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Characteristic improvements of thin film AlGaInP red light emitting diodes on a metallic substrate*

Bin Zhao(赵斌)[1,2], Wei Hu(胡巍)[1,2], Xian-Sheng Tang(唐先胜)[1,2], Wen-Xue Huo(霍雯雪)[1,2], Li-Li Han(韩丽丽)[1,2], Ming-Long Zhao(赵明龙)[1,2], Zi-Guang Ma(马紫光)[1], Wen-Xin Wang(王文新)[1], Hai-Qiang Jia(贾海强)[1], and Hong Chen(陈弘)[1,†]

[1] *Key Laboratory for Renewable Energy, Beijing Key Laboratory for New Energy Materials and Devices, Beijing National Laboratory for Condensed Matter Physics, Institute of Physics, Chinese Academy of Sciences, Beijing* 100190, *China*

[2] *University of Chinese Academy of Sciences, Beijing* 100049, *China*

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We report a type of thin film AlGaInP red light emitting diode (RLED) on a metallic substrate by electroplating copper (Cu) to eliminate the absorption of GaAs grown substrate. The fabrication of the thin film RLED is presented in detail. Almost no degradations of epilayers properties are observed after this substrate transferred process. Photoluminescence and electroluminescence are measured to investigate the luminous characteristics. The thin film RLED shows a significant enhancement of light output power (LOP) by improving the injection efficiency and light extraction efficiency compared with the reference RLED on the GaAs parent substrate. The LOPs are specifically enhanced by 73.5% and 142% at typical injections of 2 A/cm^2 and 35 A/cm^2 respectively from electroluminescence. Moreover, reduced forward voltages, stable peak wavelengths and full widths at half maximum are obtained with the injected current increasing. These characteristic improvements are due to the Cu substrate with great current spreading and the back reflection by bottom electrodes. The substrate transferred technology based on electroplating provides an optional way to prepare high-performance optoelectronic devices, especially for thin film types.

Keywords: light emitting diodes, thin film, electroplating, substrate transferred process

PACS: 78.60.Fi, 73.21.Ac, 73.40.Kp, 78.55.Cr **DOI:** 10.1088/1674-1056/27/4/047803

1. Introduction

Quaternary $(Al_xGa_{1-x})_{0.5}In_{0.5}P$ alloys are widely used to fabricate red, orange and yellow light emitting diodes (LEDs) which have great applications in full-color displays, urban landscape illuminations, automotive lighting and signal indicator lights.[1–3] Compared with other materials such as AlGaAs or GaAsP,[4,5] the lattice-matched AlGaInP with multiple quantum wells (MQWs) structure grown on a GaAs substrate is one of the most competitive candidates to prepare red light emitting diodes (RLEDs) due to the advantages of high internal quantum efficiency (IQE), large injection and high temperature resistance.[6,7] However, the achievement in high light extraction efficiency (LEE) still has much room for improvement. A main reason is the serious light absorption by the GaAs substrate.[8] Moreover, the weak electrical conductivity and inferior thermal dissipation ability of the GaAs substrate expose huge restrictions on the high power and super brightness RLEDs.[9]

To improve the LEE of AlGaInP LED, several efficient methods of reducing the substrate absorption have been proposed.[10–20] A distributed Bragg reflector (DBR) structure of repeated periodically $(Al_xGa_{1-x})As/(Al_yGa_{1-y})As$ stacks[10,11] enhances the light output by back reflection, but the reflectivity is quite sensitive to the angle and wavelength of emission. The reformative DBR structure consisting of coupled DBR, tandem DBR or hybrid-type DBR[12–14] and the omnidirectional reflector (ODR) structure[15–17] can exhibit a broader reflective bandwidth and less dependence on the incident angle. Nonetheless, extremely precise and rigorous controlling and much more layers are inevitable for the reformative DBR structures, and the ODR fabrication is also so complicated that it includes additional photo-lithography, etching steps, and even bonding procedure for flip chips. Substrate transferred LEDs generally realized by bonding effectively raise the LEE by the back metal reflectance or the fabricated ODR structure,[16,18] and the LEE can be further enhanced through shaping the replaced transparent substrate.[19,20] However, bonding may result in a yield reduction due to the wafer bowing or residual particles under high pressure and high temperature conditions, also it is challenging to place the shaping chips into industrialization associated with the cost.

