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We demonstrate the formation of well-defined InAs quantum dot (QD) arrays by self-organized engineering of anisotropic strain in a (In,Ga)As/GaAs superlattice (SL). Due to the accumulation and improvement of the uniformity of the strain-field modulation along [011], formation of InAs QD arrays along [0-11] with 140 nm lateral periodicity is clearly observed on the SL template when the number of SL periods is larger than ten. By enhancing the In adatom surface migration length at low growth rates, clear arrays of single InAs QDs are obtained. The QD arrays exhibit strong photoluminescence efficiency that is not reduced compared to that from InAs QD layers on GaAs. Hence, ordering by self-organized anisotropic strain engineering maintains the high structural quality of InAs QDs. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1503872]

The fabrication of quantum dots (QDs) by self-assembled growth methods has been intensively investigated in the last decade for basic physics and device applications.[1,2] However, in spite of the development of various growth methods,[3–5] many hurdles still remain which have to be overcome for the realization of QD devices with the predicted properties.[1,2] QDs formed in the Stranski–Krastanov growth mode, which has been most widely utilized on (100) surfaces, are usually arranged randomly.[4] For many applications, however, it is highly desirable to control the position of QDs in well-ordered arrays. To achieve this goal, many groups have investigated the formation of QD arrays using multilayer high stepped vicinal substrates or strained layer growth on patterned substrates.[6–10] These approaches, however, often suffer from a degradation of the structural perfection and optical quality of the QD arrays, which is attributed to step edge roughness or pattern irregularities on the dot-diameter and dot-to-dot distance length scales, introducing defects and size fluctuations in the QD arrays.

To overcome these problems, we report a method for InAs QD ordering on planar singular GaAs (100), which is based on the self-organized engineering of anisotropic strain in a (In,Ga)As/GaAs superlattice (SL) template. During the growth of a (In,Ga)As/GaAs SL at elevated temperatures, elongated (In,Ga)As QDs develop into very uniform and long quantum wire arrays along [0-11] with well-defined lateral periodicity.[11,12] Utilizing this self-organized (In,Ga)As quantum wire array as a template for InAs QD growth, we have realized single and multiple InAs QD arrays with 140 nm lateral periodicity. The template effect is highlighted by the distinct dependence of the QD ordering on the number of SL periods. The photoluminescence (PL) efficiency of the QD arrays is not reduced compared to that of InAs QDs grown directly on GaAs showing the high structural and optical quality of our QD arrays.

The samples were grown on GaAs (100) substrates with a miscut smaller than 0.05° by conventional solid-source molecular beam epitaxy (MBE). After growth of a 200 nm thick GaAs buffer layer at 580 °C, the samples were cooled down to 540 °C for growth of (In,Ga)As. After each (In,Ga)As layer, capped with 0.9 nm GaAs, of the $In_{0.36}Ga_{0.64}As$/GaAs (2.6 nm / 16 nm) SL, the samples were annealed at 580 °C for 2 min. before GaAs growth was completed.[11] The number of SL periods was varied between 1 and 15 in different samples. On top of the last GaAs layer of the SL, 1.5–2.1 monolayers (ML) InAs were grown at 480 °C for QD formation. For PL studies, these InAs QD layers were capped by 100 nm GaAs. The growth rates of GaAs, InAs, and $In_{0.36}Ga_{0.64}As$ were 0.067 nm/s, 0.037 nm/s or 0.0007 nm/s, and 0.104 nm/s, which were calibrated by high-resolution x-ray diffraction (XRD) measurements of (In,Ga)As/GaAs SL structures grown at 480 °C. The structural properties of the uncapped InAs QD layers were characterized by atomic force microscopy (AFM) in air. For the PL measurements, the 512 nm line of a Nd–YAG laser was used for excitation with an excitation power density of 0.2 W/cm^2. The PL was dispersed by a single monochromator and recorded by a cooled (In,Ga)As charge-coupled device.

Figures 1(a)–(d) show the AFM images of the QDs formed by 2.1 ML InAs grown at a rate of 0.037 nm/s on the (In,Ga)As/GaAs SL template with the number of SL periods of [Fig. 1(a)] 1, [Fig. 1(b)] 5, [Fig. 1(c)] 10, and [Fig. 1(d)] 15, respectively. For comparison, the AFM image of InAs QDs grown directly on the GaAs buffer layer is shown in Fig. 1(e). While on the GaAs buffer layer the InAs QDs are randomly arranged, a distinct tendency for QD ordering is observed on the SL when the number of SL periods is increased from 1 to 15. The large size QDs observed in Fig. 1 are due to coalescence of few small QDs. For one period [Fig. 1(a)], QD ordering is hardly observed, indicating large disorder or incomplete wire formation of the template. When the number of periods is increased to 5 [Fig. 1(b)], a weak modulation of the island density towards QD ordering appears. The selectivity of QD formation, however, is poor

