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Extremely high room-temperature two-dimensional hole gas mobility in $Ge/Si_{0.33}Ge_{0.67}/Si(001)$ *p*-type modulation-doped heterostructures

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To extract the room-temperature drift mobility and sheet carrier density of two-dimensional hole gas (2DHG) that form in Ge strained channels of various thicknesses in $Ge/Si_{0.33}Ge_{0.67}/Si(001)$ *p*-type modulation-doped heterostructures, the magnetic field dependences of the magnetoresistance and Hall resistance at temperature of 295 K were measured and the technique of maximum entropy mobility spectrum analysis was applied. This technique allows a unique determination of mobility and sheet carrier density of each group of carriers present in parallel conducting multilayers semiconductor heterostructures. Extremely high room-temperature drift mobility (at sheet carrier density) of 2DHG 2940 $cm^2 V^{-1} s^{-1}$ (5.11×10^{11} cm^{-2}) was obtained in a sample with a 20 nm thick Ge strained channel. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1473690]

There has been considerable attention directed towards realizing high-speed *p*-type field-effect transistors (FETs) in Si-based materials, because the performance of complementary–metal–oxide–semiconductor (CMOS) type circuits is limited by *p*-type devices due to their lower hole mobility. In order to enhance the hole mobility, several types of Si/Ge heterostructures have been intensively studied.[1] Among them, the SiGe/pure-Ge channel/SiGe heterostructure is considered to provide the highest mobility since the effective hole mass decreases with an increase in Ge content and there is no alloy scattering which may dominate transport in SiGe alloys. Strained pure-Ge channel modulation-doped (MOD) structures with very high hole mobility were successfully fabricated on Si substrates by several groups.[2,3] Hock *et al.*[4] performed mobility spectrum analysis (MSA) to extract the mobility of holes only in a pure-Ge channel excluding the effects of parallel conductions and they obtained mobility of 1665 $cm^2 V^{-1} s^{-1}$ (at 8×10^{11} cm^{-2}) at room temperature (RT), which was the highest value until Madhavi *et al.*[5] reported Hall mobility of 1700 $cm^2 V^{-1} s^{-1}$ (at 7.9×10^{11} cm^{-2}). It was achieved by reducing the contribution by parasitic conducting layers in $Ge/Si_{0.3}Ge_{0.7}$ MOD heterostructures. However, this value is still lower than the bulk Ge one (1900 $cm^2 V^{-1} s^{-1}$) in spite of modification of the band structure caused by compressive strain, i.e., decreasing the effective hole mass and increasing the band splitting between heavy-hole and light-hole bands.

We previously reported that pure-Ge channel MOD structures with very high mobility could be grown by utilizing a low-temperature buffer technique,[2,6] which provided very high quality SiGe strain relaxed buffer layers with high Ge contents. The highest measured Hall mobility at RT was 1320 $cm^2 V^{-1} s^{-1}$. However, the mobility only in the pure-Ge channel in our multilayer samples should be much higher because the effects of parallel conduction were never excluded in our measurements. Then, in order to extract the intrinsic mobility in the strained Ge channel of our samples and to investigate the amount and the origin of parallel conductions, we carried out MSA. It was found that the mobilities of holes in the strained Ge channel layers were extremely high and beyond the bulk Ge value.

Samples were grown by solid-source molecular beam epitaxy on *n*-type (5–10 Ω cm), (100)-oriented Si substrates. Relaxed $Si_{0.33}Ge_{0.67}$ buffer layers were grown by the two-step low temperature (LT)-buffer technique. In the first step, a 500 nm $Si_{0.73}Ge_{0.27}$ layer was grown at 600 °C on 50 nm LT-Si layers. Then, a 500 nm $Si_{0.33}Ge_{0.67}$ layer was grown at 500 °C on 50 nm LT-$Si_{0.73}Ge_{0.27}$ layers. LT-Si layers and LT-$Si_{0.73}Ge_{0.27}$ layers were grown at 400 and 300 °C, respectively. Next, 10 nm B-doped layers ($\sim2\times10^{18}$ cm^{-3}), 20 nm spacer layers, a Ge channel, and 40 nm capping layers were grown successively on the buffer. The channel thickness in sample A was 7.5 nm and in sample B was 20 nm and the growth temperatures were 350 and 300 °C, respectively. Lowering of the growth temperature was needed to grow a thicker channel without strain relaxation.[2]