In this study, a type of thin film AlGaInP RLED on a metallic substrate prepared by electroplating Cu is fabricated to eliminate the light absorption by GaAs grown substrate.[21]

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†Corresponding author. E-mail: hchen@iphy.ac.cn

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The Cu substrate serves as an ideal carrier by tight adhersion and adjustable thickness. Like the substrate transferred RLEDs by bonding, the GaAs substrate is removed and the bottom electrodes reflect efficiently the emitted light.[22,23] As a result, the thin film AlGaInP RLED shows remarkable improvements in electrical and optical performance.

2. Experiment

In this work, AlGaInP RLED wafers were epitaxially grown on lattice matched GaAs (100) substrates with an electron concentration of 5×18 cm^{-3} in a metal–organic chemical vapor deposition (MOCVD) system. The epilayers were comprised of 15 pairs of $(Al_xGa_{1-x})_{0.5}In_{0.5}P/(Al_yGa_{1-y})_{0.5}In_{0.5}P$ MQWs with a total thickness of about 200 nm, following the growth sequence: a 400-nm etching stop layer (ESL), a 60-nm n-type GaAs ohmic contact layer with an electron concentration of 5×18 cm^{-3} and an 800-nm n-type InAlP cladding layer. Then a 1-μm p-type InAlP cladding layer and a 4-μm GaP window layer with a hole concentration of 6×18 cm^{-3} were grown on the MOWs. The schematic diagram of epilayer structure is shown in Fig. 1(a). Standard front surface processes compatible with conventional RLEDs were accomplished sequentially as shown in Fig. 1(b). First, Ti/Au top electrodes were deposited by electron beam evaporation (EBE) and lifted off by standard photolithographic processing, followed by a rapid thermal annealing (RTA) process at 400 °C in N_2 ambient to improve the p-type ohmic contact property. RLED mesas of 1 mm×1 mm were formed by chemical etching after overlay photolithography. Then we adhered the wafer onto an intermediate carrier temporarily with thermal releasing wax. The GaAs substrate was removed by selective chemical etching, which was terminated onto the InGaP ESL, followed by removing this ESL with solutions of hydrochloric acid (HCl). Next, Au/Ge/Ni/Au bottom electrodes were deposited by EBE without RTA processing, and subsequently the Cu substrate was electroplated with a direct current power supply driving. Finally, the thin film RLED wafer was cleaned after separating it from intermediate carrier by heating on a hotplate. The schematic diagram of the fabricated thin film RLED structure is shown in Fig. 1(c). For comparison, reference RLEDs were also prepared with the bottom electrodes deposited directly on the reverse side of the GaAs substrate. Other processes such as epilayer structure and front surface processes are all the same.

