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Very high mobility 2D holes in strained Ge quantum well epilayers grown by Reduced Pressure Chemical Vapor Deposition

Maksym Myronov[1], Kentarou Sawano[2], David R. Leadley[1] and Yasuhiro Shiraki[2]

[1] Department of Physics, The University of Warwick
Coventry CV4 7AL, UK
Phone: +44 2476 574383 E-mail: M.Myronov@warwick.ac.uk
[2] Advanced Research Laboratories, Tokyo City University
8-15-1 Todoroki, Setagaya-ku, Tokyo158-0082, Japan

1. Introduction

Germanium, with its very high intrinsic hole mobility of 1900 $cm^2V^{-1}s^{-1}$ at room-temperature, is one of the candidate materials to replace Si in future CMOS devices. Biaxial compressive strain additionally enhances the hole mobility in Ge. In practice, this is obtained by epitaxial growth of a compressively strained Ge epilayer, a few nanometers thick, on an underlying standard Si(100) substrate via an intermediate relaxed SiGe buffer. The strain narrows the band gap of Ge and causes the appearance of a quantum well (QW) in the valence band. Holes confined in the strained Ge QW form a two-dimensional hole gas (2DHG) and have an increased mobility due both to their lower effective mass and reduced scattering factor in this material system. Indeed, very high room-temperature 2DHG mobilities in the range 2400 - 3100 $cm^2V^{-1}s^{-1}$, with carrier densities of 5 - 41×10^{11} cm^{-2} have become routinely achieved in 20 - 25 nm thick Ge QWs [1-5]. At lower temperatures, i.e. below 10 K, much higher 2DHG mobilities in the range of 30000 - 120000 $cm^2V^{-1}s^{-1}$ with carrier densities of 3 - 19×10^{11} cm^{-2} have been obtained [6-8]. Until now, such extremely high mobility holes, have only been obtained in strained Ge QWs that were grown by solid-source molecular beam epitaxy (SS-MBE) or low-energy plasma-enhanced chemical vapor deposition (LEPE-CVD) techniques. However, there is great interest in creating such structures by a mass production technique such as reduced pressure chemical vapor deposition (RP-CVD). RP-CVD offers the major advantage of unprecedented wafer scalability and is nowadays routinely used by leading companies in the semiconductor industry to grow epitaxial layers on Si(100) wafers of up to 300 mm diameter.

For the first time, we report a very high 2DHG mobility obtained in compressive strained Ge QW epilayers grown by an industrial type RP-CVD technique.

2. Epitaxial growth of strained Ge QW heterostructures

Modulation doping (MOD) in semiconductor heterostructures is a commonly used technique to create mobile carries in a QW and thereby assess the quality of the QW's material without the added complications of forming a gate stack that would be needed in a production device. In this work, RP-CVD has been used to grow the epitaxial layers from the substrate through an intermediate Ge/$Si_{0.2}Ge_{0.8}$ buffer to the p-type Ge QW and an undoped spacer layer, but the modulation doping surface layers were produced by SS-MBE because of its superior doping control during the epitaxial growth of SiGe layers. A schematic design of the structure is shown in Fig. 1. All the RP-CVD epilayers were grown on 200 mm Si(100) substrates in an industrial ASM Epsilon 2000 CVD system, which is a horizontal, cold wall, single wafer, load-lock reactor with a lamp heated graphite susceptor in a quartz tube. The structure consist of a 2.5 µm reverse linearly graded (RLG) relaxed $Si_{0.2}Ge_{0.8}$/Ge buffer, a 20 nm undoped compressive strained Ge QW layer and a 20 nm undoped $Si_{0.2}Ge_{0.8}$ spacer layer.

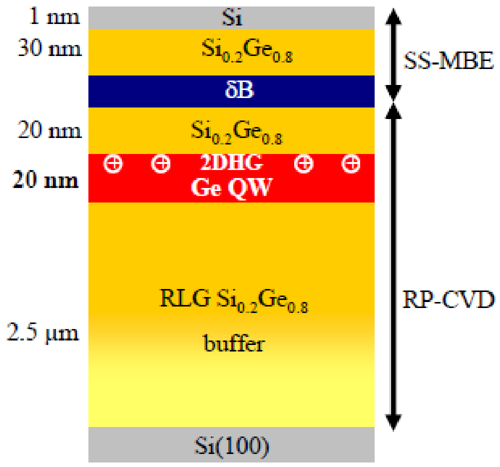

Fig. 1. Schematic design of p-Ge QW/$Si_{0.2}Ge_{0.8}$/Ge/Si(100) MOD heterostructure grown by RP-CVD and SS-MBE.

The Ge QW layer was grown from the common germane (GeH_4) precursor. The relatively thin, high Ge content buffer demonstrates good structural properties, i.e. relatively low RMS surface roughness of ~2 nm and low TDD of ~ 2x10^6 cm^{-2} [9]. These properties make it an excellent global strain tuning platform for epitaxial growth of high quality Ge QW epilayers. Epitaxial growth of remaining layers was carried out by SS-MBE in a VG Semicon V80 UHV system. They consist of a B doped delta-layer, a 30 nm undoped $Si_{0.2}Ge_{0.8}$ layer and a 1 nm Si undoped cap layer. The design of the MOD region was chosen to be similar to that of structures that previously demonstrated very high 2DHG mobilities at both low- and room temperatures [3, 8], so as to compare the quality of the Ge QW grown by RP-CVD.

