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Investigation on the materials of heavily Mg-doped AlInP layers for laser diode structure

Tao Lin [a,*], Jingjing Li [a], Tianjie Zhang [a], Nan Lin [b], Cong Xiong [b], Xiaoyu Ma [b]

[a] Department of Electronic Engineering, Xi'an University of Technology, Xi'an 710048, China
[b] National Engineering Research Center for Optoelectronics Devices, Institute of Semiconductors, CAS, Beijing, 100083, China

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High concentration p-type AlInP material is an important layer to achieve low resistant and large carrier confinement in short-wavelength red-light laser diodes (LDs). To investigate the Mg doping behavior and other characteristics in the red-light LDs with tensile GaInP well structure, two LDs wafers with different Mg-doped AlInP cladding layers were grown by the metalorganic chemical vapor deposition (MOCVD) method. Incorporation and activation behavior of Mg atoms in heavily-doped AlInP were analyzed by the comparisons between hole concentration and atom concentration. We demonstrate that it is possible to achieve hole concentration above 10^{18} cm^{-3} using Mg dopant in AlInP layers just by an in-situ annealing. Furthermore, a hole concentration as high as 2.92×10^{18} cm^{-3} was achieved after post rapid thermal annealing in the N_2 atmosphere, which is the highest hole doping concentrations reported to-date for the p-AlInP material.

1. Introduction

In recent years, short-wavelength red-light LDs operating in the range of 635 nm–642 nm have become an important component in many laser-based displays applications, such as laser television, pico-projector, large scale glasses-free three-dimensional outdoor displays, head-up displays, and retinal scanning displays [1,2]. Optoelectronic characteristics of the LD chips based on tensile GaInP wells are important to achieve long lifetime applications under high brightness and high efficiency operation for the final devices [3]. It's a challenging work to achieve short wavelength for red-light LDs because of the large carrier leakage caused by small conduction band offset of AlGaInP material system and its significant thermal saturation due to its lower thermal conductivity [4]. As AlInP has larger conduction band offset than AlGaInP material, it's appropriate to select AlInP as cladding layers for LDs chips to achieve superior temperature characteristics and high output power. However, it is a thorny problem to achieve high p-type doping and maintain perfect crystal meanwhile in the MOCVD growth. For the p-type cladding layer, hole concentration is desired to avoid the leakage of carriers from the active layer into the cladding layer and to achieve low series resistivity [5]. Two methods have been used to obtain high hole concentration in experiments. Generally, zinc (Zn) has been used as a p-type dopant in MOCVD grown AlInP layers because of its excellent controllability and reproducibility. However, the maximum obtainable hole concentration has been limited to 1×10^{18} cm^{-3} for the reason that the electrical activation decreases with the increasing of the Al fraction [6]. Magnesium (Mg) is used as an alternative p-type dopant for AlInP material growth for the advantages of high doping efficiency and low diffusion coefficient. However, Mg dopant precursor also has insufficient activation by the hydrogen passivation and the so-called memory effect, which makes it difficult to achieve sharp doping profiles [7].

As that occurred in the nitrides material, the limited solubility and high activation energy of Mg atom, which is caused by the high formation enthalpies of Mg substitution for Ga or Al, becomes increasingly obvious in high Al content layers. To enhance the effective incorporation of Mg, modified surface-engineering technique and In-Mg co-doped GaN system are used to yield sufficient amounts of active nitrogen species for gallium nitride growth [8,9]. To investigate the Mg doping behavior and other characteristics in the tensile GaInP well laser diode structure, two red-light LDs wafers with different Mg dopant flow rates were grown by MOCVD method in this study. Thermal treatments of in-situ annealing in AsH_3 atmosphere and post rapid annealing in N_2 atmosphere were adopted to improve the Mg doping properties of AlInP layers in the

* Corresponding author.
E-mail address: lintao@xaut.edu.cn (T. Lin).

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LDs structure. Incorporation and activation behavior of Mg in heavily-doped AlInP are analyzed by the comparisons between the hole concentration and atom concentration. We demonstrate that it is possible to achieve increased hole concentration and enhanced activation efficiency using the combination of two methods. Our results show that this new method may pave the way for the realization of high-efficiency short-wavelength optoelectronic devices based on the tensile GaInP wells and AlInP cladding.

2. Methods

The tensile GaInP well red-light LDs samples used in this study were carried out in a horizontal, low-pressure AIX200 MOCVD reactor with H_2 carrier gas. The precursors were trimethylgallium (TMGa), trimethylindium (TMIn), trimethylaluminium (TMAl), 100% arsine (AsH_3) and 100% phosphine (PH_3). The p-type dopant was biscyclopentadienyl magnesium (Cp_2Mg) and n-type dopant was silane (SiH_4). The growth surface was on the GaAs substrates (1 0 0) with 10° misorientation towards (1 1 1)A. During the epitaxy, the growth temperature was controlled at 650–725 °C and the growth pressure was set as 5000 Pa [10].

In the MOCVD growth of the samples, the epi-wafers were in-situ annealing from 520 °C to 320 °C in a cooling rate of 40 °C/min under a protection atmosphere of AsH_3. To activate the atomic hydrogen passivation of Mg acceptors in the AlInP layers originating from the decomposition of group V hydrides, the laser diode structure were executed post rapid thermal annealing (RTA) with a protection atmosphere of N_2 for 5 min at 500 °C and 550 °C, separately. For the post RTA processes, the heating rate was set as 10 °C/second, and naturally cooled down to room temperature after annealing.

