Extended Abstracts of the 22nd (1990 International) Conference on Solid State Devices and Materials, Sendai, 1990, pp. 373-376



# High Hole Mobility and High Sheet Hole Concentration in p-Si/SiGe Modulation Doped Heterostructures Grown by MBE

T. MISHIMA*, C.W.FREDRIKSZ, G.F.A. VAN DE WALLE,
D.J. GRAVESTEIJN, R.A. VAN DEN HEUVEL, AND A.A. VAN GORKUM.

Philips Research Laboratories,
P.O. Box 80.000, 5600 JA Eindhoven, The Netherlands.
*Exchange researcher from Hitachi CRL, Tokyo, Japan.

It is shown that a two-dimensional hole gas in a normal p-Si/$Si_{0.8}Ge_{0.2}$ modulation doped heterostructure (doped layer at surface side) shows a higher hole mobility than that in an inverted structure (doped layer at substrate side). SIMS indicates that the lower mobility in the inverted structure is due to surface segregation of boron. The influence of segregation is suppressed by using a thicker undoped spacer layer. Thus, the hole mobility in the inverted structure increased to 6000 $cm^2/Vs$ at 2K and 3800 $cm^2/Vs$ at 6 K. A very high sheet hole concentration of $2.8 \times 10^{12}$ $cm^{-2}$ has been obtained at low temperatures using a $Si_{0.6}Ge_{0.4}$ strained layer, resulting in a high conductivity ($6.7 \times 10^{-4}$ $\Omega^{-1}$).

## 1. Introduction

Recent progress in Si/SiGe strained layer heteroepitaxy has enabled the growth of high quality p-Si/SiGe modulation doped heterostructures. Previous papers have reported on p-Si/SiGe/p-Si double modulation doped heterostructures having two separated two-dimensional hole gases (2DHGs) at the interfaces[1-3]. This structure is advantageous in having a large conductance, but may suffer from a difference in electrical properties between the two 2DHGs. This phenomenon is known as "inverted interface problem" in the n-AlGaAs two-dimensional electron gas(2DEG) system in which only the surface-side 2DEG shows a high mobility[4,5]. The modulation doped structure with the doped layer at the surface side, having the highest mobility, has become called "normal type", and the other one, "inverted type".

In the present paper, it is clarified that this problem also exists in the p-Si/SiGe 2DHG system. The origin of the problem is investigated by secondary ion mass spectrometry (SIMS). Furthermore the effect of spacer layer thickness and Ge content are considered.

## 2. Experimental

p-Si/SiGe modulation doped heterostructures were grown on an n-Si substrate (≈1000 Ωcm) by molecular beam epitaxy (MBE) using a VG 6-inch wafer system. Figure 1 shows a normal and an inverted p-$Si/Si_{0.8}Ge_{0.2}$ modulation doped heterostructure

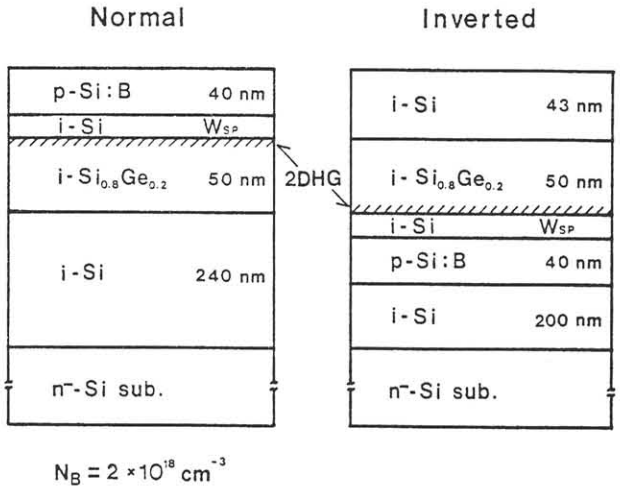


Fig.1 Normal and inverted p-$Si/Si_{0.8}Ge_{0.2}$ modulation doped heterostructures considered in this study.

which are considered in this study. The spacer layer thickness $W_{SP}$ is either 3 nm or 10 nm. The boron concentration was $2x10^{18}$ $cm^{-3}$. The growth temperature was 550°C. Rutherford backscattering spectrometry confirmed the composition and crystalline quality of the epitaxial layers.

To obtain a higher sheet hole concentration, a normal structure with a high Ge-mole fraction (40%) and a high B concentration ($5.5x10^{18}$ $cm^{-3}$) was grown. The layer structure was as follows:
i-Si(20nm)/p-Si:B (15nm)/i-Si($W_{SP}$=3nm)/ i-$Si_{0.6}Ge_{0.4}$(20nm)/i-Si(200nm)/n-Si substrate. The thickness of the $Si_{0.6}Ge_{0.4}$ layer was adapted to maintain commensurate pseudomorphic growth.

