Paper

CVD growth of high speed SiGe HBTs using SiH_4

Henry H. Radamson, Jan Grahn, and Gunnar Landgren

Abstract — The growth of high frequency HBT structures using silane-based epitaxy has been studied. The integrity of SiGe layers in the base and the control of the collector profile using As- or P-doping grown at 650°C have been investigated. The results showed that the growth rate of SiGe layers has a strong effect on the evolution of defect density in the structure. Furthermore, B-doped SiGe layers have a higher thermal stability compared to undoped layers. The analysis of the collector profiles showed a higher incorporation of P in silane-based epitaxy compared to As. Meanwhile, the growth of As- or P-doped layers on the patterned substrates suffered from a high loading effect demanding an accurate calibration.

Keywords — SiGe, epitaxy, HBT, silane.

1. Introduction

Silicon-germanium alloys are extendedly used for novel electronic devices such as heterojunction bipolar transistors (HBT) [1–5] and quantum well devices [6, 7] during recent years. The developments in the epitaxial technologies e.g. molecular beam epitaxy (MBE) [1, 3] and chemical vapor deposition (CVD) [8, 9] have provided the possibility to fabricate HBTs with high quality for high frequency application [1–5]. Both selective [10] and non-selective [4] growth processes were applied to integrate the SiGe epitaxial layers in device structures. In general, the base and the collector doping profile are the significant keys for high frequency behavior in HBTs. Selectively implanted collectors (SIC) are commonly used in high-speed medium breakdown voltage bipolar processes [11, 12]. A retrograded profile with $2\cdot10^{18}$ cm^{-3} has been used a collector layer in a HBT to obtain a cut-off frequency of 90 GHz [12]. The drawback with this technique is that a RTA step around 1000°C is needed to remove the implantation induced effects. This method may not be suitable for HBTs designed for cut-off frequency above 100 GHz since the annealing step degrades the quality of SiGe layer and can affect the performance of the device. A potentially superior method for fabricating a desired collector profile is to apply epitaxy for accurate control of the doping profile. In contrast to ion implantation, abrupt and defect-free buried layers can be grown. Low temperature epitaxy using both P and As as n-type dopants has been investigated by several authors [10, 13–15]. In these studies, the growth temperature for silane-based epitaxy has been in the range of $700 \div 800$°C and a fully controlled dopant profile was not achieved.

One of the important points for the manufacturing devices is the thermal stability of epitaxial layers. Any outdiffusion of the dopants from the base or the collector affects severely the high frequency performance behavior. Defects in a HBT structure decreases the carrier mobility causing a degradation of the device performance. It has been reported previously that SiGe layers grown at low temperature contain a higher defect density and the thermal stability was poor [16]. Thus, investigating the thermal stability can be used as a criteria to compare the defect density of the epi-layers. This can be used as a feed-back for optimizing the growth parameters to improve the quality of SiGe layer. In general, a high annealing temperature causes a partial relaxation which degrades the performance of the device. This limits the thermal budget of the process and must be considered as an important point in designing of the structure. One of the most powerful tools to detect a minor relaxation is high resolution X-ray diffraction. This technique is a non-destructive method which has been used to characterize and quantify the lattice misfit parallel and perpendicular to the growth direction. Thus the relaxation amount can be calculated from the derived misfit parameters.

Another point to be considered for the growth of HBT structures on patterned substrates is that the growth rate differs from the blanket wafers. This effect so-called loading effect can influence the Ge and dopant profiles requiring an accurate calibration in the case of the patterned substrates.

In this paper we present the growth of high frequency HBTs using silane-based epitaxy. We also propose a way to minimize the defect density in the SiGe base layer and a study of the incorporation of As or P in the Si collector layer at low temperature is presented.

2. Experimental details

Silicon-germanium samples were grown on blanket and patterned Si(100) substrates in Epsilon 2000 ASM CVD reactor. The reaction chamber is isolated from the clean room ambient by two nitrogen purged loadlocks. Si substrates were chemically cleaned and loaded for at least 30 min purging in the loadlock. *In-situ* cleaning were performed by baking at 1100°C for 2 min and 950°C for 20 min in H_2 in the reactor for the blanket and the patterned substrates, respectively. The epitaxial growth was carried out 650°C under atmospheric or reduced pressure (ATMP/RP) of 40 torr using SiH_4 as the silicon source. Gas sources of 10% Ge, 1% PH_3, 1% AsH_3 and 1% B_2H_6 in H_2 were used to grow the structures. The As, P and B concentrations in the epilayers were determined by secondary ion mass spectrometry (SIMS) and the Ge content by using X-ray diffraction. Boron concentration in SiGe was in the range of $5 \cdot 10^{18}$ to $1 \cdot 10^{21}$ cm^{-3} and the Ge amount 10÷20%. The concentration of As or P in the collector was in the range of $2 \cdot 10^{17} \div 2 \cdot 10^{18}$ cm^{-3}.

