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Review

High-quality strain-relaxed $Si_{0.72}Ge_{0.28}$ layers grown by MBE-UHV/CVD combined deposition chamber

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Surface smoothness and fully strain-relaxation $Si_{0.72}Ge_{0.28}$ virtual layer on Si(100) substrate with an inserted low temperature Ge flat layer is grown by combining molecular beam epitaxy system (MBE) and ultrahigh vacuum chemical vapor deposition system (UHV/CVD) in one vacuum chamber. The epitaxial SiGe layer with surface root-mean-square roughness of 1.22 nm and threading dislocation density of $1.5 \times 10^5 cm^{-2}$ is obtained. The influence of low temperature Ge interlayer on the high quality of SiGe epilayer is investigated. Both of the thermal stability and surface morphology of $Si_{0.72}Ge_{0.28}$ virtual layer are much better than that of SiGe layer grown by traditional UHV/CVD system.

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1. Introduction

High-quality, tensile strained SiGe/Ge superlattice and Ge epitaxial layer have attracted a great deal of attention due to their band gap modification, high electron-hole mobility and promising device applications, which can be used as tensile strained Si/SiGe quantum well infrared photo detectors and strained-Ge metal-oxide-semiconductor field-effect transistor [1–3]. So many groups have focused on this promising area due to the high performance of these strained structures. However, how to achieve strained and single crystal SiGe and Ge layers are big problems for growing technology [4], firstly, it is very hard to grow single crystal SiGe/Si superlattice and strained Ge layer on Si substrate due to the large lattice mismatch between Si and Ge. Besides, the lattice of Si is smaller than that of SiGe and Ge, so it is hard to grow tensile strained SiGe/Si superlattice and SiGe layers directly on Si substrate.

Since the lattice constant of the Si_xGe_{1-x} alloy can be

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continuously varied by changing the Ge content in the alloy, strain-relaxed and high Ge content Si_xGe_{1-x} virtual film on Si can be used as a virtual substrate. Since, the Si_xGe_{1-x} virtual substrate can provide significant band gap engineering freedom and offer a way of fabrication both compressive- and tensile-strained SiGe/Si superlattice for optoelectronic devices. In this case, the performance of the strained SiGe/Ge superlattice device depends strongly on the crystalline quality and surface morphology of the Si_xGe_{1-x} virtual substrate. Considerable efforts have been made to grow high-quality strain-relaxed Si_xGe_{1-x} virtual films on Si [5–10], such as compositionally forward- and reverse-graded buffer layer, low temperature (LT) interlayer, nano-scale patterned Si structures and ion implantation technology. Among these methods, the idea of the LT-Ge interlayer is widely adopted due to the simplification of growth condition.

The Ge interlayer, grown at low temperature, can be served as a low-energy center of defects. With the help of the defects, the strain in the SiGe layer can be fully relaxed at the interface of Si_xGe_{1-x} film and LT-Ge layer. In this case, low temperature technique is a promising method and widely utilized for molecular beam epitaxy (MBE) system. Thin, high quality and high-Ge content SiGe buffers are successfully fabricated by this technology. As these Si_xGe_{1-x} films are relatively thick, and the growth rates of MBE system is only about 0.1–0.5 A/s [11], it is very hard to grow thick Si_xGe_{1-x} layer, whereas rates of 5–10 nm/s are easily achievable by ultrahigh vacuum chemical vapor deposition (UHV/CVD), besides, it also has high throughput and in situ doping capabilities, so the growth rate is very high in CVD system. Though the growth rate is fast for this technology, the crystalline quality and the surface morphology are poor for both of Si_xGe_{1-x} and LT-Ge interlayer at low temperature by UHV/CVD system [12,13]. The method of combining MBE and UHV-CVD system for the growth of SiGe layers was reported before. Although these results have provided some impressive values, for instance, TDD of $3.4 \times 10^5 cm^{-2}$ with the RMS of 1.2 nm was found in $Si_{0.4}Ge_{0.6}$ layer by low temperature MBE technology [14], and $Si_{0.8}Ge_{0.2}$ with TDD of 6×10^4 cm^{-2} was achieved by RP-CVD [15,16], all of these references were mainly focus on surface morphologies and crystal quality of the SiGe films, and they did not give a systematic research of the effect of LT-Ge layer when the upper SiGe layer depositing.

In this paper, we combined MBE system and UHV/CVD in one chamber. Firstly we deposited the thin and flat LT-Ge interlayer on Si substrate (100) by the MBE technology, and then we combined advantages of UHV/CVD method and experimentally got surface smooth and relaxed $Si_{0.72}Ge_{0.28}$ layers on the LT-Ge interlayer. And their layers are uniform and indeed we have examined specimens from different points across the whole wafer.

