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The Influence of Rapid Thermal Annealing on SiGe/Si Multiple-Quantum Wells p-i-n Photodiodes*

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Abstract: The influence of thermal treatment on $Si_{1-x}Ge_x$/Si multiple-quantum wells (MQW) p-i-n photodiodes has been investigated by photocurrent spectroscopy combined with X-ray double crystal diffraction. The cutoff wavelength is significantly reduced due to the Si-Ge interdiffusion and partial relaxation of the strained SiGe alloy. The values of the blue shift increase slowly with the annealing temperatures in the range of 750℃ to 850℃. However, the nonlinear changes in photocurrent intensities of the samples annealed at different temperatures have been observed, which is mainly dominated by the generation of misfit dislocations and the reduction of the point defects in the heating process.

Key words: SiGe/Si MQW; photodiodes; blue shift; thermal annealing; interdiffusion

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1 Introduction

Strained SiGe/Si heterostructure has been used successfully to fabricate heterojunction bipolar transistors[1,2] and photodetectors in the long-wavelength optical fiber communication[3—8]. However, in order to avoid the strain relaxation or the generation of dislocation caused by the lattice misfit between SiGe and Si, the growth of SiGe layer is generally performed at low temperatures, which leads to the formation of metastable layer. As a result, the processing device is chosen with some limitation.

In order to strengthen the thermal stability of the strained SiGe material, much research has been done on Ge-Si interdiffusion and strain relaxation during the thermal annealing by using X-ray double crystal diffraction, Rutherford backscattering and photoluminescence, etc[9—14]. However, most of these reports are concentrated on the interdiffusion and the influence of the strain relaxation on interdiffusion. p-i-n photodetectors are fabricated to investigate the effect of annealing and the misfit dislocations on the photocurrents. In this paper, the influence of rapid thermal annealing (RTA) on $Si_{1-x}Ge_x$/Si multiple quantum wells (MQWs) p-i-n photodiodes is investigated by photocurrent spectroscopy. Bandgap energy blue shift is observed in the photodiodes of $Si_{1-x}Ge_x$/Si

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MQW samples after RAT at different temperatures. The blue shift is mainly due to Si-Ge interdiffusion, while the changes in photocurrent intensity are ascribed to the generation of misfit dislocation and the reduction of the point defects. The blue shift increases slowly while the photocurrent intensity is changed nonlinearly with the annealing temperatures in the range of 750—850℃.

2 Device Fabrication

The samples of $Si_{0.7}Ge_{0.3}$/Si MQW were grown by molecular beam epitaxy on a n-Si substrate at the temperature of 650℃, with the following layer sequence starting from the substrate: a 100nm intrinsic Si buffer layer, a MQW region consisting of 20 layers of $Si_{0.7}Ge_{0.3}$ of 6nm in thickness and 19 layers of Si of 20nm in thickness, a 100nm intrinsic Si and a 200nm p^+-Si as the capped layer. Four samples were cleaved from the same wafer and three of them were annealed in the nitrogen atmosphere at 750, 800 and 850℃ for 300s, respectively.

p-i-n photodiodes were fabricated with the four samples with the standard photolithography and dry etching technology. The schematic of the device structure is shown in Fig. 1. Round mesa

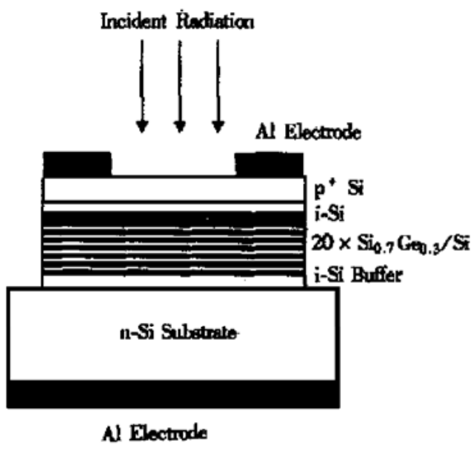

FIG. 1 Schematic of the SiGe/Si MQW p-i-n Photodiode

(with diameter being 500μm) was etched down to the intrinsic silicon buffer layer by $SF_6 + O_2$. Aluminum was then evaporated to form the top contact. Input light could pass through the window whose diameter was about 300μm in the center of the photodiodes. The wafer was thinned to about 100μm from the backside and aluminum was evaporated to form the bottom contact.