The electrical properties were measured with the conventional Hall-van der Pauw method between 4 and 300 K. B and Ge profiles were analyzed by SIMS.

## 3. Results and discussion

### 3.1 Comparison of normal and inverted p-Si/$Si_{0.8}Ge_{0.2}$ modulation doped heterostructures

Figure 2 shows the temperature-dependent electrical properties for a normal and an inverted structure with $W_{SP}$=3 nm. A 2DHG behaviour becomes apparent below 60 K, because at these temperatures holes in the p-Si layer freeze out. Sheet concentrations of two-dimensional holes in the normal type (N-2DHG) and that in the inverted type (I-2DHG) saturate at almost identical values ($\approx$ $1x10^{12}$ $cm^{-2}$). However the hole mobility of the I-2DHG saturates at a value lower than 1000 $cm^2$/Vs, while that of the N-2DHG continues to increase to more than 2000 $cm^2$/Vs with decreasing temperature. The most likely cause of this difference is thought to be surface segregation of the

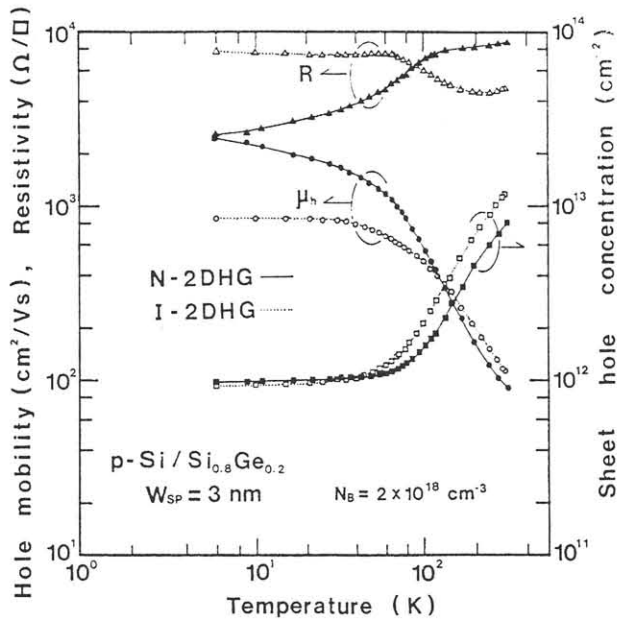


Fig.2 Electrical properties as a function of temperature for normal and inverted p-Si/$Si_{0.8}Ge_{0.2}$ modulation doped heterostructures with a spacer layer of 3 nm thickness.

dopant during MBE growth[6]. SIMS did not show any indication of this, possibly due to insufficient depth resolution. To enhance the effect of segregation, an identical inverted structure was grown, in which the p-Si layer was deposited at a higher temperature (690°C). During a 3-minutes growth interrupt the temperature was lowered to the normal value (550°C) and growth was resumed. The SIMS profile (Fig. 3) now shows that segregation has occured. Consequently a high sheet hole concentration of $1.8x10^{12}$ $cm^{-2}$ is found. The low mobility of 330 $cm^2$/Vs at 10 K is caused by ionized impurity scattering. Even during continuous epitaxial growth a 550°C some surface segregation is unavoidable. A boron concentration as low as $1x10^{16}$ $cm^{-3}$ at the Si/SiGe heterointerface is already sufficient to reduce the hole mobility[7]. The observations unambiguously show that the "inverted interface problem" also exists in the p-Si/SiGe 2DHG system.

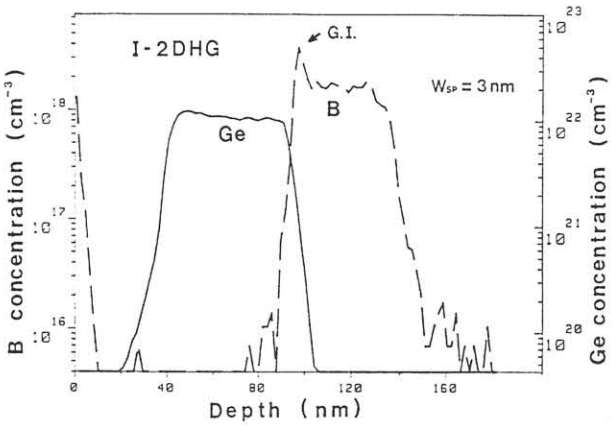


Fig.3 Results of SIMS analysis on B and Ge for a growth-interrupted inverted p-$Si/Si_{0.8}Ge_{0.2}$ modulation doped heterostructure with a spacer layer of 3 nm thickness.

