Light Extraction Improvement of LED Packages

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Abstract – The area of research relates to efficiency improvement of LED packages. The purpose of this work is to present a method for increasing of light extraction from LEDs. Light extraction is the ratio of photons emitted from the semiconductor chip into the encapsulant to the total number of photons generated in the active region. Decreasing of emitted photons is the effect of light reflection back into the chip caused by the refractive indices differences of intermediate media. Reduction of optical losses may be achieved by wide-band antireflection (AR) coatings for the intermediate elements of LED packages, with the first stage - wide-band AR coatings design.

Keywords – power LED, antireflection coatings

I. INTRODUCTION

Over the past few years an improvement in the technological characteristics of power LEDs can be seen. According to Directive 2005/32/EC of the European Parliament and to the Council of the European Union of 06.07.2005, the energy efficiency is a major evaluation of the work for each well designed system. The accepted goal by the European Commission in 2007: strategy 20-20-20 is related to 20% reduction of energy consumption by 2020 (20% increase of energy efficiency, 20% reduction of CO₂ emissions, and 20% renewables by 2020).


Light extraction losses from LEDs are considerable (up to 20%) and according to multiyear program plan of the US government should be improved to 2020, see Fig. 1. Light reflection losses from each optical boundary in LED, due to refractive indices differences, may be reduced essentially. Between the semiconductor active region and environment some subsidiary media are located – chip (GaAs, Si, InGaN, GaN), fluorescent material, silicone resin (encapsulation layer), lenses. In Fig. 2 section view of a LED is presented. It can be seen that the number of optical boundaries in a LED is quite big. The media have refractive indices n from 1.8 to 3 and refractive index of air is n = 1. LED chip is usually made from semiconductor with refractive index n = 2.5 [1- 5].

II. DESIGN OF ANTIREFLECTION COATINGS

Several approaches for design of wide-band antireflection coatings are known [2]. The simplest AR coating is a single layer with optical thickness nd = λ/4, 3λ/4, 5λ/4 ... and refractive index n = nS1/2 (nS is the substrate refractive index) which acts properly only at one wavelength [2]. Appropriate methods for multilayer coating design in wide spectral region are based on numerical optimization [2, 3]. In those methods the structure of a multilayer coating (number of layers, their refractive indices and thicknesses) is a result of numerical optimization of a proper function.

When refractive indices and thicknesses of all initial structures are calculated, their AR properties can be compared. In our case it is performed by average reflectance, which will be called as factor Q. It is calculated according to the following equation:

\[ Q = \sqrt{\frac{1}{N} \sum_{l=1}^{N} R^2(\lambda_i)_{\text{CALCULATED}}} \]

where \( \lambda_i \) is N discrete equidistant wavelength values in investigated spectral region 0.38 – 0.78 μm, \( R(\lambda_i)_{\text{CALCULATED}} \) – calculated reflectance as function of \( \lambda_i \). The structures with lower value of Q have better AR properties.

In our work structures two materials for layers are used because they are much more convenient and easy for deposition. As a rule those structures consist of layers of low- and high-refractive index materials which are usually denoted with L and H [2, 3].
For semiconductor substrates with refractive index n = 2.5, 4620 initial antireflection structures are designed and after optimizing several of them are proposed.

For appreciation of AR properties of the coating, average reflectance $Q$ in research spectral region is used. It is called $Q$-factor, $Qin$ - for initial structures or $Qopt$ - for optimized structures, their values are given in percentages. $Q$ corresponds to the average value of the reflectance in the whole selected spectral range.

All designed initial structures are 4620 number; below see some of them with better AR properties:

✓ Bilayer AR structures with different initial optical thicknesses $Din$ have an average reflection: for $Din = \lambda/4$ $Qin = 5.58\%$, for $Din = 3\lambda/4$ $Qin = 10.65\%$ and for $Din = 5\lambda/4$ $Qin = 12.09\%$.

✓ Four layers structures with initial optical thickness: $Din = \lambda/4$ $Qin = 3.12\%$; $Din = 3\lambda/4$ $Qin = 21.93\%$; $Din = 5\lambda/4$ $Qin = 17.71\%$.

✓ Six layers structures with initial optical thickness: $Din = 3\lambda/4$ $Qin = 21.06\%$; $Din = 5\lambda/4$ $Qin = 40.43\%$.

