InAs self-organized quantum dashes grown on GaAs (211)B

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We have grown InAs self-organized quantum dots and quantum dashes on GaAs (211)B substrates by molecular beam epitaxy. The growth temperature dependence of InAs nanostructures were studied by in situ reflection high-energy electron diffraction (RHEED) and ex situ atomic force microscopy. In the studied temperature range from 400 to 510 °C, the RHEED pattern changed from streaky to spotty after deposition of 6 ML of InAs, showing the formation of nanostructures. The quantum dots grown at lower growth temperatures (from 400 to 490 °C) showed bimodal dot size distribution. At higher growth temperatures, a drastic change from quantum dots to quantum dashes was observed. The quantum dashes have an asymmetric hutlike shape and align themselves along the [011] direction. The quantum dash width increases dramatically, whereas the average length and density increases slightly on further deposition of InAs.

Lattice mismatch strain-induced quantum dots (QDs) have attracted great interest for novel optoelectronic device applications and QD lasers with low threshold current density have been reported.1–4 In addition to the QD structure, the self-organized growth has led to the formation of so-called quantum dashes (QDHs), as demonstrated by Utzmeier et al.,5 who observed the formation of InSb QDHs by growing more than 3.2 monolayers (ML) InSb on InP (001) substrates. Up to now, most of the studies about self-organized nanostructures have been concentrated on (001) substrates and only a few attempts were taken on non-(001) substrates; high-quality InGaAs quantum disks have been fabricated on (311)B substrates by metalorganic vapor phase epitaxy growth,6 narrow photoluminescence linewidths (35 meV at 2 K and 41 meV at room temperature) have been observed from (311)B InAs/InGaAs QDs grown by molecular beam epitaxy (MBE),7 and the highest quantum efficiency has been observed from (711)B InGaAs QDs.8 On the other hand, the critical role of the substrate orientation in conventional quantum well (QW) laser structures has been demonstrated by a number of researchers. Recently, Sun and Towe9 and Sale et al.10 reported the strained QW lasers with low threshold current density grown on (211)B GaAs substrates. It has also been demonstrated that the (211)B orientation is the optimum direction for the second-harmonic surface emission structure.11,12 Due to the unique properties of the structures grown on (211)B substrates, it is quite interesting to investigate the self-organized nanostructure grown on the (211)B plane. In this letter, we report the MBE growth of InAs self-organized QDs and QDHs on GaAs (211)B substrates. Reflection high-energy electron diffraction (RHEED) and atomic force microscopy (AFM) were used for in situ and ex situ characterization of the InAs nanostructures.

The samples were grown by MBE (ULVAC MBC-100) with solid sources of Ga, Al, In, and As. The substrates were undoped semi-insulating GaAs (211)B epiready wafers. Growth rates were 0.6 μm/h for GaAs, 0.5 μm/h for AlAs, and 0.15 μm/h for InAs, which were determined by RHEED oscillation measurements on (001) oriented substrates. After removing surface oxide under an arsenic flux, a 0.5 μm GaAs buffer layer was grown at 600 °C, then a 40 period GaAs/AlAs (2.3 nm/1.5 nm) superlattice was deposited, followed by a 10 nm GaAs layer. InAs nanostructures were deposited at substrate temperatures (T_s) ranging from 400 to 510 °C with an As and In beam equivalent pressure ratio of 20.

Figure 1 shows the RHEED patterns of GaAs (211)B grown at 600 °C [Figs. 1(a) and 1(b)] and at 450 °C before InAs deposition [Figs. 1(c) and 1(d)], as well as the RHEED patterns of 6 ML of InAs grown on GaAs (211)B at 450 °C [Figs. 1(e) and 1(f)] and at 500 °C [Figs. 1(g) and 1(h)]. During GaAs buffer layer growth, the RHEED pattern was streaky along the [011] azimuth [Fig. 1(a)] and tilted streaky along the [111] azimuth [Fig. 1(b)]. The streaky RHEED pattern reveals a regular step array and the tilted streaky pattern indicates an array of regular facets. When T_s was lowered to the temperature for InAs deposition, the RHEED intensity decreased and the RHEED pattern kept streaky along [011] azimuth [Fig. 1(c)], whereas it changed from tilted streaky to streaky along [111] azimuth [Fig. 1(d)]. After deposition of 6 ML of InAs at 450 °C, the RHEED pattern changed from streaky to spotty patterns [Figs. 1(e) and 1(f)], which reveals a transition from two-dimensional growth mode to three-dimensional (3D) growth mode and the formation of the QDs. When the same amount of InAs was deposited at 500 °C, the RHEED pattern along [111] direction [Fig. 1(h)] was almost the same as that of InAs grown at 450 °C, but there was a drastic change of the RHEED pattern along the [011] direction, it changed from streaky to spotty patterns right after deposition of 6 ML of InAs just as T_s = 450 °C, and then the spotty pattern transformed to the streaky pattern [Fig. 1(g)] after several seconds of growth interruption, indicating the formation of a new structure.

6 ML of InAs have been grown on GaAs (211)B at T_s ranging from 400 to 510 °C and studied by AFM. The

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AFM measurements were performed using a Si$_3$N$_4$ cantilever with a reference force of $0.087 \times 10^{-9}$ N. Figure 2 shows the AFM images for 6 ML$_{\text{211}}$ of InAs deposited at 450 °C (a) at 450 °C (1 $\times$ 1 $\mu$m$^2$), (b) at 500 °C (5 $\times$ 5 $\mu$m$^2$), and (c) 12 ML$_{\text{211}}$ of InAs deposited at 500 °C (5 $\times$ 5 $\mu$m$^2$).

