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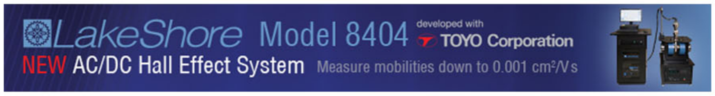

The fabrication of single heterojunction AlGaAs/InGaP electroluminescent diodes

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High quality $GaAs/Al_xGa_{1-x}As/In_{0.5}Ga_{0.5}P$ single heterostructure electroluminescent devices have been fabricated by liquid-phase epitaxy. Three different compositions ($x = 0.45$, 0.58, and 0.85) of $Al_xGa_{1-x}As$ layers were made to compare their properties. Diodes fabricated from these heterostructures have been characterized by electron beam induced current, electroluminescence, quantum efficiency, output power, and current-voltage measurements. Emission peak wavelengths and full width at half maximum values of the light emitting diodes are, respectively, 652.5, 654.4, and 652.8 nm, and 67, 67, and 75 meV. The peak wavelengths of the light emitting diode shift 6 meV towards the lower-energy side compared to the photoluminescent peak wavelength of the same electron concentration in the Te-doped $In_{0.5}Ga_{0.5}P$ layer. For most light emitting diodes, output powers and efficiency are in the range of 50–100 μW and 0.062%–0.1%, respectively.

I. INTRODUCTION

Visible electroluminescence is of great importance because of the numerous potential applications in information linkage between electronic instruments and their human users. Light emitting diodes (LEDs) are now present in a wide variety of instruments of everyday use. This interest in LEDs for these and other new applications is due to their brightness, low price, reliability, and compatibility with integrated circuit technology.

Increasing interest has been shown in recent years in the indium gallium phosphide ($In_{1-x}Ga_xP$) alloy system, because it offers the possibility of direct recombination luminescence up to photon energies of approximately 2.2 eV at 300 K.[1,2] It is one of the most promising materials for the preparation of luminescence and laser diodes throughout the near infrared and visible spectrum almost to the green. Recently, optical plastic fiber has been used, which is inexpensive and easy to handle is convenient for short distance, small capacity communication, and has minimum optical loss at 570 and 650 nm.[3] In this respect, it offers considerable advantages compared with the more commonly used $Al_xGa_{1-x}As$ and $GaAs_yP_{1-y}$ alloy systems. However, its progress has been hampered by the difficulty of the preparation.

Injection electroluminescence of $In_{0.5}Ga_{0.5}P$ *p-n* junctions has been reported.[4,5] In order to achieve efficient electroluminescence (EL) and laser emission, it seems desirable to use the principle of close confinement structures, which is well known from the fabrication of $Al_xGa_{1-x}As$ diodes and has proven to be highly successful. For this purpose it is necessary to grow a material onto it with an energy gap larger than the energy gap of $In_{0.5}Ga_{0.5}P$.

This paper reports the growth of high-quality $GaAs/A_xGa_{1-x}As/In_{0.5}Ga_{0.5}P$ single heterostructures (SH) by liquid-phase epitaxy (LPE). In this case $Al_xGa_{1-x}As$ with energy gap (E_g) larger than 1.90 eV is used as a window layer or confinement layer, and the $In_{0.5}Ga_{0.5}P$ layer is used as an emission layer. The $Al_xGa_{1-x}As/In_{0.5}Ga_{0.5}P$ SH *p-n* diodes have been characterized by electron beam induced current (EBIC), EL, quantum efficiency, output power, and current-voltage (*I-V*) measurements.

II. EXPERIMENT

The $Al_xGa_{1-x}As/In_{0.5}Ga_{0.5}P$ multilayers were grown on (100) Si-doped GaAs substrates by the conventional LPE techniques. The SH wafers as shown in Fig. 1 consist of a Te-doped *n*-type $In_{0.5}Ga_{0.5}P$ emission layer ($n \sim 8.5\text{–}16 \times 10^{17}$ cm^{-3}, $d \sim 5$ μm) and an Mg-doped *p*-type $Al_xGa_{1-x}As$ confinement layer ($p \sim 3\text{–}4 \times 10^{18}$ cm^{-3}, $d \sim 4.5$ μm). Magnesium was used as *p*-type dopant in $Al_xGa_{1-x}As$ due to the lower values of activation energy in Al-rich composition. In this study, *p*-type $Al_xGa_{1-x}As$ confinement layers with three different AlAs solid compositions were fabricated onto the single heterojunctions, namely, $p\text{-}Al_{0.45}\text{-}Ga_{0.55}As/n\text{-}In_{0.5}Ga_{0.5}P$ (labeled LED 1); $p\text{-}Al_{0.58}Ga_{0.42}As/n\text{-}In_{0.5}Ga_{0.5}P$ (labeled LED 2); and $p\text{-}GaAs/p\text{-}Al_{0.85}Ga_{0.15}As/n\text{-}In_{0.5}Ga_{0.5}P$ (labeled LED 3). For the structure LED 3, the heavily doped *p*-GaAs layer