High resolution reciprocal lattice mapping (HRRLM) [17, 18] were obtained by using a Philips Expert high resolution, multi-reflection X-ray diffractometer with Cu $K_{\alpha 1}$ radiation. The equipment limits the angular divergence of both the incident and detected beams to 12 arcsec or less. A HRRLM can be obtained by performing several $\omega/2\Theta$ scans, i.e. rotation of both the sample and the detector with a ratio of 1:2 (ω: angle of incidence, 2Θ: the diffraction angle), for a range of incident angles $\omega + \Delta\omega$ as the starting value. In a HRRLM, an ω-scan probes the orientation variations for defined interplanar spacing, while an $\omega - 2\Theta$ scan probes interplanar spacing variations for the same orientation. The shape and position of the substrate and the layer peaks in HRRLM provide information about the misfit for both the directions parallel and perpendicular to the surface and thus relaxation amount can be calculated.

3. Results and discussions

3.1. The growth of collector layers

Figure 1 shows SIMS profiles of four samples with a buried As and P layer grown at 650°C (a) $6 \cdot 10^{17}$ and $2 \cdot 10^{18}$ cm^{-3} without and with 30 sccm HCl (selective mode) and (b) P-doped layer with concentration $1 \cdot 10^{18}$ cm^{-3}. Figure 1a shows an As segregation towards the undoped Si causing a background doping of $4 \div 7 \cdot 10^{17}$ cm^{-3}. Adding HCl to obtain a selective mode decreases the growth rate, however it has no effect on the As segregation. SIMS measurements from other series of As-doped samples show that the background doping in the Si undoped cap layer remains at the same level for buried layers with As concentration in range of $5 \cdot 10^{17}$ to $3 \cdot 10^{18}$ cm^{-3}. Our results showed that an annealing treatment of the buried layers slightly improves the profile of the samples in Fig. 1a, however, it is still far from acceptable. Figure 1b illustrates that the incorporation of P is higher in SiH_4-based epitaxy with a sharper leading edge. This makes P attractive for low temperature epitaxy, however, a low thermal budget is demanded in manufacturing of the device to avoid any out-diffusion of the P from the collector layer. The previous reports have not succeeded to illustrate a fully-controlled P-doped buried layers grown at reduced pressure using silane-based epitaxy. This is due to the applied growth temperature in the range of 700 ÷ 800°C which is considerable high temperature due to high P diffusivity.

Applying the low temperature epitaxy of As-doping in a bipolar transistor structure e.g. Si:As/i-Si/Si:B ($1 \cdot 10^{19}$ cm^{-3})/i-Si creates a problem in a larger scale.

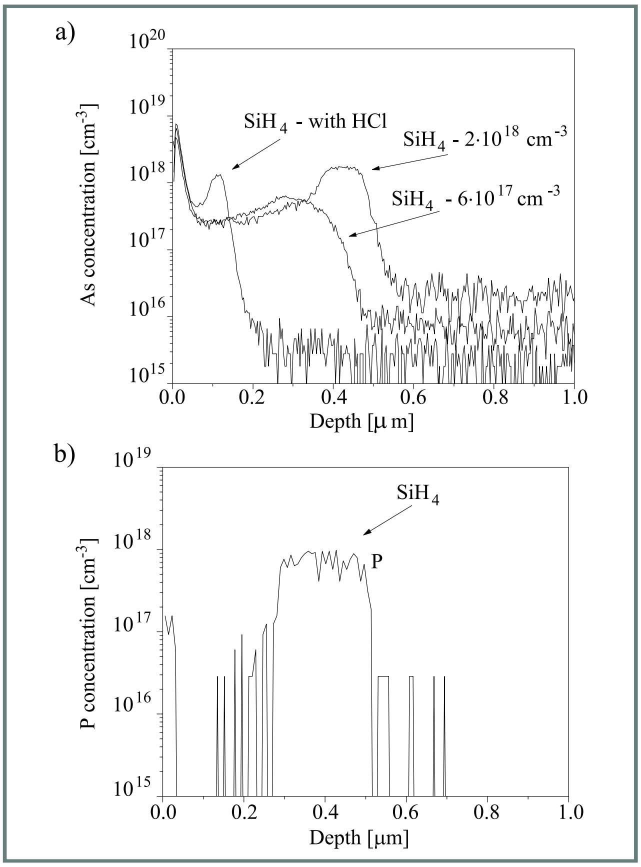

Fig. 1. SIMS profiles for buried n-type layers grown at 650°C, 40 torr (a) As-doped layers without and with HCl (selective mode), and (b) P-doped layer.

