Research Article

Photoresponse of Long-Wavelength AlGaAs/GaAs Quantum Cascade Detectors

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We study the photoresponse and photocurrents of long-wavelength infrared quantum cascade detectors (QCDs) based on AlGaAs/GaAs material system. The photocurrent spectra were measured at different temperatures from 20 K to 100 K with a low noise Fourier transforming infrared spectrometer. The main response peak appeared at 8.9 μm while four additional response peaks from 4.5 μm to 10.1 μm were observed as well. We confirmed that the photocurrent comes from phonon assisted tunneling and the multipeak behavior comes from the complicated optical transition in the quantum cascade structure. This work is valuable for the future design and optimization of QCD devices.

1. Introduction

Quantum cascade detectors (QCDs) are photovoltaic detectors. They can operate under zero bias applied and consequently do not suffer any dark current which is expected as a promising alternative of quantum well infrared photodetectors (QWIPs) [1, 2]. For focal plane array (FPA) application, the QCDs perform pure photoresponse current to reach a longer integration time [3] and lower noise equivalent temperature difference (NETD) [4]. Based on bound-to-bound intraband transition, the line width of QCDs is narrow, which means high selectivity to wavelength. Moreover, QCDs have been shown to work at higher temperature [5] and been reported in different materials and all infrared atmospheric windows [5–9].

To prevent false-alarm and improve detection accuracy, two color FPAs were studied and fabricated [10–12]. Conventionally, two-color detection is achieved by two single-color detectors fabricated together. So, secondary photoresponse peaks are undesired which would act as cross talk and noise in response spectra. QCDs perform excellent for the narrowband detection. But confined with their multisized quantum wells, the photoexcited transitions are complicated. As a result, several secondary peaks appear. To eliminate cross

talk and further improve the detector's performance, detailed study on the secondary peaks is of particularly importance.

2. Materials and Methods

The samples under study are GaAs/AlGaAs QCDs designed to operate at 8.9 μm [3, 13]. The wafer used to fabricate this QCD sample was grown by molecular beam epitaxy (MBE), and the layer sequence from substrate to top was 400 nm n-doped GaAs bottom contact (Si-doped to $1 \times 10^{18} \text{ cm}^{-3}$), 40 periods of 7 coupled $\text{Al}_{0.33}\text{Ga}_{0.67}\text{As}/\text{GaAs}$ superlattice active region, and 350 nm n-doped GaAs top contact in which doping concentration is equal to the bottom contact. The first QW of each period absorbs incident light and is n-doped with the doping concentration $5 \times 10^{17} \text{ cm}^{-3}$. The thickness of different QWs and barriers is 68/56.5/20/39.55/23/31/28/31/34/31/38/31/48/22.6 (Å) in roman and bold, respectively. The mesa size is $200 \times 200 \mu\text{m}^2$ and electrical contacts were formed by a standard lift-off deposition of AuGe/Ni/Au (100/20/400 nm). To theoretically describe the electronic properties of QCDs, we applied the standard eight-band $k \cdot p$ model. As shown in Figure 1, the electrons which the energy $h\nu = E_8 - E_1$ could be excited from E_1 to E_8 . E_7 is designed to equal E_8 which

FIGURE 1: Self-consistent calculated conduction band structure of one period.

could allow the excited electrons resonant tunneling to reduce the recombination possibility and contribute to effective transport. Then, excited electrons tended to transport in the direction $E_7 \rightarrow E_6 \rightarrow E_5 \rightarrow E_4 \rightarrow E_3 \rightarrow E_2 \rightarrow E_{1, \text{next-period}}$ by LO-phonon assisted tunneling due to the coupling of wavefunction of adjacent wells.

3. Results and Discussion

Considering the complicated interactions between the inter-subbands in QCDs, the absorption and response spectrum is not so pure and sensitive to $8.9 \mu\text{m}$ only. With the diffusion and tunneling of electrons, more than one absorption process could be figured out theoretically as Figure 2(a) dashed line indicated. Besides, we measured response photocurrent spectra under zero bias voltage at different temperature. QCD sample is soldered on a copper heat sink and placed in a closed cycle helium cryostat. The measurements were performed by using a SR570 low noise current preamplifier and a Fourier transform infrared spectrometer (Nicolet 6700). Response photocurrent spectra at different temperatures are shown as solid lines in Figure 2(a).

Three clear photoresponse peaks were found immediately in Figure 2(a) which are $E_1 \rightarrow E_7/E_8$, $E_2 \rightarrow E_8$, and $E_1 \rightarrow E_9$ processes. Other two peaks could be seen after zooming in which are corresponding to $E_2 \rightarrow E_9$ and $E_2 \rightarrow E_{10}$ transitions. It is to be noticed that the valley at 1250 cm^{-1} is a background absorption so that the peak at 1270 cm^{-1} is actually a fake one.

