Observation of two-dimensional hole gas with mobility and carrier density exceeding those of two-dimensional electron gas at room temperature in the SiGe heterostructures

M. Myronov,[a)] K. Sawano, and Y. Shiraki
Research Center for Silicon Nano-Science Advanced Research Laboratories, Musashi Institute of Technology, 8-15-1 Todoroki, Setagaya-ku, Tokyo 158-0082, Japan

T. Mouri and K. M. Itoh
Department of Applied Physics and Physico-Imformatics, Keio University, Yokohama 223-8522, Japan

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Very high two-dimensional hole gas (2DHG) drift mobility of 3100 $cm^2/V\,s$ is obtained at extremely high density of 41×10^{11} cm^{-2} in the modulation doped, 20 nm thick, strained Ge quantum well (QW) of SiGe heterostructure at room temperature. Very high 2DHG density is achieved by increasing the boron modulation doping, reducing the spacer layer thickness located between it and Ge QW, and increasing the valence-band offset of Ge QW, which also results in the enhancement of mobility. The obtained 2DHG mobility and carrier density exceed those reported for two-dimensional electron gas in the strained Si QW of SiGe heterostructures. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2773744]

Band gap engineering has innovated the electronic and optoelectronic devices particularly in the field of III-V compound material systems. The SiGe heterostructures allow both band gap and strain engineering using silicon technology. Modulation doped (MOD) SiGe heterostructures with tensile strained Si quantum well (QW) grown on underlying Si(001) substrate via implementation of intermediate relaxed SiGe buffer are attracting much attention to the fundamental research and applications mainly due to the high mobility of two-dimensional electron gas (2DEG).[1] Up to date systematic research of this material system revealed very high low-temperature 2DEG mobilities in the range from 520 000 $cm^2\,V^{-1}\,s^{-1}$ (at 0.35 K) up to 800 000 $cm^2\,V^{-1}\,s^{-1}$ (at 15 K) with carrier densities of 7×10^{11} and 2×10^9 cm^{-2}, respectively.[2,3] These values significantly exceed the mobility of electrons in bulk Si with the similar densities of impurities. At room temperature, which is more important for field effect transistor (FET) device applications, the dramatic progress in enhancement of 2DEG mobility was achieved as well. Mobilities in the range from 2600 $cm^2\,V^{-1}\,s^{-1}$ (with density of 2×10^{11} cm^{-2}) up to 2830 $cm^2\,V^{-1}\,s^{-1}$ were reported so far.[4,5] On the other hand, no pronounced enhancement of two-dimensional hole gas (2DHG) mobility was obtained in the pseudomorphic compressive strained SiGe QW grown on Si(001) substrate, which is necessary for realization of high performance complementary metal-oxide semiconductor circuits with symmetric *p*- and *n*-channel metal oxide semiconductor field effect transistors. Recently, high Ge content relaxed SiGe/Si(001) virtual substrate (VS) was developed and it became possible to grow compressive strained Ge QW with much higher 2DHG mobilities and densities instead of SiGe alloys.[6–11] Very high low-temperature 2DHG mobility of 120 000 $cm^2\,V^{-1}\,s^{-1}$ with density of 8×10^{11} cm^{-2} was obtained in the compressive strained Ge QW grown on SiGe/Si(001) VS.[8] At the same time, room-temperature 2DHG mobilities in the range of 2400–2940 $cm^2\,V^{-1}\,s^{-1}$ with densities of $(5-10)\times10^{11}$ cm^{-2} have become routinely achieved in 20–25 nm thick Ge QW.[6,7,10,12] It is very well known that electrons are fundamentally more mobile than holes for any bulk or low-dimensional elementary or compound semiconductor materials. In contrast to this, it is quite interesting that the highest 2DHG mobility obtained in the strained Ge QW exceeds that of 2DEG in the strained Si QW and that it is much higher than hole and electron mobilities in bulk Si at room temperature. These results are attracting much attention not only because of scientific interest in more mobile holes in the strained Ge but also the possibility to realize fast and/or low-power electronic devices on Si. For high performance device applications, it is important for the mobile carriers in the channel layer not only to have high mobility but also to have high conductivity. That is, it is significantly important to increase the carrier density as well as the mobility. However, previous attempts to increase the 2DHG carrier density in the range of 10^{12} cm^{-12} resulted in the decrease of mobility.