✓ Others worse multilayer structures.

The final thicknesses of all layers are found as a result of numerical minimization of $Q$, equation (1). The optimization procedure consists of steps which number is equal to the number of optimized thicknesses. Each step is one-dimensional minimization carried out by means of the golden section method [2,3]. In many cases thickness of a layer in a given k-layer initial structure becomes negligible after minimization procedure and the corresponding optimized structures are considered as (k-1)-layer.

Obtained structures are large number and a lot of them do not improve enough AR properties of substrate that is appropriate to be deposited. Therefore several conditions for assessing the quality of the multi-layer AR structures are accepted: 1) the usage of fewer materials in terms of manufacture and durability of the multilayer coating are preferable; 2) fewer layers are technologically and economically more advantageous for deposition; 3) the average reflection $Q$ should be low, $Qopt < 1\%$; 4) changes in values of layers’ refractive indices $n_H$ and $n_L$ and their thicknesses remains $Qopt$ less than 1%.

III. RESULTS AND DISCUSSION

Analysis of optimized multilayer structures in accordance with the above mentioned conditions for quality assessment shows that the best AR properties have three types of structures (two-layer, four-layer and six-layer):

✓ 2-layer structure is obtained with refractive indices of layers $n_H = 2.05$ and $n_L = 1.35$ (air/LH/ns) $Qopt = 0.33\%$, reflection spectrum is presented in Fig. 3. In the figure reflection of reduction losses comparing with those from uncoated substrate is shown. The initial structure significantly reduces reflection from substrate, but at a higher wavelengths reflection increase to $R_{opt}(\lambda = 780nm) = 10\%$. Compared with the initial structure, optimized two-layer structure has better AR properties for entire spectral range. The maximum values of reflectance $R$ for double-layer structure at one wavelength is less than 2% and the values reached at $R_{opt}(\lambda = 380nm)$ to 1.43%, at $R_{opt}(\lambda = 516nm)$ = 0.66% and $R_{opt}(\lambda = 660nm) = 0.64\%$. Total physical thickness of the 2-layer coating is 150 nm.

✓ After optimization of the initial 4-layer structures of air/LH/LH/ns type $Qopt = 0.14\%$ for $n_H = 2.4$ and $n_L = 1.3$ is obtained, see Fig. 2. The initial structure has the best AR properties for wavelengths $\lambda = 450 - 500$ nm. After optimization of 4-layer structure has a maximum value of reflectance $R_{opt}(\lambda = 380nm) = 0.32\%$, $R_{opt}(\lambda = 500nm) = 0.16\%$ and $R_{opt}(\lambda = 780nm) = 0.30\%$. 4-layer structure is better than two-layer structure. The maximum value of the reflectance R is lower than $Qopt$ of structures with 2-layer. In comparison with 2-layer the total physical thickness of the 4-layer coating is increased to 210 nm.

✓ After optimization of the initial 6-layer structures of type air/LH/LH/LH/ns the lowest average reflectance of $Qopt = 0.12\%$ at $n_H = 2.6$ and $n_L = 1.3$ is obtained, see Fig. 2. The maximum values of reflectance R are for $R_{opt}(\lambda = 380nm) = 0.2\%$, $R_{opt}(\lambda = 500nm) = 0.15\%$ and $R_{opt}(\lambda = 780nm) = 0.23\%$, they are at the same wavelengths as the 4-layer. Compared to other structures total thickness of the 6-layer coating is increased two - three times (410 nm).

In order to find a better AR properties average reflection as a function of the parameters of low- and high-refractive indices for the three structures are investigated. This study is carried out when for each combination of the changes of refractive indices values layer thicknesses have been optimized. Average reflection as a function of the refractive indices $n_H$ and $n_L$ of three AP structures is presented in Fig. 3. The areas with the average reflection $Qopt < 0.5\%$ are colored in blue and $Qopt$ with <1% - red.

Average reflection of 2-layer structure stays $Qopt < 1\%$ for $n_H = 1.9 \div 2.25$ and $n_L = 1.3 \div 1.5$. For comparison, 4- and 6-layer keep good AR properties for values of $n_H$ and $n_L$ in a much wider range.
The results obtained in the study of changes in the refractive indices can identify areas of values \( n_L \) and \( n_H \) for selecting and using materials in the coating before deposition (manufacturing), as the average reflection remain below 1%.