First, the Hall mobility and sheet carrier density were obtained by combining Hall and resistivity measurements in

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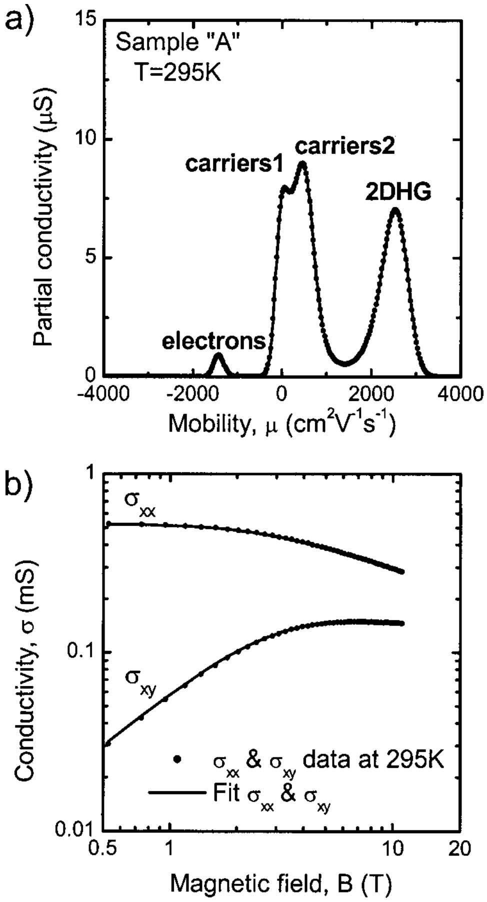

FIG. 1. Mobility spectrum (a) as the result of the $\sigma_{xx}(B)$ and $\sigma_{xy}(B)$ fits (b) measured at 295 K for sample A. The number of magnetic field points in (b) is 50 and the number of carriers in (a) is 300. Total deviation squared $\chi^2 = 8.8\times10^{-5}$.

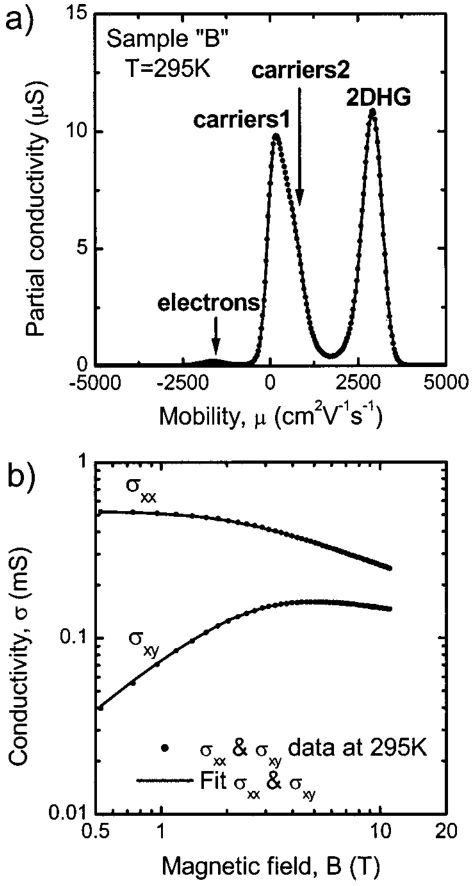

FIG. 2. Mobility spectrum (a) as the result of the $\sigma_{xx}(B)$ and $\sigma_{xy}(B)$ fits (b) measured at 295 K for sample B. The number of magnetic field points in (b) is 50 and the number of carriers in (a) is 300. Total deviation squared $\chi^2 = 7.4\times10^{-5}$.

