATURE SENSING USING TWO-COLOR PHOTODETECTOR

The use of photocurrent ratio method to measuring the target temperature is reviewed in this section, and the measured temperature accuracy of this method is derived and discussed in this section.

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* Correspondence: Email: kuan@ee.ntu.edu.tw; Telephone: +886-2-23635251 ext 439; Fax: +886-2-23671909.

2.1. Thermal Radiation

The thermal radiation of an object at temperature T is described by the Planck's law which employs the concept of statistical thermodynamics and takes the form,⁶

$$L(\lambda, T) = \varepsilon \frac{2\pi hc^2}{\pi \lambda^5 [\exp(hc / \lambda kT) - 1]} = \varepsilon \frac{1.19 \times 10^4}{\lambda^5 [\exp(\frac{14404}{\lambda T}) - 1]}, \quad (1)$$

where $L(\lambda, T)$ is the spectral radiance in watt per steradian per square centimeter of area and per micrometer of radiation wavelength ($\text{W sr}^{-1} \text{cm}^{-2} \mu\text{m}^{-1}$), ε is emissivity of the object, λ is wavelength in micrometer and T is temperature in Kelvin.

An object is called blackbody and grey body if the emissivity equals 1 and if the emissivity is smaller than 1 but remains constant in the spectral region of interest, respectively. In this paper, we restrict ourselves to the discussion of a gray body. The spectral radiance emitted from a blackbody radiation source at various temperatures is shown in Fig. 1. The radiance emitted from an object at low temperature is relatively small in the shorter wavelength region and this affects the temperature accuracy using the photocurrent ratio method which will be discussed later in the following section.

Fig. 1. Spectral radiance emitted by a blackbody radiation source at various temperatures calculated by Eq. (1).

2.2 Basics of Temperature Sensing

The photocurrent measured by a detector with spectral responsivity $R(\lambda)$ of a gray body at temperature T can be expressed as the integration of the thermal radiation falling on a detector multiplies the spectral responsivity of the detector,

$$I_p = \int \varepsilon \frac{L_{BB}(\lambda, T) A_s A_d}{r^2} R(\lambda) d\lambda, \quad (2)$$

where ε is the emissivity of the radiation source, $L_{BB}(\lambda, T)$ is the associated blackbody spectral radiance at temperature T as shown in Fig. 1, r is the distance between the source and the detector, and $A_{s(d)}$ is the area of the source(detector). It is not possible to extract the target temperature from the measured photocurrent by a detector with only one spectral responsivity because the unknown parameters ε , r , and $A_{s(d)}$, which are related with the material property and the measurement configuration, are difficult to measure or control. By the use of two linearly independent spectral responsivities $R_1(\lambda)$ and $R_2(\lambda)$, the photocurrent ratio (Pr) is defined as the ratio of the measured photocurrents I_{p1} and I_{p2} correspondingly,

$$\Pr(T) = \frac{I_{p1}}{I_{p2}} = \frac{\int L_{BB}(\lambda, T) R_1(\lambda) d\lambda}{\int L_{BB}(\lambda, T) R_2(\lambda) d\lambda} \quad (3)$$

Since the unknowns ε , r , $A_{s(d)}$ are eliminated, the resulting photocurrent ratio is a function of the target temperature only. Thus, the target temperature can be determined without pre-knowing ε , r , and $A_{s(d)}$ if ε is assumed to be independent of λ .

2.3. Temperature Accuracy

The temperature accuracy for the photocurrent ratio method with a two-color infrared photodetector can be evaluated by the temperature error ΔT ,

$$\Delta T = \left(\frac{\partial \Pr(T)}{\partial T} \right)^{-1} \Delta \Pr = \left(\frac{1}{I_{p1}} \frac{\partial I_{p1}}{\partial T} - \frac{1}{I_{p2}} \frac{\partial I_{p2}}{\partial T} \right)^{-1} \left(\frac{\Delta I_1^2}{I_{p1}^2} + \frac{\Delta I_2^2}{I_{p2}^2} \right)^{\frac{1}{2}}, \quad (4)$$

where ΔI_1 and ΔI_2 are the current noises for the measurement which contain not only the shot noise of the dark current and photocurrent of the device but also various noise sources from the measurement system. From the final expression of Eq. (4), it is observed that the temperature error depends on two factors. The first one is inverse proportional to the difference of the partial derivative of the photocurrent to T over itself. It is primarily dependent upon the shape similarity of the two spectral responsivities but not on the individual magnitude. The second factor is related to the S/N of the two measured photocurrents, which decreases as the photocurrent increases, and is dominated by the smaller S/N between the two photocurrents.

