Laterally Ordered Ge Islands on the Pre-Patterned Si (001) Substrates

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Ge islands were grown on the pre-patterned Si (001) substrates by solid-source molecular beam epitaxy. The topographies of the islands samples, obtained by atomic force microscopy (AFM), demonstrated that Ge islands tend to grow in the trenches or in the holes on one- or two-dimensionally patterned substrates, respectively. Provided the periodicities of the trenches or the holes originated from the pre-patterns, laterally ordered Ge islands were obtained. The preferential positioning of Ge islands in the trench or in the holes is attributed to a net flux of ad-dimers (or ad-atoms) downwards at the sidewalls, which is related to the growth temperature and the growth rate.

Introduction

Several authors reported the combination of pre-patterning of substrates with self-organized growth to achieve long range ordering of self-assembled islands [1] – [6]. For the growth of Ge islands on (001) Si substrates, so far for their preferential positioning, mainly lithographically defined patterned oxide features have been used. In this fabrication method, the Ge islands are grown preferentially at the edge of the stripes or mesas selectively grown in pre-patterned and etched SiO_2 windows [1] – [4]. By adjusting the size of the SiO_2 windows, a controlled arrangement of the Ge islands could be realized. This local epitaxy works particularly well if gas source (GS) molecular beam epitaxy (MBE) or chemical vapor deposition (CVD) processes are used. However, the remaining SiO_2 layer induces external strain and furthermore complicates the subsequent processes to characterize the properties of Ge islands or to fabricate devices. In this presentation, we show results of ordered Ge islands grown on pre-patterned (one- or two-dimensional (1D or 2D) Si (001) substrates. Our observations demonstrate that the growth kinetics significantly affect the positioning of Ge islands on the pre-patterned substrates without use of SiO_2 windows. In particular, 1D and 2D ordered Ge islands can be realized on these pre-patterned Si (001) substrates.

Experiments

The pre-patterned substrates were fabricated by holographic lithography and reactive ion etching. The orientation of the stripes and the square pattern was chosen to be along <110> directions. Patterns with a periodicity of less or equal than 0.5 µm and a depth of about 50 nm are used. All samples were grown by solid-source MBE. The substrates were cleaned by an RCA cleaning process followed by a HF dip to form hydrogenated surfaces. After desorption of the oxide layer at 900 °C, a Si buffer layer (about 100 nm thick) was deposited at a growth rate of 0.5 Å/s while the growth temperature was ramped from 550 °C to 650 °C. For samples grown on a 1D stripe-patterned substrate, seven monolayers (ML) Ge were then deposited at 650 °C. For the sample grown on a 2D square pattered substrate, 6ML Ge were deposited at 700 °C. For the Ge island growth, a growth rate of 0.04 Å/s was used. We also investigated samples with a stack of three Ge island layers separated by 20 nm Si spacer layers. In these samples, the upper two Ge islands layers were grown at 650 °C with only 5.7 ML Ge deposition, in order to avoid an increase of the island size. To reduce Ge-Si intermixing, the Si spacer layer was grown at 550 °C. The rather high substrate temperatures for the Ge island growth were chosen to enhance Ge adatom diffusion, which in conjunction with the low growth rates enabled us to achieve the desired ordering. The surface morphology of these samples was investigated after growth in air using a Park Scientific atomic force microscope (AFM).

