Observation of Pronounced Effect of Compressive Strain on Room-Temperature Transport Properties of Two-Dimensional Hole Gas in a Strained Ge Quantum Well

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Strong effect of compressive strain on room-temperature transport properties of two-dimensional hole gas (2DHG) confined in a strained Ge quantum well (QW) of SiGe heterostructures was observed. By increasing compressive strain in the Ge QW the pronounced increase of 2DHG gas density and conductivity were obtained in the full range of researched strain variation. At the same time the increase of 2DHG drift mobility was observed until a certain high strain in the Ge QW, but showed slight reduction under higher strain. Nevertheless the monotonous enhancement of 2DHG conductivity was observed.

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Recent progress in research on room-temperature (RT) electronic properties of holes in compressive strained Ge quantum well (QW) epilayers of SiGe heterostructures clearly shows superiority of the two-dimensional hole gas (2DHG) in comparison with the 2D electron gas (2DEG) in a tensile strained Si QW of the SiGe heterostructures. Indeed, very high RT 2DHG mobilities in the range of $2400-3100\,\mathrm{cm^2\,V^{-1}\,s^{-1}}$ with carrier densities of $5-41 \times 10^{11}\,\mathrm{cm^{-2}}$ have become routinely achieved in (20–25)-nm-thick Ge QWs grown by low energy plasma enhanced chemical vapor deposition (LEPE-CVD) and solid-source molecular beam epitaxy (SS-MBE) techniques.[1–5] On the other hand, the 2DEG mobilities in the range from $2600\,\mathrm{cm^2\,V^{-1}\,s^{-1}}$ (with carrier density of $2 \times 10^{11}\,\mathrm{cm^{-2}}$) up to $2900\,\mathrm{cm^2\,V^{-1}\,s^{-1}}$ ($1 \times 10^{11}\,\mathrm{cm^{-2}}$) were reported so far.[6–8] These results open the real possibility for realization of future high performance symmetrical complementary metal oxide semiconductor (CMOS) circuits with strained p-Ge and n-Si channels on Si(001) or SOI(001) substrates. The SiGe heterostructures with strained Si or Ge QW epilayers are grown on underlying Si(001) or SOI(001) substrates via implementation of intermediate relaxed SiGe buffers whose energy bandgap is larger than that of the QW layer. Due to this they allow both bandgap and strain engineering using silicon technology, which opens the possibilities for further enhancement of holes and electrons in SiGe heterostructures and optimization of their electronic properties for various device applications. It is predicted theoretically that compressive strain in the Ge layer can significantly enhance the hole mobility due to the reduction of the effective mass and the suppression of the interband phonon scattering by the splitting of light-hole and heavy-hole bands.[9] But only recently, the effect of compressive strain on low-temperature transport properties of 2DHG in a Ge QW was studied experimentally.[10,11] However, at RT, where this material system is used for field-effect transistor (FET) device operation, it has not been researched experimentally yet. Only RT Hall mobility, which is an average of all parallel conducting carriers in multilayer SiGe heterostructure, as a function of compressive strain up to 1.9% in a Ge QW was reported recently.[10] Moreover the previous research clearly demonstrated the absence of correlation between low-temperature and RT transport properties of 2DHG in some Ge QWs of SiGe heterostructures.[12]

In this work, the pronounced effect of compressive strain on RT transport properties of 2DHG in the Ge QW was observed. The mismatch strain in the Ge QW layer was changed in the wide range from 1.3 up to 2.9% by varying the Ge composition, y, in the relaxed $\mathrm{Si_{1-y}Ge_y}$ buffer layer from 0.7 to 0.33. Since the maximum strain of 4.2% is possible to be achieved in a SiGe heterostructure by the growth of fully strained Ge layer on bulk Si(001) substrate, we researched here ~70% range of possible variation of compressive strain in Ge QW of SiGe heterostructures.

