Extended Abstracts of the 2007 International Conference on Solid State Devices and Materials, Tsukuba, 2007, pp. 288-289

F-3-2

Demonstration of holes in strained Ge quantum wells with much higher drift mobility and density than that of electrons in strained Si channels

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1. Introduction

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 always attracts more attention for fundamental research and applications mainly due to high two-dimensional electron gas (2DEG) mobility [1]. Up to date, systematic research of this material system resulted in demonstration of very high room-temperature 2DEG mobilities in the range from 2600 $cm^2V^{-1}s^{-1}$ (with density of 2×10^{11} cm^{-2}) up to 2830 $cm^2V^{-1}s^{-1}$ [2, 3]. These values significantly exceed electrons mobility at similar densities found in bulk Si. From another side, no pronounced enhancement of two-dimensional hole gas (2DHG) mobility initially realized in the pseudomorphic compressively strained SiGe QW grown on Si(001) substrate was obtained. Just recently, with development of high Ge content relaxed SiGe/Si(001) virtual substrate (VS), it became possible to grow compressive strained Ge QW with very high 2DHG mobility and density. The room-temperature 2DHG mobilities in the range of 2400 - 2940 $cm^2V^{-1}s^{-1}$ with densities of 5-10×10^{11} cm^{-2} obtained in 20 - 25 nm thick Ge QW grown by low energy plasma enhanced chemical vapor deposition (LEPE-CVD) and solid source molecular beam epitaxy (SS-MBE) techniques were routinely achieved [4-7].

In this letter we report on demonstration of an extremely high room-temperature 2DHG drift mobility of 3100 $cm^2V^{-1}s^{-1}$ with very high density of $41\text{x}10^{11}$ cm^{-2} in a modulation doped (MOD) strained Ge QW and high 2DEG drift mobility of 2900 $cm^2V^{-1}s^{-1}$ with density of $1\text{x}10^{11}$ cm^{-2} in a MOD strained Si QW.

2. Epitaxial growth of SiGe MOD heterostructures

The *p*-type Ge QW and *n*-type Si QW MOD SiGe heterostructures were grown on a Si(001) substrates by MBE. The samples consist of relaxed $Si_{1-y}Ge_y$/Si(001) VSs necessary to produce strained Ge or Si QWs on underlying Si substrate and MOD region of the heterostructure. The active region of p-type SiGe heterostructure consists of a 20 nm undoped compressive-strained 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, a 30 nm $Si_{0.45}Ge_{0.55}$ undoped cap layer and 3 nm Si cap layer on the surface. The active region of n-type SiGe heterostructures consists of a 15 nm undoped tensile-strained Si QW layer for 2DEG, a 10 nm $Si_{1-y}Ge_y$ undoped spacer layer, a δ-doped Sb, a 30 nm $Si_{1-y}Ge_y$ undoped cap layer and 3 nm Si cap layer on the surface. Samples with various Ge content in a $Si_{1-y}Ge_y$ layers and value of doping were grown.

3. Magnetotransport characterization

Samples for room-temperature magnetotransport measurements were fabricated in mesa-etched Hall-bar device geometry. The Hall mobility and sheet carrier density of the grown sample were obtained by a combination of resistivity and Hall effect measurements. Conventional resistivity and Hall effect measurements at room temperature yield only an averaged density and mobility of carriers that exist not only in the QW layer but also in the other parallel conducting ones, e. g., the doped layer, buffer layer, substrate, etc. In order to find out the transport properties of various carriers existing in multilayer semiconductor heterostructures, the magnetic-field dependencies of magnetoresistance and Hall resistance have to be measured and the technique of mobility spectrum analysis (MSA) has to be applied [8]. In particular, an excellent agreement between 2DHG drift mobility obtained by this powerful and unique technique in p-type Ge QW SiGe MODH and effective mobility of p-type Ge QW MOSFET, fabricated from the similar material heterostructure, was demonstrated at room-temperature [5, 9]. Obtained peak effective mobility of 2700 cm^2 V^{-1} s^{-1} is much higher those reported so far for p-Ge channel MOSFETs. In present work the magnetic-field dependencies of the magnetoresistance and Hall resistance were measured as the magnetic field was swept. The measured data were converted into conductivity tensor components $\sigma_{xx}(B)$ and $\sigma_{xy}(B)$ followed by a maximum-entropy mobility spectrum analysis (ME-MSA) fit 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, and this aspect is very important for transport phenomenon analysis in semiconductor structures.

The 2DHG drift mobility of 3100 $cm^2V^{-1}s^{-1}$ with density of 41×10^{11} cm^{-2} were obtained in the 20 nm Ge QW. This 2DHG mobility is significantly higher and the carrier density is about 8 times larger than those ever reported. The higher carrier density resulted in the breakthrough enhancement of 2DHG sheet conductivity up to 2040 μS. Moreover, enhancement of 2DHG mobility and carrier density resulted in yet another record, that is, Hall mobility of 2220 $cm^2V^{-1}s^{-1}$ in p-type Ge QW MOD SiGe heterostructure.

