Investigation of superlattice infrared photodetectors to reach the background limited performance at high temperature

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ABSTRACT

We have first investigated three superlattice infrared photodetectors in order to raise their temperature for the background limited performance. Their basic structure is a 20-period GaAs(6nm)/Al_{0.32}Ga_{0.78}As(4nm) superlattice sandwiched between two 50nm Al_xGa_{1-x}As blocking layers. We changed the barrier height (x) of the blocking layers and the well doping density (N_d) to see their effects on the temperature for the background limited performance. Three samples were grown with molecular beam epitaxy. The associated parameters (x , N_d) of Devices A, B and C are (0.28, 10^{18}), (0.28, 10^{17}) and (0.24, 10^{17}) respectively. The unit for N_d is cm^{-3} . The comparison between A and B is to see the effect of the doping density while that between B and C is the barrier height. The I-V characteristics of the three detectors at various temperatures have been investigated carefully. Two important experimental results have been concluded. A high doping density not only decreases the activation energy and increases the dark current but also increases the impurity scattering for the photoelectrons. For the dark current, high activation energy puts down the dark current and extends the dominant region of the thermionic emission current. Applying those results, we changed the parameters into (0.32, 5×10^{16}) and successfully fabricated a superlattice infrared photodetector to reach the background limited performance at 77K. The D_{BLIP}^* for the detector at 77K with wavelength 8.81 μm is $4.3 \times 10^9 \text{ cm} \sqrt{\text{Hz}} / \text{W}$.

Keywords: Superlattice infrared photodetector, background limited performance, dark current, photocurrent, thermionic emission current, and thermally assisted tunneling current.

1. INTRODUCTION

Based on intersubband transitions, the quantum well infrared photodetector (QWIP) was first proposed by Smith et al.¹⁻⁵ Since the interesting physical mechanisms² and mature growth technology of GaAs/AlGaAs molecular beam epitaxy, the detector has drawn special attention and has also been applied in the focal plane array³ for the thermal imaging.^{4,5} Used as a pixel of a focal plane array, the detector has a main concern that its dark current at high temperature is very high. Especially at 77 K the dark current is so large that it saturates the read-out circuit. Due to the charge limitation of the read-out circuit, a detector with a small dark current is needed. Although a small responsivity is always accompanied with a small dark current, the detector has to maintain the same detectivity as the one with a large responsivity and a large dark current. The former is preferred in the practical application. Likewise, the limitation on the read-out circuit makes background limited performance (BLIP) highly desirable in order to utilize the limited integration capacity. Under these circumstances, all of current in the detector is originated from the incident photons, the integration time can be extended until the integrating capacity is fully used and signal over noise ratio can also be promoted.

In order to get a large responsivity, the bound-to-continuum QWIP has attracted great interest of many researchers.⁶⁻⁹ Although the goal is reached, there is always a concern to saturate the read-out circuit in the practical application. To cut down the dark current, a wide barrier¹⁰ or a low doping density¹¹ has been used but the temperature for background limited performance has still not arrived at 77K. In 1993, Choi et al. proposed an infrared hot-electron transistor for 77K operation and an energy filter was used to select the photocurrent. But the device fabrication became complicated since it had three terminals and the middle contact had a limited width to reach.

In this paper, a novel structure of two-barrier superlattice infrared photodetectors (SLIP) is proposed to put down the dark current and raise the temperature T_{BLIP} for the background limited performance (BLIP). Three devices are designed to see the possibility. The analyzed conclusion of the three devices offers the parameter values of a new device to reach high- T_{BLIP} operation. The design principles are given in Section 2 and the experimental results and analysis in Section 3. Final conclusions are described in Section 4.

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2. DESIGN PRINCIPLES

A simple formulation for the dark current and photocurrent in the quantum well infrared photodetector is reviewed at first in this section.¹³ Our emphasis is made on the dark current contributed from the electrons thermally excited into the barrier from a single well and the contribution from the adjacent quantum wells is not taken into account for simplicity. The important factors to design the QWIP are indicated and understood easily by those formulas. A novel two-barrier superlattice infrared photodetector is also proposed in this section. The simple formulation for QWIP is also a good approximation to the SLIP. The important features about the dark current and photocurrent behavior in our SLIP are also described in this section.