The photocurrent spectroscopy was carried out by using a Fourier transform infrared spectrometer with the photodiodes at reverse-bias at room temperature. Light radiated from a tungsten lamp was focused on the device.

3 Results and Discussion

Figure 2 shows the photocurrent spectra of SiGe/Si p-i-n photodiodes fabricated with an as-

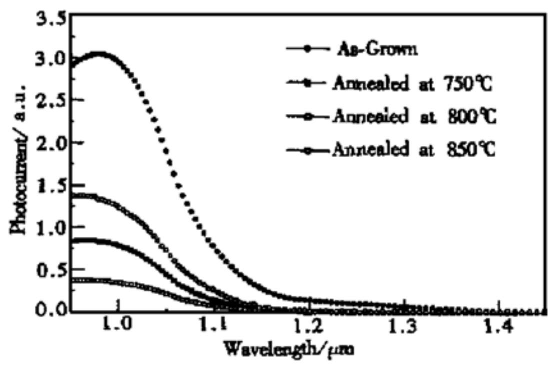

FIG. 2 Photocurrent Spectra of the SiGe/Si MQW p-i-n Photodiodes of As-Grown and Annealed Samples at Different Temperatures

grown wafer and annealed samples at 750, 800 and 850℃, respectively. The photocurrent of p-i-n photodiodes is mainly determined by the generation rate of electron-hole pairs and collection efficiency. At the wavelength less than 1.1μm, the collection efficiency is the dominant factor to differentiate the photocurrents of these photodiodes. In Fig. 2, the photocurrent intensity of the annealed samples is weaker than that of the as-grown samples, which may be caused by the generation and propagation of the misfit's dislocations induced by the relaxation of strained SiGe layer during the heating process. However, the photocurrent intensity of the sample annealed at 850℃ is stronger than that of the sample annealed at 750℃ or 800℃. We consider that the point defects induced by low temperature growth start to reduce during the annealing at a high temperature, such as 850℃. This thermal treatment improves the crystalline quality and reduces the recombination center, so that the collection efficiency is improved.

At the wavelength is more than 1.1μm, the influence of generation rate of the electron-hole pairs on photocurrent becomes more and more important. The generation rate of electron-hole pairs near the fundamental band edge is determined by the bandgap energy, which is mainly attributed to the Ge content in SiGe alloy. The cutoff wavelength of the annealed samples is reduced significantly compared with that of the as-grown samples. This blue shift may be due to the Si-Ge interdiffusion at the interface of SiGe quantum wells and Si barriers, giving rise to the reduction of Ge fraction in SiGe alloy. Another possible reason is the relaxation of the strained SiGe layers, which makes the bandgap energy larger. In addition, boron diffusion and broadening of quantum wells also affect the photocurrent of p-i-n structure.

Measuring the photocurrent spectroscopy at room temperature, we determine the bandgap energy of $Si_{1-x}Ge_x/Si$ quantum wells. The photocurrent I_{ph} of the $Si_{1-x}Ge_x/Si$ p-i-n 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 far less than 1(such as for our sample), the $I_{ph}h\nu$ is proportional to αd. The interband photon absorption in indirect bandgap semiconductors like Si and SiGe is assisted by phonon emission and absorption. The absorption coefficient can be expressed[15] as:

$$\alpha(h\nu)=\begin{cases}0 & h\nu< E_g-E_p\\ A_a(h\nu-E_g+E_p)^2 & E_g-E_p<h\nu<E_g+E_p\\ A_a(h\nu-E_g+E_p)^2+A_e(h\nu-E_g-E_p)^2 & h\nu>E_g+E_p\end{cases}$$

where E_g is the indirect bandgap, E_p is the phonon energy, $h\nu$ is the photon energy. The parameters A_a and A_e are used to weigh the phonon absorption and emission contributions. The band gap energy obtained from the photocurrent spectra by using the curve-fitting techniques[16—18] is shown in Fig. 3. The values of the blue shift of the annealed samples at 750, 800 and 850℃ are 108, 119 and 128meV, respectively. This indicates that the values of the blue shift increase slowly with the annealing temperatures in the range of 750—850℃. However, the generation of misfit disslocations and the reduction of point defects depend strongly on the annealing temperatures as described previously.

