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Enhancement of room-temperature hole conductivity in narrow and strained Ge quantum well by double-side modulation doping

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The room-temperature two-dimensional hole gas (2DHG) conductivity as high as 649.3 μS is obtained by implementation of double-side modulation doping (DS-MOD) of an 8 nm thick strained Ge quantum well in a SiGe heterostructure. This conductivity is about three times higher than that of the conventional SiGe heterostructure with single-side modulation doping (SS-MOD). While the low-temperature (T=3 K) mobility with DS-MOD is two times higher than that with SS-MOD, the room-temperature mobility of the two is practically the same, suggesting that phonon scattering is the dominant limiting mechanism at the device operating temperatures. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2737396]

Significant progress in two-dimensional hole gas (2DHG) mobilities has been achieved recently in strained Ge and SiGe quantum well (QW) channels by implementation of the high-quality relaxed SiGe buffer layers in the modulation doped (MOD) SiGe heterostructures.[1–6] Employment of such novel structures for future silicon-based field effect transistor (FET) devices requires for the channel layers to have as high conductivity as possible, i.e., significant increase of the 2DHG density and/or mobility is needed. Development of the highly conductive channels in the SiGe heterostructures at the device operating temperatures (room temperature and above) is still challenging partly because of lack of characterization techniques to determine exclusively the density and mobility of carriers in the channel. Conventional resistivity and Hall effect measurements at room temperature yield only the averaged density and mobility of carriers that are contained not only in the channel layer but also in the other parallel conductors, e.g., the doped layer, buffer layer, substrate, etc. Suppression of the parallel conduction is possible by lowering the sample temperature to well below 50 K, and therefore, it has been assumed that transport properties of 2DHG determined at low temperatures correlate to those at room temperature.[7] This assumption is appropriate for selected groups of heterostructures, but not for 2DHG in the present study as we will show in this letter.

It has been demonstrated recently that determination of the conductivity and mobility of the carriers confined in each layer of the multilayer semiconductor heterostructures is possible for an arbitrarily chosen temperature (including room temperature and above) using the so-called mobility spectrum analysis (MSA) of the magnetic-field dependence of magnetoresistance and Hall resistance.[8] In particular, an excellent agreement between 2DHG drift mobility obtained by MSA in p-type single side modulation doped (SS-MOD) Ge QW and effective mobility of p-type Ge QW metal-oxide-semiconductor FET was demonstrated at room temperature.[1,9] At the same time, even though 2DHG in narrow strained SS-MOD Ge QW showed much higher mobility at low temperatures than that in wider strained SS-MOD Ge QW SiGe, it was found that the room-temperature mobilities show an opposite behavior denying the correlation between the low and device operating temperature mobilities for this system.[6] The low temperature 2DHG mobility was limited by the interface-roughness scattering[6] and such scattering was reduced in double-side modulation doped (DS-MOD) to reach 30 000 $\mathrm{cm^2\,V^{-1}\,s^{-1}}$ at 3 K (two times enhancement with respect to that in SS-MOD),[10] because 2DHG was successfully moved away from the interface thanks to the appropriate band gap engineering realized by DS-MOD. In this letter, MSA has been employed to precisely determine the temperature dependencies of density, conductivity, and mobility of 2DHG in newly designed DS-MOD Ge QW, and the ways for further improvement of carrier transport properties at room temperature will be suggested.

The $\mathrm{Si/Si_{0.32}Ge_{0.68}/Ge/Si_{0.32}Ge_{0.68}/Si_{0.7}Ge_{0.3}/Si(001)}$ p-type DS-MOD heterostructures were grown on a Si(001) substrate by solid source molecular beam epitaxy. The active region of SiGe heterostructure with symmetric DS-MOD grown on $\mathrm{Si_{0.32}Ge_{0.68}/Si_{0.7}Ge_{0.3}/Si(001)}$ virtual substrate consists of a 10 nm $\mathrm{Si_{0.32}Ge_{0.68}}$ B-doped supply layer ($\sim 1 \times 10^{18}$ $\mathrm{cm^{-3}}$), a 10 nm $\mathrm{Si_{0.32}Ge_{0.68}}$ undoped spacer layer, an 8 nm undoped Ge QW layer for mobile holes, a 10 nm $\mathrm{Si_{0.32}Ge_{0.68}}$ undoped spacer layer, a 10 nm $\mathrm{Si_{0.32}Ge_{0.68}}$ B-doped supply layer ($\sim 1 \times 10^{18}$ $\mathrm{cm^{-3}}$), a 30 nm $\mathrm{Si_{0.32}Ge_{0.68}}$ undoped cap layer, and a 2 nm Si cap layer on the surface. The undoped spacer layers separate the ionized B dopants from the Ge QW. A reference sample of similar design but with single-side modulation doping and an inverted $\mathrm{Si_{0.32}Ge_{0.68}}$ B-doped supply layer of $\sim 2 \times 10^{18}$ $\mathrm{cm^{-3}}$ separated by 20 nm spacer was prepared for comparison. Further details of the sample structure, growth conditions, and electrical and structural characterization can be found elsewhere.[10] Magnetotransport measurements were performed using the mesa-etched Hall-bar geometry with the distance of 500 μm between potential contacts and 100 μm for the channel width. Ohmic contacts were formed by evaporating AuGa. The Hall mobility and sheet carrier density were obtained by combination of resistivity and Hall effect measurements in the temperature range of 3–293 K. The magnetic-field dependence of the magnetoresistance and

