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Fabrication of PIN Photo-Diode from $Si_{0.2}Ge_{0.8}$/Si strained MQWs

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A pin photo-diode was fabricated from the $Si_{0.2}Ge_{0.8}$/Si strained multiple quantum-well (MQW) structure grown by using ultra high vacuum chemical vapor deposition (UHV-CVD). The structural properties of the $Si_{0.2}Ge_{0.8}$/Si strained MQW were investigated using high-resolution X-ray diffraction (HRXRD). Specifically, the recent advances in the dry etching of $Si_{0.2}Ge_{0.8}$/Si strained MQW have been used to define pin photo-diode active layer mesas. The current-voltage (I-V) characteristic of pin photodiodes fabricated from these MQWs was measured. Also, the spectral response spectrum of pin photodiodes was measured at room temperature.

Keywords: MQWs, CVD, SiGe, PIN

1. INTRODUCTION

Ge and SiGe films are ideal candidate materials for photo receivers at optical communication wavelengths because of their high optical absorption and compatibility with existing Si technology. Consequently, the integration of SiGe photo detectors on Si substrates has been an active area of research. Also, there is potential for offering increased carrier mobility over that offered by pure Si. The heterostructures with SiGe and Si layers grown on Si substrates allow the realization of devices having high sensitivity in the 0.8 μm to 1.6 μm spectral range and a high-speed operation.[1-3] Although pin photodiodes do not have internal gain, a combination of a photodiode with an amplification device such as a high electron mobility transistor (HEMT) or heterojunction bipolar transistor (HBT) has led high-sensitivity optical receivers for high-rate data transmission.[4] The pin photodiodes on SiGe/Si multiple quantum wells (MQWs) are the most suitable devices for long-wavelength optical communications systems due to their high efficiency and capability of high-speed operation. Strained SiGe/Si MQWs have been generally accepted as demonstrating that holes in these heterostructures experience potential wells in the SiGe layer and barriers in the Si layer. The situation in conduction band (CB), however, is rather obscure under the influence of alloying and strain effects, resulting in some uncertainty as to whether type-I or type-II band alignment is formed in a given MQWs structure.[5-8] However, being able to precisely determine the type of alignment has a direct impact on device properties, e.g., type-I alignment offers a larger band-to-band oscillator strength than type II; thus a stronger radiative emission efficiency is expected from type-I devices. To fabricate these kinds of devices, researchers have used type-I quantum wells or superlattices because most of the band offset is located in the valance band region of about 74% to 84% of band gap energy[9,10] in the SiGe/Si heterostructure. However, the grown SiGe layer must be pseudomorphic and abrupt in its interfaces.

In this study, pin photo-diode was fabricated from the $Si_{0.2}Ge_{0.8}$/Si strained MQWs structure grown by using ultra high vacuum chemical vapor deposition (UHV-CVD). The structural properties of the $Si_{0.2}Ge_{0.8}$/Si strained MQWs were investigated using high-resolution X-ray diffraction (HRXRD). Specifically, the recent advances in the dry etching of $Si_{0.2}Ge_{0.8}$/Si strained MQW have been used to define pin photodiode active layer mesas. The current–voltage (I-V) characteristic of pin photodiode fabricated from these MQWs was measured. Also, the spectral response spectrum of pin photodiodes fabricated from $Si_{0.2}Ge_{0.8}$/Si strained MQWs was measured at room temperature.

2. EXPERIMENT

The $Si_{0.2}Ge_{0.8}$/Si strained MQW structures were grown by using ultrahigh vacuum chemical vapor deposition (UHV-CVD) on (100) Si substrates at 550°C with SiH4 and GeH4 in hydrogen carrier gas. The MQW structure was made up of a 0.1 μm thick undoped Si buffer layer, 28-period of SiGe/Si MQW, and a 0.3 μm thick Si cap layer. Since the QW was highly strained, the well width was chosen to be 4 nm below the critical thickness of ~5nm. The Si barrier thickness was 21 nm. The Ge composition and the layer thickness were determined by using HR-XRD. On the $Si_{0.2}Ge_{0.8}$/Si strained

