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High Hole Mobility $Si/Si_{1-x}Ge_x/Si$ Heterostructure

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High mobility $Si/Si_{1-x}Ge_x/Si$ p-type modulation-doped double heterostructures have been grown by RRH/VLP-CVD (rapid radiant heating/very low pressure-CVD). Hole Hall mobilities as high as about $300\,cm^2/V\cdot s(293\,K)$ and $7500\,cm^2/V\cdot s(77\,K)$ have been obtained for heterostructures with $x = 0.3$. The variation of hole mobility with temperature and the influence of Ge fraction on hole mobility were investigated.

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In recent years, the Si/SiGe modulation doped (MD) heterostructures have created a great deal of interest for fundamental investigations and for high speed device applications (modulation doped field-effect devices). High electron mobility n-Si/SiGe MD heterostructure[1,2] and high hole mobility p-Si/SiGe MD heterostructure[3-5] have been reported.

In this letter, we report the growth of $Si/Si_{1-x}Ge_x/Si$ p-type modulation doped double heterostructures by rapid radiant heating/very low pressure-CVD (RRH/VLP-CVD).[6] Their electrical properties were measured and analyzed. The variation of hole mobility with temperature and the influence of Ge fraction on hole mobility were investigated.

$Si/Si_{1-x}Ge_x/Si$ MD double heterostructures with $x = 0.20$, 0.25, 0.30 and 0.35 were grown on (100) p^--Si substrates using an RRH/VLP-CVD system.[6] The growth temperature was 600°C. In the heterostructure schematically shown in Fig. 1, p^+-Si doping layer of 200 Å thickness were doped with boron to $1\text{–}3\times10^{19}\,cm^{-3}$ and $Si_{1-x}Ge_x$ strained layers of 400 Å thickness were not intentionally doped.

The thickness of undoped Si spacer layers is 150 Å. For comparison, uniformly doped (UD) samples were also grown under the same conditions. The $Si_{0.8}Ge_{0.2}$ of 2000 Å thickness were doped with boron to $1\text{–}3\times10^{19}\,cm^{-3}$.

Both the MD and UD samples were measured by conventional Hall-van der Pauw method. Hall data obtained at 293 and 77 K are listed in the table. From room temperature to low temperature (77 K), the hole Hall mobilities μ_H for all the MD samples (No. 1–4) increased obviously, while for UD samples (No. 5–6), the hole mobilities decreased. It shows clearly that the holes of MD samples have separated from their parent impurities of doped layer (p^+-Si), transferred to the SiGe channel and formed a two dimensional hole gas (2DHG). Because the band gap offset for the Si/SiGe heterojunction presents mainly in the valence band,[7] hole potential wells are formed on the SiGe side of the Si/SiGe interface as shown in Fig. 2. Figure 3 shows the hole Hall mobility as a function of temperature for a typical MD heterostructure (sample No. 2). It can be seen that the hole mobility increased gradually with decreasing temperature. The reason of the increase is that, with decreasing temperature, the lattice scattering reduced and the remote ionized impurities scattering decreased obviously.

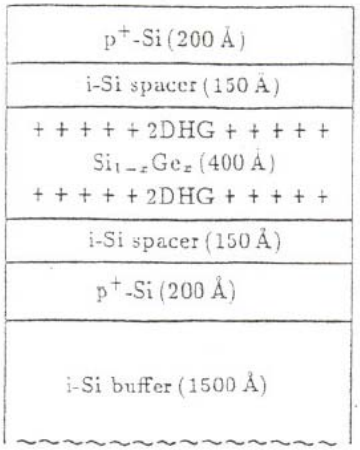

Fig. 1. Schematic for double modulation-doped heterostructure.

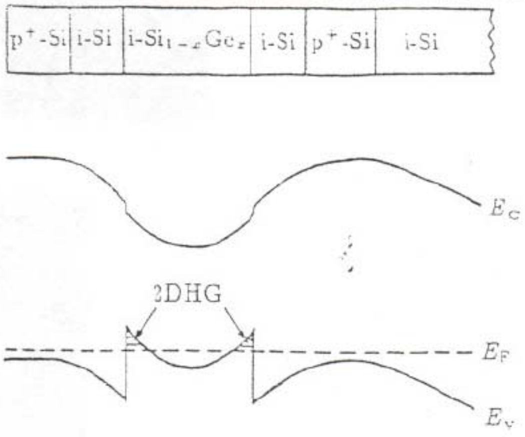

Fig. 2. Energy band diagram for $Si/Si_{1-x}Ge_x/Si$ p-type modulation-doped double heterostructures.

Table 1

	Sample		$p_s(\times 10^{13})\ cm^{-2}$		$\mu_H\ (cm^2/V\cdot s)$	
No.	Ge fraction	MD/UD	293 K	77K	293 K	77 K
1	($x = 0.20$)	MD	6.6	2.2	240	4700
2	($x = 0.25$)	MD	6.7	2.3	280	6700
3	($x = 0.30$)	MD	2.3	1.2	300	7500
4	($x = 0.35$)	MD	6.9	2.8	290	5800
5	($x = 0.20$)	UD	6.5	7.3	210	130
*6	($x = 0$)	UD	$2.1\times10^{19}\ cm^{-3}$	$3.1\times10^{19}\ cm^{-3}$	38	26

*6—A UD bulk Si

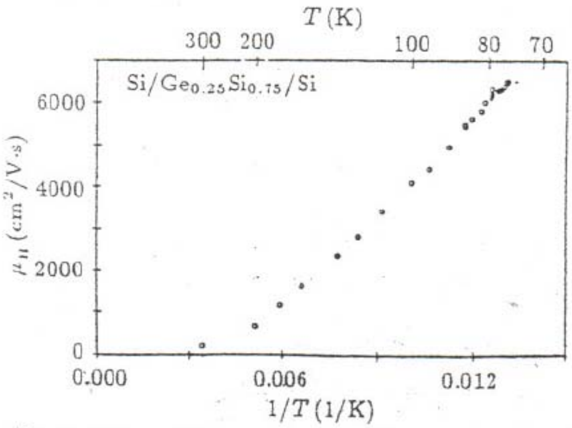

Fig. 3. Hole mobility as a function of temperature for $Si/Si_{0.75}Ge_{0.25}/Si$ MD double heterostructures.