### 3.2 Increase of hole mobility

A thicker spacer layer is expected to increase the hole mobility by reducing remote ionized impurity scattering. Especially for an inverted structure, the thicker spacer layer should also be effective in reducing the effect of segregated boron. Figure 4 shows the electrical properties of an inverted structure with a thicker spacer layer (10 nm). Now the hole mobility still increases at low temperatures, whereas the mobility for the inverted structure with the 3 nm spacer layer saturates at a low value (cf. Fig.2). The hole mobility increases up to 3800 $cm^2/Vs$ at 6 K, and 6000 $cm^2/Vs$ at 2 K.

### 3.3 Increase of sheet hole concentration

Increase of the Ge-mole fraction (40%) increases the strain in the SiGe layer. This leads to a higher valence band discontinuity ( $E_V$=296 meV [1]), and a higher sheet hole concentration. Figure 5 shows the electrical properties as a function of temperature for a normal p-$Si/Si_{0.6}Ge_{0.4}$ modulation doped heterostructure with $W_{SP}$ = 3 nm. The saturated sheet hole concentration is $2.8 \times 10^{12}$ $cm^{-2}$, which is 2.8 times higher than that in an $Si_{0.8}Ge_{0.2}$ channel with the same $W_{SP}$. The product of the sheet hole concentration and the mobility (1500 $cm^2/Vs$) results in a very high conductance ($6.7 \times 10^{-4}$ $\Omega^{-1}$), which is the highest reported so far, even when compared to double p-Si/SiGe modulation

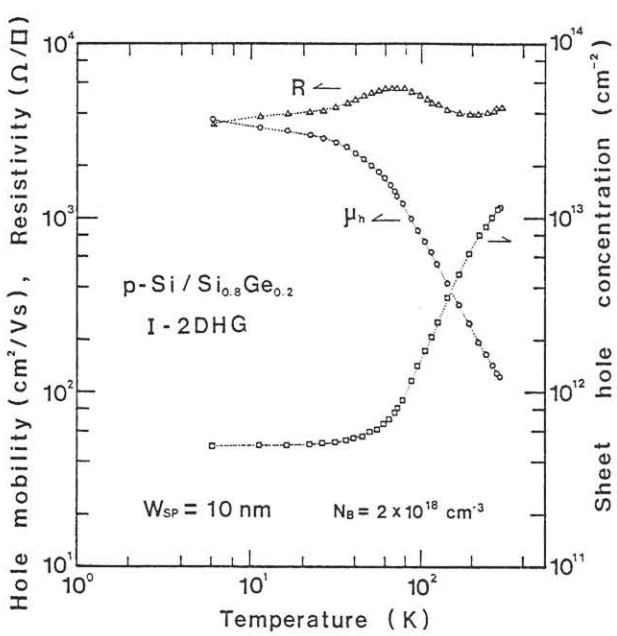


Fig.4 Electrical properties as a function of temperature for an inverted p-$Si/Si_{0.8}Ge_{0.2}$ modulation doped heterostructure with a spacer layer of 10 nm thickness.

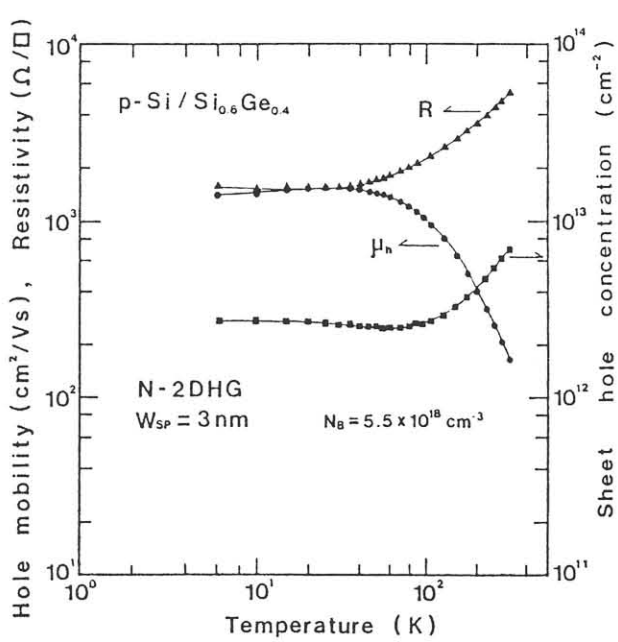


Fig.5 Electrical properties as a function of temperature for an normal p-Si/$Si_{0.6}Ge_{0.4}$ modulation doped heterostructure with a spacer layer of 3 nm thickness.

doped structures[3].