2.1 Physical Mechanisms for the Dark Current

The dominant physical mechanics¹⁴ of the dark current in the QWIP is the thermionic emission (TE) at low biases and the thermally assisted tunneling (TAT) at high biases as shown in Fig. 1. Due to the scattering process by phonons or impurities, the electron's energy which is perpendicular would be transferred into the growth direction. Therefore the electron can pass the barrier with the total energy instead of the ground energy E_0 . At low biases, most of the electrons pass the barrier with the activation energy $E_A = E_C - E_F$. The associated thermionic emission current can be approximately written as¹³

$$I_{TE} = \frac{m_w A k T}{\pi \hbar^2 \tau} \exp\left(-\frac{E_A(V_{app})}{kT}\right), \quad (1)$$

where m_w is the effective mass of electrons in the well, A the cross section area of the device, k the Boltzmann constant, T the temperature, $\hbar$ the reduced Plank constant, and τ the scattering time due to phonons or impurities to transfer the electron's energy into the growth direction. The activation energy $E_A(V_{app})$ may be a function of the applied bias V_{app} due to the voltage drop in the well to raise the Fermi level.

Fig. 1 Physical mechanisms for the dark current in the QWIP

On the other hand, due to the electric field on the barrier at high biases, the electrons can tunnel through the barrier tip with lower energy ΔE . The associated thermally assisted tunneling current can be derived with W. K. B. method and the resulting formula can be approximately written as¹³

$$I_{TAT} = \frac{m_w A \sqrt{\ln 2 \times kT} \frac{\hbar^2}{2m_B} \left(\frac{e\mathcal{E}}{kT}\right)^2}{\pi \hbar^2 \tau} \exp\left(-\frac{E_A(V_{app})}{kT}\right) \exp\left(\frac{\hbar^2}{24m_B kT} \left(\frac{e\mathcal{E}}{kT}\right)^2\right), \quad (2)$$

where m_B is the effective mass in the barrier, and $\mathcal{E}$ the applied electrical field in the barrier. The thermally assisted tunneling current is more sensitive to the applied bias than the thermionic emission current due to the last exponential factor in Eq. (2), which is increased exponentially with $\mathcal{E}$ squared. At low biases, the performance of the thermally assisted tunneling current is similar to that of the thermionic emission current and it is difficult to distinguish between them. Until the two exponential factors in Eq. (2) are compatible, we cannot see any effect from the thermally assisted tunneling current from the I-V characteristics.

The important factor to put down both current components is determined by the activation energy, especially the value of E_{A0} , which is the energy difference between the Fermi level in the well and the nominal barrier height in the barrier. In addition, it is noted from the comparison between Eqs. (1) and (2) that the electric field to divide the dominant regions of the thermionic emission current and the thermally assisted tunneling current can be estimated with E_{A0} as follows,

$$\mathcal{E} = \frac{kT}{e} \sqrt{\frac{24\gamma m_B E_{A0}}{\hbar^2}}, \quad (3)$$

where γ is a factor to mean that the exponent in the last term in Eq. (2) is about γ times the one in the last second term so that we can see the effect of the thermally assisted tunneling current in the I-V characteristics. The advantage of the E_{A0} increment not only puts down the dark current exponentially but also extends the dominant region of the thermionic emission current where the current is less sensitive to the external bias than the thermally assisted tunneling current.