the temperature range of 10–300 K. Samples were fabricated in Hall-bar geometry. Ohmic contacts were formed by evaporating AuGa. The sample with a thinner Ge channel showed better magnetotransport properties at 10 K. The Hall mobility of the two-dimensional hole gas (2DHG) (at the sheet carrier density) that formed in the Ge channel of samples A and B measured at 10 K was $15\,770\ \mathrm{cm^2\,V^{-1}\,s^{-1}}$ ($1.11\times10^{12}\ \mathrm{cm^{-2}}$) and $7570\ \mathrm{cm^2\,V^{-1}\,s^{-1}}$ ($9.55\times10^{11}\ \mathrm{cm^{-2}}$), respectively. At room temperature the situation was the reverse. The sample with a thicker Ge channel showed better Hall mobility. The Hall mobility (at the sheet carrier density) measured at 295 K in samples A and B was $1110\ \mathrm{cm^2\,V^{-1}\,s^{-1}}$ ($2.97\times10^{12}\ \mathrm{cm^{-2}}$) and $1440\ \mathrm{cm^2\,V^{-1}\,s^{-1}}$ ($2.28\times10^{12}\ \mathrm{cm^{-2}}$), respectively.

Samples A and B were optimized during different growth experiments for their best low and room temperature Hall mobilities, respectively.[2] We present two samples to show that the structure (sample A) optimized to get higher Hall mobility at low temperatures does not show higher mobility at room temperature in comparison with the structure (sample B) optimized for higher Hall mobility at room temperature. We stress this point to contrast our results to the results reported by Madhavi *et al.*,[5] who used thicker buffer layers and reported no pronounced channel thickness (in the range of 10–15 nm) effects on the Hall mobility.

The sheet carrier density determined from Hall effect technique measurements is $p_{\mathrm{Hall}} = (e\times R_H)^{-1}$. This equation is valid for one type of carrier only. At low temperatures it is true and corresponds to the value of 2DHG that formed in the strained Ge channel when all parasitic conductions and background impurities were frozen out. In our case it is in very good agreement with the values predicted by numerical solution of a one-dimensional (1D) Schrödinger–Poisson simulation. With an increase in the temperature from 20 to 300 K conduction in parasitic parallel layers occurs. In this case the average mobility and average sheet carrier density of all conducting layers are measured by the Hall effect technique and the simple equation $p_{\mathrm{Hall}} = (e\times R_H)^{-1}$ no longer represents the sheet carrier density in the Ge channel. To solve this problem the magnetic field dependences of the magnetoresistance and Hall resistance at 295 K were measured and MSA was applied. MSA was proposed by Beck and Anderson,[7] and was further developed by Dziuba *et al.*,[8] by Antoszewski *et al.*,[9] by Vurgaftman *et al.*,[10] and by Kiatgamolchai *et al.*[11,12] as a useful technique for analyzing multi-carrier galvanomagnetic phenomena. MSA is the transformation of the electrical conductivity tensor versus the magnetic field into the conductivity density versus the mobility spectrum. The technique allows a unique determination of the mobility and sheet carrier density of each group of carriers present in parallel conducting multilayers of semiconductor heterostructures. The magnetic field dependences of the magnetoresistance and Hall resistance were measured at 295 K as the magnetic field (B) was swept continuously

TABLE I. Average Hall mobility and sheet carrier density of Ge/$Si_{0.33}Ge_{0.67}$/Si(001) multilayered heterostructures at 295 K in comparison with the 2DHG drift mobility and sheet carrier density for the strained Ge *p*-channel only extracted by ME-MSA.