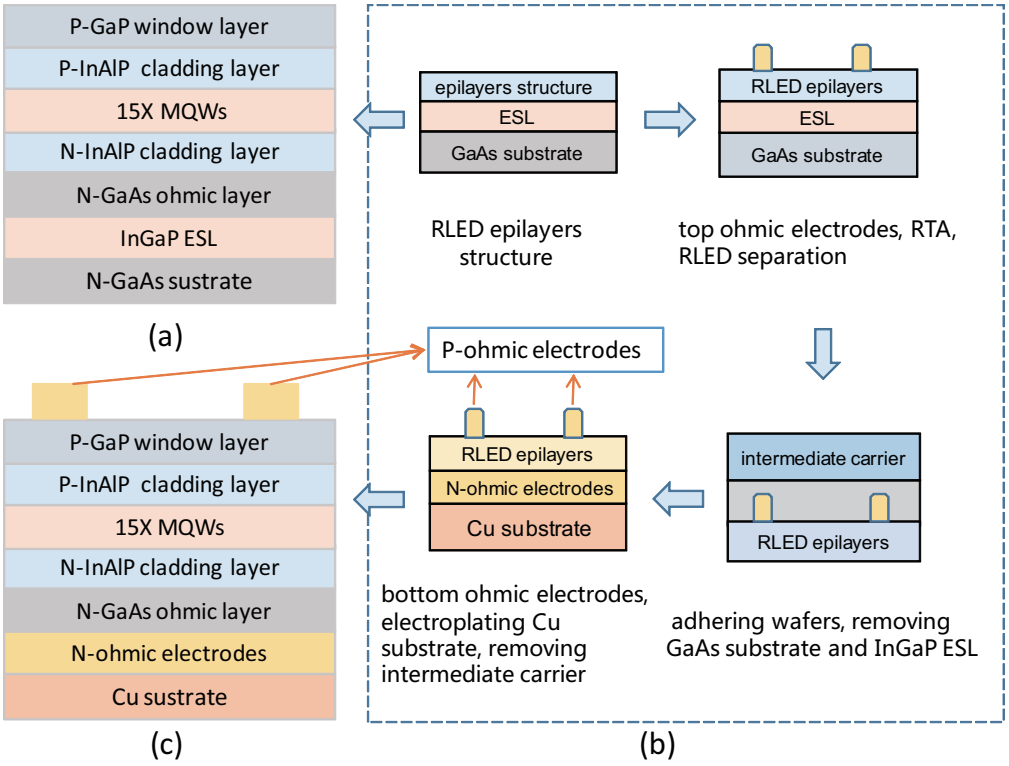


Fig. 1. (color online) (a) Schematic diagram of epilayer structure of RLED. (b) Schematic diagram of fabrication processes of thin film RLED. (c) Schematic diagram of thin film RLED.

The photoluminescence (PL) and electroluminescence (EL) were measured on both thin film RLED and reference RLED at room temperature. The PL measurement was conducted with a PL measurement system. A continuous 532-nm laser with an output power of 100 mW was used as an excitation light source. The PL signals were received by an integrated SpectraSence spectrometer and InGaAs detectors, then analyzed by a lock-in amplifier. The EL measurements were conducted with an LED comprehensive performance testing system providing pulsed direct current inputs and the lumines-

cence of RLEDs was detected by Si optical fiber detectors.

3. Results and discussion

To prepare carriers for thin film RLEDs, we adopt electroplating instead of commonly used bonding technology. Without high temperature and high pressure processing, electroplating can effectively avoid damaging the materials like bonding does. With merits of low cost, excellent thermal and electrical conductivity, Cu is one of the most favorable candidates to serve as a replacing substrate. The stress in thin film can be optimized by regulating the electroplating parameters comprehensively, such as thickness and area of Cu film, inputting current density, swing frequency of electroplated pieces, ratios of the additives, temperature and PH value of electroplating solution in our process. We find that the Cu film will bend more and more seriously with the stress accumulation. Accordingly, lowering the inputting current density to less than 20 mA/cm^2, raising the temperature of the electroplating solution to 60 °C and fastening the swing frequency of electroplated pieces are selective ways to release the stress in our electroplating technology. Besides, the additives efficiently improve the smoothness and brightness property of the Cu film. By virtue of excellent current spreading of bottom electrodes, electroplating provides a Cu film with great thickness uniformity and surface smoothness. Neither voids nor crevices appear at the interface between Cu carrier and bottom electrodes due to the electrochemical deposition.[24] As shown in Fig. 2(a), the thin film RLED wafer with an approximate 30-μm Cu substrate in natural state is almost flat, indicating that the Cu film imposes nearly little strain influence on the attached epilayers. The microscope photograph of a 2×2 thin film RLED array is shown in Fig. 2(b). Neither cracks nor other material damages are observed in the epilayers, and the one on the right bottom with an Si–Al bonded wire emits uniform red light on the whole surface at 2 A/cm^2, exhibiting an ideal current spreading through the 4-μm GaP window layer. Moreover, electroplating permits the thickness of Cu film to be adjusted optionally by controlling the time and rate of deposition. The thin film RLED shows great flexibility when Cu substrate with a thickness of dozens of micrometers is used. As indicated in Fig. 2(c), the thin film RLED wafer with a 30-μm Cu substrate is easily forced into convex bending under external force.[25] The strain of a thin film can be characterized by the bending angle. The schematic diagram of bending the thin film RLED wafer over a mandrel resulting in an average central angle of θ for a square RLED, is presented in Fig. 2(d). Of course, the thin film RLEDs can also be bent into a concave state, which in not shown here. We have done the deformation experiments for dozens of recycles, and the thin film wafer turned back to the original state immediately as the external force was withdrawn, and there are few cracks generated in the epilayers and negligible performance degradations are observed. It indicates that the thin film RLED possesses great flexibility and mechanical stability.

