Novel Type of Wide-Bandwidth GaAs/AlGaAs Infrared Photodetectors

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Abstract: A novel asymmetrical GaAs/AlGaAs photoconductance infrared detector based on the new idea proposed in this paper has been developed, which uses the intersubband transition within the same conduction (valence) band due to infrared radiation. The detectors with two wells or six wells grown by Metalorganic Chemical Vapor Deposition (MOCVD) system are fabricated by etching a mesa size of 200μm × 200μm. Evident infrared absorption on the wavelength from 5 to 10μm has been observed for two samples, so has the peak of negative differential conductance. It is demonstrated that the photocurrent together with the signal-to-noise ratio increases with the number of the wells, but have nothing to do with the increase of the noise current under the same electric field, i.e., the voltage drops per period, as is different from the conventional GaAs/AlGaAs Quantum Well Infrared Photodetectors (QWIPs). The noise current is one order's magnitude lower than that of the conventional GaAs/AlGaAs QWIPs. It is anticipated that the photocurrent and detector performances can be improved further by increasing the number of wells and optimizing the structural parameters.

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1 Introduction

Long wavelength infrared detection using intersubband transitions is progressing rapidly in recent years[1—3], and the advantages of quantum well infrared photodetectors (QWIPs), compared with the HgCdTe detectors, consist of mature GaAs growth and

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processing technologies, which lead to the high uniformity, excellent reproducibility and thus the large-area, low-cost staring arrays. In addition, the ability to accurately control the band structure, hence the spectral response, allows the monolithical integrated multispectral infrared detectors as well as the potential being monolithic integration with high-speed GaAs multiplexes and other electronics[4,5]. As a result of these advantages, GaAs/AlGaAs QWIPs have been undergoing a rapid development during the past several years, at the same time it is still necessary to know the further detailed understanding of the operating mechanism and the present problems of the conventional QWIPs photodetection system. Important problems concern the possible decaying absorption rate, small photocurrent, large refill-compensation recombination current, high noise and low-response speed, narrow spectral width (about 0.5—1μm) and the fixed response wavelength, etc. providing that the structure of the device has been determined in the intersubband photo-electronic phenomena in GaAs/AlGaAs QWIPs[6,7].

In this paper, we analyze the mechanism and these problems. It should be pointed out that a key feature is that the photo-induced deficiency (empty quantum states) of bound carriers in quantum wells can't move and contribute to current, but it can weaken the photoabsorption. Furthermore, the deficiency of bound carriers and the small intersubband energy difference lead to a strong optical-phonon assisted compensation recombination together, resulting in a shortened excited carrier lifetime[4,5]. In this paper we suggest a novel detection mechanism to solve the problem and improve the performances of the conventional GaAs/AlGaAs QWIPs. The performances of the suggested quantum well infrared photodetector were large excited-sate carrier lifetime, a large IR photocurrent response, no compensation recombination current, low noise and high response speed. This novel detection mechanism can be basically used in two different modes owing to the different structural design: one is that the device has a wide response wavelength, about 5—10μm; the other is that the spectral response of the device can be tuned with the applied bias voltage.

In this paper the principle of the device has been investigated theoretically. Two of the wide-bandwidth detectors are prepared, with the spectra width about 5—10μm by measuring the infrared absorption spectra at 300K, which corresponds with the theoretically calculated value 4.5—10μm very well. The performances of devices are measured, including the *I*-*V* characteristic at 300K and 77K, and the bias dependence of the photo-response for reverse bias (means mesa top negative). The extremely large IR photocurrent signals together with the phenomena of negative differential conductance have been experimentally observed. The optimum biases decided by *I*-*V* characteristic measurement at 77K are found to reach excellent agreement with the measured values out of the photo-response test for the two samples. In conclusion, the performances of the devices are typical of the photocurrent signal and the ratio of signal to noise increasing with the increase of the number of the wells, while there is no increases in the photocurrent signal for the conventional GaAs/AlGaAs QWIPs[1]. The noise current is about one order's magnitude lower than that of conventional GaAs/AlGaAs QWIPs[1].