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MQW surface, regular lithography techniques are used to define circular mesas with diameters ranging from 50 µm to 64 µm inside the recess. Samples are spin-coated for 30 s using spin-coater with photo-resist at 5000 rpm. Then, they are placed in an oven for soft baking at 90°C for 30 min. Photo-lithography is performed using mask aligner I-line, and ultraviolet light (365 nm) with an intensity of approximately 5 mW. The mesa is formed by ICP high density plasma dry etching. Samples are mesa etched in a load-locked BMR(HiEtch) high density plasma etch system consisting of an ICP chamber(operating at 2 MHz) and an additional rf bias (13.56 MHz) for the sample chuck. Helium back-side cooling has been incorporated to allow the temperature of the substrate to be more effectively controlled. Samples are mounted on a 6 in. Si carrier wafer with vacuum grease before they are introduced into the etching chamber. $Ar/CCl_2F_4/Cl_2$ gas of purity 99.999% is introduced for etching with varied process parameters. For current-voltage (I-V) characteristic measurement, the contact metal was annealed in N_2 ambient at 600°C for 30 s to form ohmic contacts. The spectral response spectrum was analyzed by using a 500-mm grating monochrometer. A quartz-tungsten halogen lamp was used as the photo-excitation light source. The spectral response signal was picked up with a lock-in amplifier and then recorded by a computer. The spectral response spectrum of pin photodiodes fabricated from $Si_{0.2}Ge_{0.8}$/Si strained MQWs was measured at room temperature.

3. RESULTS AND DISCUSSION

The structural properties of $Si_{0.2}Ge_{0.8}$/Si strained MQW were investigated by using HRXRD. The (004) diffraction pattern of a typical 28-period 40 Å/210 Å MQW well structure with an optimal growth procedure is shown in Fig. 1. The spectrum shows a higher order diffraction peak, indicating good layer periodicity. The observed sharp and well-defined satellite peaks imply a coherent periodicity of the $Si_{0.2}Ge_{0.8}$/Si heterostructure and suggest the presence of very abrupt interfaces. The fact that no significant broadening appears for any of the satellite peaks indicates homogeneous composition and suggests that the layers are coherently strained. For instance, the separation between the main peak (Si substrate) and the first-order satellite peak is characterized by the average MQW mismatch caused by the tetragonal compressive deformation and leads to a determination of the Ge molar fractions in the wells.[11]

From the position of the HR-XRD peaks, we estimated the thickness of one period (barrier and well). In principle, average Si composition of the QW and the period can be determined from the relative positions of the 0th-and the higher order peaks in the HR-XRD patterns. The period (*D*) is given by

