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Evidence of strong spin–orbit interaction in strained epitaxial germanium

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ABSTRACT

Spin–orbit interaction effects are of great interest, primarily for the ability to modulate spin transport in a semiconductor channel for device applications. In particular, the Rashba spin–orbit (S–O) interaction allows for a tuneable spin modulation response dependent on the applied electric field, which can be achieved using standard semiconductor gate technology. We present evidence of the Rashba S–O interaction in two modulation doped germanium (Ge) quantum well (QW) heterostructures with different layer structures, and consequently different band structures and internal electric fields across the QW region. We show that two complementary low temperature magnetotransport analyses can be used to identify and quantify the Rashba S–O parameter in these materials, although quantification is limited in one case due to significant parallel conduction. We highlight that both techniques (Weak Antilocalisation and Shubnikov de-Haas oscillations) should be used when analysing a new material system as other conduction and magnetoresistive effects can obscure evidence of the Rashba S–O interaction in one or both of these regimes.

1. Introduction

Germanium quantum well (QW) heterostructures have been studied over the past 20 years, primarily for the interesting physical effects that can be observed in the 2D hole gas formed in the QW [1–6]. Recently, extremely high hole mobilities have been achieved in this material system both at low temperatures (1.3×10^6 cm^2/Vs) [7] and room temperature (4500 cm^2/Vs) [8,9]. Because of these advances Ge QW heterostructures now look like strong candidates for high mobility electronic applications such as field effect transistors (FETs), especially due to the highest mobility structures being grown by an industrial type equipment (reduced pressure chemical vapour deposition (RP-CVD)) onto standard Si (001) substrates. Since the proposal of the spin FET in 1990 by Datta and Das [10], semiconductor materials have been studied for their spin–orbit interactions, particularly those that can be modified by an applied electric field, such as the Rashba spin–orbit (S–O) interaction [11], in order to create devices that utilise spin modulation and control to perform logic operations. Recently, evidence has begun to emerge of a strong Rashba S–O interaction in Ge QWs [12–14]. In particular, Ge QWs offer an excellent opportunity to study the cubic Rashba interaction in a material in which the Dresselhaus spin–orbit interaction due to bulk inversion asymmetry [15] is absent.

We examine the use of two complementary magnetotransport analyses for identifying and quantifying the Rashba S–O interaction in Ge. We find that both techniques are essential and either or both can be used to study the Rashba S–O interaction, dependent on other material parameters which may obscure the characteristic magnetotransport features associated with the Rashba S–O interaction. We present a detailed effective mass and scattering parameter analysis for two Ge QW heterostructures. Finally, we examine the material parameters that affect magnetotransport in Ge QWs and propose reasons the Rashba S–O effect is or is not observed, and the ideal system for studying these effects.

2. Experimental details

The Ge heterostructures studied here were grown by reduced pressure chemical vapour deposition (RP-CVD) onto standard 100 mm diameter (001) Si substrates. The layer structures of the two heterostructures (hereby referred to as sample 1 and sample 2, exhibiting parallel conduction at all temperatures) are shown schematically in Fig. 1(a) and (b), respectively. First, a 600 nm Ge layer was grown, followed by a reverse linearly graded (RLG) buffer of SiGe down to 80% Ge ($Si_{0.2}Ge_{0.8}$) over a thickness of 1600 nm [16]. At this point the growth of the two samples differs. For sample 1, a 10 nm Boron (B) doped $Si_{0.2}Ge_{0.8}$ region was grown next, followed by a $Si_{0.2}Ge_{0.8}$ spacer of 20 nm. Onto this spacer an 11 nm pure Ge quantum well (QW) was grown, which was then capped with 30 nm $Si_{0.2}Ge_{0.8}$ and 2 nm of Si. This structure is known as an inverse modulation doped heterostructure due to the remote doping layer being located below the QW channel. For sample 2, a 22 nm pure Ge QW was grown directly onto the RLG buffer, followed by a spacer of 20 nm