3. Results and discussions

The Ge content and degree of relaxation of the epilayers were obtained by high resolution X-ray diffraction (HR-XRD) and Raman spectroscopy. 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 these results confirmed the Ge content in the various SiGe epilayers of the structure and the compressive strain state of 20 nm Ge QW. Figure 2 shows a room-temperature Raman spectrum of the p-Ge QW/$Si_{0.2}Ge_{0.8}$/Ge/Si(100) MOD heterostructure excited with a 632.8 nm wavelength laser. The very sharp peak at around 305 cm^{-1}, corresponding to the Ge-Ge mode in the Ge QW, indicates this layer is fully strained and of high crystalline quality.

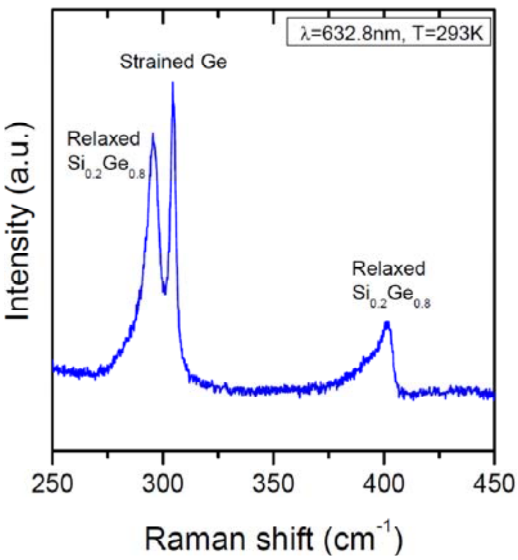

Fig. 2. Room-temperature Raman spectrum of p-Ge QW/$Si_{0.2}Ge_{0.8}$/Ge/Si(100) MOD heterostructure.

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 40 K clearly indicates the presence of a 2DHG in the strained Ge QW. At 3 K, the 2DHG Hall mobility and carrier density are 42150 $cm^2V^{-1}s^{-1}$ and 3.6×10^{11} cm^{-2}, respectively. At 300 K, the Hall mobility and carrier density are 1090 $cm^2V^{-1}s^{-1}$ and 9.98×10^{14} cm^{-2}, respectively. The measured room-temperature Hall mobility is similar to the value of 1110 $cm^2V^{-1}s^{-1}$ reported previously for a structure with a similar MOD Ge QW region and grown in the same SS-MBE system [3]. The 3 K 2DHG mobility is even slightly higher than that obtained in a similar Ge QW MOD heterostructure at the same carrier density, but grown by LEPE-CVD [2]. Up to now, the LEPE-CVD technique has been the only one capable of growing very high quality strained Ge QW epilayers, with the highest 2DHG low-temperature mobilities up to 120000 $cm^2V^{-1}s^{-1}$ at a carrier density of 8.5×10^{11} cm^{-2} [8]. In the 2DHG density range of 1 to 10×10^{11} cm^{-2} the mobility tends to increase with increasing carrier density. Hence, we believe that these first exciting results show high potential for the 2DHG mobilities in strained Ge QWs grown by RP-CVD to match those from LEPE-CVD at higher carrier densities.

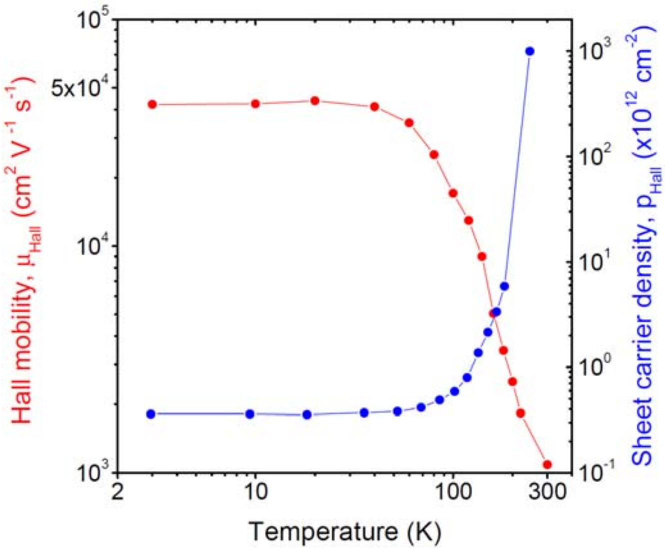

Fig. 3. Temperature dependence of Hall mobility and sheet carrier density of p-Ge QW/$Si_{0.2}Ge_{0.8}$/Ge/Si(100) MOD heterostructure.

4. Conclusions

In conclusion, we report a very high, low-temperature, 2DHG mobility in a compressively strained 20 nm Ge QW epilayer grown, for the first time, by an industrial type RP-CVD technique. The temperature dependence of the Hall mobility and carrier density clearly indicates the existence of a high mobility 2DHG in the Ge QW. At 3 K the 2DHG Hall mobility and carrier density are 42150 $cm^2V^{-1}s^{-1}$ and 3.6×10^{11} cm^{-2}, respectively. These results demonstrate the very high quality of the strained Ge QW epilayers grown by RP-CVD and appoint to a huge potential for further applications of such materials in p-MOSFET and -MODFET devices on Si(100) or SOI(100) substrates.

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