To further improve the detector's performance, detailed study on the formation of multipeak spectra is needed. As is known, photocurrent I_p could be expressed as [14]

$$I_p = n_p e v, \quad (1)$$

where n_p is the quantity of photogenerated carriers, e is electron charge, and v is the transport velocity. Moreover, for a certain wavelength λ , the photocurrent could be given by

$$I_p(\lambda) = n_p(\lambda) e v(\lambda). \quad (2)$$

Equations (1) and (2) are true when the electron concentration is high enough to be photoexcited. Otherwise, the I_p is also restricted to electron concentration. Besides, corresponding to different photoexcited transitions, the transport paths are not all the same in QCDs, which would lead to different $v(\lambda)$. At low temperature condition, the impurities are ionized less and mainly distributed in E_1 subband. Thus the optical excited transitions primarily occur from E_1 to E_7 , E_8 , and E_9 , respectively. With temperature rises, more impurities will be ionized and electron concentration will get higher. Consequently, more quantum states of E_1 subband would be occupied. According to Pauli exclusion principle and Hund's rules, electrons would tend to be distributed at higher energy levels such as E_2 by means of diffusion and tunneling. Then, optical transition from E_2 is enhanced as Figures 2(b) and 2(c) indicated.

The calculated electrons distribution at different temperatures is presented in Figure 3. It can be seen that electron density at E_2 subband is hard to be identified at 50 K, while the density at E_2 or even other subbands becomes larger with temperature increases. At temperature higher than 40 K, the electron density grows exponentially rapidly as the inset Figure 3 indicated, and corresponding to Figure 2(b), the response of $E_2 \rightarrow E_8$ transition becomes clear at 40 K. This indicated that our QCD can be operated around 80 K, but the electron concentration of E_2 grows to ten times as that at 40 K which would be a nonignorable cross talk.

In addition, band-gap and barrier height would be influenced by temperature. Energy levels would be rearranged by structure variation of quantum wells, especially the quasi-bound energy levels such as E_9 . As for photoconductive QWIPs working at nonzero applied bias, the bound-to-quasi-bound transition appears redshift with temperature rises [15]. But for QCDs, null bias working condition makes the transport mechanisms different. As is expected, $E_1 \rightarrow E_9$ transition appears blueshift with temperature getting higher as Figure 2(d) indicated. The experiment results and calculated energy gap between E_1 and E_9 are shown in Figure 4. A general agreement has been obtained.

From responsivity and dark current, we can deduce the Johnson noise limited detectivity given by [2]

$$D^* = R(\lambda) \sqrt{\frac{R_0 A}{4kT}}, \quad (3)$$

where $R(\lambda)$ is the peak responsivity, R_0 is the device resistance at null bias, A is the mesa surface, and T is the temperature of the sample. We obtained $D^*(\lambda = 8.9) = 1.4 \times 10^{10}$ Jones at 80 K as Figure 5 presented. Moreover, after the elimination of secondary response peaks, the g factor in spectra would get higher, leading to a higher D^* .

In our QCD detector samples, the $E_1 \rightarrow E_7$ and $E_1 \rightarrow E_8$ transitions are expected to be the primary optical transitions. The spectra noises which act as cross talk could be classified in two categories. The first category is the transitions from E_1 to non- E_7/E_8 subbands such as $E_1 \rightarrow E_9$ and the second is excited from non- E_1 (for example, $E_2 \rightarrow E_8$) energy levels. For the first category, thicker barriers would reduce the overlap of wavefunctions, leading to a lower transition

FIGURE 2: (a) Calculated absorption spectra at 300 K (dashed line) and measured photoresponse spectra (solid line). (b) Details (normalized) around $E_2 \rightarrow E_8$. (c) Details (normalized) around $E_2 \rightarrow E_9$. (d) Details around $E_1 \rightarrow E_9$ and $E_2 \rightarrow E_{10}$.

FIGURE 3: Calculated electron density at different temperatures (normalized). Inset is the electron concentration ratio of E_2 and E_1 subband.

FIGURE 4: Calculated and experiment $E_1 \rightarrow E_9$ transition peak energy.

rate. For the second category, an effective way is to reduce the electron occupation of ground states at non- E_1 subbands.

4. Conclusion

In conclusion, we have demonstrated a GaAs/AlGaAs multi-peak quantum cascade detector. The main response peak appeared at $8.9 \mu\text{m}$ while four other response peaks from $4.5 \mu\text{m}$ to $10.1 \mu\text{m}$ were observed and analyzed. We confirmed that the multi-peak performance comes from the complicated optical transition in the quantum cascade structure. This work is valuable for the design and optimization of QCD devices.

FIGURE 5: Peak wavelength detectivity.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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