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Investigation of Si-doped p-type AlGaAs/GaAs, AlGaAs/InGaAs quantum well infrared photodetectors and multiquantum wells grown on (3 1 1)A GaAs

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Abstract

We have studied two Si-doped p-type quantum well infrared photodetectors (QWIPs) using AlGaAs/GaAs and AlGaAs/InGaAs grown on (3 1 1)A GaAs. The Si-doped AlGaAs/GaAs p-QWIP exhibits a symmetrical dark I–V characteristic at all the measured temperatures from 40 to 120 K. The strained p-type AlGaAs/InGaAs QWIP exhibits a slightly asymmetrical dark I–V characteristic, but is markedly less asymmetrical than that doped with beryllium. The slight asymmetry in dark I–V characteristic and the large blue-shift in responsivity spectra may be due to the thickness modulation observed from TEM and the red-shift of PL peak energy, where PL peak energies from (3 1 1)A AlGaAs/InGaAs multiple quantum wells are red-shifts of 7 and 22 meV to the side-by-side grown (1 0 0).

1. Introduction

P-type quantum well infrared photodetectors (QWIPs) have attracted much attention recently because of the inherent capability of normal incidence radiation and even enhanced intersubband transition [1, 2]. To date, most of the p-type QWIPs reported so far have used either beryllium (Be) or carbon (C) for the dopant species. However, both dopants have serious shortcomings. Be suffers from the problem of fast out-diffusion [3] and asymmetrical I–V characteristics measured in p-QWIP [2, 4] while C is not compatible to the normal solid source MBE. Because high p-type concentration has been reported by Si-doped GaAs grown in (3 1 1)A orientation [5], we have studied the Si-doped p-type QWIPs in this orientation. Other advantage of the growth of AlGaAs/GaAs or AlGaAs/InGaAs p-QWIP on (3 1 1)A GaAs is due to the reduced incorporation of deep recombination centers at the quantum well interfaces [6], which may in turn increase the quantum efficiency and improve the device performance. Further reduction of deep recombination centers can be expected in (3 1 1)A orientation because of the very-low diffusion coefficient of Si, and a higher growth

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temperature can be used to grow the AlGaAs/GaAs multiple quantum wells (MQWs) in p-QWIP. It is well known that a high growth temperature can reduce the oxygen and growth-induced defect [7], while a higher efficiency of photoluminescence (PL) can be obtained.

In this paper, we report the first study of Si-doped p-QWIP grown on (3 1 1)A GaAs. Very symmetrical dark *I–V* characteristic was obtained in AlGaAs/GaAs p-QWIP, which demonstrates the low diffusion of Si impurity as compared to Be. The strained Si-doped AlGaAs/InGaAs p-QWIP shows a slightly asymmetrical dark *I–V* characteristic, but is markedly less than that of the same structure by Be-doping.

