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GaInNAs/GaAs p-i-n Photodetector with Multiquantum Well Structure

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1. Introduction

A lattice-matched GaInNAs/GaAs MQW, by substituting a few percent N in GaInAs to reduce the strain in the layer, which allows growing a thicker photon absorption layer and providing higher quantum efficiency [1]. Either GaInNAs/GaAs epitaxy or single quantum well fabricated on solar cell, laser, and photodiodes has been demonstrated [2,3]. Owing to the low-strained GaInNAs inherently incorporate few dislocations in the epitaxial layer; the thickness of the layer reduces down to 7 nm to prevent the generation of misfit dislocation [4]. However, the accumulative strain will be released as layer growing to the critical number. Although many advantages have occurred in these devices with GaInNAs/GaAs epitaxy, relatively few studies provide a satisfactory description for GaInNAs/GaAs MQW p-i-n photodetector.

In this study, GaInNAs/GaAs p-i-n photodetector with an optically active region of 3 and 15 periods MQWs were embedded as i-layer, respectively, grown successfully by MOVPE. Effects of MQWs on the responsivity, electrical characteristics of junction breakdown behavior, and conduction mechanism are investigated.

2. Experimental Procedure

Lattice-matched GaInNAs/GaAs p-i-n photodetector with MQWs as i-layer were grown on (100) GaAs substrates using a metal-organic vapor-phase epitaxy (MOVPE). The carrier gas was H_2 and source materials were TMGa, TMIn and AsH_3. Epitaxial layers of the device were illustrated as follow: a 500 nm-thick GaAs buffer, a 150 nm-thick slightly n-doped $Al_{0.3}Ga_{0.7}As$ cladding layer, then 3 or 15 periods $Ga_{0.65}In_{0.35}N_xAs_{1-x}$/GaAs MQWs that well and barrier layer thickness were 7 and 10 nm, respectively. Followed 150 nm-thick p-$Al_{0.3}Ga_{0.7}As$ and 40 nm-thick p-GaAs were grown as cladding layer. Diameter of the photodetector was 400 μm.

Thicknesses and compositions of indium and nitrogen were determined by high-resolution X-ray diffraction rocking curve (HRXRD, Bede D1 X-ray diffractometer) and theoretical dynamic simulations. A Keithley-4200 semiconductor parameter analyzer was used to measure the current-voltage characteristics of these devices in dark and under illumination. A 200 W halogens lamp was used as the light source for spectral responsivity measurement, and a standard synchronous detection scheme was employed to measure the front-side illuminated detector signal.

3. Results and Discussion

Figure 1 reveals the HRXRD of $Ga_{0.65}In_{0.35}N_xAs_{1-x}$/GaAs MQWs with x = 0.00237, along with the simulated curve for sample with 3 periods MQWs. For MQWs structure, the satelite peaks originate from the constructive interference of the diffracted beams, whcih revealing at the angle around -3500 to -7500 arcsec. It is found that the sample with 3 periods MQWs shows very sharp asymmetric satellite peaks, and is in excellent agreement with the simulated curves. For 15 periods MQWs devices, it is however significantly broader and this is indicative of some relaxation of the strain having taken place. The loss of fringes between the satellites, due to interference from the MQWs region, also indicates disruption of interfaces by misfit dislocations.

Bender et al. have observed empirically that the quality of the strained MQW degrades as the barrier thickness decreases and as the number of wells increases [5]. The lattice mismatch between the GaInNAs and GaAs are around 2.46 %, the critical thickness of was calculated to be about 10 nm. According to Fig. 1, the thickness of the GaInNAs layers is lowered to 7 nm to reduce the strain and the generation of misfit dislocations. However, the cumulative dislocation become effective as the MQWs increased to 15 periods, thus exhibiting partial relaxation phenomenon.

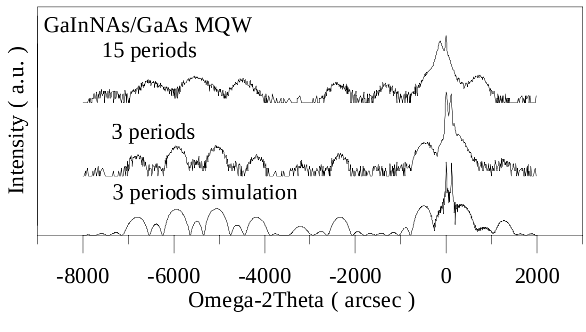

Fig. 1 HRXRD of $Ga_{0.65}In_{0.35}N_xAs_{1-x}$/GaAs MQWs epitaxy layers with x = 0.00237.

Figure 2 shows the spectral responsivity of GaInNAs/GaAs MQWs p-i-n photodetectors at reserve biased voltage of -2 V. The cutoff wavelength for these devices is around 1150 nm and the peak responsivity values equal to 1.0 and 3.7 mA/W for the device with 3 and 15 periods MQWs, respectively. It is also found that the rejection ratio value of the device with 3 periods MQWs has two orders of magnitude. However, it shows a very low rejection ratio value of the device with 15 periods MQWs.

The responsivity results are related to the carrier recombination mechanism and the photo/dark current contrast ratio which is measured with filter (not shown here). Dark current of the device with 3 periods MQWs reveals a lower value (1.45×10^{-8} mA) than that of 15 periods (1.23×10^{-5} mA) at -2 V. Dislocation is regarded as a line of recombination center, then the most relevant characteristics that determines the leakage dark current will be the length of the dislocation per unit area. Photo/dark current contrast ratio of the device with 3 periods MQWs reveals a higher value of 309.0 than that of 2.9 for 15 periods MQWs at -2 V.