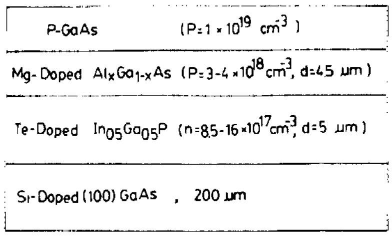

FIG. 1. Schematic structure of $Al_xGa_{1-x}As/In_{0.5}Ga_{0.5}P$ SH EL device.

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($p \sim 1 \times 10^{19}$ cm^{-3}) is used as the cap layer to facilitate ohmic contact. The $In_{0.5}Ga_{0.5}P$ layer was grown at 785 °C with a 12 °C supersaturation temperature for 30 min at a cooling rate of 0.2 °C/min. The $Al_xGa_{1-x}As$ layer was grown at 778 °C with a 6 °C supersaturation temperature for 20 min at the same cooling rate. Details of the growth conditions were given in the previous papers.[7-10]

III. DEVICE FABRICATION

After the growth process, the substrate side of wafer was lapped to a thickness of about 200 μm in order to reduce bulk resistance and the contamination from evaporated phosphorus during growth. The wafer was then etched in $5H_2SO_4:1H_2O_2:1H_2O$ solution at 50 °C for 20 s to remove surface oxide. Metal contacts were then thermal evaporated through a metal mask. The p- contact consisted of 1 wt. % Be in Au alloy. The n-contact was made to the GaAs by evaporating a 1500-Å layer of 12 wt. % Ge in Au alloy onto it and then Au plating. After deposition, the samples were alloyed at 450 °C for 5 min in a nitrogen ambient to obtain good ohmic contacts. The wafers were then sawed into 300×300 μm^2 LED dices. The final LED products were completed through dice attachment, Au wire bonding, and epoxy encapsulation.

IV. CHARACTERISTICS OF LEDs

During growth, if a small amount of In metal left over from the former In-rich InGaP source melt mixed with the latter Ga-rich AlGaAs source melt occurs, compositions of InGaP and AlGaAs growth layers will be more influenced so that the uniform crystal growth is obstructed.[11] The anomalous growth has sometimes occurred, as seen in the scanning electron microscope (SEM) image of a cleaved cross section of a DH wafer shown in Fig. 2(a). However, a flat heteroboundary between the InGaP layer and AlGaAs layer with only a few inclusionlike defects is obtained in the wafer as shown in Figs. 2(b) and 2(c), which means the melt mixing is minimal.

In a multilayer junction device structure, the electrical junction location has to be controlled precisely in order to achieve efficient electrical carrier confinement. On the other hand, a misplaced junction will deteriorate all the confinement advantages afforded by the heterobarrier. EBIC technique is employed to locate the p-n junction position. It shows that, as seen in Fig. 3(a), the AlGaAs/InGaP p-n junction is located at the heterojunction. However, the EBIC