2.4 The Relation Between Short Wavelength Peak and Temperature Accuracy

As discussed in the previous subsection, the temperature accuracy is affected by the two factors in the final expression of temperature error in Eq. (4). The temperature accuracy can be improved by increasing the dissimilarity of the two linearly independent responsivity waveshapes to reduce the first factor. This can be achieved by moving the short wavelength peak to an even shorter one. However, from Wien's displacement law,⁶

$$\lambda_{\max} = \frac{2898}{T} \mu\text{m}, \quad (5)$$

the wavelength where the maximum spectral radiance occurs ($\lambda_{\max}$) from an object is inverse proportional to the object temperature T . Therefore the signal measured by the shorter wavelength peak of the detector is reduced at low target temperature, which results in the degradation of the S/N and the temperature accuracy. To improve the temperature accuracy at low target temperature, we design the short wavelength responsivity peak of our detector to be 6.2 μm , in contrast to the 4 μm peak of the two-stack quantum well infrared photodetector with In, to improve the measured signal for an object at low temperature.

3. DESIGN PRINCIPLES AND SAMPLE DESCRIPTION

3.1. Design Principles

3.1.1. Superlattice structure

Because the photon energy corresponding to the desired short wavelength responsivity peak 6.2 μm is 200meV, the simple GaAs/AlGaAs system can be utilized without resorting to the more complex material systems related with the element In to avoid Γ -X scattering caused by the high Al fraction⁷. In addition, the superlattice structure is adopted as the active region of our photodetector to absorb infrared radiation because of the broader absorption spectrum, compared with the quantum well structure, due to its miniband transitions. The superlattice band structure is estimated by Kronig-Penney model with one band k.p model and effective mass approximation, and a 15-period 6.5nm GaAs/3.5nm Al_{0.27}Ga_{0.73} superlattice is designed with peak absorption wavelengths to be 6.2 μm and 10.1 μm corresponding to transitions at zone center and edge

respectively.

3.1.2. Current blocking layer

A current blocking layer is introduced not only to reduce the dark current³, induced by the conduction of the carriers in the first miniband of the superlattice structure. In addition, the current blocking layer serves as an energy filter⁸ for the photoexcited carriers in the second miniband. The energy barrier of the current blocking layer is designed to be 7meV higher than the second miniband minimum to prevent from the conduction by the photo-excited carriers in the second miniband minimum at low bias level. Thus the long wavelength responsivity is suppressed when the detector is operated at low bias condition. On the other hand, at high bias level, photo-excited carriers in the second miniband minimum can tunnel through the blocking layer and contribute to the responsivity of the long wavelength peak. Therefore, the detection wavelength is tunable by external bias on a single device without stacking structures with different spectral responses.

3.2. Sample Description

The schematic diagram of the superlattice infrared photodetector structure is shown in Fig. 2. The structure was grown by molecular beam epitaxy on semi-insulating GaAs substrate, contains a 500nm heavily doped GaAs bottom contact layer, a 150nm $\text{Al}_{0.23}\text{Ga}_{0.77}\text{As}$ current blocking layer, a 15-period GaAs/ $\text{Al}_{0.27}\text{Ga}_{0.73}\text{As}$ superlattice, and a 400nm heavily doped top contact layer. The contact layers are doped with $1 \times 10^{18} \text{ cm}^{-3}$ of Si. Each period of the superlattice consists of 6.5nm GaAs well doped with $5 \times 10^{17} \text{ cm}^{-3}$ of Si and 3.5nm undoped $\text{Al}_{0.27}\text{Ga}_{0.73}\text{As}$ barrier. The parameters given above is the nominal values, the actual sample parameter may be slightly different.

