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Uniaxial strain relaxation in He^+ ion implanted (110) oriented SiGe layers

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Uniaxially strained (011)Si is attractive for high performance *p*-channel metal oxide semiconductor field effect transistor devices due to the predicted high hole mobilities. Here, we demonstrate the realization of purely uniaxially relaxed (011) SiGe virtual substrates by He^+ ion implantation and thermal annealing. Perfect uniaxial relaxation is evidenced by precise ion channeling angular yield scan measurements and plan view transmission electron microscopy as predicted theoretically on the basis of the layer symmetry dependent dislocation dynamics. Strikingly, misfit dislocations propagate exclusively along the $[0\bar{1}1]$ direction in the (011) oriented crystal and, in contrast to (100)Si, no crosshatch is formed. We describe dislocation formation and propagation inducing strain relaxation of (011)SiGe and enlighten the differences to (100) oriented SiGe on Si. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3180279]

The application of strain is a well-known technique to increase carrier mobilities in silicon and thus to enhance the performance of metal oxide semiconductor field effect transistors (MOSFETs).[1] However, for (100) Si very high strain levels would be needed in order to meet the ITRS roadmap requirements for sub-45 nm MOSFETs.[2] A particular emphasis has been placed on the mobility improvement of the *p*-type MOS transistors since mobility for holes of unstrained (100) silicon is about three times lower than for electrons.[3] In addition, further hole mobility improvements are expected by the introduction of uniaxial strain.[4,5] Most recent simulations by Krishnamohan *et al.*[5] predict the largest enhancement of the hole mobilities and the drive currents by applying compressive uniaxial strain along the $[\bar{1}10]$ direction for (011) oriented Si. However, optimal enhancement of both electron and hole mobilities in (110) Si MOSFETs occurs for *tensile* strain and channel directions along [100].[6,7]

Up to now, *compressively* strained (011)Si has been produced *locally*, at the transistor level. *At the wafer level* (011) strained Si layers were realized only by Ge condensation.[8,9] In order to achieve *tensely* strained (011) Si at the substrate level, challenging epitaxial growth is needed to obtain nearly fully relaxed SiGe virtual substrates.[10,11]

In this letter we present a method to fabricate pure uniaxially relaxed (011) Si_xGe_{1-x} virtual substrates using He^+ ion implantation and subsequent annealing. So far, this method was only applied to (100)SiGe layers.[12,13] In that case, the dislocation dynamics governing strain/stress relaxation has a tetragonal symmetry thus inducing symmetrical biaxial relaxation. In contrast, asymmetric relaxation of SiGe{100} layers is only possible by reducing the tetragonal symmetry, for instance by patterning the layer into ⟨110⟩ oriented stripes.[14]

Another way to achieve asymmetric relaxation is to reduce the layer symmetry from tetragonal to orthorhombic by using a {110}Si layer orientation. Recently, asymmetric relaxation of strained {110}Si_xGe_{1-x} virtual substrates induced by thermal annealing was evidenced by Elfving *et al.*[15] using x-ray reciprocal space mapping. In addition, Moriyama *et al.*[9] reported asymmetric relaxation of strained {110}SiGe layers by the Ge condensation method. In the present letter, we will show that stress relaxation of strained {110}SiGe layers is not only asymmetric but even uniaxial.

50 nm thick $Si_{0.85}Ge_{0.15}$ layers were grown by reduced pressure chemical vapor deposition on 200 mm Si(011) and Si(001) wafers at 600 °C using growth kinetics data of Ref. 10. The SiGe layers were capped with 5 nm Si layers which may become tensely strained by plastic strain transfer during SiGe layers relaxation as demonstrated for the case of Si/SiGe(100) heterostructures.[13] Subsequently, (011) and (100) samples were implanted with He^+ ion fluences ranging from 7×10^{15} to 1.5×10^{16} cm^{-2}. The ion energies of 10 and 15 keV were chosen such that the mean ion range in the Si substrate, R_p, corresponds to a depth of 50 and 100 nm below the SiGe/Si interface, respectively.

