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Nuclear Instruments and Methods in Physics Research B 241 (2005) 470–474

NIM B
Beam Interactions
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Ion-channeling studies of InAs/GaAs quantum dots

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Abstract

Determination of the strains in and around the quantum dots is important both to assess the results of the epitaxially grown thin film and to explain the optical performance of quantum dots samples. A series of InAs/GaAs quantum dots samples were fabricated by MBE in Stranski–Krastanov growth mode. The preliminary results of ion-channeling observations along ⟨0 0 1⟩ growth direction and ⟨0 1 1⟩ direction will be presented and discussed briefly.

PACS: 61.85.+p; 68.65.H

Keywords: Quantum dots; GaAs; InAs; Ion-channeling

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1. Introduction

The self-assembled growth by molecular beam epitaxy of InAs/GaAs quantum dots (QDs) on GaAs(0 0 1) substrates has been studied extensively in recent years, primarily because of their potential for a wide range of optoelectronic device applications. The unique three-dimensional carrier confinement of QDs may provide new optical properties and therefore lead to wide applications [1]. The knowledge of the strain in and around the islands' QDs is important both to assess the crystal growth processes and to interpret the optical properties of the dots.

MeV ion channeling is a well-known technique to investigate strain of thin films [2]. Selen et al. reported evidences of strain in and around the QDs using ion-channeling measurement along the ⟨1 0 0⟩ growth direction as well as ⟨1 1 0⟩ axial direction [3]. Such work has always been carried out with the incident particles of He ions. Because of the difference in stopping power of heavy ions, signals from In can be better separated from those from Ga and As. In this work we focus on the crystallographic structure analysis of QDs sample

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doi:10.1016/j.nimb.2005.07.094

with and without capping layer using $^{12}C^{2+}$ ion-channeling technique.

2. Experiment

Samples of InAs/GaAs quantum dots were prepared by molecular beam epitaxy (MBE) technique using the Stranski–Krastanov (SK) growth method on GaAs (001) substrates at the temperature of 580 °C. The structures of the samples are shown in Fig. 1. Three layers of QD's of dimensions approximately 10–15 nm in radius and 4 nm in height were grown. Standard procedures require that a monolayer of InAs wetting layer be laid before each growth of the QD. The AFM picture of the uncapped QDs' sample is given in Fig. 2. There are about 1.4×10^{10} quantum dots per square centimeters. In general, a capping layer is necessary for fabricating QDs' devices. For this reason, a second sample of similar structure was prepared with a capping layer of 50 nm GaAs on the surface for comparison. We named the former sample as "uncapped" and the latter as "capped".

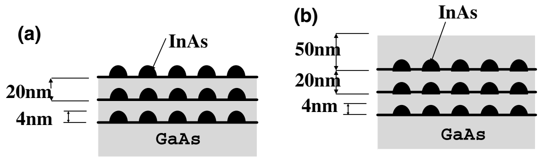

Fig. 1. Schematic view of (a) the uncapped and (b) the capped QDs samples.

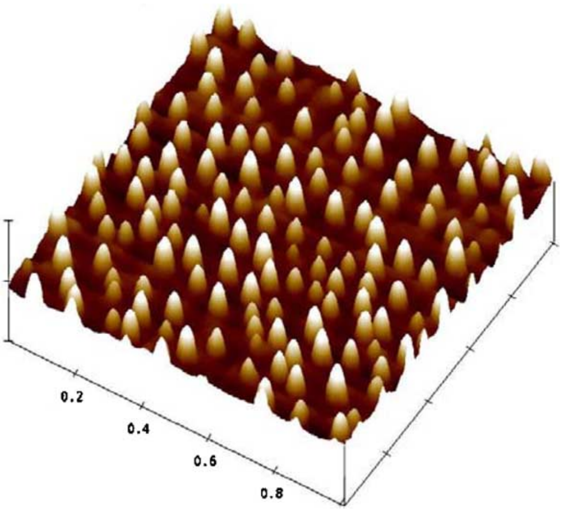

Fig. 2. Atomic force microscope (AFM) photograph of the uncapped sample.

RBS/w channeling measurement was performed with 4 MeV $^{12}C^{2+}$ beam provided by the 9SDH-2 Tandem accelerator at Tsing Hua University. The beam divergence was less than 0.02°, defined by two sets of slits 2.3 m apart. During the experiments, the incident particle flux was about 200 nA on the target. The sample was mounted in a three-axis goniometer with an angular resolution of $\approx 0.01°$. The scattering chamber was kept at a vacuum of 2×10^{-6} Torr. Backscattered particles were collected by a PIPS detector at 160° laboratory angle. The energy resolution of the system was determined by fitting the GaAs edge of the energy spectrum, shown in Fig. 3, using RBS simulation code RUMP [4] to be 90 keV. This value is significantly lower than the energy difference between the signals from In atoms and the GaAs edge in the backscattering spectrum (526 keV).

