Study of electric field distribution in AlGaInP light-emitting diode by Kelvin probe force microscopy

V.L. Oleynik¹, I.A. Prudaev¹, Vad. A. Novikov², Yu. L. Ryaboshtan³ and P. V. Gorlachuk³

¹ Functional Electronics Laboratory, Tomsk State University, 36 Lenin Avenue, Tomsk, 634050, Tomsk, Russia
² Faculty of Physics, Tomsk State University, 36 Lenin Avenue, Tomsk, 634050, Tomsk, Russia
³ JSC “M. F. Stelmakh Research Institute “Polyus”, Vvedenskogo str., 3 bld.1., 117342, Moscow, Russia

E-mail: dozorx777@gmail.com

Abstract. This work presents results of study of different AlGaInP light-emitting diodes by using Kelvin force probe microscopy. Study of current-voltage characteristics and electric field distribution had shown that for all type of experimental samples containing multiple quantum wells the most significant series resistance of heterostructures is determined by p-isotype heterojunction and confinement p-layer.

AlGaInP light-emitting diodes (LEDs) have a complex structure comprising multiple quantum wells (MQWs), confinement layers (n:conf, p:conf), and distributed Bragg reflector (DBR). Such a complex sequence of layers may cause unacceptable effects of current limitation due to sufficient resistance of heterostructures. For optimization of LED design it is important to use measurement technique with high spatial resolution such as Kelvin force probe microscopy (KFPM). This work presents results of study of different LED structures by using KFPM. The structures differ by thickness of active region, composition of AlGaInP quantum wells, and concentration of radiation defects.

Schematically investigated LED structure is shown in fig.1. The AlGaInP heterostructures were grown on the silicon doped GaAs substrates \((n = 2 \cdot 10^{18} \text{ cm}^{-3})\) with the thickness about 350 μm misoriented by 10° to the (111A) plane. A GaAs:Si layer with the electron concentration \(n = 2 \cdot 10^{18} \text{ cm}^{-3}\) and the thickness about 0.2 μm was formed on the GaAs substrate. For red LEDs a distributed Bragg reflector based on the silicon doped \((n = 1.5 \cdot 10^{18} \text{ cm}^{-3})\) Al\(_{0.45}\)Ga\(_{0.55}\)As/Al\(_{0.9}\)Ga\(_{0.1}\)As layers with the number of pairs equal 15 was used as an optical reflector. The layer thickness was chosen in accordance with the quarter-wave condition for the reflection maximum at 620–630 nm. The number of pairs was chosen so that the reflection coefficient close to 1 in the range 600–640 nm should be achieved. The composition of the layers provided non-absorbing conditions, i.e., the band gap of the reflector layers was wider than the energy transition in the GaInP QWs.

The active region of the structure was formed on the basis of the multiple quantum wells Ga\(_{0.47}\)In\(_{0.53}\)P, (10-20 )MQW with the thickness 7 nm, and Al\(_{0.27}\)Ga\(_{0.23}\)In\(_{0.5}\)P barrier layers with the
thickness 10 nm. The MQWs were restricted by the Al$_{0.27}$Ga$_{0.23}$InP$_{0.5}$ undoped layers, n-Al$_{0.5}$In$_{0.5}$P ($n = 5 \times 10^{17}$ cm$^{-3}$, $d = 0.52$ μm) and p-Al$_{0.5}$In$_{0.5}$P ($p = 1 \times 10^{18}$ cm$^{-3}$, $d = 0.52$ μm) confinement layers doped with silicon and magnesium, respectively. For yellow LED 30 MQW (Al$_{0.32}$Ga$_{0.68}$)$_{0.5}$In$_{0.5}$P/(Al$_{0.54}$Ga$_{0.46}$)$_{0.5}$In$_{0.5}$P structure was grown.

A 9.3–9.6 μm thick window layer of the LED AlGaInP structure was made on the basis of magnesium-doped gallium phosphide (GaP) ($p = 3–4 \times 10^{19}$ cm$^{-3}$). The thickness of the window layer was chosen to improve the current spreading in the plane of the p-n-junction. Previous study had shown that electroluminescence spectra of this LED structures demonstrate high homogeneity of the solid solution in the quantum wells [1].

