Self-Assembly of Semiconductor Nanostructures

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ABSTRACT.

In this work we present the growth and characterization of GaAs self-assembled quantum wires (SAQWRs), and InAs self-assembled quantum dots (SAQDs) by molecular beam epitaxy on (631)-oriented GaAs substrates. Adatoms on the (631) crystal plane present a strong surface diffusion anisotropy which we use to induce preferential growth along one direction to produce SAQWRs. On the other hand, InAs SAQDs were obtained on GaAs(631) with SAQWRs by the Stransky–Krastanov (S-K) growth method. SAQDs grown directly on (631) substrates presented considerable fluctuations in size. We study the effects of growing a stressor layer before the SAQDs formation to reduce these fluctuations.

Keywords: Quantum wires, quantum dots, self-assembly, molecular beam epitaxy.
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INTRODUCTION

Nanostructures of III-V semiconductor compounds with low dimensional quantum effects, such as quantum-wires and -dots, have attracted the interest during the past years [1]. These nanostructures have relevant technological applications in novel electronic and optoelectronic devices like, high-mobility field-effect transistors and low-threshold semiconductor lasers [2]. A variety of fabrication techniques to synthesize low dimensional structures have been proposed. Among these, one of the most preferable is the molecular beam epitaxy (MBE) with a self-assembling process, owing to the fact that it provides a possible way to fabricate low dimensional nanostructures without process-induced defects and damage, which are frequently observed in those structures fabricated by lithography and etching. In this work we present the growth and characterization of GaAs self-assembled quantum wires (SAQWRs), and InAs self-assembled quantum dots (SAQDs) by MBE. In order to synthesize SAQWRs we employed (631)-oriented GaAs substrates. We have shown that adatoms on the (631) crystal plane present a strong surface diffusion anisotropy which we use to induce preferential growth along one direction to produce SAQWRs [3]. On the other hand, InAs SAQDs were obtained on GaAs(631) substrates by the Stransky–Krastanov (S-K) growth method, which takes place in the heteroepitaxy of large lattice-mismatch semiconductor systems [4]. In this growth mode the strain energy in the overlayer is reduced by forming three-dimensional nanoislands following a few monolayers of layer-by-layer two-dimensional growth. We have studied the effects of growing SAQDs on InGaAs stressor layers on GaAs(631) substrates to reduce size fluctuations.

SELF-ASSEMBLIG OF GaAs QUANTUM WIRES

The growth experiments were carried out in a Riber-C21 MBE system. We employed semi-insulating GaAs (631) type A substrates. In order to remove the native surface oxides the substrates were chemically etched in an H_2SO_4: H_2O_2: H_2O (5:1:1) solution during 60 seconds. Thermal desorption of GaAs fresh oxides was performed under As_4 flux in the growth chamber at the substrate temperature of 585 °C during 10 min. The samples surface was in-situ monitored by reflection high-energy electron diffraction (RHEED). Finally, the samples surface morphology was investigated exsitu by atomic force microscopy (AFM) operated in contact mode.

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Figure 1(a) shows the AFM image of a 80 nm-thick GaAs layer grown at 600 °C employing an As_4/Ga flux ratio of 20 with a growth rate of 0.3 μm/hr. We clearly observe on the surface the self-assembling of nanowires with a height of 1.5 nm and a width of 20 nm running along the [-5,9,3] direction. The formation of the nanowires could be the result of a very high anisotropy in the surface diffusion and/or sticking properties of adatoms on the GaAs(631) surface [5]. In Fig 1(b) we present the autocorrelation function of the image in (a), where we can observe parallel bright lines running along the [-5,9,3] direction thus showing the short range wire ordering.

