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Optimal geometry for GeSi/Si super-lattice structure RBS investigation

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Abstract

He Rutherford Backscattering Spectrometry (RBS) depth resolution is limited by detector energy resolution, He ion energy loss in the sample material, energy straggling and geometry of the experiment. Examples of experimental results are shown for GeSi/Si super-lattice investigation for random and channeling RBS analysis in different geometry of detection. Different detection geometries are discussed and compared. For the case of axial channeling experiments, the incident beam direction is restricted to typically low index axes only. It is shown how to improve the depth resolution and sensitivity in this type of experiments. Effects of sample material as well as contributions from different physical processes including multiple scattering effects are discussed in some detail.

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1. Introduction

The interest in $Si_{1-x}Ge_xSi$ multiple quantum-well (MQW) structures is growing since the first demonstration of an inter-sub-band infrared normally incident detector [1]. Usually the growth of $Si_{1-x}Ge_xSi$ super-lattices is associated with nucleation of strain-relieving defects if the layer thickness is above a critical value and a defect-free layer is found only near the MQW-substrate interface. These non-uniform defect distributions are related to strain distributions as a function of depth. He RBS-channeling (RBS: Rutherford backscaterring spectrometry) is often used to measure strain and Ge concentration profiles in epitaxial structures. However these type of measurements are difficult for thin $Si_{1-x}Ge_xSi$ super-lattices as the He RBS depth resolution is limited by detector resolution. In order to improve RBS depth resolution usually glancing angles of detection are used [2–4]. The substantial improvement in depth resolution is limited by the multiple scattering effects if the scattering angle used is far away from the optimum value of 180° [4].

In this work it is shown how to combine He RBS channeling in $Si_{1-x}Ge_xSi$ super-lattices with

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glancing angle geometry and with the scattering angle not far away from optimum value of 180° in order to improve the depth resolution of $Si_{1-x}Ge_xSi$ super-lattice strain measurement.

2. Experimental

A 2 MeV He ion beam was used for RBS channeling analysis of $Si_{1-x}Ge_xSi$ super-lattices grown on (1 0 0) Si substrate by the MBE method. The sample was a triple thin $Si_{1-x}Ge_x$ alloy layer between thin Si layers. The Ge atomic concentration in the alloy layer was $x = 0.3$ and the thickness of this layer was about 10 nm. The Si layer thickness was about 40 nm.

The sample was positioned on a goniometer sample holder and different axial and planar channeling directions were aligned with the horizontal ion beam in order to investigate many experimental arrangements. The sample was mounted in such a way that the rotation around the vertical axis was mostly used and the other rotation (horizontal axis) were used for small corrections only. Initially the sample was oriented normal to the ion beam and the axial channeling was observed in $\langle 1\,0\,0\rangle$ direction. For the next measurements the goniometer was rotated to about 45° or 54.75° around vertical axis in order to observe ion channeling in $\langle 1\,1\,0\rangle$ or $\langle 1\,1\,1\rangle$ axis. In order to observe channeling in the $\langle 1\,1\,0\rangle$ axial direction the sample was initially rotated around the surface normal until the (1 1 0) plane (cleavage direction) was at a 45° angle to the horizontal plane. Similarly for the channeling in the $\langle 1\,1\,1\rangle$ axial direction the same (1 1 0) plane was oriented horizontally. The Si surface barrier detector with 2 mm slits limiting scattering angle range to about 2.5° was positioned at 160° or 112° scattering angle in the same horizontal plane and it was used to collect channelled and random RBS spectra. This arrangement is known as the IBM geometry.

3. Results and discussion

Fig. 1 shows $\langle 1\,0\,0\rangle$ axial channeling spectrum and random spectrum collected near $\langle 1\,0\,0\rangle$ direction with the detector at 160°, this geometry will be referred to as standard geometry. It is clear that the Ge RBS signal is well reduced in the channeling direction to about 3.5% of the random level, indicating good epitaxy. The Si signal in the same sample region shows a reduction to about 4.0%. The depth resolution, as expected for this geometry, is not good and the individual Ge layers are not resolved.

