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INCREASING THE PHOTOLUMINESCENCE INTENSITY OF Ge ISLANDS BY CHEMICAL ETCHING*

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Self-assembled Ge islands were grown on Si(100) substrate by Si_2H_6-Ge molecular beam epitaxy. After being subjected to chemical etching, it is found that the photoluminescence from the etched Ge islands became more intense and shifted to the higher-energy side compared to that of the as-deposited Ge islands. This behaviour was explained by the effect of chemical etching on the morphology of the Ge islands. Our results demonstrate that chemical etching can be a way to change the luminescence property of the as-deposited islands.

Keywords: Ge islands, chemical etching, photoluminescence, Si_2H_6-Ge molecular beam epitaxy
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A structure composed of self-assembled Ge islands is promising for optoelectronic devices compatible with standard Si technology since an enhancement of the light output from the Si-based structure can be achieved by growing Ge islands on the Si base. It is known that the optoelectronic properties of the islands are sensitive to shape, size and composition.[1−5] At present, the tuning of the island morphology, and consequently their luminescence properties, is achieved by altering the growth temperature,[6] post-growth annealing,[1] capping Ge islands,[7] and applying surfactant,[8] etc. In this paper, we propose a method of chemical etching to change the morphology of the Ge islands. It is found that their morphology was varied and their optical properties were improved through chemical etching.

The sample was grown in a Si_2H_6–Ge molecular beam epitaxy system using a Si(100) substrate.[9] Subjected to chemical cleaning, the Si substrate was loaded into an ultra-high vacuum (UHV) growth chamber with a basic pressure lower than 10^{-7} Pa and then heated up to 950°C for 1h to deoxidize. After growing a 200nm Si buffer layer at 760°C, the Ge film was deposited at 520°C for 2min, while the Ge cell temperature was held at 1100°C. The as-grown sample was then annealed *in situ* at 700°C for 6min. The *in situ* reflection high-energy electron diffraction pattern became spotty during annealing, indicating the occurrence of islanding. After growth, the sample was divided into several pieces which were chemically etched in a solution of $w(\mathrm{HF}):\omega(K_2Cr_2O_7):w(H_2O)=$ 10ml:0.15M:200ml for different etching times at a temperature of about 22°C. The island morphology was characterized by atomic force microscopy (AFM) in a contact mode in ambient air. Low-temperature (20K) photoluminescence (PL) spectra were measured in a standard lock-in configuration with an argon ion laser (514.5nm, 50mW) for excitation and using a liquid-nitrogen-cooled Ge detector.

Figure 1 shows the $2 \times 2\mu m^2$ AFM images of the samples, as-grown and after being etched for 30min. The changes of morphology of Ge islands after etching were clearly revealed. For the as-grown sample [Fig.1(a)], the dome islands dominate the image and the pyramidal ones are hardly seen. The few pyramidal islands are due to the *in situ* high-temperature annealing, and the smaller pyramidal islands coalesce to form larger dome-shaped islands. The average dome island height is about 14nm and the base width is around 135nm, yielding an aspect ratio (defined as

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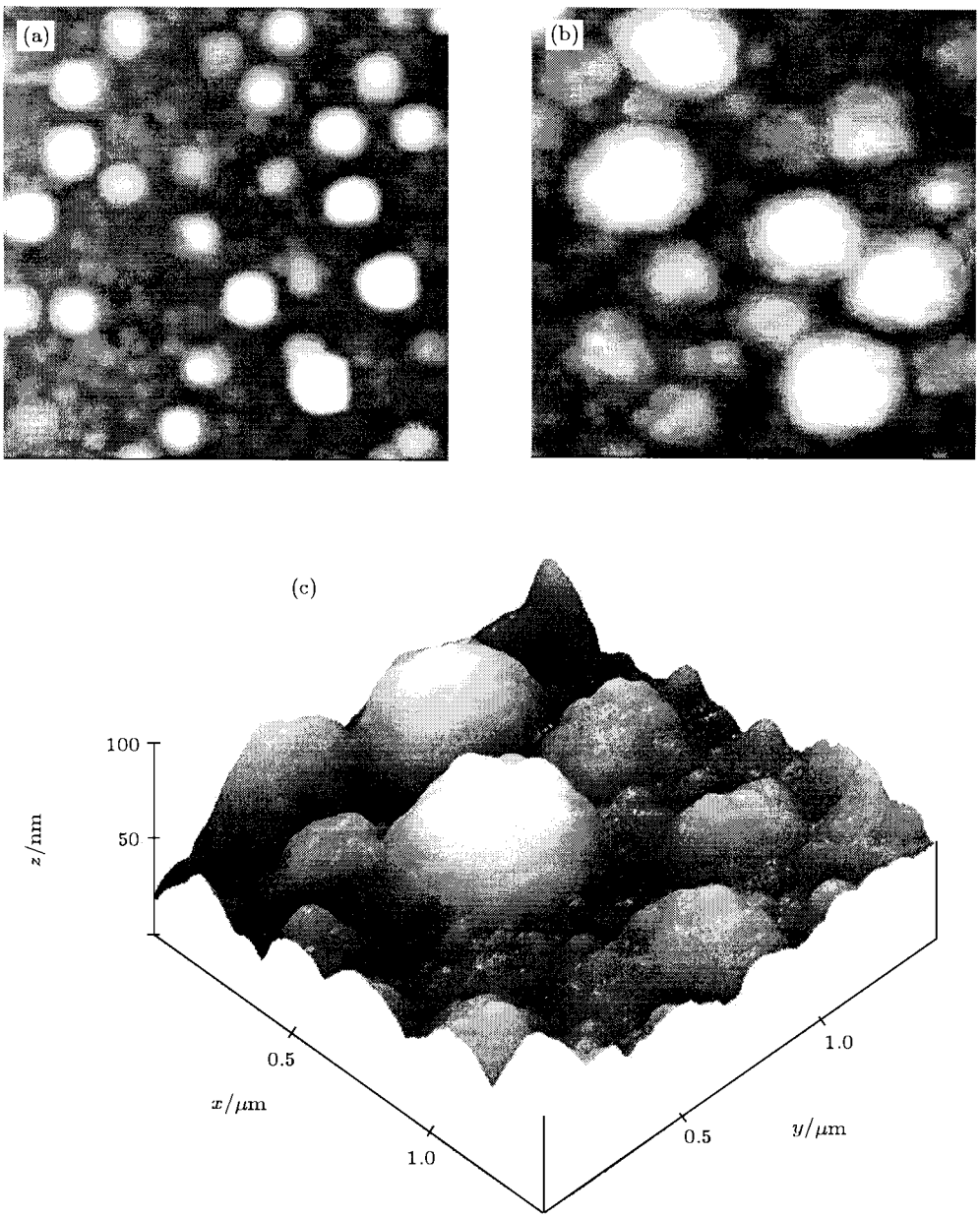

