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Effects of Overgrowth, Growth Rate, and Capping of InAs Quantum Dots Grown on Cross-hatch Surfaces by Molecular Beam Epitaxy

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Abstract

The size, shape and distribution of InAs quantum dots (QDs) grown on cross-hatch InGaAs virtual substrates via molecular beam epitaxy (MBE) are investigated by systematic variations in the degree of QD overgrowth, QD growth rate and GaAs capping layer thickness. It is found that increasing overgrowth and/or growth rate, in combination with migration-enhanced epitaxy, results in the formation of uniform, high-density QDs where preferential alignment along the two orthogonal cross-hatch directions, [110] and [1-10], is maintained. Capping of QD hatch results in asymmetrical shape transformation where quantum dashes along [110] direction and wires along [1-10] can be formed on the same substrate in one continuous MBE process. The various shapes, sizes, and distributions of QD hatches provide means for engineering of optoelectronic devices.

Key words: *quantum dots; InAs; cross-hatch; overgrowth; capping; migration-enhanced epitaxy.*

Introduction

The formation of nanostructures via bottom-up self-assembly has received significant attention due to the possibility of forming defect-free nanostructures with shapes ranging from quantum dots (QDs) to quantum rings, quantum wires and quantum dashes [1]. The electronic and optical properties of these nanostructures are influenced by quantum-sized effects, giving additional degrees of freedom in device design. We recently reported a self-assembly process where InAs quantum-dot hatches are grown in one

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continuous molecular beam epitaxial (MBE) cycle [2]. InAs-based QD devices find various applications in lasers and infrared detectors [1] and when alloyed with Mn will exhibit diluted magnetic semiconducting properties [3], which are useful in hard disk drives (HDD) applications.

With optimized condition, these InAs QDs can be formed only on the underlying cross-hatch surface—hence, lower density but more uniform comparing to as-grown QDs on flat substrates [2]. In some applications, such as in QD solar cells, dot density is required to be high while dot uniformity is not a main concern [4]. Yet in certain applications, such as super luminescent light-emitting diodes, QDs are preferred to be large and non-uniform for efficient light emission [5], whereas in quantum cellular automata, QDs are required to be identical [6]. These differing preferences imply that QD-hatch based devices will be required to have various shapes, sizes and distributions, yet only typical as-grown dots on cross-hatch surfaces have been reported so far [2, 7-9].

In order to show that QD hatch can be grown to various shapes and size distributions by *in-situ* control of growth parameters, this paper reports on the effects of overgrowth, growth rate, and capping of InAs QD hatches. The main findings indicate that dot density can be increased by increasing overgrowth and/or growth rate, while preserving preferential dot alignment along the two orthogonal cross-hatch directions. The circular features of as-grown dots are transformed into a dash-like or a wire-like features when capped with a thin layer of GaAs.

Sample Growth and Characterization

The structure under investigation is shown in Fig. 1. MBE growth details are the same as in [2]. Three sets of samples are grown to investigate the effects of overgrowth, growth rate, and capping of the QD layer grown on a cross-hatch surface of $In_{0.15}Ga_{0.85}As$. In the first set of samples which aim to study the effects of overgrowth, three samples are grown without the GaAs capping layer where the InAs QD layer is grown in the typical Stranski-Krastanow (SK) growth mode at a slow growth rate of 0.01 monolayer (ML)/s. The controlled sample A1 is grown up to the InAs QD layer and stopped when the QDs just form, thus A1 is grown with no overgrowth, while A2 is 50% and A3 is 100% overgrown. The degree of overgrowth is controlled by timing of In shutter after the detection of 2D-to-

3D growth transition which can be observed *in-situ* via reflection high-energy electron diffraction (RHEED) pattern.

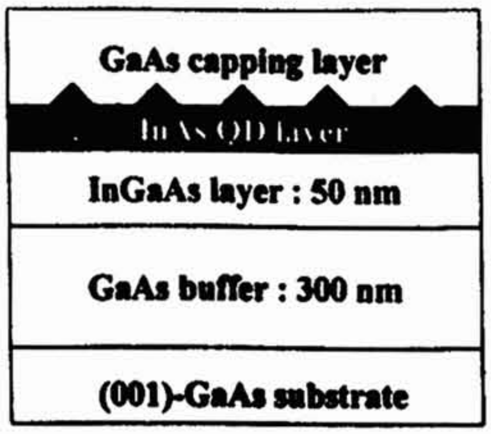

Figure 1. Schematic cross section of the structure grown (not drawn to scale).