In this work we used atomic force microscope NTEGRA Prima (NT-MDT) to measure qualitative potential distribution in LED structures under different applied bias voltages. The measurements were conducted on a cleavage plane of LED samples. Also we measured the forward current-voltage characteristics of LEDs. The measurements were conducted in a static and pulse mode at temperature $T = 300$ K using Keithley 2636 source meter, and LeCroy104Xs oscilloscope. Recently it was shown that in this structures current limitation is observed [2]. In this work additionally we studied LEDs with high series resistance which was initiated by electron beam irradiation with flux $10^{16}$ cm$^{-2}$ (average electron energy is 8 MeV). In this LEDs compensation effects are observed what leads to increase of resistivity of passive regions of diodes. In experiment it is interesting to define where the most significant compensation is. Kelvin force probe microscopy can be powerful tool for such a study.

Figure 2 shows a one- and two-dimensional images of the Kelvin voltage line scans from GaAs substrate (left side) to the p-GaP (right side). The figure corresponds to equilibrium condition for LED. It is clear that resolution of KFPM is sufficiently high, and it is possible to pick out single layers of DBR with thickness of about 50 nm. Boundaries between neighbor thick layers match to sharp potential drops.

Figure 3 shows qualitative distribution of electric field in red LED with 20 quantum wells at the different applied voltages. The distribution was obtained by differentiation of experimental KFPM data. From the experimental results we can conclude that almost all voltage is applied on the MQW region at the voltages below 1.5 V. At the higher voltages electric field distribution is changed in the confinement n- and p-layers. The most significant changes of electric field distribution is observed in p:conf layer and p:conf/p:GaP heterojunction.
The study of yellow LEDs is interesting from standpoint of determination of illumination influence on KFPM measurement results. It is well known that measured potential in KFPM is affected by laser radiation reflected from cantilever in microelectromechanical system of atomic force microscope. Part of this radiation can reach the measured sample. If the band gap of semiconductor sample is less than photon energy, the absorption of radiation leads to generation of nonequilibrium carriers at the surface of semiconductor. As a result surface potential will be changed. In our case the band gap of AlGaInP solid solution in red and yellow LEDs were 1.9 and 2.1 eV respectively. The energy of laser radiation in atomic force microscope was 1.9 eV. Hence undesirable effect of potential change under optical absorption in active region of yellow LEDs should be avoided. To verify this statement we measured yellow structures under filament lamp illumination and in dark condition. Fig.4 shows measurement results. It was found that at low forward voltages potential distributions are different in the boundary between n:DBR and n:conf layers. In the rest of the structure there is good qualitative agreement of field distributions. The difference could be explained by selective absorption of laser radiation in
Figure 6. Current-voltage characteristics of red AlGaInP LEDs with 10 quantum wells before and after radiation exposure.

Figure 7. Electric field distribution in red AlGaInP LED with 10 quantum wells at the different applied voltages after radiation exposure.

n:DBR under dark condition. The results of measurements for high forward voltages are in good quantitative agreement (fig.5). It should be noted that for yellow LEDs at the high voltages electric field distribution is changed significantly in the confinement n- and p-layers, and in p:conf/p:GaP heterojunction.

The study of LEDs with radiation defects shown that at the voltages \( U < 1.9 \) V excess current is observed which can be attributed to nonradiative recombination through defect centers in MQW [2]. On the other hand at high voltages current limitation take place (fig.6). Decreasing of the current at voltages \( U > 1.9 \) V is associated with additional resistance \( (R_d) \) of passive regions of LED with radiation defects:

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I = I_o \cdot \exp \left[ \frac{e \cdot (U - I \cdot (R + R_d))}{n \cdot k \cdot T} \right],
\]

where \( e \) - electron charge, \( k \) – Boltzmann constant, \( R \) – contact resistance, \( I_o = I_o(T) \).

Fig. 7 shows electric field distribution in red LED with 10 quantum wells after radiation exposure. As previous cases the increasing of voltage from 1.5 to 1.9 V initiates redistribution of electric field in p:conf layer and p:conf/p:GaP heterojunction. However there is no redistribution of field in n:conf layer. This fact points to donor nature of radiation defects which compensate initial p-type conductivity of p:conf layer.

In conclusion we have shown that for different AlGaInP LEDs applied voltage drops across all confinement and MQW layers. The most significant series resistance of LEDs is determined by p:conf layer and p:conf/p:GaP heterojunction what is in agreement with previous results [3].

References
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