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Demonstration of high mobility holes in a strained Ge channel grown on a novel thin and relaxed SiGe/LT-SiGe/Si(001) virtual substrate

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1. Introduction

In recent years the modulation doped (MOD) heterostructures with a compressively strained Ge quantum well (QW) grown on an underlying Si(001) substrate, via implementation of an intermediate relaxed SiGe buffer have been exhibiting significant progress in enhancing room-temperature two-dimensional hole gas (2DHG) mobilities. The QW acts as a channel for mobile carriers. Indeed, very high 2DHG mobilities in the range of 2400 - 3100 $cm^2 V^{-1} s^{-1}$ with carrier densities of 5 - 41×10^{11} cm^{-2} have become routinely achievable in 20 - 25 nm thick Ge QWs [1-5]. The strain narrows the band gap of Ge and causes the appearance of a QW in the valence band. Holes confined in the strained Ge QW then have a lower effective mass that increases their mobility. The reduction of the carrier's scattering factors also leads to enhanced mobility in this material system. Until now, very high mobility holes were only obtained in the strained Ge QWs grown on relatively thick (1-8 μm) high Ge content SiGe buffers [3, 5]. However, a drawback for nanoscale MOSFET and MODFET devices applications arises from the lower thermal conductivity of undoped SiGe, since at room-temperature, the thermal conductivity of undoped $Si_{0.3}Ge_{0.7}$ is over 12 times lower than that of Si [6]. This could lead to overheating of the material and result in degradation of nanoscale device performances as has already been demonstrated in an n-Si strained channel on $Si_{0.56}Ge_{0.44}$ buffer heterostructure MODFET [7]. Therefore, a significant reduction of the SiGe buffer layer thickness is indeed essential. Furthermore, thin SiGe buffers have certain advantages in their integration with other devices on a single chip. Moreover, none of the recently developed methods for fabricating thin SiGe/Si(001) VSs has been able to demonstrate high mobility holes in a strained Ge channel.

In this letter, we report the first results of successful epitaxial growth of a compressively strained Ge QW epilayer on a recently developed ultrathin high Ge content relaxed SiGe/LT-SiGe/Si(001) virtual substrate (VS) [8]. This material system demonstrates excellent electronic and structural properties and has a high potential for a future device applications.

2. Epitaxial growth of Ge QW heterostructures

The *p*-type Ge QW/$Si_{0.4}Ge_{0.6}$/LT-$Si_{0.4}Ge_{0.6}$/Si(001) MOD heterostructures were grown on a Si(001) substrates by solid source molecular beam epitaxy (SS-MBE), in a single process. A schematic design of the structures is shown in Fig. 1. The samples consist of a relaxed 45 nm thick $Si_{0.4}Ge_{0.6}$/LT-$Si_{0.4}Ge_{0.6}$/Si(001) VS, necessary to induce compressive strain in the Ge QW epilayers, on an underlying Si substrate and the MOD region of the heterostructure. The VS substrate was grown by a variable temperature approach followed by the growth of the 300 nm thick $Si_{0.4}Ge_{0.6}$ buffer layer [8]. By this method the initial, very thin (5 nm thick) $Si_{0.4}Ge_{0.6}$ seeding layer is grown at very low substrate temperature, followed by a 40 nm thick layer of the same Ge content grown at temperature ramping up to 550 °C. The active region of the heterostructure consists of an 8 nm undoped compressively strained Ge QW layer to contain the 2DHG, a 10 nm $Si_{0.4}Ge_{0.6}$ undoped spacer layer, a 10 nm $Si_{0.4}Ge_{0.6}$ B-doped supply layer, a 30 nm $Si_{0.4}Ge_{0.6}$ undoped cap layer and finally a 2 nm Si cap layer on the surface. The Ge QW layer is grown at 350 °C to retain the strain and to minimize Ge diffusion. The design of the MOD region was chosen to be identical to that of structures which previously demonstrated very high 2DHG mobilities at both low- and room-temperatures [3], so as to compare the quality of the $Si_{0.4}Ge_{0.6}$/LT-$Si_{0.4}Ge_{0.6}$/Si(001) VS and its effect on the transport properties of the 2DHG in the Ge QW.

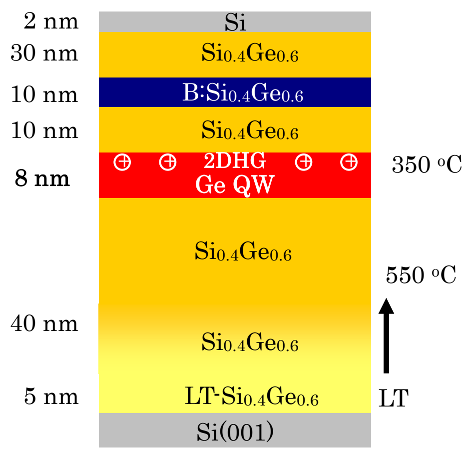

Fig. 1. Schematic design of p-Ge QW/$Si_{0.4}Ge_{0.6}$/LT-$Si_{0.4}Ge_{0.6}$/Si(001) MOD heterostructure grown by SS-MBE.

