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Normal incidence silicon doped p-type GaAs/AlGaAs quantum-well infrared photodetector on (1 1 1)A substrate

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Abstract

p-type quantum-well infrared photodetectors (QWIPs) demonstrate normal incidence response due to band mixing by utilizing valence band transitions that may break the selection rule limiting n-type QWIPs. Due to even more complicated valence band structure in (1 1 1) orientation, it is interesting to see that the p-type QWIP show both absorption and photocurrent response dominant in normal incidence. The p-type GaAs/AlGaAs QWIP was fabricated on GaAs(1 1 1)A substrate by molecular beam epitaxy (MBE) using silicon as dopant with a measured carrier concentration of 1.4×10^{18} cm^{-3}. The photocurrent spectrum exhibits a peak at a wavelength of 7 μm with a relatively broad peak width ($\Delta\lambda/\lambda_p \sim 50\%$), indicating that the final state is far deep within the continuum of the valence band. The p-QWIP demonstrates a responsivity of about 1 mA/W, which is limited by the relatively low doping concentration.
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1. Introduction

Restricted by the selection rule for electron intersubband transition [1], n-type QWIPs do not respond to light incident normal to the quantum-well (QW) layers. Comparatively, p-type QWIPs can have normal incidence response due to large band mixing effect as they utilize valence band transitions. Most studies of QWIPs have utilized the conventional (1 0 0) oriented substrates due to the relatively large window of good epitaxial growth conditions and the well-developed processing technology. However, investigations on non-(1 0 0) plane materials, e.g., Refs. [2,3], also show interest due to the effects of altering the fundamental material properties, growth mechanism, surface kinetics and impurity incorporation in non-(1 0 0) plane. Challenges exist in growing high quality material on non-(1 0 0) substrates because of more dangling bonds available in the (1 1 1) surface which reduce the surface migration velocity of adatoms and incorporate more defects during material growth. The (1 1 1)-oriented p-type GaAs/AlGaAs quantum-well infrared photodetector (QWIP) was theoretically investigated by Cho et al. [4], and the absorption coefficient, responsivity and detectivity were also estimated. p-type Si-doped AlGaAs/GaAs and AlGaAs/InGaAs QWIPs grown on (3 1 1)A substrates were reported and the dark current performance was compared with the Be-doped p-type QWIP grown on (1 0 0) substrate [5]. Due to more complicated valence band structure in (1 1 1) orientation, it is interesting to investigate the polarization response of p-type QWIPs on (1 1 1) oriented substrates.

In the following sections, we present fabrication and characterization of a GaAs/AlGaAs QWIP on GaAs (1 1 1)A substrate grown by MBE technology with Si as p-type dopant. The optical intersubband absorption and polarization photocurrent response are measured and discussed. The QWIP structure was also grown on GaAs

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(1 0 0) substrate in the same growth and its material and device characteristics are used for reference in the discussion.

2. Material growth

The GaAs/AlGaAs QWIP structure was grown on an undoped semi-insulating GaAs(1 1 1)A substrate by a solid source Riber 32 MBE system. A GaAs(1 0 0) substrate was placed together with the (1 1 1)A substrate during the epitaxial growth as a reference to understand the effects of substrate orientation on growth parameters. The multi-quantum-well (MQW) structure sandwiched by GaAs top and bottom contact layers consists of 30 periods of GaAs wells and AlGaAs barriers. Fig. 1 shows the growth structure along with the measured structural parameters for the two samples. Arsenic was supplied in the form of As_4 from a valved cracker cell and its beam equivalent pressure was fixed at 1.0×10^{-5} Torr during the growth. In order to maintain smooth morphology, the growth temperature was set at 650 °C and an As-rich growth condition (As_4/III flux ratio of ~23:1) was used. A GaAs buffer layer was grown before the growth of the QWIP structures. The Si cell temperature was fixed at 1020 °C during the growth of the GaAs wells and the contact layers.

