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Electron and Acoustic Phonon Confinement in Ultrathin-Body Ge on Insulator

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Abstract

Recent findings show significant enhancement of both the 488nm-excitation Raman signal and the electron mobility as ultrathin-body Ge-on-insulator (UTB GeOI) thickness (T_{GeOI}) scaling below 13nm [1,2]. These phenomena could be attributed to a quantum size effect causing a change in the Ge energy band structure. Here, we study the characteristics of electron and acoustic phonon confinement in UTB GeOI with T_{GeOI} = 1 – 20 nm. We observe electron band gap enlargement with a decrease in T_{GeOI} and extract E_1 exciton transverse effective mass value ~ 0.07 m_0. Another size effect is the GeOI absorption enhancement associated with the increase in the electron density of states (DOS). For T_{GeOI} < 5 nm, the $E_1(T_{GeOI})$ dependence suggests the influence of size-induced changes in the electron-phonon interaction on the E_1 gap . This idea is supported by low-frequency Raman spectroscopy of GeOI confined acoustic phonons showing a significant change in acoustic phonon spectrum at T_{GeOI} < 5 nm,

1. Introduction

High mobility Ge-on-insulator (GeOI) structures provide significant advantages in ultra-scale MOS devices such as the reduced junction leakage, the decreased parasitic capacitance, and the better short-channel immunity. Recently, high quality (001)-oriented UTB GeOI structures with precise thickness control down to few nm have been fabricated with the advanced layer transfer technology called Hetero-Layer-Lift-Off (HELLO) [1-3]. We observed a clear 488 nm (2.54 eV) excitation Raman intensity enhancement as well as a significant electron mobility enhancement in UTB GeOI with thickness T_{GeOI} < 13 nm [1,2]. These phenomena can be attributed to size-induced changes in Ge band structure. Thus, a detailed study of size effects influencing UTB GeOI band structure is required. Here, we investigate the optical property of UTB Ge on glass to verify the effects of electron and acoustic phonon confinement.

2. Experimental and Theoretical Methods

We fabricated UTB GeOI with T_{GeOI} = 1-20 nm on 50 μm thick transparent SiO_2 substrates for investigation of the optical properties. To evaluate Ge layer thickness, we selectively etched Ge layer by H_2O_2-based solution down to the Al_2O_3 surface and measured the depth of the formed trench by atomic force microscopy (AFM) (Fig. 1a).

Optical reflection and transmission spectra of GeOI and bulk Ge were measured using CRAIC micro-spectrometer. Xe lamp light was used in the 300 – 800 nm range while D_2 lamp was utilized in the 250 – 320 nm range. Al mirror was used as a reflectance reference. To extract quantum confinement effects, we compared GeOI experimental spectra with GeOI spectra calculated using optical constants of bulk Ge similar to the Si-on-oxide spectra calculation [4]. Figure 1b shows experimental and calculated reflection spectra of bulk Ge. E_1 and $E_1+\Delta_1$ peaks originate from the direct electron transitions along the Λ ([111]) direction of the Ge Brillouin zone (BZ). E_2 peak is due to the transitions at the X-point of BZ ([100] direction) while the E'_0 peak is associated with transitions near the Γ-point.

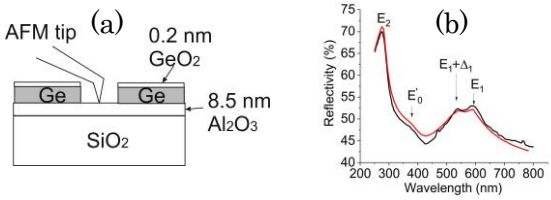

Fig. 1 Cross-section view of the GeOI sample with the illustration of the GeOI thickness measurement using AFM (a); experimental (black) and calculated (red) reflection spectra of bulk Ge (b).

