Journal of Crystal Growth 371 (2013) 50–55

Contents lists available at SciVerse ScienceDirect

Journal of Crystal Growth

journal homepage: www.elsevier.com/locate/jcrysgro

In-rich molecular beam epitaxy of InAs on Sb-terminated GaAs(001) surface

A.V. Katkov [a], C.C. Wang [b], J.Y. Chi [c,*]

[a] Department of Engineering and System Science, National Tsing-Hua University, Hsinchu 30013, Taiwan, and Taiwan International Graduation Program, Nano-Science and Technology Program, Institute of Physics, Academia Sinica, Taipei 115, Taiwan, R.O.C.
[b] Industrial Technology Research Institute, Mechanical and Systems Research Laboratories, Hsinchu 31040, Taiwan, R.O.C.
[c] Department of Electrical Engineering, National Chung Hsing University, Taichung 404, Taiwan, R.O.C.

ARTICLE INFO

Article history:
Received 31 July 2012
Received in revised form
24 December 2012
Accepted 2 February 2013
Communicated by A. Brown
Available online 21 February 2013

Keywords:
A1. Quantum dots
A3. Heteroepitaxy
A3. Surfactant
B1. Nanostructures
B2. III–V semiconductors

ABSTRACT

The effect of various Sb-terminated GaAs(001) templates on the growth of InAs was investigated by varying the As flux. The growth of InAs under In-rich growth conditions on Sb-terminated GaAs(001)-(2 × 3), (2 × 4) and (2 × 8) templates was demonstrated to occur in the Stranski-Krastanov (SK) growth mode, in contrast to the Sb-free case, where the growth process follows the Franck-van der Merwe (FM) growth mechanism. The observed antimony dependent change of growth mode from FM to SK is qualitatively explained by the decrease of the surface energy of the growing InAs layer caused by the segregation of Sb on the surface of the InAs(001).

1. Introduction

Antinomy (Sb)-assisted growth methods have been shown to substantially alter the morphology and optical properties of InAs quantum dots (QDs) grown by both molecular beam epitaxy (MBE) [1–9] and organo-metallic vapor phase epitaxy (OMVPE) [10–15]. The significant improvement of laser diodes with a longer emission wavelength of up to 1.34 μm based on InAs QDs grown by Sb-assisted OMVPE has been reported [13]. Depending on the Sb application method, the Sb-assisted epitaxial method can be further divided into three approaches. In the first approach, the flux of Sb is only used before the InAs growth process begins to form a template for the subsequent growth. In most of the Sb-assisted epitaxial cases, a template for Sb-induced growth is obtained by irradiating the freshly grown As-rich As(4 × 4)–GaAs(001) surface with the Sb flux until the desired Sb-induced (1 × 3) growth template appears [2–4]. In addition to the As-rich As(4 × 4)–GaAs(001) surface, the amount of Sb on the GaAs(100) surface has also been controlled by adjusting the Sb deposition time without regard to the surface reconstruction of GaAs(001) [5]. In the second approach, Sb is supplied only during the formation of InAs QDs [6,7] and becomes incorporated into the film in competition with As. In the third approach, Sb flux irradiation is only used after the formation of InAs QDs is completed [8–10]. These three approaches are not completely independent due to the significant intermixing and the segregation phenomena that occur during InAs growth at high growth temperatures. Nevertheless, all three of the Sb-assisted epitaxial approaches (based on either MBE or OMVPE) to produce InAs exhibit significant improvements in the optical properties resulting from a higher QD density, a growth mode with reduced coalescence, and reduced In segregation during GaAs capping.