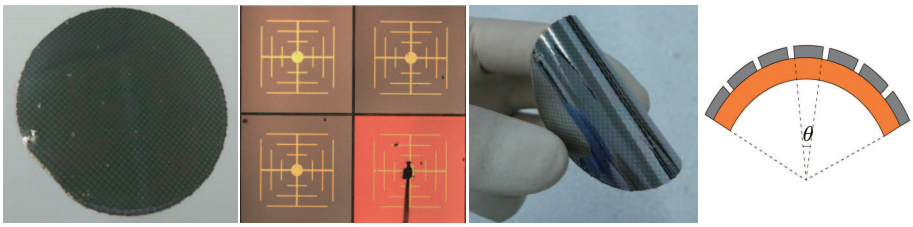


Fig. 2. (color online) (a) Photograph of a 2-inch (1 inch = 2.54 cm) thin film RLED wafer in natural state. (b) Microscope photograph of a 2×2 thin film RLED array, and the one on the right bottom with a bonded wire emitting red light at 2 A/cm^2. (c) Photograph of a 2-inch thin film RLED wafer forced into convex bending. (d) Schematic diagram of thin film RLED wafer bent over a mandrel, resulting in a central angle of θ for a square RLED.

The experimental PL curves with normalized intensities are presented in Fig. 3. Their peaks are located at the same wavelength (λ_p) of 629 nm, and specifically, they are situated at 627.6 nm and 628.2 nm according to the Gaussian fit for the reference RLED sample and thin film RLED sample respectively. The Gaussian fit also gives a full width at half maximum (FWHM) of 15.5 nm for the reference RLED, only negligible 0.2 nm narrower than that for thin film RLED. It can be regarded as no change of λ_p or FWHM from PL after the substrate transferred process, considering the measurement errors and uniformity deviations. The characteristic maintaining indicates that the substrate transferred process well remains the material properties of RLED. We also measure the PL when bending a 2-inch thin film wafer into a convex state with a total central angle θ 180°, i.e., approximately a θ of 3° on average for an individual RLED. The experimental PL curve of bending thin film RLED is presented in Fig. 3, which gives a λ_p of 631 nm and an FWHM of 15.3 nm. The FWHM can be considered to be unchanged but the λ_p shows a slight red shift of 2 nm. We attribute this red shift to the tiny tensile strain in the epilayers induced by the convex bending.[21,26] As a mechanical strain causes the bond lengths to change, the band structure is affected. The tensile strain leads to a band gap shrinkage, whose mechanism analyses have been investigated exhaustively in semiconductors.[27,28] On the other hand, the flexibility of thin film RLED manifests a stable optical prop-

erty under mechanical influence.