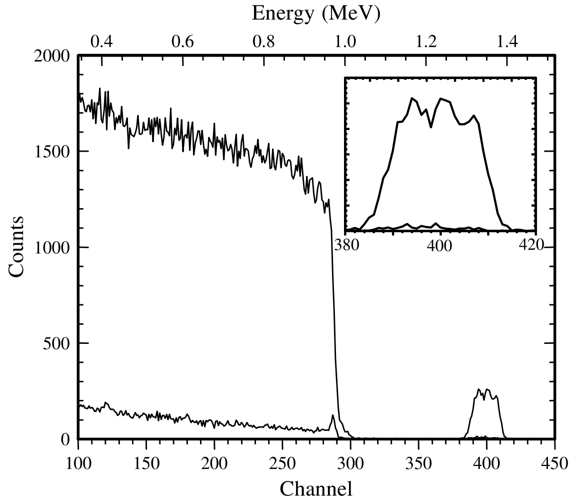

Fig. 1. 2 MeV He RBS spectra from super-lattice structure in random and channeling $\langle 1\,0\,0\rangle$ direction near sample normal with detector in 160° scattering angle.

Fig. 2 shows typical glancing angle detector (112° scattering angle) spectra in the same $\langle 1\,0\,0\rangle$ channeling position as in Fig. 1. The depth resolution is substantially improved in this case as the ion exit path is elongated 2.5 times compared to the standard geometry. The Ge and Si signals are well reduced in channeling mode to about 3.5% in comparison to random orientation again indicating good epitaxy.

Fig. 3 compares the $\langle 1\,1\,0\rangle$ axial channeling spectrum with the associated random spectrum near the $\langle 1\,1\,0\rangle$ axis position. The sample is rotated 45° around vertical axis and the detector is positioned at 160° position. In this case the ion exit path is elongated 2.22 times compared to the standard geometry and the sample normal to the beam. Furthermore the incident ion path in the sample is increased 1.41 times due to 45° rotation

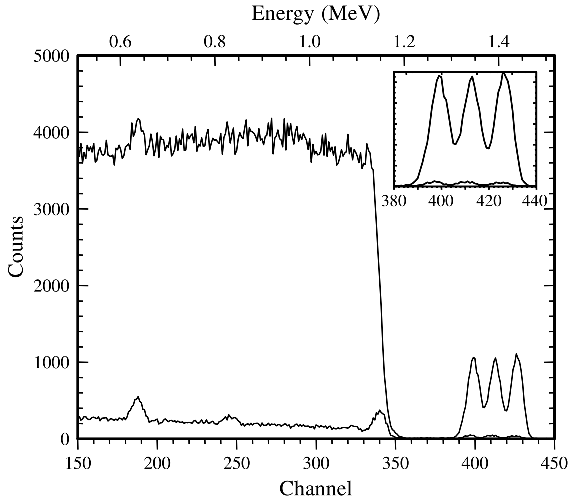

Fig. 2. 2 MeV He RBS spectra from super-lattice structure in random and channeling $\langle 100 \rangle$ direction near sample normal with detector in 112° scattering angle.

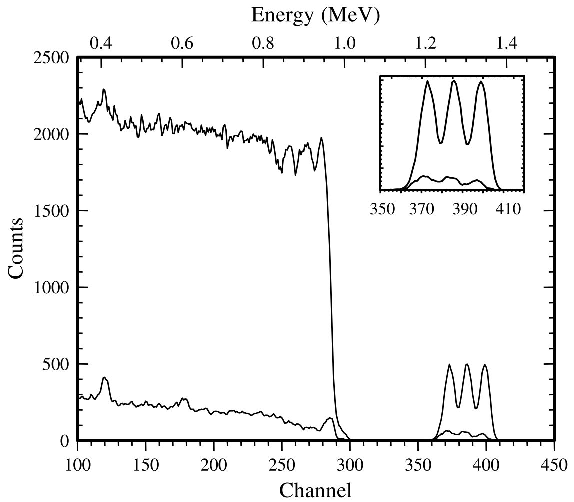

Fig. 3. 2 MeV He RBS spectra from super-lattice structure in random and channeling $\langle 110 \rangle$ direction near 45° to the sample normal with detector in 160° scattering angle.

of the sample around the vertical axis. The resulting depth scale is very close to the results shown on Fig. 2 and the separation of the Ge individual layer signals in random case is similar to the random case separation in Fig. 2. In the channeling mode the individual Ge peaks show clearly different counts indicating that a rapid dechanneling is taking place in the super-lattice region. The first Ge layer shows channeling to random ratio $\chi = 8.6\%$, the second layer 11.9% and the third layer 13.9%. This suggests that $\langle 110 \rangle$ channels are distorted in the super-lattice region and ion channeling is substantially reduced. It should be pointed out that the results shown on Figs. 1 and 2 are for $\langle 100 \rangle$ axial channels and that in this case the $\langle 100 \rangle$ channel is not distorted by strain related to Si–Ge lattice mismatch.