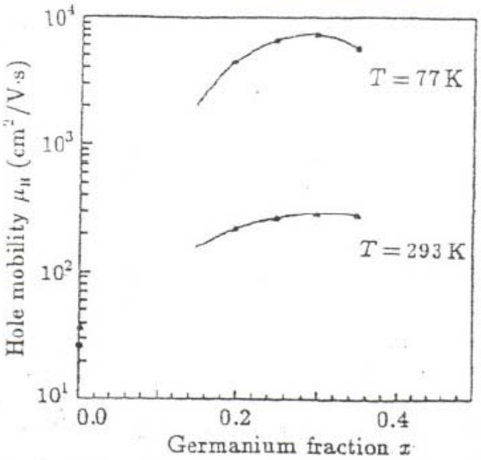

Fig. 4. Hole mobility vs Ge fraction at 293 and 77 K for $Si/Si_{1-x}Ge_x/Si$ p-type MD double heterostructures.

The dependence of hole mobilities on Ge fraction (x) for MD heterostructures at room temperature (293 K) and low temperature (77 K) is shown in Fig. 4. The mobilities increase with increasing x. At room temperature, the scattering mechanisms consist primarily of lattice scattering and alloy scattering. With the increasing x, the hole mean free time increases and hole effective mass decreases, although the alloy disorder scattering increases with increasing

x, the influence is small, so the hole mobility tends to increase. This is in accordance with the results of theoretical calculations.[8] At low temperature the hole mobilities increased with increasing x; this was induced primarily by the decrease of hole effective mass. However, for the sample with $x = 0.35$ the mobility decreases slightly (see Fig. 3). This is due to the 400 Å thickness of the $Si_{0.65}Ge_{0.35}$ alloy layer which is almost the critical thickness of strained layer.[9] This will bring about some misfit dislocations leading to increasing in dislocation scattering.

High sheet carrier concentration and high mobility are essential for MD field effect devices, and the sheet carrier concentration is mainly determined by dopant concentration and the thickness of spacer layer. In our samples, a high dopant concentration ($1\text{–}3\times10^{19}\,cm^{-3}$) was used. Considered that the additional potential field range of ionized impurities should be greater than the range of electron wave function ($\sim$100 Å) and the segregation of boron, the thickness of spacer layer was designed to be 150 Å. This thickness made it possible that not only the coulumb field of ionized impurities in p^+-Si layer exerted little influence on the moving holes in the potential wells of SiGe layer, but also a sufficient number of holes in the p^+-Si layer could transfer to SiGe potential wells. The sheet carrier concentrations p_s measured for all the MD samples (listed in the Table 1) are greater than $10^{13}\,cm^{-2}$, indicating a proper design of the spacer layer thickness.

Moreover, the mobility in SiGe MD heterostructures depends strongly upon the lattice integrity of SiGe alloy layers and Si/SiGe interfaces. Misfit dislocation, background impurity scattering and interface roughness scattering will get the mobility reduced, especially at low temperature.[10] The high hole mobilities achieved for our samples both at room and low temperatures are evidences of high quality SiGe strained layers and Si/SiGe interfaces with no apparent misfit dislocations.

In conclusion, a $Si/Si_{1-x}Ge_x/Si$ p-type MD double heterostructure with high hole mobility is achieved by RRH/VLP-CVD. The hole Hall mobilities as high as about 300 $cm^2/V\cdot s$ (293 K) and 7500 $cm^2/V\cdot s$ (77 K) for $x = 0.3$ are the highest values reported so far. It was found that the hole mobility enhances apparently with decreasing temperature and increases with increasing Ge fraction.

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REFERENCES

[1] Y. H. Xie *et al.*, *Proceedings of the 21st International Conference on Physics of Semiconductors*, 1992.

[2] F. Schäffler, D. Többen, H. J. Herzog, G. Abstreiter and B. Holländer, Semicond. Sci. Technol. 7 (1992) 260.

[3] P. J. Wang *et al.*, Appl. Phys. Lett. 55 (1989) 2333.

[4] D. J. Gravesteijn, *et al.*, J. Cryst. Growth. 111 (1991) 916.

[5] V. Venkataraman *et al.*, Appl. Phys. Lett. 59 (1991) 2871.

[6] Zheng Youdou *et al.*, *Proceedings of 20th International Conference on the Physics of Semiconductors*, Vol. 2 (1990) p. 869.

[7] R. Dingle, H. L. Störmer, A. C. Grossard and W. Weigmann, Inst. Phys. Conf. Set. No. 45 (1979) 248.

[8] T. Manku and A. Nathan, IEEE Electron Device Letters, 12 (1991) 704.

[9] R. People, IEEE J. Quantum Electron. QE-22 (1986) 1696.

[10] A. Gold, Phys. Rev. B 35 (1987) 723.