Growth of high quality InAs quantum-dot multilayer structures on InP for infrared photodetector applications

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We present a growth technique to improve the structural property of InP-based multilayer quantum-dot (QD) structures. A thin layer of AlGaNAs grown under a group-III stabilized condition can effectively smooth out the three-dimensional growth front caused by the QD formation. Thus, the AlGaNAs barrier layers with high crystal quality and smooth interfaces can be achieved. Using this technique, an InP-based QD infrared photodetector structure containing ten-period QD layers has been grown using molecular beam epitaxy, and its high structural and optical quality was confirmed by x-ray diffraction and photoluminescence measurements. © 2006 American Vacuum Society. [DOI: 10.1116/1.2201452]

I. INTRODUCTION

Recently, extensive research has been devoted to photodetectors in the infrared (2–20 μm) range of the optical spectrum for many exciting applications.1–5 The state-of-the-art photodetectors employ either intrinsically infrared radiation detection using narrow band gap semiconductors, such as (Hg,Cd)Te and (Pb,Sn)Te,3 or intersubband transitions in quantum well infrared photodetectors (QWIPs).5 However, materials used for intrinsic infrared photodetectors usually have weak mechanical properties, which make it very difficult for large array processing and fabrication. Meanwhile, due to the quantum mechanical selection rules, QWIP is insensitive to normal incident light. Furthermore, both of these photodetector approaches are unable to achieve room-temperature operation.

Quantum-dot infrared photodetectors (QDIPs) have emerged as a device with a great potential to outperform the state-of-the-art bulk and QWIP devices.6 However, current device performance lags behind the theoretical predictions, partly due to the difficulties in controlling the self-assembled QD formation process. The resultant nonuniform QD size distribution with low dot density as well as the nonuniform doping in QDs degrade the device performance, resulting in a low responsivity and a high dark current. One of the effective methods to improve the device performance is to employ structures with multiple, vertically stacked QD layers, which improve the uniformity of the QD size distribution.7 The multilayer structure also effectively increase the absorption of incident photons.8 However, stacking a large number of QD layers causes two problems. Firstly, since QDs are compressively strained over the substrate, strain accumulation may generate dislocations, which serve as the nonradiative recombination centers and degrade the device performance dramatically. This can be solved using strain balanced QD structure, which was discussed in details in Ref. 9. The other problem is due to the three-dimensional growth front formed during the QD deposition. When stacking a large number of QD layers, the growth front is hard to smooth out, leading to a nonplanar interface between neighboring layers and poor optical properties. In this study, we demonstrated that utilizing the group-III stabilized growth can effectively smooth out the three-dimensional growth front after the deposition of QDs. In this way, multilayer QDs with high structural and optical qualities have been achieved.

II. EXPERIMENT

Samples used in this work were grown in a molecular beam epitaxy (MBE) system on sulfur-doped (100) InP substrates. The InP surface oxide desorption temperature was set as 500 °C. Right after the desorption, a 20-period In0.52Al0.48As/In0.53Ga0.47As short period superlattice (SPS) followed by a 1 μm InGaAs buffer layer was grown at 490 °C. These layers were doped with silicon to a doping concentration of $1 \times 10^{18}$ cm$^{-3}$. The substrate temperature was then gradually lowered to 470 °C during the growth of an undoped 1000 Å Al0.24Ga0.76As layer prepared for the QD deposition. The active region of the device contained ten-period δ-doped InAs QD layers separated by 500 Å AlGaInAs barrier layers. Before the deposition of InAs, a 30 s growth interruption under an arsenic flux was inserted to stabilize the surface of the AlGaInAs layer. QD nanostructures were then self-assembled under Stranski-Krastanov (SK) growth mode by depositing 5 ML (ML denotes monolayer) of InAs at an As overpressure of $1 \times 10^{-6}$ Torr. After the deposition of InAs, another 30 s interruption under an arsenic flux was used. The doping concentration in QD layers was calibrated according to the QD density to a level of around two electrons per QD. After the QD formation, during the growth of the first 40 Å AlGaInAs, the As overpressure was maintained at $1 \times 10^{-6}$ Torr. The chevron pattern of QDs was replaced by a c(8×2) or (4×2) reflection high-energy electron diffraction (RHEED) pattern, indicating that the growth front was under a group-III stabilized condition.10 Then the As overpressure was increased to $2 \times 10^{-6}$ Torr for the rest of the AlGaInAs barrier layer. The observed (2×4)

