THERMAL INTERDIFFUSION IN InGaAs/GaAs STRAINED MULTIPLE QUANTUM WELL INFRARED PHOTODETECTOR

Alex S. W. Lee and E. Herbert Li
Department of Electrical and Electronic Engineering, University of Hong Kong, Pokfulam Road, Hong Kong

Gamani Karunasiri
Department of Electrical Engineering, National University of Singapore, Singapore 119260.

Abstract:

RTA at 850 °C for 5 and 10 s is carried out to study the effect of interdiffusion on the optical and electrical properties of strained InGaAs/GaAs quantum well infrared photodetector. Photoluminescence measurement at 4.5 K shows that no strain relaxation or misfit dislocation formation occurs throughout the annealing process. Absorption and responsivity peak wavelengths are red shifted continuously without appreciable degradation in absorption strength. The normal incident absorption, which is believed to be the result of band-mixing effects induced by the coupling between the conduction and valence and is usually forbidden in conventional polarization selection rule, is preserved after interdiffusion. Responsivity spectra of both 0° and 90° polarization are of compatible amplitude and the shape of the annealed spectra becomes narrower. Dark current of the annealed devices is not very sensitive to temperature variation and is found to be an order of magnitude larger than the as-grown one at 77K.

Introduction

Much progress has been made in bound-to-bound and bound-to-continuum[1] quantum well infrared photodetectors (QWIPs) after the first observation of intersubband absorption and a large dipole moment in AlGaAs/GaAs multiple quantum wells (MQW) has been reported.[2] With the development of strained layer QW and bandgap engineering, high quality pseudomorphic QW is achievable and it has been demonstrated that normal incident strained InGaAs/GaAs QWIP[3] is possible without grating coupling. However, the thermal stability of strained layers subjected to heat treatment is of prime importance and of great interest for optoelectronic device applications, especially for structure with higher In concentration. This is because highly strained heterostructure will result in smaller critical layer thickness[4] and will increase the risk of strain relaxation by the generation of misfit dislocation. Recently, fabrication of high-speed semiconductor lasers containing highly strained InGaAs/GaAs MQW in the active region has been reported using impurity-free interdiffusion by means of rapid thermal annealing (RTA).[5] Postgrowth tuning of AlGaAs/GaAs absorption peak[6] and QWIP detection wavelength have also been demonstrated.[7] In this communication, we report on the effect of dopant-enhanced layers interdiffusion on the performance of n-type strained $In_{0.3}Ga_{0.7}As$/GaAs QWIP annealed at 850 °C at different annealing times using RTA. Other than the continuous redshift of the detection wavelength, we also demonstrate that both the transverse magnetic (TM) and transverse electric (TE) infrared (IR) intersubband transitions are retained and that the responsivity performance of these annealed samples is compatible with the as-grown one by means of interdiffusion.

Results and discussions

The MQW structure was grown by molecular beam epitaxy on a (100) semi-insulating substrate. It consists of 50 periods of 40 Å wide as-grown $In_{0.3}Ga_{0.7}As$ well and 300 Å thick GaAs barrier. The Si doping is about 2×10^{18} cm^{-3} in the well. The MQW is sandwiched between a n^+ buffer (1 μm) and a cap layer (0.5 μm) as ohmic contact. It is designed to have only one bound state inside the well and the first excited state is in the continuum above the barrier. Before annealing, the samples were capped with approximately 250 nm thick electron-beam evaporated SiO_2 dielectric layer. RTA was carried out in a halogen lamp annealing system (AST SHS10) with double strip graphite heater under flowing nitrogen ambient. One of the samples was annealed for 5s at 850 °C while the other for 10s at the same temperature. Photoluminescence (PL) measurements were performed at 4.5 K after annealing using the 514.5 nm Argon laser at a power of 200 mW. Fig. 1 shows the PL spectra of the as-grown and interdiffused MQW. The PL peak shifts progressively to higher energy with anneal time from as-grown 1.316 eV to 1.319 eV and 1.323 eV, respectively. The blue shift of the bandgap energy indicates the intermixing of group III elements near the heterostructure interfaces. The PL peak intensity of the 5s annealed sample is increased by nearly one fold while the 10s annealed sample decreases by almost one fold in comparison with the as-grown intensity. The full width at half maximum (FWHM) PL line-width does not vary very much as compare to the as-grown sample; less than 4 meV difference for the 5s annealed sample and 1 meV difference for the 10s annealed sample. Since the well width of the sample currently under investigation is below the critical thickness for 30 % In concentration, the small variation in FWHM indicates that there is no strain relaxation or misfit dislocation formation during annealing and that there may even be a recovery of strain or an improvement in structural quality after RTA.[8, 9] Peaks were also observed at about 1.5 eV, which were red shifted with interdiffusion, in contrast to the PL peaks observed above. These peaks may due to the luminescence from GaAs either in the top cap layer or the bottom buffer layer.