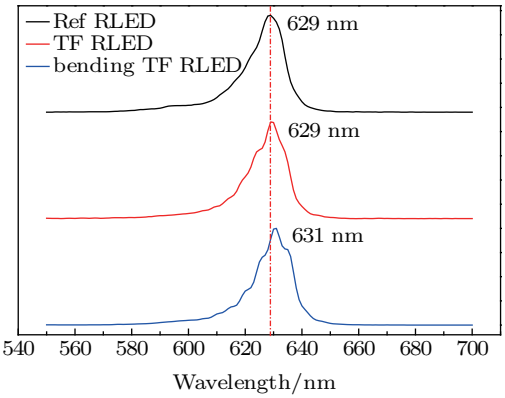


Fig. 3. (color online) Experimental PL curves of reference (Ref) RLED, thin film (TF) RLED in natural state, and bending thin film (TF) RLED into a convex state.

The EL spectra of the thin film RLED sample and the reference RLED sample at 2 A/cm^2 are shown in Fig. 4(a). The λ_p and FWHM are 627.8 nm and 14.8 nm, turning into 627.5 nm and 15.5 nm for reference RLED and thin film RLED respectively according to Gaussian fit. The λ_p and FWHM characteristic maintaining of EL after the substrate transferred process is consistent with the PL results. However, the integrated EL intensity of thin film RLED in our system runs up to 138.8 a.u. (the unit a.u. is short for arbtrary unit) in contrast with 80 a.u. of reference RLED, increasing by 73.5% significantly. It demonstrates that the thin film RLED distinctly outputs a larger LOP and shows a higher external quantum efficiency (EQE). These results are comparable to those gained by bonding.[16,23] If the structure design, material growth and device fabrication are optimized to the state of the art level, it is promising that the thin film AlGaInP RLEDs through our substrate transferred technology will achieve the optimum performance.

According to the substrate transferred procedures and fabricated RLEDs, attainable effects of thin film RLED sample on the LOP are mainly attributed to several factors, such as the stress, the interface defects and the substrates. As is well known, the EQE originates from the multiplication of the injection efficiency, the IQE and the LEE. Factors of the LOP enhancement should be analyzed individually and synthetically. In general, the stress in the epilayers induces a larger strain or generates more defects that degrade the RLED performances, especially the IQE. It is noted that the interface defects deteriorate the device performances by forming nonradiative recombination centers, and the pinning effect worsens the metal–semiconductor ohmic contact property with the interface defect density increasing, which blocks the current from flowing laterally and lowers the injection efficiency. The substrate changing from absorption GaAs into metallic Cu not only raises the injection efficiency by improving the current spreading, but also increases the LEE due to light reflection by the back electrodes. In a word, the improvement of LOP should be the combination effects of these factors.

