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Observation of high mobility 2DHG with very high hole density in the modulation doped strained Ge quantum well at room temperature

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Abstract

Very high two-dimensional hole gas (2DHG) drift mobility of $3100\,cm^2\,V^{-1}\,s^{-1}$ is obtained at extremely high density of $4.1 \times 10^{12}\,cm^{-2}$ in the modulation doped (MOD), 20 nm thick, strained Ge quantum well (QW) of SiGe heterostructure at room temperature. Obtained 2DHG mobility is higher and the carrier density is about eight times larger than those ever reported for SiGe MOD heterostructures. It is also noted that obtained values are not only the highest ones among 2DHG in the strained Ge QW but also larger than those of two-dimensional electron gas in the strained Si QW.

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1. Introduction

During the last years, the modulation doped heterostructures (MODHs) with strained Ge and SiGe quantum wells (QWs) grown on underlying Si(0 0 1) substrate via implementation of intermediate relaxed SiGe buffer have been exhibiting significant progress in enhancement of low- and room-temperatures two-dimensional hole gas (2DHG) mobilities [1–3]. At room-temperature 2DHG mobilities in the range of $2400–2940\,cm^2\,V^{-1}\,s^{-1}$ with densities of $5–10 \times 10^{11}\,cm^{-2}$ have become routinely achieved 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 [1,3–5]. Before the dramatic progress in enhancement of two-dimensional electron gas (2DEG) mobility in strained Si QW was achieved as well. Mobilities in the range from $2600\,cm^2\,V^{-1}\,s^{-1}$ (with density of $2 \times 10^{11}\,cm^{-2}$) up to $2830\,cm^2\,V^{-1}\,s^{-1}$ were reported so far [6,7]. These SiGe heterostructures will allow realizing high performance complementary metal-oxide semiconductor (CMOS) circuits with symmetric p- and n-channel metal-oxide semiconductor field effect transistors (MOSFETs). For high performance device applications it is important for the mobile carriers in the channel layer (or QW) not only to have high mobility but also to have high conductivity. That is, it is significantly important to increase the carrier density as well as the mobility. However, previous attempts to increase the 2DHG carrier density in the range of $10^{12}\,cm^{-2}$ resulted in the decreasing of mobility.

In this work, very high 2DHG drift mobility of $3100\,cm^2\,V^{-1}\,s^{-1}$ is obtained at extremely high density of $4.1 \times 10^{12}\,cm^{-2}$ in the MOD, strained Ge QW of SiGe heterostructure at room temperature.

2. Experimental

The $Si/Si_{0.45}Ge_{0.55}/Ge/Si_{0.45}Ge_{0.55}/Si(0\,0\,1)$ p-type MODH was grown on an n-type Si(0 0 1) substrate by SS-MBE in VG Semicon V80M UHV system. The sample consisted of relaxed $Si_{0.45}Ge_{0.55}/Si(0\,0\,1)$ virtual substrate (VS) necessary to grow compressive strained 20 nm thick Ge QW on underlying Si substrate and MOD region of the

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heterostructure with Ge QW. The active region of SiGe heterostructures consists of a 20 nm undoped 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 a 3 nm Si cap layer on the surface.

3. Results and discussion

The Ge composition and the state of strain of the grown Ge and SiGe epilayers were determined with the help of high-resolution X-ray diffraction (HR-XRD). Both symmetric (0 0 4) and asymmetric (2 2 4) HR-XRD reciprocal space maps were measured in order to obtain lattice parameters in various epilayers and to determine Ge composition and the strain. The degree of relaxation in the top $Si_{0.45}Ge_{0.55}$ layer of VS was found to be 96%. Analysis of the Ge QW layer peak's position shows 4% degree of relaxation.

The root mean square (RMS) surface roughness obtained by atomic force microscopy (AFM) and threading dislocations density (TDD) obtained by wet chemical etching [8] of gown sample were found to be 13 nm and $1.4\times10^{8}\,cm^{-2}$, respectively. These values are high, but reasonable for relatively thin SiGe/Si(0 0 1) VS with final Ge content of 0.55.