2.2 Physical Mechanisms for the Photocurrent

There are primarily two designs for the second energy level in the well as shown in Fig. 2. If the second energy level is less than the adjacent barrier height E_C and bound in the well, the detector is so-called a bound-to-bound type. A threshold voltage is needed to collect the photoelectrons and is determined by an important parameter ΔE_p , which is the energy difference between the nominal barrier height and the second energy level. Using the W. K. B. method and this parameter gives the photocurrent formulated as¹³

$$I_p = eG\tau_f v_2 A \exp\left(-\sqrt{\frac{2m_B}{\hbar^2}} \frac{4\Delta E_p^{3/2}}{3e\mathcal{E}}\right), \quad (4)$$

where G is the generation rate of the photoelectrons per unit volume for the infrared photon $h\nu$, τ_f the lifetime of the photoelectrons in the well, and v_2 the associated velocity of the second energy level for the photoelectrons to oscillate between the barriers. In order to avoid the threshold voltage, the second energy level is pushed into the continuum states and ΔE_p becomes negative. The photoelectrons can hence be collected at low biases as indicated by the voltage on the barriers in Fig. 2(a). The dark current in the bound-to-continuum QWIP is definitely higher than that in the bound-to-bound one since the corresponding E_{A0} is lower.

Fig. 2 physical mechanism for the photocurrent

2.3 Two-barrier Superlattice Infrared Photodetector

We propose a novel structure of the superlattice infrared photodetector with a superlattice sandwiched between the front and rear blocking layer. Compared with the conventional QWIP, the primary advantage can be indicated in Fig. 3.

Suppose the front and rear blocking layers are wholly identical and the differences of the electron densities of states between the bulk material and superlattice are neglected. When there is no incident radiation upon the detector, the applied biases on the front and rear blocking layers are the same and the band diagram is shown in Fig. 3(a). The electrons injected

from the front contact through the front barrier would be recaptured by the superlattice. If the resulting current is larger than that flowing through the rear blocking layer, the accumulated charge in the superlattice would prohibit the current. Therefore, the dark current primarily depends on the electrons injected from the superlattice through the rear blocking layer by thermionic emission or thermally assisted tunneling. Equations (1) and (2) are also a good approximation to describe the dark current in such a detector.

Fig. 3 Band diagrams under an external bias for the two-barrier superlattice infrared photodetectors

On the other hand, when the infrared radiation is incident upon the detector, the photoelectrons in the second miniband oscillate between the two blocking layers as shown in Fig. 3(b). Due to the higher barrier height caused by the external bias in the front blocking layer, the photoelectrons have larger opportunity to pass the rear blocking layer and produce the photocurrent. Assume the magnitude of the photocurrent especially by the background radiation is compatible with that of the dark current. Since the photocurrent passes only the rear blocking layer, and the current continuity requires the same amounts of current passing the two blocking layers, the external bias must be redistributed and most of it needs to be dropped on the front one in order to supply the photocurrent. In the aspect of the dark current, the bias drop on the rear blocking layer needs to be decreased and the dark current is hence decreased, either. Therefore, the front blocking layer has the capability to adjust the bias distribution as the background radiation is incident upon the detector. Because the background radiation is stable, the potential profile in the detector is also stable. Similar to the QWIP as shown in Fig. 2, the barrier height of the blocking layer can be higher or lower than the bottom of the second miniband and their difference is defined as ΔE_p . The case for $\Delta E_p < 0$ is a bound-to-continuum type while that for $\Delta E_p > 0$ is a bound-to-bound type. The photocurrent formulated in Eq. (4) is still good for our detector. It is also noted that the Fermi levels in the superlattice may be higher than that in the front and rear contacts. Carrier transfer may result in the tilt-up of the two blocking barriers and the detector may become bound-to-bound at thermal equilibrium for the case with $\Delta E_p < 0$. As the bias increases, the barrier height would be lower than the bottom of the second miniband in the end. Such kind of detector still belongs to the bound-to-continuum type in our definition.

As the additional photocurrent is concerned, that is, the AC signal of the photocurrent, we can understand the phenomenon easily with the small signal model as shown in Fig. 4.