In this work, we obtained very high 2DHG drift mobility of 3100 $cm^2/V\,s$ with extremely high carrier density of 41×10^{11} cm^{-2} at room temperature in the MOD heterostructures (MODHs) consisting of 20 nm thick strained Ge QW and relaxed $Si_{0.45}Ge_{0.55}/Si(001)$ VS.

The $Si/Si_{0.45}Ge_{0.55}/Ge/Si_{0.45}Ge_{0.55}/Si(001)$ *p*-type MODH was grown on a *n*-type Si(001) substrate by solid source molecular beam epitaxy (SS-MBE) in VG Semicon V80M UHV system. All epilayers of the sample were grown in a single process. At first, a 1 μm thick step-graded $Si_{1-x}Ge_x/Si(001)$ VS with Ge content grading from 8% up to 55% were grown at 600 °C, followed by the growth of 1 μm thick relaxed $Si_{0.45}Ge_{0.55}$ buffer layer with constant Ge content. After that, the temperature was reduced down to 300 °C for the growth of MOD region of the heterostructure. The active region of SiGe heterostructures consists of a 20 nm undoped Ge QW layer for 2DHG, a 10 nm $Si_{0.45}Ge_{0.55}$ undoped spacer layer, a 10 nm $Si_{0.45}Ge_{0.55}$ B-doped supply layer ($\sim4\times10^{18}$ cm^{-3}), a 30 nm $Si_{0.45}Ge_{0.55}$ undoped cap layer, and a 3 nm Si cap layer on the surface.

a)Electronic mail: maksym_myronov@yahoo.co.uk

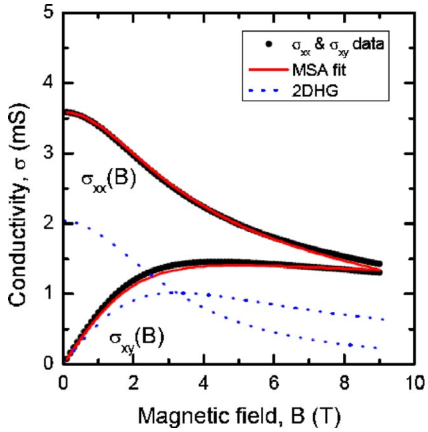

FIG. 1. (Color online) Measured (circles) at temperature of 290 K and fitted (lines) magnetic field dependence of magnetoconductivity tensor components $\sigma_{xx}(B)$ and $\sigma_{xy}(B)$ of $Si/Si_{0.45}Ge_{0.55}/Ge/Si_{0.45}Ge_{0.55}/Si(001)$ *p*-type MODH. Dot lines show $\sigma_{xx}(B)$ and $\sigma_{xy}(B)$ of 2DHG calculated from 2DHG drift mobility and carrier density obtained from mobility spectrum.

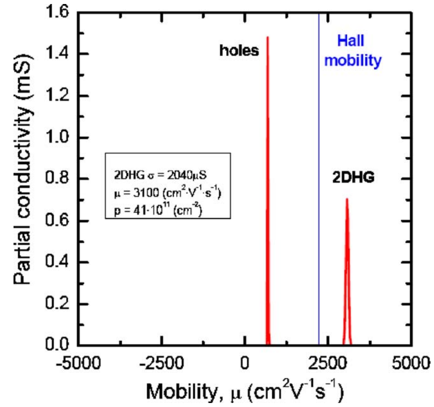

FIG. 2. (Color online) Mobility spectrum of $Si/Si_{0.45}Ge_{0.55}/Ge/Si_{0.45}Ge_{0.55}/Si(001)$ *p*-type MODH as the result of $\sigma_{xx}(B)$ and $\sigma_{xy}(B)$ first shown in Fig. 3. Hall mobility of the sample is shown for clarity.

The Ge composition and the state of strain of the grown Ge and SiGe epilayers were determined with the help of high-resolution x-ray diffraction (HR-XRD). Both symmetric and asymmetric HR-XRD reciprocal space maps were measured in order to obtain lattice parameters in various epilayers and to determine the Ge composition and the strain. The degree of relaxation in the top $Si_{0.45}Ge_{0.55}$ layer was found to be 96%. The analysis of the peak's position originated from Ge layer shows 4% degree of relaxation. Surface morphology of the grown samples was characterized by atomic force microscopy (AFM) in a tapping mode. Cross-hatch pattern related to the strain field distribution in the underlying epilayers caused by inhomogeneous distribution of misfit dislocations is clearly visible in AFM images. Root mean square (rms) surface roughness was found to be 13 nm. The threading dislocation density (TDD) was evaluated by counting the density of etch pits DEPs which were formed by wet chemical etching using diluted Schimmel etching solution.[13,14] The DEP is known to associate with TDD and the average TDD was found to be 1.4×10^{8} cm^{-2}. The measured values of TDD and rms surface roughness are high but reasonable for relatively thin SiGe/Si(001) VS with final Ge content of 0.55.