The dot size distribution in Fig. 2(a) is displayed in Fig. 3(a), showing a bimodal distribution. The average dot density, the average lateral size, and the average height of small dots and large dots are $1.9 \times 10^{10}$ and $1.6 \times 10^9$ cm$^{-2}$, 13 and 47 nm, 3 and 10 nm, respectively. Similar bimodal dot size distribution was observed at $T_s$ ranging from 400 to 490 °C. The average dot size increases and the average density decreases monotonically with increasing $T_s$. The bimodal dot size distribution has also been reported by Bogani et al.$^{13}$ and Yu et al.$^{14}$ on InAs QDs grown on GaAs (001) substrates. When the same 6 ML$_{\text{211}}$ of InAs was deposited at 500 or 510 °C, a drastic change of nanostructures from QDs to QDHs was observed [Fig. 2(b) for 500 °C]. The QDH structure was formed with no trace of the existence of small QDs. The QDHs align themselves along the [011] direction and their length-to-width ratio is about 1–3. The QDHs length distribution is illustrated in Fig. 3(b). The average density of QDHs is $2.8 \times 10^8$ cm$^{-2}$ with the average size of 163 nm $\times$ 65 nm and 20 nm in height. When 12 ML$_{\text{211}}$ of InAs was deposited at 500 °C, the QDH width increased dramatically, whereas the average length and the density increased only slightly [Fig. 2(c)], indicating the presence of a critical length and density in QDHs.

Figure 4(a) shows the 3D AFM image of QDHs for

![FIG. 1. RHEED patterns of (a) and (b) GaAs (211)B grown at 600 °C, (c) and (d) GaAs at 450 °C before InAs deposition, (e) and (f) 6 ML$_{\text{211}}$ of InAs grown on GaAs (211)B at 450 °C, and (g) and (h) 6 ML$_{\text{211}}$ of InAs grown at 500 °C. (a), (c), (e), and (g) were taken along the [011] azimuth and (b), (d), (f), and (h) were taken along the [111] azimuth.](image1)

![FIG. 2. AFM images for 6 ML$_{\text{211}}$ of InAs deposited (a) at 450 °C (1 $\times$ 1 $\mu$m$^2$), (b) at 500 °C (5 $\times$ 5 $\mu$m$^2$), and (c) 12 ML$_{\text{211}}$ of InAs deposited at 500 °C (5 $\times$ 5 $\mu$m$^2$).](image2)

![FIG. 3. (a) Lateral size distribution of QDs with 6 ML$_{\text{211}}$ of InAs grown at 450 °C. (b) Length distribution of QDHs with 6 ML$_{\text{211}}$ of InAs grown at 500 °C.](image3)
12 ML$_{211}$ of InAs grown at 500 °C. It can be seen from the AFM images that the QDHs have an asymmetric hutlike geometry. They are found trapezoidal in the [011] direction (the length) and with triangular cross sections in the [111] direction (the width). The facets observed along [011] correspond to the (101) and (110) surfaces as evaluated from the tilt angle of about 30°, and the facets along [111] correspond to the (100) and (111) surfaces from the tilt angles of about 35° and 20°. The schematic diagram of a quantum dash structure is shown in Fig. 4.

For comparison, the initial stages of the InAs QDs deposited on GaAs (001) and (311)B substrates at $T_s$ ranging from 450° to 530 °C were also studied by RHEED and AFM (figures not shown here). The average dot lateral size and height increases and the average density decreases monotonically with increasing $T_s$. This behavior is essentially identical to that of QDs grown on (211)B orientation at lower $T_s$. However, only QDs were observed and no QDHs formed at higher $T_s$ after deposition of 2 ML$_{001}$ of InAs on GaAs (001) or 4 ML$_{311}$ of InAs on GaAs (311)B under the same growth conditions, suggesting the transition from QDs to QDHs is a unique property of the (211)B orientation.

The observation of the time evolution of RHEED images of InAs deposited on the (211)B plane at higher $T_s$ suggests that an intermediate state of QDs exists before the formation of the QDHs. RHEED observation indicated that when InAs was deposited on GaAs, an InAs wetting layer was formed at first, and then the QDs developed on the wetting layer for further deposition of InAs. At lower $T_s$, the QD structure is stable most probably due to the limited migration length of In adatoms. At higher $T_s$, however, due to the thermally enhanced In surface migration, the QDs are metastable and coalesce each other, forming the QDH structure. The hutlike shape of the QDHs is believed to be a result of the minimization of the surface strain energy as discussed by Tersoff and Tromp. They showed that in strained epitaxial growth, islands grow in a rectangular shape to minimize the surface energy when the islands pass a critical size. They also argued that when the stress is anisotropic, the islands align themselves perpendicular to the direction of the maximum stress. This suggests that the present InAs QDHs self-aligned along the [011] direction might be due to the stress anisotropy on the (211)B plane. Their model, however, does not explain the reason for the presence of the critical length ([011] direction), above which the QDHs start to grow in width ([111] direction). The existence of such critical length may be explained by the change of the strain field during the formation of the QDHs.

In summary, InAs self-organized QDHs grown on GaAs (211)B substrates were demonstrated for the first time. The InAs QDs and QDHs grown by MBE on (211)B substrates have been studied by in situ RHEED and ex situ AFM. The QDs with bimodal dot size distribution were formed at lower $T_s$. The average dot size increases and the average density decreases monotonically with increasing $T_s$. At higher $T_s$, a drastic change from QDs to QDHs have been observed. The QDHs have an asymmetric hutlike shape and align themselves along the [011] direction. The QDH width increases dramatically, whereas the average length and density increases only slightly on further deposition of InAs. This behavior might be understood by the stress anisotropy on the (211)B plane and the metastability of the intermediate state of QDs at higher $T_s$.

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