Samples for room-temperature magnetotransport measurements were fabricated in mesa-etched Hall-bar device geometry. Conventional resistivity and Hall effect measurements yield only the averaged density and mobility of carriers existing not only in the QW layer but also in the other parallel conducting ones, e.g., the doped layer, the buffer layer, the substrate and their interfaces. In order to separately find out the transport properties of various carriers existing in multilayer semiconductor heterostructures, the technique of mobility spectrum analysis (MSA), where the magnetic-field dependencies of magnetoresistance and Hall resistance were measured, was applied [9].

The drift mobility and carrier density of the 2DHG formed in the strained, 20 nm thick, Ge QW extracted from the mobility spectrum are $3100\,cm^{2}\,V^{-1}\,s^{-1}$ and $4.1\times10^{12}\,cm^{-2}$, respectively. In contrast to the mobility of carriers in the parallel conducting layers, the 2DHG mobility was found to increase with decreasing temperature and coincide with the Hall mobility at low temperatures when carriers in parallel conducting layers freeze out. The measured Hall mobility was $2220\,cm^{2}\,V^{-1}\,s^{-1}$ at room temperature.

It is well established that high structural quality of SiGe/Si(0 0 1) VS is essential for achieving high carrier mobility in Si, SiGe or Ge QWs [10,11], because high density of TDD and very rough surface are thought to degrade the carrier mobility. In this work, however, very high 2DHG mobility is interestingly obtained in the Ge QW grown on a relatively low quality SiGe/Si(0 0 1) VS with high density of defects ($TDD=1.4\times10^{8}\,cm^{-2}$) and very rough surface (RMS = 13 nm). This result indicates that although the structure exhibiting high mobility at low temperatures is believed to show high mobility even at room temperature and provide better device performances, it is not always true and that different scattering mechanisms may dominate the transport behavior of 2DHG in the QW at low- and room temperatures [12]. Since the mean free path of carriers at room temperature is much shorter than that at low temperature, threading dislocations and some surface roughness are less responsible for scattering of 2DHG at room temperature.

Fig. 1 summarizes the drift mobility as a function of the carrier density at room temperature both for 2DHG and 2DEG. The highest 2DHG drift mobility of $2940\,cm^{2}\,V^{-1}\,s^{-1}$ is obtained in the strained Ge QW with thickness of 20 and 25 nm grown by LEPECVD and SS-MBE techniques on different SiGe/Si(0 0 1) VSs [1,3–5]. The highest value of 2DEG drift mobility of $2830\,cm^{2}\,V^{-1}\,s^{-1}$ was obtained in the tensile strained Si QW so far [6]. However, since 2DEG carrier density is not mentioned in that publication, the 2DEG drift mobility of $2600\,cm^{2}\,V^{-1}\,s^{-1}$ at density of $2\times10^{11}\,cm^{-2}$ obtained in the similar strained 10 nm Si QW [7] is shown for comparison in Fig. 1. It is clearly seen that the 2DHG in the compressively strained Ge QW provides higher drift mobility at much higher density. The 2DHG density exceeds 2DEG density by 20 times. Also, these data show much higher conductivity at higher mobility of 2DHG than 2DEG that is very important for FET devices applications.