Fig. 2. Schematics of the superlattice infrared photodetector structure. The GaAs well region of the Superlattice is doped with $5 \times 10^{17} \text{ cm}^{-3}$ of Si.

The device was fabricated into a $200 \times 400 (\mu\text{m})^2$ mesa diode by standard photolithography, chemical wet etching, evaporation and lift-off processes. The top and bottom contacts were made by evaporating 100nm Ni/Ge/Au and 200nm Au. After evaporation and lift-off, thermal annealing at 390°C was performed to make omic contact with the n^+ contact layer in the semiconductor. Finally, a 45° facet on the substrate was polished to allow TM polarized infrared radiation back illuminating onto the detector.

4. CHARACTERIZATIONS OF THE SUPERLATTICE PHOTODETECTOR

4.1. Dark Current

Dark current at various temperatures (with 77K cold shield) and background photocurrent of the detector at 25K are shown in Fig. 3. The voltage polarity is defined as positive if higher potential is applied on the top contact as shown in the inset of Fig. 3. A strong asymmetry in the I-V characteristic is observed in this figure. It can be attributed to the migration of the Si

dopants into the blocking layer from the bottom contact. This assists the electron tunneling process at the positive bias. The temperature range with background limited operation of the detector is below 55K when the detector is bias at -0.5V , and 65K at -0.2V . For the operation with background limited performance in the bias range between 0V and -0.5V , the detector should be cooled below 55K.

Fig. 3. Dark current at various temperatures ranging from 20K to 75K and the background photocurrent at 20K

4.2. Noise

Figure 4 shows the current noise power spectral density of the detector at 77K at negative bias region. The measurement was performed with sample immersed in 77K liquid nitrogen and is shielded to prevent from illumination of the room temperature infrared radiation. The current noise power spectral density matches well with the shot noise performance $2eI$. It may be attributed to the thermally assisted tunneling process of the electrons through the edge tip of the blocking layer.

Fig. 4. The solid curve is the calculated shot noise $2eI$ from the dark current at 77K, and the solid squares are the measured data with sample immersed in 77K liquid nitrogen

4.3. Responsivity and Detectivity

The spectral responsivity was measured by a chopper and lock-in-amplifier system at various temperatures and biases with monochromator and glow bar radiator as light source. The peak responsivity is calibrated by a blackbody radiation source. The observed spectral responsivity shows little temperature dependence, and the representative one at 25K is shown in Fig. 5. It is clear that at zero bias, the detection wavelength is mainly at 6.9 μ m. While negative bias increases in magnitude, another peak at 9.7 μ m rises, and dominates the spectral responsivity at high bias region. Therefore, the ratio of responsivity at 6.9 μ m and 9.7 μ m can be tuned by varying external bias.

Fig. 5. Spectral responses at various biases at 25K.

The detectivity is a figure of merit of detector, and is expressed as

$$D_p^* = \frac{\sqrt{A_d \Delta f}}{NEP} = \frac{\sqrt{A_d \Delta f}}{i_{rms}} R_p, \quad (6)$$

where A_d is the area of the detector, Δf is the band width of measurement, NEP is the noise equivalent power, R_p is the peak responsivity and i_{rms} is the current noise of the detector. The current noise matches well with the shot noise of dark current at 77K. Thus the peak detectivity is estimate with the assumption that the current noise is also shot noise at other temperatures. The peak detectivity is hence $3.7 \times 10^9 \text{ cmHz}^{0.5}/\text{W}$ (9.7 μ m) at -0.5V and $2.2 \times 10^{10} \text{ cmHz}^{0.5}/\text{W}$ (6.7 μ m) at -0.1V at 45K. In contrast to the well-understood quantum well infrared photo-detectors, the performance of the superlattice detector could be improved by optimization, which is not carried out in this paper.