In view of the intriguing role Sb played in the heteroepitaxy of InAs quantum dots as a second group V element that is in competition with As, the present work investigated the effects of Sb and As coverage on the growth mode of InAs on GaAs(100) from the As-rich regime to the As-poor regime (corresponding to the In-rich growth if no Sb was supplied). While most of the prior works employed the As-rich growth, the In-rich growth has both practical and academic importance. From the perspective of applications, the InAs growth front can remain two dimensional in the "In-rich" mode while the locations of any misfit dislocations remain in the vicinity of the hetero-interface [16]. Thus, a thick InAs epitaxial film virtually free of misfit dislocations can be grown, even on GaAs or InP(001) substrates [17]. In addition, an In-rich InAs(001) surface has been reported to provide an interface with reduced oxide defects compared to its As-rich counterpart (see, for example, the recent paper of Punkkinen et al. [18]

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[*] Corresponding author. Tel.: +886 4 22851549; fax: +886 4 22851410.
E-mail address: chij@nchu.edu.tw (J.Y. Chi).

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http://dx.doi.org/10.1016/j.jcrysgro.2013.02.004

IOP Publishing
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Semiconductor Science and Technology
Semicond. Sci. Technol. **26** (2011) 022001 (4pp)
doi:10.1088/0268-1242/26/2/022001

FAST TRACK COMMUNICATION

Enhanced optical properties of InAs/GaAs quantum dots grown by radio-frequency hydrogen plasma-assisted molecular beam epitaxy

A V Katkov[1,2], Jim Chi[3], C C Wang[4] and C Cheng[5]

[1] Department of Engineering and System Science, National Tsing-Hua University, Hsinchu, Taiwan 30013, Republic of China
[2] Taiwan International Graduation Program, Nano-Science and Technology Program, Academia Sinica, Institute of Physics, Taipei, Taiwan, Republic of China
[3] National Dong-Hwa University, Institute of Electronic Engineering, Hualien, Taiwan, Republic of China
[4] Mechanical and System Research Labs, Industrial Technology and Research Institute, Hsinchu, Taiwan, Republic of China
[5] Department of Electronics Engineering, National Chiao Tung University, Hsinchu 30010, Taiwan, Republic of China

E-mail: chij@mail.ndhu.edu.tw

Received 26 October 2010, in final form 24 November 2010
Published 17 December 2010
Online at stacks.iop.org/SST/26/022001

Abstract
Strong enhancement of photoluminescence (PL) efficiency has been observed in a GaAs/InAs quantum dots-in-a-well structure, grown with *in situ* irradiation of atomic hydrogen supplied by a radio-frequency hydrogen plasma source. The PL enhancement and wavelength position at room temperature have been found to be stable under extensive thermal annealing up to 630 °C in vacuum. As shown by the corresponding improvement of the barrier material, the possible mechanism for PL enhancement is the reduced nonradiative recombination in the barrier region by *in situ* passivation of defects while they are generated.

(Some figures in this article are in colour only in the electronic version)

Many device applications of nanostructures, including InAs/GaAs self-assembled quantum dots, are often restrained or hampered by the unavoidable presence of imperfections due to mismatched materials, complicated growth process and low growth temperature generally employed for their formation. Many attempts have been reported to alleviate the negative effects using novel growth techniques [1] and post-growth annealing. Hydrogen has also been reported to passivate defects in bulk and quantum well materials [2] and, recently, the quantum dot structures [3]. It is also reported that continuous irradiation by atomic hydrogen during epitaxial growth is more efficient for passivation of misfit dislocations than after growth H-plasma treatment [4–6]. However, for most of the cases the improvement drops after thermal treatment above around 300 °C due to the escape of hydrogen at elevated temperature. Since stable thermal stability is desirable for device fabrication, the present work investigates the thermal stability of the improved optical properties due to hydrogen. In contrast to most of the previous work, *in situ* hydrogen exposure during growth was employed. Self-assembled InAs QDs embedded in a well structure were grown on a GaAs(0 0 1) substrate with a different exposure to hydrogen plasma generated with a radio-frequency plasma source. Order-of-magnitude enhancement in PL efficiency

Optical property improvement of InAs/GaAs quantum dots grown by hydrogen-plasma-assisted molecular beam epitaxy