To manufacturing 2-layer AR coatings materials with refractive indices \( n_L = 1.3 \div 1.45 \) and \( n_H \) of 1.9 + 2.2 are suitable. It is seen (Fig. 4) that the number of possible combinations of materials \( n_L \) and \( n_H \) is not large.

For 4-layer AR coating may be used for layer’s materials \( n_L = 1.3 \) to 1.55 and \( n_H = 2.1 \) to 3.5 values. Their number are the greatest in comparison with the other two structures.

6-layer AR coating required materials with \( n_L = 1.45 \) to 1.5 and \( n_H = 2.0 \) to 2.55 refractive indices. For low refractive index can be used \( n_L = 1.5 \) (a material with such a refractive index in a visible spectral region is silica, a material with very good density of the coating and mechanical strength, which makes it preferable for the outer layer of the multilayer AR coatings [2, 4, 5]) but \( n_H \) should be in the range of 2.1 to 2.5.

![Fig. 4. Average reflectance \( Q \) as a function of refractive indices \( n_L \) (1.3 ÷ 1.6) and \( n_H \) (1.8 ÷ 3.5) for 2-layer, 4-layer, 6-layer structure on substrate \( n_S = 2.5 \) for the visible spectral region.](image)

From the presented above we can see that the number of possibilities to use various materials in \( n_L \) and \( n_H \) of coating layers is the largest for 4-layer AR structure (according to condition that \( Q_{opt} < 1\% \)) and the lowest – for 2-layer. Changes in the values of \( n_S \) at 4-layer and at 6-layer affect less to coating AR properties than \( n_L \).

The phase thickness deviations’ influence on the properties of AR coatings for designed three multilayer structures on substrate with \( n_S = 2.5 \) is analyzed, too. Phase thickness is a parameter, which depends on wavelength \( \lambda \), thickness \( d \) and refractive index \( n \) of antireflective coating’s layers. The investigation is performed in three stages. Those three steps have been described in detail in our previous work [6].

The investigation was performed as layers materials for 2-, 4- and 6-layer structures substituted with values of the refractive indices of real materials. Materials with high refractive index are usually used: \( n_L = 2.05 \) (ZrO\(_2\), Si\(_3\)N\(_4\)), \( n_H = 2.35 \) (TiO\(_2\)) and material of low refractive index \( n_L = 1.38 \) (MgF\(_2\)) [3 - 6]. Magnesium fluoride is characterized by good resistance to external influences, which makes it convenient to use as a outer layer of the coating. With this substitution values of \( Q \) is obtained:

- 2-layer structure of \( \text{Air}/LH/n_S \) – type, where are used \( n_L = 1.38 \) and \( n_H = 2.05 \) \( Q_{opt} = 0.39 \% \). In this case total thickness of coating is obtained 156 nm.
- 4-layer structure of \( \text{Air}/LHLH/Substrate \) – type, where are used \( n_L = 1.38 \) and \( n_H = 2.05 \) \( Q_{opt} = 0.34 \% \). Total thickness of coating is obtained 174 nm.
- 6-layer structure of \( \text{Air}/LHLHLH/Substrate \) – type, where are used \( n_L = 1.38 \) and \( n_H = 2.05 \) \( Q_{opt} = 0.43 \% \). Total thickness of coating is obtained 326 nm.

**First stage.**

Dependences of average reflectance \( Q \) of the substrate with AR coating as a function of refractive indices \( n_L \) (from 1.3 to 1.5) and \( n_H \) (from 1.9 to 2.7) at constant thicknesses of separate layers are investigated.

![Fig. 5. Averaged reflectance \( Q \) as function of refraction indices \( n_L \) (from 1.3 to 1.5) and \( n_H \) (from 1.9 to 2.7) for AR structures on substrate \( n_S = 2.5 \) at constant thicknesses of separate layers for the visible spectral region. \( Q_{opt} \) - point where chosen multilayer structures have best AR properties.](image)
It can be seen in Fig.5, that the change of \( n_H \) mostly affect the 2-layer AR properties, therefore \( n_H \) should be in the range from 1.9 to 2.1, and \( n_L \) can be changed from 1.3 to 1.45. AR properties of 6-layer influenced mostly from deviations of refractive indices. 4-layer structure has a better resistance to changes in the refractive indices of the layers than other investigated multilayer AR structures. Even with large changes in refractive indices \( n_H \) and \( n_L \) within the interval \( n_L = 1.3 \div 1.5 \) and \( n_H = 2.7 \div 3.4 \), \( Q \) factor remains below 1%.