Room temperature intersubband absorption measurement is taken using Nicolet Magna-IR 850 Fourier transform infrared spectrometer with a 45° polished multipass waveguide geometry. Effect of interdiffusion on the optical properties of annealed QWs is evidenced in Fig. 2. It shows the absorption spectra with 0° angle polarization, i.e., a mixture of TE and TM polarizations that contains a component of photon electric field along the growth direction as well as a component in the plane of the layers. The absorption peak of the as-grown sample originally at 10.2 μm is shifted to 10.5 μm after 5s annealing, and continuously red shifted to 11.2 μm in the subsequent 10s annealing. The red shift of the absorption peaks indicates both the bound state energy and the first excited state energy are being modified and/or the interdiffusion-induced changes in the depolarization shift,[6] which result in the postgrowth tuning of the absorption wavelength. But the first excited energy remains in the continuum under the different annealed conditions produced here, as can be seen from the high-energy tail and asymmetry of all the absorption spectra shown in Fig. 2, which are the characteristic features of bound-to-continuum intersubband transition in QWs.[1]

The absorption spectra of the annealed samples reduced in amplitude and broadened proportionally with increasing annealed time. This can possibly be attributed to the layers intermixing by RTA and to the modification in the QW profile. It is known that the solubility of Ga is very high in SiO_2 and so an increase in the concentration of group III vacancies is expected by the diffusion of Ga into the SiO_2 dielectric layer. This in turn will increase the dopant (Si) diffusion into the undoped GaAs barrier and converts it to a strongly n-typed material.[10] The Si diffusion across the heterointerfaces not only reduces the free carrier concentration but also enhances layers intermixing which results in the modification of the subband structure. Since absorption coefficient $\alpha(h\omega) \propto \rho_s$, the two dimension electron density in the well, the reduction in the number of carriers available to be excited by the incident IR radiation may render to a reduction in the absorbance. The change in the subband structure, which may result in smaller intersubband transition oscillator strength, together with impurity scattering may give rise to the broadening and decreasing in amplitude of the absorption spectra.

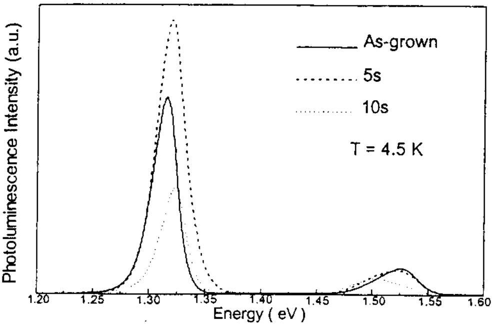
Mesa diodes (200 x 200 µm) were fabricated by standard lithography technique and 45° facet was polished at one end of the sample for responsivity measurement. The photocurrent was measured using grating monochromator and glowbar source with lock-in detection. Polarizer was inserted before the glowbar source in order to study the polarization dependence of the photoresponse. Figure 3 and 4 show the response spectra for 0° and 90° polarizations, respectively, as a function of wavelength at 25 K. For both polarization responsivity spectra, the peak positions were observed to be red shifted and independent of polarization. Note in both figures that there are a few peaks appear in the spectra with rather identical wavelength positions for both polarizations. Since the QW structure is designed to have the first excited state above the barrier, they are most probably due to intersubband transition from the bound state E_1 to other excited states in the continuum[11(15)] or the interaction between the first excited state E_2 and other states in the continuum.[12(16)] With the modification of QW structure by means of interdiffusion, the annealed spectra in Fig. 3 and 4 show that regardless of polarization, all these peaks are subdued except the designed main transition peak. For 0° polarization, the corresponding responsivity amplitudes 0.8, 0.79, and 0.77 A/W do not vary much for the as-grown and annealed detectors, as shown in Fig. 4(a), where all the spectra have almost identical rising edge. This is as expected since the MQW properties and its structure have not been substantially modified or deteriorated after interdiffusion, once the photoexcited carriers overcome the threshold barrier into the continuum states they are ready to be collected as photocurrent. The normal incident absorption, which is believed to be the result of band-mixing effects induced by the coupling between the conduction and valence[13(17)] and is usually forbidden in conventional polarization selection rule,[2] is preserved after interdiffusion. As shown in Fig. 4, the responsivity peaks in the as-grown spectrum due to the transition to other excited states in the continuum are subdued and the designed transition peak that is weak and lower in amplitude originally has become dominant and red shifted in the annealed spectra.