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RHEED pattern indicated that the growth was governed by the group-V stabilized condition. After the growth of the active region and a 1000 Å undoped upper AlGaInAs layer, a 500 Å undoped InAlAs current blocking layer was grown to suppress the dark current of the device. Finally, a 5000 Å InGaAs contact layer doped with silicon to $1 \times 10^{18}$ cm$^{-3}$ was used to cap the whole structure. The surface morphology of samples used in this study was studied with the atomic force microscope (AFM) in contact mode. Room-temperature and 77 K photoluminescence (PL) measurements were used to characterize optical properties of the QD samples. The 77 K PL measurements were performed in a liquid nitrogen cooled cryostat. The excitation source of the PL measurements was the 514.5 nm line of an Ar$^+$ laser. A liquid nitrogen cooled Ge detector mounted on a 0.5 m spectrometer was used for detection in lock-in mode. The high-resolution x-ray diffraction (HRXRD) measurements were used to study the structural properties of the QD samples.

III. RESULTS AND DISCUSSIONS

QDIPs with high device performance require a QD structure with high structural and optical quality. In multilayer QD structures, this requirement translates to a high density of QDs with a uniform size distribution in each QD layer, and a defect-free structure with smooth interfaces and well-defined periodicity. The high density of QDs provides a high responsivity, while the uniform size distribution leads to a uniform doping in QDs resulting in a low dark current. For these purposes, a very low growth rate (0.06 ML/s) and a low As overpressure ($1 \times 10^{-6}$ Torr) were used in the QD formation to facilitate a homogeneous surface diffusion of the In adatoms.$^{11}$ Using these growth conditions, InAs QDs grown on InP with uniform size distribution have been achieved.$^{12}$ The QD density can reach up to $5 \times 10^{10}$ cm$^{-2}$, which is high considering the weak strain confinement between InP and InAs.

Although a high quality single QD layer has been achieved, stacking them into multilayer structure still remains problematic. This is caused by the formation of three-dimensional growth front above the QD layer. Since QDIP structure usually requires stacking a large number of QD layers (>$10$) to improve the responsivity, the growth front becomes severely corrugated in the later QD layers. This leads to a nonplanar interface between neighboring layers, which degrade the structural and optical properties of the structure. In order to solve this problem, a thin barrier layer grown under a group-III stabilized condition is used to smooth out the three-dimensional growth front above the QD layer.

Figure 1 shows the AFM image of the surface morphology of a 100 Å AlGaInAs grown under the group-III stabilized condition with an As overpressure of $1 \times 10^{-6}$ Torr. As shown in the picture, surface ridges along the [110] direction are clearly observed. During the growth, a $(4 \times 2)$ or $c(8 \times 2)$ pattern changed from $(2 \times 4)$ pattern was observed when the As overpressure was lowered, indicating a group-III stabilized growth front. The $(4 \times 2)$ reconstructed surface under the group-III stabilized condition contains As dimers aligned along the [110] direction.$^{10}$ Therefore, during the growth of the AlGaInAs on group-III stabilized surfaces, the adsorbed group-III adatoms will preferentially align along the same [110] direction and form the surface ridges as shown in Fig. 1. The group-III stabilized growth usually can be changed back to the more conventional group-V stabilized growth by raising the As overpressure (i.e., increasing V/III ratio). However, it is worthy to point out that the group-III stabilized growth cannot last for an extended period of time without affecting the crystal quality. Too low As overpressure or too long deposition duration under the group-III stabilized condition will cause the formation of three-dimensional surface structure and eventually, group-III droplets. In those cases, the growth front gets permanent damage, resulting in a poor crystal quality.