$$D = \frac{n\lambda}{2(\sin\theta_n - \sin\theta_{0th})} \quad (1)$$

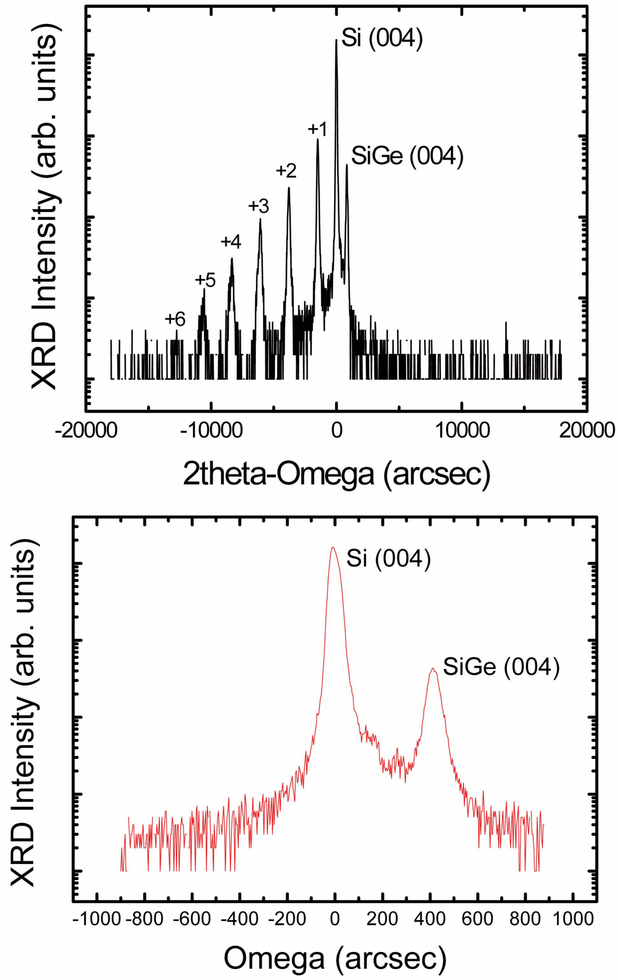

Fig. 1. HRXRD (004) rocking curves of as-grown SiGe/Si strained MQW at room temperature.

where n is the order of satellite peaks, θ_n is their diffraction angle, and θ_{0th} is an angle of 0th-order peak. From the results of HR-XRD analysis on the as-grown $Si_{0.2}Ge_{0.8}$/Si MQW, D is calculated as about 250 Å. Ge composition in well layer was determined as about 20% and the well width and the barrier width are 21 Å and 4 Å, respectively.

The SEM photograph of ICP dry etched Mesa of the pin photo-diode fabricated from $Si_{0.2}Ge_{0.8}$/Si strained MQWs is shown in Fig. 2. Figure 3 shows the schematic diagram of the pin photo-diode fabricated from $Si_{0.2}Ge_{0.8}$/Si strained MQWs. The MQWs structure consisted of a 0.1-µm-thick undoped Si buffer layer, 28-period of SiGe/Si MQWs, and a 0.3 µm thick Si cap layer. Since the QW was highly strained, the well width was chosen to be 4 nm below the critical thickness of ~5 nm. The Si barrier thickness was 21 nm.

Figure 4 shows the dark current characteristics of pin photo-diode fabricated from $Si_{0.2}Ge_{0.8}$/Si strained MQWs at different annealing temperatures to form ohmic contacts. The low dark current is attributed to the excellent material quality.

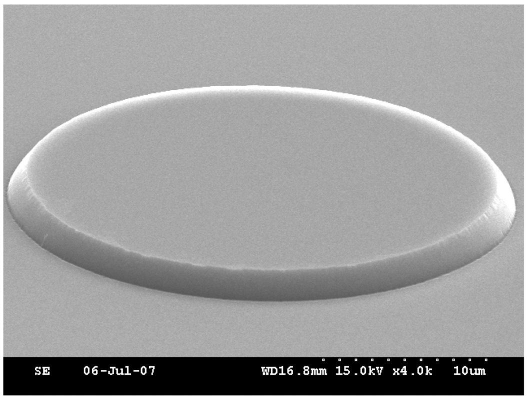

Fig. 2. SEM photograph of ICP dry etched Mesa of the pin photodiode fabricated from $Si_{0.2}Ge_{0.8}$/Si strained MQWs.

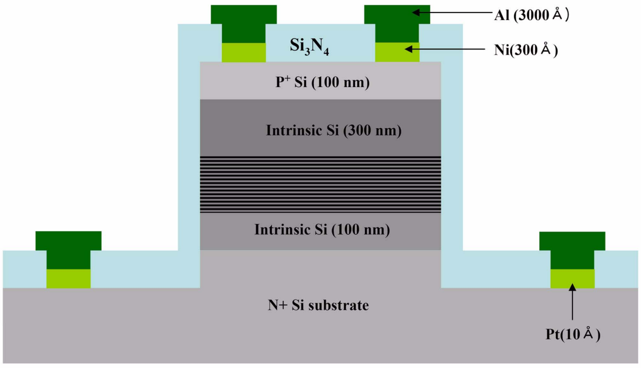

Fig. 3. Schematic diagram of the pin photodiode fabricated from $Si_{0.2}Ge_{0.8}$/Si strained MQWs (SiGe : 4 nm, Si : 21 nm, Total : 700 nm, Period : 28).