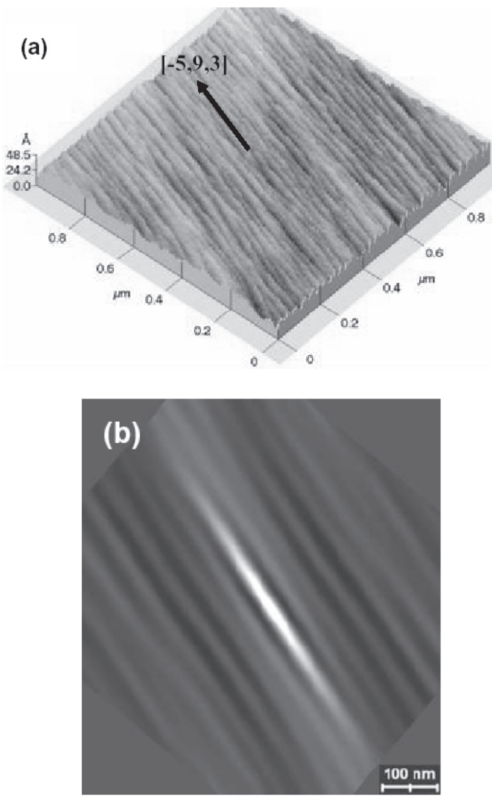

Figure 1. (a) AFM image of 80 nm-thick GaAs layer grown on GaAs(631)A substrate. (b) Autocorrelation function of the image in (a)

In order to obtain one dimensional quantum structures, we prepared a sample with the nanowires embedded in AlGaAs layers as schematically shown in Fig. 2(a). In this sample the thickness of the AlGaAs barriers is 30 nm with an Al concentration of 23%, and the GaAs-wires layer thickness is 20 nm. The optical properties of this sample were studied by photoreflectance spectroscopy (PR) employing a standard setup [6]. Figure 2(b) shows the PR spectrum (dotted line) at 300 K, and a fitting (continuous line) to a third-derivative functional form according to the following equation [7]:

$$\frac{\Delta R}{R} = \sum \mathrm{Re}\left[Ce^{i\theta}\left(\hbar\omega - E_j + i\Gamma\right)^{-5/2}\right] \qquad (1)$$

A reasonable fitting was obtained employing seven energy transitions Ej as indicated by the arrows in the figure.

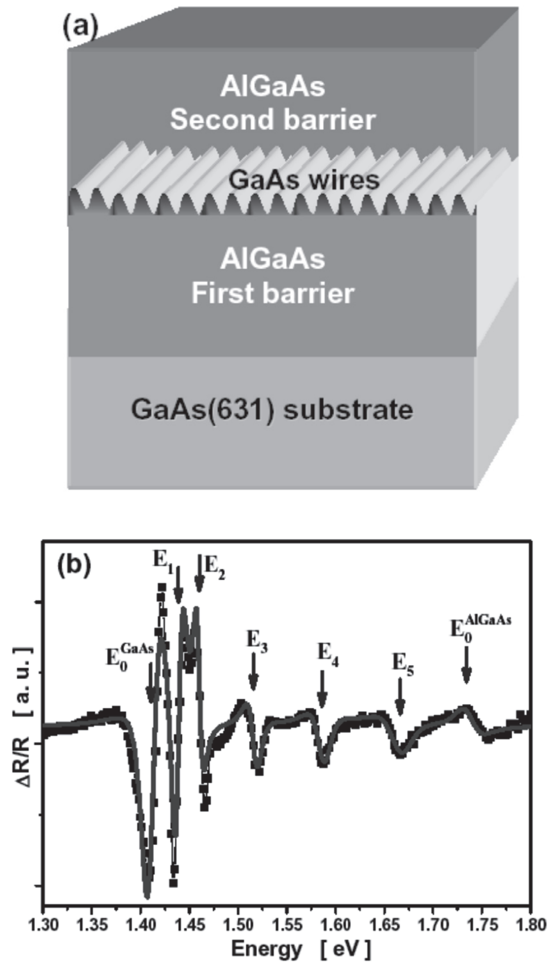

Figure 2. (a) Schematic figure of the quantum wire structure. (b) Photoreflectance spectrum from SAQWRs at 300 K.

The transitions at 1.42 and 1.74 eV correspond to the bulk-GaAs band-gap energy (E_0^{GaAs}), and to the AlGaAs barriers band-gap energy (E_0^{AlGaAs}), respectively. On the other hand, the transitions leveled as E_1 to E_5 in Fig. 2(b) correspond to transitions in the GaAs quantum wires. The origin of these transitions was investigated employing a model of cylindrical-shaped GaAs quantum wires embedded in $Al_{0.23}Ga_{0.77}As$ barriers.
With this model and within the mass-effective approximation we calculated the energy levels in the conduction and valence band of the quantum wires. By solving the Schrödinger equation in cylindrical coordinates we obtained the energy levels for electrons ($E^e lm$), heavy holes ($E^{hh} lm$), and light holes ($E^{lh} lm$) described by two quantum numbers: l=1,2,3…., and m=0,1,2,3…. In Table 1 we summarize the transitions observed in the PR spectrum, and the results obtained by the above explained theoretical model for transitions between the electron levels and heavy (light) holes levels denoted as $E^e_{lm} \longrightarrow E^{hh(lh)}_{l'm'}$. We note that the calculated transitions are very close to the transitions that best fit the PR spectrum.