Fig. 4 Equivalent circuit for the small AC photocurrent in the two-barrier SLIP

In the figure, R_f and R_r represent the differential resistors of the front and rear blocking layers respectively. The notation i_p is the additional photocurrent except due to the background radiation, i.e., the AC photocurrent. The measured additional photocurrent i_{mp} by the external current meter is

$$i_{mp} = \frac{R_r}{R_f + R_r} i_p. \quad (5)$$

It is obvious that R_r is much larger than R_f due to the bias distribution as shown in Fig. 3(b). Therefore with the two-barrier superlattice infrared photodetector, we just lose a small part of the AC photocurrent. But the advantage is the decrement of the dark current due to the background radiation. It is expected that the temperature for the background limited performance in such detectors can be higher than that in the QWIP

2.4 Variable Parameters in Our Design

To get a large photocurrent, the barrier height of the blocking layer should be lower than the bottom of the second miniband in the superlattice i.e., $\Delta E_p < 0$. But for the purpose to raise the temperature for BLIP, we may have to put down the dark current further. As shown in Eqs. (1) and (2), if E_{A0} is raised, the dark current is definitely decreased dramatically. The two parameters, ΔE_p and E_{A0} , are related and limited by the wavelength we want to detect. If E_{A0} has to be large enough to decrease the dark current, ΔE_p would become positive. Equation (4) shows the photoelectrons may be collected for the case of $\Delta E_p > 0$ with a large bias. Since a large E_{A0} may also extend the dominant region of the thermionic emission current, we may operate the device at high-bias region but still have a small dark current.

The doping density N_d in the superlattice structure is a key factor to affect the magnitudes of the dark current and photocurrent. Just for the consideration of the dark current, E_{A0} is related to the Fermi level, which is approximately proportional to the doping density in the superlattice. In addition, another factor to affect E_{A0} is the aluminum fraction x in the blocking layer. Appropriate choice of the four parameters, x , N_d , E_{A0} , and ΔE_p , will raise the working temperature T_{BLIP} for background limited performance. In particular, we may fix the superlattice structure and vary the first two parameters to see their effect on T_{BLIP} .

3. EXPERIMENTS AND ANALYSIS

3.1 Device Structure

Three devices A, B, and C are designed at first to see the effect on the T_{BLIP} by varying the aluminum fraction x in the blocking layer and doping density N_d in the superlattice. Their analysis conclusion offers the redesigned structure of Device D. The associated band diagram of all the devices is shown in Fig. 5. Their common superlattice structure is the same. It is composed of 20 periods of $40\text{\AA}$ $\text{Al}_{0.32}\text{Ga}_{0.68}\text{As}$ / $60\text{\AA}$ GaAs and has two primary absorption peaks at the wavelengths of $8.76\mu\text{m}$ and $5.99\mu\text{m}$. The top and bottom contacts are both doped with $1.0 \times 10^{18} \text{ cm}^{-3}$. All of the calculated results of the miniband are based on the Kronig-Penny model. The barrier height of the $\text{Al}_x\text{Ga}_{1-x}\text{As}$ is taken as $801x \text{ meV}$, which is an empirical formula for our molecular beam epitaxy.

Fig. 5 Band diagrams of our devices

The important parameters (x , N_d) for Devices A, B and C are $(0.28, 10^{18})$, $(0.28, 10^{17})$, and $(0.24, 10^{17})$ respectively. The unit for N_d is cm^{-3} . The comparison between A and B is to see the effect of the doping density while that between B and C is the barrier height. The parameters of Device D are determined by the analysis results of the above three devices. All of the

important parameters for various devices are summarized in Table 1. At thermal equilibrium, the barrier would be tilted up due to the transferred carrier from the superlattice into both contacts. The associated activation energy at zero bias is $E_A(0)$ in the table. Except that Device C is a bound-to-continuum type, all others are bound-to-bound. All of these devices are fabricated into the $100\mu\text{m} \times 100\mu\text{m}$ mesas by wet chemical etching and have a 45° facet for the light coupling.

