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Thickness Dependences of Stress, Poisson's Ratio and Longitudinal Optical Phonon Lifetime in Ultrathin Strained-Silicon-on-Insulator

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Abstract

Using linearized radial polarization of the incident 364 nm light, we obtained strained Si-on-insulator (SSOI) Raman spectra with clear domination of the forbidden transverse optical (TO) phonon band over the allowed longitudinal (LO) one. An increase in the LO and TO phonon Raman band strain-induced downshifts and a decrease in their ratio with a decrease in the SSOI thickness (*H*) down to ~10 nm were observed. This indicates an increase in strain and a decrease in the Poisson's ratio. At *H* < 10 nm, LO phonon confinement and reduction of the phonon lifetime are observed.

1. Introduction

Ultrathin strained Si-on-insulator (SSOI) with the enhanced electron mobility is attractive for the field-effect-transistor fabrication. A decrease in SSOI thickness (*H*) leads to size effects in elastic and phonon properties, which in their turn influence electron mobility and other important parameters. Effects like free-surface relaxation and surface tension influencing Young's modulus and Poisson's ratio were observed in ultrathin Si structures. A variety of studies reached two opposite results. Some works showed that the elastic modulus increased as the size was scaled down to nanometers [1], while others showed that the reverse was true [2]. It is important to study the size-induced changes in SSOI elastic properties using Raman scattering with a linearized radial polarization of the incident light [3], which allows detecting forbidden TO phonon and, therefore, to quantitatively determine SSOI strain and Poisson's ratio as we show in this paper. It is also important to study SSOI phonon confinement (PC) and related effects taking place at *H* < 10 nm. As we recently showed, the main size effect in the high-quality-SOI nanofilm (NF) and nanowire (NW) Raman spectra (RS) appeared to be a size-inversely-proportional homogeneous Raman band broadening due to phonon boundary scattering (PBS), phonon lifetime and mean free path being determined [4,5]. It is important to find similar data for SSOI.

2. Experimental

(001)-oriented 50 nm thick commercially available SOITEC SSOI substrates on 145 nm thick buried oxide (BOX) layers/Si substrates were used (Fig. 1). Then H was decreased using the repeated processes of the oxidation with the H_2SO_4 and H_2O_2 mixture followed by the etching in HF. Raman measurement was done using a Nanofinder-30 system (Tokyo instruments) equipped with a 364 nm Ar^+ laser corresponding to the resonant Raman enhancement and small (10-15 nm) penetration depth of light in Si. We used an Echelle grating working in the 65th order and, therefore, providing a high spectral resolution ~0.6 cm^{-1}. Bulk Si Raman band with the full width at half-maximum (FWHM) ~2.9 cm^{-1} was obtained.

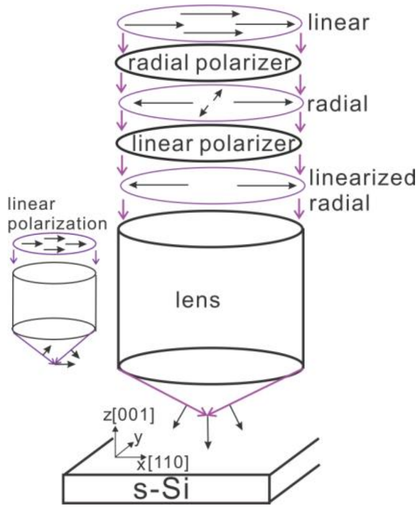

Fig. 1. Conversion of linear polarization to linearized radial one resulting in *z*-component enhancement and *y*-component suppression after focusing. Inset shows focusing of light with linear polarization.

In this work, we utilize enhancement of the SSOI TO phonon Raman signal using a radial polarizer in combination with linear one and a high N.A. lens enhancing z-polarized component in the focused light and suppressing the allowed LO phonon band [3]. Laser linear polarization was converted to the radial one using a 12-sector quartz radial polarizer (Photonic Lattice Inc.). 1.4 N.A. oil-immersion objective lens with 100x magnification was used for laser light focusing and RS collection.

Figure 1 shows conversion of the linear polarization to the radial one, then to the linearized radial one and, finally, to the *z*-polarization in the lens focus [3]. No *z*-component is observed in the focus of the x-polarized light with no radial polarizer (inset in Fig. 1).

3. Results

Figure 2 shows RS taken from the same area of 20 nm thick SSOI in two polarization configurations: a) with the incident light linearized radial polarization parallel to the *x* axis and the scattered light linear polarization parallel to the *y* axis; b) with the same incident light polarization and the scattered light polarization parallel to the *y* axis. The spectrum in Fig. 2a displays the allowed LO phonon

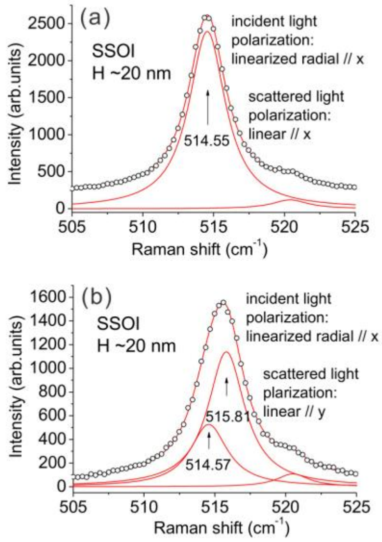

Fig.2. Allowed LO phonon Raman band at 514.55 cm^{-1} (a) and enhanced forbidden TO phonon band at 515.8 cm^{-1} (b) observed in different polarization configurations.