Raman spectra of GeOI were measured using Nanofinder 30 Raman/AFM system (Tokyo Instruments Inc.) equipped with the 561 nm wavelength laser and a set of volume Bragg grating notch filters. Calculation of acoustic phonon Raman spectra was done using photo-elastic model (PEM) [5].

3. Results

Figure 2a shows experimental reflection spectra of GeOI and bulk Ge. E_1 and $E_1+\Delta_1$ peaks display a blue shift with a decrease in T_{GeOI} as expected for the band gap enlargement due to electron confinement. However, one can see a slight red shift of 17.8 nm thick GeOI peak compared to that of bulk Ge due to light interference in the Ge layer. The interference effect is clearly presented in the theoretical GeOI reflection spectra calculated with bulk Ge optical constant excluding any electron confinement effect (Fig. 2b).

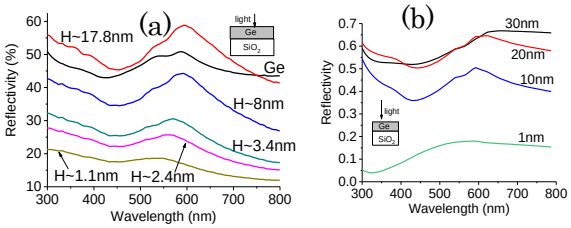

Fig. 2. Experimental reflection spectra of GeOI and bulk Ge (a); theoretical reflection spectra of GeOI calculated using bulk Ge optical constants.

For correct extraction of the quantum confinement effect, we compared experimental and calculated absorption spectra. We measured GeOI reflection (R) and transmission (T) spectra at the light incidence from the substrate side and obtained absorption A = 100% - R-T (Fig. 3a). Such measurement geometry is beneficial for the GeOI absorption enhancement compared to the geometry with the light incidence from the Ge layer side that is favourable for the reflection enhancement due to high Ge/air dielectric contrast, with the transmission being equal in both geometries. Figure 3b shows experimental (black) and calculated with bulk Ge optical constants (red) absorption spectra for GeOI with T_{GeOI} ~ 17.8 nm and ~2.4 nm. A clear blue shift is observed for the experimental 2.4 nm thick GeOI absorption bands compared to the theoretical ones while the shift is much weaker for the 17.8 nm thick GeOI. It is important that the experimental absorption increases compared to the theoretical one. This can be associated with a size-induced density-of-states (DOS) increase.

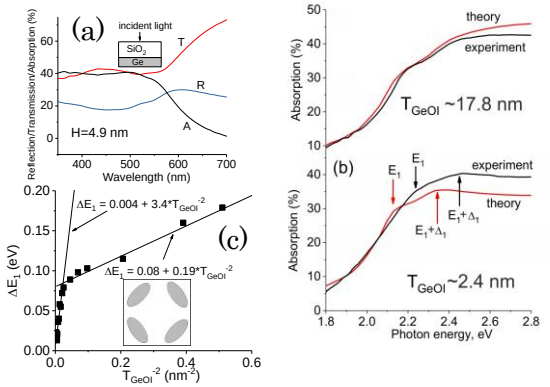

Fig. 3. a) Transmission, reflection and absorption spectra of 4.9 nm thick GeOI; b) experimental and theoretical absorption spectra of 17.8 nm and 2.4 nm thick GeOI. Calculation was made using bulk Ge optical constants; c) $\Delta E_1(T_{GeOI}^{-2})$ dependence of GeOI (squares) and its linear fitting (lines)

