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Photoluminescence from heterogeneous SiGe/Si nanostructures prepared via a two-step approach strategy

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ABSTRACT

A two-step approach of preparation for SiGe/Si heterogeneous nanostructures, which combined with ultra-high vacuum chemical deposition and electrochemical anodization techniques, is demonstrated. Uniformly distributed nanostructures with a quite uniform distribution of size and morphology are obtained. A strong room-temperature photoluminescence from the nanostructures was observed with a narrow full-width at half-maximum of around 110 meV. The possible origins of the two main peaks at around 1.6 and 1.8 eV have been discussed in detail. The two-step approach is proved to be a promising method to fabricate new Si-based optoelectronic materials.

1. Introduction

Light emission in bulk silicon-based materials is poor in wavelength up to the infrared range due to its indirect bandgap [1], which limits its applications for optoelectronics. Since the first observation of strong visible luminescence from porous Si [2] in 1990, many methods such as pulse laser ablation [3], ion implantation [4], spark processing [5], low-pressure chemical vapor deposition [6,7] stained etch [8], electrochemical anodization (ECA) [9], and strain-induced Stranski–Kranstanov (SK) model [10] have been used to prepare Si-based nanostructures to mimic the porous Si, which can give rise to visible luminescence. Although the Si-based nanostructured materials as prepared via the above methods indeed show good optical properties from visible to infrared wavelength, there is still great challenge in further enhancing the optical performance because it is difficult to control size or position of the nanocrystals or to attain high density of the nanocrystals in the structure. Recently, the light emission from the Si nanostructures in Si/SiN_X and Si/SiO_2 multilayers has made great progress particularly because in this kind of luminescent structures the size of Si nanocrystals can be constrained by the thickness of the ultrathin Si sublayer [11,12]. However, there is still a long way to go in terms of practical application for Si-based light-emitting devices (LEDs) because of their insufficient light intensity, which is due to the difficulties in injecting carriers from the contact layer into the Si nanostructures via the dielectric layer (silicon nitride or silicon oxide film).

SiGe alloy is an attractive semiconducting material due to their variable band gaps between those of Si and Ge based on so-called 'band-structure engineering' [13]. In nearly 20 years, some researchers have studied the microstructure [14] and photoluminescence (PL) property [8,9,15] of porous SiGe alloy prepared by stain etching or anodic etching. However, there are few reports on porous material of SiGe/Si heterostructure multiple quantum wells (MQWs).

In this paper, we demonstrate a two-step approach (TSA) for SiGe/Si heterogeneous nanostructures fabrication via a combination of ultra-high vacuum chemical vapor deposition (UHV/CVD) and ECA. UHV/CVD is a well-developed epitaxy system, which has been widely used in SiGe single-crystal film growth on Si

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substrate with the precise control of film thickness and alloy composition. ECA is a promising method for preparing nanostructured materials such as nanowires or nanopillars structure [16–18] with an ease of processing and an ability to produce a high density of nanostructures whereas without changing crystal property of starting material. By combining the above two methods, we can obtain SiGe/Si heterogeneous nanostructures of uniform size and corresponding strong room-temperature PL. In this work, the structural and optical characteristics of the SiGe/Si heterogeneous nanostructures synthesized by the TSA have been investigated by a scanning electron microscope (SEM), micro-Raman spectroscope, and room-temperature PL. The origins of the multi-peak PL have been discussed in detail, and both quantum confinement (QC) effect and interface states play important roles.

2. Experimental details

The SiGe/Si heterogeneous nanostructures were fabricated by the TSA. The samples consist of strained SiGe/Si MQWs as deposited on n-type Si (0 0 1) substrate in the UHV/CVD system with a base vacuum of 5×10^{-8} Pa. In detail, the SiGe/Si MQWs consist of 6 periods of an ~7-nm-thick $Si_{0.87}Ge_{0.13}$ layer and an ~28-nm-thick Si layer alternatively and a final 160-nm-thick silicon cap layer, which were characterized by double-crystal X-ray diffraction (DXRD). Subsequently, after Ohmic contact was formed on the backside of a silicon wafer by evaporating aluminum in a vacuum evaporator, the ECA was performed on the MQWs using a mixture of 40% hydrofluoric (HF) acid solution and ethanol in a 1:2 volume ratio. The samples were etched with a current density of 20 mA/cm^2 for 3, 8, and 15 min.. The surface microstructures of the samples were characterized by SEM. In addition, the prepared samples were examined by Raman spectroscopy to evaluate the composition of SiGe nanostructures in the SiGe/Si heterogeneous nanostructures. PL spectra from the as-etched and post-annealed samples were measured by excitation of an Ar^+ laser with a wavelength of 514.5 nm and a power of 20 mw. All these measurements were performed at room temperature.

