ISSN 1009-3095 *Journal of Zhejiang University(SCIENCE)* V.1, No.4, P.427-430, Oct.-Dec., 2000
http://www.chinainfo.gov.cn/periodical; http://www.zju.edu.cn;
http://lib.zju.edu.cn/English; http://www.zjupress.com

AN ULTRAHIGH VACUUM CHEMICAL VAPOR DEPOSITION SYSTEM AND Si, GeSi EPITAXY ON A THREE-INCH Si WAFER*

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Received Oct.12, 1999; revision accepted May.15, 2000

Abstract: An ultrahigh vacuum chemical vapor deposition (UHV/CVD) system with reflection high energy electron diffraction (RHEED) was introduced. The Si epilayers and SiGe strained-layers on three-inch Si (100) substrates were grown in this UHV/CVD system. The substrate temperature during growth was from 550℃ to 780℃. The properties of epilayers were characterized by high-resolution cross-sectional transmission electron microscopy (TEM), double crystal X-ray diffraction (DCXRD), and spreading resistance (SPR). A B-doped SiGe epilayer with uniform resistivity distribution was grown.

Key words: UHV/CVD, silicon, germanium-silicon, epitaxy
Document code: A **CLC number:** TN304.055

INTRODUCTION

The drive to reduce the dimensions of high performance integrated circuitry is running into limitations owing to physical phenomena implicit in the materials preparatory techniques (Meyerson, 1986). Low temperature and low pressure silicon epitaxy can effectively avoid autodoping, wafer warping and dopant redistributing via solid-state diffusion, and can meet the need of high performance, scale-down bipolar and complementary metal oxide semiconductor devices requiring precise control of abrupt dopant profile (Hu et al., 1968).

Molecular beam epitaxy and ultrahigh vacuum chemical vapor deposition (UHV/CVD) techniques are widely used for low temperature epitaxy. UHV/CVD is particularly attractive because it is capable of multiple-wafer growth and has produced devices with recordbreaking performance (Patton et al., 1990). The characteristics that make the CVD process attractive for commercial film growth are excellent film uniformity, conformity, compatibility with large area processing, and relatively low apparatus costs compared with the physical vapor deposition techniques.

SiGe strained layer has high carrier mobility and its energy gap can be freely tailored, furthermore, it is compatible with the plane-silicon technique. As "the second micro-silicon technology" silicon-germanium strained layers have been used to make heterojunction bipolar transistors (HBT), modulation doped field effect transistors, photo-detectors (People, 1986).

The UHV/CVD technique was first developed by Meyerson (1986), who then successfully grew the silicon-germanium strained layer in 1988 (Meyerson, 1992). It was reported that the Si and SiGe epitaxy at 500-650℃ with growth rate 0.01-0.1nm/sec could be achieved by UHV/CVD (Racanelli et al., 1990; Ismail et al., 1991). Moreover, superlattice and quantum well can also possibly be fabricated by UHV/CVD. Generally speaking, a 200-500 nm thick epitaxial layer of Si or SiGe is necessary for microwave devices; heterostructure bipolar transistors and photoelectric detectors, however, such a thick layer is quite time-consuming

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* Project supported by NSFC and Science Commission Program of Zhejiang Province of China.

if grown at 500 – 650℃. The present work aims not only to grow Si and SiGe epilayers at low temperature, but also to find an appropriate growth temperature for high quality Si and SiGe epilayers grown at considerably high growth rate.

SYSTEM AND EXPERIMENTAL

Fig. 1 illustrates our homemade UHV/CVD system. The system can be pumped to 1.33 μPa by a turbomolecular pump and an ion-getter pump. This system was made of polished stainless steel (except for some accessories). The growth chamber contained facilities for *in situ* reflection high-energy electron diffraction. The heater was made of graphite shoes with optimal resistance distribution to uniformly heat the substrate. The cleaned silicon wafer was first put into the sample chamber that was immediately pumped for about 30 min., and was then transferred into the growth chamber by a magnetic club.

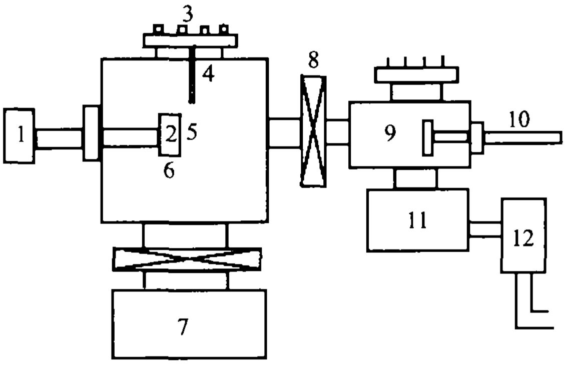

Fig. 1 Schematic of our UHV/CVD system with HREED
1. rotating device; 2. heater; 3. four gas ways; 4. pipeline; 5. sample; 6. growth chamber; 7. pump; 8. valve; 9. sample chamber; 10. magnetic club; 11. turbomolecular pump; 12. off-gas pump