2 Principle and Preparation of Devices

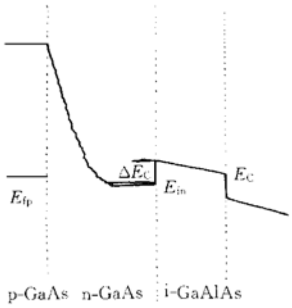

FIG. 1 Band Diagram Showing Conduct Band Edge Under Reverse Bias

The basic detector structure cell consists of three layers: p^+ GaAs layer, n^+ GaAs layer and the intrinsic $Al_xGa_{1-x}As$ barrier layer (denoted as p^+-n^+-i cell in the following), which correspond to the n-type high doped GaAs well (heavily silicon doped) embedded between the p-type high carbon doped GaAs (heavily carbon doped) and the intrinsic $Al_xGa_{1-x}As$ barrier. The conduct band edge diagram at reverse bias is schematically shown in Fig. 1. Based on the basic structure model, the detector can be designed to work in two modes owing to different structural parameters. And one type is that the doped well is designed to be thin and the quantum energy level (or levels) in the conduction band has (have) been formed, in which the infrared irradiation of a certain wavelength is absorbed by the excitation of an electron from the doped quantum well ground state in the conduction band to an unoccupied excited state (or continuum state) in the same band, then the excited electrons are escaping from the well and collected as photocurrent; on the contrary, the other type is that the doped well is designed to be wide, in which the infrared irradiation of a certain wavelength is absorbed by the free electrons in the conduction band and from the doped quantum well to be collected as photocurrent. As for the former, the response wavelength can be tuned by the applied bias with the well width varying with the applied bias. And for the latter, the spectra response is wide because the Fermi energy level has entered into the conduction band owing to the high doping in the well as shown in Fig. 1. All the electrons residenting between the conduction band bottom (E_c) and the electron Fermi energy level (E_{fn}) can absorb the infrared irradiation of a certain wavelength and escape from the well with a certain probability to form the photocurrent. Of course, the spectra response for the two types of the devices can be tuned by varying the structural parameters such as the doping concentration of doping regions and the width of each layer in p^+-n^+-i cell. From the figure it can also be seen that the photo-excited electrons will be accelerated by the huge potential energy difference between p^+ GaAs and n^+ GaAs while arriving to the interface between p^+ GaAs layer and n^+ GaAs layer under a certain reverse bias. The hot electrons will ballisticaly fly through the structure and be collected as the photocurrent, so the device is typical of the ultra-high response speed[6].

The focus of attention in this paper is the preparing of the detectors with wide spectra width and to verify the basis detection mechanism experimentally. So we choose two samples with the same structural parameters except for the number of wells to indicate the influence of the number of wells on the device performance. The structural parameters of the samples are chosen as follows: the doping concentrations of p^+ GaAs layer and n^+ GaAs layer are 1×10^{20} cm^{-3} and $4\times10^{18}cm^{-3}$ respectively; the widths of each layer of p^+-n^+-i cell are 10nm, 40nm and 60nm respectively; the periods of the p^+-n^+-i cell are two for sample cid01 and six for sample cid02. The $Al_xGa_{1-x}As$ barrier of Al composition for the two samples is x of 0.37. The samples grown via Metalorganic Chemical Vapour Deposition (MOCVD) should be high doped in order to tunnel. The typical structure of devices consists of a 1μm n^+ GaAs (doped $n=2\times10^{18}cm^{-3}$) contact layer grown on a semi-insulating substrate followed by p^+-n^+-i cell, with different period one layer of 50nm $Al_xGa_{1-x}As$ ($x=0.37$) and the top 0.9μm n^+ GaAs (doped $n=2\times10^{18}cm^{-3}$) contact layer. The detectors are processed into 200μm×200μm mesa. The mesa is formed by wet etching to the bottom n^+ GaAs contact layer according to the usually photolithographic process. Ohmic contacts are realized on the top and bottom of n^+ GaAs contact layers by Au-Ge-Ni alloying at 470℃.