Table 1 Important parameters of all devices

Device	x	$N_d (\text{cm}^{-3})$	$E_{A0} (\text{meV})$	$\Delta E_p (\text{meV})$	$E_A(0) (\text{meV})$	Type
A	0.28	1.0×10^{18}	131.1	16.5	169.6	Bound-to-Bound
B	0.28	1.0×10^{17}	163.5	16.5	169.8	Bound-to-Bound
C	0.24	1.0×10^{17}	131.4	-15.6	137.8	Bound-to-Continuum
D	0.32	5.0×10^{16}	197.3	48.5	201.9	Bound-to-Bound

3.2 Experiments

In order to keep the device's temperature stable and accurate, the samples are connected to the ceramic pads with indium. The pad and the cold finger in the cryostat are also connected with indium. All these careful procedures are for the purpose to maintain good thermal contact. The dark-current characteristics are measured with a cold shield at the same temperature as the cold finger around the devices. For the background photocurrent measurement, a window with a FOV (field of view) angle of 20° is open for the 45° facet of the device under test. Besides the device, a silicon diode is used to measure the operating temperature.

The I-V characteristics of the dark current are measured for the temperature 30K up to 100K. Under the same situation but with the window open for the background radiation incident upon the devices, the I-V curves with the background photocurrent and dark current coexisting are also measured. Figures 6, 7 and 8 show the characteristics at around the T_{BLIP} for Devices A, B and C respectively. The data for the three devices at 40K and 80K are collected in Fig. 9 for comparison. The data for Device D will be described in another subsection. In all those figures, the solid curves stand for the dark current while the dash ones do for the photocurrent.

The external bias is defined as positive when the voltage on the top contact is positive. It is noted that the characteristics are not symmetrical with the respect to the bias polarity (especially for A) and the zero point of the current level may not occur at the origin. The former is attributed to the dopant migration¹⁵⁻¹⁷ from the contact or wells into the barriers. The latter may originate from the space charge accumulated in the superlattice structure. Most of the discussion in the following will hence make emphasis on the negative-bias result without the effect of the dopant migration.

3.3 Analysis of the First Three Devices

The I-V curves for the dark current in the three devices show that the principal physical mechanisms are thermionic emission (TE) at low biases and thermally assisted tunneling (TAT) at high biases especially for low temperatures. The former varies gradually with biases while the latter does dramatically. For the background photocurrent, it is noted that they all coincide with the dark current at the same temperature at high bias range. This demonstrates our careful calibration of the operating temperature and the effort to prevent from the heating effect as the background photocurrent is measured.

As shown in Fig. 6 for the dark current in Device A at 40K, the thermionic emission current is dominant at about 0~(-0.16) V and the thermally assisted tunneling current is at about larger than - 0.16 V in magnitude. The kink point to divide the two regions is marked by an upward arrow. At 50K and 60K, similar kink points are also marked by peering along the curves from low biases to high ones. The associated bias voltages for these three kink points are -0.16V, -0.2V, and -0.24V. These values are consistent with Eq. (3) for $\gamma = 0.06$, i.e., about 6% of E_{A0} to see the effect of the thermally assisted tunneling current. The value is calculated under the assumption that no bias is dropped on the superlattice and the electric fields in the front and rear blocking layers are the same.

Device A is a bound-to-bound type. For the background photocurrent, the working bias range at 40 K for the background limited performance is 0.2V. The difference between the background photocurrent and the dark current at the same temperature is shrunk as the temperature increases and disappears at 80K. The highest T_{BLIP} seems to be 70K. The maximum background photocurrent is about 20 nA and may be estimated from the data at 40K. Comparing it with the dark current level ($> 10^{-7}$ A) at 80K for biases larger than - 0.05 V in magnitude gives the reason why the background limited

performance disappears at 80K. Suppose the electric field is uniform in the blocking layers and no bias is dropped on the superlattice. We can use Eq. (4) to calculate the percentage of the collected photoelectrons for the device at -0.23 V. The result is about 15%.

