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Spin resonance spectroscopy of grown-in defects in Ga(In)NP alloys

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Abstract

We employ the optically detected magnetic resonance (ODMR) technique to study and identify important grown-in defects in Ga(In)NP grown by molecular-beam epitaxy (MBE). Several types of defects were revealed from ODMR studies. The dominant defects were found to be related to Ga interstitials, evident form their characteristic hyperfine interaction arising from the spin interaction between the electron and the Ga nucleus. Some other as yet unidentified intrinsic defects were also found to be commonly present in the alloys. The effects of growth conditions (ion bombardment, N_2 gas flow, etc.) and post-growth rapid thermal annealing on the formation of these defects were studied in detail, shedding light on the formation mechanism of defects.

Keywords: Dilute nitrides; GaInNP; Defects; Interstitials; ODMR; MBE

1. Introduction

The newly emerging dilute nitrides such as Ga(In,Al)NP and Ga(In)NAs are derived from conventional III–V semiconductors Ga(In,Al)P and Ga(In)As by insertion of a few per cent of N into the group-V sub-lattice [1–3]. They exhibit unusual and fascinating new physical properties that are rarely seen in other conventional alloys, including giant bandgap bowing, increasing electron effective mass values, a crossover from an indirect bandgap in GaP to a quasi-direct

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bandgap in GaNP, etc. The potential technological advantages of the novel dilute nitrides derive not only from widely extended bandgap engineering but also from the possibility for these alloys to be lattice matched to GaAs and Si substrates. Such a unique combination of the remarkable fundamental properties with the technological advantages has opened the door for a range of desired device applications in optoelectronics and photonics, such as cheaper and improved solid-state lasers for fiber-optic communications, high-performance multi-junction solar cells, novel OEIC exploring integration of efficient III–V optoelectronics with microelectronics based on silicon.

Unfortunately, epitaxial growth of dilute nitrides remains a great challenge. The required non-equilibrium growth conditions together with the disparity between N and the replaced group-V atoms are known to favor formation of various defects, which leads to poor optical quality of alloys. In fact, the issue of point defects is one of main problems we are currently facing that hinders a rapid progress of dilute nitrides for various device applications in optoelectronics and photonics. Up to now, band-to-band transitions in GaNP have not been observed in spite of the crossover to a quasi-direct bandgap, due predominantly to non-radiative recombination via defects. Identifying and understanding of the relevant defects in dilute nitrides and designing strategies to eliminate them are therefore crucial to the success of these materials for optoelectronic device applications.

The aim of this work is to employ the optically detected magnetic resonance (ODMR) technique to study and identify important grown-in defects in Ga(In)NP prepared by molecular-beam epitaxy (MBE).

2. Experimental

The Ga(In)NP samples studied in this work were grown at 460–590 °C on (001) GaP substrates by solid-source MBE using a RF plasma nitrogen radical beam source. Prior to the growth of the Ga(In)NP layer, a 100 nm thick GaP buffer layer was deposited on a substrate. Both GaNP epilayers with a typical thickness of about 300 nm and three-period $Ga_{0.55}In_{0.45}N_{0.02}P_{0.98}$(2.5 nm)/$GaN_{0.016}P_{0.984}$(18 nm) Quantum Wells (QW) were studied. They were finally capped by a 20 nm thick GaP layer. N composition in the GaNP alloys ranged between 0.7 and 2%, as determined by high-resolution x-ray rocking curve measurements. To evaluate possible effects of ion bombardment on defect formation the samples were grown both with and without an ion collector.

The ODMR measurements were performed at a microwave frequency of ∼9.3 GHz using a modified Bruker ER-200 D X-band spectrometer. The 532 nm line of a solid-state laser was used as an excitation source. An ODMR signal was detected as spin-resonance-induced changes of spin-dependent recombination due to on–off modulation of the microwave field using the lock-in technique, by monitoring photoluminescence (PL) intensity in the visible and near-infrared (NIR) spectral region with a photomultiplier and cooled Ge detector, respectively. The measurements were performed at liquid helium temperature.

3. Results and discussion

Upon above-bandgap optical excitation, the studied Ga(In)NP alloys exhibit PL emissions in the visible spectral range that are known to arise from N-related localized states [4]. They also give rise to defect-related deep PL emissions within the NIR spectral range whose origins are still largely unknown. Typical ODMR spectra obtained by monitoring these NIR PL emissions are shown in Fig. 1. Besides the ODMR signals arising from the GaP substrate, revealed by a separate