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Photocurrent Measurement of $Si_{1-x}Ge_x/Si$ Multiple Quantum Wells With Ion Implantation and Thermal Annealing*

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Abstract　Si-Ge interdiffusion in $Si_{1-x}Ge_x/Si$ multiple quantum-wells (MQW) is investigated by photocurrent spectroscopy, which is induced by ion implantation of Si^+ and thermal annealing. The band gap energy of the $Si_{1-x}Ge_x/Si$ samples implanted plus annealed has a blue shift up to 97meV compared to the annealed-only samples. The blue shift may be caused by the Si-Ge interdiffusion and the relaxation of the SiGe quantum wells.

Key Words: Photocurrent Measurement, SiGe, MQW, Ion Implantation, Thermal Annealing
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1　Introduction

Photocurrent spectroscopy is a well-known method for the investigation of the band gap energy of SiGe alloy[1~3]. The measurement is relatively simple and the photocurrent

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spectroscopy can provide some useful data for its application in the future.

The monolithic integration of silicon-based photonic devices with integrated circuits is an attractive topic for its promising future. Quantum well intermixing, which is induced by the ion-implantation-enhanced interdiffusion, has been proved to be an effective method for the integration of III-V compound semiconductors[4,5].

Recently, SiGe/Si quantum well intermixing induced by ion-implantation, laser beam radiation and thermal annealing has been studied by photoluminescence[6~11]. But no device based on this material has been fabricated. In this paper, photocurrent spectroscopy of PIN photodiode is used to investigate $Si_{1-x}Ge_x/Si$ quantum well intermixing. The cutoff wavelength of the implanted plus annealed samples is reduced comparing with that of annealed-only samples due to the implantation-enhanced Ge-Si interdiffusion between wells and barriers. The band gap is blue shifted by up to 97meV from the photocurrent spectroscopy.

2 Device Structure and Fabrication

The samples of $Si_{0.7}Ge_{0.3}/Si$ MQW in this study were grown by molecular beam epitaxy on a n-Si substrate at the temperature of 750℃, with the following layer sequence from the substrate: 100nm intrinsic Si buffer, a MQW region consisting of 20 layers of $Si_{0.7}Ge_{0.3}$ (10nm thickness) and 19 layers of Si (25nm thickness), 100nm intrinsic Si and 200nm p^+-Si cap layer. Point defects were introduced as implanting Si ions into the half of each sample at a dose of 1×10^{14} ions/cm^2. The peak depth for ion distribution was near the middle of the quantum wells. After implantation, the samples were annealed in N_2 at 850℃ for 300s in a home-made RTA system.

The grown samples were used to fabricate PIN photodiodes for measurement using standard photolithography and reactive ions etching (RIE) processes. The schematic of the PIN structure is shown in Fig. 1. Circle mesas (800μm in diameter) were etched down to the intrinsic silicon buffer layer by RIE using SF_6. Aluminum ring was then evaporated to form the top contact. Input light can pass through the aluminum ring (as a window) with the diameter about 500μm. The wafer was thinned to about 100μm from backside and Al was evaporated to form the bottom contact.

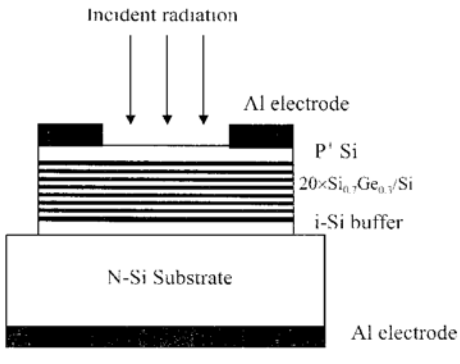

FIG. 1　Schematic of PIN Structure

The photocurrent spectroscopy was carried out using a Fourier Transform Infrared Spectrometer with PIN photodiodes at the reverse-bias and room temperature. Light radiated from a tungsten lamp passed through a narrow aperture before it focused on the window of the devices.

3 Experimental Results and Discussion

Figure 2 shows the photocurrent spectra of the as-grown sample 1#, the annealed-only one 2# and the implanted plus annealed one 3#. The cutoff wavelengths are longer than 1.35μm for sample 1#, approximate 1.25μm for sample 2# and 1.2μm for sample 3# respectively. When the samples are annealed, Si-Ge interdiffusion between quantum wells and barriers is enhanced through the point defects introduced by ion implantation. The Ge fraction in the quantum wells is reduced, as giving rise a increased energy bandgap.