Fig. 4 show the results of axial channeling in $\langle 111 \rangle$ direction and the random spectrum recorded near this orientation. In this case the sample is rotated 54.75° around vertical axis and the ion exit path is elongated about 3.57 times compared to the standard geometry. The incident ion path in the sample is increased about 1.73 times due to 54.75° rotation of the sample around the vertical axis. This geometry provides very good depth resolution and all three Ge peaks are well separated. In the channeling mode the individual Ge peaks show again different areas indicating that rapid dechanneling is taking place in the super-lattice region. The first (near the surface) Ge layer shows the channeling to random ratio 14.8%, the second layer 19.7% and the third layer 26.1%. This suggests that $\langle 111 \rangle$ channels are distorted in the

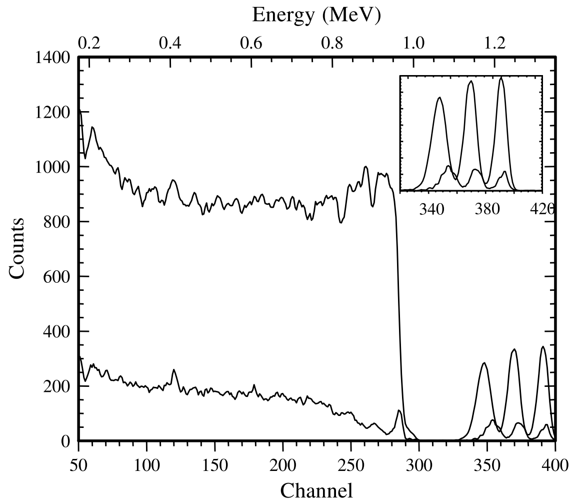

Fig. 4. 2 MeV He RBS spectra from super-lattice structure in random and channeling $\langle 111 \rangle$ direction near 54.75° to the sample normal with detector in 160° scattering angle.

super-lattice region and the ion channeling is substantially reduced. The channeling to random ratio in the Si substrate near interface is about 19%, substantially lower than in the deepest Ge layer. This observation suggests that direct scattering is observed in Ge sub-layers [5]. It must be pointed out that $\langle 111 \rangle$ channels in comparison with $\langle 110 \rangle$ channels have 20% smaller critical angle and the channeling in this direction is very sensitive to the ion channel distortion related to the lattice mismatch strain in this structure. This orientation is very good for crystal quality analysis with high depth resolution because the $\langle 111 \rangle$ channeling is very sensitive to lattice distortion and in this geometry the best depth resolution is obtained. It should be pointed out that in this geometry (160° scattering angle) the multiple scattering process in the sample material is not substantially reducing the depth resolution.

In comparison, in the geometry used for the typical glancing angle analysis (data shown on Fig. 2 for scattering angle = 112°) the same multiple scattering contribution will in effect produce three times higher energy variation due to three times stronger angular dependence of RBS kinematic factor for this scattering angle.

Fig. 5 shows the Ge and Si angular scans (integrated yield over the $Si_{1-x}Ge_xSi$ super-lattice layer) through the $\langle 111 \rangle$ axis in the (1 1 0) plane, as a function of sample rotation from $\langle 100 \rangle$ axis (normal to the sample surface). As expected the

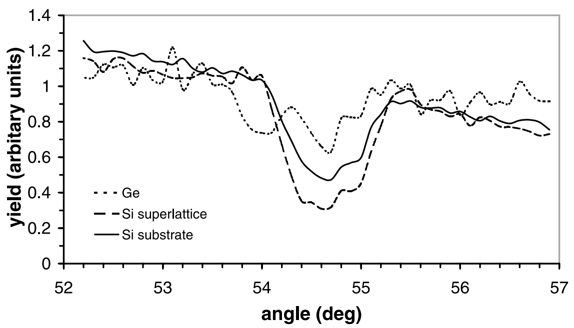

Fig. 5. 2 MeV He RBS angular scans in (1 1 0) plane near $\langle 111 \rangle$ axis from super-lattice structure (Ge and Si signal). Ion beam is about 54.75° to the sample normal and the detector in 160° scattering angle.