TABLE 1. Energy transitions in GaAs quantum wires

PR transition (eV)	Calculated Transition E^e_{lm} $E^{hh(/h)}_{lm}$ (eV)
$E_1 = 1.454$	E^e_{01} $E^{hh}_{01} = 1.454$
$E_2 = 1.474$	E^e_{01} $E^{hh}_{02} = 1.472$
$E_3 = 1.524$	E^e_{11} $E^{/h}_{11} = 1.538$
$E_4 = 1.595$	E^e_{02} $E^{hh}_{02} = 1.580$
$E_5 = 1.676$	E^e_{12} $E^{/h}_{11} = 1.678$

SELF-ASSEMBLIG OF INAS QUANTUM DOTS

In this section we present the growth of InAs SAQDs on GaAs nanowires that were prepared on (631)-substrates employing the growth conditions explained in the above section (Fig. 1(a)). For obtaining InAs SAQDs we employed the Stransky-Krastanov growth mode with a substrate temperature of 480 °C, and an InAs growth rate of 0.06 ML/s. Samples were prepared with two different growth procedures, in the first procedure InAs was directly deposited on the GaAs nanowires. A set of samples was prepared varying the amount of InAs deposited from 1 to 6 ML. Figure 3(a) shows the AFM image of the surface of the sample with 1.8 ML of InAs. We observe a surface corrugation produced by structures oriented along the [-5,9,3] direction with a height of 1.1 nm and a width of 80 nm. This result indicates that for 1.8 ML of deposition InAs grows on GaAs reproducing the nanowires orientation but changing their dimensions. We could observe the formation of SAQDs only for samples with more than 2 ML of InAs. It is worth to comment that this growth behavior is different from that observed on GaAs(100) substrates, where the SAQDs formation is observed from 1.7 ML of InAs growth. The AFM image of the surface of the sample with 3 ML of InAs is shown in Fig. 3(b). We observe SAQDs with an average height of 6.7 nm, an average lateral dimension of 80 nm, and a total density of $4.6x10^9/cm^2$. From a close inspection of AFM images we observed that the SAQDs tend to align along the GaAs nanowires, that is along the [-5,9,3] direction, however as observed in Fig. 3(b) the dispersion in size is large.

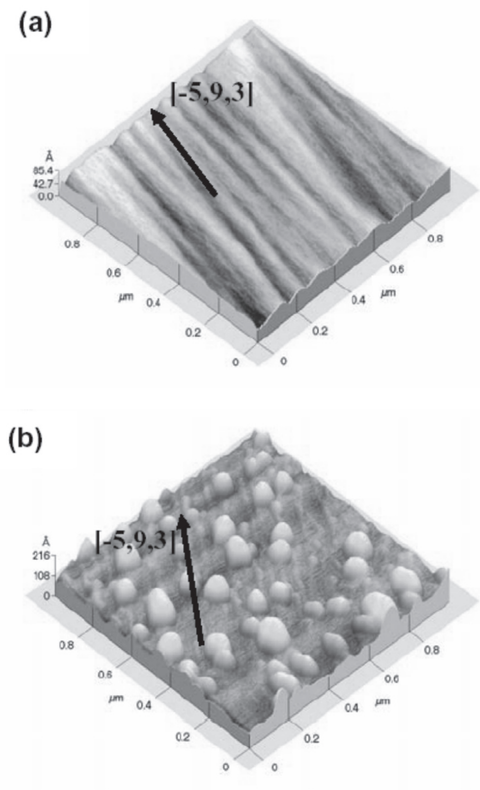

Figure 3. AFM images of the surface of samples with: (a) 1.8 ML of InAs, (b) 3 ML of InAs grown directly on

GaAs nanowires on (631) oriented substrates.
For the second growth procedure we grew SAQDs on a structure with InGaAs stressor layers as schematically shown in Fig. 4(a). First, a 80 nm-thick GaAs layer was grown on the (631)-substrate to produce the GaAs nanowires. Then a 2.1 nmthick InGaAs stressor layer with an In concentration of 28% was grown, followed by a 80 nm-thick GaAs layer, and last one 1.4 nm thick InGaAs stressor layer was grown.