The samples were examined using high resolution X-ray diffraction (HRXRD) from after the growth to determine the average MQW periodicities. With simulated results the average growth rates of AlGaAs and GaAs were calibrated to be about 1.18 μm/h and 0.88 μm/h on the (1 1 1)A substrate and 0.78 μm/h and 0.66 μm/h on the (1 0 0) substrate, respectively, under the same growth conditions. The epitaxial growth rate on (1 1 1)A surface is higher due to three dangling bonds for each group III adatom on (1 1 1)A surface in contrast to only two on (1 0 0) surface and is associated with both the As4/Ga flux ratio and the growth temperature [6]. Moreover, the Al fraction in AlGaAs epitaxial layers is reduced on (1 1 1)A with respect to that on (1 0 0) surface due to the poor efficiency of Al atom adsorption to Ga atom site under a Ga-predominant (1 1 1)A surface [7].

Silicon was incorporated as p-type dopant in the (1 1 1)A oriented QWIP sample. On a GaAs(1 1 1)A surface, each Ga atom has three bonds appending the surface while each As atom has only one. Therefore, Si atoms easily replace weakly-bonded As atoms and behave as acceptors. The conduction type of incorporated Si atoms on the (1 1 1)A surface can be controlled by the growth conditions, such as the substrate temperature and V/III flux ratio [8]. As examined by electrochemical *C–V* profiles, carrier concentrations of about 1.4×10^{18} cm^{-3} are reached in both samples, but of opposite conduction types.

3. *I–V* characteristics and activation energy

To facilitate the measurements of *I–V* characteristics and photocurrent spectra, mesa diodes with an active area of about 200×200 μm^2 were fabricated using standard photolithographic techniques and wet chemical etching. The dark current as a function of applied bias at different temperatures is given in Fig. 2 for the p-type (1 1 1)A and the n-type (1 0 0) QWIPs. To determine the activation energies, dark currents at low bias and relatively high temperatures which are thermionic emission dominant [9] are used to extract activation energies, i.e., $I(T)/T \propto \exp(-E_{ac}/k_BT)$. The activation energies E_{ac} are shown in Fig. 3 for a set of bias voltages. The activation energies at different bias can be fitted quite well with the relation $E_{ac} = E_{ac0}\exp(-V/C)$ that is related to the reduction of barrier height due to the bias across the QW [10]. As the bias increases, the energy bands are not symmetric any more and start to bend gradually. Thus the barrier height over which the holes are excited for conduction also become lower. Accordingly the activation energy under a biasing field could drop. The extrapolated zero-bias activation energies E_{ac0} for thermal equilibrium and flat band condition are 59 meV and 74 meV for (1 1 1)A p-QWIP and (1 0 0) n-QWIP diodes,

	Si-doped GaAs cap layer $1.4{\times}10^{18}$ cm^3	p-GaAs 0.7 μm	n-GaAs 0.5 μm
30-repeat MQW	Undoped AlGaAs barrier	$Al_{0.18}Ga_{0.82}As$ 563 Å	$Al_{0.22}Ga_{0.78}As$ 347 Å
30-repeat MQW	Si-doped GaAs well $1.4{\times}10^{18}$ cm^3	p-GaAs 38 Å	n-GaAs 22 Å
	Undoped AlGaAs barrier	$Al_{0.18}Ga_{0.82}As$ 563 Å	$Al_{0.22}Ga_{0.78}As$ 347 Å
	Si-doped GaAs contact layer $1.4{\times}10^{18}$ cm^3	p-GaAs 1.4 μm	n-GaAs 1.0 μm
	GaAs buffer layer	GaAs buffer layer	GaAs buffer layer
	Undoped GaAs substrate	(111)A semi-insulating	(100) semi-insulating

Fig. 1. The growth structure with measured structural and composition parameters of the p-type (1 1 1)A and the n-type (1 0 0) QWIPs.