$\langle 111 \rangle$ axial channeling dips for Si in the substrate and in $Si_{1-x}Ge_xSi$ super-lattice are located very close to the angle of 54.75° from $\langle 100 \rangle$ axis. The FWHM of Si dips in the substrate and in the super-lattice are about 0.9° in agreement with known data for 2 MeV He channeling in $\langle 111 \rangle$ direction [2].

The Ge angular scan shows two narrow dips, one near 54.75° and the second at 54.0°. These two dips can be treated as one broad dip (FWHM about 1°) with little peak in the middle of it. This double dip is most likely an effect of ion beam steering in this distorted super-lattice structure [6]. The $Si_{1-x}Ge_xSi$ super-lattice used in this experiment has a period of 50 nm in a direction normal to the surface. In the direction of the $\langle 111 \rangle$ axis used for channeling the period will be about 87 nm. This is almost the period of natural channeling oscillations in $\langle 111 \rangle$ axial channel estimated as 60–80 nm and within a range of expected planar channeling oscillations in (1 1 0) plane: 80–100 nm [2,7,8]. In this case a resonance effect takes place and so called resonance dechanneling is observed. It is difficult to estimate resonance dechanneling quantitatively but it is very strong indication of periodic lattice tetragonal distortion with a period close to channeling oscillation. It should be pointed out that the ion steering and resonance dechanneling are not affecting study of tetragonal distortion in much thinner Si/Ge structures studied previously by Feldman and others [9–11]. Our case is more complex as the ion steering and resonance dechanneling effects are very strong and difficult to separate.

4. Conclusions

The proposed geometry for 2 MeV He RBS channeling in $\langle 111 \rangle$ axial direction offer the best depth resolution for analysis of $Si_{1-x}Ge_xSi$ super-lattice grown on (1 0 0) Si substrate. The Ge RBS signal from individual 10 nm thick $Si_{1-x}Ge_x$ layers can be well resolved and the channeling can be investigated in each layer separately. The channeling in $\langle 111 \rangle$ axis is very sensitive to channel distortion and it can be used to estimate tetragonal distortion in the individual $Si_{1-x}Ge_x$ layers.

The proposed experimental geometry provides all benefits of glancing angle detection without substantial reduction of depth resolution related to multiple scattering.

The depth of analysis can be extended, because in the proposed geometry (160° scattering angle) the mass separation in RBS is improved in comparison with typical glancing angle detection.

References

[1] R.P.G. Karunasiri, J.S. Park, K.L. Wang, Appl. Phys. Lett. 59 (1991) 2588.

[2] M.L. Swanson, in: J.R. Tesmer, J.W. Mayer (Eds.), Handbook of Modern Ion Beam Materials Analysis, Materials Research Society, Pittsburgh, Pennsylvania, 1995, Chapter 10.

[3] O.A. Mironov, P.J. Phillips, E.H.C. Parker, M.G. Dowsett, N.P. Barradas, C. Jeynes, M. Mironov, V.P. Gnezdilov, V. Ushakov, V.V. Eremenko, Thin Solid Films 306 (1997) 307.

[4] N.P. Barradas, C. Jeynes, O.A. Mironov, P.J. Phillips, E.H.C. Parker, Nucl. Instr. and Meth. B 139 (1998) 239.

[5] L.S. Wielunski, S. Hashimoto, W.M. Gibson, Nucl. Instr. and Meth. B 13 (1986) 61.

[6] M. Nagaki, T. Narusawa, A. Hiraki, T. Saitoh, M. Kubo, Thin Solid Films 369 (2000) 143.

[7] L. Wielunski, D. Wielunska, G. Della Mea, A. Turos, Nucl. Instr. and Meth. B 168 (1980) 323.

[8] D. Wielunska, L. Wielunski, A. Turos, Phys. Status Solidi A 67 (1981) 413.

[9] L.C. Feldman, J. Bevk, B.A. Davidson, H.-J. Gossmann, J.P. Mannaerts, Phys. Rev. Lett. 59 (1987) 664.

[10] A.T. Fiory, J.C. Bean, L.C. Feldman, I.K. Robinson, J. Appl. Phys. 56 (1984) 1227.

[11] B.A. Davidson, L.C. Feldman, J. Bevk, J.P. Mannaerts, Appl. Phys. Lett. 50 (1987) 135.