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Ordered quantum dots formation on engineered template by molecular beam epitaxy

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Abstract

We have achieved partial ordering of InAs quantum dots (QDs) grown on a flat GaAs (0 0 1) substrate. Although the growth of the first QD layer results in random distribution of QDs, subsequent processes that involve multiple cycles of capping, regrowth and annealing have turned the flat substrate into a template with stripes in the $[1\,\bar{1}\,0]$ direction. Regrowth on the engineered template results in chains of relatively uniform InAs QDs connected in series.

Keywords: Ordered InAs quantum dots; Engineered template; Molecular beam epitaxy

1. Introduction

Quantum dots (QDs) are taking an increasingly important role in nano- and optoelectronic devices. Self-assembled semiconductor QDs are usually grown by molecular beam epitaxy (MBE). The crystalline quality of quantum dots could be controlled by parameters such as growth temperature, substrate temperature, annealing temperature, etc. [1]. High quality quantum dots emit strong luminescence at room temperature, giving rise to quantum dot lasers [2,3]. InAs QD lasers, in particular, are useful in optical communication systems. The growth of InAs QDs on a lattice-mismatched GaAs substrate by a typical Stranski-Krastanow (SK) growth mode, however, results in dots of varying dimensions randomly distributed across the substrate. The randomness of QD sizes gives rise to devices with varied electrical and optical characteristics. To obtain QD-based devices with predictable behavior, it is essential to fabricate or grow a QD

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ensemble where all dots are identical. This, however, has yet to be achieved in practice and is still an issue which receives much attention.

The ordering of quantum dots could be achieved via top-down and bottom-up approaches. An example of the former is the use of optical- and electron-beam lithography in combination with a shadow-mask technique, for example, see [4]. An example of the latter is the growth of quantum dots on high-index substrates; for example, the growth of InAs on (3 1 1)A, (4 1 1)A and (N 1 1)-GaAs substrates [5–8].

In this work, we report a simple growth process that results in a partially ordered InAs QDs over a large surface area. The key step in our work is the use of an engineered template that has been preconditioned with a series of capping, regrowth and annealing cycles. Some degree of randomness still persists. Nevertheless, our approach may serve as a foundation which, when used in conjunction with other growth techniques, may result in a truly ordered QD ensemble.

2. Experiments and results

All samples are grown using a Riber 32P solid-source molecular beam epitaxial system. The starting semi-insulating (0 0 1)-GaAs substrates undergo in situ oxide desorption stage prior to growth. After oxide desorption, a 400 nm thick GaAs buffer layer is grown at 610 °C and at arsenic pressure of 8×10^{-6} Torr. This is followed by the growth of 1.8 ML of InAs at 500 °C which results in QDs with an average dot height of 6 nm as can be seen in the atomic force microscopy (AFM) image in Fig. 1. The dots are randomly distributed across the surface as can be expected from a typical SK growth mode.

On top of this QD layer, we grow 6 ML of GaAs capping layer (~1.66 nm) at a reduced temperature of 470 °C. The lattice-mismatched capping layer increases the strain energy around the upper surface of the covered QDs and causes In atoms to migrate out of the dot, leaving a hollow middle part [9,10]. As a result of the hollowing-out effect, the originally rounded InAs QDs are transformed into a camel-like structure shown in the AFM image in Fig. 2 which shows that each dot has a nanohole in the middle.

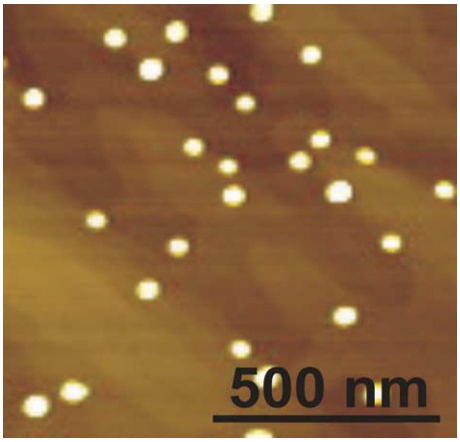

Fig. 1. AFM image of self-assembled InAs QDs on GaAs substrate.

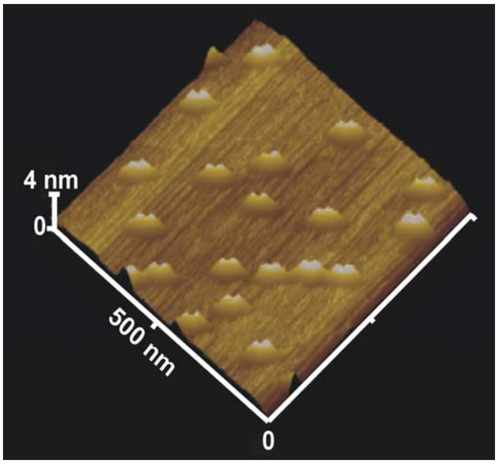

Fig. 2. AFM image of camel-like structure created by capping the QDs of Fig. 1 with a thin lattice-mismatched GaAs layer.

The sample is then subject to a 30 s annealing at 550 °C. While the temperature is increased to 550 °C, the arsenic pressure is decreased from 8×10^{-6} to 4×10^{-6} Torr. The annealing causes limited rearrangement of atoms in the vicinity of the nanoholes, thus, some smoothening can be expected. After the annealing, the holes have disappeared and are replaced by stripes which point towards the $[1\,\bar{1}\,0]$ azimuth. These stripes could serve as a template for subsequent QD regrowth