3. Results and discussion

The RBS/channeling results of random and aligned spectra on uncapped and capped samples were plotted in Fig. 3(a) and (b), respectively. Yields were measured for particles scattered from Ga and As atoms, including the surface signals and substrate signals. Additional data were collected for In signals of the entire depth range. Data were collected for the region where the crystal axis was nearly aligned with the beam direction. Fig. 4 showed the angular scans measured near the $\langle 001 \rangle$ and $\langle 011 \rangle$ axes of the uncapped sample as well as the capped sample. The measured half width, $\varphi_{1/2}$, is proportional to the characteristic angle φ_1 as defined in the Lindhard model [5]:

$$\varphi_1 = \left(\frac{2 Z_1 Z_2 e^2}{4 \pi \varepsilon_0 E d} \right)^{1/2}, \qquad (1)$$

which roughly predicts the Z_1, Z_2, d and E dependence correctly. Fig. 4 showed a smaller $\varphi_{1/2}$ of InAs ($Z_2 = 49$ and 33) than that of the GaAs

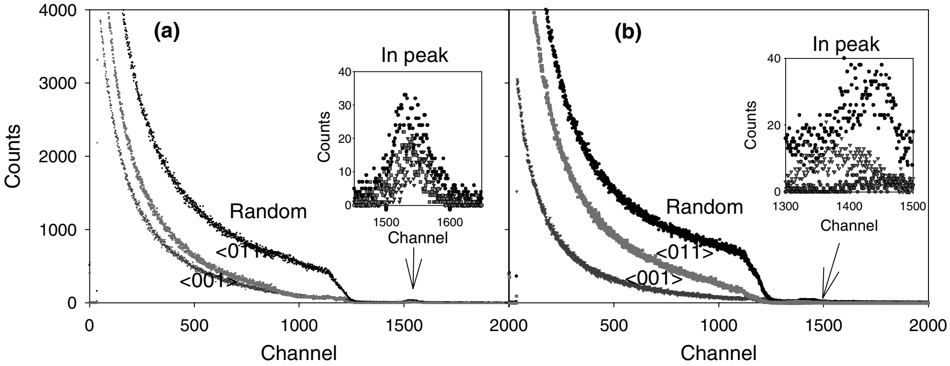

Fig. 3. Random and channeled backscattering spectra for 4 MeV ^{12}C ions incident on (a) the uncapped sample and (b) the capped sample. The inset shows the In peak.

($Z_2 = 31$ and 33), inconsistent with the predicted Z_2 dependence.

The shape of the angular scan represents not only the position of measured atoms but also the flux pattern of the incident particles. Comparing Fig. 4(a) and (c), the $\langle 0\,0\,1 \rangle$ curves for signals from GaAs in different layers look very similar. This proved that in both samples all of the surface GaAs atoms were lined up with those in the substrate in the $\langle 0\,0\,1 \rangle$ axial direction. However, as shown in Fig. 4(d), the $\langle 0\,1\,1 \rangle$ angular scan curve of the capped sample had an unexpectedly high minimum yield for the substrate signals compared with the curve representing GaAs surface, or the curves of the uncapped sample in Fig. 4(b). This unexpectedly high minimum value of the GaAs substrate curve might have been the result of a steering effect, caused by distortion of the crystal lattices between the capping layer and the QDs, mainly due to the lattice constant mismatch between InAs and GaAs. In other words, the channeled incident particles would have to steer their direction when traveling from the capping layer into the InAs QDs before reaching the underlying GaAs substrate. Because of the possibility of ions being steered in the capped sample, Fig. 3(b) showed de-channeling effect in $\langle 0\,1\,1 \rangle$ aligned spectrum.

The angular scan curves of In signals revealed quite different behaviors from the GaAs curves. Due to existence of the wetting layers, the interpretation of the In angular scan curves became complicated. From Fig. 4(a), the In curve appeared to have a higher minimum yield extended over a wider angular range. It is believed that the channeling phenomenon is caused by a shadow cone formed behind the surface atoms which reduces the nuclear encounter probability of the incident particles with deeper atoms. The first few layers of atoms attribute to the surface peaks in channeled RBS spectra. A rough estimate of the number of layers leading to the surface peak can be made according to Feldman et al. [6] as well as Stensgaard et al. [7] using the shadow cone radius and the two-dimensional, root-mean-square vibrational amplitude, ρ, which is temperature dependent. For our samples ($\rho = 15$ pm for InAs [8]), the surface layer was approximately 3.2 atoms, or 1.94 nm ($d\langle 0\,0\,1 \rangle = 0.606$ nm) thick in the $\langle 0\,0\,1 \rangle$ direction, and 3.8 atoms, or 1.63 nm ($d\langle 0\,1\,1 \rangle = 0.429$ nm) thick in the $\langle 0\,1\,1 \rangle$ direction. Note that the QDs were typically 4 nm in height. Due to the low counting rate of In signals, we were unable to identify the surface peaks. Besides, the structure of the QDs made it inevitable to include signals from the InAs wetting layers. The minimum of In angular scan curve could increase from 20% to 38% by the surface peak effect. However, the experimental curve as shown in Fig. 4(a) appeared to have a flat bottom of yield 46%, still somewhat higher than the estimated value. During QDs formation some strain may have been released from the grown InAs layer, and consequently causing possible displacements of In atoms perpendicular to growth direction. Such displacements tend to contribute to some of the dechanneling.