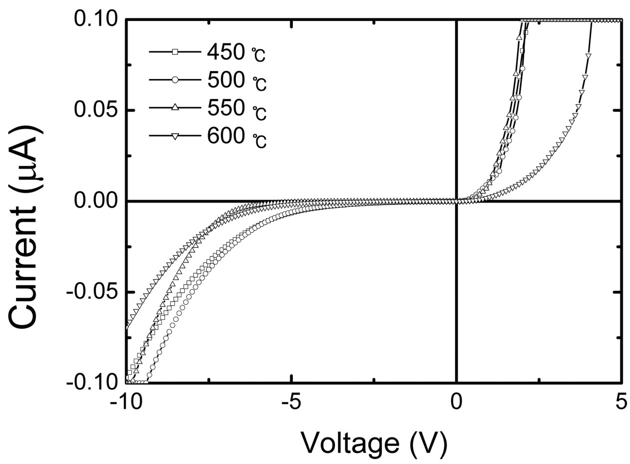

Fig. 4. I-V characteristics of pin photo-diode fabricated from $Si_{0.2}Ge_{0.8}$/Si strained MQWs at different annealed temperature to form ohmic contacts.

Figure 5 shows the room-temperature spectral response spectrum for pin photodiodes. The large spectral range of 0.6 μm to 1.2 μm is due to photogeneration in the $Si_{0.2}Ge_{0.8}$/Si strained MQWs at long wavelength.[12] The photodiodes have a high value for responsivity at a range of 0.7 μm to 0.85 μm wavelength. The spectral response spectra are dominated by the MQWs related transition corresponding to the transition of the electron- heavy hole sub-band (e-hh) and the electron-light hole sub-band (e-lh). In Fig. 5, four distinct sub-band peaks are observed. This suggests that two carrier-transition mechanisms are responsible for the spectral response spectra.[13] This structure is attributed to transitions between quantum-confined states in the valence and conduction bands. We now compare the experimental photocurrent spectrum data with theoretical transition energies. The experimental energies were compared and agreed with the results of envelope function calculations for a finite rectangular QW.[14] The lowest energy peak is identified as the fundamental e-hh_1 transition (1.46 eV). The second peak detected at 1.51 eV is attributed to the e-lh_1 transition. The third peak detected at 1.65 eV is attributed to the e-hh_2 transition. The fourth peak detected at still 1.72 eV is attributed to the e-lh_2 transition.[15-17]

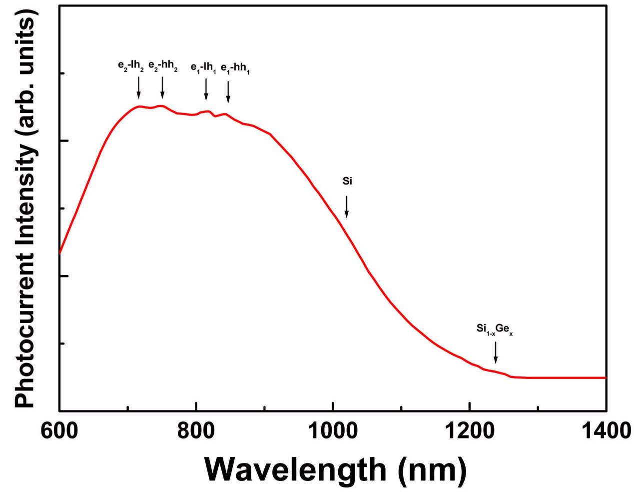

Fig. 5. Spectral response spectrum of the pin photodiode fabricated from $Si_{0.2}Ge_{0.8}$/Si strained MQWs (annealed temperature: 550°C).

SiGe has a type-I band structure once it grows on Si pseudomorphically.[18,19] In other words, the energies of both conduction band and valence band in SiGe are lower than those of Si. However, with high Ge composition, it becomes a type-II band structure because the energy of the lowest band Δ_4 in the conduction band is higher than that of Si. It has been suggested that SiGe has type-II even for small Ge composition because the band offset of the conduction band in Si and SiGe is very small (20 meV).[20] It has also been reported that an actual type-II structure was observed as a the type-I because of band bending by the high excitation.[20]

This interpretation is based on the assumption that light holes are confined within the well in a type-I band alignment. The intensity of the e-hh_1 transition rules out a type-II alignment where light holes would be confined in the Si barrier layers.

