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Molecular-beam-epitaxy grown InAs islands on nominal and vicinal GaAs(2 5 11)A surfaces

Y. Temko, T. Suzuki, M.C. Xu, K. Jacobi *

Fritz-Haber-Institut der Max-Planck-Gesellschaft, Faradayweg 4-6, D-14195 Berlin, Germany

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Abstract

InAs was deposited onto nominal and vicinal (1.0°-off-oriented) GaAs(2 5 11)A surfaces by means of molecular beam epitaxy and studied by scanning tunneling microscopy and photoluminescence measurements. Both surfaces show step bunches along the $[3 1 \bar{1}]$ direction which form fairly large (0 1 1) nano-facets. Large, inhomogeneously distributed InAs islands are formed on these nano-facets. The InAs islands exhibit a wide size distribution and vanishing photoluminescence intensity, both being characteristic for incoherent islands. The shape of the incoherent InAs islands is composed mainly of (1 1 1)A, (0 1 1), (0 0 1), and (3 1 7)A surfaces. During growth the latter undergoes a transition into the steeper (1 0 1) facet. The shape of the incoherent islands exhibits no symmetry in accordance with the missing of any symmetry at the GaAs(2 5 11)A bulk-truncated substrate surface. On the flat terraces of the nominal GaAs(2 5 11)A surface a second kind of QDs develops which are of the same shape but of a sharp size distribution. The photoluminescence intensity of the latter is quenched presumably by the coexistent incoherent InAs islands.

Keywords: Molecular beam epitaxy; Scanning tunneling microscopy; Photoluminescence; Faceting; Gallium arsenide; Indium arsenide; High-index single crystal surfaces; Quantum dots

1. Introduction

For epitaxial growth of materials with different lattice constants (e.g., InAs on GaAs, 7.2% mismatch) there are two possibilities to decrease the misfit-induced strain. The first one is the well-known Stranski–Krastanow (SK) growth mode [1]: The deposited material with larger lattice constant grows in a layer-by-layer mode first, and then—after a critical thickness is reached—three-dimensional (3D) islands or quantum dots (QDs) develop abruptly on the remaining wetting layer. It is believed that the energy gain, caused by the relaxation of the strained InAs layer into islands,

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[*] Corresponding author. Tel.: +49 30 8413 5201; fax: +49 30 8413 5106.
E-mail address: jacobi@fhi-berlin.mpg.de (K. Jacobi).

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compensates the energy cost due to the increase in surface area [2]. A prerequisite for such a modeling of the SK growth is the knowledge of the atomically resolved shape of the QDs [3].

If the fitting of the InAs and GaAs lattices in the SK growth occurs without introduction of dislocations or other defects one speaks of elastic relaxation and calls such coherent islands QDs. A relatively sharp size distribution and high internal quantum efficiency in photoluminescence (PL) are inherent features of a QD ensemble [4]. InAs QDs appear on GaAs(001) [4–6], (113)A [7–9], $(\bar{1}\bar{1}\bar{3})$B [7,10,11], (114)A [7,12], and $(\bar{5}\bar{2}\,\overline{11})$B [13]. The other possibility of strain relaxation is the introduction of 1D-line defects (called dislocations) somewhere at the interface, so that the unstrained InAs material grows further layer-by-layer without the formation of the QDs. This case of plastic relaxation occurs for InAs growth on GaAs(110) [14] and (111)A,B [14,15]. In the case, that we have reason to believe that dislocations are introduced in spite of the SK growth, we speak of InAs *islands* and not of QDs in the following.

High-performance optical devices, based on InAs QDs, require a homogeneous size distribution and the absence of incoherent islands, which form due to the coalescence of QDs or due to the incorporation of dislocations [16,17]. Several authors have proposed to use vicinal (off-oriented) GaAs substrates in order to create dense arrays of the uniform QDs along step edges [18,19]. Such proposals are based on the experimental fact that QDs tend to nucleate on or near to steps even on nominally oriented GaAs substrates [18,20,21]. As shown for GaAs(001) by means of PL measurements [22], the QDs become smaller and more uniform in size if one increases the off-orientation angle up to 7°. This has been explained in terms of a lateral confinement of the QDs. An appearance of wire-like InAs QDs at the steps on 2°-off-oriented GaAs(100) substrates has been demonstrated using atomic force microscopy [23]. It has been concluded that intervals between wire-like QDs were significantly affected by the terrace width. However, detailed knowledge on the mechanism of island nucleation at steps as well as on the role of step bunching is still missing mainly because of a lack of the atomically resolved structure of steps.

Recently, it has been demonstrated in our laboratory that the GaAs(2511)A surface is a stable, low-energy surface which unexpectedly lies in the middle of the stereographic triangle [24–26]. The high degree of perfection of its surface makes it an interesting candidate for QD studies. Furthermore, since we have already studied the atomic structure of the steps on this surface [27], we could now elucidate the role of step bunching on the development of InAs QDs. In the present paper we report on the InAs growth on nominal and 1°-off-oriented GaAs(2511)A surfaces. 3D InAs islands appear on both substrates and were characterized by in situ reflection high-energy electron diffraction (RHEED), in situ scanning tunneling microscopy (STM), and ex situ PL studies, the latter after overgrowth with GaAs.

2. Experimental

Experiments were carried out in a multi-chamber ultrahigh-vacuum (UHV) system that is described in detail elsewhere [28]. It consists of a small MBE chamber with RHEED optics, an STM chamber (Park Scientific Instruments, VP2), and a UHV analysis chamber with an Ar ion gun for sputter cleaning and a low-energy electron diffraction (LEED) optics.

Samples with a typical size of about $10 \times 10\,\mathrm{mm}^2$ were cut from GaAs epi-ready wafer (n-type, Si-doped, carrier concentration $1.0\text{–}4.8 \times 10^{18}\,\mathrm{cm}^{-3}$, manufactured by MaTecK or Wafer Technology for the nominal or 1°-off-oriented GaAs(2511)A surfaces, respectively). The off-orientation direction of the vicinal GaAs(2511)A surface has been reported in detail elsewhere [27]. The samples were mounted with indium onto a Ta carrier and treated with several ion-bombardment and annealing (under As_2 flux) cycles under control of RHEED and LEED. Homoepitaxial layers, 200–4000 Å thick, were grown by MBE at a temperature of 520–550 °C. The temperature was measured by a pyrometer calibrated against the GaAs(001)-c(4 × 4) to β2(2 × 4) transition at 465 ± 10 °C. The As_2:Ga beam equivalent pressure ratio was 7–20 (at an As_2 pressure of $4\text{–}7 \times 10^{-7}$ mbar). After GaAs growth, samples were