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Textured zinc oxide prepared by liquid phase deposition (LPD) method and its application in improvement of extraction efficiency for 650 nm resonant-cavity light-emitting diode (RCLED)

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ABSTRACT

In this article, we report on the textured zinc oxide (ZnO) prepared by liquid-phase deposition (LPD) method and apply it as a window layer of 650 nm resonant-cavity light-emitting diode to enhance the extraction efficiency. The treatment solution for LPD ZnO (LPD-ZnO) growth consists of ZnO powder saturated with hydrochloric acid (HCl) and hydrogen peroxide (H_2O_2). Temperature-controlled water bath system was used to maintain a constant temperature of 40 °C in LPD system. The experimental results indicate that the deposition rate was determined by the concentration of H_2O_2 and growth temperature, and the average roughness of LPD-ZnO is dominated by the concentrations of HCl. In order to perform the practicability of LPD-ZnO, the textured LPD-ZnO is used as a window layer of 650 nm AlGaInP/GaInP resonant-cavity light-emitting diode (RCLED) to enhance the light output power. In addition, the calculated results indicate that the optimum roughness for enhancing the light output power of RCLED is in the range of 80–100 nm, which are close to the experimental results. As compared to the conventional RCLED, the RCLED with textured LPD-ZnO, which has the optimum average roughness of 82 nm, performs a high light output power, a high external quantum efficiency, a narrow linewidth of electroluminescence spectrum and the same far-field angle.

1. Introduction

In the past decade, zinc oxide (ZnO) semiconductor materials with the high direct band-gap (~3.37 eV) and high exciton binding energy (~60 meV) have been attracted much attention in the applications for the functional window materials in laser diodes (LDs), light-emitting diodes (LEDs) and solar cell [1–3]. Several techniques such as chemical vapor deposition (CVD) [4,5], pulsed-laser deposition (PLD) [6], molecular-beam epitaxy (MBE) [7], sputtering [8], and hydrothermal method [9] were used for growth of ZnO film. Among them, CVD, especially metal-organic chemical vapor deposition (MOCVD), are the most popular technique to grow ZnO film due to that it directly creates a textured surface with strongly light scattering capacity. However, the substrate temperature should be heated above 200 °C to obtain a high-quality ZnO film by CVD techniques. Recently, liquid-phase deposition (LPD) method was reported to grow SiO_2 on Si substrate under a low growth temperature [10]. LPD technology takes advantages such as low growth temperature, low cost, large area growth, good step coverage, and simple deposition instrument.

In this article, we have grown ZnO textured film on GaAs substrate under the temperature about 40 °C by LPD method. The experimental results represents that the average roughness of LPD-ZnO films can be modulated by the concentration of hydrochloric acid (HCl) and the deposition rate of LPD-ZnO films can be controlled by the concentration of hydrogen peroxide (H_2O_2).

Recently, light sources in the telecommunication systems, such as fiber-to the home (FTTH) and low-cost parallel interconnects, are required of low cost, high-temperature sensitivity, high reliable and eye safe components. For these demands, high external efficiency, low temperature sensitivity, and low cost light emitting diodes (LEDs) are needed [11]. In 1946, Purcell [12] suggested that the spontaneous emission of a radiating system can be replaced by a so-called microcavity which has the dimension on the order of the emitted light wavelength. The microcavity can provide a redistribution of emitting light through the enhancement or inhibition of spontaneous emission, depending on the position of the emission dipole with respect to the cavity-standing wave pattern. LEDs with the microcavity can be named microcavity light-emitting diodes (MCLEDs) or resonant-cavity light-emitting diodes (RCLEDs). They consisted of three parts, including a multiple-quantum-well active region, a microcavity, and two parallel mirrors surrounding the cavity. Due to the coupling of the quantum wells with Fabry–Perot cavity mode, the emitting wavelength of RCLEDs can be selected.