In the second set of samples which aim to study the effects of growth rates, three samples B1, B2 and B3 with equal amount of 50% QD overgrowth are grown with different growth rates of 0.02-, 0.05- and 0.1 ML/s, respectively. This second set of samples are grown using migration-enhanced epitaxy (MEE) [10], without the GaAs capping layer. In the third set of samples which aim to study the effects of capping, four samples C1, C2, C3 and C4 with identical InAs QD layer (no overgrowth, SK mode) are capped with different thickness of GaAs of 2-, 3-, 6- and 15 ML, respectively. After growth, the samples are removed from the MBE chamber and characterized by non-contact atomic force microscopy (AFM) in air.

Result and Discussion

The AFM images of the first, second and third sets of samples are shown in Figs. 2, 3 and 4, respectively. The effects of *overgrowth* as seen in the first set of AFM images in Fig. 2 show that when overgrowth increases from none in Fig. 2(a) to 50% in Fig. 2(b) and to 100% in Fig. 2(c), the dot density correspondingly increases while dot alignment along both the [1-10] and [110] crystallographic directions still persists even when overgrowth reaches 100% in Fig. 2(c). The surface of sample A1 in Fig. 2(a) is covered only by [1-10]- and [110]-aligned QDs while those of sample A3 in Fig. 2(c) is fully covered by uniform QDs. This characteristic feature is in contrast to overgrown QDs on (100)-GaAs where QDs are non-uniform: large, ripened islands co-exist with small, dislocations-free islands [11], reducing radiative combination efficiency of the QD layer. The insertion of appropriate InGaAs cross-hatch layer between the GaAs buffer layer and the InAs QD layer thus establishes a *surface* condition appropriate for the growth of uniform, high-density QD layer which can serve as an efficient active layer in optoelectronic devices, provided non-radiative recombination due to dislocations in the *bulk* of the cross-hatch layer is suppressed.

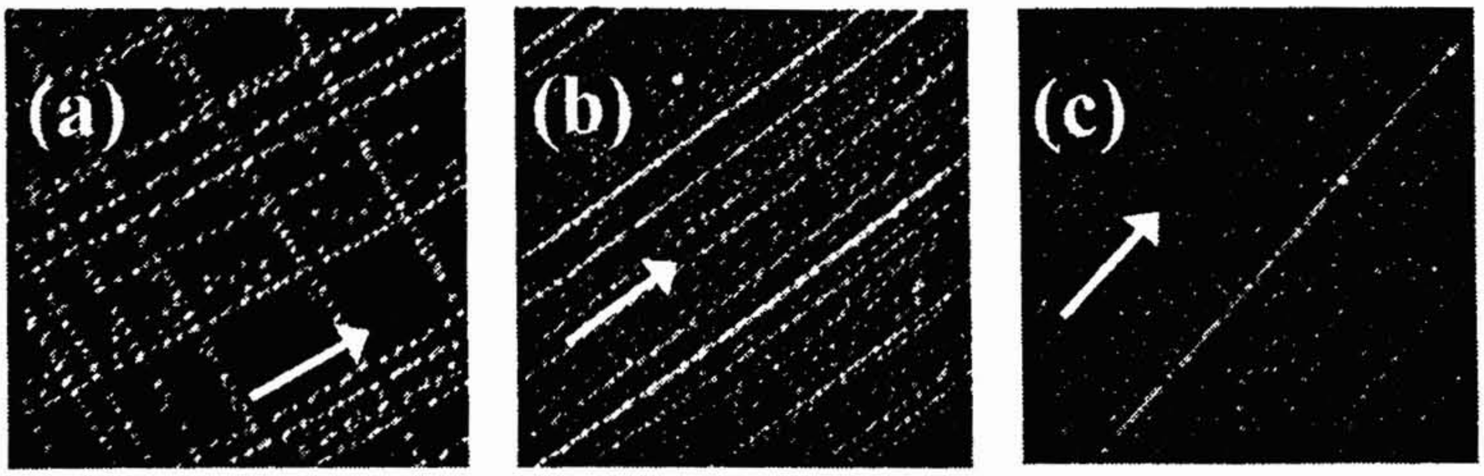

Figure 2. AFM images (3×3 μm^2) of SK InAs QDs formed on the cross-hatch layer (a) without overgrowth, and with overgrowth of (b) 50% and (c) 100%. The arrows indicate the [1-10] direction.