In conclusion, very high 2DHG drift mobility of $3100\,cm^{2}\,V^{-1}\,s^{-1}$ was obtained at extremely high density of $4.1\times10^{12}\,cm^{-2}$ in the MOD, 20 nm thick, compressively

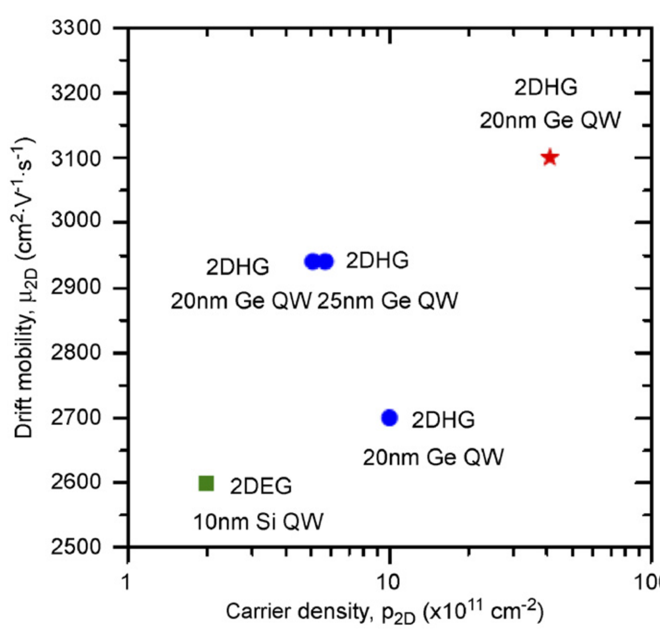

Fig. 1. The drift mobility as a function of carrier density at room temperature. The 2DHG in a 20 and 25 nm Ge QWs from Refs. [1,3–5] are shown by circles. The 2DHG in a 20 nm Ge QW obtained in this work is shown by star. The 2DEG in a 10 nm Si QW from Ref. [7] is shown by square.

strained Ge QW at room temperature. This high 2DHG density was achieved by increasing doping, reducing the spacer layer thickness located between it and Ge QW and increasing strain in Ge QW. At the same time the enhancement of mobility was obtained. The obtained 2DHG mobility is significantly higher and the carrier density is about eight times larger than those ever reported, which resulted in the breakthrough enhancement of 2DHG sheet conductivity up to 2040 μS. It is also noted that the 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 of SiGe heterostructures.

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References

[1] M. Myronov, T. Irisawa, O.A. Mironov, S. Koh, Y. Shiraki, T.E. Whall, E.H.C. Parker, Appl. Phys. Lett. 80 (2002) 3117.
[2] M. Myronov, C.P. Parry, O.A. Mironov, E.H.C. Parker, Appl. Phys. Lett. 85 (2004) 3145.
[3] H. von Kanel, M. Kummer, G. Isella, E. Muller, T. Hackbarth, Appl. Phys. Lett. 80 (2002) 2922.
[4] H. von Kanel, D. Chrastina, B. Rossner, G. Isella, J.P. Hague, M. Bollani, Microelectron. Eng. 76 (2004) 279.
[5] R.J.H. Morris, T.J. Grasby, R. Hammond, M. Myronov, O.A. Mironov, D.R. Leadley, T.E. Whall, E.H.C. Parker, M.T. Currie, C.W. Leitz, E.A. Fitzgerald, Semicond. Sci. Technol. 19 (2004) L106.
[6] K. Ismail, S.F. Nelson, J.O. Chu, B.S. Meyerson, Appl. Phys. Lett. 63 (1993) 660.
[7] S.F. Nelson, K. Ismail, J.O. Chu, B.S. Meyerson, Appl. Phys. Lett. 63 (1993) 367.
[8] J. Werner, K. Lyutovich, C.P. Parry, Eur. Phys. J.: Appl. Phys. 27 (2004) 367.
[9] S. Kiatgamolchai, M. Myronov, O.A. Mironov, V.G. Kantser, E.H.C. Parker, T.E. Whall, Phys. Rev. E 66 (2002) 036705.
[10] F. Schaffler, Semicond. Sci. Technol. 12 (1997) 1515.
[11] D.J. Paul, Semicond. Sci. Technol. 19 (2004) R75.
[12] M. Myronov, T. Irisawa, S. Koh, O.A. Mironov, T.E. Whall, E.H.C. Parker, Y. Shiraki, J. Appl. Phys. 97 (2005) 083701.