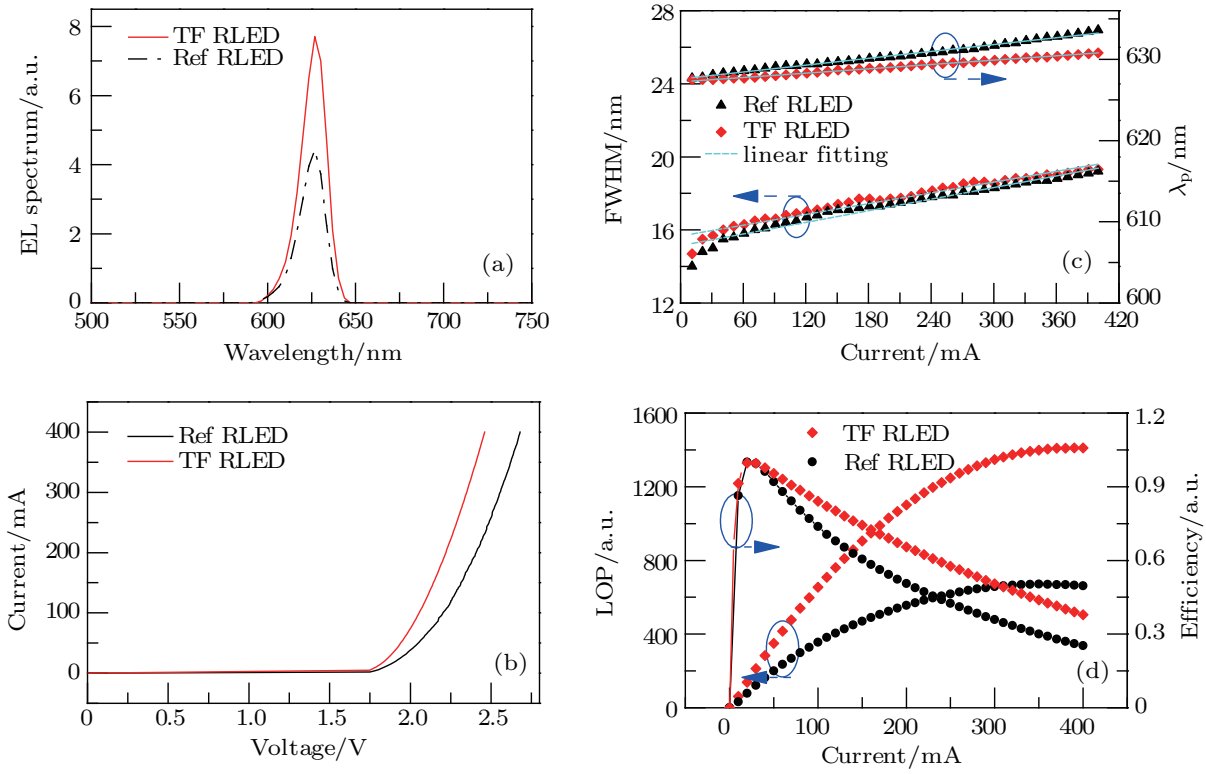


Fig. 4. (color online) (a) EL spectra of thin film (TF) RLED and reference (Ref) RLED at 2 A/cm^2. (b) Forward current–voltage (I–V) curves of thin film (TF) RLED and reference (Ref) RLED. (c) FWHM and λ_p curves of thin film (TF) RLED and reference (Ref) RLED depending on injected currents. (d) LOP and efficiency curves of thin film (TF) RLED and reference (Ref) RLED depending on injected currents.

To further investigate the combined LOP enhancement, the forward current versus voltage (I–V) behavior, the FWHM and the λ_p, the LOP and the efficiency of thin film and reference RLED samples depending on injected currents ranging from 0 to 400 mA are characterized by the EL system. Figure 4(b) shows the forward I–V behaviors of two RLED samples. Both I–V curves present classic P–N diode characteristics. The threshold voltages are located at the same value, i.e., at 1.75 V. Correspondingly, the forward voltage of thin film RLED is lower than that of reference RLED at any operating current. With typical injections at 20 mA and 350 mA, i.e., 2 A/cm^2 and 35 A/cm^2, thin film RLED shows the forward voltages of 1.84 V and 2.41 V, and reference RLED shows 1.91 V and 2.62 V respectively. The voltage reduction is attributed to the lower series resistance.[29] Based on the analyses above, the stress hardly affects the series resistance, but the interface defects and the substrate transformation indeed vary it. Actually, quite a few interface defects are generated after the InGaP ESL removal by diluted HCl solutions. The improved I–V behavior for thin film RLED is mainly ascribed to the removing of GaAs substrate and InGaP ESL. Moreover, the electroplated Cu substrate forming a tight interface contact with bottom electrodes, supports a more uniform spreading due to the great electrical conductivity, which consequently reduces the series resistance and raises the power injection efficiency effectively.