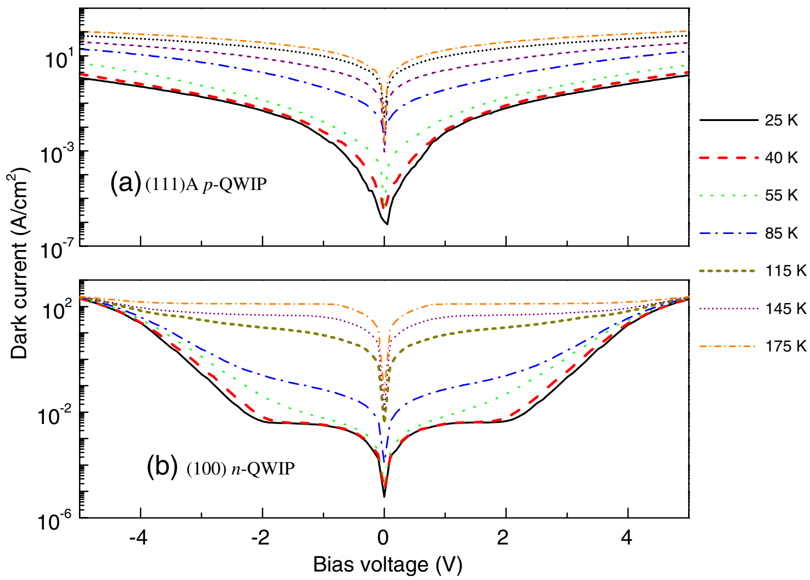

Fig. 2. I–V characteristics of (a) the p-type (1 1 1)A and (b) the n-type (1 0 0) QWIPs under a series of temperatures.

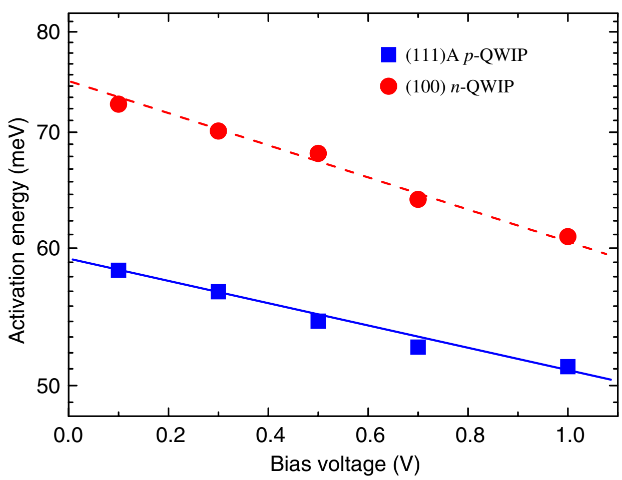

Fig. 3. The measured activation energies of (a) the p-type (1 1 1)A and (b) the n-type (1 0 0) QWIPs versus bias voltage.

respectively. The experimental results of activation energies verify the calculated energy band structures of QWIPs as they are in good agreement with $E_{ac} = V_b + E_{ex} - E_{HH1} - E_F$ for p-type QWs and $E_{ac} = V_b - E_{e1} - E_F$ for n-type QWs, where V_b is the barrier energy height, E_F is the Fermi energy of 2D carrier gas referenced to the ground state, and E_{ex} is the exchange energy due to the exchange effect in QWs [11].

4. Photocurrent spectra

The spectral dependence of the photoresponse was measured at low temperature using an Oriel 6575 infrared source coupled by an infrared lens to a Jobin Yvon Triax 320 monochromator. Light is coupled to the mesa diodes through a 45°-facet polished on the substrate, and can also be polarized by inserting a ZnSe wire-grid polarizer after the monochromator such that 90° polarization denotes normal-incident radiation or TE mode and 0° polarization denotes TE + TM mode with TE and TM components in equal shares. The photoresponse spectra measured at 25 K under several bias voltages are shown in Fig. 4. Both samples have nearly equal photoresponse for the bias at the same level but of opposite polarities, implying good symmetry of the grown MQW structures. The n-type (1 0 0) QWIP has an average spectral linewidth ($\Delta\lambda/\lambda_p$) of 24% with a detection wavelength of near 11 μm, which is a typical linewidth value of bound-to-continuum QWIPs. However, the photocurrent spectra of the p-type (1 1 1)A QWIP sample are much wider ($\Delta\lambda/\lambda_p \sim 50\%$) than commonly reported results of (1 0 0) p-type GaAs/AlGaAs QWIPs, e.g., Ref. [11]. This implies that the transitions occur from the ground state to continuum states far above the barrier top. Combining the experimental results into the simulation, we derive the energy-band diagrams for the