Leakage current is measured at 77 K using 4156A Parameter Analyzer and cold finger. The (I-V) characteristic is shown in Fig. 5 for the three devices. Note the asymmetry of the I-V curves between the two polarities. For the as-grown sample, leakage current is larger in reverse bias (i.e., mesa top negative) than in forward bias, which is attributed to inhomogeneity in material composition introduced during growth.[1] While for the annealed devices, the trend is just the opposite with leakage current larger at positive voltage. This is most probably due to the difference in diffusion rate of In and Ga species across the interfaces of the annealed QWs, which results in asymmetric barrier height[14(11)] seen by the thermal excited electrons, and to the re-distribution of dopant impurity as described in the previous section. These two factors together with the thinner 300 Å barrier not only explain the asymmetry[15(12)] I-V curves but also give rise to nearly an order of magnitude larger in leakage current than the as-grown one at 77 K. This is evidenced in Fig. 6. It shows that the annealed leakage current is not very sensitive to temperature variation from 25 to 90 K and remains almost constant for $T < 50$ K, if compare to the as-grown one. In this temperature range, the over all dark current increased nearly by one order of magnitude for the 5s annealed samples and by a factor of 8 for the 10s annealed sample, whereas the as-grown sample has increased by more than 5 orders of magnitude. Note also the leakage current of both the annealed devices is a few orders of magnitude larger than the as-grown one for $T < 50$ K. The huge increase in leakage current below this temperature is related to the defect-assisted tunneling mechanism as a result of the diffusion of Si and the group III constituent atoms in the heterostructure,[10] which introduced defects and dopant impurity into the barrier. At temperature larger than this where thermionic emission mechanism is dominant, all the leakage currents increase linearly to almost the same magnitude at $T = 90$K.

Conclusion

In conclusion, high In composition pseudomorphic interdiffused InGaAs/GaAs QWIP using dopant-enhanced vacancy interdiffusion has been demonstrated for its post-growth tunability. No strain relaxation and deterioration in the MQW structure are observed. The TE polarization infrared intersubband transition, as a result of the band-mixing effects, is preserved. Both 0° and 90° polarizations absorption peaks are red shifted with respect to the as-grown one without much degradation in absorption strength. Photoresponse peaks due to resonances in the continuum states are subdued after interdiffusion, which is most probably a consequence of the modification in subband structure. The annealed photoresponse spectra for 0° polarization are comparable to the as-grown device with a narrower FWHM, while the designed photoresponse peak becomes dominant for 90° polarization. Dark current of the annealed devices is about an order higher in amplitude than the as-grown one at 77 K. The I-V characteristic is less sensitive to the variation in temperature from 25-90 K where the overall dark current of both the annealed devices are varied in between a range of about one order in magnitude.

This work is support in part by the HKU-CRCG, RGC-Earmarked Research Grants and Academic Research Fund of National University of Singapore. The author would like to thank Prof. S. J. Chua for valuable suggestions, T. Mei, and Dr. S. J. Xu for technical assistance.



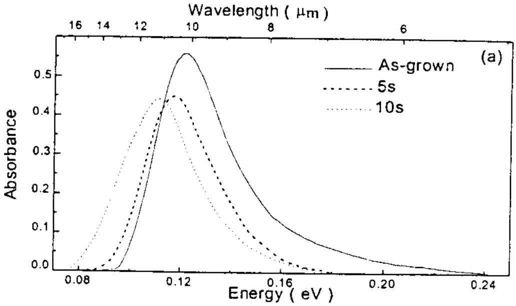
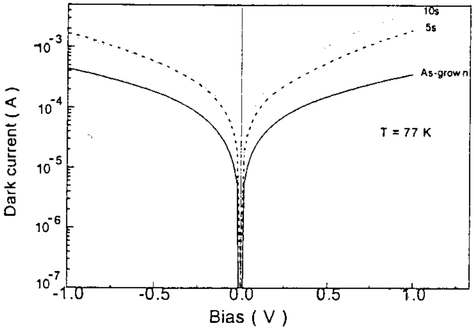


Fig. 1. Photoluminescence spectra of the as-grown, 5 s, and 10 s interdiffused InGaAs/GaAs MQW at T = 4.5 K.

Fig. 2. Absorption spectra of the as-grown, 5 s, and 10 s annealed samples at 300 K as a function of wavelength for 0° polarization.



