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Groundbreaking room-temperature mobility of 2D holes in a strained Ge quantum well heterostructure grown by Reduced Pressure Chemical Vapor Deposition

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A groundbreaking room-temperature 2DHG mobility of 4230 $cm^2V^{-1}s^{-1}$ in a compressively strained Ge QW heterostructure grown by an industrial type RP-CVD technique is reported. The obtained mobility is substantially higher than those reported so far and reveal a huge potential for further application of strained Ge in a wide variety of electronic devices.

1. Introduction

Germanium, with its very high intrinsic hole and electron mobilities of 1900 and 3900 $cm^2V^{-1}s^{-1}$ at room-temperature, respectively, is the most promising candidate material to replace Si channels in future Complementary Metal Oxide Semiconductor (CMOS) devices. Adoption of Ge technology recently came closer to reality after demonstration of superior quality GeO_2 gate dielectric and very high electron and hole mobilities obtained near the GeO_2/Ge interface in bulk Ge Metal Oxide Semiconductor Field Effect Transistor (MOSFET) devices [1]. Biaxial compressive strain further 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(001) substrate via an intermediate strain-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 factors 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} are routinely achieved in 20 - 25 nm thick Ge QWs [2-6]. At lower temperatures, i.e. below 10 K, much higher 2DHG mobilities in the range of 0.03 - 1.1×10^6 $cm^2V^{-1}s^{-1}$ with carrier densities of 3 - 19×10^{11} cm^{-2} have been obtained [7-10]. Until recently, 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(001) wafers of up to 300 mm diameter. Recently we reported an ultra-high low-temperature (12K) 2DHG mobility exceeding one million in a strained Ge QW heterostructures grown by RP-CVD [10].

For the first time, we report groundbreaking room-temperature 2DHG mobility obtained in compressively strained Ge QW epilayers grown by the 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 carriers in a QW and thereby assess the quality of the QWs 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 entire p-type Ge QW MOD heterostructures. A schematic cross-section of a typical structure is shown in Fig. 1. The epilayers were grown on 100 mm Si(001) substrates in an industrial type 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 consists of a 2.1 µm reverse linearly graded (RLG) strain-relaxed $Si_{0.25}Ge_{0.75}$/Ge buffer, an undoped SiGe buffer, an undoped compressive strained Ge QW layer, an undoped SiGe spacer layer, a Boron doped SiGe supply layer and an undoped SiGe cap layer on the surface.

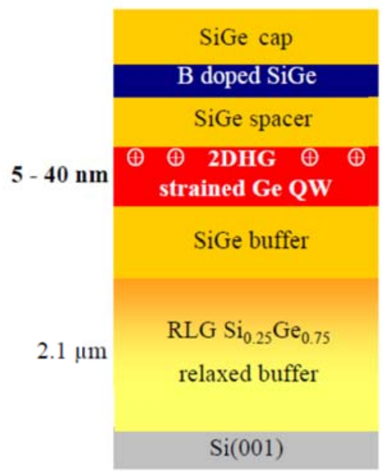

Fig. 1. Schematic cross-section of a typical p-Ge QW MOD heterostructure grown on Si(001) substrate by RP-CVD.

The Ge QW layer was grown using 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 threading dislocation density of ~ $2\text{x}10^6$ cm^{-2} [11]. These properties make it an excellent global strain tuning platform for epitaxial growth of high quality Ge QW epilayers.

3. Results and discussions

The Hall mobility and sheet carrier density of the Ge QW MOD heterostructures were obtained by a combination of resistivity and Hall effect measurements on mesa-etched Hall-bar devices, as a function of temperature from 0.3 – 300 K. The low-temperature mobility of 2DHG exceeds 700,000 cm^{2}V^{-1}s^{-1}. At 300 K, the Hall mobility and carrier density are 800 cm^{2}V^{-1}s^{-1} and 4.3×10^{12} cm^{-2} respectively.

