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Effect of the lower and upper interfaces on the quality of InAs/GaAs quantum dots

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ABSTRACT

The aim of this work is to influence quantum dot (QD) formation by improving the lower and upper InAs/GaAs QD interface quality. QD properties were studied by reflectance anisotropy spectroscopy, atomic force microscopy and high resolution transmission electron microscopy. All structures were prepared by low pressure metal organic vapor phase epitaxy.

Concerning the lower interface, a good epitaxial surface planarity is required for QD formation with high QD density and narrow size distribution. Therefore the growth conditions of the QD buffer layer are very important. We demonstrate the improvement of the QD size distribution and homogeneity, when the growth rate of the buffer layer was decreased.

The upper QD interface is formed during the covering process. InAs quantum dots were capped by GaAs or by GaAsSb. The presence of Sb atoms in covering layer strongly influences the interface abruptness. In the case of GaAs covering layer, an InGaAs layer with gradual decrease of In concentration is unintentionally formed at the interface between InAs and GaAs. The presence of Sb in GaAsSb covering layer helps to form abrupt interface between InAs and covering layer. However, enhanced surfacting of In atoms was observed for GaAsSb SRL. An optimal GaAsSb composition profile is suggested to prevent dissolution of QDs during the covering process and to minimize the amount of surfacting In atoms.

Introduction

The technology of the self assembled InAs quantum dot (QD) preparation and the sensitivity of QD formation to many technological parameters were intensively studied during past twenty years. The usual task for technologist preparing InAs QD by Stranski–Krastanow growth mode for optoelectronic applications is to prepare structure with high QD density, narrow QD size distribution, big QDs for long emission wavelength and abrupt interfaces for good electron confinement in QDs. Different approaches to improve QD preparation technology were used. Buffer layers with different composition like InGaAs or GaAsSb [1–3] as well as low V/III ratio for the QD formation [4] were used to increase the QD density. An increase of the QD size was achieved by higher InAs growth temperature [5,6], higher InAs dosage [4], slower InAs growth [6,7], longer growth interruption [8] or by using so called strain reducing layers (SRLs) [1,2,9–11]. QD structures grown by molecular beam epitaxy are preferred, probably due to the higher quality of interfaces between QDs and buffer and covering layers. The aim of this work is to study the effect of quality of lower and upper QD interface on QD structures prepared by metal organic vapor phase epitaxy (MOVPE). We have focused on two tasks: to improve the planarity of the lower interface between buffer layer and QDs and to increase the abruptness of the upper interface between QDs and a covering layer.

Materials and methods

InAs/GaAs QD structures were prepared by low pressure MOVPE in AIXTRON 200 with non rotating graphite susceptor. Structures were prepared on semiinsulating (1 0 0) GaAs substrates using Stranski–Krastanow growth mode. Trimethylgallium (TMGa), triethylgallium (TEGa), trimethylindium (TMIn), arsine (AsH_3), tertiarybutylarsine (tBAs) and triethylantimony (TESb) were used as precursors for the structure growth. The structures

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were grown at a total pressure of 7 kPa, total flow rate through the reactor was 8 slpm. The growth temperature was 650 °C for the first buffer layer (TMGa + AsH_3). Then the temperature was lowered to 510 °C for the growth of the rest of the structure: second buffer layer (TEGa + tBAs), InAs QDs (TMIn + tBAs), GaAsSb triangular barrier and QDs (TEGa + tBAs + TESb) and 100 nm GaAs capping layer (TEGa + tBAs). Two different growth rates, 0.09 and 0.18 ML/s were used for the second buffer layer growth. The growth rate of InAs was 0.05 ML/s. The growth interruption for InAs QD formation was 15 s. The InAs QD layer was covered by GaAsSb layer. The growth rate of GaAsSb was 0.1 nm/s and the growth interruption after GaAsSb growth was 10 s.

Four structures with different types of QD capping layer were prepared: A: GaAs, B: GaAsSb with increasing Sb concentration, C: GaAsSb with constant Sb concentration, and D: GaAsSb with decreasing Sb content.

Reflectance anisotropy spectroscopy (RAS) in situ measurement using EpiRAS 200 TT (LayTec) monitored the growth of structures, see [12] for more details.

Atomic force microscopy (AFM) images were obtained by the TMX 2000 model EXPLORER AFM. Surfaces were observed in-air by a high-frequency non-contact mode using AFM 10 μm Z dry scanner (2500 μm *x*, *y*). The tip radius was ~10 nm.

Transmission electron microscopy (TEM) samples were prepared in cross sectional geometry and thinned down to electron transparency using mechanical polishing followed by Ar^+ ion milling in the Gatan PIPS. TEM and high resolution TEM (HRTEM) observations were performed using a JEOL 2011 electron microscope (point resolution 0.19 nm, Cs = 0.5 mm).