Fig.1. $2 \times 2\mu m^2$ AFM images of the as-grown (a) and 30min etched (b,c) Ge islands grown on a Si(100) substrate.

the island height- to-base width ratio) of about 0.104. The density of the dome islands is about $7\times10^8 cm^{-2}$. After etching for 30min [shown in Fig.1(b)] the islands become large. Meanwhile, it is found that the large island is not a single island, but consists of many small islands. The small island density increases sharply. Figure 1(c) clearly reveals the three-dimensional morphology of the islands shown in Fig.1(b). It is seen that there are many small islands on the large islands.

The effect of chemical etching on the PL properties of the Ge islands was investigated. Figure 2 displays two PL spectra taken from the unetched and 30 min etched samples, respectively. For spectrum 1 of the unetched sample, a broader peak around 887meV is dominant, which was assigned to that coming from the Ge islands.[7,10] We consider that the other two weak peaks located at 985 and 1010meV originate from the Ge wetting layer, corresponding to no phonon (NP) and transverse optical phonon (TO) luminescence, respectively.[7] The PL peak of the 30 min etched islands has a blueshift, and a much larger intensity and width than the unetched sample has.

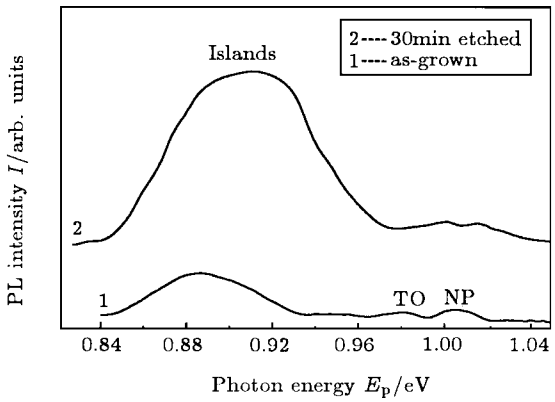

Fig.2. PL spectra from the as-grown and 30min chemical etched samples, measured at 20K with the excitation light of 514.5nm and 50mW.

The epitaxial Ge layer on the Si substrate is highly strained due to the large lattice mismatch (4.2%) between the Ge layer and Si substrate. The misfit strain is relieved mainly by the formation of the still coherent three-dimensional islands on top of the Ge wetting layer and by misfit dislocations which are introduced in the larger three-dimensional island.[11] The large three-dimensional island is formed by the coalescing of many small cohered islands with dislocations existing between the small islands.[12] Meanwhile, at the relatively high growth and annealing temperatures of 520 and 700°C, respectively, the intermixing of Ge and Si is expected to occur. This leads to the non-uniformity of the Ge/Si content distribution in the Ge island and wetting layer. It has been reported that the Si/Ge ratio remains approximately constant from the SiGe island centre upward. In the area between the island centre and the substrate, there is a tendency for the Si/Ge ratio to be higher at positions closer to the substrate.[4]

The morphology variation of the Ge islands after etching, as shown in Fig.1, can be explained by the influence of the microstructure and Ge/Si content distribution non-uniformity in the Ge islands and the surrounding wetting layer on the etching rate. In addition to the Si/Ge distribution non-uniformity in the Ge islands along the growth direction, the Si/Ge distribution non-uniformity exists in the wetting layer near the base of the Ge islands along the in-plane direction. The position which is closer to the island base along the in-plane direction in the wetting layer has a higher Ge content (i.e. larger Ge/Si ratio). The position with a higher Ge content is more difficult to be etched than the position with a lower Ge content. So the position which is closer to the island base along the in-plane direction in the wetting layer near the island base has a smaller downward etching rate. As a result, the etched island size becomes larger than that of the unetched, as indicated in Fig.1. The reason for the occurrence of many small islands on the large islands after 30 min of etching is that the large islands originate from the coalescing of many small islands with dislocations existing between the small islands (as discussed above), and the dislocation regions are preferably etched.

Due to the occurrence of many small islands in the 30 min etched sample, we believe that the main reason for the blueshift of the island luminescence is the reduction of the island size, resulting in an increased quantum confinement energy. At the same time, the increase in the density of the islands and their size fluctuation lead to the island-related PL peak becoming more intense and broader than that of the unetched sample.

In summary, the effect of chemical etching on the morphology and photoluminescence of the Ge islands grown by Si_2H_6–Ge molecular beam epitaxy on a Si(100) substrate has been studied. It was found that the energy and intensity of the Ge island related emission have been improved through the chemical etching. Thus, the chemical etching can be an effective method to change the morphology and luminescence properties of Ge islands.

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