3. Results and discussions

The Ge content and degree of relaxation of the epilayers were obtained by high resolution X-ray diffraction (HR-XRD). All measurements were carried out at room-temperature using a Philips XPert MRD system. In order to determine the lattice parameters of the SiGe and Ge layers, symmetric (004) and asymmetric (224) reciprocal space mapping (RSM) measurements were performed. Analysis of the (004) RSM did not reveal any tilt of the SiGe epilayers grown on Si(001) substrate, which is a common feature of thick graded SiGe buffers. Thus corrections to the (224) RSM were unnecessary and the data can be analysed as it is, see Fig. 2. Analysis of the peak positions showed the Ge content was 60 % in the SiGe layers and these were fully relaxed; the 8 nm Ge QW layer was similarly shown to be under full compressive strain.

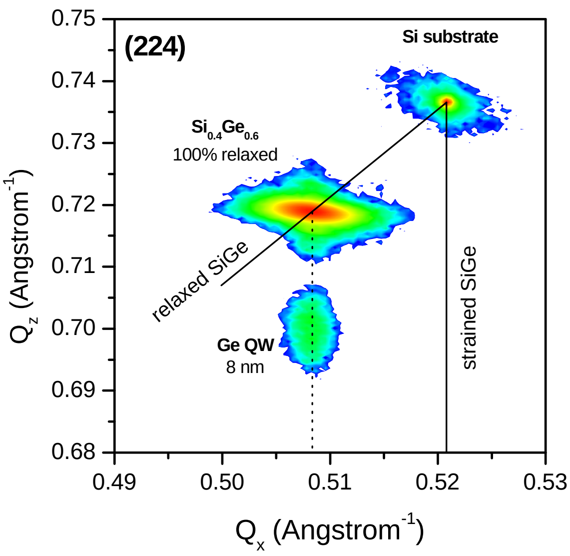

Fig. 2. HR-XRD asymmetric (224) RSM of p-Ge QW/$Si_{0.4}Ge_{0.6}$/LT-$Si_{0.4}Ge_{0.6}$/Si(001) MOD heterostructure.

The Hall mobility and sheet carrier density were obtained by a combination of resistivity and Hall effect measurements on mesa-etched Hall-bar devices as a function of temperature in the range of 3 – 300 K and are shown in Fig. 3. The saturation of the Hall mobility and carrier density below 50 K clearly indicates the presence of a 2DHG in the strained Ge QW. At 3 K the 2DHG Hall mobility and carrier density are 6360 $cm^2V^{-1}s^{-1}$ and 1.21×10^{12} cm^{-2}, respectively. At 293 K the Hall mobility and carrier density are 1415 $cm^2V^{-1}s^{-1}$ and 1.88×10^{12} cm^{-2}, respectively. The measured room-temperature Hall mobility significantly exceeds the value of 1110 $cm^2V^{-1}s^{-1}$ reported previously for the structure with an identical MOD Ge QW region, but grown on a much thicker (1100 nm) SiGe/Si(001) VS. The results obtained demonstrate the suitability of proposed thin $Si_{0.4}Ge_{0.6}$/LT-$Si_{0.4}Ge_{0.6}$/Si(001) VS for use in high mobility strained Ge QW heterostructures.

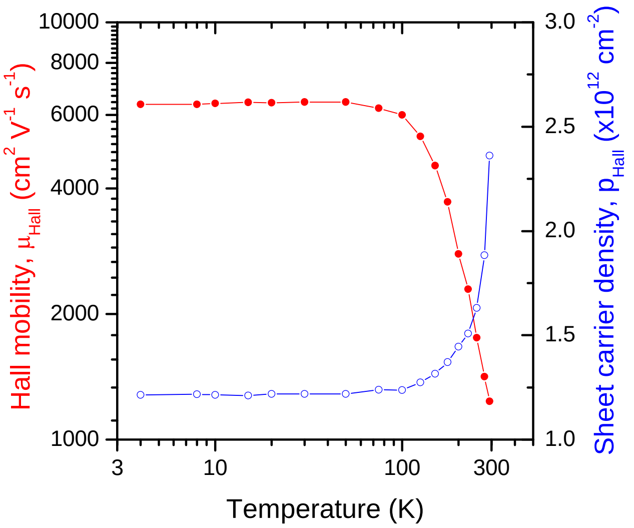

Fig. 3. The temperature dependence of Hall mobility and sheet carrier density of p-Ge QW/$Si_{0.4}Ge_{0.6}$/LT-$Si_{0.4}Ge_{0.6}$/Si(001) MOD heterostructure.

4. Conclusions

In conclusion, the first results of successful epitaxial growth of a compressively strained Ge QW on an ultrathin (45 nm) $Si_{0.4}Ge_{0.6}$/LT-$Si_{0.4}Ge_{0.6}$/Si(001) VS have been demonstrated. HR-XRD shows that the VS is fully relaxed and the 8 nm Ge QW layer is fully strained. Furthermore, the temperature dependence of Hall mobility and carrier density clearly indicate the existence of a high mobility 2DHG in the Ge QW. At room-temperature, which is more relevant for FET devices applications, the samples show a very high Hall mobility of 1415 $cm^2V^{-1}s^{-1}$ at a carrier density of 1.88×10^{12} cm^{-2}. These results exhibit that there is a huge potential for further applications of such a material system for p-MOSFET and -MODFET devices on Si(001) or SOI(001) substrates.

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