The E_1 absorption feature has an excitonic origin. The confinement-induced band gap enlargement is $\Delta E_1 = \hbar^2(\pi/T_{GeOI})^2/2m$, where $\hbar$ is the reduced Plank's constant and m is the reduce mass of the exciton. According to this model, the energy shift should display a linear dependence on T_{GeOI}^{-2}. Figure 3c displays the dependence of the measured ΔE_1 on T_{GeOI}^{-2}. The dependence displays two parts with different slopes. For T_{GeOI} > 5 nm, the slope reveals the exciton mass $m \sim 0.07m_0$, the projection of the 2D E_1 exciton on the (001) plane being taken into account (inset in Fig. 3c). The exciton is very heavy along the Λ or [111] direction while it is rather light in the (111) plane with the transverse mass $m_\perp \sim 0.045m_0$, the value close to the observed $0.07m_0$ confirming the quantum confinement origin of the E_1 band blue shift for T_{GeOI} > 5 nm. A decrease in the slope of the $\Delta E_1(T_{GeOI}^{2})$ dependence for T_{GeOI} < 5 nm (Fig. 3c) suggests that a size effect different from the electron confinement occurs. This can be a size effect in the electron-phonon interaction. Fig. 4a shows experimental and calculated (PEM) Raman spectra of GeOI confined acoustic phonons. For T_{GeOI} > 5 nm, theory reasonably agrees with experiment when the longitudinal sound velocity of bulk Ge 4.81x10^5 cm/sec is used, 0.2 nm GeO_2 and 8.5 nm Al_2O_3 layers being considered. A sound velocity reduction is required to reach agreement with experiment for T_{GeOI} ~ 5 nm,. With further decrease in T_{GeOI}, no agreement between theory and experiment was obtained using PEM, probably, due to dispersionless phonons generated by the oxide-layer-induced surface disorder. Dependence of the dominant experimental acoustic phonon band Raman shift on $1/T_{GeOI}$ (Fig. 4b) shows deviation from the confinement-induced linear dependence at T_{GeOI} < 5 nm.

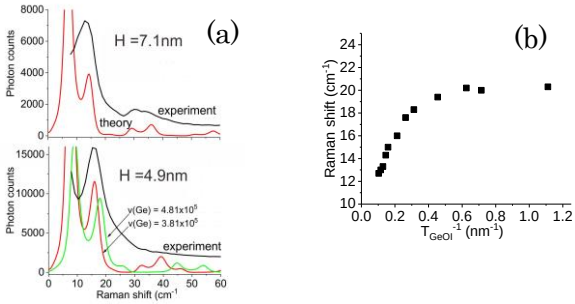

Fig. 4. a) experimental (black) and theoretical (red and green)) Raman spectra of 7.1 nm and 4.9 nm thick GeOI. Ge layer sound velocity v(Ge) = 4.81x10^5 cm/sec like in bulk Ge was used in calculation for T_{GeOI} = 7.1 nm while v(Ge) = 4.81x10^5 cm/sec (green) and v(Ge) = 3.81x10^5 cm/sec (red) for T_{GeOI} = 4.9 nm; b) dependence of the dominant experimental acoustic phonon band Raman shift on $1/T_{GeOI}$.

Electron-phonon interaction influences the E_1 band: the lower the average phonon frequency, the stronger the contribution of acoustic phonons to the E_1 band position. Recently, it was shown that the contribution of acoustic phonons to the E_1 band of SOI increases with decreasing SOI thickness [6]. The change in the slope in the $\Delta E_1(T_{GeOI}^{-2})$ dependence in Fig. 3c can be explained by the decrease in the average frequency of GeOI acoustic phonons and enhancement of their contribution to the E_1 band for $T_{GeOI} \leq 5$ nm, dispersionless phonons playing an important role.

3. Conclusions

GeOI electron and acoustic phonon confinement are studied. E_1 band gap and DOS increase are detected with a decrease in T_{GeOI} explaining the GeOI Raman enhancement [1]. The E_1 exciton transverse mass of ~ 0.07 m_0 was extracted from the $\Delta E_1(T_{GeOI}^{-2})$ dependence. The slope decrease in this dependence for T_{GeOI} < 5 nm is, probably, caused by the size-induced change in the electron-phonon interaction. Acoustic phonon Raman spectra support this. GeOI E_2 and E'_0 gaps study is in progress to clarify effects responsible for the electron mobility enhancement.

Acknowledgements

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