The origin of improved QD uniformity possibly stems from the fact that impinging In adatoms have higher mobility on InGaAs surface than on GaAs surface, making them move a greater distance before nucleating and forming new QDs. The sticking coefficient of In adatoms on the InGaAs surface is lower than on GaAs because at the growth temperature of 500°C, re-evaporation of In from InGaAs surface is not negligible [12]. Growing InAs QDs on InGaAs thus results in a greater In adatoms movement, a less statistically diverse QD nucleation and growth, and ultimately more uniform QDs.

The effects of *growth rates* as seen in the second set of AFM images in Fig. 3 show that when the rate increases from 0.02 ML/s in Fig. 3(a) to 0.05 ML/s in Fig. 3(b) and 0.1 ML/s in Fig. 3(c), the dot density correspondingly increases. Comparing to SK QDs in Fig. 2, MEE QDs seen in Fig. 3 are larger and similarly uniform.

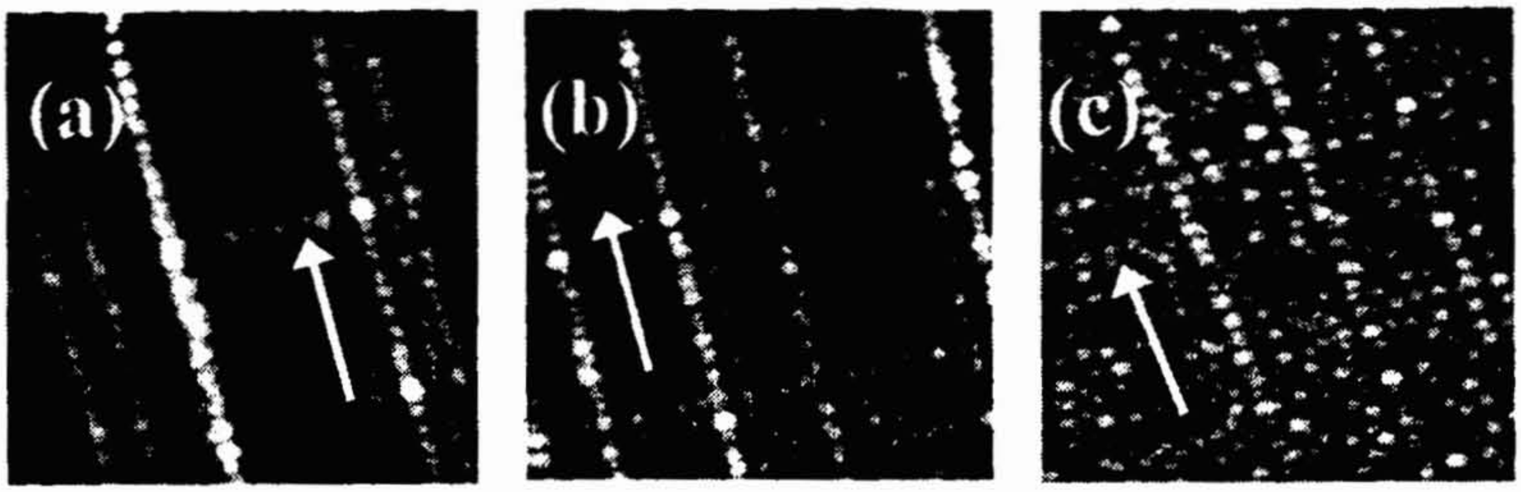

Figure 3. AFM images (2×2 μm^2) of MEE InAs QDs (50% overgrown) formed on the cross-hatch layer with a growth rate of (a) 0.02-, (b) 0.05- and (c) 0.1 ML/s. The arrows indicate the [1-10] direction.

The increase in the base diameter of MEE QDs as compared to SK QDs is attributed to the enhancement of In adatoms migration via two different mechanisms: alternatively supplying In and As_4 beams (MEE), and increasing growth rate. The latter usually gives rise to small InAs QDs on (100)-GaAs substrates with worsened uniformity [1]. Thus by increasing the growth rate and simultaneously applying MEE, the size of InAs QDs can be increased, yet uniformity can be maintained.

