

# Opto-Electronic Optimization of Light Emitting Diode Based on $GaAs_{1-x}P_x$

M. Bouafia, and Ai. Manallah

**Abstract**—In this work the optical performance of  $GaAs_{0.4}P_{0.6}/GaP$  LED structure was optimized. This structure is considered as a system of optical layer  $GaAs_{0.4}P_{0.6}$  with a thickness  $d$  on a GaP substrate. The optical constants ( $n$ ,  $k$ ) were calculated by the method of Afromowitz dielectric model starting from the calculation of real part and imaginary part of the dielectric function. The model used in these conditions is based on the transformation of Kramers-Kroning and is strongly linked to the structures of the energy band of the electronic state of the material. The second aspect of the work consists in optimization the optical performance of the light emitting diodes by applying an optical modeling of thin layers on substrate. It is based on the Fresnel formulas, where it is possible to make a simulation of four layers on a substrate by varying the wavelength, light incidence angle, and for each layer the refractive index, the absorption coefficient, and the thickness.

**Keywords**—  $GaAs_{1-x}P_x$ , LED optical properties, optical efficiency

## I. INTRODUCTION

APPLICATIONS of light-emitting diodes LED are numerous [1-4], the most typical include LEDs indicating the presence of a voltage indicator function logic displays mainly used in measuring and counting and opto-couplers. LEDs replace incandescent lamps in many applications because of their low voltage, long service life and communication saturation-quick release.

Intensive research has been undertaken on the optical properties and especially some III-V compounds, in particular gallium arsenide (GaAs), which is better suited to this type of electroluminescence.

Different materials currently used can cover practically the entire visible spectrum [5,6]. Most semiconductors III-V are mixed together in any proportion, so that the realization of ternary alloys, type  $GaAs_{1-x}P_x$  or  $GaIn_{1-x}P$ , to cover a large spectral range. A LED may contain gallium arsenide (GaAs), phosphate gallium arsenide (GaAsP), or gallium phosphate (GaP). GaAs LEDs emit invisible infrared radiation (IR), those made in GaAsP emit light in red or yellow, and GaP material emit visible blue light. Referring to the table III-V, it's

possible to produce wavelengths rang from 590 nm to 620 nm from the ternary compound with  $x = 0.6$ , and  $0.85$  respectively [7].

The efficiency of LEDs is the product of quantum yield and the optical yield. The quantum yield is the ratio between the number of photons really emitted to the outside and the number of electrons that gave them creation in the junction. The optical efficiency is the ratio between the luminous flux, in lumens, and energy flow. [7]

In general, the study of optical emitting diodes and their optical performance requires the determination of the optical properties which are the refractive index "n", the extinction index "k", the fundamental absorption and energy gap [8,9].

The values of "n, k" relating to a thin film deposited on a transparent or metal depends on many factors such as structure of the material and deposition techniques employed. Various calculation process ( $n$ ,  $k$ ) have already been described in the literature, mainly based on spectrophotometric methods or ellipsometry [10-12].

Starting from the calculation of real part and imaginary part of the dielectric function, the refractive index  $n$  and absorption coefficient  $k$  were calculated using Afromowitz dielectric model. The model used in these conditions is based on the transformation of Kramers-Kroning and it is strongly linked to the structures of the energy band of the electronic state of the material [7, 10].

The second part of the work consists in optimization of the optical performance of the light emitting diodes by applying an optical modeling of thin layers on substrate. It's based on the Fresnel formulas, where it is possible to make a simulation of four layers on a substrate by varying for each layer the refractive index, the absorption coefficient, the thickness and the incidence angle of light.

## II. PRINCIPLES

The wavelength emitted by a light emitting diode is of course dependent on the gap of the p-type material, wherein there is the most radiative recombination. Since some transitions involve impurity levels, the emission spectrum is determined by the type of doping. The mechanism of electroluminescence in the inter band transitions consists in the recombination of the majority carriers which pass the potential barrier reduced by the polarization. If the recombination mechanism is radiative, the light will be produced. One understands immediately that to have an efficient light emitting diode it would be necessary to realize rapid recombination

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mechanism occurs as soon as possible. This requires a short lifetime and short diffusion length, both also closely linked.

Emissions caused by impurities have a definite advantage in terms of light reabsorption. Indeed, as the energy of emission is less than the gap of the semiconductor material, the light can pass through without being reabsorbed into the semiconductor material. In addition, there is the excitons recombination due to the coupling of an electron from the conduction band with a hole in the valence band.

The emission diagram follows the law of Lambert such that the power  $P$  emitted in the direction  $\theta$  is given by the relation:

$$p(\theta) = p_o \cdot \cos(\theta) \quad (1)$$

Two factors limit the emission of photons outside the structure: The value of the refractive index and the existence of a total reflection angle (see Fig. 1).