A. V. Katkov[a]
Department of Engineering and System Science, National Tsing-Hua University, Hsinchu, Taiwan 30013, Republic of China and Taiwan International Graduation Program, Nano-Science and Technology Program, Institute of Physics, Academia Sinica, Taipei 115, Taiwan, Republic of China

C. C. Wang
Mechanical and System Research Laboratories, Industrial Technology and Research Institute, Hsinchu, Taiwan 31040, Republic of China

J. Y. Chi[b]
Institute of Electronic Engineering, National Dong-Hua University, Hualien, Taiwan 97401, Republic of China

C. Cheng
Department of Electronics Engineering, National Chiao Tung University, Hsinchu, Taiwan 30010, Republic of China

A. K. Gutakovskii
Institute of Semiconductor Physics, Academy of Sciences of Russia, Siberian Division, Novosibirsk 630090, Russia

(Received 28 October 2010; accepted 6 March 2011; published 28 March 2011)

An order-of-magnitude increase of photoluminescence (PL) efficiency at room temperature has been observed in the GaAs/InAs quantum dots (QDs)-in-a-well structure grown with *in situ* irradiation of atomic hydrogen supplied by a radio-frequency hydrogen-plasma source. The enhancement in PL intensity rapidly increases with the hydrogen flow rate and is stable with a variation of excitation power in the radio-frequency plasma source. Extensive thermal annealing of grown samples up to 634 °C did not show any significant degradation of photoluminescence intensity compared with the reference sample. The reduction of nonradiative recombination centers in the as-grown sample causes the greatly enhanced luminescence property. In addition to PL enhancement the authors observed that the H-assisted growth of InAs QDs has suppressed bimodal distribution of QD shape. In contrast to the hydrogen-plasma-assisted growth, irradiation by hydrogen in molecular form has a detrimental effect on the optical properties of similar structures. The high thermal stability of improved optical properties suggests that the formation of the defects which are responsible for nonradiative recombination channels is suppressed during H-assisted epitaxy although *in situ* defect passivation by atomic hydrogen cannot be completely ruled out. © *2011 American Vacuum Society.* [DOI: 10.1116/1.3570870]

I. INTRODUCTION

The major challenges for the heteroepitaxial growth are to minimize the crystalline defects that to hold back many promising device applications. Numerous techniques have been developed to minimize defects during epitaxial growth and/or to anneal them out after growth. Since the presence of defects is inevitable, particularly for the low temperature or lattice mismatched growths, the passivation of defects is also an effective means to neutralize their deleterious effects on device performances. Hydrogen-plasma-assisted molecular beam epitaxy (HA-MBE) has been reported for the epitaxial growth of GaAs based bulk and quantum well materials,[1–3] GaAs on Si(001) substrate,[4] and recently quantum dot (QD) structures.[5,6] H-assisted growth has been used to eliminate the lateral composition modulation during the deposition of the InGaAsP active region for laser structures.[3] It is also reported that the continuous irradiation by atomic hydrogen during epitaxial growth is more efficient for passivation of misfit dislocations than the postgrowth H-plasma treatment.[7] In most of the cases, thermal cracking of molecular hydrogen on a hot tungsten filament is used to provide the atomic hydrogen flux.[1–7] Application of the radio-frequency atomic hydrogen source for HA-MBE is much less studied although some promising results have been demonstrated on InAs transport properties[8] and GaSb/InAs infrared photodiode performance.[9] To improve optical quality by suppressing the formation of nonradiative centers in the GaAs barrier layer grown at low temperature and the highly strained InAs wetting layer[10,11] we focus on the use of the rf plasma source for HA-MBE of the Stranski–Krastanov (SK) growth of InAs QDs on GaAs(001) substrate. Exactly the same QD-in-a-well structure has been grown with different exposure conditions to hydrogen plasma. Order-of-magnitude enhancement in the PL efficiency has been observed for the as-grown samples.

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[a] Electronic mail: andrei.katkov@gmail.com
[b] Electronic mail: chij@mail.ndhu.edu.tw