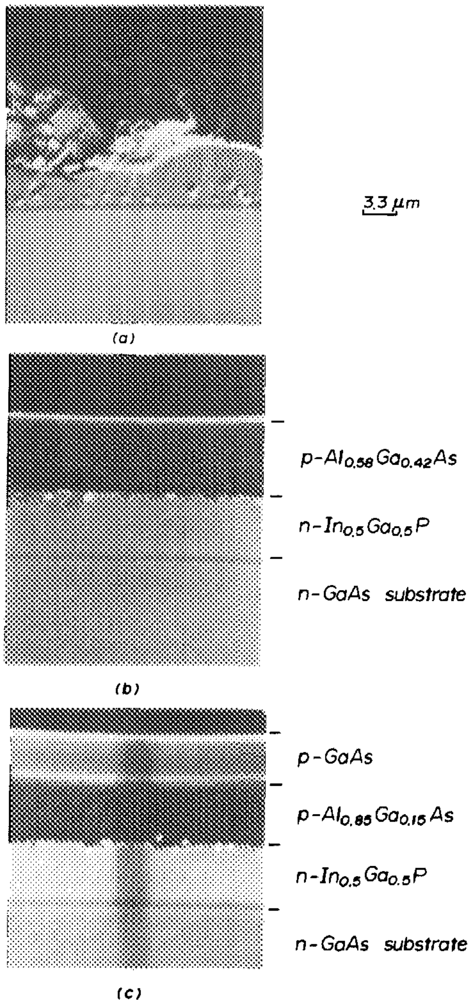

FIG. 2. The cleaved SEM photographs of (a) anomalous growth, (b) p-$Al_{0.58}Ga_{0.42}As$/n-$In_{0.5}Ga_{0.5}P$ (LED 2), and (c) p-GaAs/p-$Al_{0.85}Ga_{0.15}As$/n-$In_{0.5}Ga_{0.5}P$ (LED 3).

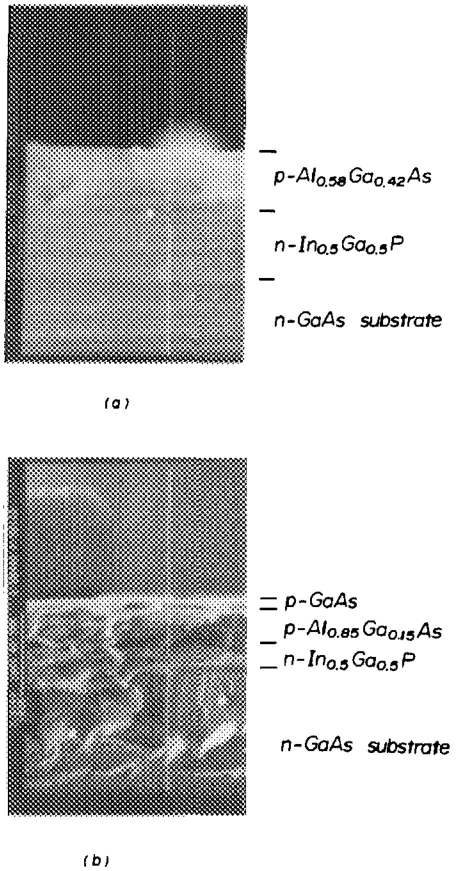

FIG. 3. Cleaved cross-section SEM photographs of the heterostructures (a) $Al_{0.58}Ga_{0.42}As/In_{0.5}Ga_{0.5}P$ and (b) $GaAs/Al_{0.85}Ga_{0.15}As/In_{0.5}Ga_{0.5}P$ superimposed a trace of the EBIC signals.