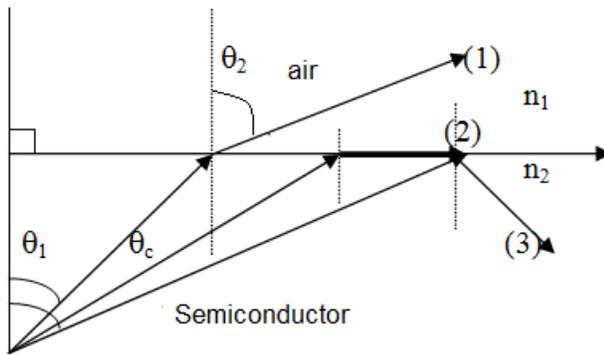


Fig.1 Emission of photon outside the structure

The angle of total reflection is given by the law of Descartes:

$$n_1 \sin(\theta_1) = n_2 \sin(\theta_2) \quad (2)$$

Knowing that for air  $n_2=1$  and at the total reflection  $\theta_2=\pi/2$ , it follows:

$$n \sin \theta_c = \sin(\pi/2) = 1 \Rightarrow \sin \theta_c = 1/n \quad (3)$$

The photons that reach the surface of the diode under an incidence greater than the critical angle are totally reflected within the semiconductor. The transmission and reflection thus vary depending on the angle. Only photons emitted by the junction in a cone of solid angle  $\Omega_c$  emerge from the diode. The solid angle subtended by the angle  $\theta$  is shown in Fig. 1 such as is given by:

$$\Omega_c = \int_0^{2\pi} d\Phi \int_0^{\theta_c} \sin \theta d\theta = 2\pi(1 - \cos \theta_c) \quad (4)$$

The radiation being emitted isotropically in all the space in the junction, the efficiency of the radiation output is given by:

$$\eta_0 = \frac{\Omega_c}{\Omega_0} T = \frac{1 - \cos \theta_c}{2} T \quad (5)$$

Since  $\theta_c$  is small, then  $\cos \theta_c \approx 1 - \theta_c^2/2$ , Therefore the optical efficiency  $\eta_0$  can be written as:

$$\eta_0 = \frac{\Omega_c}{\Omega_0} T = \frac{\theta_c^2}{4} T = \frac{\theta_c^2}{4} (1 - R) \quad (6)$$

Where  $T$  and  $R$  are respectively the transmission and the reflection.

### III. MODEL AND RESULTS

Afromowitz model consists in making an approximation of the imaginary dielectric function  $\varepsilon_2(E)$  by the following relation:

$$\begin{cases} \varepsilon_2(E) = \eta E^4 & \text{for } E_G < E < E_f \\ 0 & \text{if not} \end{cases} \quad (7)$$

$$\text{with } \eta = \frac{\pi}{2} \frac{E_d}{E_{oe}^3 (E_{oe}^2 - E_g^2)} \quad (8)$$

$$\text{and } E_f = (2E_{oe}^2 - E_g^2)^{1/2} \quad (9)$$

$E_d$ : dispersion energy

$E_{oe}$ : effective oscillation energy

$E_g$ : energy gap

The real dielectric function  $\varepsilon_1(E)$  is obtained using The Kramers-Kronig relationship and the proposition of Afromowitz:

$$\varepsilon_1(E) = 1 + \frac{2}{\pi} VP \int_0^{\infty} \frac{E' \varepsilon_2(E')}{E'^2 - E^2} dE' \quad (10)$$

where  $VP$  is the principal value.

After development, the relationship proposed of real part  $\varepsilon_1(E)$  by Afromowitz can be written as a function of energies:

$$\varepsilon_1(E) = 1 + \frac{\eta}{2\pi} (E_f^4 - E_g^4) + \frac{\eta}{2\pi} (E_f^2 - E_g^2) E^2 + \frac{\eta}{\pi} \ln \left[ \frac{E_f^2 - E^2}{E_g^2 - E^2} \right] \quad (11)$$

The values necessary for the calculations are given in the table 1 for the semiconductor alloy.

TABLE I  
UNITS FOR MAGNETIC PROPERTIES  
VALUES OF ENERGIES  $E_{oe}$ ,  $E_d$  AND  $E_g$  FOR THE SEMICONDUCTOR ALLOY

	$GaAs_{1-x}P_x$
$E_{oe}$ (ev)	$3.65 + 0.721x + 0.139x^2$
$E_d$ (ev)	$36.1 + 0.35x$
$E_g$ (ev)	$1.441 + 1.091x + 0.21x^2$

After calculating  $\varepsilon_1(E)$  using Afromowitz model, we deduce the complex refractive index and the corresponding curves are plotted for  $(n, k)$  as a function of photon energy.

