Applied Surface Science 257 (2011) 8078–8084

Contents lists available at ScienceDirect

Applied Surface Science

journal homepage: www.elsevier.com/locate/apsusc

Femtosecond pulsed laser deposition of Ge quantum dot growth on Si(1 0 0)-(2×1)

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ARTICLE INFO

Article history:
Received 27 February 2011
Received in revised form 18 April 2011
Accepted 22 April 2011
Available online 30 April 2011

Keywords:
Quantum dots
Self-assembly
Pulsed laser deposition
RHEED
AFM

ABSTRACT

Ge quantum dots were grown on Si(1 0 0)-(2×1) by femtosecond pulsed laser deposition at various substrate temperatures using a femtosecond Ti:sapphire laser. *In situ* reflection high-energy electron diffraction and *ex situ* atomic force microscopy were used to analyze the film structure and morphology. The morphology of germanium islands on silicon was studied at different coverages. The results show that femtosecond pulsed laser deposition reduces the minimum temperature for epitaxial growth of Ge quantum dots to ∼280 °C, which is 120 °C lower than previously observed in nanosecond pulsed laser deposition and more than 200 °C lower than that reported for molecular beam epitaxy and chemical vapor deposition.

1. Introduction

Self-assembled Ge quantum dots (QDs) grown on Si are suitable for applications in nanoelectronics and optoelectronic devices [1–3]. In order to fully use their potential in various applications, the size distribution of QDs must be well controlled.

Low-temperature thin film growth is strongly desirable in microelectronic fabrication. Lowering the growth temperature in Si/Ge suppresses misfit dislocation [4]. Extrinsic assistance by energetic particles, such as ions, electrons and photons, is used to lower the epitaxial growth temperature [5–8].

The growth of Ge on Si follows the Stranski-Krastanov mode, also known as layer-plus-islands growth, which is observed when lattice mismatch is between 3 and 7% [9]. The initial several monolayers ($1\,\text{ML} \sim 6.2 \times 10^{14}\,\text{atoms/cm}^2$) grow in a layer-by-layer fashion on the substrate. Upon completion of the wetting layer, the film undergoes three-dimensional islands growth to relieve lattice strain. Those islands could be dislocation free, while some larger ones develop misfit dislocations to reduce their strain energy [10]. The first faceted islands, in the shape of square-based pyramids or rectangular-based hut clusters with four facets, appear following completion of the wetting layer. Those huts are rectangular-shaped {1 0 5}-faceted clusters with a contact angle ∼11° with {1 0 0} planes, whereas at higher temperatures another kind of multi-faceted, larger dome-shape islands coexist with huts [11,12]. While hut clusters are {1 0 5}-faceted and have a 15–20 nm average size, the dome islands are mainly bound by steeper facets such as {1 1 3}, {1 0 2} making ∼25° and 26°, respectively, with the substrate, and have an average size of 50–100 nm [13,14]. The evolution of the {1 0 5}-faceted hut clusters to {1 0 5}-, {1 1 3}-, and {15 3 23}-faceted domes is well documented along with the final, larger {1 1 1}-faceted superdomes containing dislocations [14]. It was shown that the {1 0 5} facet is energetically favorable on smaller islands, while the {1 1 3} facet is favorable on larger islands [15]. The shape of the initial islands was found to depend on the deposition technique. For example, if Sb is used as a surfactant in the molecular beam epitaxy (MBE) of Ge/Si(1 0 0), the initial island shape changes from {1 0 5}-faceted to {1 1 7}-faceted [16]. If Ge is grown by liquid phase epitaxy (LPE), {1 1 5}-faceted islands are first observed instead of the {1 0 5}-faceted ones, and as the coverage increases, {1 1 1}-faceted pyramids are formed [17,18].

The morphological evolution of islands is also dependent on growth conditions. For example, as the substrate temperature is increased, the Ge adatoms diffuse more over the surface which increases the probability of these adatoms finding energetically suitable sites for epitaxial growth. Generally, increasing the substrate temperature above that needed for epitaxial growth causes an increase in island size and height, a decrease in the number of islands, and their shape transition from hut to dome [3,19,20].

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doi:10.1016/j.apsusc.2011.04.106