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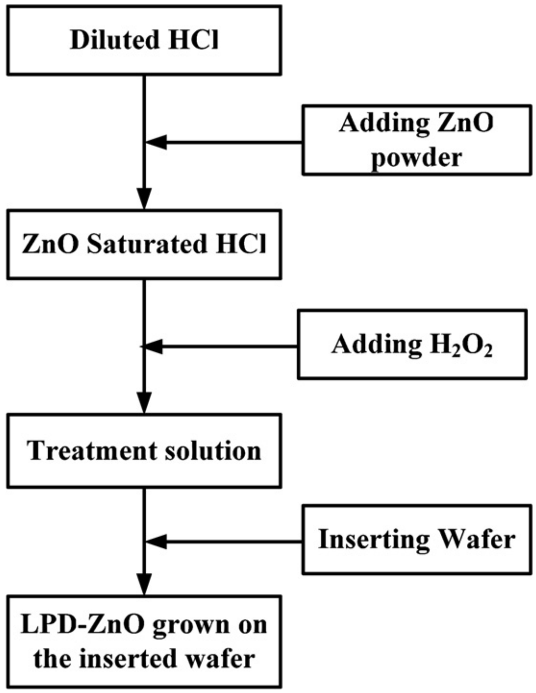

Fig. 1. Schematic flow chart for LPD-ZnO.

Recently, the 650 nm RCLEDs with a high output power and a narrow line width, which have low attenuations of 0.13–0.18 dB/m [13,14] in red-wavelength region, can be applied to optical communication system, such as FireWire or i. Link (IEEE 1394b) in polymethyl-methacrylate (PMMA) plastic optical fiber (POF). Royo et al. [15] presented the analytical and numerical calculation of the extraction efficiency for RCLEDs by the first derivative of the distributed Bragg reflectors (DBRs) phase with respective to the angle and energy at the Bragg condition, and by approximations of the amplitude and phase of the complex reflection coefficients through a constant and first-order Taylor development. Due to a redirection of the Airy mode inside the escape window, the RCLEDs have higher extraction efficiency than the conventional LEDs. Streubel et al. [16] indicated that RCLEDs have an extraction efficiency of one order in magnitude stronger than the conventional planar LEDs, and this result has been proven in many literatures [17–19]. In order to perform the practicability of LPD-ZnO, the textured LPD-ZnO film was applied to AlGaInP/GaInP resonant cavity light emitting diodes (RCLEDs) to meliorate the extraction efficiency. The random texturing improves light extraction via efficient surface randomization where photons emitted out of an escape cone have increased [20]. According to the calculated results, the optimum average roughness of textured LPD-ZnO for enhancing light output power of 650 nm RCLED is around 82 nm. As compared to that of RCLED without LPD-ZnO textured window layer, RCLED with LPD-ZnO textured window layer showed an improvement of 26% and a decrease of 13.5% in light output power and FWHM of emission spectra, respectively.

2. Experimental details

The schematic flow chart of ZnO film prepared by LPD method is shown in Fig. 1. The treatment solution to grow textured LPD-ZnO film was prepared by the following steps. First, 50 ml HCl (12 M, Taimax) was diluted with deionized (DI) water to 1.72 M, 2.01 M, 2.412 M, and 3.015 M, respectively. Second, the diluted HCl solution was stirred with the ZnO powder (J. T. Baker) for 1 h at 25 °C to ensure that HCl is saturated with ZnO powder. Third, the undissolved ZnO powder was removed by the filtration. Finally, the 1 ml H_2O_2 (Taimax) solution with the different concentrations including 1.02 M, 1.13 M, 1.27 M, 1.7 M, 2.55 M, and 5 M, was added to the ZnO-saturated HCl solution to form the treatment solutions. The LPD-ZnO deposition system contains a Teflon vessel immersed in a temperature-controlled water bath system, which can offer a uniform temperature distribution by the cyclic water with the accuracy of 0.1 °C. In LPD-ZnO growth process, the Teflon vessel contained treatment solution should immerse in the temperature-controlled water bath system for 3–5 min at the setting growth temperature. This preheated step can guarantee the uniformity of the roughness of the ZnO film grown on the inserted substrate. Then, the (1 0 0)-oriented GaAs substrate with doping Si concentration of 1×10^{18} cm^{-3} was inserted in the treatment solution for LPD-ZnO growth.