3. Results and discussion

3.1. SEM observation for surface morphology

SEM was used to determine the surface features of the as-etched sample. Fig. 1(a) shows typical SEM top-view image of the SiGe/Si MQWs after the ECA treatment. The uniformly distributed, well-separated, square island-like or checked nanostructures are observed in the top-view, which is significantly different from micropore-network structures of as-etched Si as obtained by ECA in Ref. [17]. The size distribution of the checked nanostructures in the top-view was estimated from measurements of diameters of 510 islands as shown within the white-line-box area in Fig. 1(a). Fig. 1(b) shows the estimated size distribution of the checked nanostructures with an average diameter of 21.2 ± 6.4 nm. In terms of the ECA mechanism of Si [18], we can infer that heterogeneous nanowires or nanopillars with high density in 3D space could have been attained in our samples.

3.2. Raman measurements

Raman measurements were carried out to establish a relation between the nanostructures and the ECA parameters. Fig. 2 shows Raman spectra of SiGe/Si MQW samples with a Ge content of 0.13 after being etched with a current density of 20 mA/cm^2 for 3, 8, and 15 min. For comparison, the Raman spectrum of the non-etched sample is also shown in Fig. 2. In addition to the strong Si substrate signal at 520.6 cm^{-1}, Ge–Ge, Si–Ge, and local Si–Si peaks can be seen, respectively, at about 303, 405, and 435 cm^{-1} in all samples. With the increase in etched time, no obvious shift of the

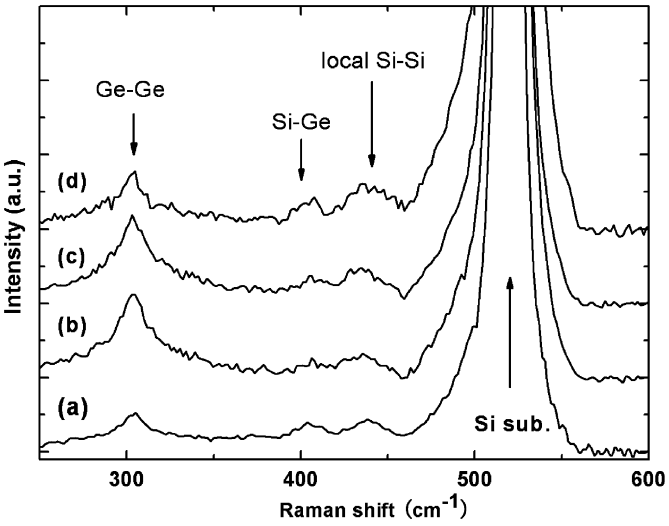

Fig. 2. Raman spectra of samples after being etched at a constant current density of ~20 mA/cm^2 but with different etching times: (a) non-etched; (b) 3 min; (c) 8 min; and (d) 15 min.

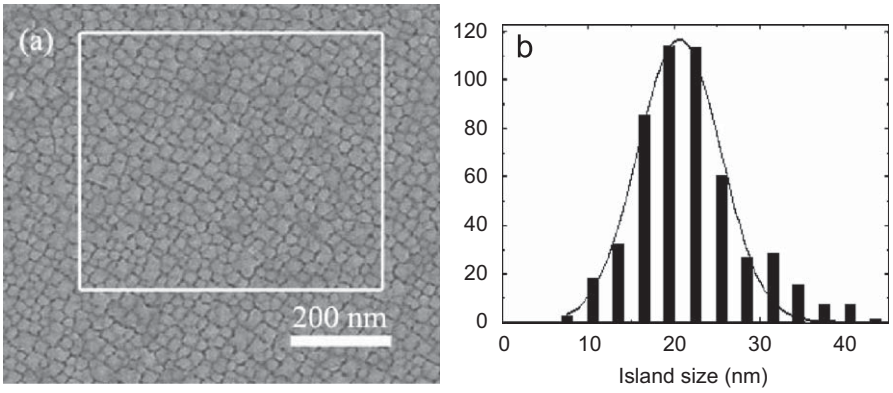

Fig. 1. (a) Typical SEM top-view image of the as-etched SiGe/Si MQWs sample, etching time 8 min, current density ~20 mA/cm^2. (b) Histogram illustrating the island size distribution.