2. Experimental procedure

The layer structure of AlGaAs/GaAs p-QWIP consists of a 1.0 μm Si-doped GaAs bottom contact layer, 40 periods of 2.8 nm GaAs well with 30 nm $Al_{0.29}Ga_{0.71}As$ barrier, and a 1.0 μm Si-doped GaAs top contact layer. The quantum wells and contact layers are doped with Si to a concentration of 3×10^{18} cm^{-3}. The layer structure for strained AlGaAs/InGaAs p-QWIP is similar to the unstrained AlGaAs/GaAs, except that the quantum well region consists of 20 periods of 5 nm $In_{0.12}Ga_{0.88}As$ well with 50 nm $Al_{0.1}Ga_{0.9}As$ barrier. The growth temperatures were 600 and 550°C for AlGaAs/GaAs and strained AlGaAs/InGaAs p-QWIPs, respectively. A low V/III beam equivalent pressure (BEP) of ~ 10 is used to achieve high p-type doping. We have also grown AlGaAs/GaAs and AlGaAs/InGaAs multiple quantum wells (MQWs) in order to further characterize the quality of quantum well in (3 1 1)A orientation. The AlGaAs/GaAs MQWs consists of a 0.1 μm $Al_{0.29}Ga_{0.71}As$ buffer, 5 periods of 5 nm GaAs well with 20 nm $Al_{0.29}Ga_{0.71}As$ barrier, and a 0.1 μm $Al_{0.29}Ga_{0.71}As$ top layer. The strained AlGaAs/InGaAs MQWs consists of a 0.1 μm $Al_{0.1}Ga_{0.9}As$ buffer, 5 periods of 10 nm $In_{0.12}Ga_{0.88}As$ well with 20 nm $Al_{0.1}Ga_{0.9}As$ barrier, and a 0.1 μm $Al_{0.1}Ga_{0.9}As$ top layer. Photoluminescence (PL) was used to characterize the optical properties of the MQWs. Hall measurement was used to measure the p-type doping for Si-doped (3 1 1)A GaAs. In order to measure the *I–V* characteristic and the responsivity, the p-QWIPs were processed into 216×216 μm^2 mesas.

3. Results and discussion

Fig. 1 shows the PL spectra for (3 1 1)A AlGaAs/GaAs MQWs grown at 600°C. A (1 0 0) AlGaAs/GaAs MQWs, grown at 550°C, is also shown for comparison. It is well known that significant Be out-diffusion occurs at a growth temperature of 600°C, and for that reason we have chosen the growth temperature of 550°C in (1 0 0) orientation for comparison. PL full-width-at-half-maximum (FWHM) line width of 9.2 and 11.2 meV are measured from an undoped AlGaAs/GaAs MQWs grown on (1 0 0) and (3 1 1)A GaAs, respectively, which indicates sharp interfaces can be obtained in both directions. However, one order of magnitude of PL intensity enhancement was measured from the 600°C grown (3 1 1)A MQWs than that grown on (1 0 0) at 550°C, which suggests better material quality can be achieved in (3 1 1)A direction. The increased PL intensity may be due to the

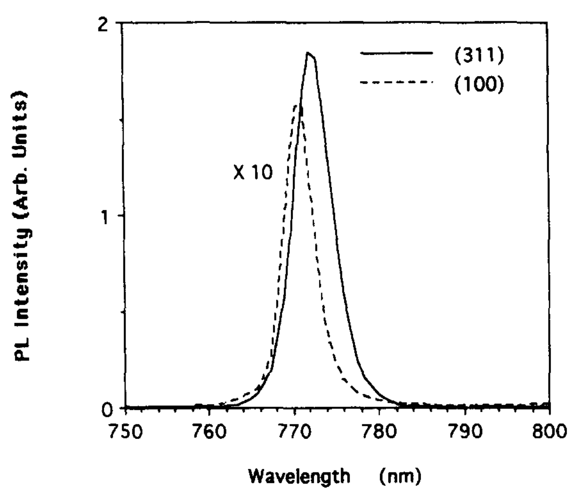

Fig. 1. Low temperature (15 K) PL spectra of AlGaAs/GaAs MQWs grown on (3 1 1)A and (1 0 0) GaAs at 600°C and 550°C, respectively.

improved material quality at a 50°C higher growth temperature or by the inherent lower interface recombination in (3 1 1)A orientation to (1 0 0) [6].