Samples for room-temperature magnetotransport measurements were fabricated in mesa-etched Hall-bar device geometry. The Hall mobility and sheet carrier density of the samples were obtained by a combination of resistivity and Hall effect measurements. Conventional resistivity and Hall effect measurements yield only the averaged density and mobility of carriers existing not only in the QW layer but also in the other parallel conducting ones, e.g., the doped layer, the buffer layer, the substrate, and their interfaces. In order to separately find out the transport properties of various carriers existing in multilayer semiconductor heterostructures, the technique of mobility spectrum analysis, where the magnetic-field dependencies of magnetoresistance and Hall resistance are measured, has to be applied.[15]

Figure 1 shows conductivity measured at 290 K and the fitted magnetic field dependence of conductivity tensor components $\sigma_{xx}(B)$ and $\sigma_{xy}(B)$ of $Si/Si_{0.45}Ge_{0.55}/Ge/Si_{0.45}Ge_{0.55}/Si(001)$ *p*-type MODH. The fitted data are in very good agreement with the measured ones. Dot lines show $\sigma_{xx}(B)$ and $\sigma_{xy}(B)$ of 2DHG calculated from 2DHG drift mobility and carrier density obtained from the mobility spectrum shown in Fig. 2. The mobility spectrum is seen to consist of two narrow clearly resolved peaks. The higher intensity peak with the positive mobility around 700 cm^{2} V^{-1} s^{-1} and the conductivity of 1550 μS were found to decrease with decreasing temperature presumably due to carrier freeze-out,[11] and therefore, it is thought to correspond to the groups of carriers in the boron-doped slightly strained SiGe and/or SiGe buffer layers. The peak with the highest mobility in the spectrum is attributed to the 2DHG formed in the strained, 20 nm thick Ge QW. The drift mobility and carrier density of the 2DHG extracted from the mobility spectrum are 3100 cm^{2} V^{-1} s^{-1} and 41×10^{11} cm^{-2}, respectively. The conductivity of 2DHG can be deduced to be 2040 μS. In contrast to the mobility of carriers in the parallel conducting layers, the 2DHG mobility was found to increase with decreasing temperature and coincide with the Hall mobility at low-temperatures when carriers in parallel conducting layers freeze out. The measured Hall mobility and sheet carrier density were 2220 cm^{2} V^{-1} s^{-1} and 101×10^{11} cm^{-2} at room temperature, respectively. The Hall mobility is shown in Fig. 2 for clarity. It is clearly seen that the room-temperature 2DHG drift mobility is much higher than the average Hall mobility.

In the previous reports,[6,11] the importance of a thicker Ge QW for obtaining high 2DHG mobility at room temperature was clearly demonstrated and very high 2DHG drift mobility of 2940 cm^{2} V^{-1} s^{-1} at carrier density of 5.1×10^{11} cm^{-2} was obtained in the single-side MOD 20 nm Ge QW. In the present work, the 2DHG density was increased in the same 20 nm Ge QW by increasing boron doping, reducing SiGe spacer thickness, and increasing strain in the Ge QW. Although these changes were thought to lead to the degradation of 2DHG mobility in the QW due to the increased remote ionized impurity scattering and defect generation, the mobility was found to rather increase. It is well established that high structural quality of SiGe/Si(001) VS is essential for achieving high carrier mobility in Si, SiGe, or Ge QWs,[1,16] because high density of TDD and very rough surface are thought to degrade the carrier mobility. In this work, however, very high 2DHG mobility is interestingly obtained in the Ge QW grown on a relatively low quality SiGe/Si(001) VS with high density of defects (TDD=1.4×10^{8} cm^{-2}) and very rough surface (rms=13 nm). This result indicates that although the structure exhibiting high mo-

