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2007

Ma, B. S., Fan, W., Dang, Y. X., Cheah, W. K., Loke, W. K., Liu, W., Li, D. S., Yoon, S. F., Zhang, D. H., Wang, H., & Tung, C. H. (2007). GalnNAs double-barrier quantum well infrared photodetector with the photodetection at 1.24 μm . *Applied physics letters*, 91(5), 051102.

<https://hdl.handle.net/10356/100759>

<https://doi.org/10.1063/1.2767185>

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GaInNAs double-barrier quantum well infrared photodetector with the photodetection at 1.24 μm

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(Received 2 May 2007; accepted 8 July 2007; published online 30 July 2007)

A GaInNAs/AlAs/AlGaAs double-barrier quantum well infrared photodetector was grown by molecular beam epitaxy and fabricated by standard device processes. The growth structure of the as-grown sample was verified by x-ray diffraction measurement. The photoluminescence emission peak, which is related to the interband transition in the GaInNAs well, was observed at ~ 1.2 eV. After annealing at 650 °C, a large blueshift of 40 meV was observed. The photocurrent peak at 1.24 μm is associated with the intersubband transitions in the conduction band of the GaInNAs quantum well. The ten-band $k \cdot p$ calculations agree with the above observations. © 2007 American Institute of Physics. [DOI: 10.1063/1.2767185]

In the past decade, there has been intensive interest in III-V dilute nitride semiconductors, such as the GaAsN and GaInNAs (GINA) material system, due to their unique physical properties and various device applications. The incorporation of small amounts of nitrogen results in a large decrease in the band gap so that it is possible to grow narrow band gap epilayers in the technologically important 1.3–1.55 μm wavelength range on GaAs substrates.¹ The band anticrossing model is one of the popular explanations to the nitrogen induced band gap reduction.² In recent applications, much effort has been paid to extending the interband transition wavelength range to 1.55 μm . The GINA resonant cavity enhanced photodetector operating at 1.55 μm has been reported.³ However, such a wavelength extension always requires large indium and/or nitrogen compositions, leading to serious deterioration of the material and optical quality due to large strain, high concentration of nonradiative recombination centers, and strong phase separation.⁴

On the other hand, the nitrogen induced band gap shrinkage gives rise to a large conduction band offset. For example, the conduction band offset of GaInNAs/GaAs and GaInNAs/AlGaAs can reach 600 meV and 1 eV, respectively.^{5,6} Thus, it is possible to apply Ga(In)NAs to the field of intersubband transitions such as quantum well infrared photodetectors⁷ (QWIPs) in the near- and mid infrared wavelength range, especially below 4 μm .^{5,6,8} This may also be another approach to the fabrication of the 1.3–1.55 μm optical and electronic devices. However, few devices and experimental results in this intersubband-transition QWIP have been reported. Guzmán and co-workers have ever reported the GaAsN/AlAs/AlGaAs double-barrier (DB) QWIPs in the wavelength range below 4 μm and 1.64–1.67 μm .^{8,9} In this letter, a GaInNAs/AlAs/AlGaAs DB QWIP was grown and fabricated. X-ray diffraction (XRD), photoluminescence (PL), and photocurrent (PC) spectroscopy were used to characterize its structural and optical properties. The photocurrent was observed to peak at

1.24 μm , which is the shortest intersubband transition wavelength ever reported in GaAs-based QWIP structures.

The GINA QWIP structure was grown on a semi-insulating (001)-oriented GaAs substrate by solid-state molecular beam epitaxy using a Riber MBE 32 system with a N_2 radio frequency plasma nitrogen source. The active region of the as-grown sample contains 10 periods of double-barrier quantum well structures, each of which consists of a 2.3-nm-thick Si-doped $\text{Ga}_{1-y}\text{In}_y\text{N}_x\text{As}_{1-x}$ ($x=0.015$ and $y=0.293$) quantum well sandwiched between two undoped 1.3-nm-thick AlAs inner barriers and further separated by 13.1-nm-thick $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ outer barrier layers. The whole 10-period multiquantum well (MQW) active region was buffered by a 0.5- μm -thick Si-doped GaAs bottom contact layer and capped by a 0.5- μm -thick Si-doped GaAs top contact layer. The Si dopant concentration in each quantum well is $1 \times 10^{18} \text{ cm}^{-3}$ and that in the two GaAs contact layers is $2 \times 10^{18} \text{ cm}^{-3}$. The GaInNAs/AlAs/AlGaAs region was grown at 460 °C and the contact layers at 590 °C.