Figure 6 shows experimental and calculated sheet hole concentrations as a function of spacer layer thickness at 10 K. Both data from Shubnikov-de Haas and Hall measurements are depicted in the figure. The solid lines were calculated using the Fang-Howard (F-H) approximation[8] and applying a horizontal shift of 2.3 nm to larger $W_{sp}$-direction. It is known that in the case of n-AlGaAs/GaAs heterostructures, this procedure yields good agreement with selfconsistent numerical calculations[9]. A similar coincidence is expected in the p-Si/SiGe system because of the similarity in the most important parameters such as band-gap discontinuity. The curves in Fig.6 agree quite well with experiments, indicating the validity of the simple method. The figure indicates how effective the increase of the Ge fraction in SiGe and of the boron concentration in p-Si is to increase the sheet hole concentration.

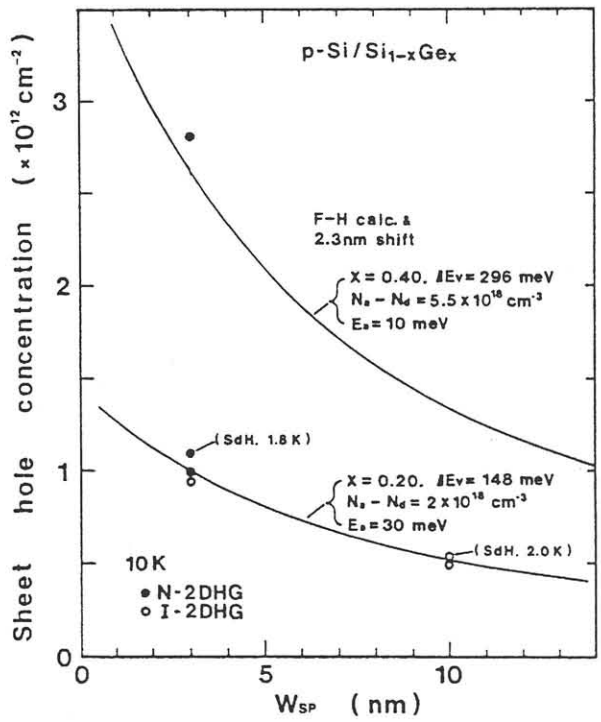


Fig.6 Comparison of measured and calculated sheet hole concentration as a function of the spacer layer thickness $W_{SP}$.

## 4. Summary

The hole mobility in a normal p-Si/-$Si_{0.8}Ge_{0.2}$ modulation doped heterostructure is higher than that in an inverted structure. The lower mobility in the inverted structure is most likely caused by surface segregation of B. The hole mobility in the inverted structure is improved by increasing the spacer layer thickness to 10 nm. High hole mobilities of 6000 $cm^2/Vs$ at 2 K and 3800 $cm^2/Vs$ at 6 K are observed. A very high hole concentration of $2.8 \times 10^{12}$ $cm^{-2}$ is obtained by increasing the Ge-mole fraction in the SiGe layer to 0.4. The structure shows record values both in sheet hole concentration at the single heterointerface and in conductivity.


## Acknowledgements

The work described in this paper was carried out as part of the researcher exchange program of Hitachi, Ltd and Philips. The first author gratefully acknowledges the hospitality of the Philips Research Laboratories.


## References


1) R. People, IEEE J. Quantum Electron., QE22 (1986), 1696.
2) R. People, J.C. Bean, D.V. Lang, A.M. Sergent, H.L. Störmer, H.W. Wecht, R.T. Lynch and K. Baldwin, Appl.Phys.Lett. 45 (1984), 1231.
3) P.J. Wang, B.S. Meyerson, F.F. Fang, J. Nocera and B. Parker, Appl.Phys.Lett. 55 (1989), 2333.
4) H. Morkoc, T.J. Drummond, R. Fischer and A.Y. Cho, J.Appl.Phys. 53 (1982), 3321.
5) S. Sasa, J. Saito, K. Nanbu, T. Ishikawa and S. Hiyamizu, Jap.J.Appl.Phys. 23 (1984), L573.
6) T. Tatsumi, H. Hirayama, N. Aizaki, Jap.J.Appl.Phys. 27 (1988), L954.
7) K. Takeda, A. Taguchi and M. Sakata, J.Phys.C. 16 (1983), 2237.
8) F.F. Fang and W.E. Howard, Phys.Rev.Lett. 16 (1966), 797.
9) T. Ando, J.Phys.Soc.Japan, 51 (1982), 3900.