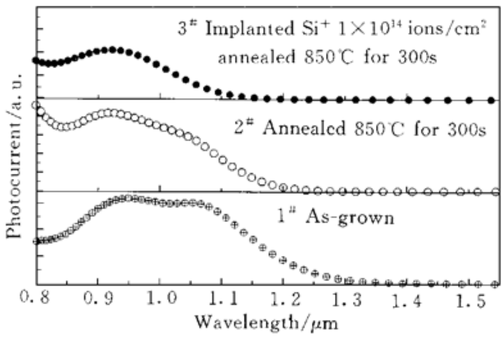

FIG.2 Photocurrent Spectroscopy of Photodiodes 1#, 2# and 3#

We have used the photocurrent spectroscopy measured at the room temperature to determine the band gap energy of SiGe/Si quantum wells. The photocurrent I_{ph} of the SiGe/Si PIN photodiodes is proportional to $(1-\exp(-\alpha d))/h\nu$, where α is the absorption coefficient, $h\nu$ is the photon energy, d is the effective thickness of absorption layer. If αd is less than 1(it is our case), the $I_{ph}\times h\nu$ is proportional to αd. Interband photon absorption in indirect band gap semiconductors is assisted by phonon emission and absorption. The absorption coefficient is described by the sum of two square terms——one term is proportional to $(h\nu-E_g+E_p)^2$ and the other is proportional to $(h\nu-E_g-E_p)^2$, where E_g is the band gap and E_p is the phonon energy. Plotting the square root of $I_{ph}\times h\nu$ versus $h\nu$, we can obtain the band gap energy E_g and phonon energy E_p by curve-fitting technique[3,12]. The band gap energy and phonon energy are summarized in Table 1. The band gap of SiGe quantum well in implanted plus annealed samples is blue shifted by up to 97meV compared to that in annealed-only samples and 150meV to that in as-grown ones. The energy blue shift is possible due to the Si-Ge interdiffusion, the relaxation of SiGe alloy and the broadening of the quantum wells. Implantation of Si ions can generate vacancies, interstitials and other defects in the quantum wells structure, which enhance the Si-Ge interdiffusion between well and barrier regions. The reduction of Ge fraction caused by Si-Ge interdiffusion in SiGe wells increases the band gap. On the other hand, because of the Si-Ge interdiffusion, the quantum wells are broadened, as also increases the band gap of SiGe quantum wells. Double X-ray diffraction has proved that our samples are partially relaxed by rapid thermal annealing at 850℃[13], which could also cause a blue shift in SiGe/Si quantum wells independently. Comparing the values of blue shift of sample 2#, sample 3# and sample 1#, it is inferred that the blue shift may mainly be induced by Si-Ge interdiffusion. The phonon energy obtained from the photocurrent measurements is found to be in the range of TO_{Si-Si} phonon energy.

Table 1 Bandgap Energy E_g and Phonon Energy E_P Inferred from Photocurrent Spectroscopy

Samples No.	Samples	E_g/meV	E_P/meV
1#	As-grown	875	59
2#	Annealed-only	928	62
3#	Implanted and annealed	1025	64

4 Conclusion

In conclusion, photocurrent spectroscopy is firstly used to investigate $Si_{1-x}Ge_x/Si$ quantum well with ion implantation and thermal annealing. The cutoff wavelength of the implanted plus annealed photodiodes is significantly reduced compared with that of annealed-only and as-grown PIN photodiodes. The band gap of SiGe alloy in the implanted plus annealed samples obtained from the photocurrent spectroscopy is blue shifted approximately 97meV and 150meV relative to that of annealed-only samples and as-grown samples, respectively. The energy blue shift is mainly due to the Si-Ge interdiffusion during thermal annealing process and partially due to the relaxation of strained SiGe alloy. The implantation of Si^+ in SiGe/Si multiple quantum-wells enhances the Si-Ge interdiffusion strongly.

References

[1] J. Olajos, J. Engvall and H. G. Grimmeiss, Phys. Rev. B, 1992, **46**: 12857.

[2] D. V. Lang, R. Peaple, J. C. Bean and A. M. Sergent, Appl. Phys. Lett., 1985, **47**: 1333.

[3] A. Chowdhury, M. Rashed, C. Maziar *et al.*, J. Vac. Sci. Technol. B, 1993, **11**: 1685.

[4] P. Gavrilovic, D. G. Deppe, K. Meehan *et al.*, Superlattice Microstruct., 1985, **47**: 130.

[5] P. J. Poole, P. G. Piva, M. Buchanan *et al.*, Semicond. Sci. Technol., 1994, **9**: 2134.

[6] D. Labrie, H. Lafontaine, N. Rowell *et al.*, Appl. Phys. Lett., 1996, **69**: 993.

[7] D. Labrie, G. C. Aers, H. Lafontaine *et al.*, Appl. Phys. Lett., 1996, **69**: 3866.

[8] H. Lafontaine, N. L. Rowell, G. C. Aers *et al.*, SPIE, 1997, **3007**: 48.

[9] Zhu Yuqing, Yang Qinqing and Wang Qiming, Chinese Journal of Semiconductors, 1997, **3**: 237(in English)[朱育清, 杨沁清, 王启明, 半导体学报, 1997, **3**: 237].

[10] J. J. Dubowski, N. Rowell, G. C. Aers *et al.*, Appl. Phys. Lett., 1998, **74**: 1948.

[11] Si Junjie, Yang Qinqing, Wang Hongjie *et al.*, Chinese Journal of Semiconductors, 1998, **6**: 477(in Chinese)[司俊杰, 杨沁清, 王红杰等, 半导体学报, 1998, **6**: 477].

[12] S. S. Murtaza, R. Qian, D. Kinosky *et al.*, Appl. Phys. Lett., 1993, **62**: 1976.

[13] Zhu Yuqing, Thesis for Ph. D, Institute of Semiconductors, The Chinese Academy of Sciences, 1997.