Fig. 6 Current versus voltage for Device A

Fig. 7 Current versus voltage for Device B

Device B is a bound-to-bound type. The similar phenomenon occurs at the characteristics for Device B shown in Fig. 7. The important parameters can be derived from the same observation procedure as Device A. The working bias range for BLIP at 40K is 0.4V. The maximum background photocurrent is also about 20 nA. For the operation at 70K, the BLIP is more apparent for Device B than that for Device A. The background limited performance also disappears at 80K and the highest T_{BLIP} seems to be 70K. The percentage of the collected photoelectrons at -0.4 V is calculated as 34%.

For the kink point of the dark current in Fig. 7, it appears at -0.3V for 40K and at -0.31V for 70K . Obviously it does not follow the prediction of Eq. (3). This is attributed to the voltage drop on the superlattice in particular at low temperature because the doping density in Device B is low and carriers may be frozen-out at low temperature. The doping density in the superlattice is ten times less than that in A and some of the biases are dropped on the superlattice in order to conduct the current. The kink point at low temperature appears at a larger bias than that predicted by Eq. (3) because some of the voltage is needed on the superlattice. Calculation of Eq. (3) with $\gamma = 0.06$ for Device B gives the kink point at 40K as -0.18V . Compared with the experimental value of -0.3V , this value indicates that about 0.12V may drop on the superlattice.

Fig. 8 Current versus voltage for Device C

Device C is a bound-to-continuum type. As shown in Fig. 8, the background photocurrent rises and goes into saturation very rapidly. The working range at 40K for BLIP is 0.2V and shrunk as the temperature increases. It covers the TE and TAT current dominant regime at 40K but is gradually shifted into the TE dominant one. In the end, it disappears at 80K . The highest T_{BLIP} also seems to be 70K . The difference between the background photocurrent and the dark current at the same temperature in the BLIP range is much larger than that for Devices A and B. The maximum background photocurrent estimated from the data at 40K is about 50 nA . For the operation at 70K , the working bias range still has 0.1V .

As shown in the same figure, the bias where the photocurrent goes into saturation is shifted into a lower value as temperature increases. This is consistent with the bias redistribution shown in Fig. 3 (b). As the temperature increases, the front contact can supply more current through the front blocking layer at the same voltage on it. Because of the current continuity, this voltage drop becomes less to reduce the supplied current and more voltage is dropped on the rear blocking layer to increment the photocurrent. The total current through the front and rear blocking layers are hence the same even as the temperature increases. Therefore, not only the background photocurrent but also the temperature may both cause the external bias to be redistributed.

For the kink point in Fig. 8, it occurs at -0.11V for 40K and at -0.6 for 50K . Equation (3) is not appropriate to describe them. In fact, it is distorted by the tilt-up of the barrier at low biases. As indicated by $E_A(0)$ in Table 1, the tilt-up energy is 6.4 meV and corresponds to suppressing the thermionic emission current 6.4 times at 40K . Recovery of the current level gives the kink point as -0.16V which Eq. (3) predicts.

In order to compare those data, we have summarized the I-V curves at 40K and 80K for all devices in Fig. 9. For the dark current, it is found that B's is lowest and C's is highest. In our design, $E_A(0)$'s for the dark current in the three devices at thermal equilibrium are 169.6 , 169.8 , and 137.8 meV . And E_{A0} 's are 131.1 , 163.5 , and 131.4 meV in sequence. As the bias increases, the activation energy will be decreased from the former values because the tilt-up amount of the barrier height

gets decreased. At high bias, the activation energy would approach the latter values in the end. The dark-current result at 80K is consistent with the above argument. At low bias, A's dark current is close to B's while to C's at high biases. It is hence concluded that $E_A(0)$ determines the behavior of the dark current at low biases while E_{A0} does at high biases.

