Structural and Infrared Absorption Properties of Self-Organized InGaAs/GaAs Quantum Dots Multilayers

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Self-organized InGaAs/GaAs quantum dots (QDs) stacked multilayers have been prepared by solid source molecular beam epitaxy. Cross-sectional transmission electron microscopy shows that the InGaAs QDs are nearly perfectly vertically aligned in the growth direction [100]. The filtering effect on the QDs distribution is found to be the dominant mechanism leading to vertical alignment and a highly uniform size distribution. Moreover, we observe a distinct infrared absorption from the sample in the range of 8.6–10.7 μm. This indicates the potential of QDs multilayer structure for use as infrared photodetector.

Key words: InGaAs/GaAs quantum dots, infrared absorption, self-organization

INTRODUCTION

The fabrication of quantum dots (QDs) by self-organization processes has attracted increasing attention in the last few years.[1] Since free surfaces and etch-induced defects are avoided, Stranski-Krastanow growth is regarded as a promising road toward zero-dimensional quantum structures. Although these QDs have a well-defined shape, their random nucleation in a single layer results in a broad distribution of QDs size and positions. Because arrays of QDs of the same size and shape are required for practical applications, the identification of growth mechanism that lead to a narrowing of the size distribution is of great importance.

Lateral and vertical ordering of QDs in multilayers has been studied in both the SiGe/Si,[2–4] and the InGaAs/GaAs[5,6] systems. For the SiGe/Si (100) system, it has been shown by atomic force microscopy (AFM) that coherent QDs undergo a transition from a broad size distribution in a single layer to intraplanar size equalization in a SiGe/Si multilayer structure.[2] This transition has been referred to as "self-organized" growth. On the basis of the AFM investigation of the surface morphology, a model was proposed to account for the vertical alignment of QDs in successive layers.[7] Q. Xie et al.[5] have studied the QDs vertical alignment in the InAs/GaAs multilayers, and proposed a model based upon the nature of QDs-induced strain fields and their impact on the directed nature of mechanochemical diffusion to analyze this self-organization behavior.

Here we report the successful fabrication of a nearly perfectly vertically aligned InGaAs/GaAs QDs multilayers with a uniform size distribution. In addition, we observe a distinct infrared absorption 8.6–10.7 μm from the sample. This work indicates the self-organized growth can offer an attractive route of the fabrication of QDs arrays, which is sufficiently uniform for infrared photodetector application.

EXPERIMENTS

The samples were grown on semi-insulating GaAs [100] substrates in a Riber-32p molecular beam epitaxy. It consists of a 1.5 μm GaAs contact layer, a 30 period InGaAs/GaAs superlattice and 1.2 μm GaAs contact cap layer. The growth rate for GaAs was 2.82Å/s, which was determined by reflection high energy electron diffraction (RHEED), equivalent beam pressure (EBP), surface profiling on calibration samples and double-crystal x-ray diffraction. The nominal indium component of InGaAs was about 0.3, and the corresponding growth rate was 2.22Å/s. The nominal thickness of InGaAs and GaAs was 4.0 and 20 nm, respectively. The InGaAs dot layers and the GaAs contact layers were Si-doped with concentrations of 1.0×10^{18} cm^{-3}, and 2.0×10^{18} cm^{-3}, respectively. A 580°C substrate temperature was kept for the growth of the contact layers and 500°C for the growth of the InGaAs/GaAs QD superlattice.

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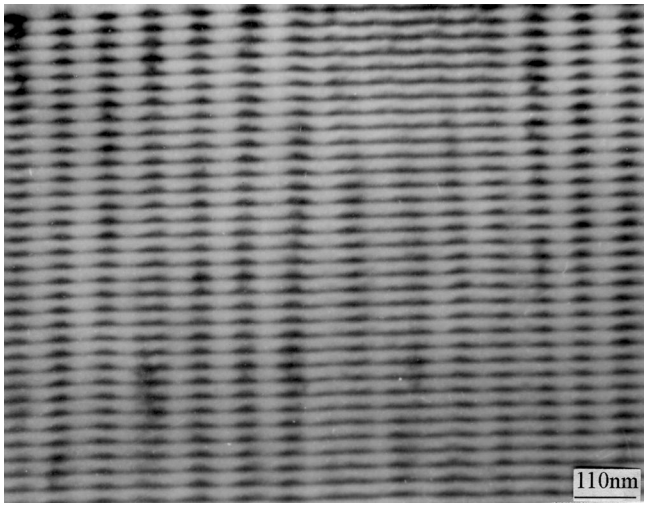

Fig. 1. Cross-sectional TEM image of 30 period InGaAs/GaAs quantum dot superlattice.