Results and discussion

Buffer layer/QD interface

Concerning the lower interface, we have found out that it is extremely important to achieve high planarity of epitaxial surface before the growth of InAs layer. Flat interface can be obtained by low growth rate, high V/III ratio or higher growth temperature. The second buffer layer was used as a base for QDs and was prepared at two different growth rates, 1.5 nm/min and 3 nm/min (e.g. 0.09 and 0.18 ML/s). The impact of lowering twice the growth rate and increasing the V/III ratio by decreasing TMIn partial pressure in the reactor can be recognized by comparison of Fig. 1(a) and (b). Homogeneous QD density and narrow distribution of QD size was achieved on GaAs buffer layer prepared at lower growth rate. The density of big InAs objects with misfit dislocations was also significantly suppressed.

QD/capping layer interface

In the case of the upper QD interface, the main task is the formation of an abrupt interface without In concentration gradient. To achieve this, it is neccessary to prevent QD dissolution during the capping process [12–14]. Diffused interfaces with graded In concentration have consequence in worse carrier and especially electron localization in QDs. The In atoms present on the interface originate from QDs or from relaxed InAs hillocks, which are partly dissolved due to the increased strain during the capping process [12]. These released In atoms are immediately incorporated into the growing capping layer, which causes diffused interface between InAs and covering GaAs layer, see Fig. 2(a).

The suppression of InAs dissolution during the capping process should help to obtain steeper In gradient on the InAs QDs/covering layer interface. Since GaAsSb strain reducing capping layer (SRL) was reported to prevent QD dissolution [11], we have concentrated

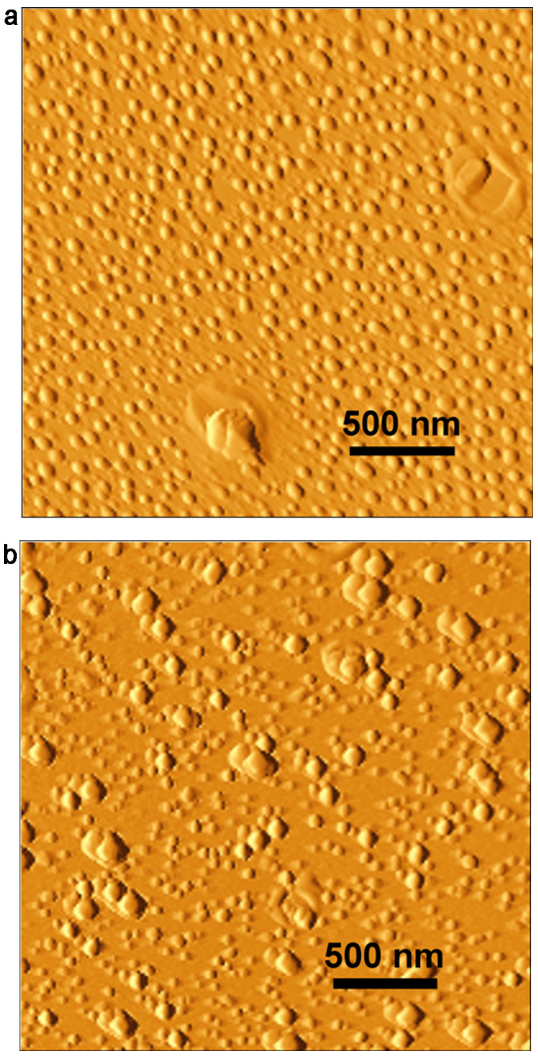

Fig. 1. AFM images of uncapped InAs QDs formed on the GaAs buffer layer prepared at different growth rates (a) 0.18 ML/s and (b) 0.09 ML/s.

on this type of covering layer. The InAs QD/GaAsSb SRL interface was studied in situ during the growth by RAS and afterwards ex situ by HRTEM. It can be seen from Fig. 2(b) that the usage of GaAsSb SRL results in more pronounced 2 ML thick InAs wetting layer with very sharp upper interface in comparison to GaAs capping layer in Fig. 2(a).

More information about the processes on the epitaxial surface during the covering layer growth was obtained by in situ RAS measurement. This optical method is very useful for monitoring surface processes during MOVPE growth since it does not require vacuum conditions in reactor chamber [12,13,15,16]. It takes advantage of the surface anisotropy for different surface reconstructions. The surface sensitivity of RAS signal is achieved by subtracting the reflectance in two crystallographic directions [1 1 0] and [−1 1 0], which eliminates the contribution of the isotropic bulk reflection. The measured RAS signal for photon energy *E* can be expressed as:

$$Re\left\{\frac{\Delta r(E)}{r(E)}\right\} = Re\left\{\frac{r_{[110]}(E) - r_{[\bar{1}10]}(E)}{1/2(r_{[\bar{1}10]}(E) + r_{[100]}(E))}\right\}$$

Each surface reconstruction has typical reflectance anisotropy spectrum, different finger print, and also different materials can be distinguished by the typical shape of RAS spectrum as is demonstrated in Fig. 3. A map of the RAS signal detected during the growth