The surfaces of all epitaxial samples were measured by the optical microscope. Lattice strain mismatches were determined by rocking curves tested by the double-crystal X-ray diffraction, and room-temperature photoluminescence (PL) spectra were investigated by photoluminescence spectroscopy measurements with a 532 nm laser excitation. Hole concentration was measured by electrochemical capacitance-voltage (ECV) depth profiling and Mg atom concentration was measured by secondary ion mass spectrometry (SIMS).

3. Results and discussion

3.1. Structures of the laser diode

The designed tensile GaInP well LDs structure contains the following layers: 200 nm Si-doping n-$Ga_{0.51}In_{0.49}P$ buffer layer, 1000 nm Si-doping n-$Al_{0.51}In_{0.49}P$ cladding layer, 120 nm $Al_{0.307}Ga_{0.213}In_{0.48}P$ lower waveguide layer, an active region with single-quantum-well structure (barrier: AlGaInP layer, well: tensile strain GaInP layer), 120 nm $Al_{0.307}Ga_{0.213}In_{0.48}P$ upper waveguide layer, 999 nm Mg-doping p-$Al_{0.51}In_{0.49}P$ cladding layer (three 333 nm p-$Al_{0.51}In_{0.49}P$ layers with different doping concentration), 50 nm p-$Ga_{0.51}In_{0.49}P$ barrier reduction layer, 120 nm p^+-GaAs Ohmic contact layer. To obtain the highest doping concentration and to excogitate the saturation of Mg incorporation simultaneously, the two samples were both grown using a step epitaxy method that doubles dopant flow rate for next layer. Schematic structures of the LDs samples are shown in Fig. 1. Flow rates of TMIn, TMAl and PH_3 were all kept constant in the growth of the different Mg-doped AlInP layers, and the H_2 flow rates of Cp_2Mg were 6 sccm, 12 sccm, 24 sccm for the three 333 nm Mg-doped AlInP upper cladding layers in the sample A and 20 sccm, 40 sccm, 80 sccm in the sample B, respectively. To maintain the growth stability, the corresponding flow rates of Cp_2Mg were kept at 24 sccm and 80 sccm for the p-GaInP barrier reduction layers in the two samples.

3.2. Lattice mismatch of the LDs structure

Fig. 2 shows the rocking curves of sample A and sample B. The curve (1), curve (2), curve (3) in both figures correspond to the rocking curves tested before etching, after 20 s etching, and after 60 s etching using the bromine solution. For the both samples, the highest peak in the 66.05° is the diffraction peak of the GaAs substrate, and other peaks from left to right are deduced to be the

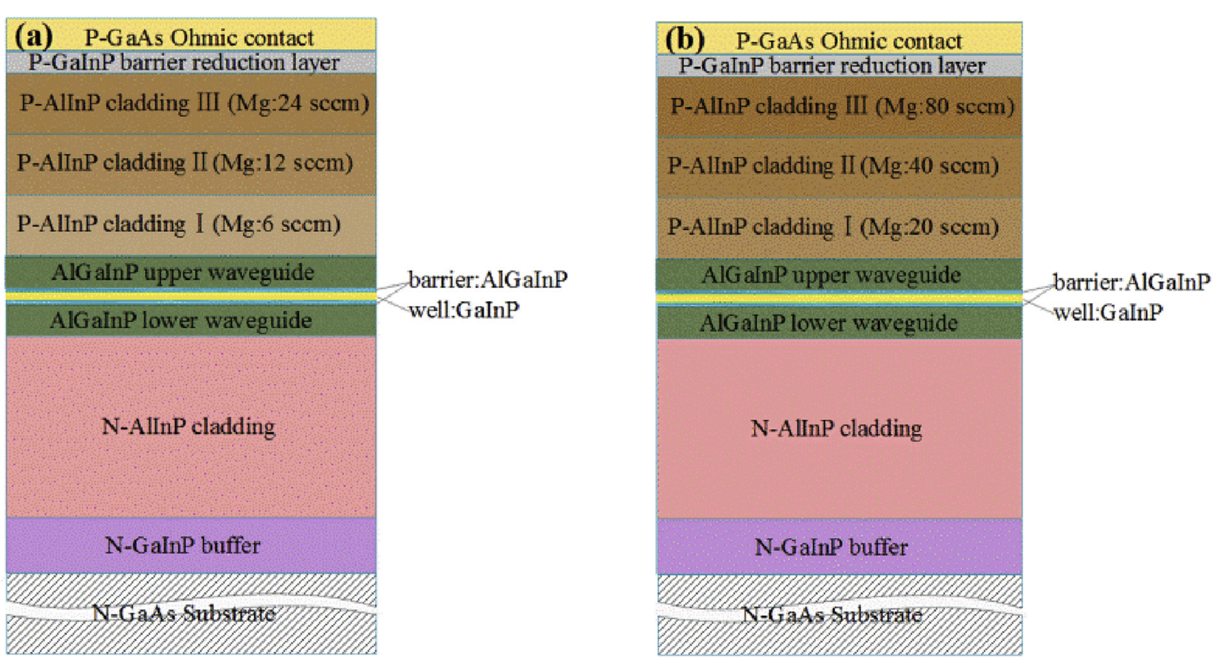

Fig. 1. Schematic structures of the LDs samples (a) sample A, (b) sample B.