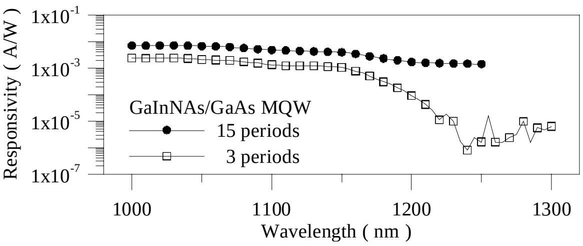

Fig. 2 Spectral responsivity of $Ga_{0.65}In_{0.35}N_xAs_{1-x}$/GaAs MQW p-i-n photodetectors with x = 0.00237.

Figure 3 (a) reveals the current-voltage characteristics of GaInNAs/ GaAs MQWs p-i-n photodetectors. When a certain reverse voltage value is exceeded, the dark current will dramatically upswing in a p-n or p-i-n diode, thus junction breakdown occurs. We define the breakdown voltage, V_b, when a dark current of 10 pA is reached. Junction breakdown voltages are at about -18.4 and -11.5 V for the device with 3 and 15 periods MQWs, respectively.

Misfit dislocation plays as the trapping site as well as the recombination center of the carrier. When the electric field in epitaxy layer is increased to above a certain value, the carriers obtain a critical kinetic energy to generate electron-hole pairs by an avalanche process. Consequently, the device with 3 periods MQWs brings the lower density of misfit dislocation will provide the higher breakdown voltage than that of 15 periods MQWs.

According to Fig. 3 (a), Fig. 3 (b) reveals the forward I-V characteristics of GaInNAs/GaAs MQWs p-i-n photodetectors. Ideality factor, n, of the devices are 1.40 and 1.76 of the 3 and 15 periods MQWs, respectively.

Ideality factor, n, the conduction mechanism of the photodetector, is determined from the forward bias, V, as expressed by equation (1) [6]

$$I_f = I_o \exp(\frac{qV}{nkT}) \quad (1)$$

where I_f is the forward current, I_o is the reverse saturation current, q is the electron charge, k is the Boltzmann constant, and T is the absolute temperature. The device with 3 periods MQWs shows an n value closed to 1, illustrating that the conduction mechanism of the minority carriers across the junction depletion region is the diffusion process. On the other hand, the n value is closed to 2 for the device with 15 periods MQWs, behaving the generation-recombination current on the misfit dislocation.

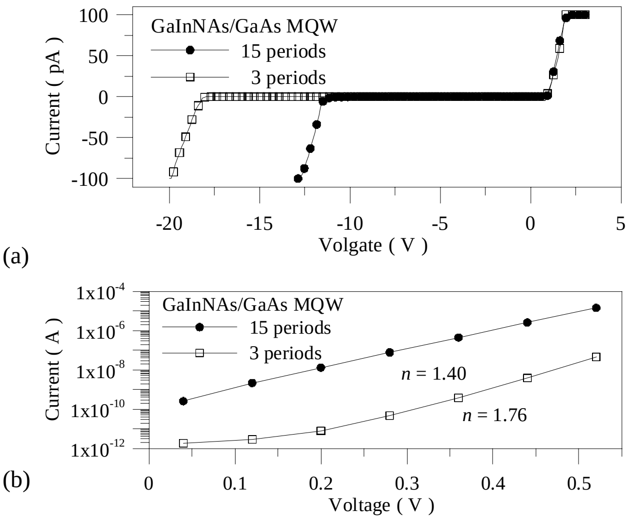

Fig. 3 (a) Current-voltage and (b) forward bias characteristics of $Ga_{0.65}In_{0.35}N_xAs_{1-x}$/GaAs MQW p-i-n photodetectors with x = 0.00237.

4. Conclusions

GaInNAs/GaAs p-i-n photodetector with 3 and 15 periods MQWs as i-layer, respectively, are grown successfully by MOVPE. Cutoff wavelength of the spectral responsivity occurs at around 1150 nm. Owing to the excellent crystal quality that the devices with 3 periods MQWs having, it reveals a two orders of magnitude rejection ratio value of the spectral responsivity and a higher junction breakdown voltage. The ideality factor indicating that the conduction mechanism is dominated by the diffusion process and the defect of scattering is slightly. On the other hand, the device with 15 periods MQWs induces a higher value of misfit dislocation and shows a partial relaxation phenomenon. Thus, it demonstrates a poor performance relatively.

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References

[1] J.Y. Duboz, J.A. Gupta, M. Byloss, G.C. Aers, H.C. Liu and Z.R. Wasilewski, Appl. Phys. Lett. **81** (2002) 1836.
[2] W.W. Chow, E.D. Jones, N.A. Modine, A.A. Allerman, S.R. Kurtz, Appl. Phys. Lett. **75** (1999) 2891.
[3] D. Jackrel, H. Yuen, S. Bank, M. Wistey, J.X. Fu, X.J. Yu, Z.L. Rao, J.S. Harris, Proceedings of SPIE **5726** (2005) 27.
[4] M. Kondow, S. Nakatsuka, T. Kitatani, Y. Yazawa and M. Okai, Jpn. J. Appl. Phys. **35** (1996) 5711.
[5] G. Bender, E.C. Schneider, J.D. Ralston, and P. Koidl, Appl. Phys. Lett. **63** (1993) 2920.
[6] H. Bayhan and S. Özden, Solid-State Electron. **50** (2006) 1563.