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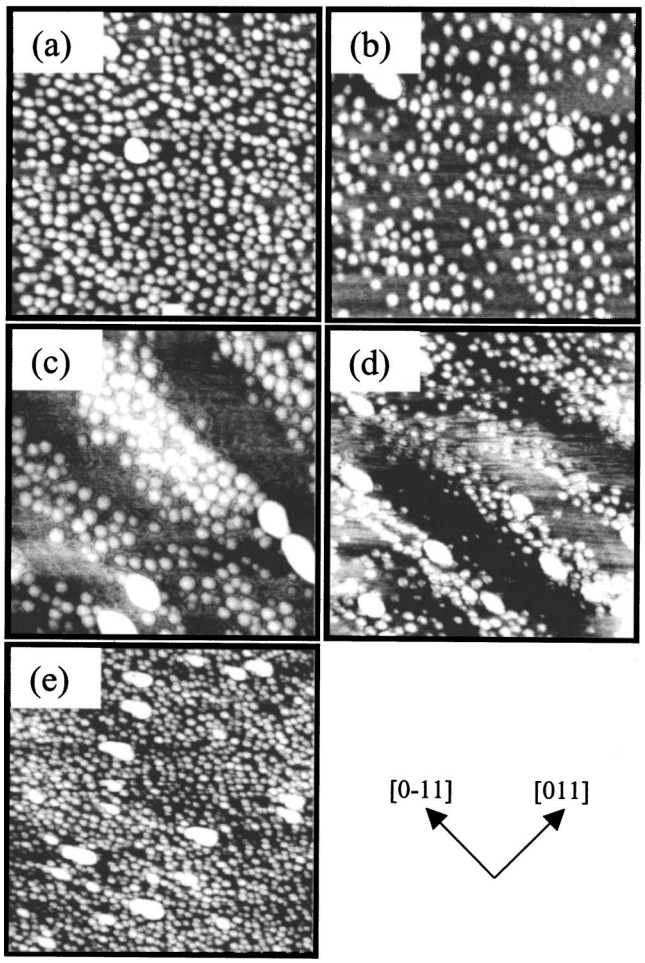

FIG. 1. (a), (b), (c), and (d) are AFM images of 2.1 ML InAs QDs grown on 1, 5, 10, and 15 periods SL template with a growth rate of 0.037 nm/s. (e) is the AFM image of 2.1 ML InAs QDs grown on GaAs (100) buffer layer. The scan field is 500 nm×500 nm and the black-to-white height contrast is 7 nm for all images.

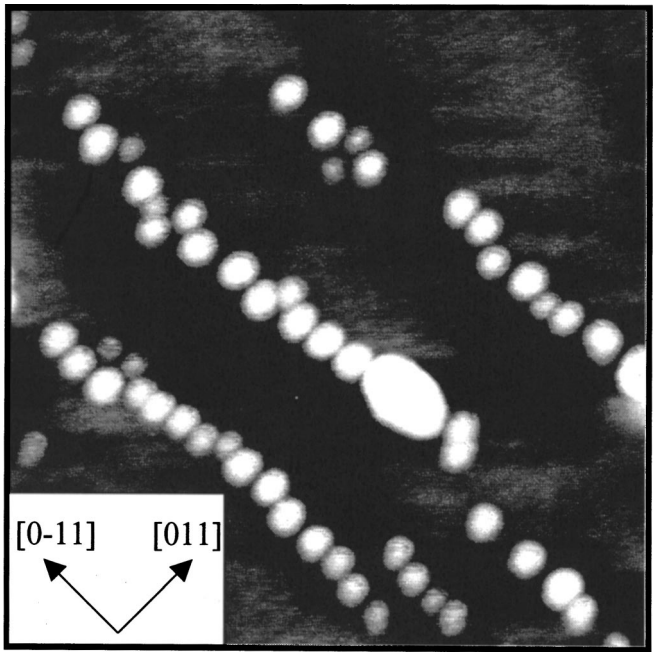

FIG. 2. AFM image of 1.5 ML InAs QDs grown on 15 periods SL template with a growth rate of 0.0007 nm/s. The scan field is 500 nm×500 nm and the black-to-white height contrast is 15 nm.