4.4. The Voltage Dependence of Responsivity

The measured responsivity versus external bias at 6.7 μ m and 9.7 μ m is shown in Fig. 6(c), which shows different bias dependence. The responsivity at 9.7 μ m is negligible at zero bias, but increases with external bias and reaches 140mA/W at -0.7V. In contrast to the voltage dependence of the 9.7 μ m responsivity, the responsivity at 6.7 μ m increases from 8mA/W at zero bias to 32mA/W. Since the energy of the current blocking layer is between the second miniband in the superlattice, there are two ways for the photo-excited carriers to contribute to the photocurrent. The photo-excited carriers can simply pass through the blocking layer if their energy is higher than it, or they have to tunnel through the blocking layer with the

assistance of the applied bias if their energy is lower than it. The photocurrent caused by the aforesaid two ways are assigned as the emission photocurrent and the tunneling photocurrent.

The illumination of $9.7\mu\text{m}$ light induces the transition of the carriers in the top of the first miniband to the bottom of the second miniband in the superlattice region. The photocurrent at $9.7\mu\text{m}$ is mainly tunneling current because the energy of the photoexcited carriers in the bottom of the second miniband is lower than the blocking layer. Therefore, the voltage dependence can be simulated using the WKB approximation to describe the tunneling of the photo-excited carriers through the blocking layer. The simulated voltage dependence is shown as the solid line in Fig. 6(c). For the responsivity at $6.7\mu\text{m}$, the nonzero photocurrent at zero bias is the result of the emission photocurrent induced by the carriers excited to the top of the second miniband maximum. However, the increase of the photocurrent with bias suggests that there is also tunneling photocurrent when the detector is illuminated by the $6.7\mu\text{m}$ light. The tunneling current is caused by the accumulation of the relaxed photo-excited carriers from the top to the bottom of the second miniband. The solid line in Fig. 6(c) shows the simulated bias dependence for the $6.7\mu\text{m}$ responsivity, and the corresponding carrier distribution is schematically drawing in Fig. 6(b).

Fig. 6. (a) Tunneling photocurrent dominates the photocurrent when carriers are excited by low energy photons. (b) The photocurrent contains both tunneling photocurrent and emission photocurrent. (c) The voltage dependent of photocurrent responsivity at $9.7\mu\text{m}$ and $6.7\mu\text{m}$.

5. PHOTOCURRENT RATIO AND TEMPERATURE ACCURACY OF THE SUPERLATTICE INFRARED PHOTODETECTOR

We have found that the noise performance of the dark current in our detector is shot noise, and results from the tunneling mechanism through the blocking layer. The photocurrent noise is hence assumed to have the same noise performance. In this paper, the detector is operated in the background limited performance (BLIP). The current noise is therefore due to the shot noise of the background photocurrent and is not related with the dark current. Assuming that the photocurrent is measured by lock-in amplifier and the equivalent noise bandwidth (ENBW) is 1Hz, the temperature accuracy for the various bias combinations of our detector ranging from 0V to -0.5V is calculated according to Eq. (4), and the first four smallest temperature errors and their corresponding bias combinations are shown in Fig. 7(a). The minimum temperature error can be achieved by operating the detector at 0V and -0.5V , and Fig. 7(b) shows the measured photocurrent ratio under this bias combination. The solid curve in Fig. 7(b) is the estimated photocurrent ratio and the solid dots are the measured data. The error between the estimation and the measurement is due to the temperature fluctuation of our black body radiation source.

Fig. 7. (a) The first four smallest temperature errors and their bias combinations. The temperature errors are evaluated under the assumption that the blackbody radiation source at 800K causes 29.1nA at $-0.5V$. The inset shows the two factors in the final expression of Eq. (3). F_1 and F_2 correspond to the first and second factors respectively. (b) The measured photocurrent ratio for the bias combination of 0V and $-0.5V$.

