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Growth and surface passivation of near-surface InGaAs quantum wells on GaAs (1 1 0)

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Abstract

The growth and surface passivation of near-surface InGaAs quantum wells (QWs) on GaAs (1 1 0) substrate have been investigated. Triangular shaped small islands, approximate areal density of $10^7\,cm^{-2}$, are observed on metal organic vapor phase epitaxially grown GaAs single layer and InGaAs multi-quantum wells (MQWs) surfaces in a wide range of growth temperatures. By optimizing the growth conditions, high quality $In_{0.22}Ga_{0.78}As$ QWs with optical properties comparable to the same structure grown on GaAs (1 0 0) are obtained. Near-surface single QWs are used to study the surface passivation. Epitaxially *in situ* grown mono-layer thick GaP and InP layers as well as surface phosphorization with tertiarybutylphosphine (TBP) are utilized as passivation methods. Passivation significantly increases photoluminescence (PL) intensity and carrier lifetime of near-surface QWs. The best passivation efficiency is obtained by surface phosphorization with TBP on (1 1 0)-oriented near-surface QW while the ultra-thin InP layer is the best on (1 0 0)-oriented near-surface QW. After 7 months of air exposure, all passivated near-surface QWs still show high PL intensity comparable to deep QW while the PL intensity of unpassivated samples degraded severely. Also, the differences between the optical properties of QWs on GaAs (1 1 0) and (1 0 0) substrates are observed and discussed.

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1. Introduction

GaAs (1 1 0) orientation is more favorable than GaAs (1 0 0) in some applications due to its high impact ionization efficiency [1] in optical devices and preference in epitaxial growth of zincblende-on-diamond system [2]. (1 1 0)-Oriented AlGaAs quantum wells (QWs) were also found to be particularly suitable for spintronic application due to their long carrier relaxation times [3]. Epitaxial growth of bulk [4–6] and QW [7,8] structures on GaAs (1 1 0) substrates by molecular beam epitaxy (MBE) has been reported in detail before. In all these studies the surface structure was found to be faceted with triangular shaped islands having surface densities of approximately $10^6\,cm^{-2}$ [6]. However, growth of (1 1 0)-oriented GaAs and QWs has not been widely studied by using metal organic vapor phase epitaxy (MOVPE).

In addition, various GaAs surface passivation techniques have been intensively studied due to the high density of surface states which can bring some serious limitations to the material and device performance. QW lasers grown on GaAs (1 0 0) substrates have (1 1 0)-oriented mirrors. Destruction of laser mirror surfaces due to the overheating caused by optical absorption on the surface states is the most significant factor limiting the power density of high-power laser [9,10]. Better passivation methods for (1 1 0) surfaces could provide improved laser performance. The *in situ* epitaxial passivation is considered to be a more efficient method than the other techniques [11–14] on the

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surface passivation of GaAs (1 0 0). However, the epitaxial passivation methods of GaAs (1 1 0) surface are rarely reported.

In this paper, we study MOVPE growth and surface passivation characteristics of near-surface InGaAs QWs on GaAs (1 1 0) substrates. GaAs single layer and InGaAs multi-quantum wells (MQWs) are used to study the surface morphologies and structural properties. High quality QW structures were grown on the GaAs (1 1 0) substrate and significant passivation effects were obtained by using *in situ* grown ultra-thin passivation layers. Different passivation methods show different passivation efficiency on (1 1 0) and (1 0 0)-oriented near-surface QWs. All passivated samples show good time stability after long time air exposure.

2. Experimental procedure

All the samples were grown on GaAs (1 1 0) substrates in a horizontal MOVPE reactor at atmospheric pressure using trimethylindium (TMIn), trimethylgallium (TMGa), tertiarybutylarsine (TBAs), and TBP as precursors for indium, gallium, arsenic, and phosphorus, respectively. GaAs single layers with 10, 50, and 100 nm thicknesses and $In_xGa_{1-x}As$ MQWs were grown for studying the surface morphology and structural quality. The five-period MQW structure consists of 4 nm thick InGaAs QWs and 20 nm thick GaAs barriers grown on top of a 100 nm thick GaAs buffer layer. The growth temperature of GaAs single layer is 650 °C, and it was varied in the range of 600–720 °C for the MQW growth while the V/III ratio was 23. The temperatures mentioned in this report are thermocouple readings [15] and V/III ratios are molar flow ratios. There was also a (1 0 0) GaAs substrate, in addition to the (1 1 0) substrate, in the reactor in each growth run for reference.