The group-III stabilized growth can be used to effectively smooth out the three-dimensional growth front above the QD layer. The AFM images shown in Fig. 2 compare the surface morphologies of 40 Å AlGaInAs layers grown under group-III stabilized and group-V stabilized conditions right above the QD layer. As shown in Fig. 2(a), after the deposition of 40 Å AlGaInAs under the conventional group-V stabilized condition (with an As overpressure of $2 \times 10^{-6}$ Torr), the surface was only partially smoothed out. QD strings along the $\{110\}$ direction are clearly observed. This is because under the group-V stabilized growth, the $(2 \times 4)$ reconstructed surface contains As dimers aligned along the $\{110\}$ direction.$^{14}$ In this surface structure, the migration of group-III adatoms is preferred along the same [110] direction. As a result, the three-dimensional growth front above the QD layer cannot be smoothed out uniformly. In contrast, Fig. 2(b) shows a flat
surface after a 40 Å AlGaInAs growth under group-III stabilized condition (with an As overpressure of $1 \times 10^{-6}$ Torr). At this point, a $(2 \times 4)$ RHEED pattern was already emerged indicating a flat growth front. The formation of the flat morphology is an act of balance between the surface migration of adatoms during the group-III stabilized growth and the strain field caused by the underneath QDs. As pointed out in an earlier study, the existing strain field in the InAs/InGaAs QD system promotes the formation of QDs along the $\langle 1\bar{1}0 \rangle$ direction. This strain field also affects the growth of the barrier AlGaInAs layer, making the growth preferably aligned along the $\langle 1\bar{1}0 \rangle$ direction. Meanwhile, in the group-III stabilized growth, the surface migration of group-III adatoms is preferred along the $\langle 1\bar{1}0 \rangle$ direction. The balance of these two effects can smooth out the three-dimensional growth front uniformly and effectively, resulting in a flat surface as shown in Fig. 2(b).

Figure 3 shows the diffraction rocking curves of a device sample and a reference sample having identical structure with ten-period QDs separating by 500 Å AlGaInAs barrier layers. For the device sample, the AlGaInAs barrier layers were also grown under group-V stabilized condition except the first 40 Å, which was grown under group-III stabilized condition. In the reference sample, the AlGaInAs barrier layer was grown entirely under group-V stabilized condition. After the stacking of more than five layers QDs in the reference sample, spotty RHEED patterns were observed after the deposition of the AlGaInAs top barrier layer, indicating that the barrier layer had a rough growth front. The low structural quality of the reference sample is confirmed by the HRXRD rocking curve, which displays a weak intensity and incoherent satellite peaks. The rocking curve of the device sample has more satellite peaks with much higher intensities than the reference sample. This indicates that the device structure maintains its structural integrity throughout the whole structure, with very smooth interfaces and well-defined periodicity. Figure 4 shows the room-temperature and 77 K PL spectra of the device sample and reference sample. A strong room-temperature PL intensity of the device sample is 50% higher than the reference sample, showing that the group-III stabilized growth used in the AlGaInAs barrier layers can improve the optical quality of the multilayer QD structure.

Finally, the device sample was fabricated into QDIP devices. The details of the device fabrication and characterization will be published elsewhere. Device characterizations at 10 K indicate infrared detections around 5.5, 8, and 18 μm. The peak detectivity ($D^*$) of this device at 18 μm was calculated as $3 \times 10^{9}$ cm Hz$^{1/2}$/W. However, due to the excessive dark current, no device performance has been
achieved in the reference sample, indicating the structural advantages due to the group-III stabilized growth used in the AlGaInAs barrier layers are critical in QDIP device fabrications.

IV. SUMMARY

In preparation of the InP-based QDIP device structures, a group-III stabilized barrier layer growth technique was developed to improve the structural property of QD samples. By capping InAs QDs with a 40 Å AlGaInAs layer grown under a group-III stabilized condition before the deposition of the conventional group-V stabilized AlGaInAs barrier layer, the three-dimensional growth front induced by the QD formation can be effectively smoothed out. Thus, AlGaInAs barrier layers with high crystal quality and smooth interfaces have been achieved. Using this technique, the device structure containing ten-period QD layers has shown high structural and optical properties. This makes it possible to fabricate the QD structure into an InP-based QDIP device. A detectivity of $3 \times 10^9$ cm Hz$^{1/2}$/W at 10 K has been achieved in this device.

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