The p-type modulation doped (MOD) $\mathrm{Si/Si_{1-y}Ge_y/Ge/Si_{1-y}Ge_{1-y}/Si(001)}$ heterostructures were grown by combination of gas-source MBE (GS-MBE) and SS-MBE techniques. The $\mathrm{Si_{1-y}Ge_{1-y}}$ relaxed buffers were grown by GS-MBE at 700 °C on Si(001) substrates. They consist of 2 μm SiGe layer with graded Ge content and 1 μm SiGe layer with uniform Ge content. After the growth, the substrates were removed from the GS-MBE chamber and planarized by chemical mechanical polishing (CMP) in order to produce smooth surface and to minimize the effect of $\mathrm{Si_{1-y}Ge_y/Si(001)}$ virtual substrate (VS) surface roughness on mobility of holes in the Ge QW. Later, the cleaned samples were loaded in the SS-MBE system for the following growth of MOD structures. Two set of samples with normal and inverted doping structures were grown. The samples with normal doping consist of a 50 nm $\mathrm{Si_{1-y}Ge_y}$ buffer layer, a 7.5 nm compressive strain Ge QW layer for 2DHG, a 10 nm $\mathrm{Si_{1-y}Ge_y}$ spacer layer, a 10 nm boron doped $\mathrm{Si_{1-y}Ge_y}$ supply layer, a 30 nm $\mathrm{Si_{1-y}Ge_y}$ cap layer and a 3 nm Si cap layer on the surface. The samples with inverted doping are different from the previous ones by the location of boron doped $\mathrm{Si_{1-y}Ge_y}$ supply layer underneath the Ge QW layer only. All epilayers were grown at 300 °C in order to increase the metastable critical thickness of Ge QW layer and consequently to prevent the early relaxation of it at higher compressive strain.

Samples for RT magnetotransport measurements were fabricated in mesa-etched Hall-bar device geometry. Ohmic contacts were formed by evaporating AuGa. The Hall mobility and sheet carrier density of the samples were obtained by a combination of resistivity and Hall effect measurements. In order to separately find out the transport properties of various carriers existing in multilayer semiconductor heterostructures, the technique of maximum-entropy mobility spectrum analysis (ME-MSA), where the magnetic-field dependencies of magnetoresistance and Hall resistance are measured and analyzed, was applied.[13] A typical obtained mobility spectrum of the samples consists

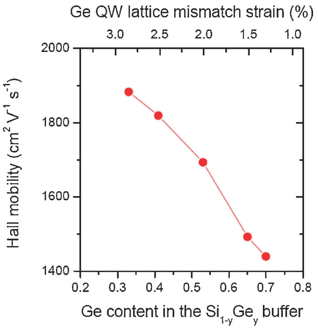

Fig. 1. Room-temperature Hall mobility of p-type MOD Si/$Si_{1-y}Ge_y$/Ge/$Si_{1-y}Ge_y$/Si(001) heterostructures as function of Ge content, y, in the relaxed $Si_{1-y}Ge_y$ buffer and lattice mismatch between compressive strained Ge QW epilayer and relaxed $Si_{1-y}Ge_y$ buffer layer. The data for samples with inverted doping and strain 2.5 and 2.9%, and samples with normal doping and strain 1.3–2.0% are shown.

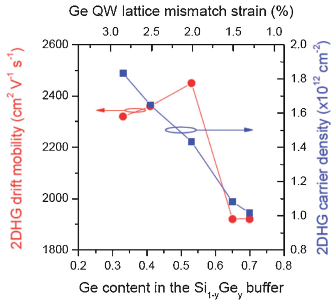

Fig. 2. Room-temperature drift mobility and carrier density of 2DHG existing in the Ge QW of p-type MOD Si/$Si_{1-y}Ge_y$/Ge/$Si_{1-y}Ge_y$/Si(001) heterostructures as function of Ge content, y, in the relaxed $Si_{1-y}Ge_y$ buffer and lattice mismatch between compressive strained Ge QW epilayer and relaxed $Si_{1-y}Ge_y$ buffer layer. The data for samples with inverted doping and strain 2.5 and 2.9%, and samples with normal doping and strain 1.3–2.0% are shown.

of a few peaks associated with 2DHG in the strained Ge QW and carriers in parallel conduction layers. Below, the transport properties of 2DHG in Ge QWs with various strain will be discussed in details after demonstration of strain effect on Hall mobility.