To verify the above growth structure, x-ray diffraction measurements were carried out using a Philips x-ray diffractometer with a conventional x-ray generator and a copper target ($K\alpha_1=0.15406 \text{ nm}$) as the radiation source. Dynamic rocking curves obtained by performing $(\omega-2\theta)$ (004) symmetric reflection scans for the QWIP structures before and after postgrowth rapid thermal annealing (RTA) at 650 °C are shown in Fig. 1. For the RTA experiments, $6 \times 6 \text{ mm}^2$ wafer pieces were cut from the main sample and were capped by GaAs wafers to prevent As evaporation at the surface during annealing. Annealing was carried out under N_2 environment at 650 °C for a short duration of 20 s. For the as-grown structure, the clear satellite peaks, as can be seen in Fig. 1, indicate the good structural quality of the MQW. Because the lattice constants of GINA and Al(Ga)As are larger than GaAs, giving rise to the compressive strain in the MQW, strong satellite features were observed at the left side of the GaAs (004) substrate peak. After annealing at 650 °C, the diffraction peaks become broader and weaker. This indicates that the structural quality (sharpness of the

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FIG. 1. XRD rocking curves of the as-grown (asgr.) and annealed (ann.) QWIP structures and the dynamical simulated (sim.) pattern of the as-grown sample (dashed line). The curves are vertically shifted for clarity.

layer interface) deteriorates after annealing due to atom interdiffusion. We simulated the rocking curves of the as-grown QWIP structures to obtain the actual structure parameters, such as the layer widths and elemental compositions of the well and barrier layer, using Philips EPITAXY 4.1 software. All the variables were allowed to vary within reasonable limits around the designed parameters until the following PL and PC transition energies were reproduced. The best fit to the experimental results using the above-mentioned structure parameters for the as-grown samples is illustrated by the dashed line in Fig. 1.

For the PL measurements, the 514.5 nm Ar^+ laser line was used as excitation. The luminescence signals were dispersed by a Spex 0.75 m monochromator and then detected using a liquid nitrogen cooled Ge photodetector with standard lock-in techniques. Figure 2 depicts the PL spectra of

FIG. 2. Photoluminescence spectra of the as-grown and annealed GINA QWIP structures measured at 5 K. The spectra are vertically shifted for clarity. The arrows together with the energy values show the energy positions of the PL peaks.

FIG. 3. Photocurrent spectra of the as-grown GINA QWIP measured (a) at different bias voltages at 20 K (b) at different temperatures at 2 V. The arrow shows the theoretical results obtained from the ten-band $k \cdot p$ calculation.

the as-grown and annealed QWIP sample. In the spectra of the as-grown sample, the stronger and sharper peak at about 1.5 eV is related to GaAs. Its low-energy wing signifies the presence of impurity and defect centers resulting from heavy silicon doping. The weaker and much broader peak at about 1.2 eV arises from the band gap transition in the GINA quantum well. The long tail at the low-energy side of the GINA peak arises not only from the localized states due to alloy fluctuations¹ but also from impurity and defect traps induced by both silicon and nitrogen doping, such as interstitial nitrogen and other nitrogen complexes.¹⁰

After RTA for 20 s, the GINA PL peak increases drastically in intensity and dominates the GaAs peak. It shows a more symmetric shape with a weaker low-energy tail and the full width at half maximum decreases. These changes indicate a strong enhancement of the radiative efficiency in the GINA quantum well. As can be seen in Fig. 2, the improvement in optical efficiency of GINA is accompanied by a blueshift of about 40 meV after annealing. This blueshift, widely observed in GaInNAs/GaAs structures, originates mainly from atom interdiffusion across the AlAs/AlGaAs and GaInNAs/AlAs heterojunction interface.¹¹ This interdiffusion may be a defect-assisted one considering the heavy silicon doping. The annealing reduces the density of nonradiative centers, resulting in the improvement of the PL characteristics.^{10,12} On the other hand, the elemental interdiffusion leads to the broadening and weakening of the XRD satellite peaks because it diminishes the periodicity.¹³