Fig. 9 Comparison for the three devices

The maximum background photocurrents as shown in Fig. 9 are 20, 20, and 50 nA for Device A, B and C respectively. Comparing A's and B's indicates that the low doping density in the well does not decrease the photo responsivity.¹⁸ This may be attributed to the not enough bias in Device A. Only 15% of the photoelectrons are collected. But it cannot explain the whole story as compared with 34% in Device B. Another reason may be due to the impurity scattering in the well. As the electrons are excited by the photons into the second miniband of the superlattice and oscillate between the two blocking layers, the scattering by the impurities in the wells would transfer their energy along the growth direction into the superlattice plane. Under this situation, the electrons in the second miniband are actually scattered into the high-energy state in the first miniband. They finally reach the bottom in the first miniband by emitting the LO phonons. It is expected that the absorption rate of photons and the scattering rate of electrons in the superlattice are both proportional to the doping density in the well. Their effects on the photocurrent cancel each other. Therefore, we have observed the same maximum background photocurrent. It is hence concluded from the above results that the optimized doping density in our superlattice is about 10^{17} cm^{-3} in order to prevent from the impurity scattering.

On the other hand, comparing B's and C's maximum background photocurrent implies that the photoelectrons collected by the tunneling process with the high enough applied bias may reaches about 40% of those by the continuum states. This value is consistent with that calculated with Eq. (4) for Device B. This suggests that we should go to the high bias region to collect the photoelectrons. On the other hand, the dark current is decreased dramatically as we compare the dark currents in Devices B and C. As shown in Table 1, with both $E_A(0)$ and E_{A0} in B higher than those in C for 32 meV, two orders of magnitude in the dark current at 80K are expected to decrease for C compared with B. The experimental curves at 80K in Fig. 9 agree with the estimation. Comparison between B's and C's dark current at 40K indicates that B has a wide bias region for thermionic emission current. In brief, high E_{A0} not only puts down the dark current but also extends the dominant region of the thermionic emission current where the current level is less sensitive to the external bias than the thermally assisted tunneling current. In addition, a high E_{A0} may also expand the BLIP bias range into the high bias regime where thermally assisted tunneling current is dominant. The advantage for the device to be operated in the high bias regime is that the photoelectrons can be collected with high biases and the current supplying capability of the front contact can also be easily controlled by the applied bias.

3.4 Further Optimization

All of the above three devices have some region to work on background limited performance at 70K which is higher than conventional QWIP (60K). Based on the maximum background photocurrent, more than 1.5 orders of magnitude in the dark current have to be cut down in order to operate the detector at 77K. The experimental results offers two possibilities to optimize the device for the operation at 77K. One is to suppress the dark current in Device C for the operation in the low bias regime where the thermionic emission current is dominant. The barrier height needs to be increased up to matching the bottom edge of the second miniband in order to put down the dark current but also maintain the bound-to-continuum type. But the decrement amount of the dark current may still be not enough. As shown in Fig. 9, the dark current in Device B at 80K just coincides with the background photocurrent in Device C at 40K. The dark current in Device B is definitely less than the proposed one since Device B has higher barrier height.

The other possibility is to suppress the dark current in Device B with higher barrier height and lower doping density. A new device D is designed to have aluminum fraction $x = 0.32$ in the blocking layer and the doping density $N_d = 5.0 \times 10^{17} \text{ cm}^{-3}$ in the superlattice. Its associated important parameters are also summarized in Table 1. In particular, E_{A0} and $E_A(0)$ in Device D are 33.8 meV and 32.1 meV respectively higher than those in Device B. At 80K, the dark current in D is expected to one-500th times that in B. It is noted that ΔE_p is equal to 48.5 meV and 1.86V is needed to collect 30% of the photoelectrons. Based on the above conclusion that high E_{A0} not only puts down the dark current but also extends the dominant region of the thermionic emission current, it is possible for the device to operate at such high bias.