The Hall mobility as a function of Ge content in the $Si_{1-y}Ge_y$ buffer and corresponding lattice mismatch strain in the compressive strained Ge QW layer is shown in Fig. 1. The enhancement of Hall mobility of p-type MOD Si/$Si_{1-y}Ge_y$/Ge/$Si_{1-y}Ge_y$/Si(001) heterostructures was obtained in the full range of researched strain in the Ge QW layer. Due to activation of carriers at RT in parallel conduction layers of p-type MOD Si/$Si_{1-y}Ge_y$/Ge/$Si_{1-y}Ge_y$/Si(001) heterostructures, the measured Hall mobility and carrier density give an averaged mobility and carrier density of all conduction layers. The Hall mobility is seen to increase from 1440 up to 1880 $cm^2\,V^{-1}\,s^{-1}$ while the strain in the Ge QW layer increases from 1.3 up to 2.9%, respectively. It should be noted that the observed enhancement of Hall mobility is achieved not only due to enhancement of 2DHG drift mobility but also due to reduction of parallel conduction in boron-doped supply layer. Since the valence band offset increases with increasing strain, the number of carriers transferred to the Ge QW channel increases with the strain and therefore the contribution of parallel conduction decreases. This suggests that the enhancement of Hall mobility not necessarily correlates with the enhancement of 2DHG drift mobility.

Figure 2 shows RT 2DHG drift mobility and carrier density as a function of Ge content in the $Si_{1-y}Ge_y$ buffer and corresponding lattice mismatch strain in the compressive strained Ge QW layer. The data are shown for samples with inverted doping and strain of 2.5 and 2.9%, and samples with normal doping and strain 1.3–2.0%. The pronounced increase of 2DHG carrier density from 1×10^{12} up to $1.83 \times 10^{12}\,cm^{-2}$ by the increase of compressive strain in the Ge QW layer from 1.3 up to 2.9% is clearly seen in Fig. 2. The increase of strain leads to the increase of the valence band offset of Ge QW and consequently results in better carriers confinement and the increase of 2DHG carrier density in the Ge QW with the same thickness. Estimations show that in our case, ~2.2 times increase in the strain causes ~2.2 times increase of the valence band offset and consequently ~2 times enhancement of 2DHG carrier density is expected. Moreover, it is interesting to note the constant slope of 2DHG carrier density dependence on mismatch strain. Along with the results of structural analysis, this indicates that the strain can be well introduced even in the sample with the highest strain of 2.9% and that the chosen low-temperature growth approach is very effective for Ge QW region. Otherwise, if the relaxation of Ge QW layer takes place, the decrease of valence band offset and consequently the decline of 2DHG carrier density may occur.

As seen in Fig. 2, the 2DHG drift mobility of 1920 $cm^2\,V^{-1}\,s^{-1}$ remains the same for the holes in the Ge QW with relatively low strain and it increases pronouncedly up to 2450 $cm^2\,V^{-1}\,s^{-1}$ with increasing strain up to 2% followed by the monotonic decrease down to 2320 $cm^2\,V^{-1}\,s^{-1}$ at the 2.9% strain. This obtained behavior of 2DHG drift mobility is not trivial. There may be various factors affecting transport of holes at RT. First of all it is expected that higher strain enhances the mobility of holes due to reduction of interband phonon scattering as a result of increased splitting between light-hole and heavy-hole bands.[9] Indeed, the splitting monotonically increases from ~70 up to ~115 and ~150 meV when the strain in the Ge QW layer increases from 1.3 up to 2 and 2.9%, respectively.[14] The 2DHG mobility can also monotonically increase with increasing strain due to screening both of background ionized impurities and remote ionized impurities since 2DHG carrier density increases. Moreover the mobility determined by interface roughness scattering is also proportional to the carrier density as $\mu_{IR} \sim p_{2DHG}{}^{1.5}$.[15] Therefore, higher 2DHG mobility can be achieved at higher carrier density. Combination of these reasons well explains the observed pronounced ~28% enhancement of 2DHG mobility at 43% increase of compressive strain. The reason for the fact that 2DHG drift mobility remains the same in the lower strain region, <1.5%, is not clear, but this fact may suggest that there exists the threshold strain at which the band splitting as well as screening become effective for mobility enhancement. Reduction of mobility down to 2320 $cm^2\,V^{-1}\,s^{-1}$ with the further increase of strain up to 2.9% can be explained by stronger influence of interface roughness scattering on 2DHG mobility. Even the decrease of Ge QW layer growth temperature hardly prevented the roughening of its top interface at higher strain. For both set of samples, with normal and inverted modulation doping, the maximum mobility was observed for Ge QW with 2% compressive strain. Roughening of the top interface on the preliminary stage of Ge QW layer relaxation can also introduce strain fluctuations in it. It may affect not only the mobility of holes located near the top Ge QW layer interface of the sample with normal modulation doping, but also the mobility of holes near the bottom interface of the sample with inverted modulation doping. It is necessary to remind that no additional interface roughening due to $Si_{1-y}Ge_y/Si(001)$ VS with CMP flat surface is expected. And the observed changes of 2DHG drift mobility are due to variation of strain in the Ge QW layer only. It is also necessary to mention that the hole effective mass linearly increases by ~70% with increasing 2DHG carrier density from 1×10^{12} up to 2×10^{12} cm^{-2}.[16] In contrast to the expected reduction of hole effective mass due to the increase of strain, this provides a negative effect on 2DHG mobility by increasing compressive strain in a Ge QW layer. Therefore one can say that more enhancement of 2DHG drift mobility at higher strain, that is 2.9%, is achievable by further optimization of growth conditions and design of the heterostructure.