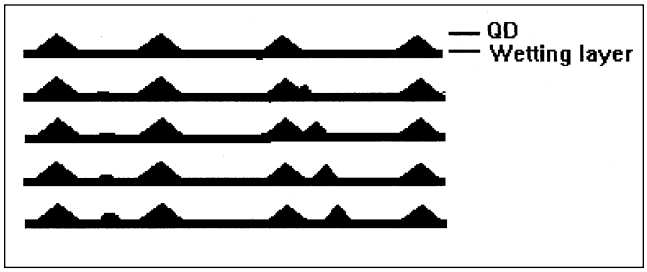

Fig. 2. Schematic of filtering effect of quantum dots spacing on the self-organization behavior shown in Fig. 1.

The structure of the multilayers was investigated by cross-sectional electron transmission microscopy (TEM) using a Philips CM200 microscopy. TEM samples were prepared by tripod polishing followed by brief ion milling. Low-temperature (10K) photoluminescence (PL) measurement is used to characterize the optical properties of the QDs multilayers, and an IF120HR infrared spectrometer is used to analyze the signals from samples absorption at the room temperature (300K).

RESULTS AND DISCUSSIONS

Figure 1 shows a representative (100) cross-section bright-field micrograph of a 30 period InGaAs/GaAs QDs superlattice. Regions of light contrast correspond to the GaAs spacer layers, while contrast in the dark region strains from the QDs InGaAs and the thin wetting layer. QDs formation is evident in the cross-sectional transmission electron microscopy (XTEM) image through the strain contrast. The figure shows that the GaAs spacer layer is thick enough to flatten the growth front prior to deposition of the subsequent layers. One striking observation is that the QDs in subsequent layers are nearly perfectly vertically aligned along growth direction [100]. It is worthy noting, this vertical alignment is strongly dependent on the distribution of the QDs size and positions in the first layer. Contrast to the regime where the QDs are perfect one-to-one vertically aligned, in the regime

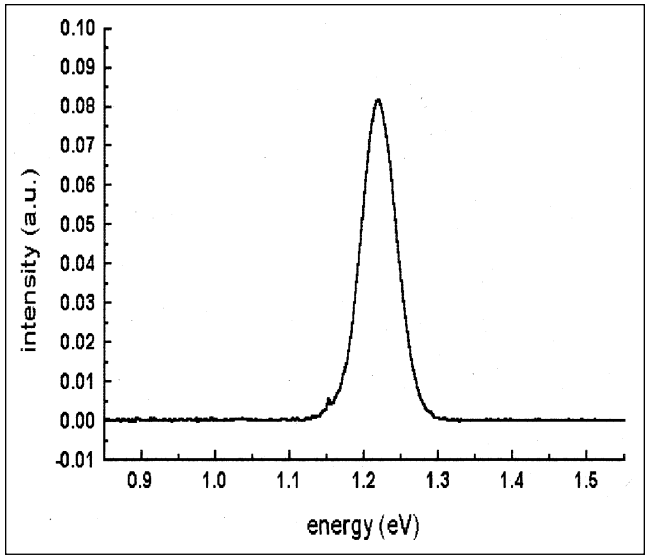

Fig. 3. Low temperature photoluminescence spectrum of sample.

where lateral size and spacing[8] in the first layer are nonuniform, sets of QDs interact with one another. This interaction gives rise to a uniform size distribution and perfectly vertical alignment with an increasing number of bilayers, performs a filtering effect.

The effect of spacing on the observed self-organization can be understood qualitatively in the frame-work of a model based on continuum elasticity theory. According to this model,[7] there exists a critical value of lateral QDs spacing, which can be expressed as $l = 3.5 \times d$, where l is the medium lateral distance between the QDs within the first QDs layers, and the d is the distance between the stacked QDs layers. For the low density QDs regime, from Fig. 1, we obtain an estimate of lateral spacing $l = 80$ nm, reaching critical value $3.5 \times 24 = 84$ nm, the QDs then perform perfectly vertical alignment.

