Design and Characterization of Superlattice Infrared Photodetector Operating at Low Bias Voltage

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Abstract—In this paper, we investigate the performance and characterization of a 15-period superlattice embedded between two thick AlGaAs barriers. The structure can operate at low bias voltage with less power consumption for 8–10 μm long-wavelength infrared detection. In our design, one barrier is used to reduce the dark current and the other one is designed to enhance the collection efficiency of photoelectrons at the collector contact. The fabricated detector can be operated at a bias voltage lower than 0.1 V and exhibits pronounced photovoltaic response. The spectral response shows voltage dependence around 0 V. At high bias voltage (>25 mV) the spectral lineshape is independent of bias and is around 8–10 μm with peak wavelength at 9.3 μm . At lower bias voltage the response is shifted toward shorter wavelength range. The peak responsivity was found to be 12 mA/W at $\lambda_p = 8.7$ μm and zero bias and 85 mA/W at $\lambda_p = 9.3$ μm and 0.1 V. Background limited can be achieved up to 65 K with bias voltage less than 0.1 V. The measured noise power spectral density of the dark current at 77 K shows the characteristics of full shot noise rather than the generation-recombination noise. The peak detectivity is determined to be $D^* = 3.5 \times 10^9$ $\text{cm}^2/\text{Hz/W}$ at 77 K and 0.1 V. In comparison with a conventional 30-period QWIP, our detector has the advantages of better performance at low bias voltages with lower power consumption and a tunable feature of spectral range.

Index Terms—Noise, noise measurement, photodetector, quantum-well infrared photodetector.

I. INTRODUCTION

LONG wavelength infrared detection using intersubband transitions in quantum well structures has been under intensive investigation [1]–[6], since the first observation of intersubband transition of GaAs/AlGaAs quantum wells [7]. These intersubband infrared photodetectors can be implemented in wide bandgap materials as a result of the detectable photonenergy determined by the subband energies of the quantum well or superlattice structures rather than by the fundamental bandgap of the building materials. Due to the mature growth and processing technology of building materials, quantum well intersubband photodetectors (QWIP's) are potentially suitable for large area focal plane array (FPA). Recently, large area focal plane array (FPA) with QWIP's has been demonstrated with high uniformity and performance [8].

Using photoexcitation between localized states and the continuum, QWIP is usually operated as a photoconductive device. An external bias voltage is required to accelerate the excited

carriers and generate the measurable photocurrent. Typically a QWIP consists of 30 to 50 quantum wells. Although the responsivity is insensitive to well number [9], a large well number is favorable to reduce the noise level. In addition, to reduce the tunneling and thermally assisted tunneling current [10], [11], a QWIP is typically implemented with thick barriers (300–500 Å) [1]. As a result, a typical QWIP requires a relatively high bias voltage (1–4 V) [1], [8] to optimize its performance. For certain applications, a lower bias voltage with less power dissipation would be advantageous. Due to the formation of miniband to facilitate the transportation of excited electrons, superlattice infrared detectors (SLIP's) are expected to operate at very low bias voltage. Several designs for SLIP's have been investigated [12]–[16]. To reduce the large ground-state tunneling current, most SLIP's were designed with a thick barrier at the collector side as a current blocking layer [12]–[15]. The blocking layer is designed to allow the photoelectrons to pass but block the tunneling current. The detection mechanism of a SLIP with such a blocking barrier is similar to that of an internal emission detector [17]. As those internal photoemission detectors, some of the reported SLIP's, with the built-in field in the blocking layer, were demonstrated as photovoltaic detectors [13], [14].

Although the reported detectivity of SLIP's seems to be inferior to that of QWIP's using thick barriers [1], we should note that the comparisons were made between the optimized QWIP's and the SLIP's without further optimization. Therefore, the performance of SLIP's might be underestimated. In this article, we investigate a modified design for superlattice infrared photodetectors. As illustrated in Fig. 1, a superlattice (SL) layer is embedded between two thick barriers. The thick barrier on the right-hand side (collector side) is a current blocking barrier. Another thick barrier with an energy height higher than the top of the excited miniband is designed to enhance the probability of photoelectron being emitted toward the collector contact. Without such a barrier, part of photoelectrons would escape from the left-hand side boundary of the SL region because photoelectrons can be emitted toward either right-hand or left-hand directions. The escaping photoelectrons would result in a lower net quantum efficiency. With this barrier, photoelectrons moving toward this barrier can be blocked and redirected into right-hand direction. In addition, the confinement of ground state carriers caused by the two thick barriers might also improve the absorption strength. Due to scattering and relaxation processes, the probability of these reflected carriers to be collected at the collector will be decreased with their travel distance. To reduce the distance, we used a 15-period SL instead of a typical 50-period one. The emitter was fabricated on the end periods of SL layer to replenish the photo-depleted SL.

