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Effects of the substrate misorientation on the structural and optoelectronic characteristics of tensile GaInP quantum well laser diode wafer

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ABSTRACT

Three tensile GaInP quantum well laser diode wafers were grown in the same run by low-pressure metalorganic vapor phase epitaxy on GaAs substrates misoriented by 10°, 15°, and 22° toward (1 1 1)A respectively. The photoluminescence peak wavelength and intensity of the active region, the strain mismatch and the doping carrier concentration of the epitaxial layers, the whole thickness and the surface morphology of the wafers were all found to be strongly dependent on the misorientation of the substrates. Considering the comprehensive effects of material, electrical, and optical properties, the 15° substrate was superior to the 10° substrate for the growth of shorter wavelength red-light laser diode wafer, while substrate with too large misorientation of 22° was not a good choice for the epitaxy of red-light laser diode wafer.

1. Introduction

Red-light laser diodes (LDs) with output wavelengths from 650 nm to 670 nm based on (Al)GaInP material had been a well-established technology in the 2000s, because such LDs had expanded their markets in the digital versatile disks for optical data storage and laser printing industries [1,2]. Unfortunately, the market had shrunk because of the spread of alternative data storage technology such as huge data centers and high speed internet connection especially as wireless fidelity [3]. In recent years, a very compact laser module with a red, a green, and a blue laser diode has 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. This new type display technique has the merits of wide color expression range, high luminance, low power consumption, small and light equipment, and highly reliable operation [4]. As for the laser-based displays applications, red-light LDs operating in range of from 630 nm to 640 nm are required to achieve a trade-off between highly reliable operation of the LDs and large spectral luminous efficiency to the human eyes. However, it has been a very challenging work to achieve a good performance for these devices because of both the large carrier leakage due to small conduction band offset between GaInP and AlGaInP and the significant thermal saturation due to lower thermal conductivity of AlGaInP material system [5].

Optoelectronic characteristics of the red-light LDs chips are very important to achieve long lifetime applications under high brightness and high efficiency operation for the final device, and they can be improved by using tensile GaInP quantum wells and AlInP cladding layers. Therefore, assessment and optimization of the grown materials is crucial to the production of high efficiency optical devices. It had been shown that the misorientation toward (1 1 1)A of (0 0 1) GaAs substrate is a very important element in altering the morphology, optical, and electrical properties of (AlGa) InP ternary or quaternary alloy [6–11]. However, few reports focused on the relationship between substrate misorientation and the whole red-light LDs wafers. In this study we seek to investigate the effects of substrate misorientation on the photoluminescence properties, strain mismatch, doping concentration, layer thickness

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and surface morphology of the tensile GaInP quantum well LDs wafers. Through a series of experiments, we present the factors affecting the structural and optoelectronic characteristics of the short wavelength red-light laser diode wafer based on the tensile GaInP quantum wells.

2. Experiment

The designed LDs structure contains the following layers: a silicon doped n-GaInP buffer layer, a silicon doped n-AlInP lower cladding layer, an un-doped AlGaInP lower waveguide layer, an active region with single-quantum-well structure [barrier: AlGaInP layer, well: tensile strain GaInP layer], an un-doped AlGaInP upper waveguide layer, a zinc doped upper p-AlInP cladding layer, a zinc doped p-GaInP barrier reduction layer, and a highly zinc doped p^+-GaAs Ohmic contact layer. In the design, AlInP cladding layers were employed to obtain superior temperature characteristics and high output power for the reasons of large conduction band offset and low refractive index.

Epitaxial growth was carried out in an AIXTRON AIX200 low pressure metalorganic vapor phase epitaxy (MOVPE) system which contained a horizontal multi-wafer reactor. Three LD wafers were grown in the same run on three different Si-doped (0 0 1) GaAs substrates with misorientation of 10°, 15° and 22° towards (1 1 1)A respectively. For brevity, three LD wafers grown on the different misorientated substrates were referred to as 10°, 15° and 22° sample respectively in the next discussions. During the epitaxy, the growth temperature was controlled at 650–725 °C and the growth pressure was set as 10000 Pa. The source precursors were trimethylgallium (TMGa), trimethylindium (TMIn), trimethylaluminium (TMAl), 100% arsine (AsH_3) and 100% phosphine (PH_3). The doping sources were diethylzinc (DEZn) for p-type doping and 2% silane (SiH_4) in hydrogen for n-type doping.

The room-temperature photoluminescence (PL) spectrum of all the samples were investigated by Nano Metrics RPM2000 with a 532 nm laser excitation. The X-ray rocking curves were determined by Philips X'pert PRO high resolution double-crystal X-ray diffraction. The ionized carrier concentrations were measured by WEP CVP21 electrochemical capacitance-voltage (ECV) profiler. The cross-section images were observed by Nikon JCM-5000 scanning electron microscope (SEM). The surface texture parameters were tested by Zygo New view 7100 metrology system.