Quantitative determination of the strain in thin relaxed heterostructures is a challenging task. X-ray diffraction has been shown to underestimate strain contributions of low misfit dislocation (MD) densities and thus to overestimate the asymmetry in patterned structures.[16] However, ion channeling angular yield scans provide absolute angles between various crystal directions and allow the deduction of the full strain tensor.

We performed ion channeling angular yield measurements of the Ge backscattering signal with a high-precision goniometer using 1.4 MeV He^+ ions at a scattering angle of 170°. For (011) samples, we have chosen angular scans through the [011] sample normal and the [010] direction along the (100) plane and, through the [011] and the inclined [111] directions along the $(0\bar{1}1)$ plane. Figure 1 shows the channeling angular yield scans of the Ge backscattering signal for a 50 nm thick SiGe (011) layer in the [111] and [010] directions for as grown and relaxed samples. The scan minima represent the absolute angles $\theta_{[010]}$ and $\theta_{[111]}$ be-

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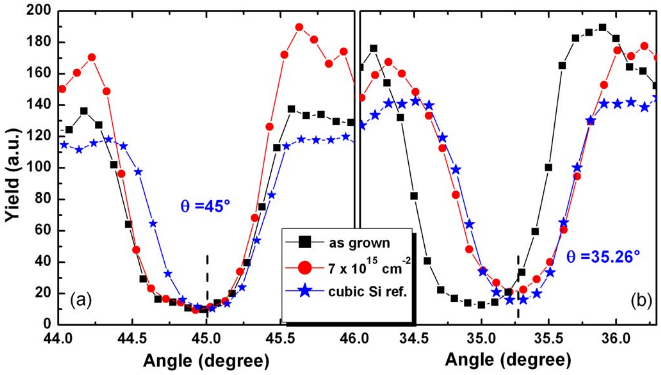

FIG. 1. (Color online) Angular channeling scans of as-grown and relaxed 50 nm thick (011) $Si_{0.85}Ge_{0.15}$ layers in (a) the [010] and (b) the [111] direction. The corresponding angles in a cubic Si crystal are shown for reference.

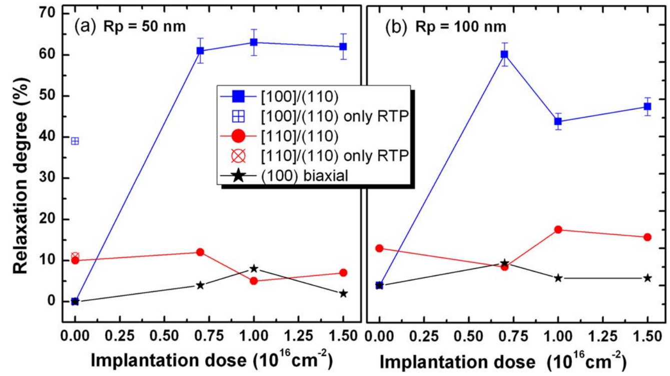

FIG. 2. (Color online) The relaxation degree of 50 nm thick (011) $Si_{0.85}Ge_{0.15}$ layers function of the He^+ implantation dose for (a) R_p =50 nm and (b) R_p=100 nm implantation depths (in the Si substrate). The biaxial relaxation degree of 50 nm thick (100) $Si_{0.85}Ge_{0.15}$ layers is shown for comparison.

tween the [011] sample normal and the [010] and [111] directions, respectively.

