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 CO_2 emissions, and 20% renewables by 2020).

Also in a multiyear program plan of the US government (Solid - State Lighting Program featuring Building Technologies Office, Office of Energy Efficiency and Renewable Energy, US Department of Energy) 2011, 2012, 2013, 2014 [1] trends in the booming LED lighting equipment are presented. The losses in LED packages achieved efficiency and expected improvements in efficiency until 2020 (green colored ones) are presented in Fig. 1.

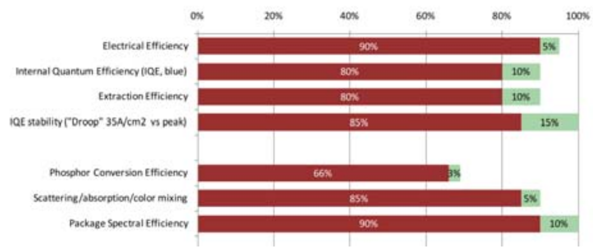

Fig. 1. LED package and luminaire loss channels and efficiencies [1].

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].

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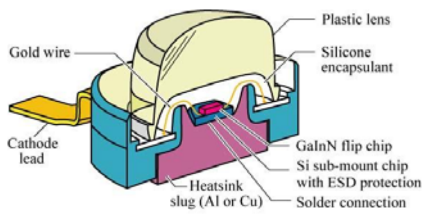

Fig. 2. LED power section view.

Reducing reflection losses can increase the efficiency of LED light extractions. Optical losses only from LED chip at normal incidence of a boundary without antireflection (AR) coatings are over than 18% [2-5]. If we add reflections in the optical elements (n = 1,5 ÷ 1,8), the total optical losses are expected to be more than 25 – 30 %. The usage of AR coatings can reduce them.

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 $n = n_S^{1/2}$ (n_S 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:

$$Q = \sqrt{\frac{1}{N}\sum_{i=1}^{N} R^2(\lambda_i)_{CALCULATED}} , \qquad (1)$$

where λ_i is N discrete equidistant wavelength values in investigated spectral region 0.38 – 0.78 μm, $R(\lambda_i)_{CALCULATED}$ – calculated reflectance as function of λ_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* = λ/4 *Qin* = 5,58%, for *Din* = 3λ/4 *Qin* = 10.65% and for *Din* = 5λ/4 *Qin* = 12.09%.

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

✓ Six layers structures with initial optical thickness: *Din* = 3λ/4 *Qin* = 21.06%; *Din* = 5λ/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/n_S) *Qopt* = 0.33%, reflection spectrum is presented in Fig. 3. In the figure reduction of reflection 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 $R_{(\lambda = 780nm)}$ = 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 $R_{(\lambda=380nm)}$ to 1,43%, at $R_{(\lambda=516nm)}$=0,66% and $R_{(\lambda = 660nm)}$ = 0,64%. Total physical thickness of the **2-layer** coating is 150 nm.

✓ After optimization of the initial **4-layer** structures of air/LHLH/n_S 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 wavelengthes λ = 450 - 500 nm. After optimization of *Q* **4-layer** structure has a maximum value of reflectance $R_{(\lambda = 380nm)}$ = 0.32%, $R_{(\lambda = 500nm)}$ = 0.16% and $R_{(\lambda = 780nm)}$ = 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.

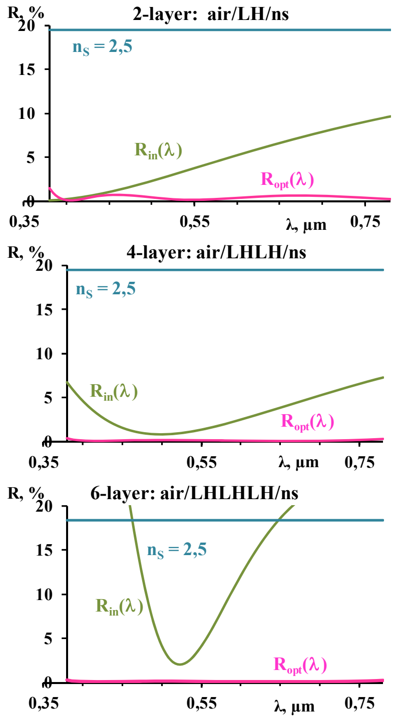

Fig. 3. Reflectance spectra of uncoated substrate n_S of refractive index 2.5 (blue line); of initial structure *Rin(λ)*(green line) and of optimized antireflection coatings R_{opt} *(λ)*(pink line).

✓ After optimization of the initial **6-layer** structures of type air/LHLHLH/n_S the lowest average reflection 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 $R_{(\lambda = 380nm)}$ = 0.2%, $R_{(\lambda = 500nm)}$ = 0.15% and $R_{(\lambda = 780nm)}$ = 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 ÷ 2.25 and n_L = 1.3 ÷ 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 ÷ 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.