As discussed in the subsection 2.4, the temperature accuracy is affected by two factors in the final expression of temperature error in Eq. (4). The temperature accuracy can be improved by moving the short wavelength responsivity peak to an even shorter one in order to reduce the contribution from the first factor to the temperature error through the increase of the dissimilarity of the two responsivity wave shapes. However, this results in the reduction of the signal measured by the short wavelength responsivity peak at low target temperature, and the degradation of the S/N and the temperature accuracy.

To investigate the effect of the short wavelength peak on the temperature accuracy using photocurrent ratio method, two sets of responsivity waveshape are analysed using Eq. (4). The responsivity set (A), which is shown in the upper part of the inset of Fig. 8, contains a gaussian function peaks at short wavelength ($7\mu m$) and the sum of two gaussian functions peaks at long ($10\mu m$) and short ($7\mu m$) wavelengths to model the superlattice responsivities in this paper. The other responsivity set (B) contains a long wavelength peak ($10\mu m$), and a shorter wavelength peak ($4\mu m$) as shown in the lower part of the inset of Fig. 8. Although the two sets of responsivity waveshapes are artificial, set (A) can be realized by the superlattice structure of this paper, while set (B) can be realized by various techniques related with quantum well structure¹, for example, by stacking two quantum well structures with different responsivity wave shapes in series. It is noted that to achieve the $4\mu m$ spectral responsivity, one should expand the material system of GaAs/AlGaAs to the compound semiconductors with In to avoid a high Al fraction which makes the AlGaAs material indirect.

The peak responsivities of the two sets of responsivity waveshape are normalized to have the same values, and the bandwidth for the set (B) is assumed to be smaller than that of set (A) to simulate the narrow bandwidth nature of the quantum well structure. Further, the current noise due to background photocurrent corresponding to the two responsivities are assumed to be the same. According to Eq. (4) and the assumptions, the estimated relative temperature errors for responsivity set (A) and (B) are shown as the solid and dashed line in Fig. 8.

The temperature error for the responsivity set (B), which has a shorter responsivity peak, is excellent at high target temperature because of both the enhancement of the detected signal at high target temperature and the larger dissimilarity between the responsivity wave shapes. However, the temperature error increases drastically at low target temperature in contrast to the high temperature accuracy at high target temperature. The fast degradation of temperature accuracy at low target temperature can be improved by moving the short wavelength responsivity to a longer one, or use the simple superlattice structure in this paper to realize the responsivity wave shapes like those of set (A). The responsivity set (A)

reduces the temperature error at low target temperature and the difference of temperature error between high and low target temperature is shrunk. Therefore the superlattice infrared photodetector is useful for temperature sensing at low target temperature. In general, to obtain optimum temperature accuracy in specific applications, the operation of long and short wavelength responsivity peak should be properly designed.

Fig. 8. Estimated relative temperature accuracy for two sets of the responsivity wave shape as shown in the inset.

6. CONCLUSION

We derived an equation to evaluate the temperature accuracy using photocurrent ratio method and designed an infrared photodetector utilizing a superlattice structure with a current blocking layer to improve the temperature accuracy at low target temperature. The current blocking layer serves as an energy filter for the photo-excited carriers and reduces the dark current. Therefore, the spectral responsivity of the superlattice infrared photodetector can be tuned by external bias, and this makes it a suitable photodetector for temperature sensing. The characteristics of the superlattice infrared photodetector is measured and the detectivity is $3.7 \times 10^9 \text{ cmHz}^{0.5}/\text{W}$ ($9.7 \mu\text{m}$) at -0.5V and $2.2 \times 10^{10} \text{ cmHz}^{0.5}/\text{W}$ ($6.7 \mu\text{m}$) at -0.1V at 45K . The short wavelength responsivity peak is longer than the conventional two-stack quantum well infrared photodetectors with In to increase the conduction band offset. However, the signal measured with the longer short wavelength responsivity peak is increased at low target temperature, and this increases the S/N and improves the temperature accuracy. By analyzing the temperature accuracy for two sets of responsivity wave shapes, we found that the superlattice infrared photodetector is suitable for temperature sensing especially at low target temperature. This shows that the superlattice structure is a simple but efficient structure in designing two-color infrared photodetectors for temperature sensing at low target temperature.

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