The absorption spectra for the samples cid01 and cid02 are measured at 300K using the Fourier Transform Infrared Spectrometer (FTIR). Figure 2 shows the infrared-absorption spectra for the sample cid02. The I-V characteristic measured at 300K with forward bias (means mesa top positive) for sample cid02 is shown in Fig. 3, and the I-V characteristic with reverse bias measured at 77K for samples cid01 and cid02 (plotted on a log scale) are shown in Fig. 4(a) and Fig. 4(b) respectively. A 45° angle is polished on the substrate to allow the infrared light to back illuminate the detector at a 45° angle incidence, as allows for a large optical field normal to the well[1,6]. The optical response of the detector's testing structures is measured at 77K on a polished substrate facet with a 800K blackbody source, 1kHz frequency and bandwidth Δf of 10Hz, with the bias dependence of the optical response under the reverse bias for the two samples shown in Fig. 5(a) and Fig. 5(b) respectively. No attempt has been made to enhance the quantum efficiencies during the use of anti-reflection coating or multiple passes (through the reflector or optical cavity)[1].

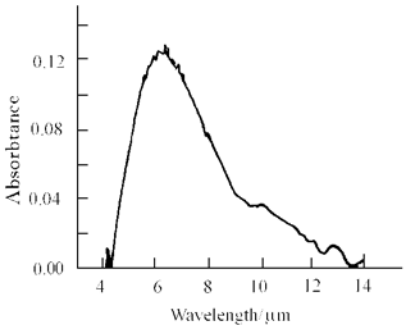

FIG. 2　Absorption Spectrum for Sample cid02

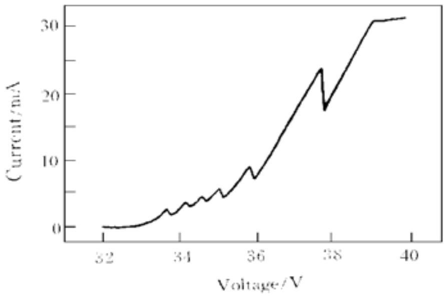

FIG. 3　Negative Differential Conductance Under Forward Bias Voltage at 300K for Sample cid02