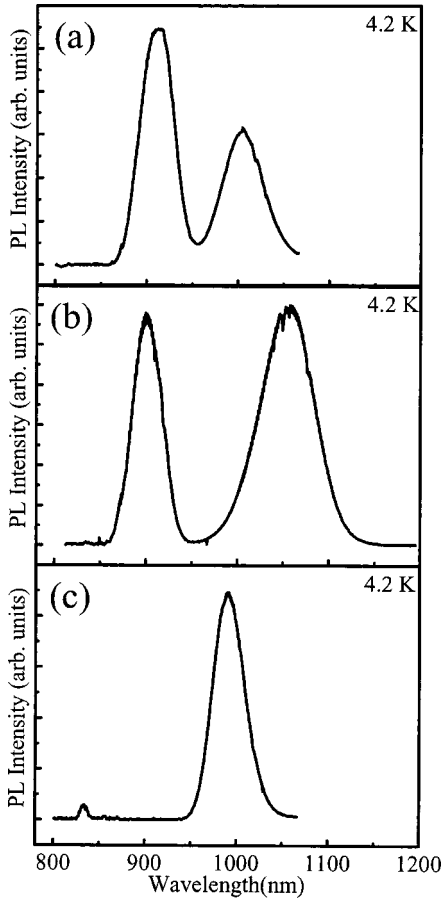

FIG. 3. (a) and (b) are PL spectra taken at 4.2 K from 2.1 ML InAs QDs (0.037 nm/s) and 1.5 ML InAs QDs (0.0007 nm/s) grown on 15 periods SL template. (c) shows the PL spectrum of 2.1 ML InAs QDs (0.037 nm/s) grown on GaAs (100) buffer layer.

with many dots located randomly. On the other hand, for 10 and 15 SL periods [Figs. 1(c) and 1(d)], very clear ordering in arrays of multiple QDs along [0-11] is observed. The length of the arrays easily exceeds 3 μm with a lateral periodicity of 140 nm along [011]. This periodicity is consistent with the lateral periodicity of the (In,Ga)As wires, measured by XRD,[13] thus additionally confirming the template effect.

The improved InAs QD ordering with increasing number of (In,Ga)As/GaAs SL periods is attributed to the improved uniformity of the wires and related uniformity and accumulation of the strain field on the GaAs surface. This generates a well-defined lateral strain-field modulation perpendicular to the wires with sufficiently deep minima above the wires providing the preferred locations for QD nucleation.[14] It should be noted that the GaAs surface of the SL exhibits an anisotropic mound structure with 2–5 nm height, which is enhanced due to the strain accumulation of the underlying wires, though the reflection high-energy electron diffraction patterns are streaky. The length of these mounds along [0-11], which are composed of (100) terraces and ML high steps, is between 500 nm and about 1 μm, determined by AFM. This is considerably shorter than the length of the QD arrays, underlining the dominance of the uniform strain field to be in origin of the QD ordering.

Formation of single QD arrays is achieved by reducing the InAs coverage and, most important, enhancing the In adatom migration length at low growth rates.[15] QD nucle-

ation is then expected only at the most favored locations, which are assumed above the centers of the wires. Figure 2 shows the AFM image of the QDs formed by 1.5 ML InAs grown at a rate of 0.0007 nm/s on the 15 periods SL template at 480 °C. The formation of single InAs QD arrays with an average lateral spacing of 140 nm and QD distance of only a few nanometers is clearly observed on the SL template.

The PL spectra of capped 2.1 ML InAs QDs (growth rate: 0.037 nm/s) and 1.5 ML InAs QDs (growth rate: 0.0007 nm/s) on the 15 periods SL template are shown in Figs. 3(a) and 3(b), respectively. For comparison, the PL spectrum of capped InAs QDs grown directly on the GaAs buffer layer at the rate of 0.037 nm/s is shown in Fig. 3(c). The QD arrays on the SL template reveal strong PL emission centered [Fig. 3(a)] at 1005 nm (1.23 eV) and [Fig. 3(b)] at 1057 nm (1.17 eV). The line at 911 nm (1.36 eV) stems from the SL template. Most important, the PL efficiency of the QD arrays on the SL template is not degraded compared to that from the reference sample with comparable full width at half maximum. We relate this high structural and optical quality of the QD arrays to the smoothness of the strain-field modulation on the dot-diameter and dot-to-dot distance length scales which is an advantage of our method based on self-organized strain engineering for QD ordering.

In conclusion, well-defined InAs QD arrays along [0-11] were formed by MBE on planar GaAs (100) by self-organized anisotropic strain engineering of a (In,Ga)As/GaAs SL template. The template effect was demonstrated by the dependence of the QD ordering on the number of SL periods. For low growth rates, single QD arrays were realized. The separation between the arrays along [011] is 140 nm while the QD distance along [0-11] is only a few nanometers. The QD arrays exhibit strong PL emission indicating that ordering by self-organized anisotropic strain engineering maintains the high structural quality of InAs QDs. Hence, this technique is highly promising for QD ordering in well-defined arrays of high quality.

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