The PC spectra were measured at 20 and 78 K by using an Oriel 6575 infrared light source as excitation, which was chopped before passing through a Triax 320 monochromator. The as-grown structure was first etched into mesas using standard photolithography and wet etching processes for the photocurrent measurement. The Ni-Ge-Au-Ni-Au alloy was then deposited onto the contact layers and annealed to form a n -type Ohmic contact. The wafer edge was polished to 45° relative to the sample surface to enhance the photon absorption in the QWIP structure. The measured photocurrent spectra at different bias voltages and temperatures are shown in Figs. 3(a) and 3(b), respectively. The photocurrent

spectra are not normalized. Three main features at about 1.24, 2.03, and 3.89 μm , respectively, were observed in all the spectra. The feature at 1.24 μm is the shortest wavelength intersubband transition ever reported in GaAs based QWIPs. The photocurrent peak can still be resolved even though the bias is as low as 0.5 V. The QWIP photocurrent decreases at 78 K compared with that at 20 K.

In order to identify the measured PC peaks, we performed ten-band $k\cdot p$ calculations to ascertain theoretically the energy band structure and the intersubband transitions in the QWIP. The strain effect and the conduction and valence band offset profile in each period of the QWIP structure have been considered in the 10×10 $k\cdot p$ Hamiltonian, where the nitrogen effect is considered by the matrix elements associated with two additional nitrogen-related states.¹⁴ The detailed 10×10 Hamiltonian is described in our previous work.¹⁵ The arrows in Fig. 3(a) show the energy positions of the theoretical intersubband transitions for comparison with the experimental results. Based on the comparison, we assign the peak at 1.24 μm mainly to the $E_{2+}-E_{1-}$ transition (1.3 μm in theory), and that at 2.03 μm partly to the $E_{2-}-E_{1-}$ transition (2.2 μm in theory), where E_{1-} , E_{2-} , and E_{2+} are the split levels of the first two sublevels at the Γ point in the conduction band of the GINA well.⁶ This splitting arises from the strong nitrogen repulsion to the sublevels in the GINA quantum well.⁶ To verify the validity of the optical transitions, we further calculated the absorption spectra and found that the $E_{2+}-E_{1-}$ transition shows the largest absorption. The detailed ten-band $k\cdot p$ calculations for the energy levels and the absorption spectra will be published elsewhere. The broad peak at 3.89 μm has originated from the transition between the E_{1-} energy level and the first energy level in the conduction band of the AlGaAs barrier-well, and the second- and the third-order diffractions of the 1.24 μm peak and the second-order diffraction of the 2.03 μm peak.

In conclusion, we grew the GaInNAs/AlAs/AlGaAs DB QWIP structure using solid-state molecular beam epitaxy and fabricated the QWIP device using standard wet etching and n -type-Ohmic-contact evaporation processes. The as-grown sample shows XRD satellite peaks with better resolution. However, due to nitrogen and heavy silicon doping, the as-grown sample shows a weak and broad PL feature at ~ 1.2 eV, which is related to the interband transition in the

GINA well. In the PC spectra of the as-grown sample, the features at 1.24 and 2.03 μm are associated with the intersubband transitions related to the N-induced split subband levels in the conduction band of the GINA well. The sample annealed at 650 $^{\circ}\text{C}$ shows inferior resolution in the XRD spectrum, but a stronger and more symmetric PL feature with a large energetic blueshift mainly due to the elemental interdiffusion. The theoretical results obtained from the ten-band $k\cdot p$ calculation agree with the PC observations.

One of the authors (B.S.M.) would like to thank Deny Sentosa, Y. W. Liu, and Lew Kim Luong for their kind help in the annealing of the materials and the device process. Another author (W.J.F.) would like to acknowledge the support for this work from A*STAR (Grant No. 042 101 0077).

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