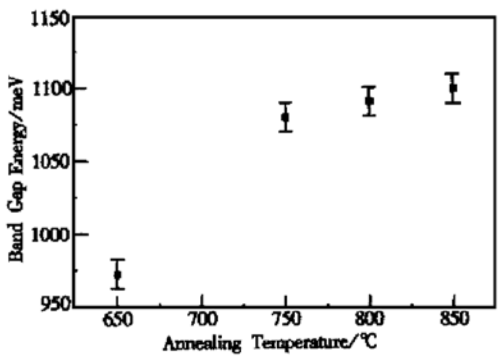

FIG. 3 Bandgap Energy of the Samples Annealed at Ddifferent Temperatures

Double crystal X-ray diffraction rocking curves of the as-grown and annealed samples are presented in Fig. 4. The as-grown sample exhibits well-defined satellites with pendellösung streaks arising from the finite-size effects. After thermal anneal in the range of 750—850℃, the number of the satellites is reduced and the diffraction peaks are slightly broadened. This proves the Si-Ge interdiffusion and the generation of misfit dislocations. According to the improved photocurrent of the diode fabricated with the sample annealed at 850℃ and the double crystal X-ray, the point defects are believed to be reduced in the heating process at 850℃, which improves the collection efficiency without any effects on the X-ray rocking curves.

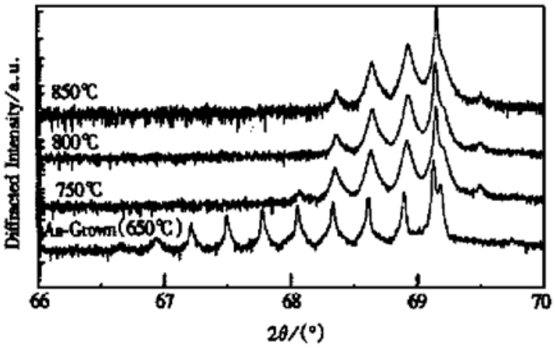

FIG. 4 X-Ray Double Crystal Diffraction Rocking Curves of the Samples (a) As-Grown; (b) Annealing at 750℃; (c) 800℃ and (d) 850℃

4 Conclusion

The influence of RTA on the $Si_{1-x}Ge_x/Si$ MQW p-i-n photodiodes are presented in this paper. The cutoff wavelength of annealed samples is significantly reduced compared with that of the as-grown samples, owing to Si-Ge interdiffusion at the interface of SiGe wells and Si barriers. The values of blue shift increase slowly with the increase of annealing temperatures in the range of 750℃ to 850℃. The quality of SiGe/Si MQW becomes degradation because of the generation and propagation of the misfit dislocations with the increase of the annealing temperature. However, annealed at 850℃, the photocurrent intensity of SiGe/Si p-i-n diode is improved compared with that annealed below 800℃, which may be due to the reduciton of the point defects formed in the low-temperature growth.

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快速退火对 SiGe/Si 多量子阱 p-i-n 光电二极管的影响*

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摘要: 利用光电流谱, 结合 X 射线双晶衍射研究了快速退火对 $Si_{1-x}Ge_x$/Si 多量子阱 p-i-n 光电二极管的影响. 由于应变 SiGe 的部分弛豫和 Si-Ge 互扩散, 退火后的二极管的截止波长有显著的减小. 但是, 在 750—850℃范围内, 波长蓝移量随着退火温度的增加而变化缓慢, 而样品的光电流强度却随温度是先减弱而后又增强, 这可能主要是由于在不同温度退火过程中失配位错的产生和点缺陷的减小造成的.

关键词: SiGe/Si 多量子阱; 光电二极管; 蓝移; 热处理; 扩散

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