Fig. 10 Current versus voltage of Device D

The I-V characteristics for the dark current and background photocurrent in Device D are shown in Fig. 10. It is obvious that the device shows the background limited performance at the temperature of 70K for bias $0 \sim (-1.3)\text{V}$ and at 80K for bias $0 \sim (-0.5)\text{V}$. The BLIP working range at 77K is definitely larger than that at 80K. The background limited performance seems to disappear at 90K. The maximum background photocurrent is observed at high bias (-1.7V) and reaches about 15nA (indicated by the leftward arrow), which is compatible with that of Device B. It is noted that the kink point reaches -1.1V and high voltage drop on superlattice is expected. Besides, the thermionic emission current at low biases does not increase with the temperature. Those phenomena indicate that there are limited carriers in the superlattice. The background photocurrent generated by those carriers in the superlattice is still larger than the dark current at the low biases. Background limited performance hence appears at a wide bias range.

In order to demonstrate that the device can indeed operate at high temperatures, the responsivity versus wavelength has been measured at 80K and 90K, and is shown in Fig. 11. Only one peak of the 8.81- μm wavelength is observed and consistent with the transition of electrons from the top of the first miniband to the bottom of the second miniband. The maximum responsivity is about 63 mA/W at 80K and 90K for -1.7V and even higher at the positive bias. At -1.7V , the detector does

not show BLIP at 60~90K. The associated specific detectivity D^* is $3.9 \times 10^9 \text{ cm}\sqrt{\text{Hz}}/\text{W}$ at 80K. Consider the operating point at -1.5V in Fig. 10. It indeed shows BLIP even at 70K. The corresponding dark current at 80K is 50 nA and very close to the maximum background photocurrent. The associated responsivity is 36 mA/W and D^* is $4.3 \times 10^9 \text{ cm}\sqrt{\text{Hz}}/\text{W}$. At 77K, this operating point is able to show BLIP.

In the same figure, the responsivity for Device A at -0.55V is shown as the dash curve. It is broader than that in Device D. The short wavelength absorption corresponding to the transition of electrons from the bottom of the first miniband to the top of the second miniband is also observed except that the experimental short wavelength is longer than the designed one. The disappearance of the short-wavelength responsivity in Device D may also attributed to the voltage drop on the superlattice. The miniband may not be formed due to the misalignment of the energy states in the adjacent wells and the responsivity becomes sharper and larger because the wave function is localized.

Fig. 11 Responsivity versus wavelength of Device D, The dash curve is the result of Device A for comparison

4. CONCLUSIONS

The two-barrier SLIP offers the possibility to operate at high temperatures and high biases with the background limited performance. The devices, A, B and C investigated in this paper demonstrate that the T_{BLIP} for the three detectors is about 70K and more than 1.5 orders of magnitude in the dark current have to be cut down in order to operate the device at 80K with BLIP. There is no chance for the bound-to-continuum detector to subdue such large dark current because of the limited barrier height. The only choice is to raise the barrier height (i.e., E_{A0}) and collect the photoelectrons with high biases.

The comparison between Devices A and B gives the effect of the doping density. A high doping density not only decreases the activation energy and increases the dark current but also increases the impurity scattering for the photoelectrons. The optimized density is about 10^{17} cm^{-3} in our superlattice. Comparing Device B and C concludes the effect of the barrier height of the blocking layers. High E_{A0} , corresponding to a large barrier height, not only puts down the dark current but also extends the dominant region of the thermionic emission current where the current is less sensitive to the external bias than the thermally assisted tunneling current. In addition, a high E_{A0} may also expand the BLIP bias range into the high bias regime where thermally assisted tunneling current is dominant.

A device with the aluminum fraction 0.32 of the blocking layers and the doping density $5 \times 10^{16} \text{ cm}^{-3}$ in the superlattice is used to confirm the conclusion. The nominal activation energy E_{A0} is 197.3 meV and about 29 times kT at 80K. The dark current is not only decreased dramatically but also the dominant region of the low thermionic emission current is extended

into -1.2V . The background limited performance indeed appears at 80K . The specific detectivity D^* at 80K with wavelength $8.81\mu\text{m}$ at -1.5V is $4.3 \times 10^9 \text{ cm}\sqrt{\text{Hz}}/\text{W}$.

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