A systematic derivation and compilation of the relations between changes of angles between crystal directions and the accessible components of the strain tensor are presented elsewhere. Using for the orthorhombic (011) layer system and ([100], $[0\bar{1}1]$, [011]) as the coordinate directions, we relate the angle changes $\Delta\theta_{[010]}=\theta_{[010]}-\theta_{[010]}^{\mathrm{cub}}$ and $\Delta\theta_{[111]}=\theta_{[111]}-\theta_{[111]}^{\mathrm{cub}}$, respectively, where $\theta_{[010]}^{\mathrm{cub}}$ and $\theta_{[111]}^{\mathrm{cub}}$ are the corresponding angles in the cubic crystal, to the degrees of layer relaxation in the [100] and $[0\bar{1}1]$ directions as

$$R_{[100]}=1-[(3/\sqrt{2})(1+\rho_{[0\bar{1}1]})\Delta\theta_{[111]} - 2\rho_{[0\bar{1}1]}\Delta\theta_{[010]}]/[\varepsilon_0(1+\rho_{[100]}+\rho_{[0\bar{1}1]})],$$

$$R_{[0\bar{1}1]}=1-[2(1+\rho_{[100]})\Delta\theta_{[010]} - (3/\sqrt{2})\rho_{[100]}\Delta\theta_{[111]}]/[\varepsilon_0(1+\rho_{[100]}+\rho_{[0\bar{1}1]})].$$

Here the Poisson type ratios have the values $\rho_{[100]}=2C_{12}/(C_{11}+C_{12}+2C_{44})=0.3287$ and $\rho_{[0\bar{1}1]}=C_{11}+C_{12}-2C_{44})/(C_{11}+C_{12}+2C_{44})=0.1811$. The principal values of the strain tensor in the [100] and $[0\bar{1}1]$ directions of (011) the layer system, $\varepsilon_{[100]}$ and $\varepsilon_{[0-11]}$, are related to the corresponding relaxation degrees by

$$\varepsilon_{[100],[0\bar{1}1]}=x\cdot\varepsilon_0(1-R_{[100],[0\bar{1}1]}),$$

where ε_0 is the maximum strain defined by perfect epitaxial connection between the layers and the substrate and x denotes the Ge atomic content in the layer.

Measurements of the as grown (011) sample show angular shifts of $\Delta\theta_{[010]}=0.25°$ and $\Delta\theta_{[111]}=0.26°$, indicating lattice matched (pseudomorphic) growth, with $R_{[100]}^{(011)}=0\%$, in the [100] direction and an initial relaxation of $R_{[0\bar{1}1]}^{(011)}=10\%$ in the $[0\bar{1}1]$ direction. The relaxation degrees of the as grown, thermally relaxed and He^+ implanted and annealed samples are presented in Figs. 2(a) and 2(b). Thermal annealing at 850 °C for 10 min induces for nonimplanted (011)SiGe layers a degree of relaxation in the [100] direction of 34%, while no changes were measured for relaxation along $[0\bar{1}1]$.

He^+ ion implantation and annealing results in a significant enhancement of the $R_{[100]}^{(011)}$ relaxation degree. In the case of shallow implantation, i.e., R_p=50 nm, the relaxation degree saturates at a value of about 64% for implantation doses equal or superior to 7×10^{15} ions/cm^2 [see Fig. 2(a)]. For deeper implants, i.e., R_p=100 nm, the relaxation efficiency slightly decreases with increasing implantation dose. Relaxation is indeed maximal (64%) for a He^+ dose of 7×10^{15} cm^{-2} [see Fig. 2(b)]. Regarding the $[0\bar{1}1]$ direction, the (011)SiGe layer relaxation is independent of the implantation energy and dose, remaining constant at the "as grown" level, i.e., $R_{[0\bar{1}1]}^{(011)}\sim10\%$.

The results presented above provide clear evidence that (011)SiGe layer relaxation is purely uniaxial rather than only asymmetric, as reported in previous articles.[9,15] This observation is confirmed by the plan view transmission electron microscopy (PV-TEM) image shown in Fig. 3 where only one set of parallel MDs orientated along the $[0\bar{1}1]$ crystal direction is observed at the SiGe/Si interface. Regarding the crystalline quality, channeling measurements in the $[0\bar{1}1]$ normal direction revealed a minimum yield of only 3% for the as- grown material and 3.7% for the relaxed samples, indicating that the high crystal quality is maintained.