Raman band at ~514.55 cm^{-1} (the same as observed in the polarization configuration with both incident and scattered lights polarized parallel to the *x* axis (*xx*) or the y axis (*yy*)) and a weak band from Si substrate. The spectrum in Fig. 2b displays TO phonon band at ~515.8 cm^{-1} dominating over the significantly suppressed singlet phonon band.

Figure 3 shows *H* dependence of the Raman shifts of both LO (circles) and TO (squares) phonons. A slight decrease in the Raman shift with a decrease in *H* is observed for both phonons. This is an indication of an increase in the tensile strain, which is associated with the fact that the SSOI bottom is strained more than the SSOI top due to the free surface strain relaxation. While SSOI thinning, less strained top layers are removed but more strained bottom layers remain. The *H* dependence of the strain-induced Raman shifts of singlet LO and doublet TO phonons $\Delta\omega_s/\Delta\omega_d$ is shown in the same figure.

Figure 4 shows good agreement between Poisson's ratio ν extracted from $\Delta\omega_s/\Delta\omega_d$ experimental data (scatters) and ν deduced from calculations based on the semi-continuum atomistic lattice model (line) [6]. The model is taking into account a contractive relaxation of few surface layers with the relaxation coefficient $k = 0.8$ [6].

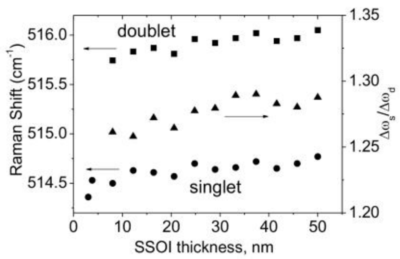

Fig.3. Thickness dependencies of singlet LO (circles) and doublet TO (squares) phonon Raman shifts and that of their strain-induced shifts ratio $\Delta\omega_s/\Delta\omega_d$ (triangles).

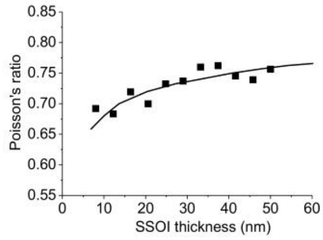

Fig.4. Thickness dependence of experimental (scatters) and theoretical [6] (line) Poisson's ratio of SSOI

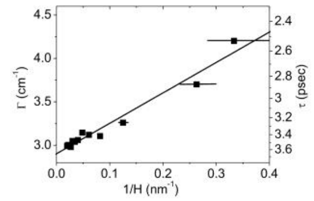

Fig.5. Experimental SSOI $\Gamma(1/H)$ dependence (scatters) and its linear fitting.

RS of SSOI with H < 10 nm display size-induced LO phonon band broadening compared to 50 nm thick SSOI. Fitting of 3 nm thick SSOI Raman band with modified Richter-Campbell-Fauchet model [4,5] reveals damping value $\Gamma \sim 4.2$ cm^{-1}, which is significantly larger than $\Gamma \sim 3$ cm^{-1} for 50 nm thick SSOI. This corresponds to size-induced phonon lifetime reduction from ~3.6 to ~2.5 psec. Experimental dependence $\Gamma(1/H)$ fits linear function $\Gamma = \Gamma_{bulk}\,(1 + \Lambda_{bulk}/(2H))$ (Fig. 5) giving LO phonon mean free path $\Lambda_{bulk} \sim 2.3$ nm assuming PBS origin of the effect. Correspondingly, the phonon mean free path Λ varies from 1.6 nm in 3nm SSOI to 2.3 nm in 50 nm thick SSOI. PC-induced asymmetric Raman band broadening ~0.3 appeared to be much smaller than the PBS-induced one.

3. Conclusions

We studied RS of SSOI with different *H*. For 10 – 50 nm thick SSOI, we measured both LO and TO phonon Raman bands using linearized radial polarization of the incident light and observed an increase in the strain-induced band downshift with a decrease in *H*, which indicates stronger strain in the SSOI bottom layers. From $\Delta\omega_s/\Delta\omega_d$ ratio, we obtained dependence of the Poisson's ratio on the SSOI thickness, which is in agreement with theory assuming a contraction surface relaxation. For H < 10 nm, we observed size effect on the LO phonon Raman band, which is mainly determined by PBS causing a *H*-inversely-proportional symmetric band broadening.

Acknowledgements

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References

[1] J.Wang, Q.Huang, H.Yu, Solid State Comm.. **145** (2008) 351

[2] X.Li, T.Ono, Y.Wang, M.Esashi, Appl.Phys.Lett. **83** (2003) 3081

[3] V. Poborchii, T. Tada, and T. Kanayama, Jap. J. Appl. Phys. **51** (2012) 078002

[4] V. Poborchii, T. Tada, Y. Morita and T. Kanayama, Appl. Phys. Lett., **103** (2013) 153104

[5] V. Poborchii, T. Tada, Y. Morita, S. Migita, T. Kanayama, and P. I. Geshev, *Extended Abstracts of the 2013 International Conference on Solid State Devices and Materials* (2013) 608

[6] J-H. Zhang, Q.-An Huang1, H. Yu and J. Wang, J. Phys. D: Appl. Phys. **42** (2009) 045409