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Fig. 1. Schematic energy band structure diagram for the SLIP.

The characterization of a detector based on this design will be presented. The performance of this detector will be compared to that of a 30-period QWIP which covers a similar spectral range.

II. SAMPLE STRUCTURE, GROWTH AND PROCESSING

The sample was grown by molecular beam epitaxy on a semi-insulating GaAs substrate. First, a 300 Å $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ barrier was grown followed by a SL layer. The SL layer consists of 15 periods of 60 Å GaAs doped with $n = 5 \times 10^{17} \text{ cm}^{-3}$ and 30 Å undoped $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$. After the SL layer is a 1500 Å undoped $\text{Al}_{0.22}\text{Ga}_{0.78}\text{As}$ layer. Finally, a 3000 Å n^+ layer ($n = 1.2 \times 10^{18} \text{ cm}^{-3}$) is grown on top for the ohmic contact. Based on the Kronig–Penny model taking into account the position dependent effective mass, we estimate the first miniband to be located at 45–69 meV and the second miniband to be located at 182–260 meV. The height of the blocking layer is just below the second miniband. The sample was processed into $180 \mu\text{m} \times 180 \mu\text{m}$ mesas by standard lithography and wet chemical etching. AuGeNi/Au were evaporated on top and bottom to form the ohmic contacts. Selective area of the sample was polished into a 45° facet for a light coupling.

III. DARK CURRENT AND BACKGROUND PHOTOCURRENT

The current–voltage (I – V) characteristics were measured by using a Keithley 236 source measurement unit. The sample was mounted on the cold head of a closed-cycle cryostat to control sample temperature. A Si-diode temperature sensor was placed beside the samples to ensure the accuracy of sample temperature. Fig. 2 shows the resulting I – V curves. The solid lines were taken with a cold shield (about 77 K) and within a temperature range from 35 to 85 K while the dashed line was at 35 K but with the room temperature background through a KRS-5 window. Thus, the difference between the 35 K solid line and dash line represents the background photocurrent. Even at zero bias voltage, we can observe a photocurrent resulting from the background radiation. For $T > 65$ K, the dark current begins to be dominant over the background photocurrent. Thus, under the field of view determined by the window (roughly 2π solid-angle field of view), the device is in background limited performance (BLIP) up to 65 K for bias voltage smaller than 0.1 V.

The increase of dark current at high temperatures is primarily due to the thermal current which consists of thermionic emission and thermally assisted tunneling currents. To demonstrate this, we plot the dark current as a function of inverse temperature

Fig. 2. Dark I – V curves for the SLIP from 35 K–85 K. The dash line is the I – V curve measured at 35 K under room temperature background radiation. Positive voltage means top contact positive.

Fig. 3. Plot of dark current versus inverse temperature for three different operating bias points. The activation energy decreases with the increase of bias voltage.

at three different bias voltages in a semi-log scale as shown in Fig. 3. The linearity of the dark current in the figure indicates

$$I_d \propto e^{-\Delta E/kT} \quad (1)$$

where I_d is the dark current and ΔE is the thermal activation energy. This result implies that the thermal current is dominant for $T > 65$ K. In particular, the activation energy is about 107 meV at low bias voltage (< 0.1 V), which is consistent with the energy difference of the blocking barrier height and the Fermi level. The dominant mechanism at the low bias range is then due to thermionic emission. With the increment of bias voltage, because of the thermally assisted mechanism, the effective height and width of the blocking barrier decrease and the resulting activation energy decreases dramatically.

IV. RESPONSIVITY MEASUREMENTS

The spectral response was measured using Perkin Elmer 2000 Fourier transform infrared (FTIR) spectrometer. The absolute value of the responsivity was determined by measuring the blackbody responsivity with a calibrated blackbody source. Fig. 4 shows the spectral responsivity measured at 77 K under several different biases. For the bias voltage > 25 mV, the response spectrum has one pronounced peak around $9.3 \mu\text{m}$ and its lineshape is insensitive to bias voltage. The lineshape shows a shoulder-like feature at short wavelength range. Similar lineshapes have also been observed in the reported absorption spectra of other superlattice structures [18]. The

Fig. 4. Spectral response measured at several bias voltages. The lineshape at high biases (>25 mV) is insensitive to bias voltage, while around 0 V the peak wavelength is shifted toward high-energy position.