The passivation effects were studied by investigating the optical properties of a near-surface single QW structure consisting of a 4 nm thick $In_{0.22}Ga_{0.78}As/GaAs$ QW and a 5 nm thick GaAs cap layer. An unpassivated deep QW sample, with a 20 nm thick cap layer, was grown for reference. Three kinds of *in situ* passivation methods were utilized. Nominally 1 ML thick GaP and InP passivation layers were grown on top of the cap layer at a temperature of 580 and 650 °C with a V/III ratio of 130 and 230, respectively. The surface phosphorization was realized by exposing the sample surface to a TBP flow of 330 μmol/min during the cooling from 600 to 400 °C after the growth of the GaAs cap layer. All the passivated and unpassivated near-surface QW structures were also grown in the same growth run on GaAs (1 0 0) substrates for comparison.

A contact-mode atomic force microscope (AFM) was used to investigate sample surface morphology. Layer thickness and indium composition of the QW were determined by a high-resolution X-ray diffractometer (HR-XRD). The low-temperature (10 K) continuous-wave PL measurements were conducted by utilizing a diode-pumped frequency-doubled Nd:YVO_4 laser emitting at 532 nm for excitation. A liquid-nitrogen-cooled germanium detector and standard lock-in techniques were used to record the PL spectra. The low-temperature time-resolved photoluminescence (TRPL) measurements were performed by exciting the samples with 150 fs pulses at 780 nm from a mode locked Ti:Sapphire laser and by detecting the signal using a Peltier-cooled microchannel plate multiplier and time-correlated single photon counting electronics.

3. Results and discussion

3.1. Growth of QWs on GaAs (1 1 0) substrate

Surface morphology and the structural quality of GaAs single layers and $In_xGa_{1-x}As$ MQWs grown on GaAs (1 1 0) substrate were studied. Triangular shaped small islands were observed on the surfaces of the GaAs epilayers. Fig. 1 shows the AFM images of GaAs layers (grown at 650 °C) with the thickness of 10 and 100 nm. The average base size and average height of a typical island are 100 and 1–2 nm, respectively. The approximate density of

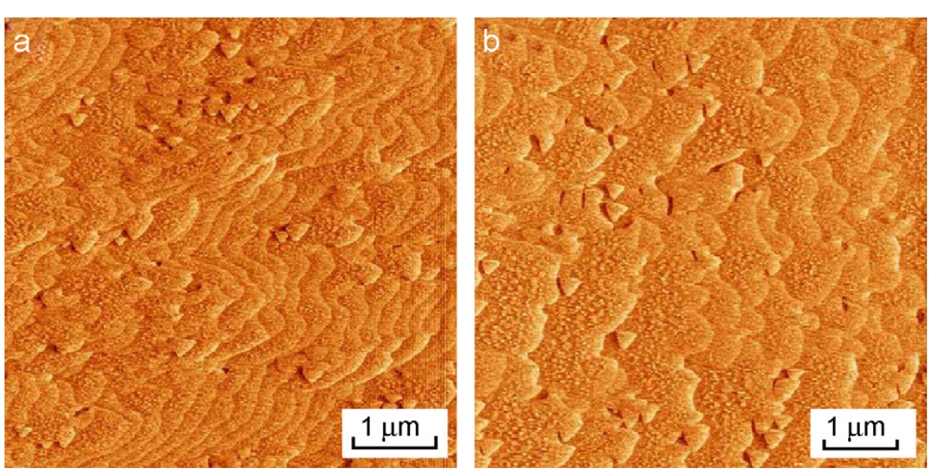

Fig. 1. Surface AFM images of GaAs layers (grown at 650 °C) on GaAs (1 1 0) substrate with the thickness of (a) $d = 10$ nm and (b) $d = 100$ nm. The scan size is $5 \times 5\,\mu m^2$ and the vertical scale is 5 nm.