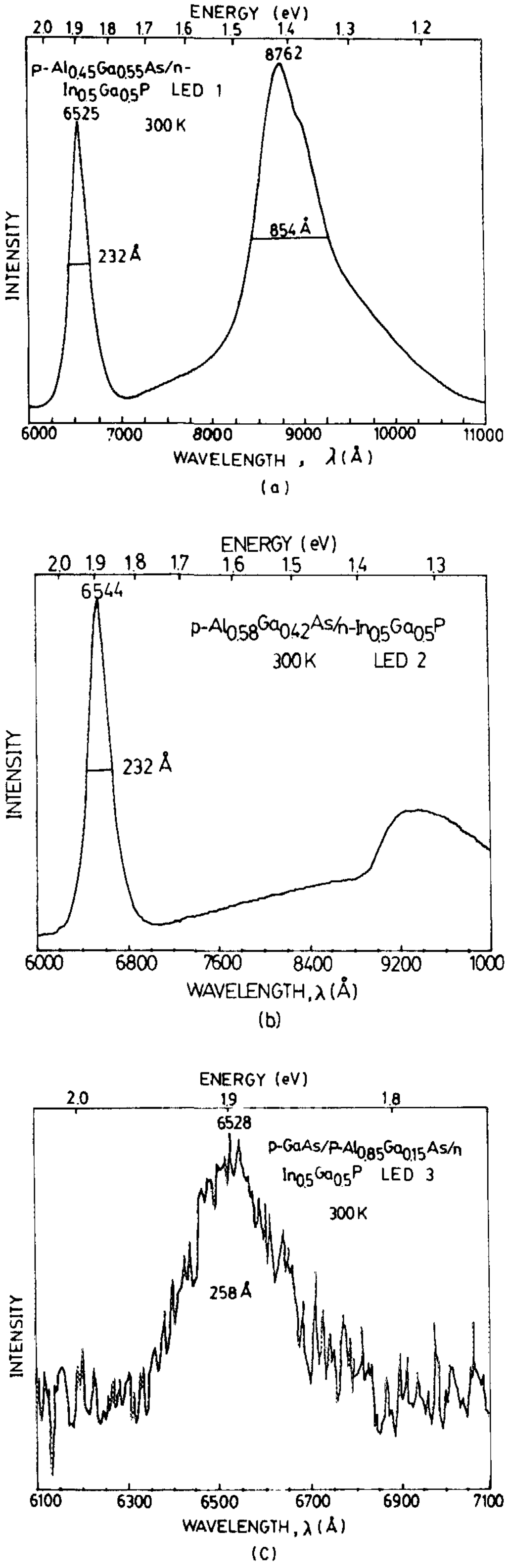

FIG. 4. 300-K EL emission spectra at 10 mA of (a) LED 1, (b) LED 2, and (c) LED 3.

signal of Fig. 3(b) shows, from the location of the peak, that the junction is displaced from the metallurgical heterojunction and is within the $In_{0.5}Ga_{0.5}P$ layer by 1.6 μm. The problem of the misplaced junction has been attributed to the higher Mg-doped concentration. To control the exact junction, the amount of Mg in the p-type solution has to be carefully controlled to a minimum value necessary to achieve the desired conductivity of the p-type layer. Since the diffusion coefficient of Mg is so small ($\sim 10^{-13}$ cm^2/s at 900 °C in GaAs), accurate controls of p-n heterojunction are easily achieved. However, Mg has a high segregation coefficient in $Al_xGa_{1-x}As$ (~ 0.6 with $x \geqslant 0.1$), only a small amount of Mg is necessary to obtain a p-type carrier concentration in the grown layer of greater than 5×10^{17} cm^{-3}. If all of these steps are taken to ensure the correct location of the p-n junction, better EL devices can be obtained.

Figures 4(a)–4(c) show the room temperature EL emission spectra at 10 mA of LED 1, LED 2, and LED 3. The emission intensities of LED 1 and LED 2 are almost equal and are about 50 times larger than that of LED 3 which has the misplaced junction. Emission peak wavelengths and full width at half maximum (FWHM) values of the LEDs are, respectively, 652.5, 654.4, and 652.8 nm, and 67, 67, and 75 meV. The peak wavelengths of the LEDs shift 6 meV towards the lower-energy side compared to the photoluminescence (PL) peak wavelength of the same electron concentration in the n-type Te-doped $In_{0.5}Ga_{0.5}P$ layers.[8] The difference in peak wavelength shift is considered to be the temperature change at the p-n junction. Beneking *et al.*[12] reported the results of FWHM of 81 meV (30 nm) and peak wavelength of 680 nm in 300-K EL spectra of the GaAs-$Al_{0.68}Ga_{0.32}As$-$In_{0.5}Ga_{0.5}P$ heterostructure EL diodes.

The EL emission spectra of LED 3 at 300 K as a function of current at 10 and 20 mA are shown in Fig. 5. It is seen that the peak wavelength shifts from 652.8 nm at 10 mA to 655.2 nm at 20 mA and is also due to the temperature increase at the p-n junction at 20 mA. The emission intensity at 20 mA is 4 times stronger than that at 10 mA and the FWHM value decreases to 67 meV. For LED 1 and LED 2,

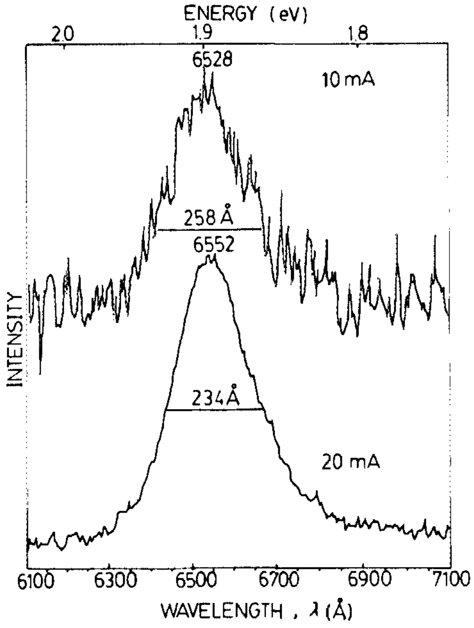

FIG. 5. 300-K EL emission spectra of LED 3 as a function of current at 10 and 20 mA.