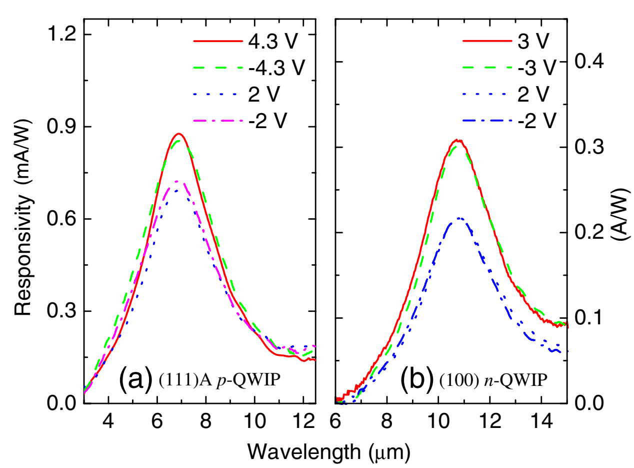

Fig. 4. The measured photocurrent spectra at 25 K for different bias voltages for (a) the p-type (1 1 1)A and (b) the n-type (1 0 0) QWIPs.

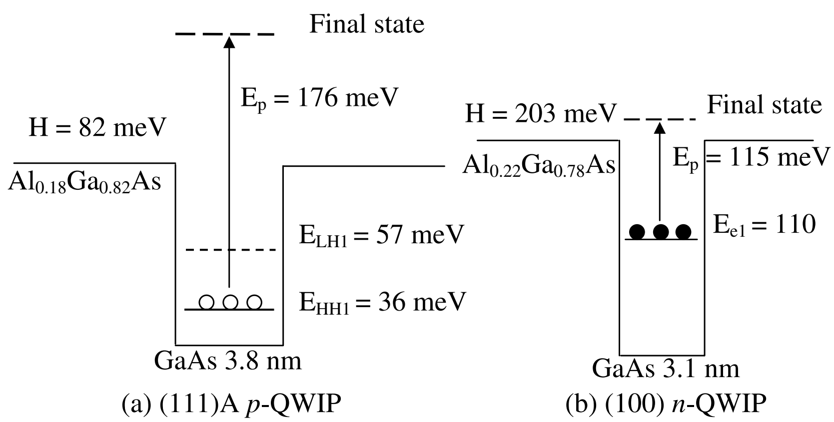

Fig. 5. The energy band diagrams for (a) the p-type (1 1 1)A and (b) the n-type (1 0 0) QWIPs.

two QWIPs in Fig. 5. In our experiment, the photocurrent spectrum exhibits peak responsivity of about 1 mA/W, which is relatively low compared with typical p-type QWIPs. The low peak responsivity is mainly due to the low doping concentration (equivalent 2D density, $N_D = 5.7 \times 10^{11}\ cm^{-2}$) and the large spectrum width $\Delta\lambda/\lambda_p$. This (1 1 1)A p-QWIP has comparable peak responsivity to that of a low doping sample, i.e., sample A, $N_D = 1 \times 10^{12}\ cm^{-2}$, under the same bias in a study of doping density effects for (1 0 0) GaAs/AlGaAs p-QWIPs [12], whereas the photoresponse spectrum is much broader.

5. Normal incidence response

Normal incidence response is usually expected in p-QWIPs due to the interactions between components of s-symmetry states in the LH(SO) subbands and p-symmetry states in the HH subbands [13]. However, in the (1 1 1)A QWIP sample, we have observed the strongest response at normal incidence. The polarized infrared absorption spectra measured at room temperature and photocurrent spectra measured at 25 K under bias voltage of 4.3 V are shown in Figs. 6 and 7, respectively. The infrared intersubband absorption of the samples was measured by a Fourier transform infrared spectrometer (FTIR) at

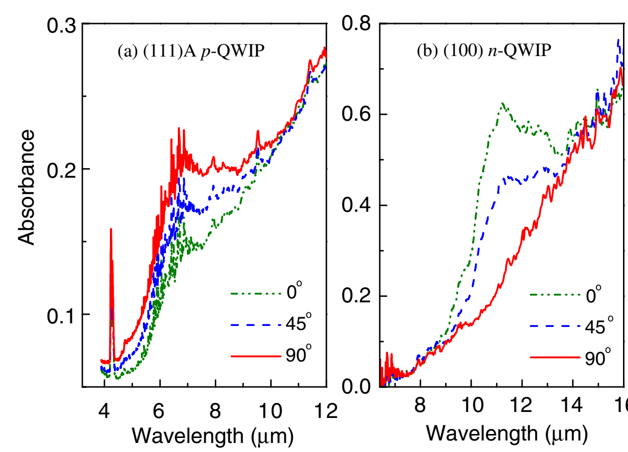

Fig. 6. The polarized absorption spectra for (a) the p-type (1 1 1)A and (b) the n-type (1 0 0) QWIPs measured at 300 K using a waveguide structure.