3. Results and discussion

To obtain optical properties for the active regions in the three LDs wafers, p^+-GaAs Ohmic contact layer and p-GaInP potential barrier layer were removed through wet etching before PL tests. Fig. 1 shows the room temperature PL spectra of the 10°, 15° and 22° samples. Although the three samples were grown under the same condition, there are quite distinct differences in their peak wavelength, intensity, and full width at a half maximum (FWHM). As shown in the figure, the LDs wafer grown on 10° substrate has the strongest intensity and the narrowest FWHM among the three samples, and the LDs wafer grown on 15° substrate has moderate intensity and FWHM. However, the 22° sample has much weaker intensity than the other two in the spectra curves. The peak wavelength for the 10° and 15° samples are 633.5 nm and 628.2 nm respectively. While for the 22° sample, the irregular spectra peak can be resolved as two peaks, and the fitted peaks are shown in the enlarged inset of Fig. 1. The fit curve 1 has a peak wavelength of 630.1 nm which came from the active region, and the fit curve 2 has a strong peak at 644.3 nm which came from the GaInP buffer layer. As photoluminescence emitting from the active region was so strong that the PL peaks coming from the GaInP buffer layers were

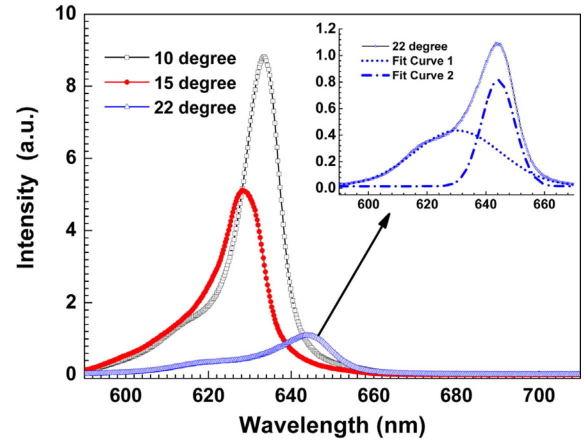

Fig. 1. Room temperature PL spectra of the 10°, 15° and 22° samples.

masked for the 10° and 15° samples. However, the PL peaks coming from the GaInP buffer layers for the two samples could be observed clearly after we had wet-etched their active regions layers. The differences in main peaks appearance and symmetry among the three samples were thought to be the influences of transformations between the electron-heavy hole (1e-1hh) recombination and electron-light hole (1e-1lh) recombination in the quantum wells under different lattice mismatch strains.

In the previous investigation of other reports, the increase in GaInP band-gap with increasing misorientation angle was thought to be caused by a decreasing tendency for the material to order on the group III sub-lattice [12]. This interpretation conformed to the PL results of 10° and 15° samples performed in our study. However, the 22° sample had PL abnormality of substantial weakening in the relative intensity and a little bit increasing in the peak wavelength, which showed that there were some uncertain mechanisms in the large misorientation angle sample besides the material order transition. As the photoluminescence spectra emitting from the GaInP/AlGaInP active region, the PL peak wavelength may be affected by the GaInP quantum wells thickness, composition and material order, and the PL intensity may be affected by the non-radiative recombination in the active region and the light transmission among the laser structure. G. Jones et al. had indicated that the ordering degrees of $(Al_xGa_{1-x})_{0.51}In_{0.49}P$ alloy had not changed significantly between 10° misorientations substrate and 15° substrate [12], so the red-shift in the peak wavelength of the 22° sample in our study was thought to be due to the increasing growth rate of the GaInP wells. While, the substantial weakening in the PL intensity was thought to be due to lattice defects in the GaInP wells grown on the 22° substrate for that there were no differences in the laser structures and the non-radiative deep level centers of oxygen in the material.

Fig. 2 shows the rocking curves of the 10°, 15° and 22° samples. Because of the thin thickness in the tensile GaInP quantum wells, the diffraction peaks in the curves are the information of the other thick layers in the LDs structure. The highest peak in the rocking curves is the diffraction peak of the misorientation GaAs substrate, and other peaks from left to right are deduced to be the diffraction peaks of the n-AlInP upper cladding layer, p-AlInP lower cladding layer, AlGaInP waveguides layers, and n-GaInP buffer layer respectively. Although investigations on the photoluminescence characteristics and material order in the AlGaInP alloy had been conducted in the past years, effort in analyzing lattice constant shift induced by the misorientation of GaAs substrate was lacking. Previous work showed the lattice mismatch to be similar for different