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S. Barik, L. Fu, H. H. Tan, and C. Jagadish

Citation: Applied Physics Letters 90, 243114 (2007); doi: 10.1063/1.2748845
View online: http://dx.doi.org/10.1063/1.2748845
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Impurity-free disordering of InAs/InP quantum dots

S. Barik, a L. Fu, H. H. Tan, and C. Jagadish
Department of Electronic Materials Engineering, Research School of Physical Sciences and Engineering, The Australian National University, Canberra, Australian Capital Territory 0200, Australia

(Received 27 April 2007; accepted 22 May 2007; published online 15 June 2007)

Impurity-free disordering (IFD), commonly known as impurity-free vacancy disordering, is a simple yet promising method for monolithic integration of active/passive components of optoelectronic devices. InAs/InP quantum dots (QDs) are promising active materials for high performance optoelectronic devices operating at long wavelength region (1.3–2 μm). However, IFD of InAs/InP QDs has not been studied comprehensively and its mechanism needs to be further clarified. Wang et al. carried out impurity-free group III intermixing of an InGaAs/InP bilayer and reported that the maximum differential energy shift between samples capped with a SiO2 or TiO2 layer is 90 meV. They attributed the energy shift observed in the samples capped with SiO2 to group V outdiffusion to a SiO2 layer whereas Ga, In, and P outdiffuse to a TiO2 layer leading to different degrees of intermixing. The results indicate that a group V interstitial diffusion mechanism might be responsible for IFD of InAs/InP QDs. © 2007 American Institute of Physics. [DOI: 10.1063/1.2748845]

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sputtering. The atomic concentration is replotted to show the outdiffusion of atoms to the dielectric layer more clearly. The samples are annealed at 850 °C for 30 s. However, for the QDs capped with the InGaAs/InP bilayer, a SiO2 layer gives more energy shift than a TiO2 layer. After annealing at 850 °C, the InGaAs/InP capped QD structure coated with a SiO2 layer shows a large energy shift of 157 meV, which is much larger than the reported maximum differential energy shift of 90 meV between a SiO2 layer and a SiN layer coated InAs/InP QD samples having an InP cap layer.4

To understand the effects of different cap and coating layers, XPS measurements are carried out. The XPS depth profiles of different elements of InAs QDs capped with the InGaAs/InP bilayer and coated with a TiO2 layer and a SiO2 dielectric layer are shown in the insets of Figs. 3(a) and 3(b), respectively. To show the outdiffusion of different atoms to the dielectric layer more clearly, the atomic concentration is replotted up to 5% in Fig. 3. The samples are annealed at 850 °C for 30 s. Figure 3(a) shows that only In atoms outdiffuse to the TiO2 layer, whereas Fig. 3(b) shows that both In and Ga outdiffuse to the SiO2 layer. The outdiffusion of these group III atoms to the dielectric layers may lead to the creation of either group III vacancies or group V interstitials in the QD structure. However, the intermixing due to the group III vacancy diffusion will have a minimal role in our QD system. Because of a small thickness of 0.6 nm, the effect of the GaAs interlayer underneath the InAs QD layer is negligible and there is no other group III atomic concentration gradient across the QD layer. Teng et al.5 proposed...
that the group V interstitials generated at the SiO2 and InGaAs surface diffused through the InGaAsP/InP quantum well (QW) heterostructure and led to the enhanced QW intermixing. We also believe that in an InP system, the intermixing by the diffusion of group V interstitials is a dominant mechanism, as also reported by other groups.6,9 The outdiffusion of group III atoms to the dielectric layer results in As interstitials in the InGaAs layer and eventually, P interstitials in the InP layer by the kick-out mechanism. The concentration of P interstitials due to only In outdiffusion. As a result, the SiO2 coated sample shows much higher energy shift than the TiO2 coated sample, as shown in Fig. 2. From the insets of Fig. 3, it is also noted that the atomic concentration of In is higher than that of P in the InGaAs/InP cap layer region. This is due to different sputtering rates of different elements during the depth profiling process. More P atoms are sputtered preferentially compared to In atoms leading to an In rich surface. However, since all samples are analyzed under the same conditions, we focus our discussion on the effects of elemental outdiffusion from a cap layer to a dielectric layer rather than trying to quantify the exact atomic percentages of different elements.

The XPS depth profiles of different elements of the InAs QDs capped with an InP layer and coated with a (a) TiO2 or (b) SiO2 dielectric layer are shown in the insets. The atomic concentration is replotted to show the outdiffusion of atoms to the dielectric layer more clearly. The samples are annealed at 850 °C for 30 s.

Figure 4 shows that unlike As, P outdiffuses to the dielectric layers. Figure 4(a) shows that more In atoms compared to P atoms outdiffuse to the TiO2 layer. The outdiffusion of excess In atoms compared to P atoms results in P interstitials in the InP cap layer. These P interstitials diffuse through the QD layer causing significant intermixing of the InAs/InP QDs. On the other hand, as shown in Fig. 4(b), the comparable amounts of In and P outdiffusion to the SiO2 layer result in a small net concentration of P interstitials leading to a much reduced energy shift, as depicted in Fig. 2.

Our results show that a TiO2 dielectric layer does not suppress interdiffusion as observed in InGaAs/GaAs QD systems, in which intermixing was governed by group III vacancy diffusion.6 TiO2 has been recently reported to enhance QW intermixing on InP/InGaAs/InGaAsP heterostructures due to faster In interstitial diffusion.10 The thermal expansion coefficient (α) of TiO2 (α=8.2×10^{-6}/°C) is larger than those of GaAs (α=6.8×10^{-6}/°C), InGaAs (α=5.69×10^{-6}/°C), and InP (α=6.33×10^{-6}/°C). TiO2 generates a tensile stress in the semiconductor structure during annealing, and thus inhibits vacancy diffusion but promotes interstitial diffusion.10 However, InP and InGaAs become compressive during annealing when it is coated with a SiO2 layer (α=0.52×10^{-6}/°C) and thereby group V interstitial diffusion should be inhibited leading to a suppression in energy shift. However, we observe the maximum energy shift in the InGaAs/InP bilayer capped sample with a SiO2 coating. Based on the XPS results, we believe that in our InAs/InP QD system, intermixing is mainly governed by group V interstitial diffusion and influenced by the outdiffusion of different elements to the dielectric layers. The stress may have only a small or insignificant role.

In conclusion, we have studied IFD of the InAs/InP QDs containing a thin GaAs interlayer. Our results show that both SiO2 and TiO2 layers promote IFD of InAs/InP QDs. The XPS and PL studies indicate that group V interstitial diffusion might be the dominant mechanism. XPS depth profiles show that both In and P outdiffuse to a TiO2 layer whereas Ga, In, and P outdiffuse to a SiO2 layer. A large differential energy shift of 157 meV is obtained in the QDs capped with an InGaAs/InP bilayer and coated with a SiO2 layer indicating that the use of an InGaAs cap layer in an InAs/InP QD system could be beneficial for the monolithic integration of QD based optoelectronic devices.

The authors are thankful to Bill Gong and Robert Lamb from the University of New South Wales, Sydney, Australia for XPS measurements and fruitful discussions. The financial support from the Australian Research Council is also gratefully acknowledged.