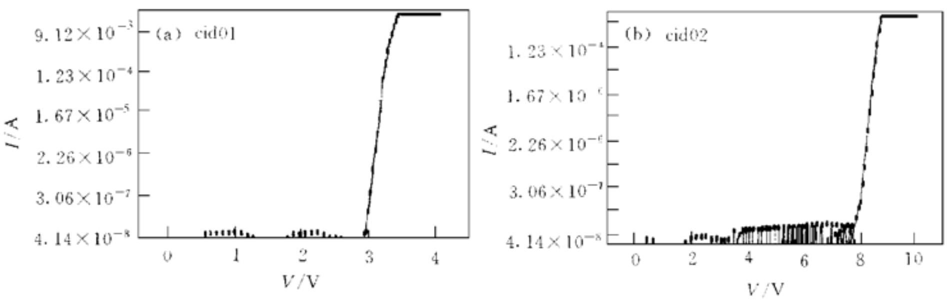

FIG. 4 Experimental I-V Curve Under Reverse Bias at 77K: (a) cid01, (b) cid02

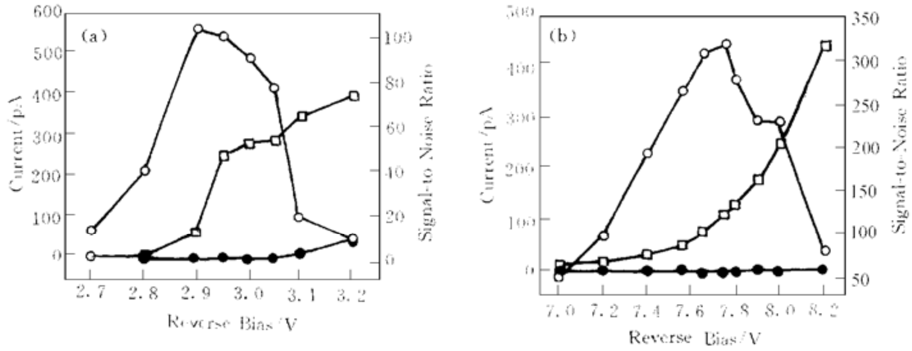

FIG. 5 Measured Photocurrent, Noise Current and Signal-to-Noise Ratio Versus Reverse Bias at 77K: (a) cid01 and (b) cid02

—□—Photocurrent; —●—Noise Current; —○—Signal-to-Noise Ratio

3 Results and Discussion

The absorption spectra for samples cid01 and cid02 measured at 300K are quite similar in the position of absorption peak and the spectra width except for a few difference in peak height, that is, the peak height of the cid02 is higher, as implies the absorption is stronger. Figure 2 shows the measured absorption spectrum for the sample cid02. From the plotting, it can be seen that the spectra width is about 5—10μm, which is well consistent with the calculating value of 4.5—10μm, corresponding to the Fermi energy level of 153meV above the conduction band bottom.

The I-V characteristic for sample cid02 measured at 300K with forward bias is shown in Fig. 3. The striking negative differential conductance under the forward bias can be seen, indicating that the heavily doping has been formed. Each of peak-to-valley ratios is 1.38 on the average. Figure 4(a) and Figure 4(b) show the I-V characteristics of the two samples with reverse bias at 77K in a logarithm scale. It can be clearly seen that the dark current increases abruptly at the bias about 2.95V (the corresponding dark current is

11.44nA) for sample cid01, and about 7.8V (the corresponding dark current is 33.08nA) for sample cid02 respectively. Both of the bias are well consistent with the optimum bias points as measured in the following bias-dependent optical response. The dark currents of the two samples are about one order of magnitude lower than that of the conventional QWIPs[1,8].

The most evident advantage of the detectors is that the photocurrent at the same electric field increases with the increasing of well number but the noise don′t. By comparing the optical response of the two samples cid01 and cid02, which have the same structural parameters except the different number of wells, sample cid01 two and sample about cid02 six, we can see that the photocurrent 110pA for cid02 at the optimum bias of 7.8V is twice as large as the 64pA for cid01 at the corresponding optimum bias 2.9V, as shown in Fig. 5(a) and Fig. 5(b), and the noise current for the two samples is almost same, about 0.19pA/(Hz)$^{1/2}$, one order of magnitude lower than that of the conventional GaAs/AlGaAs QWIPs[1,8]. The ratio 316 of signal to noise for sample cid02 is about three times as large as 101 for sample cid01 at their corresponding optimum biases. Both the measured optimum biases for two samples are well consistent with the corresponding bowing points decided by the current-voltage characteristic test. So the working bias of the detectors can be pre-determined by the dark current measurement. It can be expected that the photocurrent will be further improved with the increasing of well number, the structural parameters optimizing and the use of anti-reflection coating, or multiple passes (through reflector or optical cavity).

4 Summary

In conclusion, a novel detector approach has been demonstrated in order to solve the problems of the conventional QWIPs. Degenerately doping is required so that the tunneling can be formed. The novel detecting mechanism is designed to work in two different modes: the device with wide-bandwidth or the one with the adjustable response wavelength with the applied voltage varying. Two of the detectors with wide-bandwidth have been prepared with different number of the wells, one with two and the other six. Large infrared absorption is observed in the two samples at the wavelength from 5 to 10μm, so is the peak of the negative conductance. It demonstrates that the detector performances (including the photocurrent and the signal to noise ratio) can be improved by increasing the number of wells, but not increasing of the noise current. Using the anti-reflection coating and an optical cavity structure, further improvement of the detector performance can be expected. Finally, with mature material growth and processing, the presented device structure offers potential for the large photocurrent and multicolor of high-performance producible array.

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