Sample	Ge channel thickness (nm)	μ_{Hall} ($cm^2\ V^{-1}\ s^{-1}$)	p_{Hall} (cm^{-2})	μ_d (2DHG) ($cm^2\ V^{-1}\ s^{-1}$)	p_s (2DHG) (cm^{-2})
A	7.5	1110	2.97×10^{12}	2540	5.12×10^{11}
B	20	1440	2.28×10^{12}	2940	5.11×10^{11}

from -11 up to $+11$ T and the reversd. After that an average was taken and the magnetoresistance and Hall resistance were converted into conductivity tensor components $\sigma_{xx}(B)$ and $\sigma_{xy}(B)$ followed by a maximum entropy-MSA (ME-MSA) fit procedure.[11,12] It is worth pointing out that the ME-MSA approach does not require any preliminary assumptions about the number of different types of carriers and this aspect is very important for transport phenomena analysis in semiconductor structures.

Mobility spectra as a result of the conductivity tensor component $\sigma_{xx}(B)$ and $\sigma_{xy}(B)$ fits of samples A and B are presented in Figs. 1 and 2, respectively. The fitted magnetic field dependences of $\sigma_{xx}(B)$ and $\sigma_{xy}(B)$ are in very good agreement with the measured ones for both samples (see Figs. 1 and 2). For both samples the mobility spectrum consists of four peaks. The small peaks with negative mobility around $-1500\ cm^2\ V^{-1}\ s^{-1}$ in the spectrum show the existence of electrons, which may come from a Si *n*-type substrate or a thin Si tensile strained cap layer on the surface. Two merged peaks around $\sim300\ cm^2\ V^{-1}\ s^{-1}$ correspond to the group of carriers in B-doped $Si_{0.33}Ge_{0.67}$ layers and to $Si_{0.33}Ge_{0.67}$ and $Si_{0.73}Ge_{0.27}$ layers in the two-step LT buffer. These parallel conductions significantly reduce not only the Hall mobility but also device performance. Work on optimizating the doping profile and reducing the background impurities to decease these parallel conductions is now underway. The peaks with the highest mobilities in the spectra correspond to the 2DHG that formed in the strained Ge channels. In contrast to the mobilities of carriers in the parallel conducting layers, the mobilities of 2DHG increase with a decrease in temperature (further details of this will be published). Also, the increase in conductivity of 2DHG with a decrease in temperature was observed. Others peaks showed conductivity freeze out behavior with a decreasing in temperature and could be considered to be from parasitic channels in our structures. The drift mobility (at the sheet carrier density) of 2DHG at 295 K extracted from the mobility spectrum is $2540\ cm^2\ V^{-1}\ s^{-1}$ ($5.12\times10^{11}\ cm^{-2}$) and $2940\ cm^2\ V^{-1}\ s^{-1}$ ($5.11\times10^{11}\ cm^{-2}$) for samples A and B, respectively. These are, we believe, the highest published values of drift mobility of 2DHG formed in the Ge strained channel at room temperature and much higher than the bulk Ge mobility. This indicates that strain increases the hole mobility in the Ge channel probably by reducing the effective hole mass and increasing the band splitting between heavy-hole and light-hole bands to reduce intervalley scattering. To the best of our knowledge, this is one of the first reports to show that the mobility of strained Ge exceeds that of the bulk. The results of the Hall and resistivity measurements and MSA at 295 K for both samples are summarized in Table I. The higher mobility of sample B is consistent with the results of the Hall measurements, and may be caused by the difference in interface roughness scattering due to the lower growth temperature and the thicker Ge channel in sample B.

In conclusion, we characterized pure-Ge strained channel *p*-type MOD heterostructures by mobility spectrum analysis and found that the drift mobility (at the sheet carrier density) of holes in Ge channel layers reached $2940\ cm^2\ V^{-1}\ s^{-1}$ ($5.11\times10^{11}\ cm^{-2}$) at 295 K which exceeded the bulk Ge value. This result clearly indicates that strain really does increase the carrier mobility.

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