The dependence of FWHM and that of λ_p on injected current are plotted in Fig. 4(c). The FWHMs of both samples increase gradually with injected current, which is caused by the band filling effect.[30] The FWHMs of thin film RLEDs are 15.5 nm and 19.8 nm, which are a little broadening compared with 14.8 nm and 18.7 nm of reference RLED at 2 A/cm^2 and 35 A/cm^2 respectively. The broadening is attributed to the partial stress relaxation of epilayers, especially in MQWs.[21] However, the slight stress induced by substrate transformation only exerts negligible influences on the material quality and IQE in our experiments. As presented in Fig. 4(c), the FWHM gap between two samples verifies this tiny influence that turns increasingly narrower with injected current increasing. The λ_p shows a gradual red shift with injected current increasing for each of both RLED samples. It is observed that the λ_p standing at 627.5 nm and 627.8 nm at 2 A/cm^2, turns into 630.3 nm and 632.7 nm at 35 A/cm^2 for thin film RLED and reference RLED respectively. The peak red shift is due to the junction temperature rising in the active region[21] with the injected currents increasing. The rising junction temperature caused by the current crowding is effectively alleviated by the metallic Cu substrate, because the thermal conductivity of Cu is 400 W·m^{-1}·K^{-1} while that of GaAs is only 46 W·m^{-1}·K^{-1}.[31] The smaller λ_p shift for thin film RLED is hence observed in Fig. 4(c), due to the more uniform current injection and stronger heat dissipation ability of Cu substrate.[32] It also indicates that the power injection efficiency could be indirectly raised, with less Joule heat generated. This stable λ_p also implies that the thin film RLEDs show better heat stability and reliability in large injection.

According to the results of forward I–V behavior, FWHM and λ_p, we further analyze the LOP and the efficiency carefully. Figure 4(d) shows the LOP and the efficiency dependence on injected currents for two samples. With the injection increasing, the LOP values both increase rapidly at the beginning and are saturated gradually at large current. It is consistent with the scenario of LOP varying that the efficiency rises up when the injections are less than 25 mA and then the efficiency droop occurs[24,33] for both samples. The thin film RLED presents an outstanding enhancement of LOP in the whole current range. For example, the LOP is enhanced by 73.5% from 80 a.u. to 138.8 a.u. at 2 A/cm^2, and is enhanced by 142% from 578 a.u. to 1399 a.u. at 35 A/cm^2 compared with that of reference RLED. The LOP enhancement contributes to the removal of GaAs substrate, the reflection of the back electrodes and the great current spreading of Cu substrate.[34,35] The GaAs substrate has a super high absorption coefficient for the emission, on the other hand, the reflectivity of Au/Ge/Ni/Au layers is measured to be 92% near the wavelength of 630 nm. It is noteworthy that the efficiency curves are almost the same when the currents are less than 25 mA, but the efficiency droop of thin film RLED is improved remarkably when the current is larger than 25 mA. As mentioned above, the efficiency is determined together by the injection efficiency, the IQE and the LEE. Based on our EL measurement, the substrate transferred technology improves the injection efficiency and LEE efficiently, at the same time, and it hardly deteriorates the IQE at the same time. As a matter of fact, the improvement becomes more obvious with the current increasing. The efficiency curves conform to the analyses according to the EL measurement.

4. Conclusions

In this work, electroplating offers an optional method of preparing thin film AlGaInP RLEDs to eliminate the absorption of GaAs grown substrate. The stress in the Cu film can be alleviated greatly by optimizing the electroplating process. Our substrate transferred technique can maintain the original IQE due to negligible damage or stress influence on the epilayers. The LOP is enhanced efficiently by increasing the injection efficiency and LEE. These improvements are attributed to the removal of GaAs substrate, the reflection of the back electrodes, and the excellent current spreading of the Cu substrate. In addition, the thin film RLED also exhibits excellent flexibility, thermal dissipation ability and reliability. This substrate transferred technology based on electroplating has

great potential applications in the fields of GaAs, InP and GaN based, especially thin film types, optoelectronic devices such as LEDs, solar cells, laser diodes and photoelectric detectors.

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