Si and GeSi strained epilayers were deposited on 75 mm diameter Si (100) wafer by the UHV/CVD system as described above at temperatures from 550℃ to 780℃. In this work the samples studied were grown at relatively high temperature (780℃) to gain a relatively high growth rate. The substrate was vertically placed and the gas flow was parallel to it. Reactants were highly pure saline (SiH_4) and germane (GeH_4); and the dopant source was highly pure $B_2H_6$0.01% in hydrogen (99.999%). The growth pressure ranged from 2.66 – 13.3 Pa. The Si wafer was cleaned by the improved "RCA" process (Ye et al., 1996), and etched by dilute hydrofluoric acid ($HF : H_2O = 1 : 10$, volume ratio) prior to being put into the sample chamber (Meyerson, 1990). In the growth chamber, the substrate was first baked at 800℃ for 30 seconds in GeH_4 atmosphere with 5 cm^3/s flow to remove the remnant silicon oxide (SiO_2) via the following reaction, then cooled down to the growth temperature of 780℃.

$$SiO_2 + 2GeH_4 = Si + 2GeO\uparrow + 4H_2\uparrow$$

The growth conditions for 1 – 5 samples are described in Table 1. The sample 1 was a Si epilayer on N(100) Si, and samples 2 – 4 were SiGe epilayers. The sample 5 was B-doped SiGe epilayer on heavy dopant P(100) Si.

The epitaxial layer microstructure was investigated using high-resolution cross-sectional transmission electron microscopy (TEM) operating at an accelerating voltage of 200 keV. The cross-sectional TEM samples were prepared by the conventional method. Double crystal X-ray diffraction (DCXRD) was also used to characterize the epilayer. The X-ray source was $CuK_{\alpha 1}$. The rocking curves were obtained by keeping the detector fixed at an angle 2θ, and making the incoming X-ray beam and rocking sample respectively vary from θ at a small amount. Spreading resistance measurement (SPR) was used to investigate the dopant distribution in the transition region between the epilayer and substrate.

Table 1 Growth conditions for some samples

Sample No	Substrate	SiH_4 flow (cm^3/s)	GeH_4 flow (cm^3/s)	B_2H_6 flow (cm^3/s)	Growth time (min.)
1	N(100)	50			90
2	N(100)	50	4		60
3	N(100)	50	10		60
4	N(100)	50	15		60
5	P(100)	50	10	10	60

RESULTS AND DISCUSSION

After deposition, the samples were removed from the system and examined by scanning electron microscopy, which showed that the surface morphologies of the epilayers were smooth and homogeneous.

Fig. 2 shows a high-resolution cross-sectional TEM lattice image of the sample 1, indicating the epilayer was of quite good quality. However, stacking faults, which were propagated from the interface into the epilayer, were observed. The stacking faults possibly originated from thermal strain, substrate imperfection, improper growth conditions, etc. Actually, the most frequently generated defects in the epitaxial layers were dislocation, stacking fault and twins (Ye et al., 1993).