Figure 2 shows SIMS results of integrated As-doped layers with concentration of (a) $2 \cdot 10^{18}$ cm^{-3}, and (b) $2 \cdot 10^{17}$ cm^{-3}. The surface segregated As atoms incorporate strongly in the in the base layer due to presence of B impurities, creating a highly compensated layer. The device simulations show that the high n-type doping concentration (segregated atoms) in the base results in a punch-through condition for the low forward bias. These results indicate that As-doped layers using silane is not suitable for low temperature epitaxy of HBT structures. In addition, the growth of As-doped layers on patterned substrates showed a high loading effect of ~30% (a thinner collector layer) while P-doped layers showed a lower value of ~15%.

3.2. The growth of SiGe base layers

The other crucial point for the high frequency performance of HBTs is the base technology. In order to study the evolution of the defects in SiGe layers a series of undoped layers were grown at atmospheric and reduced pressure. Figure 3 shows Ge-content vs germane flux for different silane flux for samples grown at ATMP or RP. There is a sensitivity limitation for Mass-Flow-Controller which has also marked in the figure. The figure shows that a higher germane flux is required for RP-grown layers compared to ATMP-grown layers in order to obtain a certain Ge content. Our results

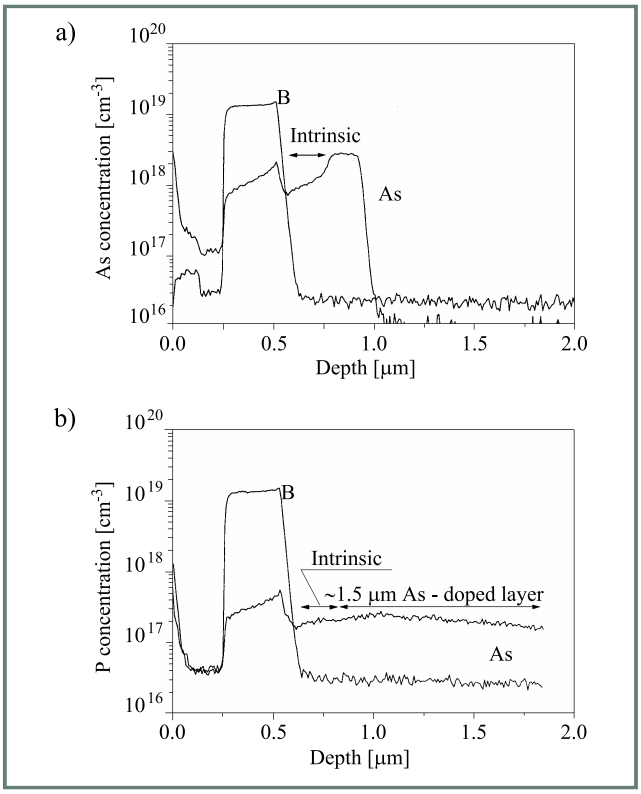

Fig. 2. SIMS profiles of As-doped layer with concentration of (a) $2 \cdot 10^{18}$ cm^{-3}, and (b) $2 \cdot 10^{17}$ cm^{-3} integrated in a bipolar transistor structure.

show also that the growth rate of RP-grown samples is higher than ATMP-grown for a specific Ge in above figure. This raises the question if the incorporation of defects is affected by growth rate and consequently could alter the