Results

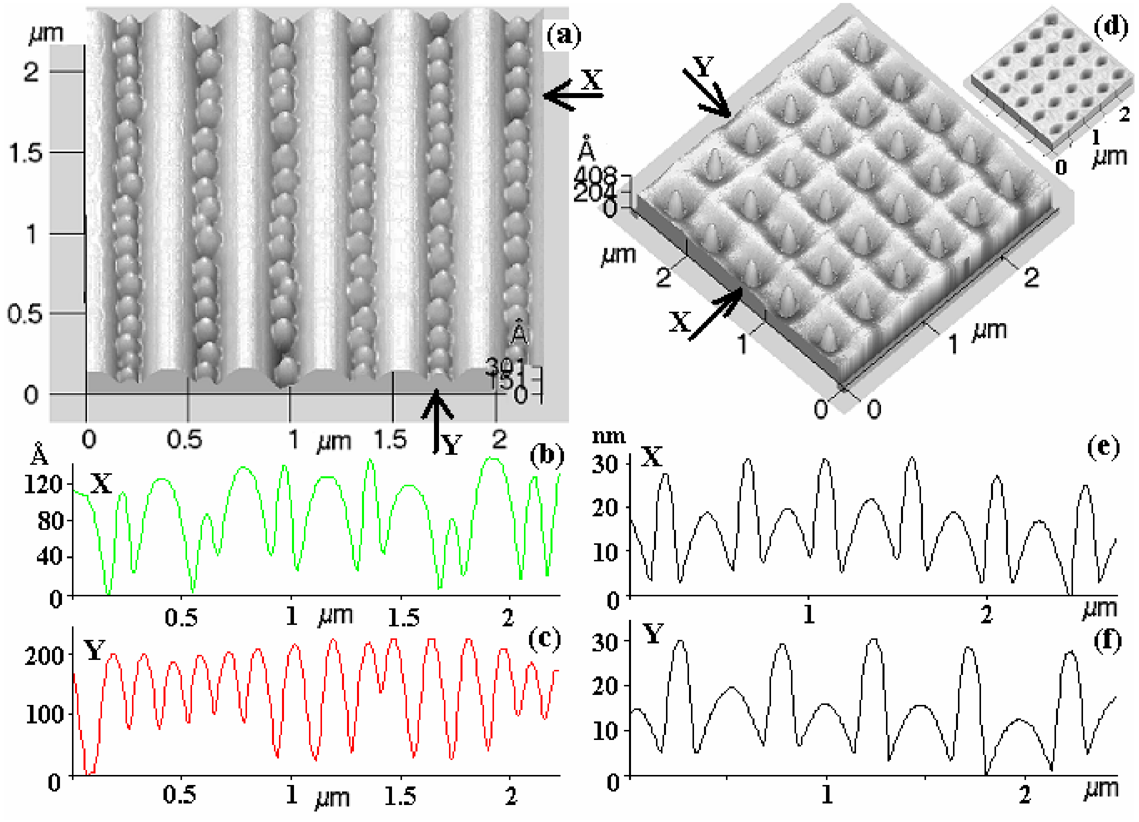

Fig. 1: AFM micrographs of 1D (a) and 2D ordered Ge islands (d), with corresponding line scans (b, c) and (e, f).

The 2D or 3D AFM images of samples A and B are shown in Figs. 1 (a), (b) and (c), respectively. For sample A, which was grown on a 1D patterned substrate, we observe an ordering of the islands along the trenches with a lateral period of 40 nm. In addition, height profiles are shown. Along the trenches (Fig. 1 (b)) and perpendicular to it (Fig. 1 (c)), we observe long range ordering of dome-shaped islands not only for the “one dimensional” sample A but also for the “two-dimensional” sample B. For the square patterned substrate, the Ge islands nucleate in the holes formed by the orthogonally etched trenches and *not* on top of the mesas. This observation differs from previously reported gas source MBE growth of islands on etched mesas [2], [3]. Figures 1 (e) and (f) show line scans, i.e. height profiles of the 2D ordered islands along two orthogonal directions. These line scans reveal both the achieved precision of the two- dimensional lateral positioning as well as size uniformity of the islands.

The nearly perfect lateral ordering of the islands can be used to stack several layers of Ge islands to form a three dimensional island crystal. We chose a Si spacer layer thickness of 20 nm, which ensures a vertical ordering of the islands, due to the strain fields of the buried ones. Figure 2 shows the surface morphology of samples C and D which consist of a stack of three Ge island layers separated by Si spacer layers, which were grown at 550 °C, These AFM data nicely demonstrate the long range ordering and size homogeneity of the Ge islands. The line scans along two orthogonal <110> directions not only demonstrate the periodicity and the size homogeneity but also the fact that in the stacked island samples the regions in between the islands are flattened through the coverage with Si.

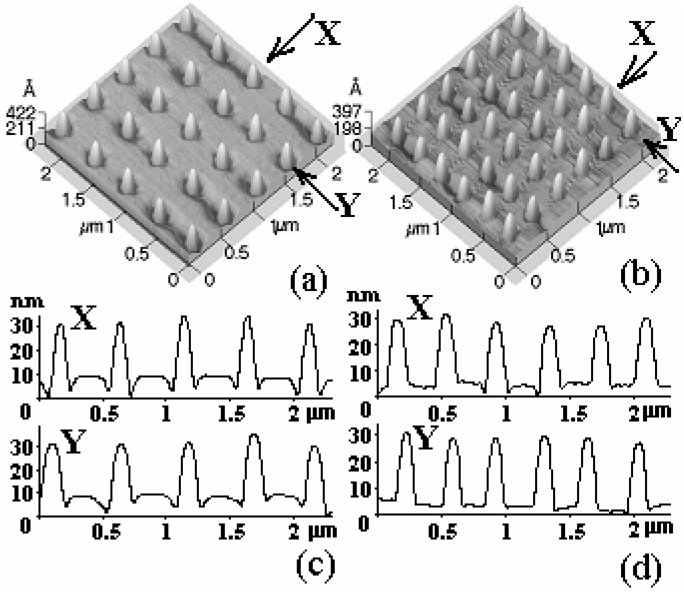

Fig. 2: Surface morphology of three period stacked Ge island samples with a lateral period of 500 nm (sample C, (a)) and 400 nm (sample D, (b)). Line scans along two orthogonal <110> directions marked by X and Y are shown in (c) (sample C) and (d) (sample D).

In samples that were capped with Si we investigated also the photoluminescence (PL). Clear PL signatures both from the islands as well as from the wetting layers were found.

Conclusions

In conclusion, we have demonstrated two-dimensional lateral ordering of Ge islands on pre-patterned Si substrates without the use of patterned oxide layers or of buried stressor layers.

We explain our observations of this two-dimensional ordering by the importance of the growth kinetics of Ge on Si, which primarily affects the preferential positioning of Ge islands on the pre-patterned Si substrates. The formation of Ge islands in the trenches or in these holes is attributed to the accumulation of Ge adatoms migrating downwards from the sidewalls of trenches or holes or even from the neighboring mesas to the bottom. The reason for this downward flux of adatoms is an asymmetry of the activation barrier at steps [7]. The Ge atoms that remain on top of the ridges or mesas form a Ge layer with a thickness less than the critical value for 2D-3D transition, resulting in the absence of islands. This kinetic origin of island formation in trenches or holes agrees with our previous results on the formation of Ge islands on 1D pre-patterned stripes [7].

The growth technique described makes a precise addressing of individual islands possible, a prerequisite for any application of these self-organized Ge nanostructures in electronic or optoelectronic applications.

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