4. CONCLUSION

A pin photo-diode was fabricated from the $Si_{0.2}Ge_{0.8}$/Si strained MQWs structure grown by using UHV-CVD. The structural properties of the $Si_{0.2}Ge_{0.8}$/Si strained MQWs were investigated using HR-XRD. The spectrum shows a higher order diffraction peak, indicating good layer periodicity. Specifically, recent advances in the dry etching of $Si_{0.2}Ge_{0.8}$/Si strained MQWs have been used to define pin photodiode active layer mesas. The low dark current is attributed to the excellent material quality. The spectral response spectra are dominated by the MQWs related transition corresponding to the transition of the electron- heavy hole sub-band (e-hh) and electron-light hole sub-band (e-lh). The large spectral range of 0.6 μm to 1.2 μm is due to photogeneration in the $Si_{0.2}Ge_{0.8}$/Si strained MQWs at long wavelength.

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REFERENCES

1. T. H. Loh, H. S. Nguyen, R. Murthy, M. B. Yu, W. Y. Loh, G. Q. Lo, N. Balasubramanian, D. L. Kwong, J. Wang and S. J. Lee, *Appl. Phys. Lett.* **91**, 73503 (2007).
2. C. Li, Q. Q. Yang, H. J. Wang, J. L. Zhu, L. P. Luo, J. Z. Yu, Q. M. Wang, Y. K. Li and J. M. Zhou, *Appl. Phys. Lett.* **77**, 157 (2000).
3. S. Famá, L. Colace, G. Masini, G. Assanto, and H.-C. Luan, *Appl. Phys. Lett.* **81**, 586 (2002).
4. S. K. Choi, J. M. Jang, W. G. Jung, J. Y. Kim, and S. D. Kim, *Electron. Mater. Lett.* **4**, 67 (2008)
5. M. Virgilio and G. Grosso, *J. Phys.* **18**, 1021 (2006).
6. R. People and J. C. Bean, *Appl. Phys. Lett.* **48**, 538 (1986). M. M. Rieger and P. Vogl, *Phys. Rev. B* **48**, 14276 (1993).
7. D. C. Houghton, G. C. Aers, S. R. Eric Yang, E. Wang, and N. L. Rowell, *Phys. Rev. Lett.* **75**, 866 (1995).
8. M. L. W. Thewalt, D. A. Harrison, C. F. Reinhart, and J. A. Wolk, *Phys. Rev. Lett.* **79**, 269 (1997).
9. R. People, *Phys. Rev. B* **32**, 1405(1985).
10. C. G. Van de Walle and R. Martin, *Phys. Rev. B* **34**, 5621(1986).
11. D. D. Cannon, J. F. Liu, D. T. Danielson, S. Jongthammanurak, U. U. Enuha, K. Wada, J. Michel, and L. C. Kimerling, *Appl. Phys. Lett.* **91**, 252111 (2007).
12. F. Y. Huang, and K. L. Wang, *Appl. Phys. Lett.* **69**, 2330 (1996).
13. B. Q. Sun, D. S. Jiang, X. D. Luo, Z. Y. Xu, Z. Pan, L. H. Li, and R. H. Wu, *Appl. Phys. Lett.* **76**, 2862 (2000).
14. S. L. Chuang, *Physics of Optoelectronic Devices*, Chap. 3, Wiley, New York (1995).
15. S. Richard, F. Aniel, G. Fishman, and N. Cavassilas, *J. Appl. Phys.* **94**, 1795 (2003).
16. N. Fraj, I. Saïdi, S. Ben Radhia, and K. Boujdaria, *J. Appl. Phys.* **102**, 53703 (2007).
17. S. Richard, F. Aniel, and G. Fishman, *Phys. Rev. B* **72**, 245316 (2005).
18. J. B. Posthill, R. A. Rudder, S. V. Hattangady, G. G. Fountain, and R. J. Markunas, *Appl. Phys. Lett.* **56**, 734 (1990).
19. J. C. Tang, K. Eberl, S. Zollner, and S. S. Iyer, *Appl. Phys. Lett.* **61**, 961 (1992).
20. H. J. Osten, M. C. Kim, K. Pressel, and P. Zaumseil, *J. Appl. Phys.* **80**, 6711 (1996).