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GISAXS characterization of Ge islands on Si(1 0 0) substrates

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Abstract

We present a preliminary study of Ge island formation on Si(1 0 0) substrates using grazing-incidence small-angle X-ray scattering (GISAXS). Samples were prepared by high-vacuum evaporation of a 5 nm thick Ge layer on Si(1 0 0) substrate held at 200 °C. The samples were subsequently annealed at different temperatures for 1 h in vacuum, yielding to island formation. The Fortran program IsGISAXS was used for the simulation and analysis of Ge islands. The vertical cut (perpendicular to the surface) of the experimental 2D GISAXS pattern has been fitted using a Guinier approximation. The obtained parameters were used for the simulations. The simulated 2D GISAXS pattern well reproduce experimental data for cylindrically shaped islands with morphological parameters $R = 4\,\text{nm}$, $H/R = 0.25$ and the average inter-island distance $D = 5\,\text{nm}$.

Keywords: GISAXS; Nanostructures; Silicon; Germanium

1. Introduction

The growth and the self-organization of Ge islands on Si substrates have been extensively studied in the last few years because of their technological potential in the field of Si-based quantum optical devices. In particular, the self-organization of nanostructures with quantum dot properties could be used for the new light emitting diodes and quantum computers.

There are few studies that have focused on the growth kinetics, electrical and optical characteristics of Ge islands on Si substrates under various growth conditions [1–4]. From the fundamental point of view, Ge growth on Si has been studied very extensively as a result of a modified Stranski–Krastanov growth process [2]. The Stranski–Krastanov growth mode is a combination of two growth modes, namely layer-by-layer and Volmer–Weber. In the layer-by-layer growth mode the incoming material uniformly wets the surface while in the Volmer–Weber growth mode the deposited materials does not wet the surface, but generates 3D faceted droplets on the substrate.

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From the microscopic point of view, the most relevant factor that determines the growth mode is the lattice mismatch. If mismatch is up to 10% Stranski–Krastanov growth mode occurs.

The Ge islands form spontaneously on silicon substrates due to the 4.17% lattice mismatch. The lattice mismatch causes the film to undergo a layer-to-island transition, when Ge coverage exceeds three monolayers. The 3D Ge (energy gap 0.6 eV) islands embedded in a Si (energy gap 1.12 eV) matrix with a larger forbidden band gap may act as confining centres both for electrons and holes. Following island formation, the islands evolve further, undergoing a rich sequence of shape changes, as they seek the shape and composition that minimizes their free energy [3].

Following the first experimental detection of Ge so-called hut clusters on Si(1 0 0) made by Mo et al. [4], several types of islands have been observed in different systems. For better device performance, it is important to obtain islands of the same size, shape, and to find a mechanism for self-organized ordering. Despite the intensive research in the last few years, careful cataloguing of the shape and size evolution of the islands as a function of growth conditions has not yet been performed.

A variety of methods, such as molecular beam epitaxy (MBE) [3,5–8], chemical vapour deposition (CVD) [9] and thermal evaporation [10], has been used for Ge nanostructure deposition on different substrates. Most of the studies have been performed on Si(1 0 0) substrates and some on Si(1 1 1).

The size and shape of islands are usually determined using microscopy techniques such as transmission electron microscopy (TEM), scanning tunnelling microscopy (STM) and atomic force microscopy (AFM). However, in the case of buried islands these techniques are of limited use. Because of the variable probed depth as a function of the incident angle, X-rays can be used for characterization of island on a substrate or buried islands. Grazing incidence small angle X-ray scattering (GISAXS) is a powerful technique for structural characterization of islands supported on a substrate [11]. From the GISAXS pattern it is possible to determine the size, the shape, inter-island distance and size distribution of islands.

In this work, we present a study of Ge islands on Si (1 0 0) substrates using a GISAXS.

2. Experimental

Samples were prepared by high-vacuum evaporation of a 5 nm thick Ge layer on a Si(1 0 0) substrate held at 200 °C. Annealing was performed at 700 °C for 1 h under high-vacuum, yielding to island formation.

The GISAXS experiments were carried out at the SAXS beam-line [12] of the storage ring Elettra, Trieste, Italy, using synchrotron radiation with wavelength $\lambda = 0.154$ nm and photon energy of 8 keV. A 2D CCD detector containing 1024×1024 pixels, positioned perpendicular to the incident beam was used to record SAXS intensity. A thin Al-strip was placed in front of the 2D detector to avoid overflow of the detector in the specular plane direction where the usually much stronger surface scattering is present. The spectra were corrected for background intensity and detector response. The initial analysis of SAXS intensity was based on the Guinier approximation [13] in which the scattering at very small angles is of Gaussian form, independent of the shape of the scattering particle.

3. Results and discussion

Fig. 1 represents a schematic diagram of the sample preparation. On a clean Si surface a 5 nm layer of Ge was evaporated in high vacuum at 200 °C. Subsequent annealing in high vacuum at 700 °C was performed to induce island formation. The island growth mode resulted in a distribution

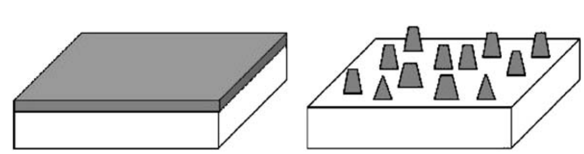

Fig. 1. A schematic illustration of Ge nanostructure formation on silicon substrate.