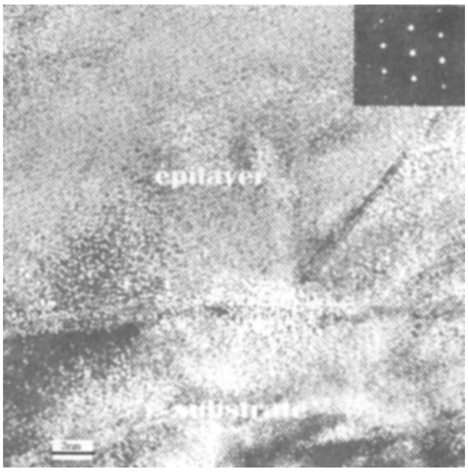

Fig.2 High resolution cross-sectional TEM image of the silicon epilayer at 780℃

Fig. 3 shows the DCXRD rocking curves for samples 2 – 4 respectively corresponding to curves a, b, c. Table 1 shows that the Ge contents in samples 2 – 4 increased with increasing GeH_4 flow. In Fig. 3, the sharp peak in the rocking curve corresponds to Si (400), the broad peak to the SiGe epilayer. It can be seen that the SiGe peak shifts toward more negative rocking angle and becomes much broader with increasing Ge content in the SiGe epilayer. With the Ge content increasing, the misfit between SiGe epilayer and the substrate becomes larger, leading to a smaller critical layer thickness, and relatively high growth temperature also makes the critical layer thickness smaller (Huang et al., 1998). Therefore, in sample 4 the SiGe epilayer was almost fully relaxed, as reflected by the quite broad peak in the rocking curve c in Fig. 3. Generally, the width of the diffraction peak originated from the mosaic structure in the strain-relaxed epilayer with the lattice planes bent by the strain field of the dislocations. P. M. Mooney (1993) found that the mosaic structure originated from the network of misfit dislocations underneath the epilayer; and that the effect of the threading dislocations on the X-ray diffraction peak widths was not obvious compared with that of the misfit dislocations. Therefore, the misfit dislocations primarily determine the widths of diffraction peak. Higher Ge content and growth temperature will lead to larger misfit between the SiGe epilayer and the Si substrate, and so, will probably generate more misfit dislocations. As mentioned above, the misfit dislocation will further produce mosaic structure responsible for the broadening of the diffraction peak.

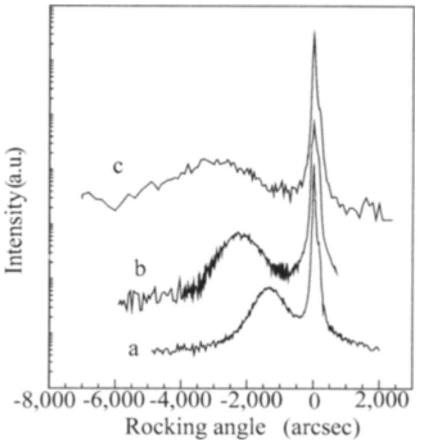

Fig.3 DCXRD rocking curves for sample 2 – 4
Curve a is that of sample 2; curve b is that of sample 3; curve c is that of sample 4. The FWHMs broaden with the increasing of Ge content

From Fig. 4 of the spreading resistance for sample 5, it is deduced that the dopant (B) was uniformly distributed across the epilayer, and that the transition region was at about 0.15 μm. Obviously, the self-doping is greatly suppressed in the UHV/CVD process due to the relatively lower growth temperature compared with other processes.

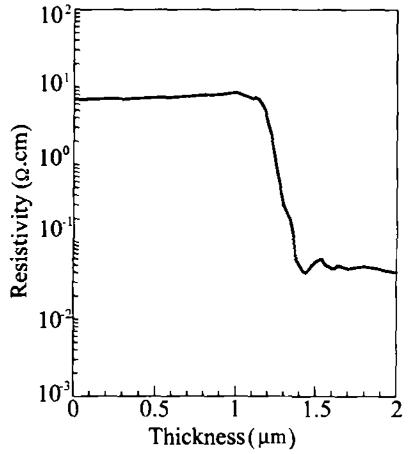

Fig.4 Resistivity distribution of B-doped film by SPR. The epilayer resistance was uniform and the transit region was sharp

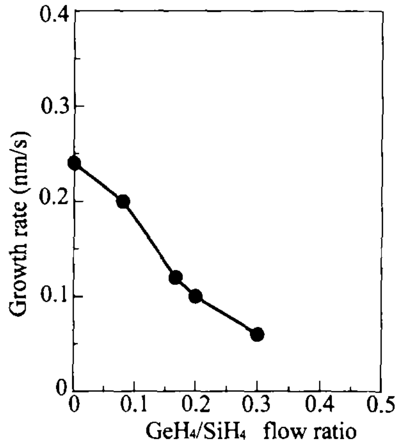

Fig.5 The growth rate curve versus germane saline flow ratio at 780℃. The growth rate reduced with increasing of germanium content

Fig. 5 of epilayer growth rate versus germane saline flow ratio indicated that the growth rate decreases with increase of germanium flow. The growth rate was 0.05 – 0.25 nm/sec at a temperature of 780℃. It is estimated that 200 – 500nm thick epilayers, which might be feasible for microwave devices and heterostructure bipolar transistors, can be grown within an hour at 780℃ by the UHV/CVD system presented in this paper.

CONCLUSIONS

We grew Si and SiGe epilayers by UHV/CVD technique successfully at temperature of 550 – 780℃ and characterized the epilayers by high resolution cross-sectional TEM and DCXRD. The surface of the epilayers was smooth and the crystal quality was perfect. The increasing of Ge fraction for SiGe epilayers broadened the peak width. A B-doped SiGe epilayer with uniform resistivity distribution was grown whose impurity distribution was uniform and the transition region was only 0.15 μm. When the substrate temperature was relatively high the growth rate was relatively fast. The growth rate of the SiGe epilayer decreases with increasing of germanium flow. Si and SiGe epilayers that meet the requirements of microwave devices, transistors, photo-detectors and other electronic devices can be grown with this system.

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