APPLIED PHYSICS LETTERS VOLUME 82, NUMBER 9 3 MARCH 2003

Hole density dependence of effective mass, mobility and transport time in strained Ge channel modulation-doped heterostructures

T. Irisawa[a)]
Department of Applied Physics, The University of Tokyo, 7-3-1, Hongo, Bunkyo-ku, Tokyo 113-8656, Japan

M. Myronov
Department of Physics, University of Warwick, Coventry, CV4 7AL United Kingdom

O. A. Mironov
Department of Physics, University of Warwick, Coventry, CV4 7AL United Kingdom and International Laboratory of High Magnetic Fields and Low Temperatures, 53-421 Wroclaw, Poland

E. H. C. Parker
Department of Physics, University of Warwick, Coventry, CV4 7AL United Kingdom

K. Nakagawa
Center for Crystal Science and Technology, 7 Miyamae-cho, Kofu 400-0021, Japan

M. Murata, S. Koh, and Y. Shiraki
Department of Applied Physics, The University of Tokyo, 7-3-1, Hongo, Bunkyo-ku, Tokyo 113-8656, Japan

(Received 25 November 2002; accepted 13 January 2003)

We performed systematic low-temperature ($T=350$ mK–15 K) magnetotransport measurements on the two-dimensional hole gas with various sheet carrier densities $P_s=(0.57-2.1)\times 10^{12}$ cm^{-2} formed in the strained Ge channel modulation-doped (MOD) SiGe heterostructures grown on Si substrates. It was found that the effective hole mass deduced by temperature dependent Shubnikov–de Hass oscillations increased monotonically from $(0.087\pm 0.05)m_0$ to $(0.19\pm 0.01)m_0$ with the increase of P_s, showing large band nonparabolicity in strained Ge. In contrast to this result, the increase of the mobility with increasing P_s (up to 29 000 cm^2/V s) was observed, suggesting that Coulomb scattering played a dominant role in the transport of the Ge channel at low temperatures. In addition, the Dingle ratio of the transport time to the quantum lifetime was found to increase with increasing P_s, which was attributed to the increase of remote impurity scattering with the increase of the doping concentration in MOD SiGe layers.
[DOI: 10.1063/1.1558895]

The enhancement of carrier mobility is one of the most attractive features concerning the band engineering based upon SiGe heterostructures and it is expected to open the way to surpassing the limit of conventional Si metal–oxide–semiconductor field-effect transistors (MOSFETs). Especially, the enhancement of hole mobility in Si-based materials is very attractive because the *p*-type device limits the performance of complementary MOS type circuits due to its lower mobility. Among various types of SiGe heterostuctures designed to increase the hole mobility, the strained Ge channel modulation-doped (MOD) structure has provided the highest mobilities at both low temperature (87 000 cm^2/V s at 4.2 K)[1] deduced by standard Hall measurement and room temperature (3000 cm^2/V s)[1,2] extracted from mobility spectrum technique.[3] This mobility increase comes from the fact that the effective hole mass decreases with increasing Ge content and the alloy scattering dominating transport in SiGe alloys does not exist in the pure-Ge channel. By utilizing this ultrahigh mobility structure, the strained Ge channel MOSFET with the effective hole mobility of 2700 cm^2/V s at room temperature was demonstrated recently.[4] The basic transport properties of two-dimensional hole gas (2DHG) in the strained Ge channel, however, have not been systematically studied so far. Not only the carrier density dependence of the effective hole mass but also that of the mobility itself has not been well investigated yet. This is partly because the fabrication of the strained Ge channel structures with high quality $Si_{1-x}Ge_x$ strain relaxed buffer layers is very difficult for high Ge content ($x>0.6$). To overcome this problem, we developed the so-called low-temperature buffer technique and demonstrated that very high quality strained Ge channel MOD structures could be grown on Si substrates.[5,6] By using these samples, we can perform the systematic magnetotransport measurements on 2DHG in the strained Ge channel MOD structures and clarify the carrier density dependence of the effective hole mass, mobility, and the Dingle ratio of the transport time to the quantum lifetime.