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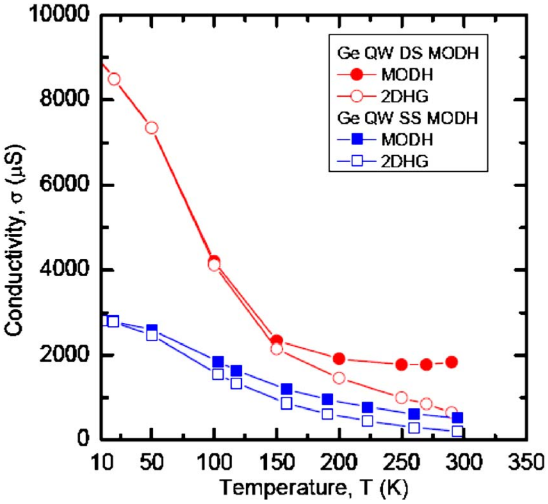

FIG. 1. (Color online) Temperature dependence of conductivities of 2DHG in DS-MOD (open circles) and in SS-MOD (open squares) samples obtained by the mobility spectrum analysis and the temperature dependence of the averaged conductivity of the whole heterostructures for DS-MOD (filled circles) and in SS-MOD (filled squares) samples obtained from the standard resistivity measurements.

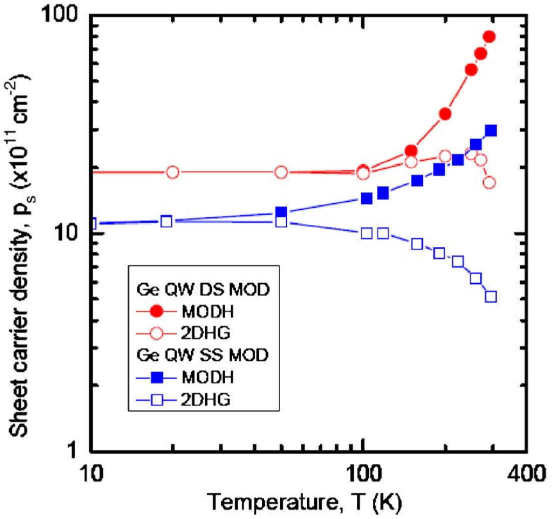

FIG. 2. (Color online) Temperature dependence of the 2DHG densities obtained by the mobility spectrum analysis for DS-MOD (open circles) and SS-MOD (open squares) samples. The temperature dependence of the total carrier densities in the whole structure obtained by the conventional Hall effect measurements is also shown for DS-MOD (filled circles) and SS-MOD (filled squares) samples.

Hall resistance were measured as the magnetic field was swept continuously from −9 up to +9 T and reversed. After the average was taken, the data were converted into conductivity tensor components followed by a maximum-entropy mobility spectrum analysis (ME-MSA) fitting procedure.[8] It is worth pointing out that the ME-MSA approach does not require any preliminary assumptions about the number of different types of carriers.