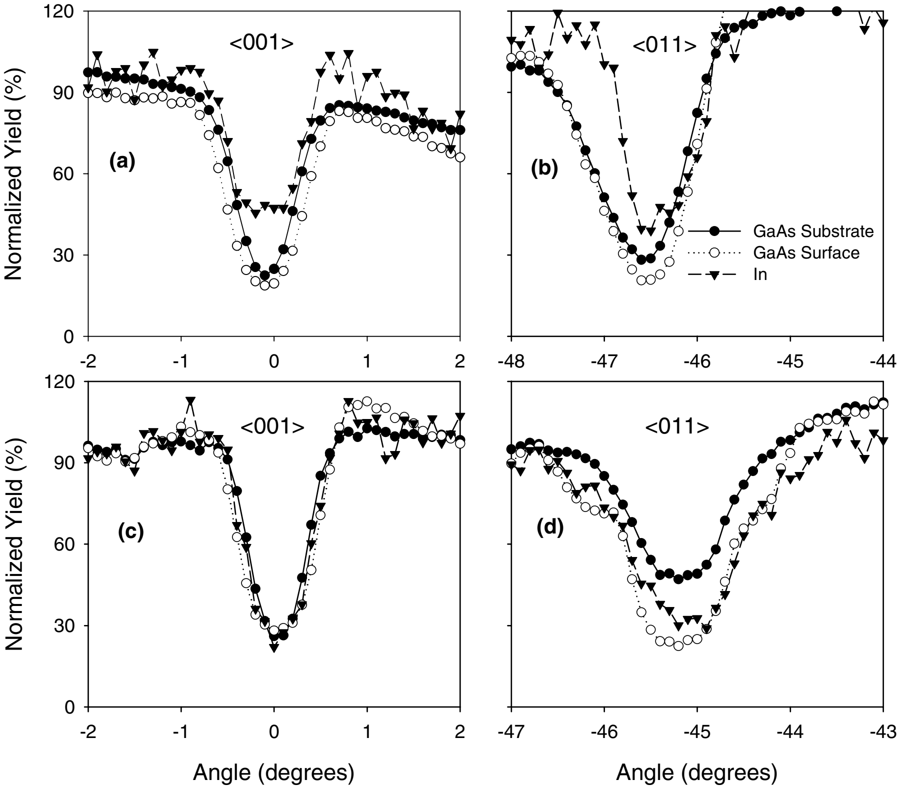

Fig. 4. Angular scans of (a,b) the uncapped sample and (c,d) the capped sample through the ⟨0 0 1⟩ and the ⟨0 1 1⟩ axes direction.

When the incident ions move along ⟨0 1 1⟩ direction, the effective passing distance in the QDs would be increased by a factor of $\sqrt{2}$. In combination with the smaller surface layer thickness (1.63 nm) in ⟨0 1 1⟩ direction, the surface peak effect mentioned above would be less influential. According to the argument given in the previous paragraph, one would expect the minimum of In angular scan curve to increase from 20% to 37%. This is consistent with the result shown in Fig. 4(b), with a minimum yield of about 40%.

The In curves for the capped sample revealed somewhat different features. The capped layer served as a guide for the crystal alignment. In Fig. 4(c), the In curve shaped almost identically as the GaAs surface or substrate curve. This is contradictory to Eq. (1), to indicate the buried InAs do not influence the incident particle flux pattern in the ⟨0 0 1⟩ direction. Such arguments would not apply for the ⟨0 1 1⟩ direction. The mismatched lattices at the interface would cause channeled ions to be steered when moving from the GaAs layer into the InAs layer, as discussed above. Indeed, Fig. 4(d) showed a little higher minimum value with comparison to the GaAs surface curve. Such lattice mismatching happens along the crystal growth direction, and hence would not influence the In curve in Fig. 4(c). The steering effect could also be seen on the uncapped sample, but the effect should be smaller than the case of the capped one.

4. Conclusion

We have studied InAs QDs on GaAs substrates with and without capped layer. The angular scan curve of the uncapped sample showed displacement both along and perpendicular to the crystal growth direction. However, the capped sample showed displacement only along the crystal growth direction.

We have also observed steering effect of the incident particles traveling through the InAs layer, especially when the measurements were performed near the ⟨0 1 1⟩ direction. The different behavior of GaAs surface and substrate curves is of some interest. Further investigation should lead to quantitative knowledge of strain in InAs.

Acknowledgement

The support of this work was given by the National Science Council under Grant No. NSC93-2212-E-007-032 and NSC93-2112-M-007-036.

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