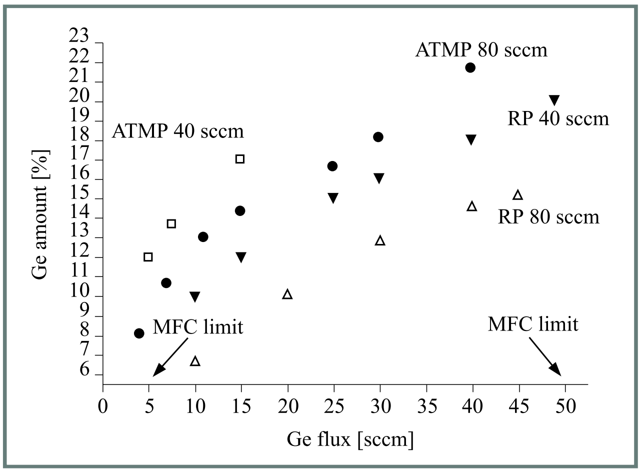

Fig. 3. A plot of Ge amount versus Ge flux for ATMP- and RP-grown samples with silane flux of 80 and 40 sccm.

thermal stability. To support this hypothesis we have grown SiGe samples at atmospheric and reduced pressure with different growth rates. By changing SiH_4 and GeH_4 fluxes but preserving the fraction of the fluxes, the growth rate could be modulated for a certain Ge amount. In order to compare the epitaxial growth quality of the epilayers we have

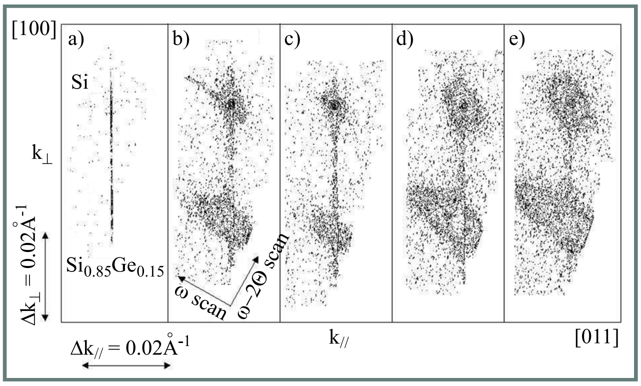

Fig. 4. High resolution reciprocal lattice mapping around the (311) reflection of a 1200 Å thick as-grown or RTA at 900°C for 10 s of $Si_{0.85}Ge_{0.15}$ layers with growth rate; (a) ÷ (d) explanation in the text.

studied the thermal stability of the samples by annealing at 900°C for 10 s. In this way, the samples with different defect density can be easily distinguished. Figure 4 shows HRRLM of $Si_{0.85}Ge_{0.15}$ RP-grown layers with a thickness of 1200 Å: (a) as-grown with growth rate of 156 Å/min, and annealed samples at 900°C for 10 s grown with growth rate of (b) same in (a), (c) 218 Å/min, (d) 368 Å/min, and (e) 392 Å/min. All the as-grown samples in Figs. 4b to 4e had an identical feature shown in Fig. 4a. The parallel-to-surface lattice mismatch for as-grown samples is zero to the accuracy of the measurements indicating that the layers were fully strained. However, all annealed samples in Figs. 4b to 4e show a mosaicity broadening in ω-direction which is an indication of a partial relaxation of SiGe layers. The amount of mosaicity broadening is an image of defect density of epi-layers. It is obvious that SiGe layer illustrated in Fig. 4c has a minimum defect density.

Figure 5 shows the growth rate versus Ge-content for RP- or ATMP-grown samples. In this investigation the samples were grown with the same thickness for a certain Ge concentration in the metastable region. HRRLM was performed to investigate the thermal stability of all samples in Fig. 5 similar shown in Fig. 4. A „×” mark in the figure show the samples with minimum defect density. These results indicate that the defect density in SiGe layers can be decreased by choosing an appropriate growth rate which varies depending on the Ge-content. These results show that the optimized growth rate is a parameter which must be considered in the integrity of SiGe layers for device applications.

Figure 6 shows HRRLM of ATMP-grown $Si_{0.87}Ge_{0.13}$ with 1200 Å thick (a) as-grown undoped layer, (b) sample in (a) was annealed at 900°C for 10 s, (c) B-doped with concentration of $1 \cdot 10^{19}$ cm^{-3}, (d) sample in (c) was annealed at 900°C for 10 s. The as-grown layers show no defects while the annealed layers show a mosaicity broadening indicating partial relaxation. The B-doped SiGe samples show a smaller mosaicity broadening in comparison with the undoped layers in the figure. In general, the boron atoms at substitutional sites induce a tensile