Fig. 2 shows the dark *I–V* characteristics of AlGaAs/GaAs p-QWIP grown at 600°C. Very symmetrical dark *I–V* characteristics are observed in both the forward and the reverse bias regions over the entire temperature range from 40 to 120 K, which is markedly improved when compared to Be-doped p-QWIP reported by Levine et al. [1]. The symmetrical *I–V* characteristic indicates the uniform doping in the quantum wells and the negligible impurity out-diffusion during growth. Similar low out-diffusion of Si impurity is also reported in a heterojunction bipolar transistor by Li et al. [8] even at a high growth temperature of 670°C. It is noticed that the dark current is in the same order to similar structure by Levine et al. [1] of a 4×10^{18} cm^{-3} Be-doped AlGaAs/GaAs p-QWIP with 3 nm well separated by 30 nm $Al_{0.3}Ga_{0.7}As$, which indicates the excellent material quality of p-QWIP grown in (3 1 1)A direction. The measured hole mobility at a hole concentration of 3×10^{18} cm^{-3} is 75 $cm^2/(V\ s)$, which is comparable to the mobility value of ~ 100 $cm^2/(V\ s)$ doped by Be [5]. The slightly lower mobility is believed to be due to the compensation effect from the higher V/III BEP ratio. However, a higher As flux is required to grow the AlGaAs and InGaAs layers.

To further reduce the dark current, we have studied the strained AlGaAs/InGaAs p-QWIP with the same device size. Fig. 3 shows the dark *I*–V characteristic of the AlGaAs/InGaAs p-QWIP grown at 550°C. A low growth temperature of 550°C is chosen to reduce the In re-evaporation from the InGaAs layer. In spite of the expected reduction of dark current, a slight asymmetry was observed under forward and reverse biased conditions. However, the asymmetry is markedly less than that of the Be-doped QWIP. It is unlikely that the asymmetry is due to Si out-diffusion, because the growth temperature is lower than that of AlGaAs/GaAs p-QWIP. Furthermore, in sharp contrast to the Be-doped p-QWIP, the dark current asymmetry is opposite to that from doping migration effect [1].

Fig. 4 shows the measured photo-responsivity spectra of strained AlGaAs/InGaAs p-QWIP doped by Si. A strong absorption peak at 3.7 μm is observed, with a shoulder around 3.0 μm and a small absorption at 5.7 μm. The primary absorption peak at 3.7 μm is much shifted from the designed absorption peak at 10 μm, which may be due to either the mis-estimated parameters in

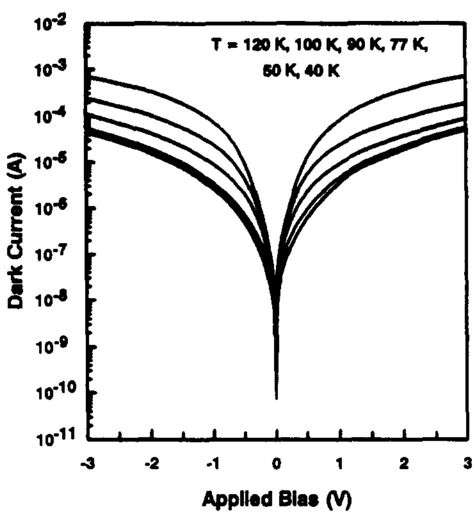

Fig. 2. Dark *I–V* characteristics of AlGaAs/GaAs p-QWIP measured at different temperatures.

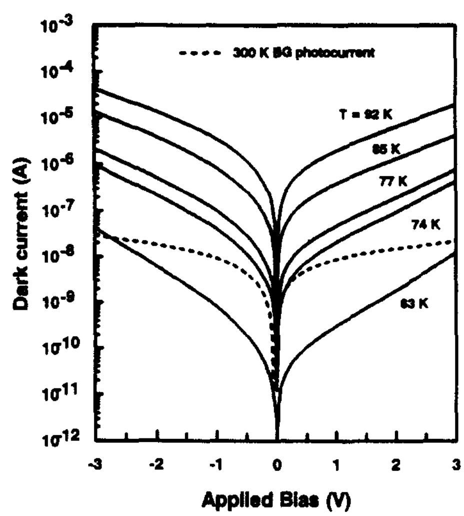

Fig. 3. Dark *I–V* characteristics of the strained AlGaAs/InGaAs p-QWIP measured at different temperatures.

(3 1 1)A orientation or the formation quantum wires reported by Notzel et al. [9].