All samples were grown on *n*-type (5–10 Ω cm), (100)-oriented Si substrates by solid-source molecular-beam epitaxy. To obtain high quality $Si_{0.3}Ge_{0.7}$ strain relaxed buffer layers, we utilized a two-step low-temperature (LT) buffer technique, where 500 nm $Si_{0.7}Ge_{0.3}$ layers were grown on 50 nm LT–Si layers followed by 500 nm $Si_{0.3}Ge_{0.7}$ layers grown on 50 nm LT–$Si_{0.7}Ge_{0.3}$ layers. The details of the growth conditions were reported elsewhere.[6] The active areas grown on $Si_{0.3}Ge_{0.7}$ buffer layers consisted of 10 nm B-doped layers beneath and/or above the channel, 10 or 20 nm spacer layers,

a)Electronic mail: irisawa@photonics.rcast.u-tokyo.ac.jp

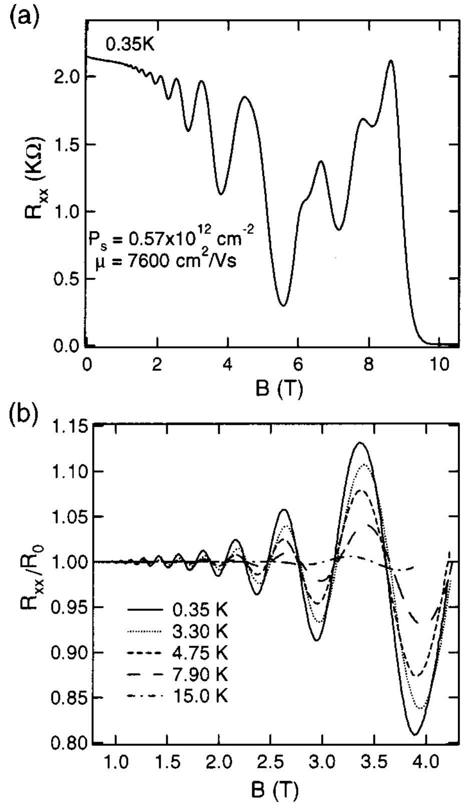

FIG. 1. (a) Magnetic field dependence of longitudinal resistance at 0.35 K for the sample with d_{ch} and d_{sp} of 20 nm. (b) Magnetic field dependence of longitudinal resistance at various temperatures for the same sample as that for (a). Here, the longitudinal resistance is normalized to that at $B=0$ and the nonoscillatory background magnetoresistance is subtracted out.

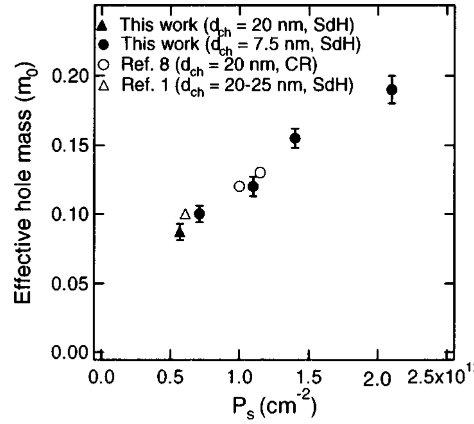

FIG. 2. Effective hole mass as a function of P_s. Filled symbols indicate the values obtained in this work (●: d_{ch}=7.5 nm, ▲: d_{ch}=20 nm) and open ones are from Ref. 8 (○: d_{ch}=20 nm) and Ref. 1 (△: d_{ch}=20–25 nm). Only the values from Ref. 8 are obtained by cyclotron resonance.

7.5 or 20 nm Ge channels, and 40 nm $Si_{0.7}Ge_{0.3}$ and 3 nm Si capping layers. The channel thickness (d_{ch}) of 7.5 and 20 nm gave rise to the highest low- and room-temperature mobility, respectively.[6] To change the sheet carrier density (P_s), the nominal doping concentration was varied from 5×10^{17} to 2.0×10^{18} cm^{-3}. Hall bars have been processed by optical lithography and conventional wet etching techniques. Ohmic contacts were made by AuGa deposition. Magnetotransport measurements were carried out by using standard low frequency ($f=13$ Hz) ac look-in amplifiers technique in the temperature range of 350 mK–15 K with magnetic fields up to 11 T.