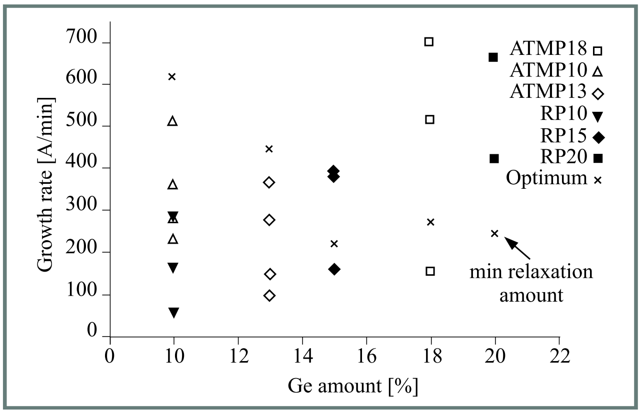

Fig. 5. A plot of growth rate versus Ge amount for ATMP- and RP-grown samples. „×” mark shows the samples with minimum defect.

strain with lattice contraction coefficient relative to silicon of $6.3 \pm 0.1 \cdot 10^{-24}$ cm^{-3}/atom [19] which counteract the strain induced by Ge atoms. This compensation effect results in a shift in the (100)-direction of the layer. This compensation effect in principle should increase the thermal stability of SiGe. However, the effects is negligible for boron concentration of $1 \cdot 10^{19}$ cm^{-3} and the tetragonal lattice strain induced by Ge atoms is dominant. The boron doping in SiGe is high causing a decrease in the density of the self-interstitials. This may act as an important factor for retarding the relaxation of SiGe layer since the activation energy for nucleation and formation of dislocations has been increased due to a lower defect density. This in turn may be responsible for the higher thermal stability of B-doped SiGe layers. HRRLMs showed that a defect-free SiGe layer with boron concentration of $5 \cdot 10^{20}$ cm^{-3} can be obtained. This value is close to the earlier reported value of $3 \cdot 10^{20}$ cm^{-3} for B-doped SiGe layer grown by MBE [20].

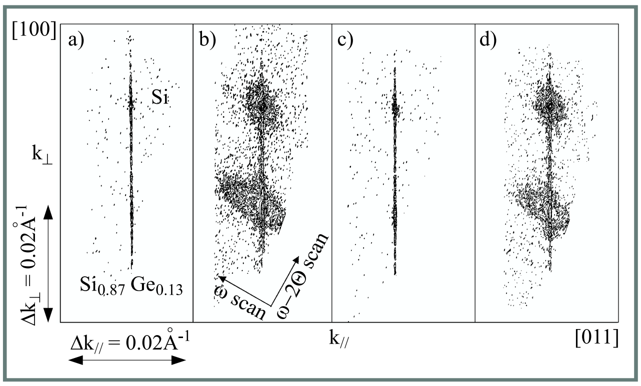

Fig. 6. High resolution reciprocal lattice mapping around the (311) reflection of a 1200 Å thick $Si_{0.87}Ge_{0.13}$ (a) undoped layer, (b) sample in (a) was RTA at 900°C for 10 s, (c) B-doped layer with concentration of $1 \cdot 10^{19}$ cm^{-3}, (d) sample in (c) was RTA at 900°C for 10 s.

4. Conclusions

P-doped buried layers grown at 650°C using silane as Si source shows abrupt profiles in contrary to As-doped layers which suffers from a high segregation. This makes P an attractive dopant for the growth of collector layers in HBTs. A high loading effect was observed in growth of As- and P-doped layers on the patterned substrates demanding an accurate calibration. The incorporation of defects in SiGe base layer depends strongly on the growth rate and an optimum point with minimum defect density can be obtained. B-doping in SiGe increases thermal stability in comparison with the undoped SiGe layers. Moreover, a defect-free SiGe B-doped layers with concentration $5 \cdot 10^{20}$ cm^{-3} has been obtained.

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References

[1] A. Schuppen, U. Erben, A. Gruhle, H. Kibbel, H. Schumacher, and U. König, „Enhanced SiGe heterojunction bipolar transistors with 160 GHz-f_{max}”, *IEEE*, vol. 1026, p. 743, 1995.

[2] A. Pruijmboom, D. Terpstra, C. E. Timmering, W. B. de Boer, M. J. J. Theunissen, J. W. Slotboom, R. J. E. Hueting, and J. J. E. W. Hageraats, „Selective-epitaxial base technology with 14 ps ECL-gate delay, for low power wide-band communication systems”, *IEEE*, vol. 1026, p. 747, 1995.

[3] A. Gruhle and A. Schueppen, „Recent advances with SiGe heterojunction bipolar transistors”, *Thin Solid Films*, vol. 294, p. 246, 1997.