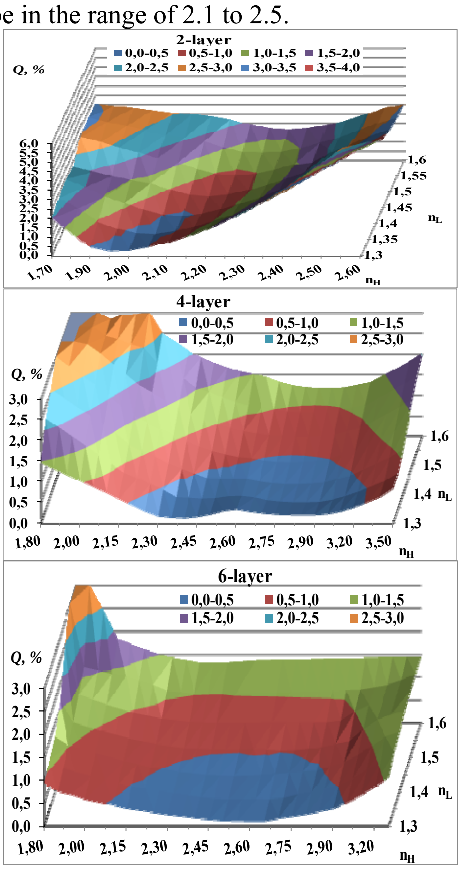

Fig. 4. Average reflectance Q as a function of refractive indices n_L (1,3 ÷ 1,6) and n_H (1.8 ÷ 3.5) for 2-layer, 4-layer, 6-layer structure on substrate n_S=2.5 for the visible spectral region.

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 *Qopt* < 1%) and the lowest – for **2-layer**. Changes in the values of n_H at **4-layer** and at **6-layer** affect less to coatign 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 λ, 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_H=2.05 (ZrO_2, Si_3N_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 *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 *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 *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.

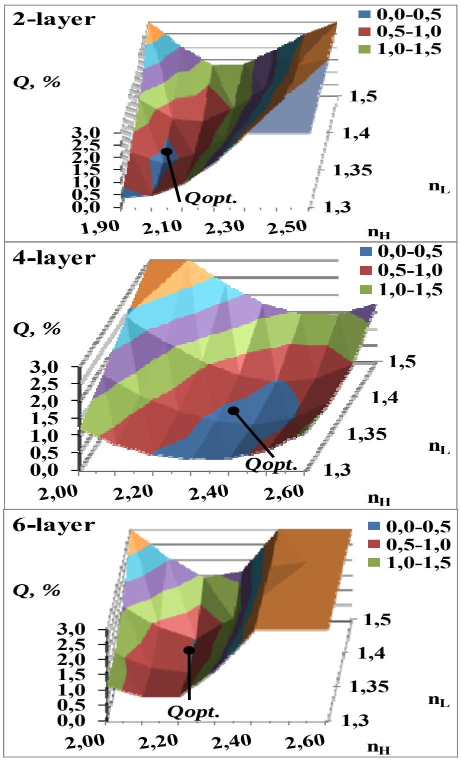

Fig. 5. Averaged reflectance Q as function of refraction indices n_L (from 1.3 to 1.5) and n_H (from 1.9 to 2.7) for AR structures on substrate n_S=2.5 at constant thicknesses of separate layers for the visible spectral region. *Qopt* - point where chosen multilayer structures have best AR properties.

2-layer structure is more sensitive to deviations of refractive indices $\mathbf{n_H}$ and $\mathbf{n_L}$ of layers which have coating.

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 $\mathbf{n_H}$ and $\mathbf{n_L}$ 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 ± 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 $Qopt$ = 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_L layers +5 nm and d_H 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.

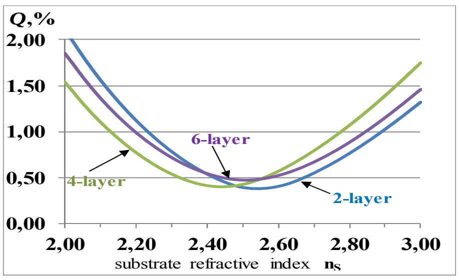

Fig. 6. Averaged reflectance Q as a function of substrate refractive index n_S at constant thicknesses and refractive indices of separate layers for the visible spectral region.

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 or n_S) with values from about 2 to 3 [1-5].

The differences between the three structures are minimal. For values of 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 2.0 to 2.45, and in this range the Q factor preserves lower than the 2-layers and 6-layers Q factors.

For values of $n_S = 2 \div 2.45$ it is appropriate to use **4-layer** coating, and $n_S = 2.45 \div 3.0$ - **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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References

[1] Solid-State Lighting Research and Development, Bardsley Consulting, Navigant Consulting Inc., Radcliffe Advisors Inc., SB Consulting, and Solid State Lighting Services Inc., p.130.

[2] Macleod H. A. *Thin film optical filters*. - Macmillan, New York (2001) pp. 590.

[3] J. A. Dobrowolski, Daniel Poitras, Penghui Ma, Himanshu Vakil, Michael Acree, *Toward perfect antireflection coatings: Numerical investigation*, Applied Optics, 41 (2002) 3075-3083.

[4] *Optical element having anti-reflection coating*, US7619821, 2009.

[5] *Anti-reflective coating for light bulbs*, US20110193465, 2011

[6] Gyoch B., P. Mashkov and S. Penchev. *Phase thickness deviations' influence on properties of antireflection coatings for near infrared detectors*, IEEE, Proc. of 35th International Spring Seminar on Electronics Technology - *ISSE 2012*, May 11th – 15th 2012, Bad Aussee, Austria, E09, art. no. 6273094 , pp. 318-323.