We have studied the AlGaAs/InGaAs MQWs to further understand the unusual *I–V* asymmetry and the blue-shift of absorption wavelength. Fig. 5 shows the PL spectra of the strained AlGaAs/InGaAs MQWs grown on (3 1 1)A and (1 0 0) GaAs

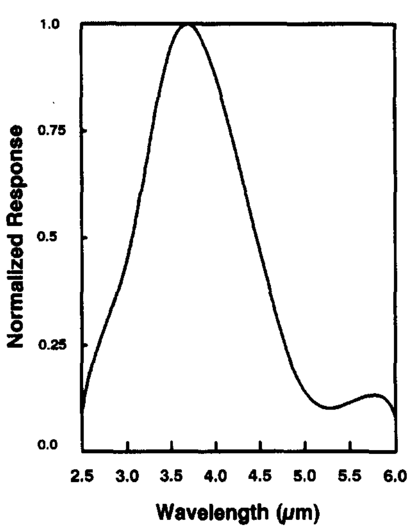

Fig. 4. Normalized responsivity for the strained AlGaAs/InGaAs p-QWIP grown on (3 1 1)A GaAs.

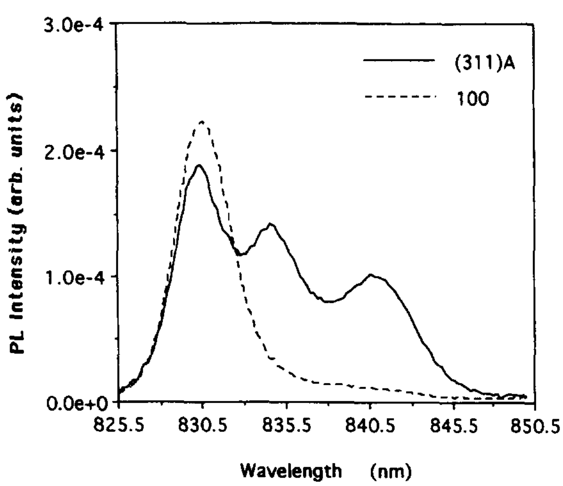

Fig. 5. Low temperature (15 K) PL spectra of the AlGaAs/InGaAs MQWs grown on (3 1 1)A and (1 0 0) GaAs at 550°C.

at 550°C. Although strong PL intensity was also observed for AlGaAs/InGaAs MQWs grown on (3 1 1)A GaAs, multiple PL transitions were measured with peak energy red-shifts of 7 and 22 meV to that of side-by-side grown (1 0 0) GaAs. We have used cross-sectional transmission electron microscopy (TEM) to study this effect. The PL energy red-shift is due to the growth-induced thickness modulation of quantum wells, which form quasi quantum wires in (3 1 1)A orientation [9]. More detailed study of TEM and the formation of quantum wires will be published elsewhere. Therefore the slight asymmetry in dark *I–V* characteristic of AlGaAs/InGaAs p-QWIP may be attributed to the thickness modulation. The large blue-shift of peak absorption in responsivity spectra may be also due to the formation of wider quantum wells as observed from TEM and PL.

4. Conclusions

We have demonstrated that the Si can be used as an alternative dopant for p-type QWIP. The highly symmetrical dark *I–V* characteristic from the AlGaAs/GaAs p-QWIP suggests the negligible dopant migration of Si impurity during growth. The strained p-type AlGaAs/InGaAs QWIP exhibits a lower dark current and a slightly asymmetrical dark current characteristic, but the asymmetry is markedly less than that doped by Be. The asymmetry in the strained p-QWIP is not due to the impurity out-diffusion, because the dark current asymmetry is opposite to that from doping migration. The slight asymmetry in dark *I–V* characteristic and the large blue-shift in responsivity spectra may be due to the thickness modulation observed from the red-shift of PL peak energy and TEM.

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