Phonon-softening in Germanium by Free Carrier Accumulation

-Experimental Distinction between Impurity and Free Carrier Effect-

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[Introduction] Heavy acceptor doping in Ge is known to change the peak position and width of the LO-phonon Raman peak[1]. Theoretically, the origin of peak shift and broadening of Raman peak is considered to be discrete-continuum Fano-type interaction between phonon scattering and electron excitation[2]. However, it has been quite hard to experimentally distinguish the effects of free carrier from impurity itself. In this work, we have investigated these effects individually by using low- and high-doped p-type Germanium-on-insulator (GeOI) substrate.

[Experiment] 60-nm-thick p-GeOI and 40-nm-thick p^+-type GeOI substrate were used. According to resistivity measurements, the acceptor concentrations were ~1x10^{15} /cm^3 and ~1x10^{19} /cm^3, respectively. After thinning each GeOI substrate by wet etching process with $HCl+H_2O_2+H_2O$ solution, junction-less FETs were fabricated with these GeOI substrates by the same process as ref.[2]. Then, Raman measurement was performed with applying the back-gate bias, as shown in **Fig. 1**. Argon ion laser with λ=488 nm was used as excitation lasers. Here, it should be noted that, by applying the back-gate bias to JL-FET during Raman measurement, only the free carrier density in p- or p^+-Ge can be controlled while the impurity concentration is fixed. Namely, the free carrier effect on Raman-peak can be extracted.

[Results and Discussion] **Fig. 2** shows the back-gate bias dependence of Raman peak position and drain current in 20-nm-thick low-doped p-GeOI. To avoid the temperature increase of the sample by Joule heat, Raman and I-V measurement were conducted individually. Then, the red-shift of Raman peak was clearly observed by applying the negative back-gate bias. It is indicated that the phonon softening can occur even in low-doped Ge by accumulating holes, although the Raman peak shift due to Fano interference has been reported only in heavily-doped Ge. In other words, the impurity itself is considered not to attribute to the phonon softening so much. On the other hand, **Fig. 3** shows the back-gate bias dependence of Raman peak positions in p^+-GeOI substrates with various Ge thicknesses. The phonon softening by hole accumulation is also the case in all p^+-GeOI substrates. Furthermore, it should be noted that the blue-shift of Raman peak was observed with decreasing Ge thickness, and that this trend is different from that in low-doped p-GeOI which was explained to be attributed to the strain enhancement[3]. It means that the origin of blue-shift is resulted from the free carrier effect rather than strain one. Since the amount of Raman shift by Fano interference is determined by the energy range of the inter-valence-band transition, energy range modulation by quantum confinement effect is considered be the origin of the Ge thickness dependence of Raman peak position in p^+-GeOI. In summary, by using GeOI substrate and back-gate bias, it is experimentally demonstrated that the phonon softening in Ge can be caused by free carrier accumulation as theoretically expected[1], and that the amount of softening is strongly affected by the electronic structure modified by confinement as well.

[Reference] [1] F. Cerdeira. et al., Phys. Rev. B **5**, 1440 (1972). [2] D.-D. Zhao et al., Jpn. J. Appl. Phys. **51**, 04DA03 (2012). [3] C. H. Lee et al., Appl. Phys. Lett. **102**, 232107 (2013).

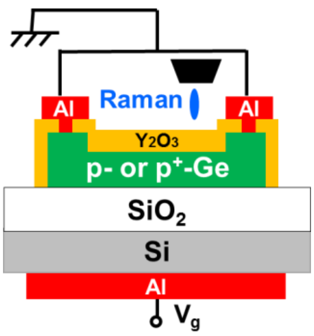

Fig. 1 The schematic image of Raman measurement with back gate bias.

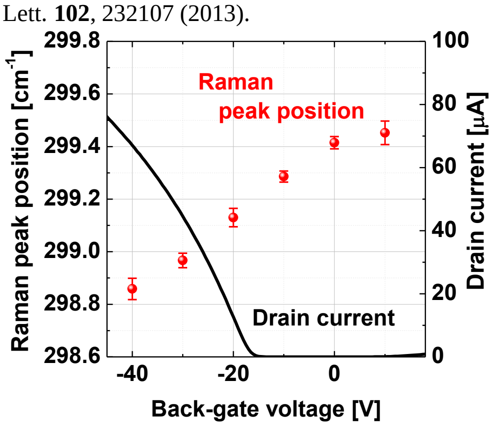

Fig. 2 The back-gate bias dependence of Raman peak position and drain current of 20-nm-thick p-GeOI.

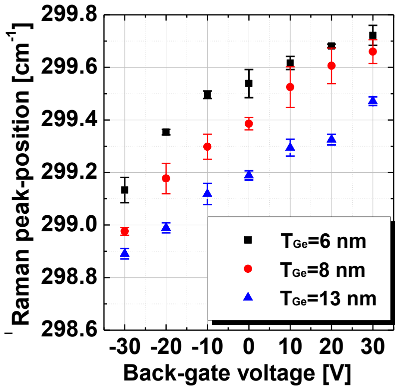

Fig. 3 Raman peak position of p^+-GeOI with various Ge thicknesses as a function of back-gate bias.