CARRIER-DENSITY DEPENDENT ENERGY BAND-GAP AND PHONON FREQUENCY IN GE

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Dopant atoms in nano-devices should be countable and dopant atom discreteness cannot be ignored. The energy band- gap and phonon frequency in a semiconductor are, however, believed to be material-specific constants except quantum size effects, though apparent band-gap narrowing and phonon-softening in doped semiconductors have been experimentally reported and theoretically discussed [1, 2]. On the other hand, in doped semiconductors, it is experimentally difficult to differentiate dopant effects from free carrier ones. Thus, the objective of this study is to separate the dopant from free carrier effects on “intrinsic properties in Ge” experimentally, and to discuss about their physical implications.

Lightly doped GeOI wafers were used. Bottom gated FETs were fabricated with Y_2O_3 passivation on the top surface [3], as shown in Fig. 1. Thanks to this sample structure, PL and Raman investigations were successfully carried out for a same sample as a function of the bottom gate bias, from the top surface without being masked by the top gate metal.

PL peak positions in Ge n- and p-FETs are shown in Fig. 2, together with drain currents. In Ge, we can luckily detect the direct energy band-gap PL, because the direct energy band-gap at *Γ*-point in Ge is very close to the indirect one, and this experiment enables us to differentiate the dopant from free carrier (hole) effects under a fixed dopant density. PL peak position shifts to a lower energy with the increase of free carriers in both polarities. This is clear evidence that PL peak shifts only by changing free carrier density in the channel.

Fig. 3 shows the Raman shift in the same sample as that in Fig. 2. The Raman shift to the lower wave number is clearly seen in the negative back bias (hole accumulation), while it does not change in the positive one (electron accumulation). This is in a striking contrast to PL results. Furthermore, FWHM of the Raman spectrum even in the hole accumulation does not change at all (data not shown). This indicates that the shift is not due to the Fano-effect, which has been employed for explaining the Raman shift in heavily doped semiconductors [2].

The results presented here are direct evidences that the *rigid phonon and rigid energy band-gap* models are violated anyway in highly carrier accumulated Ge. Hole density effects are intuitively and simply understandable by considering the covalent bonding of two-atoms system [4].

The free carrier effects on the phonon and electronic structures of Ge with a fixed dopant density have been experimentally studied. Although such free-carrier effects have not been considered so far, “beyond rigid bond and rigid energy band-gap” views will become more important in smaller devices.

[1] D. B. M. Klaassen et al., SSE 35, 125 (1992). [2] F. Cerdeira. et al., PRB 8, 4734 (1973). [3] S. Kabuyanagi et al., APEX 8, 051301 (2015). [4] S. Kabuyanagi et al., Tech. Dig. IEDM (2015).

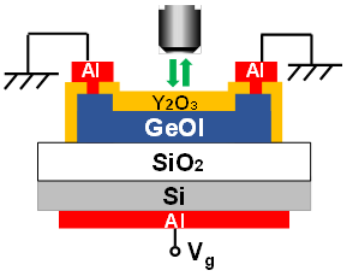

Fig. 1 *Schematic image of the Ge sample structure and optical measurement system. The excitation lasers with λ=488 nm for Raman and with λ=457 nm for PL were used. GeOI thickness was ~11 nm and with N_A<1x10^{15}cm^{-3}.*

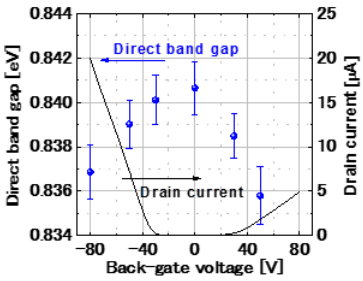

Fig. 2 *PL Peak position and drain current as a function of back-bias voltage. Under applied back bias condition, PL peaks are decreased for both positive and negative biases.*

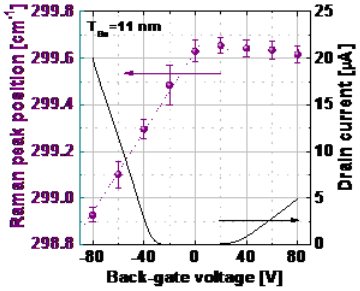

Fig. 3 *Raman shift position and drain current as a function of back-bias voltage. By applying negative back bias Raman peak is decreased, while by applying positive back bias, the Raman shift is not changed.*