The effects of *capping* as seen in the third set of AFM images in Fig. 4 show that as the thickness of the GaAs capping layer increases from 2 ML in Fig. 4(a) to 3 ML in Fig. 4(b), to 6 ML in Fig. 4(c), and to 15 ML in Fig. 4(d), the bases of all QDs increasingly elongates along the [1-10] direction. The elongation of [110]-aligned QDs along the *orthogonal* [1-10] direction, see example inside ○ in Fig. 4(a), means that the elongated dots are isolated, resulting in a dash-like nanostructure. On the other hand, the elongation of [1-10]-aligned QDs along the *parallel* [1-10] direction, □ in Fig. 4(a), means that the elongated dots are connected and some even merged, resulting in a wire-like nanostructure.

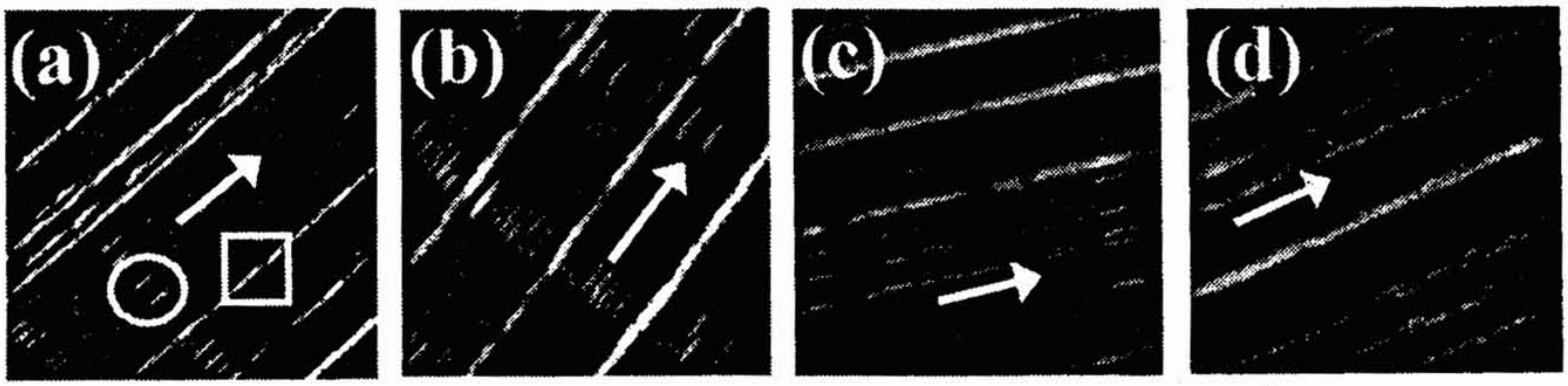

Figure 4. AFM images (2×2 μm^2) of SK InAs QDs with GaAs capping of (a) 2-, (b) 3-, (c) 6- and (d) 15 ML. The arrows indicate the [1-10] direction. The circle (○) in (a) indicates quantum dashes, while box (☐) indicates merged quantum dashes, or a quantum wire.

QD elongation and surface planarization are the main observable phenomena in this set of capped samples. The elongation as a result of capping has previously been reported for InAs QDs grown on (100)-GaAs substrates and is caused by anisotropic strain fields [13]. But in the capped InAs QDs grown on cross-hatch layers as shown in Fig. 4, pre-existing strain fields from the underlying cross-hatch surface combine with those from the overlying capping layer, driving the formation of quantum dashes and wires.

The planarization as a result of increasing capping thickness can be explained by energy minimization driven by surface step elimination [14]. Figures 4(a)-(d) show that with increasing capping thickness, the quantum dashes tend to disappear while quantum wires are more continuous. Varying GaAs capping thickness thus provides a means to control the distribution of quantum dashes and wires. It is important to note that thin-capped InAs QD hatch demonstrated here provides a means to form quantum dashes *and* wires on the same sample. Applications of this type of same-substrate dual nanostructures may include optical sources or detectors, each with two different optical signatures that can be electrically-controlled, for example, using surface gates [15] that are transparent at the interested wavelengths.

Conclusion

The effects of overgrowth, growth rate and thin capping of InAs QDs grown on cross-hatch InGaAs substrates are investigated. The size, shape and distribution of QD hatch can be controlled *in-situ* during MBE growth. Overgrowth of InAs QD hatch results in high-density, uniform QD layer. Preferential alignments of QDs along the two orthogonal directions are maintained despite significant overgrowth. QD size can be increased and uniformity maintained by increasing the growth rate of the QD layer while applying migration-enhanced epitaxy. Finally, capping as-grown InAs QDs with a thin GaAs layer results in asymmetrical shape transformation: dots along the [110] direction turn into dashes while those along the [1-10] direction merge into wires, driven by strain fields interaction and surface step elimination.

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