In the previous reports the importance of a thicker Ge QW (due to domination of phonon scattering) for obtaining high 2DHG mobility at room-temperature was clearly demonstrated [5, 10]. Very high 2DHG drift mobility of 2940 $cm^2V^{-1}s^{-1}$ at density of 5.1×10^{11} cm^{-2} were obtained in the single-side MOD 20 nm Ge QW. In the present work, over 8 times enhancement of 2DHG density in the similar 20 nm Ge QW was obtained. This was achieved by increasing Boron modulation doping, reducing SiGe spacer thickness and increasing strain in the Ge QW However, these changes could lead to the degradation of 2DHG mobility in the QW due to increased remote ionized impurity scattering if most of dopants are not fully ionized and all carriers are not transferred to the QW. To overcome this problem, the valence band offset in the Ge QW was increased by increasing strain in the Ge QW. This was done by employing almost fully relaxed $Si_{0.45}Ge_{0.55}$/Si(001) VS.

The highest drift mobility of 2DEG was obtained in the sample with the smallest conduction band offset of 15 nm Si QW grown on $Si_{0.75}Ge_{0.25}$/Si(001) VS and the smallest value of doping. For this sample the 2DEG drift mobility of 2900 $cm^2V^{-1}s^{-1}$ with carrier density of 1×10^{11} cm^{-2} was obtained. This value is similar to previously reported ones [2, 3]. However, it is necessary to mention that in most cases only the mobility of 2DEG was reported and quite simple approaches were used for calculation of 2DEG drift mobility from an average Hall one. Due to these reasons we fabricated several samples with various 2DEG densities in order to see the behavior of the mobility. It was found that with increasing carrier density up to 4.4×10^{11} cm^{-2}, the 2DEG drift mobility was reduced down to 2670 $cm^2V^{-1}s^{-1}$.

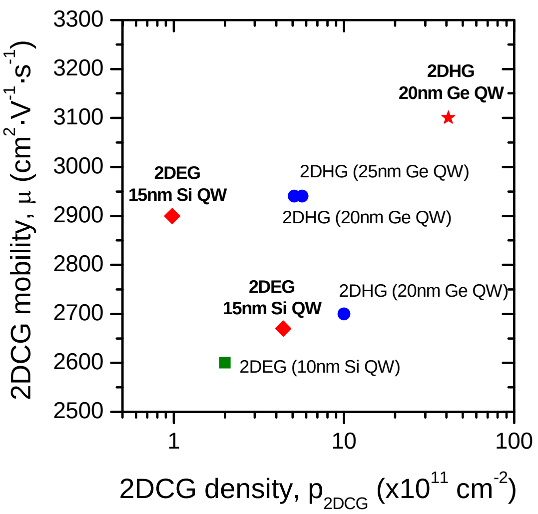

Fig. 1. The 2DCG drift mobility as a function of density at room-temperature. The 2DHG in a 20 and 25 nm Ge QWs from references [4-7] are shown by circles. The 2DEG in a 10 nm Si QW from reference [3] is shown by square. The 2DHG in a 20 nm Ge QW and 2DEG in a 15 nm Si QW obtained in this work are shown by star and diamonds, respectively.

Figure 1 shows two-dimensional carrier gas (2DCG) drift mobility dependence on 2DCG density. The highest values for previously published mobilities of 2DHG in the strained Ge QWs and 2DEG in the strained Si QWs along with the results obtained in this work are shown. It is clearly seen that the highest 2DHG mobility obtained in the strained 20-25 nm Ge QWs exceeds 2DEG ones obtained in the strained 10-15 nm Si QWs and many times higher than hole and electron mobilities in bulk Si at room-temperature. At the same time, the high 2DHG mobilities are obtained at much higher density. This demonstrates that p-type strained Ge QW channels have much higher conductivity than n-type strained Si QW channels. For high performance device applications, it is important for the mobile carriers in the channel layer, i.e. QW, not only to have as high mobility as possible but also high conductivity.

4. Conclusions

In conclusion, extremely high 2DHG drift mobility of 3100 $cm^2V^{-1}s^{-1}$ with very high density of 41x10^{11} cm^{-2} were obtained in the MOD, 20 nm thick, compressive strained Ge QW at room-temperature. It is also demonstrated that 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. Obtained extremely high room-temperature 2DHG mobility exceeds three-dimensional mobility of holes in bulk Si and Ge at the same impurity concentration by over 25 and 10 times, respectively. These results open the possibility for realization not only of future high performance symmetrical CMOS with strained p-Ge and n-Si channels on Si(001) or SOI(001) substrates but also high performance p-Ge channel (with extremely high mobility) MODFET for RF applications.

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