In spite of degradation of 2DHG mobility observed at higher strain, the enhancement of 2DHG conductivity in the full range of researched strain was obtained. Figure 3 shows the 2DHG conductivity as a function of Ge content in the $Si_{1-y}Ge_y$ buffer and corresponding lattice mismatch strain in the compressive strained Ge QW layer. The small enhancement of 2DHG conductivity at 1.5% strain is due to enhancement of 2DHG carrier density while 80% enhancement of conductivity at 2% strain is thought to be due to both increase of 2DHG mobility and carrier density. At maximum strain of 2.9%, 120% enhancement of 2DHG conductivity, up to 682 µS was obtained due to the enhancement of 2DHG carrier density though the mobility rather decreased. The enhancement of the 2DHG conductivity shows big advantage for using strained Ge QW layer as a p-channel in FET devices.

In summary, the effect of compressive strain on RT transport properties of 2DHG in a Ge QW layer of SiGe heterostructures was researched. With increasing strain in the Ge QW from 1.3 up to 2.9%, the pronounced increase of 2DHG carrier density from 1×10^{12} up to 1.83×10^{12} cm^{-2} and conductivity from 313 up to 682 µS were observed. The increase of 2DHG carrier density is reasonably considered to be due to the increase of Ge QW valence band offset. At the same time, the increase of 2DHG drift mobility up to 2450 cm^2 V^{-1} s^{-1} was observed until the strain in the Ge QW caused roughening of the interfaces, indicating that on preliminary stage of relaxation the slight degradation of the mobility is brought by increased interface roughness scattering of holes. Also the hole effective mass which increases with increasing carrier density can be responsible for degradation of 2DHG mobility. In contrast to 2DHG drift mobility the enhancement of Hall mobility of p-type MOD $Si/Si_{1-y}Ge_y/Ge/Si_{1-y}Ge_y/Si(001)$ heterostructures in the full range of researched strain in the Ge QW layer was obtained. This result clearly shows that in some cases Hall mobility does not correlate with 2DHG drift mobility and can be increased by reduction of parallel conduction.

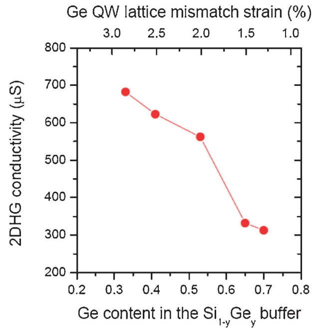

Fig. 3. Room-temperature conductivity of 2DHG existing in the Ge QW of p-type MOD $Si/Si_{1-y}Ge_y/Ge/Si_{1-y}Ge_y/Si(001)$ heterostructures as function of Ge content, y, in the relaxed $Si_{1-y}Ge_y$ buffer and lattice mismatch between compressive strained Ge QW epilayer and relaxed $Si_{1-y}Ge_y$ buffer layer. The data for samples with inverted doping and strain 2.5 and 2.9%, and samples with normal doping and strain 1.3–2.0% are shown.

Nevertheless higher strain in the Ge QW was found to provide higher 2DHG conductivity which is very important for FET devices applications. Obtained results demonstrate that variation of strain in a Ge QW can be used for tuning of transport properties of 2DHG and consequently FET device parameters when this material system is used. Moreover these results open the possibility for realization of future high performance symmetrical CMOS devices with strained p-Ge and n-Si channels on Si(001) or SOI(001) substrates.

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