This filtering effect on the QDs distribution is schematic shown in Fig. 2. The bigger InGaAs QDs with uniform distribution are reproduced in the upper layers due to the strong and uniform strain field above them. This leads to a vertical alignment along growth direction [100]. The smaller QDs of the first layer are not reproduced in the upper layers due to the weaker strain field above small QDs, or they coalesce with a neighboring QD to form bigger QDs. In addition, the bigger QDs with a closer spacing move toward each other with increasing number of bilayer, and merge to form a single large QD with an appropriate position. This filtering effect gives rise to a perfectly vertical alignment and uniform size distribution, involving a typical length scale of the lateral spacing of the order of 80 nm (for this alloy composition and these layer thickness). After this larger value is reached, we observe a pronounced stabilization of the QDs size and position.

Figure 3 shows the low temperature (10K) PL spectrum of QDs superlattice. A strong luminescence peak around 1.23 eV from the QDs is noted, further confirms the formation of QDs. The luminescence

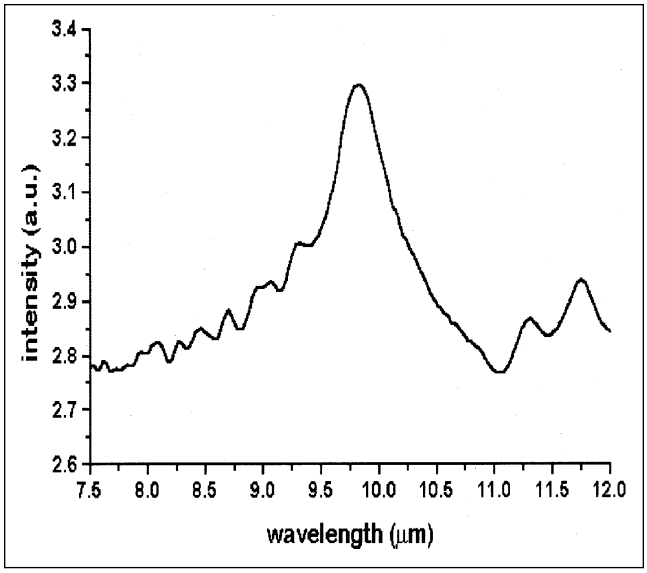

Fig. 4. Measured infrared absorption spectrum in multipass 45° waveguide configuration.

peak has a full width at half maximum (FWHM) of 50 meV. The PL spectrum does not indicate luminescence corresponding to excited-state transitions. No additional luminescence peaks from InGaAs wetting layers are observed.

For infrared absorption measurements, a multipass 45° waveguide configuration was used to increase net absorption.[9] Waveguides of dimensions of 6 mm × 6 mm were fabricated with polished backsides and polished 45° facets for optimum light input and output. In order to effectively eliminate substrate absorption and other optical effects from the spectra, we used a similarly polished bulk sample (without QDs) as reference for absorption measurements. Measured infrared absorption spectrum is shown Fig. 4, an obvious infrared absorption peak is clearly observed at 9.8 μm with a FWHM of 8.3 meV. The absorption spectrum is asymmetric, with a relatively sharp rise at the low energy end and a decay tail on the high energy side, performs a characteristic feature of bound-to-continuum electron transitions in QWs. By analogy with the case of intraband absorption in the conduction band in the InAs/GaAs QDs,[10,11] the intraband absorption most likely corresponds to transitions between the bound states to the continuum states lying in the wetting layer and GaAs layer. The measured multi-peak absorption spectrum may be due to the different size of QDs. The intraband absorption is due to either quantum dot superlattice or wetting layers, since the normal incident intraband transition is possible with InGaAs/GaAs QWs.[12] However, possible incident absorption from 26Å thick $In_{0.28}Ga_{0.72}As$ (indium component is calibrated by double-crystal rocking curve modulation) wetting layers is not expected to occur around 9.8 μm. Hence, the infrared absorption observed in Fig. 4 can be unambiguously attributed to the intraband transition from QDs.

CONCLUSIONS

In summary, we report the self-organized growth of high quality 30 period InGaAs/GaAs quantum dots stacked multilayers with the structure of a quantum well infrared photodetector by solid source molecular beam epitaxy. Cross-sectional electron microscopy shows that the InGaAs QDs are nearly perfectly vertically aligned in the growth direction [100]. The filtering effect on the QDs distribution is found to be the dominant mechanism leading to a perfectly vertical alignment, and a highly uniform size distribution. Moreover, we observe a distinct infrared absorption from the sample in the range of 8.6–10.7 μm. This indicates the potential of this QDs multilayer structure for use as infrared photodetector.

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