Therefore the most resistant to deviations of refractive indices \( n_H \) and \( n_L \) is 4-layer.

Furthermore by comparison of Fig. 4 and Fig. 5 can be seen the complex relationship between the thicknesses of the separate layers and their refractive indices for the respective AR coating.

**Second stage.**

Optical properties of 2-layer, 4-layer and 6-layer AR structures are evaluated by modeling at thickness’ variations of each layer by \( \pm 5 \) nm at constant values of layer’s refractive indices \( n_H \) and \( n_L \).

For all investigated AR structures the most influenced is the increase in the total thickness of the coating on AR properties, so it is important to do not increase the thickness of designed optimum values. At least influenced change thicknesses \( (d_H) \) of layers with high refractive indices minus 5 nm, and \( d_L \) unchanged.

Thickness’ deviations impact minimal on 2-layer with \( \Delta Qopt = 0.39\% \), \( n_L = 1.38 \), \( n_H = 2.05 \). For this structure, the number of combinations of thickness’ deviations are greatest and average reflectance stays - \( Q < 1\% \). Compared with 6-layer and 4-layer it is more resistant to changes in the thickness of the layers. The biggest impact in 4-layer has change of \( d_H \) layers \( \pm 5 \) nm and \( d_L \) layers minus 5 nm simultaneously, at which the value of \( Q \) deteriorates only to 1.06%. Therefore it can be argued that 4-layer also has good resistance to thickness’ deviations of separate layers.

**Third stage.**

Dependencies of average reflectance \( Q \) for substrate with AR coating to deviations of substrate refractive index \( n_S \) (from 2 to 3) at constant \( n_L \) and \( n_H \) and at constant thicknesses of separate layers are investigated. In Fig.6 it is shown for 2-layer, 4-layer and 6-layer AR structures.

![Fig. 6. Averaged reflectance \( Q \) as a function of substrate refractive index \( n_S \) at constant thicknesses and refractive indices of separate layers for the visible spectral region.](image)

The analysis of all multi-layer structures with deviations in the value of the refractive index of the substrate \( n_S \) to predict deterioration on properties of multilayer antireflection coatings after deposition of coating is carried out. Moreover possibility of the use of these coatings for substrates with different values of the refractive index is investigated, because refractive indices of the various optical elements in LED are not made from the same materials. Light emitting diodes (GaAs, Si, InGaN, GaN), lenses, the fluorescent material, silicone resin (encapsulation layer) and the surrounding air. They have refractive indices \( n_S \) with values from about 2 to 3 [1-5].

The differences between the three structures are minimal. For values of \( n_S = 2.4 < n_S < 2.65 \) 2-layer has the lowest average reflection \( (Q < 0.5\%) \), and for values \( 2.32 < n_S < 2.55 - 4\)-layer.

2-layer can be used on \( n_S \) in the range of 2.45 to 3.0, and in this range the \( Q \) factor preserves lower than the 4-layers and 6-layers Q factors.

4-layer can be used for \( n_S \) in the range of 2.4 to 2.45, and in this range the \( Q \) factor preserves lower than the 2-layers and 6-layers Q factors.

For values of \( n_S = 2 + 2.45 \) it is appropriate to use 4-layer coating, and \( n_S = 2.45 + 3.0 - 2\)-layer.

**IV. CONCLUSION**

From the analysis of the results in this research can be concluded that universal one is not designed yet, but the designed coatings can be selected to satisfy different needs and substrates. Best resistance to the influence of external factors to AR properties is performed at three stages. First place is assigned to 4-layer and 2-layer lags behind only in changes of \( n_L \) and \( n_H \). Taking into account a lower number of coating layers it can be considered that 2-layer mostly appropriate AR structure for values of \( n_S = 2.45 \div 3.0 \) and for \( n_S = 2 \div 2.45 \) it is appropriate to use 4-layer coating.

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