Fig. 5. Voltage dependence of peak responsivity at 77 K.

shoulder is attributed to the transitions near the miniband zone center (i.e., the Γ point). It is noted the lineshape of response spectra has a dramatic change at around zero bias when the bias voltage of the detector is changed from the positive bias toward the negative bias. The voltage dependence of spectral response near zero bias voltage can be explained by the effect of the blocking layer. Because the Fermi level in SL layer is higher than that of collector contact layer, we expect the energy height of the blocking layer is tilted up on the collector side at zero bias voltage. As a result, the energy height of the blocking layer is above the bottom of second miniband and those photoelectrons excited into the miniband edge are blocked by the tilted blocking layer near zero bias voltage. The effect becomes more obvious when the detector is under slightly negative bias voltage. As we can observe from the curve of -10 mV in Fig. 4, the low energy peak disappears and only those high-energy photoelectrons contribute to the photoresponse. Fig. 5 shows the voltage dependence of peak responsivity. The peak responsivity is 12 mA/W at 0 V and is 85 mA/W at 0.1 V. After 0.1 V the increasing rate becomes sluggish, and the responsivity is saturated at a value about 105 mA/W after 0.45 V. The responsivity under reverse bias voltages is almost 20 times smaller than that under forward bias voltages, as can be seen by the background photocurrent in Fig. 2.

V. NOISE PERFORMANCE

The noise current power spectral density was measured through a low noise current amplifier (SR570) connected to an

Fig. 6. Noise spectral density versus frequency. The spectrum is flat and an average value is taken as the associated PSD.

Fig. 7. Noise power spectral density versus dark current at 77 K. The Johnson noise has been subtracted from the noise power spectrum.

FFT spectrum analyzer (AD9112B), and the bias was supplied by a Nd/Cd battery with resistor network. After deducting the noise contribution from the amplifier and bias resistors the noise current power spectral density (PSD) of a device can be obtained. The analyzed frequency range is 0–10 KHz, which is limited by the bandwidth of the low noise amplifier. A typical measurement of the noise current PSD of the device is shown in Fig. 6. It shows a plateau of PSD in our measured frequency range.

After subtracting the Johnson noise from noise current PSD, the PSD versus dark current is plotted in Fig. 7. The result suggests that the noise current power spectral density S_i of the dark current is

$$S_i = \frac{i_n^2}{B} = 2eI_d \quad (2)$$

where i_n is the noise current and B is the measurement bandwidth. The shot noise characteristic is similar to that of an undoped single QW with a thin injection barrier [19]. After an excited electron escapes from the SL region, an electron is immediately refilled from the emitter contact. Since the energy of the refilled electron is lower than the blocking barrier, the refilled electron cannot recirculate in the structure. Therefore, each excited electron makes exact one pass through the structure. The optical gain g is thus expected to be unity. We should note that since there is no uncertainty in the refilled process (i.e., the recombination process) [17], the $g = 1$ in this structure results

TABLE I
THE STRUCTURE AND PERFORMANCE
PARAMETERS OF THE SLIP AND THE 30-PERIOD QWIP

Sample	SLIP	QWIP
Barrier Material	$\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$	$\text{Al}_{0.25}\text{Ga}_{0.75}\text{As}$
Barrier Width	30 Å	500 Å
Well width	60 Å	50 Å
Dopant density	$5 \times 10^{17} \text{cm}^{-3}$	$1.2 \times 10^{18} \text{cm}^{-3}$
Periods	15	30
Peak wavelength λ_p	9.3	9.1
Cutoff wavelength λ_c	10	9.8
Spectral bandwidth $\Delta\lambda$ (FWHM)/ λ_p (%)	19%	20%
Peak responsivity (mA/W), Bias voltage	70mA/W, 0.05V	92mA/W, 0.9V
Dark current (A), Bias voltage	$1.9 \times 10^{-7} \text{A}$, 0.05V	$1.7 \times 10^{-6} \text{A}$, 0.9V
Detectivity ($\text{cm}\sqrt{\text{Hz}}/\text{W}$), Bias Voltage	4.2×10^9 , 0.05V	4.7×10^9 , 0.9V

in $i_n^2 = 2egIB$ rather than the usual generation-recombination noise characteristics $i_n^2 = 4egIB$ observed in QWIP's. Assuming photoelectrons to transport through the same path as that of thermal excited electrons, we expect the noise performance of the background photocurrent also following the same characteristics.