Figure 1(a) shows the magnetic field (B) dependence of longitudinal resistance (R_{xx}) at 350 mK for the sample with d_{ch} and spacer layer thickness (d_{sp}) of 20 nm. It is noted that this sample has the highest room-temperature mobility[2] as high as 2940 cm^2/V s which is much higher than that of bulk Ge (1900 cm^2/V s). Well-resolved Shubnikov–de Hass (SdH) oscillations can be seen, confirming the existence of 2DHG and good crystal quality of the strained Ge channel. The single periodicity of R_{xx} in $1/B$ below $B<4$ T indicates that the only lowest heavy hole subband is occupied. The lifting of the degeneracy of the light and heavy hole bands is caused by the compressive strain in the Ge channel. The sheet carrier density, P_s, obtained from this periodicity is 5.7×10^{11} cm^{-2}. Peak splitting caused by the Zeeman effect was clearly observed above $B>6$ T. Figure 1(b) shows the temperature dependence of SdH oscillations ($B<4$ T) up to 15 K for the same sample as that of Fig. 1(a). Here, R_{xx} is normalized to the resistance at $B=0$ (R_0) and the negative nonoscillatory background magnetoresistance is subtracted out. The thermal damping of the SdH oscillations enable us to determine the effective mass[7,8] and it was deduced to be $(0.087\pm0.005)m_0$ where m_0 is free electron mass. This value is much smaller than unstrained bulk Ge heavy hole mass ($0.28\,m_0$), which clearly indicates the effect of strain on decreasing hole mass. This extremely reduced effective hole mass can be a main reason for ultrahigh room-temperature mobility reported so far.[2] Of course, band splitting between light and heavy hole bands which decreases interband scattering may also contribute to the increase of mobility.

Since it was considered that the effective hole mass strongly depends on P_s because of the band nonparabolicity in the valence band structure, we prepared a series of samples having various P_s. The samples with P_s higher than 1.3×10^{12} cm^{-2} had two MOD SiGe layers beneath and above the channel while the others had the MOD layer only beneath the channel. We observed single periodicity of SdH oscillations in all samples, confirming that the second subband occupation did not occur in these samples. The obtained effective hole mass deduced from the temperature dependent SdH oscillations is shown as a function of P_s in Fig. 2. The values reported by Nützel *et al.*[9] (from cyclotron resonance, $d_{ch}=20$ nm) and Känel *et al.*[1] (from SdH oscillations, $d_{ch}=20$–25 nm) are also plotted in this figure. It is seen that the effective hole mass monotonically increases up to $(0.19\pm0.01)m_0$ at P_s of 2.1×10^{12} cm^{-2} with increasing P_s, which is a direct evidence of large nonparabolicity in the valence band structure of strained Ge. Meanwhile, there is no significant d_{ch} dependence of the effective hole mass.

In Fig. 3 we show the P_s dependence of the mobility at 8 K obtained by Hall measurements for samples with d_{ch} of 7.5 or 20 nm and d_{sp} of 10 nm. Although the effective hole mass increased with increasing P_s, the Hall mobility was seen to increase with increasing P_s in both series of samples with different d_{ch}. It reached the maximum value of 29 000 cm^2/V s at 2.1×10^{12} cm^{-2} in the sample with d_{ch} of 7.5 nm. The increase of the mobility with the increase of P_s can be explained in terms of the increased screening effect on Coulomb scattering, suggesting that the scattering due to ion-

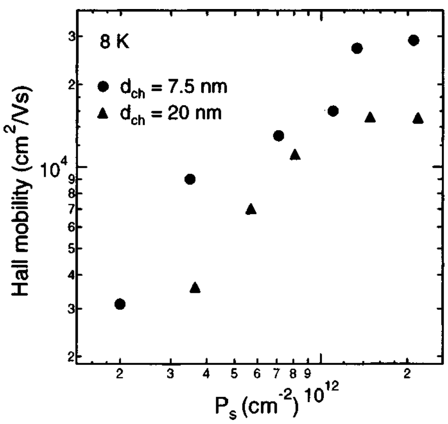

FIG. 3. Hall mobility as a function of P_s at 8 K in samples with d_{ch} of 7.5 (●) or 20 nm (▲) and d_{sp} of 10 nm.

ized background impurities and/or remote impurities in MOD layers plays a dominant role at low temperatures in the present samples and that the screening effect overcomes the effect of the increase of the effective hole mass. This result is in contrast to the report of Madhavi *et al.*[10] that only interface roughness scattering limits the low temperature mobility. The reason for smaller mobility of wider channel (20 nm) samples in the entire range of P_s is that there are additional scattering mechanisms in these samples. Partial strain relaxation of the Ge channel[6] is one of possible mechanisms and it may cause surface roughening, strain fluctuations and formation of misfit dislocations.