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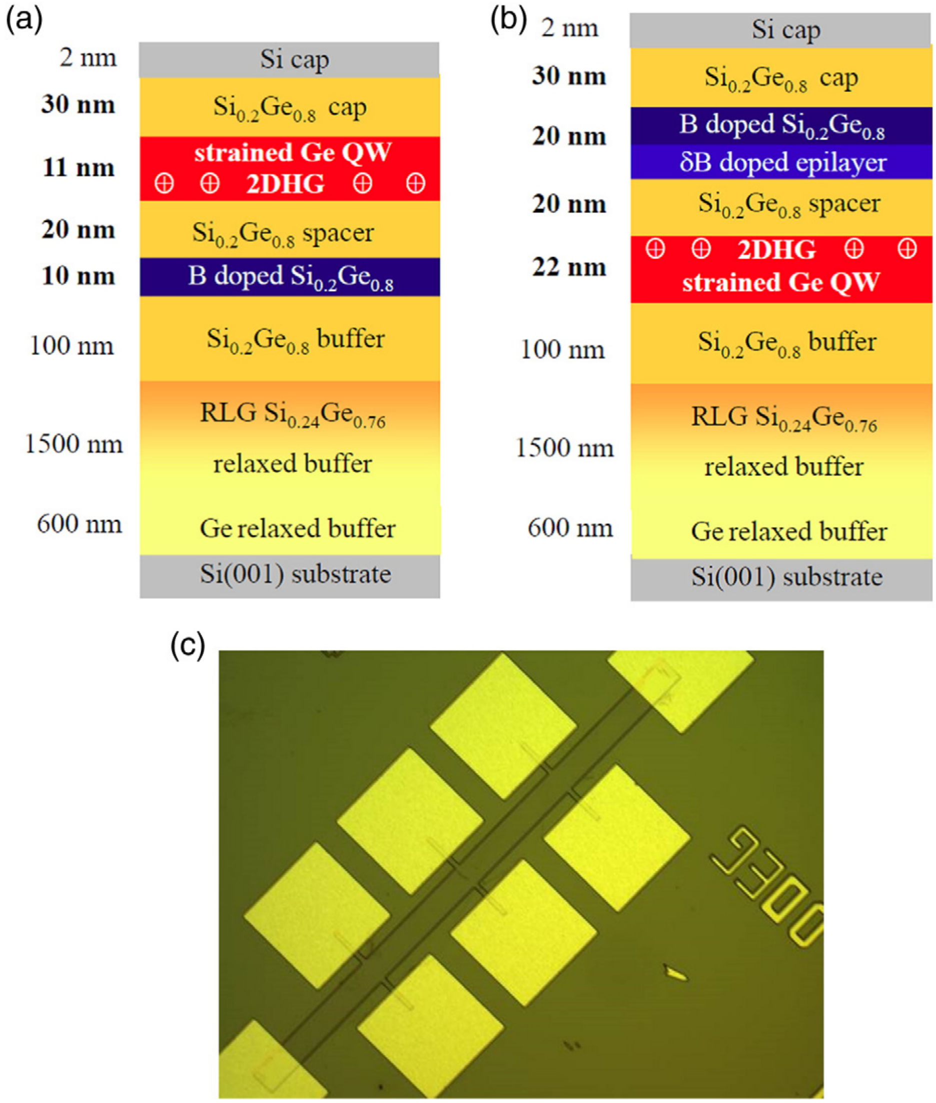

Fig. 1. (a) Layer structure of sample 1. (b) Layer structure of sample 2. (c) Optical image of an example Hall bar device fabricated on sample 2.

$Si_{0.2}Ge_{0.8}$. A delta layer of B was then grown, followed by a further 20 nm $Si_{0.2}Ge_{0.8}$ doped with B. Sample 2 was then capped with 30 nm of undoped $Si_{0.2}Ge_{0.8}$ and 2 nm of Si.

Hall bar devices were fabricated on both samples using the same process. First, contact pads were defined using photolithography and metallised with Al or Au/Ag deposited by thermal evaporation. The mesa region was then defined with photolithography and a dry plasma etch in SF_6 with a small percentage of O_2 was used to etch the heterostructure down to the Si substrate. An image of one of the fabricated Hall bar devices is shown in Fig. 1(c). Finally, the devices were annealed at 425 °C for 25 min for Al contacts or 300 °C for 30 min for Au/Ag contacts to diffuse the metal down through and below the Ge QW to form an ohmic contact directly to the layer. While this results in contact to all of the upper layers in the heterostructure, these layers freeze out at low temperatures leaving transport only in the QW. This is evidenced by metallic transport behaviour where a constant, high mobility is measured at temperatures below 20 K (450,000 cm^2/Vs for sample 1 and 777,000 cm^2/Vs for sample 2) with a constant carrier density (5.9×10^{11} cm^{-2} for sample 1 and 1.9×10^{11} cm^{-2} for sample 2). If Ohmic contact is not made to the QW region then we instead observe freeze out at low temperatures and a large increase in sheet resistance corresponding to transport through a semiconducting region at low temperature.

Low temperature magnetotransport measurements were performed in an Oxford Instruments Heliox AC-V ^{3}He cryostat with a base temperature of 0.3 K and maximum magnetic field of 12 T and a Quantum Design Physical Property Measurement System with ^{3}He insert with a base temperature of 0.4 K and maximum magnetic field of 9 T. Longitudinal (R_{xx}) and transverse (R_{xy}) resistances were measured using either a Stanford Research Systems SR830 lock-in amplifier or a LakeShore Model 372AC resistance bridge. In both cases an applied current of 100 nA was used at a frequency of 19.77 Hz.

3. Magnetotransport properties

Low temperature magnetotransport measurements are shown in Fig. 2 for sample 1 (2(a)) and sample 2 (2(b)). Clear Shubnikov de-Haas (SdH) oscillations are visible for both heterostructures, arising from Landau level quantisation under the applied magnetic field. For sample 1, the SdH oscillations display a structure that deviates from that expected from integer Landau level formation at finite temperature (i.e. a damped sinusoid), displaying instead a 'beating' structure with