Obtained mobility spectrum consists of a few peaks representing different groups of carriers with specific mobilities associated with 2DHG in the strained Ge QW and parallel conduction layers. Conductivity of the latter ones decreases with decreasing temperature due to carrier freeze out, similar to previously reported data.[6] The conductivity due to each group of carriers was obtained by the integration of the area of each peak in the mobility spectra. Figure 1 shows the conductivities of 2DHG in DS-MOD and SS-MOD samples obtained from the mobility spectrum analysis and the averaged conductivity of the whole heterostructures obtained from the standard resistivity measurements. At room temperature, about 65% and 60% of the conductivity in DS-MOD and SS-MOD, respectively, originate from the parallel conduction. However, with reduction of temperature the conductivity of parallel layers (integrated areas of peaks arising not from 2DHG in the mobility spectra) decreases due to the carrier freeze out, and below certain temperatures (100 K for DS-MOD and 20 K for SS-MOD), the parallel conduction disappears and 2DHG conductivity obtained from the mobility spectra analysis coincides with the average conductivity obtained by the conventional resistivity measurements. Because conductivity is given as a product of the carrier density and mobility, we shall discuss below the contribution of each component for identification of the limiting mechanisms of the conductivity.

Figure 2 shows the temperature dependence of the 2DHG densities obtained by the mobility spectra, i.e., conductivity of the specific layer divided by the corresponding mobility (2DHG peak position). The temperature dependence of the total carrier density in the whole structure obtained by the conventional Hall effect measurement is also shown. Due to the modification of the Ge QW valence energy band profile from the triangularlike of the SS-MOD to the rectangularlike of the DS-MOD, the room- and low-temperature 2DHG carrier densities in DS-MOD are increased by ~3.3 times and ~1.7 times, respectively, with respect to those in SS-MOD. For both samples the Hall sheet carrier densities of the whole structures decreases with decreasing temperature due to the freeze out of carriers in parallel conduction layers. In contrast to this behavior, the 2DHG density of SS-MOD increases with decreasing temperature by ~2 times from 5.1×10^{11} cm^{-2} at room temperature to 11×10^{11} cm^{-2} at 10 K. The 2DHG density of DS-MOD also increases with decreasing temperature from 17×10^{11} cm^{-2} at room temperature to the maximum value of 23×10^{11} cm^{-2} at 250 K. Further decrease of the temperature reduces the density and it becomes constant below 100 K at 19×10^{11} cm^{-2}. The 2DHG density of DS-MOD at room temperature is only ~10% lower than that at 10 K. This implies that it is the mobility enhancement with the reduction of the temperature that is responsible for the dramatic enhancement of 2DHG conductivity in DS-MOD at low temperatures. One of the explanations for experimentally observed temperature dependence of 2DHG density could be due to incomplete ionization of boron dopants. The 2DHG density in the Ge QW depends on the thickness of the spacer layer and the boron doping level in the supply layer. The number of electrically active impurities in the supply layer is not always equal to the number of dopant atoms, which is called incomplete ionization. For boron doped Si, it is well known to depend on impurity concentration and the temperature.[11] Although the experimental data on incomplete ionization of boron in the high Ge content SiGe is not obtained yet we can reasonably consider that the similar behavior exists in SiGe and that lower room-temperature 2DHG density in SS-MOD heterostructure with higher doping occurs.

Figure 3 shows the temperature dependence of the drift mobility of 2DHG determined by the mobility spectrum

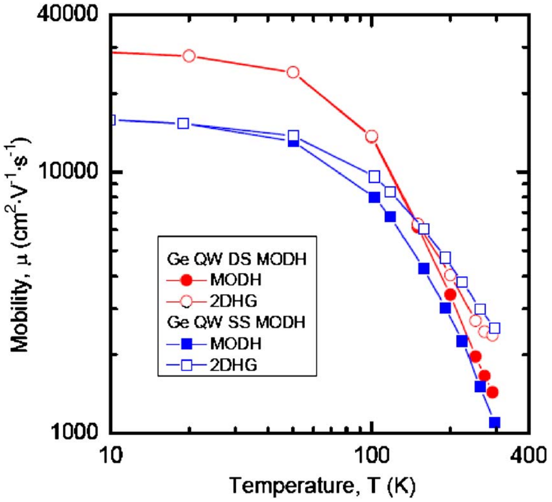

FIG. 3. (Color online) Temperature dependence of the drift mobility of 2DHG determined by the mobility spectrum analysis for DS-MOD (open circles) and SS-MOD (open squares) samples and the Hall mobility of the whole structure obtained from the standard Hall effect and resistivity measurements for DS-MOD (filled circles) and SS-MOD (filled squares) samples.