The as-grown 50 nm thick SiGe (100) samples were proved to be pseudomorphic. Earlier experiments showed that efficient biaxial relaxation was obtained for (100)SiGe layers with thicknesses exceeding 150 nm using a He^+ implantation dose of 7×10^{15} cm^{-2}.[12,14] As presented in Fig. 2

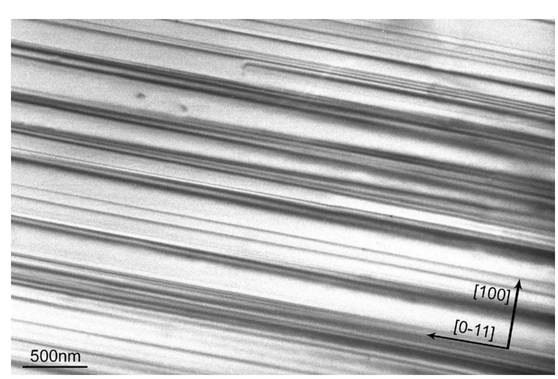

FIG. 3. PV-TEM of a 50 nm (110)$Si_{0.85}Ge_{0.15}$ layer after He implantation and annealing. Only parallel MDs along the $[0\bar{1}1]$ crystal direction is observed at the SiGe/Si interface indicating uniaxial strain relaxation in the [100] direction.

no strain relaxation is measured, within the experimental accuracy, for the (100)SiGe layers, independent of the process parameters in the investigated range.

To our understanding, strain/stress relaxation by He implantation and annealing is due to the generation of dislocation loops from overpressurized He filled cavities in the Si substrate below the relaxing SiGe layer. Gliding of these loops to the Si/SiGe interface and their spreading out through the SiGe layer results in the formation of a strain relaxing network of MDs at the SiGe/Si interface.[12] The general requirement for the relaxation of a SiGe layer is its shearing along those {111} glide planes which are oblique to the layer ("active glide planes"), induced by the extension of loops with $\langle 110 \rangle /2$ Burgers vectors oblique to the layer ("active loops").

In the case of {100}SiGe layers, shearing along the four active sets of {111} glide planes, with the same probabilities, results in the formation of two orthogonal sets of strain relaxing $\langle 110 \rangle$MDs of equal densities as traces of the active glide planes, thus inducing symmetrical biaxial relaxation. In contrast, in a (011)SiGe layer, for instance, the restriction of shearing to the two active (111) and $(\bar{1}11)$ glide planes oblique to the SiGe layer results in a restriction in the formation of MDs to the $[0\bar{1}1]$ direction. This implies a purely uniaxial relaxation of the SiGe layer in the [100] direction and a corresponding uniaxial straining of the top Si layer.

The symmetry of the layers and their associated dislocation dynamics can, however, not explain the difference in the relaxation efficiency of {100} and {110} SiGe layers of similar thickness. We attribute this difference to the anisotropy in the dependence of the critical thickness for strain relaxation on the elastic strain in the layer. There are two reasons for such anisotropy.

(1) At *given layer thickness*, the effective width of the active glide planes intersecting the SiGe layer from the SiGe interface to the surface depends on the layer orientation; it is larger for {110} than for {100} oriented layers.

(2) *At given strain* determined by the Ge content in the SiGe layer, the stress, representing the driving force for dislocation motion, depends on the layer orientation because of the elastic anisotropy; it is higher for {110} than for {100} layers.

Therefore, the critical thickness for relaxation, at given strain, is significantly smaller for {110} than for {100} layers. The 50 nm layer thickness considered in the present paper seems to be subcritical for {100} layers and is obviously supercritical for {110} layers.

