JOURNAL OF APPLIED PHYSICS **117**, 045705 (2015)

Photoluminescence study of Be-acceptors in GaInNAs epilayers

Y. Tsai,[1] B. Barman,[1] T. Scrace,[1] M. Fukuda,[2] V. R. Whiteside,[2] I. R. Sellers,[2] M. Leroux,[3] M. Al Khalfioui,[3,4] and A. Petrou[1]

[1]*Department of Physics, SUNY at Buffalo, Amherst, New York 14260-1500, USA*
[2]*Department of Physics and Astronomy, 440W Brooks Street, University of Oklahoma, Norman, Oklahoma 73019-2061, USA*
[3]*CRHEA-CNRS, Rue Bernard Gregory, 06560 Valbonne, France*
[4]*University of Nice Sophia Antipolis, Parc Valrose, 06102 Nice Cedex 2, France*

(Received 21 November 2014; accepted 10 January 2015; published online 23 January 2015)

We have studied Be-acceptors in a p-type GaInNAs epilayer using magneto-luminescence spectroscopy. The band edge photoluminescence (PL) spectra at $T = 7$ K contain two features: the first is associated with the free exciton while the second with the conduction band to acceptor (CB → A) transition. The intensity of the latter decreases with increasing temperature while the excitonic feature survives up to $T = 250$ K. From the energies of the two PL features, as well as the exciton binding energy in GaInNAs, we determined the Be-acceptor binding energy to be equal to 42 meV. The energy of the CB → A feature varies linearly with magnetic field B and has a slope of 5.5×10^{-4} eV/T. © *2015 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4906409]

INTRODUCTION

Dilute nitride semiconductors have stimulated much recent interest due to the potential to tune the bandgap of GaAs-based alloys into the near infrared of the spectrum.[1] This offers the potential for applications in telecommunications, lasers, and photovoltaics (PV). For PV applications, dilute nitrides have been proposed as the fourth-junction in next generation multi-junction solar cells (MJSCs) since they can be grown lattice matched to GaAs and have their bandgap tuned to the desirable 1 eV absorption window.[1] MJSCs incorporating GaInNAs materials have been predicted to have power conversion efficiencies exceeding 44%.[1] Recently, a triple-junction MJSC based on GaInNAsSb set an efficiency record of 43.5%.[2] Despite this success, dilute nitride semiconductors still suffer from problems such as yield, reproducibility, and carrier lifetime when used in PV devices. The low solubility of nitrogen, and the tendency for phase segregation during growth, results in the necessity of non-optimum *lower* growth temperature for reasonable nitrogen incorporation.[3,4] Low growth temperature produces poor material quality with low minority carrier diffusion lengths and low current extraction in GaInNAs-based solar cells.[1,5] The inclusion of Sb as a surfactant[6] and postgrowth rapid thermal annealing improves these materials considerably.[7] On the other hand, the formation of nitrogen clusters, defects, and impurity centers remains unavoidable,[4,8] limiting the performance of these systems, and inhibiting their implementation in practical PV applications.[1] The formation of impurity centers during growth complicates the ability to dope these materials n- or p-type, since large background impurity concentrations can occur in as-grown nominally intrinsic materials.[1,4,9]

Here, we present a magneto-luminescence investigation of GaInNAs epilayers doped with Be-acceptors, the incorporation of which has been demonstrated previously to passivate background donor impurities facilitating the dominance of free carrier recombination,[10] and the removal of the s-shape dependence of the energy gap on temperature.[10,11] The inclusion of Be-acceptors during growth is shown to result in a photoluminescence (PL) feature due to acceptor-to-conduction band transitions at low temperatures.

EXPERIMENT

In this paper, we studied a p-type GaInNAs epilayer (sample 1) grown by molecular beam epitaxy (MBE) at 420 °C on a GaAs substrate with atomic composition: $n_{Ga} = 91\%$, $n_{In} = 9\%$, $n_{As} = 97.2\%$, and $n_N = 2.8\%$. The sample was doped with Be-acceptors at $n_{Be} = 2 \times 10^{18}$ cm^{-3}, has a thickness of 1 μm, and was terminated with a 75 nm GaAs cap. Sample 2 is a nominally undoped 1.6 μm GaInNAs layer grown at a temperature of 450 °C with same atomic composition and terminated with a 75 nm GaAs cap. After growth, samples 1 and 2 were subjected to rapid thermal annealing at 800 °C in nitrogen-rich conditions. We also used a GaAs p-type reference sample (sample 3) to compare the slope dE/dB of the energy of the conduction band to acceptor (CB → A) transition with that from sample 1. The samples were placed in a variable temperature optical magnet cryostat equipped with a 7 T superconducting coil. The photoluminescence spectra of sample 1 and sample 2 were excited using a semiconductor laser emitting at 785 nm and the 1064 nm line of a Nd:YAG laser; for sample 3, PL spectra were excited by the 488 nm line from an Argon-ion laser. The power densities were all 1.1 W/cm^2. The emitted light was collected in the Faraday geometry (light propagation along the direction of the magnetic field) and focused onto the entrance slit of a single monochromator equipped with a cooled InGaAs detector array operating in the 900–1700 nm wavelength range.

RESULTS AND DISCUSSION

In Fig. 1, we show the PL spectrum at T = 7 K from sample 1 (black points). The spectrum contains three features