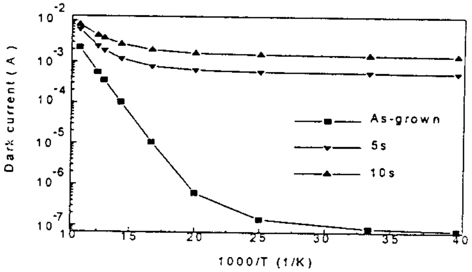
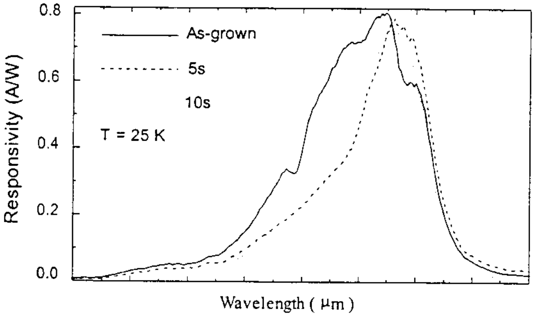


Fig. 3. I-V curve of the as-grown, 5 s, and 10 s annealed samples at 77 K as a function of bias.

Fig. 4. Arrhenius plot of leakage current at 1 V bias as a function of the reciprocal of temperature in the range between 25-90 K.



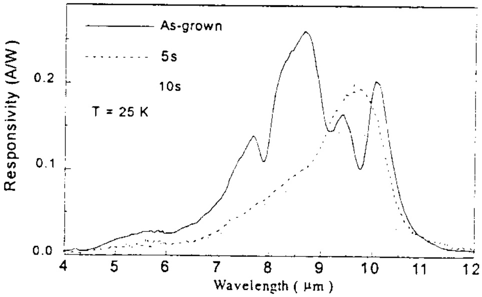


Fig. 5. Photoresponse spectra at 25 K of the as-grown, 5 s, and 10 s annealed samples bias at2.5 V, 1.05 V, and 1.65 V for 0° polarization as a function of wavelength.

Fig. 6. 90° polarization photoresponse spectr for the as-grown, 5 s, and 10 s annealed samples at 25 K and bias at 2.5 V, 1.05 V and 1.65 V as a function of wavelength.

Reference

1. B. F. Levine, A. Zussman, S. D. Gunapala, M. T. Asom, J. M. Kuo, and W. S. Hobson, J. Appl. Phys. Lett. **72**, 4429 (1992)
2. L. C. West, S. J. English, Appl. Phys. Lett. **46**, 1156 (1985).
3. R. P. G. Karunasiri, J. S. Park, J. Chen, and R. Shih, Appl. Phys. Lett. **67**, 2600 (1995).
4. J. W. Matthews and A. E. Blakeskee, J. Cryst. Growth **27**, 118 (1974).
5. S. Bürkner, J. D. Ralston, S. Weisser, J. Rosenzweig, E. C. Larkins, R. E. Sah, and J. Fleiβner, IEEE Photon. Technol. Lett. **7**, 941 (1995).
6. J. D. Ralston, M. Ramsteiner, B. Discher, M. Maier, G. Brandt, P. Koidl, and D. J. As, J. Appl. Phys. **70**, 2195 (1991).
7. A. G. Steele, M. Buchanan, H. C. Liu, and Z. R. Wasilewski., J. Appl. Phys. **75**, 8234 (1994).
8. B. Elman, E. S. Koteles, P. Melman, C. Jagannath, C. A. Armiento, and M. Rothman, J. Appl. Phys. **68**, 1351 (1990).
9. S. Burker, M. Baeumler, J. Wanger, E. C. Larkins, W. Rothemund, and J. D. Ralston, J. Appl. Phys. **79**, 6818 (1996).
10. D. G. Deppe and N. Holonyak, Jr., "Atom diffusion and impurity-induced layer disordering in quantum well III-V semiconductor heterostructures," J. Appl. Phys. **64**, R93 (1988).
11. K. M. S. V. Bandara, B. F. Levine, and M. T. Asom, J. Appl. Phys. **74**, 346 (1993).
12. K. K Choi, M. Taysing-Lara, P. G. Newman, and W. Chang, "Wavelength tuning and absorption line shape of quantum well infrared photodetectors." Appl. Phys. Lett. **61**, 1781 (1992).
13. L. H. Peng and C. G. Fonstad, "Multiple coupling effects on electron quantum well intersubband transitions," J. Appl. Phys. **77**, 747 (1995).
14. A. S. W. Lee and E. H. Li, "Effects of interdiffusion of quantum well infrared photodetector," Appl. Phys. Lett. **69**, 3581 (1996).
15. H. C. Liu, Z.R. Wasilewski, M. Buchanan, and Hanyou Chu, Appl. Phys. Lett. **63**, 761 (1993).