Figure 4 shows the P_s dependence of the ratio α of the transport time to the quantum lifetime which was deduced from Dingle plots of SdH oscillations.[8] It is known that α becomes close to unity when large angle scattering such as interface roughness scattering and background impurity scattering are dominant while it becomes 10 or significantly larger when such small angle scattering as remote impurity scattering is dominant.[11] In the present case, α is around 5 and increases slightly with increasing P_s up to 1.1×10^{12} cm^{-2} but it increases drastically to around 15 when P_s increases to 2.1×10^{12} cm^{-2}. This means that the background impurity scattering is screened by the increased P_s and finally the remote impurity scattering becomes dominant, which is consistent with the earlier conclusion that the impurity scattering dominates the transport of the Ge channels at low temperatures. The extremely small α, 1.5, of the sample with d_{ch} of 20 nm may be attributed to the additional scattering arising from the strain relaxation of the Ge channel as mentioned earlier.

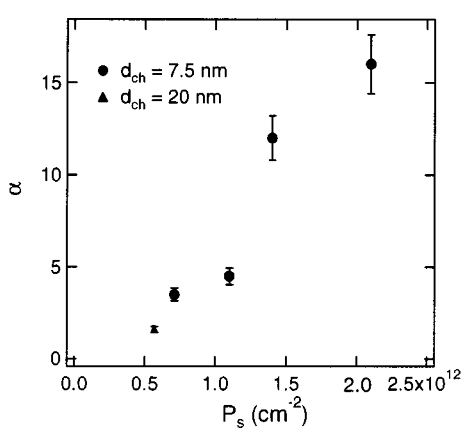

FIG. 4. The ratio α of the transport time to the quantum lifetime as a function of P_s in samples with d_{ch} of 7.5 (●) or 20 nm (▲). Each point corresponds to that in Fig. 2.

In summary, we have measured P_s dependence of the low temperature hole mobility and the effective hole mass in the strained Ge channel MOD structures and found that the effective hole mass monotonically increased from $(0.087 \pm 0.05)m_0$ to $(0.19\pm 0.01)m_0$ with increasing P_s from 5.7×10^{11} to 2.1×10^{12} cm^{-2} while the mobility also increased with the increase of P_s. The Dingle ratio α of the transport time to the quantum lifetime was obtained from SdH measurements and found to increase up to around 15 with increasing P_s. These results clearly indicate that Coulomb scattering plays a dominant role in the strained Ge channels at low temperatures and that the remote impurity scattering increases with increasing doping concentration.

The authors would like to acknowledge S. Otake for his technical assistance. This work was supported in part by the grants-in-Aid for Scientific Research on Priority Area (Nos. 11232202, 13650007) from the Ministry of Education, Culture, Sports, Science and Technology and International Collaboration program of Japan Society for the Promotion of Science (JSPS), the UK HMOS Program, and by INTAS-01-0184 Project. One of the authors (T.I.) would like to acknowledge the support from JSPS Fellowships for Japanese Junior Scientists.

[1] H. Känel, M. Kummer, G. Isella, E. Müller, and T. Hackbarth, Appl. Phys. Lett. **80**, 2922 (2002).
[2] M. Myronov, T. Irisawa, O. A. Mironov, S. Koh, Y. Shiraki, T. E. Whall, and E. H. C. Parker, Appl. Phys. Lett. **80**, 3117 (2002).
[3] S. Kiatgamolchai, M. Myronov, O. A. Mironov, V. G. Kantser, E. H. C. Parker, and T. E. Whall, Phys. Rev. E **66**, 036705 (2002).
[4] T. Irisawa, S. Tokumitsu, T. Hattori, K. Nakagawa, S. Koh, and Y. Shiraki, Appl. Phys. Lett. **81**, 847 (2002).
[5] T. Ueno, T. Irisawa, and Y. Shiraki, Thin Solid Films **369**, 320 (2000).
[6] T. Irisawa, H. Miura, T. Ueno, and Y. Shiraki, Jpn. J. Appl. Phys., Part 1 **40**, 2694 (2001).
[7] P. T. Coleridge, R. Stoner, and R. Fletcher, Phys. Rev. B **39**, 1120 (1989).
[8] T. E. Whall, N. L. Mattey, A. D. Plews, P. J. Phillips, O. A. Mironov, R. J. Nicholas, and M. J. Kearney, Appl. Phys. Lett. **64**, 357 (1994).
[9] J. F. Nützel, C. M. Engelhardt, R. Wiesner, D. Többen, M. Holzmann, and G. Abstreiter, J. Cryst. Growth **150**, 1011 (1995).
[10] S. Madhavi, V. Venkataraman, and Y. H. Xie, J. Appl. Phys. **89**, 2497 (2001).
[11] A. Gold, Phys. Rev. B **38**, 10798 (1988).