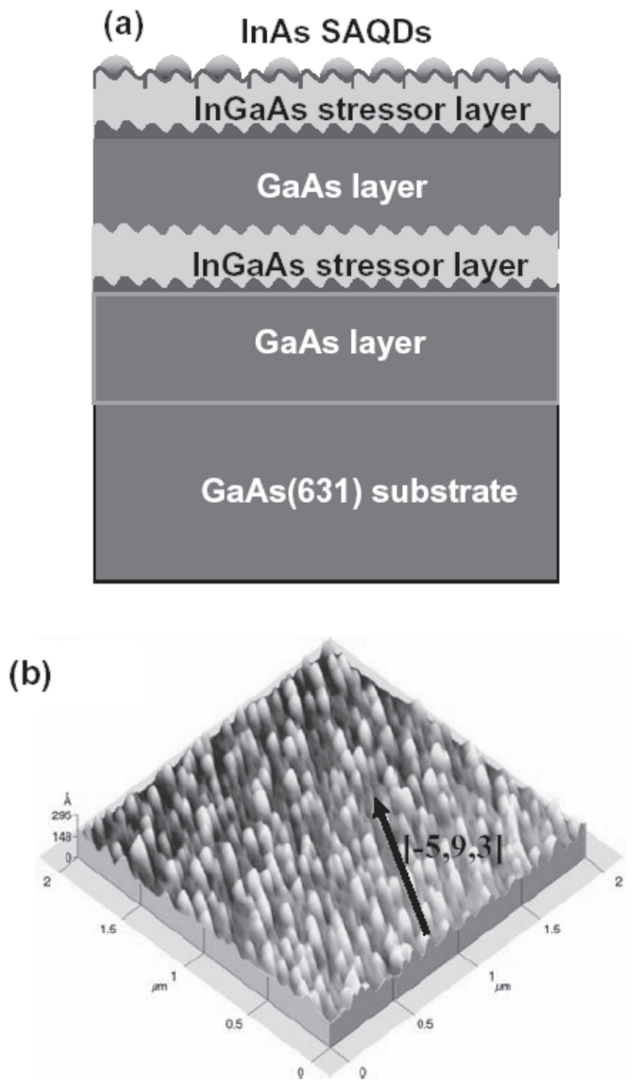

Figure 4. (a) Schematic figure of InAs-SAQDs structures grown on InGaAs stressor layers. (b) AFM
image of the surface of a sample with 1.8 ML of InAs.

On top of this last layer SAQDS were deposited employing the same conditions as in the first growth procedure. Figure 4(b) shows an AFM image of the surface of a sample with 1.8 ML of InAs on InGaAs stressor layers, where we clearly observe the formation of SAQDS. This result is completely different to that obtained employing the first procedure where no SAQDs were observed for 1.8 ML of InAs growth.

Moreover, the SAQDs present higher size uniformity with an average height of 5.2 nm, an average width of 58 and 132 nm along the [0,1,-3] and [-5,9,3] directions, respectively, and a total density of $5.5x10^9$/cm2. The difference in growth behavior with that observed in the direct deposition of InAs on GaAs could be the more uniform strain field produced by the insertion of InGaAs stressor layers.

CONCLUSION

We have studied the MBE growth of GaAs on (631)-oriented substrates to produce SAQWRs. Under appropriate growth conditions GaAs nanowires with a height of 1.5 nm and a width of 20 nm were obtained. The PR spectrum of GaAs-SAQWRs embedded in AlGaAs layers presented a series of transitions that were explained employing a model of cylindrical-shaped quantum wires. On the other hand, we studied the growth behavior of InAs on GaAs nanowires on (631)-oriented substrates. In order to obtain SAQDs grown directly on the GaAs nanowires a large amount of InAs ($\geq$ 2ML) is required. In contrast, employing InGaAs stressor layers SAQDs with a higher uniformity in size were obtained with 1.8 ML of InAs growth.

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