VI. QUANTUM EFFICIENCY AND DETECTIVITY

With the measurement of responsivity and noise current, we can determine the quantum efficiency and the detectivity of this device. The net quantum efficiency at the peak wavelength can be calculated from

$$R_p = \frac{e\lambda_p}{hc} \eta g \quad (3)$$

where R_p is the peak responsivity, h the plank constant, c the speed of light, and g the photoconductive gain. Taking $g = 1$ and $R_p = 105 \text{ mA/W}$ at $9.3 \mu\text{m}$, we estimated $\eta = 1.4\%$. The net quantum efficiency is composed of two factors, the optical quantum efficiency η_a and the escape probability P [6]. That is, $\eta = \eta_a P$. In a bound-to-continuum QWIP, the P is usually reached unity at the maximum responsivity. In this 15-period SLIP, the optical quantum efficiency determined from the absorbance of the sample with an eight-pass 45° facet waveguide configuration is about 1.6%. The escape probability at the maximum responsivity is estimated to be about 88%. For a SLIP without a reflection barrier, the typical escape probability is expected to be about 50% because half of the photoelectrons are emitted to the emitter contact. If we take the mean free path of the photoelectron into account, the escape probability is expected to decrease with increased thickness of the SL layer. Therefore, although the optical quantum efficiency can be increased with a larger period number, the net quantum ef-

Fig. 8. Detectivity of the SLIP and the 30-period QWIP as a function of bias voltage at 77 K. The decrease of detectivity of both samples is caused by the rapid growth of dark current at high bias voltage.

iciency may not increase much from the larger period number due to the decrease of the escape probability.

The peak detectivity is defined as

$$D_{\lambda_p}^* = \frac{R_p \sqrt{AB}}{i_n} \quad (4)$$

where R_p is peak responsivity, A the detector area, and i_n the noise current. The estimated peak detectivity D^* is $3.5 \times 10^9 \text{ cm}\sqrt{\text{Hz}}/\text{W}$ at $V = 0.1$ and $T = 77 \text{ K}$. At lower temperatures ($< 65 \text{ K}$) the detector becomes background limited. The D_{BLIP}^* is estimated about $1.5 \times 10^{10} \text{ cm}\sqrt{\text{Hz}}/\text{W}$.

We compared our results with a 30-period bound-to-continuum QWIP, which has a similar spectral response to our SLIP. The structure and performance parameters of the two devices are summarized in Table I. The voltage-dependence detectivity of the two devices is shown in Fig. 8. We found that the detectivity of the SLIP is comparable to that of the QWIP. However, the SLIP can work at the low bias range (0–0.3 V) whereas the detectivity of the QWIP is low in this bias range. The optimum bias point of the QWIP is about 0.9 V. The responsivity is 92 mA/W and the dark current is $1.67 \times 10^{-6} \text{ A}$ at this bias voltage. On the other hand, the optimum bias voltage for the SLIP is about 50 mV. At this bias voltage, the responsivity is 70 mA/W, and the dark current is $1.9 \times 10^{-7} \text{ A}$. With comparable detectivity and responsivity, the power dissipation of our SLIP is nearly two orders of magnitude smaller than this QWIP.

VII. CONCLUSION

We have investigated a 15-period superlattice structure for infrared detection with low operating voltage and lower power consumption. A strong photovoltaic response is observed in this asymmetrical structure. We also found a tunable feature of spectral response due to effect of the current blocking barrier in our device. The response spectrum shows voltage dependence around 0 V. At higher bias voltage ($> 25 \text{ mV}$) the spectra are independent of the bias and are approximately $8\text{--}10 \mu\text{m}$ with peak wavelength at $9.3 \mu\text{m}$. Due to the asymmetrical lineshape, the detector still has a responsivity of about 30% of its peak value at $6 \mu\text{m}$. The measured lineshape of response spectra are similar to the reported absorption spectra of superlattice structures.

At lower negative bias voltages the response is shifted toward shorter wavelength range. The magnitude of the responsivity also shows a strong dependence on the bias polarity. The responsivity under reverse bias voltages is almost 20 times smaller than that under forward bias voltages. The noise power spectral density of the dark current at 77 K shows the characteristics of $i_n^2 = 2eI_dB$ rather than generation-recombination noise. The peak wavelength detectivity is $D^* = 3.5 \times 10^9 \text{ cm}\sqrt{\text{Hz}}/\text{W}$ at 77 K and 0.1 V with a responsivity of 85 mA/W. Background limited performance can be achieved up to 65 K with $D_{\text{BLIP}}^* = 1.5 \times 10^{10} \text{ cm}\sqrt{\text{Hz}}/\text{W}$. The lower bias voltage, lower power consumption, and tunable spectral response of the detector should have advantages for practical applications.

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