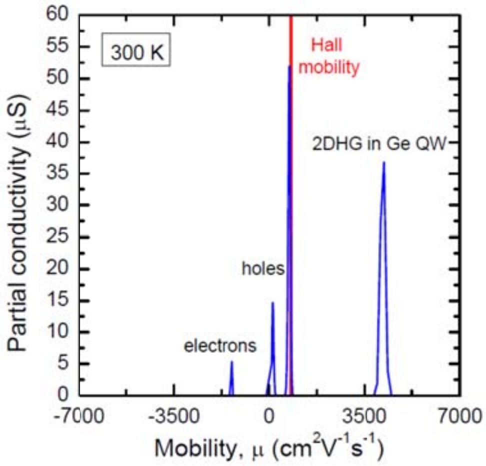

Fig. 2. Room-temperature mobility spectrum as the result of conductivity tensor components σ_{xx}(B) and σ_{xy}(B) fits for the Ge QW MOD heterostructure. The measured Hall mobility is shown for clarity.

High-temperature measurements and interpretation of the transport properties of any multilayered MOD heterostructure are complicated by the existence of parallel conduction paths in doping supply layers, buffer layers and a substrate. The measured Hall mobility deviates to some degree from the drift mobility. At high temperatures parasitic parallel conduction paths are activated. In this case an average mobility and an average sheet carrier density arising from all conducting layers are measured by the Hall-effect technique. A solution to this problem is to measure the magnetic-field dependences of magnetoresistance and Hall resistance and to apply the technique of Mobility Spectrum Analysis (MSA) [12]. The mobility spectrum resulting from 300 K conductivity tensor components σ_{xx}(B) and σ_{xy}(B) fits for a Ge QW MOD heterostructure is shown in Fig. 2. The spectrum consists of four peaks; the highest mobility peak is attributed to the 2DHG in the strained Ge QW. The drift mobility and sheet carrier density of the 2DHG extracted from the mobility spectrum are 4230 cm^{2}V^{-1}s^{-1} and 1×10^{11} cm^{-2} respectively.

The highest previously reported mobilities for 2DHG in compressive strained Ge QWs, grown by various approaches, and 2DEG in the tensile strained Si QWs along with the results obtained in this work are shown in Fig. 3. The obtained value of 2DHG mobility exceeds the highest previously reported by over 30%.

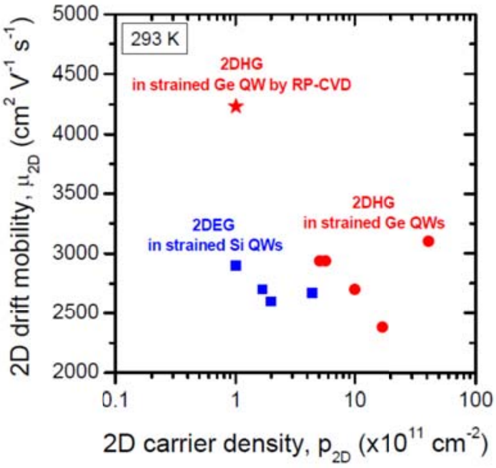

Fig. 3. The highest 2DHG and 2DEG drift mobilities as a function of the carrier density at room temperature. The 2DHG mobilities in Ge QWs are shown by red circles. The 2DEG in Si QWs are shown by blue squares. The 2DHG obtained in this work is shown by red star.

4. Conclusions

In conclusion, we report groundbreaking room-temperature 2DHG mobility of 4230 cm^{2}V^{-1}s^{-1} in a compressively strained Ge QW grown by an industrial type RP-CVD technique. The obtained mobility is substantially higher than those reported so far and grown by research type epitaxial growth techniques, i.e. SS-MBE and LEPE-CVD. This result demonstrates the very high quality of the strained Ge QW epilayers grown by the RP-CVD and demonstrates the huge potential for further applications of such materials in CMOS, p-MOSFET and -MODFET devices on Si(001) or SOI(001) substrates.

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