[4] J. V. Grahn, H. Fosshaug, M. Jargelius, P. Jönsson, M. Linder, B. G. Malm, B. Mohadjeri, J. Pejnefors, H. H. Radamson, M. Sanden, Y.-B. Wang, G. Landgren, and M. Ösling, „A low-complexity 62 HHz f_T SiGe heterojunction bipolar transistor process using differential epitaxy and in situ phosphorous-doped poly-Si emmitter at very low thermal budget”, *Solid State Electron.*, vol. 44, p. 549, 2000.

[5] W. Klein and B.-U. H. Klepser, „75 GHz bipolar production technology for the 21st century”, in *Proc. ESSDERC'99*, 1999, p. 88.

[6] D.-X. Xu, G. D. Shen, M. Willander, and G. V. Hansson, „The properties of resonant transmission in triple-barrier/double-quantum-well heterostructures”, *J. Appl. Phys.*, vol. 71, p. 3859, 1992.

[7] A. Zaslavsky, K. R. Milkove, Y. H. Lee, B. Ferland, and T. O. Sedgwick, „Strain relaxation in silicon-germanium microstructures observed by resonant tunneling spectroscopy”, *Appl. Phys. Lett.*, vol. 67, p. 3921, 1995.

[8] W. B. de Boer and D. J. Meyer, „Low-temperature chemical vapor deposition of epitaxial Si and SiGe layers at atmospheric pressure”, *Appl. Phys. Lett.*, vol. 58, p. 1287, 1991.

[9] D. J. Meyer and T. I. Kamin, „The deposition of Si-Ge strained layers from GeH_4, SiH_2Cl_2, SiH_4 and Si_2H_6”, *Thin Solid Films*, vol. 222, p. 30, 1992.

[10] W. B. de Boer, D. Terpstra, and J. G. M. Van Berkuum, „Selective versus non-selective growth of Si and SiGe”, *Mat. Sci. Eng.*, vol. B67, p. 46, 1999.

[11] E. F. Crabbe, B. S. Meyerson, J. M. C. Stork, and D. L. Harame, „Vertical profile optimization of very high frequency epitaxial Si- and SiGe-based bipolar transistors", *IEDM Tech. Dig.*, p. 83, 1993.

[12] M. S. Peter, G. A. M. Hurkx, and C. E. Timmering, „Selectively-implanted collector profile optimization for high-speed vertical bipolar transistors", in *Proc. ESSDERC'97*, 1997, p. 308.

[13] T. O. Sedgwick, D. A. Grutzmacher, A. Zaslavsky, and V. P. Kesan, „Selective SiGe and heavily As doped Si deposited at low temperature by atmospheric pressure chemical vapor deposition", *J. Vac. Sci. Technol. B*, vol. 11, p. 1124, 1993.

[14] R. Bashir, A. E. Kabir, and P. Westrom, „Phosphorus and arsenic profile control for high performance epitaxial base bipolar junction devices", *Appl. Phys. Lett.*, vol. 75, p. 796, 1999.

[15] T. I. Kamins and D. Lefforge, „Control of n-type dopant transitions in low-temperature silicon epitaxy", *J. Electrochem. Soc.*, vol. 144, p. 674, 1997.

[16] H. H. Radamson, W.-X. Ni, and G. V. Hansson, „The role of low temperature growth defects for the stability of strained Si/SiGe heteroestructures", *Appl. Surf. Sci.*, vol. 102, p. 82, 1996.

[17] P. F. Fewster and N. L. Andrew, „Determining the lattice relaxation in semiconductor layer systems by X-ray diffraction", *J. Appl. Phys.*, vol. 74, p. 3121, 1993.

[18] P. van der Sluis, „High-resolution X-ray diffraction of epitaxial layers on vicinal semiconductor substrates", *Philips J. Res.*, vol. 47, p. 203, 1993.

[19] M. R. Sardela Jr., H. H. Radamson, J. O. Ekberg, J. E. Sundgren, and G. V. Hansson, „Growth, electrical properties and reciprocal lattice mapping characterization of heavily B-doped, highly-strained Si-MBE structures", *J. Cryst. Growth*, vol. 143, p. 184, 1994.

[20] H. H. Radamson, K. B. Joelsson, W.-X. Ni, L. Hultman, and G. V. Hansson, „Characterization of highly boron-doped Si, SiGe and Ge layers by high-resolution transmission electron microscopy", *J. Cryst. Growth*, vol. 157, p. 80, 1995.

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