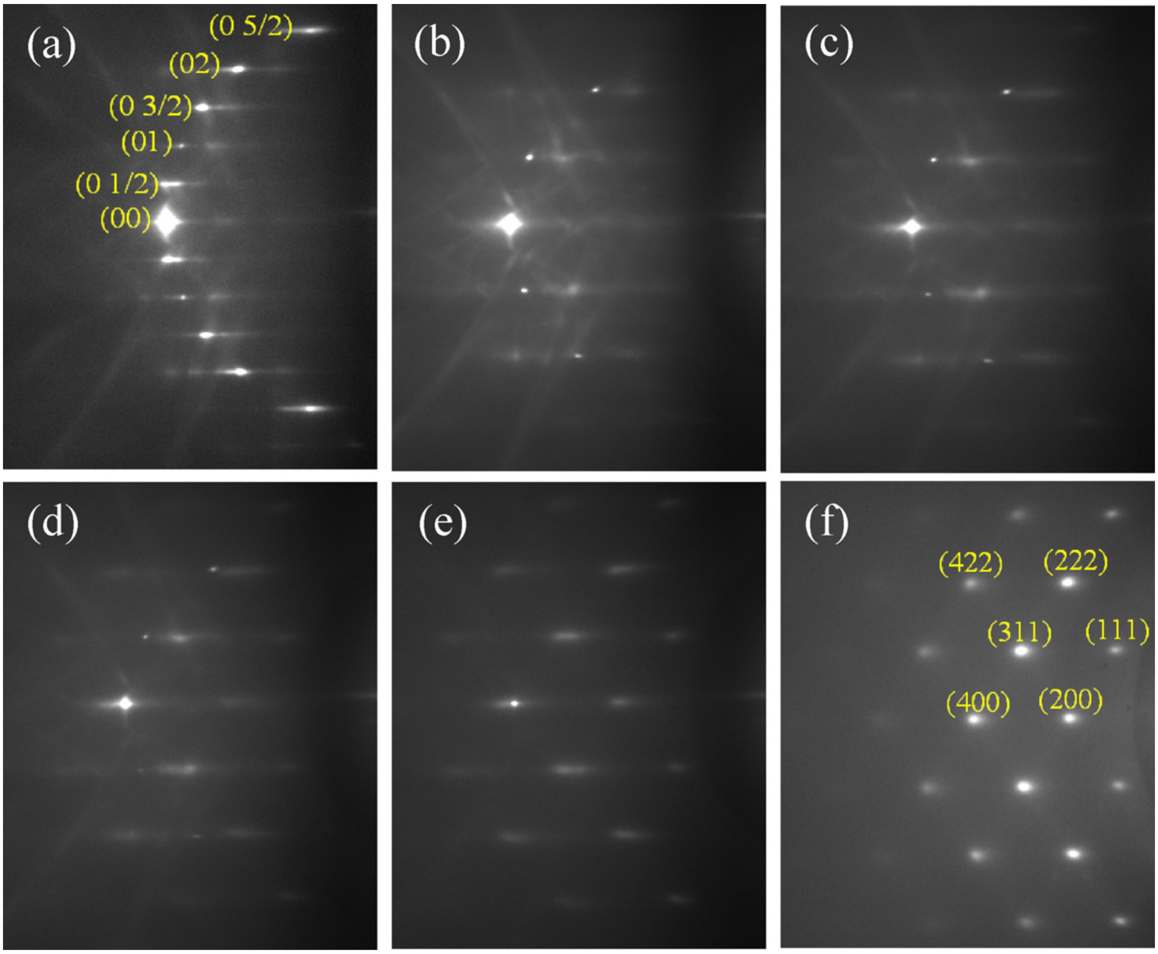

Fig. 1. RHEED pattern of Ge deposited on Si(1 0 0)-(2 × 1) at 400 °C at different coverages. (a) Initial Si(1 0 0)-(2 × 1) structure, (b) 4 ML, (c) 5 ML, (d) 6 ML, (e) 8 ML, and (f) 12 ML.

For many years pulsed laser deposition (PLD) has been recognized as having many attractive features, such as good composition transfer control, ability to grow thin films from many types of material such as semiconductors, metals, and ceramics, and the energetic nature of the PLD plume [21–23]. PLD can be conveniently used to grow multilayers of different materials or with different doping without the need for residual gases or doping sources. In quantum dot devices, tens of multilayers of doped films, each grown on top of wetting layer, are required [24–26]. Compared to other vapor phase deposition methods, PLD is particularly suitable for multilayer growth, since the laser can be used to ablate different doped semiconductor targets, one after another, while growing the doped material in the form of thin films [27].

A well-recognized shortcoming of PLD is the presence of particulates in the grown films. Particulate formation is governed by target density, target surface quality, laser wavelength, laser fluence, and laser pulse duration [3,28]. Using femtosecond PLD rather than longer pulses results in a lower ablation threshold, less damage to the surface, formation of highly ionized energetic plasma, higher evaporation rate, and reduction of particulate formation [20,29,30]. In femtosecond laser interaction with solids, ablation is often a direct solid-vapor transition, minimizing liquid splashing [31]. The ultrashort pulse duration reduces the heat-affected zone, thus reducing target damage. Better quality films are usually achieved when using ultrashort laser pulses with high repetition rate [32–34].

In this article, we present results on the growth of self-assembled Ge quantum dots (QDs) on Si(1 0 0)-(2 × 1) using femtosecond laser ablation. Reflection high-energy electron diffraction (RHEED) is used as an *in situ* monitoring tool of the surface structure while *ex situ* atomic force microscopy (AFM) is used for analysis of the morphology of the grown films. The evolution of the Ge QDs grown at 400 °C was studied. Pyramidal-shaped islands were observed after the formation of the wetting layer. With additional coverage, elongated hut clusters formed. After ~8 ML coverage, dome-shaped clusters started to appear. The results show that femtosecond pulsed laser deposition reduces the minimum temperature for epitaxial growth of Ge QDs on Si(1 0 0) to ~280 °C, which is 120 °C lower than previous nanosecond pulsed laser deposition work [3,19], and more than 200 °C lower than some of the reported growth temperatures in molecular beam epitaxy and chemical vapor deposition [20,35]. The result is attributed to the high energy of plume species in femtosecond PLD results in adatom energy which leads to increased surface diffusion of adatoms.

2. Experiment

Ge QDs were grown on Si(1 0 0) in an ultrahigh vacuum (UHV) chamber (base pressure $<1.0 \times 10^{-9}$ Torr) by femtosecond PLD. The Ge target was mounted on a rotation stage with a variable rotation speed. Target rotation at 5 rpm was used to minimize the particulate formation and to ablate target material uniformly with successive laser shots during deposition. Each laser pulse ablates the same spot 2 times at this rotation speed. The Si(1 0 0) substrates (dimensions of 2.0 mm × 10 mm × 0.5 mm *p*-type boron doped, and