In conclusion, we have experimentally confirmed the theoretical prediction of perfect uniaxial relaxation of (110)SiGe layers. Using high-precision ion channeling angular scans we studied the strain relaxation in SiGe/Si(110) heterostructures. The pure uniaxial strain relaxation was attributed to the reduced layer symmetry compared with the corresponding heterostructures on Si(100). Our results indicate that He^+ ion implantation and annealing is a suitable method for the fabrication of uniaxially relaxed (110)SiGe layers on large wafers. Moreover, strained Si grown on these substrates will fulfill the optimum condition for electron and hole mobility enhancement.

[1] E. A. Fitzgerald, Y.-H. Xie, M. L. Green, D. Brasen, A. R. Kortan, J. Michel, Y.-J. Mii, and B. E. Weir, Appl. Phys. Lett. **59**, 811 (1991).
[2] T. Ghani, M. Armstrong, C. Auth, M. Bost, P. Charvat, G. Glass, T. Hoffmann, K. Johnson, C. Kenyon, J. Klaus, B. McIntyre, K. Mistry, A. Murthy, J. Sandford, M. Silberstein, S. Sivakumar, P. Smith, K. Zawadzki, S. Thompson, and M. Bohr, Tech. Dig. - Int. Electron Devices Meet. **2003**, 978.
[3] S. Takagi, A. Toriumi, M. Iwase, and H. Tango, IEEE Trans. Electron Devices **41**, 2363 (1994).
[4] P. Packan, S. Cea, H. Deshpande, T. Ghani, M. Giles, O. Golonzka, M. Hattendorf, R. Kotlyar, K. Kuhn, A. Murthy, P. Ranade, L. Shifren, C. Weber, and K. Zawadzki, Tech. Dig. - Int. Electron Devices Meet. **2008**, 63.
[5] T. Krishnamohan, D. Kim, T.V. Dinh, A. Pham, B. Meinerzhagen, C. Jungemann, and K. Saraswat, Tech. Dig. - Int. Electron Devices Meet. **2008**, 899.
[6] T. Mizuno, N. Sugiyama, T. Tezuka, and T. Takagi, IEEE Electron Device Lett. **24**, 266 (2003).
[7] H. Irie, K. Kita, K. Kyuno, and A. Toriumi, Tech. Dig. - Int. Electron Devices Meet. **2004**, 225.
[8] T. Mizuno, N. Sugiyama, T. Tezuka, Y. Moriyama, S. Nakaharai, and S. Takagi, Tech. Dig. VLSI Symp. **2003**, 97.
[9] Y. Moriyama, N. Hirashita, N. Sugiyama, and S. Takagi, Thin Solid Films **517**, 285 (2008).
[10] V. Destefanis, J. M. Hartmann, M. Hopstaken, V. Delaye, and D. Bensahel, Semicond. Sci. Technol. **23**, 105018 (2008).
[11] V. Destefanis, J. M. Hartmann, A. Abbadie, A. M. Papon, and T. Billon, J. Cryst. Growth **311**, 1070 (2009).
[12] H. Trinkaus, B. Holländer, St. Rongen, S. Mantl, H.-J. Herzog, J. Kuchenbecker, and T. Hackbarth, Appl. Phys. Lett. **76**, 3552 (2000).
[13] D. Buca, B. Holländer, H. Trinkaus, S. Mantl, R. Carius, R. Loo, M. Caymax, and H. Schaefer, Appl. Phys. Lett. **85**, 2499 (2004).
[14] D. Buca, B. Holländer, S. Feste, St. Lenk, H. Trinkaus, S. Mantl, R. Loo, and M. Caymax, Appl. Phys. Lett. **90**, 032108 (2007).
[15] A. Elfving, M. Zhao, G. V. Hansson, and W.-X. Ni, Appl. Phys. Lett. **89**, 181901 (2006).
[16] H. Trinkaus, D. Buca, B. Holländer, S. Mantl, A. R. Khan, and G. Bauer, *Conference Digest of the Third International Silicon Germanium Technology and Devices Meeting* (IEEE, New York, 2006), p. 120, May 15–May 17.