The device structure of the 650 nm AlGaInP/GaInP RCLED consists of (i) a 0.5 μm n-GaAs buffer layer, (ii) 32-pair Si-doping AlGaAs/AlAs n-type DBR layers, (iii) a 32.8 nm n-type doping $(AlGa)_{0.7}In_{0.3}P$ waveguide layer, (iv) a 41.8 nm undoped $(AlGa)_{0.5}In_{0.5}P$ layer, (v) an active region composed of three 8 nm undoped GaInP wells separated by two 11 nm undoped $(AlGa)_{0.5}In_{0.5}P$ quantum barriers, (vi) a 41.8 nm undoped $(AlGa)_{0.5}In_{0.5}P$ layer, (vii) a 32.8 nm p-type doping $(AlGa)_{0.7}In_{0.3}P$ waveguide layer, (viii) 8-pair C-doping AlAs/AlGaAs p-type DBR layers, and (ix) a 0.01 μm p^+-GaAs ohmic layer. The uniformity of the epitaxial wafer is in term of photoluminescence (PL) intensity and FWHM, and the thickness is controlled within 5% across the 3-inch-in-diameter epitaxial wafer. The contact metal for device was composed of Ti/Pt/Au.

The thickness of LPD-ZnO film was measured by the field-emission scanning-electron microscope (FE-SEM) and the average roughness of LPD-ZnO film was analyzed by atomic force microscope (AFM) (D13100, Digital instruments Veeco Metrology Group). The typical light output power-current-voltage (*L*–*I*–*V*) measurements were performed by using a current measured unit and a calibrated power meter (Keithley 2520). The emission spectra were detected by Optical Spectrum Analyzer (ADCMT 8341). The far-field angle was found by profile meter (HIGHER WAY).

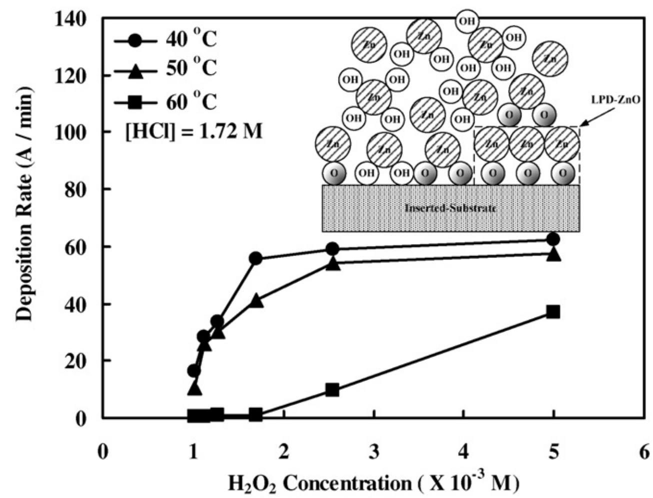

Fig. 2. The growth rate of LPD-ZnO as a function of H_2O_2 concentration at deposition temperature of 40, 50, and 60 °C. The inset represents the growth mechanism.

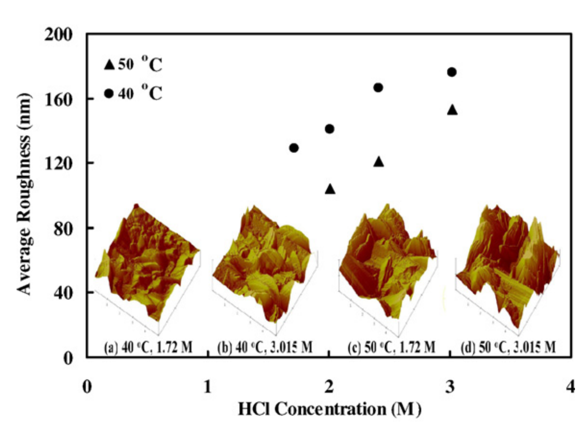

Fig. 3. The average roughness of LPD-ZnO as a function of HCl concentration at deposition temperature of 40 and 50 °C. The inset shows the AFM microscope.