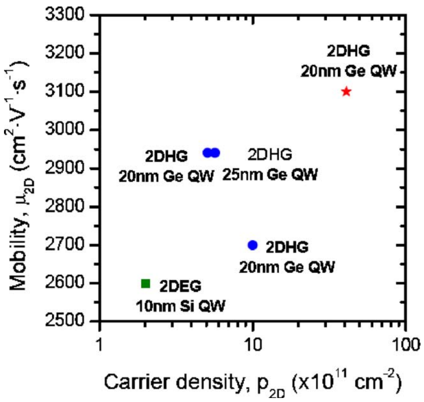

FIG. 3. (Color online) Drift mobility as a function of carrier density at room temperature. The 2DHG in a 20 and 25 nm Ge QWs from Refs. 6, 7, 10, and 12 are shown by circles. The 2DHG in a 20 nm Ge QW obtained in this work is shown by star. The 2DEG in a 10 nm Si QW from Ref. 5 is shown by square.

bility at low-temperatures is believed to show high mobility even at room temperature and provide better device performances, it is not always true and that different scattering mechanisms may dominate the transport behavior of 2DHG in the QW at low and room temperatures.[11] Since the mean free path of carriers at room temperature is much shorter than that at low temperature, threading dislocations and some surface roughness are less responsible for scattering of 2DHG at room temperature. The surface roughness with long-range correlation length produced in a typical graded SiGe buffer causes less scattering to carriers in the QW compared with the short-range Ge QW interface roughness. In our case, although this interface is probably rough due to small relaxation of Ge QW layer, but enhancement of mobility is achieved due to higher 2DHG density. The mobility determined by interface roughness scattering is proportional to the carrier density as $\mu_{\mathrm{IR}} \sim p_{\mathrm{2DHG}}^{1.5}$.[17] Therefore, higher 2DHG mobility can be achieved at higher carrier density. However, the increase of 2DHG density did not lead to the expected pronounced enhancement of mobility in our samples. Thereby, these results yet strongly suggest the importance of phonon scattering on limitation of 2DHG drift mobility at room temperature. Moreover, the higher 2DHG drift mobility in the Ge QW leads to higher Hall mobility of $\mathrm{Si/Si_{0.45}Ge_{0.55}/Ge/Si_{0.45}Ge_{0.55}/Si(001)}$ *p*-type MODH of 2220 cm^2 V^{-1} s^{-1}. It is interesting to note that very high Hall mobility is obtained in the sample with very rough surface and that the value is much higher than the Hall mobility of ~1200 cm^2 V^{-1} s^{-1} reported for the sample with similar 20 nm Ge QW grown on the VS with a smooth surface produced by chemical mechanical polishing technique.[18] This shows the possibility of further enhancement of 2DHG mobility at room-temperature.

Figure 3 summarizes the drift mobility as a function of the carrier density at room-temperature for both 2DHG and 2DEG. The highest 2DHG drift mobility of 2940 cm^2 V^{-1} s^{-1} is obtained in the strained Ge QW with thicknesses of 20 and 25 nm grown by low-energy plasma-enhanced chemical-vapor deposition and SS-MBE techniques on different SiGe/Si(001) VSs.[6,7,10,12] The highest value of 2DEG drift mobility of 2830 cm^2 V^{-1} s^{-1} was obtained in the tensile strained Si QW so far.[4] However, since 2DEG carrier density is not mentioned in that publication, the 2DEG drift mobility of 2600 cm^2 V^{-1} s^{-1} at density of 2×10^{11} cm^{-2} obtained in the similar strained 10 nm Si QW[5] is shown for comparison in Fig. 3. It is clearly seen that the 2DHG in the compressively strained Ge QW provides higher drift mobility at much higher density. The 2DHG density exceeds 2DEG density by 20 times. Also, these data show much higher conductivity at higher mobility of 2DHG than 2DEG that is very important for FET devices applications.

In conclusion, very high 2DHG drift mobility of 3100 cm^2/V s was obtained at extremely high density of 41×10^{11} cm^{-2} in the MOD, 20 nm thick, compressively strained Ge QW at room temperature. This high 2DHG density was achieved by increasing doping, reducing the spacer layer thickness located between it and Ge QW, and increasing strain in Ge QW. At the same time, the enhancement of mobility was obtained. Moreover, enhancement of 2DHG mobility and carrier density resulted in very high Hall mobility of 2220 cm^2/V s in *p*-type $\mathrm{Si/Si_{0.45}Ge_{0.65}/Ge/Si_{0.45}Ge_{0.65}/Si(001)}$ MODH. The obtained 2DHG mobility is significantly higher and the carrier density is about eight times larger than those ever reported, which resulted in the breakthrough enhancement of 2DHG sheet conductivity up to 2040 μS. It is also noted that the obtained values are not only the highest ones among 2DHG in the strained Ge QW but also higher than those of 2DEG in the strained Si QW of SiGe heterostructures.

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