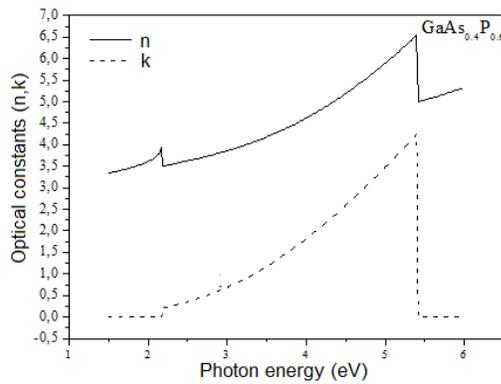


Fig. 2 refractive index real part  $n$  and imaginary part  $k$  of  $\text{GaAs}_{0.4}\text{P}_{0.6}$  versus photon energy

The curves are computed from Afromowitz model shown an increase in real and imaginary index up to the limit of about 5.5 eV. Starting from this last value of photon energy the refractive index fall drastically and takes anomale dispersion behavior. Note that both curves present around 2.2 eV a sharp peak which corresponds eventually to the E2 transition.

#### IV. OPTICAL OPTIMIZATION

In this work part the optical performance of the LED structure  $\text{GaAs}_{0.4}\text{P}_{0.6}/\text{GaP}$  was optimized. This structure is considered as a system of optical layer  $\text{GaAs}_{0.4}\text{P}_{0.6}$  with a thickness  $d_u$  on a GaP substrate. The calculation of the transmission and reflection is based on the Fresnel's formulas, taking into account the refractive index and the absorption coefficient of each medium as well as the optical thickness of the layer and the angle of incidence.

The particularity that we have introduced is the use of inverse system layers because the light is emitted from the inside of the LED junction to the ambient. The optimization results are presented in Figure 3, giving the transmission and reflection as a function of the wavelength.

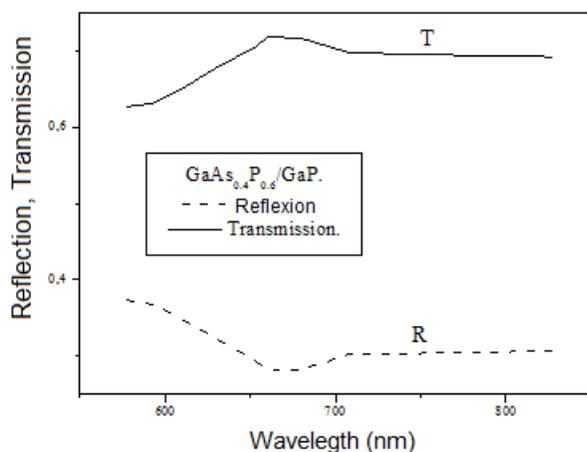


Fig.3 Reflection and transmission as function of wavelength

The behaviour of both reflection and transmission depend on two spectral domains. The visible range between 500 and 700 nm is characterized by a decrease of the reflection and consequently an increase of the transmission. This explains the use of this structure for the emission in the orange and red

wavelength. The second spectral range of infrared is marked by a relatively constant reflection.

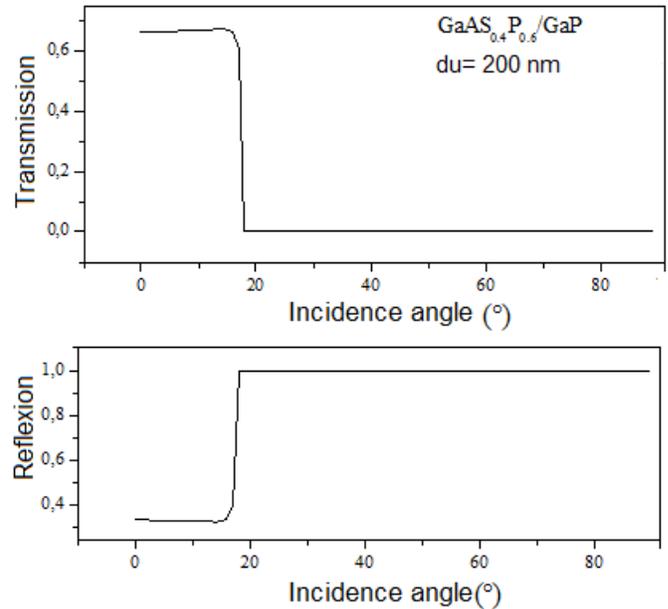


Fig.4 Behaviour of the transmission and reflexion as function of the angle of incidence, Layer thickness  $d_u=200$  nm.

The transmission and reflection of the structure depending on the angle of incidence are marked by a constant value of about  $T = 70\%$  for a critical angle  $\theta_c = 18.18^\circ$ . Beyond this value, the transmission is very low, so the rays emitted outside the cone are limited by the critical angle and are therefore totally reflected (see fig.4).

Consequently the optical efficiency of the studied structure is limited to the transmission of photons created in the layer  $\text{GaAs}_{0.4}\text{P}_{0.6}$ .

#### V.CONCLUSION

Two factors limit the emission of photons outside the structure: the value of the refractive index and the existence of a total reflection angle. The results obtained from Afromowitz model shown a normal dispersion of refractive index up to the photon energy of 5.5 eV. The emission spectral range of the structure has been found limited between 500 nm and 700 nm. Because in this wavelength interval reaches the reflection the minimum value and the transmission is about 70%. The critical angle of light incidence has been found of about  $18.18^\circ$  according to the optical optimization.

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