2. Experimental details

In this system, there is a chamber ultra high vacuum chemical vapor deposition (UHVCVD). The chamber is equipped with eight-growth road gas source pipelines, and has two solid source beam source furnaces (MBE system). Besides, this system has advantages that the gas source and the solid state source can be alternately or mixed grown. Fig. 1 is a schematic representation of the growth system developed, installed and used in this work. The chamber is connected to pumping systems allowing a base pressure of 10^{-10} Torr. While system is under the UHVCVD mode, the working pressure range is between 10^{-2} and 10^{-6} Torr. Pure Si_2H_6 and GeH_4 are used as precursors being injected through mass flow/baratron flux/pressure controllers and decomposed at the substrate surface. The material of the hot-plate is Graphite, the mode is non-contract, and the plate can be heated from room-temperature to 1200 °C.The substrate temperature is measured by the thermocouple technology, and the accuracy of the heating temperature is 1 °C in this system. While system is under the MBE mode, a working pressure typically in the 10^{-7}–10^{-5} Torr range. Silicon and Germanium are generated from valved effusion cells which can be heated to 1200 °C. Silicon and Germanium beam deposit on the surface of substrate through the valve of cells. A reflection high-energy electron diffraction (RHEED) is used to monitor the growth processes.

The virtual substrate is epitaxially grown on a 4 inch n-type Si (100) wafer with resistivity of 0.1–1 Ω cm. Firstly, the wafer is cleaned by Radio Corporation of American (RCA) method and dried by N_2 before loading into the growth chamber. And then, the wafer is baked at 900 °C for 30 min to de-oxide. After that, low-temperature Ge (LT-Ge) is grown by using MBE mode. The purity of Ge beam source is 99.999%. The effusion cell can be heated to 1100 °C, and the working pressure range is between 10^{-7} and 10^{-5} Torr. Samples are divide into four groups, substrate temperature are room temperature, 150 °C, 180 °C, 200 °C respectively. Then, chamber is switched into UHVCVD system, and 50 nm and 250-nm-thick $Si_{0.72}Ge_{0.28}$ layers can be deposited on LT-Ge layer with the same flux ratio of $Si_2H_6{:}GeH_4 = 3{:}5$ at 400 and 500 °C, respectively. The higher temperature firstly may result in the Ge layer unstable, leading to the unsmooth surface of the upper SiGe layer. Secondly, the LT-Ge deposited by MBE method is not only has the flat surface morphology, but also contains many point defects on the surface. As a result, the threading dislocations can be captured by surface point defects of LT-Ge, leading to the dislocation pinning at the interface. For the LT-SiGe layer, there are also some point defects can be formed, which can also capture the threading dislocations, in this condition, lower TDD SiGe layer can be formed by this method. The surface morphology is analyzed by atomic force microscopy (AFM) using Seiku Instruments SPI4000/SPA-400 system operating in tapping mode. The Ge content in SiGe film and the degree of strain relaxation are evaluated by high-resolution X-ray diffraction (HRXRD) and Raman scattering spectrum. Symmetric (004) and asymmetric (224) Omega–2theta measurements are performed at room temperature in the Bede, D1 system, by using a Cu Kα1 (λ = 0.15406 nm) radiation. Raman scattering measurements are carried out at room temperature using the backscattering geometry with 532 nm Ar^+ line as the excitation source. The vertical distribution of Si and Ge in the samples is tested using Auger electron spectrum (AES). The depth profile of threading dislocation density is measured by counting pits formed from selectively chemical etching and the detail distribution of these threading dislocations are captured by Transmission electron microscope (TEM).

3. Results and discussion

To study the effect of LT-Ge interlayer, a reflection high-energy electron diffraction (RHEED) images are recorded in real-time to monitor the LT-Ge and SiGe surface. In the white block scheme of Fig. 1 are AFM images and corresponding RHEED of LT-Ge layer. After the deposition of Ge layer at room temperature (Fig. 2(a)), there is no pattern shown in the RHEED, which means only amorphous Ge can be formed in this condition. Besides, island structures appear on the surface, and the LT-Ge islands act as the strain-accommodating layer where strain energy stemming from the lattice mismatch between Si and Ge is relieved via formation of systematic misfit dislocations. With the increasing of deposition temperature, the RHEED patterns exhibit a weak 2 × 1 streaks (Fig. 2(b)), and finally a well-developed longitudinal 2 × 1 streaks are rebuilt (Fig. 2(c)), This pattern is related to the two-dimensional (2D) growth of the Ge layer [17], and the root-mean-square (RMS) is 0.61 nm, which means the growth mode switches from three-