analysis and the Hall mobility of the whole structure obtained from the standard Hall effect and resistivity measurements. As expected, both the drift and Hall mobilities of carriers in DS-MOD and SS-MOD increase with decreasing temperatures. The 2DHG drift mobilities for both samples are higher than the Hall mobilities in the higher temperature range and they become equal below a certain temperature when the parallel conduction disappears. In accordance with Fig. 1, the drift and Hall mobilities coincide with one another below 100 and 20 K for DS-MOD and SS-MOD, respectively. The 2DHG drift mobility of 30 000 $\mathrm{cm}^2\,\mathrm{V}^{-1}\,\mathrm{s}^{-1}$ in DS-MOD at low temperatures is a factor of 2 higher than that in SS-MOD. However, the 2DHG drift mobilities at room temperature are about the same for both samples; 2380 $\mathrm{cm}^2\,\mathrm{V}^{-1}\,\mathrm{s}^{-1}$ for DS-MOD and 2540 $\mathrm{cm}^2\,\mathrm{V}^{-1}\,\mathrm{s}^{-1}$ for SS-MOD. The temperature dependence of the drift mobility in the high temperature region, 200–295 K, can be fitted very well using an empirical relation of $\mu \sim T^{-\alpha}$, with $\alpha = 1.57$ and 1.42 for DS-MOD and SS-MOD, respectively. The power-law behavior with $\alpha \geqslant 2$ is established for the mobility limited by dominating phonon scattering in bulk Si and Ge,[12] and $\alpha \approx 1.6$ obtained here is likely to represent the 2DHG drift mobility, in 8 nm compressive strained Ge QW, limited by phonon scattering. The small difference between $\alpha = 1.42$ and 1.57 arises from the reduction of interface-roughness scattering in DS-MOD compared to SS-MOD. The mobilities limited by acoustic- and optical-phonon scatterings are known to be proportional to the width of the QW.[13] Therefore, further enhancement of the 2DHG mobility at room temperature can be achieved in the future by increasing the width of Ge QW. This conclusion is in good agreement with previously reported results.[6] However, the significance of the present work is the demonstration of the pronounced increase of the conductivity and mobility of 2DHG for the channel width of the same thickness as a result of making DS-MOD. The room temperature 2DHG conductivity of 649.3 μS in this work is much higher than the previous record of 240.8 μS in 20 nm Ge QW SS-MOD.[6] The room-temperature transport properties of 2DHG are summarized in Table I.

TABLE I. Summary of room-temperature 2DHG drift mobility ($\mu_{2\mathrm{DHG}}$), carrier density ($p_{2\mathrm{DHG}}$), and conductivity ($\sigma_{2\mathrm{DHG}}$) of double-side modulation doping (DS-MOD) Ge quantum well and single-side modulation doping (SS-MOD) quantum well samples. The parameter α was obtained by fitting of temperature dependence of 2DHG drift mobility in the high temperature range of 200–295 K using an empirical relation of $\mu \sim T^{-\alpha}$.

Sample	$p_{2\mathrm{DHG}}$ ($\times 10^{11}$ cm^{-2})	$\mu_{2\mathrm{DHG}}$ ($\mathrm{cm}^2\,\mathrm{V}^{-1}\,\mathrm{s}^{-1}$)	$\sigma_{2\mathrm{DHG}}$ (μS)	α
DS MOD Ge QW	17.0	2380	649.3	1.57
SS MOD Ge QW	5.1	2540	208.5	1.42

The present results show high potential for further improvement of the room-temperature 2DHG mobility in SiGe heterostructures, especially because such high hole mobility has been obtained in the present SiGe heterostructures with the relatively high root mean square surface roughness of 6.8 nm and etch pit density of 2×10^7 cm^{-2} which are commonly regarded to be responsible for degradation of hole and electron mobilities in SiGe heterostructures.[7] The reduction of these parameters via further optimization and development of SiGe/Si(001) virtual substrates may lead to much higher hole mobility in Ge QW.

In conclusion, the room-temperature 2DHG conductivity as high as 649.3 μS has been obtained by implementation of DS-MOD with an 8 nm thick strained Ge QW in the SiGe heterostructure. Such improvement was achieved by successful increase of the 2DHG density in the QW. On the other hand, the room-temperature mobilities in the QW are the same between double- and single-side modulation dopings. However, the room-temperature 2DHG mobilities of about 2400 $\mathrm{cm}^2/\mathrm{V\,s}$ achieved by both double- and single-side modulation dopings exceed the three-dimensional mobility of holes at the same density in bulk Si by a factor of 13 and that in bulk Ge by a factor of 8.

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