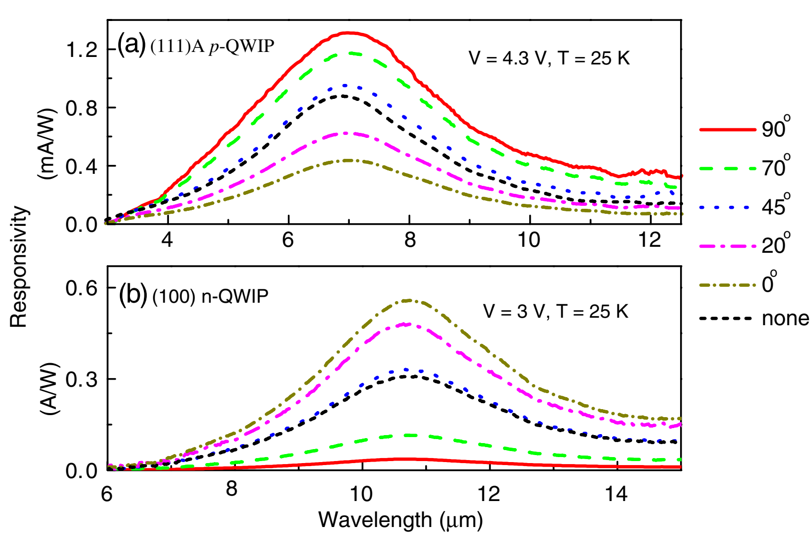

Fig. 7. The polarized photocurrent spectra measured at 25 K for (a) the p-type (1 1 1)A and (b) the n-type (1 0 0) QWIPs.

room temperature with a 45° polished multipass waveguide geometry. In both absorption spectra and the photocurrent spectra, the p-type (111)A QWIP exhibits different polarization dependence from the n-type (100) QWIP which observes the intersubband transition selection rule. The transition in this p-type (111)A QWIP is TE-mode dominant (*x*–*y* in-plane polarization).

In a p-type QW, transitions between HH states should be mainly sensitive to light polarized in *z* direction, similar to the case of an n-type quantum well [14]. Transitions of in-plane (*x*–*y*) polarization are due to the interband-like process between p-symmetry and s-symmetry components and thus the band-mixing effect plays an essential role for the normal incidence response [15]. The band-mixing effect becomes stronger as states go far above the band edge of the barrier and the in-plane wave vector $k_{\|}$ becomes larger, and the momentum matrix element for the in-plane polarization has a maximum at nonzero in-plane wave vector [15]. In the p-type (111)A QWIP, the final states about 130 meV above the barrier are of highly mixed nature and have nonzero in-plane wave vectors. Transitions of in-plane (*x*–*y*) polarization are expected to be strong between different hole bands, i.e., HH to LH [13,16]. Higher photoresponse of s-polarization than p-polarization was obtained by aligning LH2 in resonance with the top of the barrier in the (100) p-QWIPs [17]. The heavy hole has much larger effective mass along (111) than (100), while the light hole has slightly smaller effective mass along (111). This can partially explain the dominant normal incidence response in the (111) p-QWIP, since the lighter excited state mass should give a better absorption and responsivity depending on the carrier transport.

6. Conclusion

A p-type GaAs/AlGaAs QWIP on GaAs (111)A substrate was successfully demonstrated. The positive carrier type was achieved using Si-doping for the (111)A-oriented GaAs epitaxial layer with a carrier concentration of $1.4 \times 10^{18}\ \mathrm{cm}^{-3}$, similar to the level of n-type doping obtained in the reference (100)-oriented GaAs layer. The (111)A GaAs/AlGaAs p-QWIP gave the strongest photoresponse at normal incidence, indicating the strong mixing of conduction and valence band Bloch states. The p-type (111)A QWIP sample has a responsivity of about 1 mA/W, which can be improved by increasing the doping concentration to the typical level of $10^{19}\ \mathrm{cm}^{-3}$ used in p-type QWIPs.

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