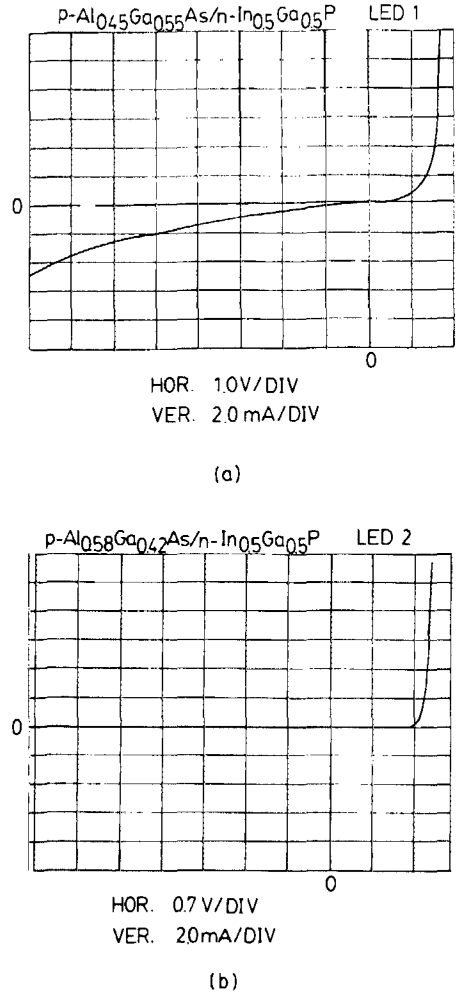

FIG. 6. Current-voltage characteristics of heterostructure *p-n* diodes with (a) $Al_{0.45}Ga_{0.55}As/In_{0.5}Ga_{0.5}P$ and (b) $Al_{0.58}Ga_{0.42}As/In_{0.5}Ga_{0.5}P$.

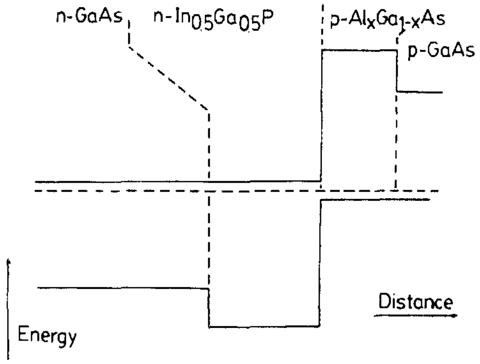

FIG. 7. Energy-band diagram of heterostructure *p-n* diode.

the light output power and quantum efficiency defined as the ratio of output photocurrent collected by photodetector to the applied current are all the same and are 50–100 μW and 0.062%–0.1%, respectively. A lower light output power of 5–20 μW and quantum efficiency of 0.005%–0.05% is obtained in LED 3 at 20 mA.

The *I-V* characteristics of LED 1 and LED 2 are shown in Figs. 6(a) and 6(b), respectively. It is seen that both the LEDs have a forward turn-on voltage of 1.4 V. In the reverse direction, the soft breakdown occurs in LED 1 and the sharp breakdown occurs at 6 V in LED 2. The lower breakdown voltage may be due to higher *n*- and *p*-type carrier concentration in our study. Figure 7 shows the energy-band diagram of the obtained structures.

V. CONCLUSION

We have demonstrated the feasibility of growing $Al_xGa_{1-x}As/In_{0.5}Ga_{0.5}P$ single heterojunction structures of good crystalline quality with *p-n* junctions generated by doping magnesium and tellurium, respectively. Diodes fabricated from these heterostructures have been characterized by EBIC, EL, quantum efficiency, output power, and *I-V*. So far, the performances of these LEDs are still not very good, but if the thickness and amount of Mg in the *p*-type layer can be appropriately adjusted or double-heterojunction (DH) AlGaAs/InGaP/AlGaAs can be made, then the efficiency, output power, and EL spectra can be improved.

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