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# Hot Laminated Multilayer Polymer Illumination Structure Based on Embedded LED Chips

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## ABSTRACT

The dominant technology for manufacturing backlight illumination structure (BLIS) is typically based on the use of individually packaged Surface Mount Device (SMD) Light Emitting Diodes (LEDs) and special light guide plate (LGP) and diffuser films. The prevailing BLIS package, however, contains several separate diffuser films, which results in a thick and costly structure. In addition, the light coupling from LED to the LGP is sensitive to alignment errors causing non-uniform and inefficient illumination. We have demonstrated a novel hot laminated packaging structure for backlighting solutions, which is based on inorganic LED chips and multilayer polymer structure. The main advantages of the implemented system compared to traditional light guiding system are easy optical coupling with high efficiency in an integrated and thin package.

The performed designs of 3 x 3, 5 x 5 and 5 x 7 LED chip matrices, verified by test structure implementations and characterizations, showed that the final thickness of the backlight illumination structure depends on the required uniformity of illumination, allowed LED device pitch and efficiency of the diffuser. The final BLIS demonstrator size was 50 x 75 mm$^2$ consisting of six 25 x 25 mm$^2$ modules. Each module consisting 5 x 5 LED devices resulting total number of 150 LED devices with 5 mm pitch. The measured key characteristics of the demonstrator were as follows: average brightness 11.600 cd/m$^2$ ($I_{LED}$=2 mA), luminous efficiency 22 lm/W, color temperature 5550 K, CIE values (x=0.331, y=0.411), CRI $\geq$ 70 and total power conversion efficiency of 6.3%.

Combination of the developed Matlab™ performance simulation tool and COO cost evaluation tool enables us to estimate the manufacturing cost of a specific BLIS element against the required performance, assisting decision making in different applications and specific individual customer cases.

Key words: illumination structure, inorganic LED chips, hot lamination, embedding, multilayer polymer substrate

## INTRODUCTION

Generally, a backlight illumination structure (BLIS) is considered for the light module of a thin film transistor (TFT) LCD [1]. A typical BLIS is comprised of a light guide plate (LGP) and some optical foils, such as two diffusion sheets and a reflection sheet. Each optical sheet has different function in BLIS. For instant, the reflection sheet under the LGP can diminish the optical loss to increase the luminance. Typically, a conventional LGP is not designed to control the luminous angle; therefore, it has poor luminance and luminous uniformity. A BLIS is widely used in the display panel of notebook, LCD-TV, laptop computer, and many portable information devices, such as cellular phones and personal digital assistants. Because the market of small size panel is increasing, it is desirable to make the BLIS to be thinner, brighter and lighter [2], [3], and [4]. An integrated polarizing light guide as an LCD backlight is designed and fabricated [5]. Also a LED BLIS implementing a LGP with 2-D array of grating micro-dots is proposed [6]. The polymethylmethacrylate (PMMA) micro prisms are constructed on the integrated LGP, which can yield required uniformity of intensity [7]. A LGP with the double-sided microstructures is fabricated by using Microelectromechanical Systems (MEMS) technique for BLIS application [8].

In comparison to previous researches, a multi-layer polymer structure with integrated inorganic LED chips backlight structure has been developed. The structure combines several optical functions of optical sheets to save the space and fabrication costs. The implemented basic BLIS consists of three polycarbonate foils, which are patterned with screen printed silver paste conductors and vias to contact bare LED devices embedded in the openings of the middle foil layer. A fourth foil is coated with phosphor paste converting the blue emission of the LED device to a wider wavelength band and that way forming a white light diffuse emitting surface.

The developed technology allows versatile tuning of characteristics of the thin and flexible BLIS element including tuning of dimensions, brightness, color temperature, CRI and uniformity.

## DESIGN AND IMPLEMENTATION OF BACKLIGHT ILLUMINATION STRUCTURE

Laminated structure schematics are shown in Fig. 1. It consists of 3 sheet layers with a LED device embedded within it. The processing was started by stabilizing polycarbonate sheets with temperature treatment. Via holes (Ø=100…275 µm) and a cavity (Ø=400 µm) for the LED were punched. Vias were filled in with Asahi LS-106D-1 Ag paste using stencil printing. Then the conductors for layers L1b and L3b were screen printed. The paste used was Asahi SW1400 Ag. After printing the sheets were dried at 80 °C for 20 min. The pads for LED chips were printed next. Then the LEDs were assembled with manual die bonder one-by-one into the cavity. Two types of LED devices were embedded within the laminated structure, namely blue LED, type C470RT290 and green LED, type C527RT290. The bottom area of the chip was 300 µm x 300 µm and the thickness 115 µm. The devices were manufactured by Cree. The manual pick-and-place cycle took 10 s/chip and the working time was about 12 min for the 25 chips assembly. The assembled sheets were dried at oven for improving the electrical as well as the thermal conductivity of the epoxy and the adhesion between the chip and pad. The assembly of LED device to wet paste was also tested and proved to be a feasible method. By utilizing wet paste in the LED device assembly process, the use of epoxy is avoided, which results cost savings in the attachment process.

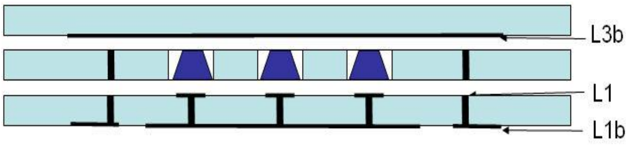

**FIGURE 1**. Laminated BLIS structure schematics

The sheets were eventually stacked over each other in the alignment jig and laminated in vacuum. The laminator used in the experiments was Lauffer Pressen RLKV 25/1, designed for lamination of multilayer boards, plastic boards and cards, etc. The press utilizes heated steel plates. The heating is done with thermal oil which is integrated in canal system. The presses are located in a vacuum chamber. The thermal oil allows the lamination in high temperature, such as 300°C. The lamination profile is shown in Fig. 2. The peak temperature was 165 °C and the total lamination took about 1 h. During the lamination the polycarbonate sheets were shielded with Tedlar films in order to avoid sticking of them to steel plates.

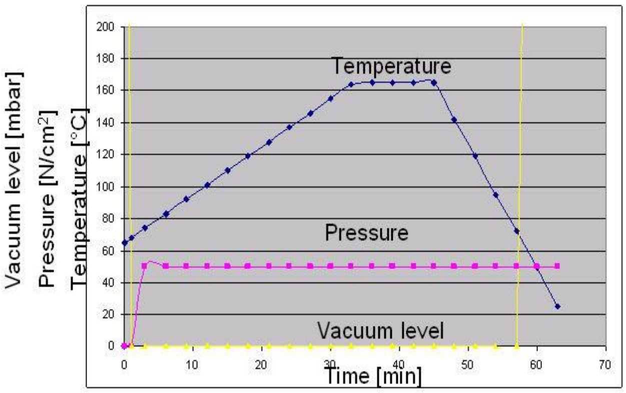

**FIGURE 2**. Lamination Profile Used for Laminating Polycarbonate Sheets

During the technology development several test circuits were designed and fabricated. The key element was the size of the pad for the chip assembly. The LED chip had an open active area very near on the bottom of the chip. In practice this meant that the wet paste on the pad was not allowed to rise up along the vertical chip edge. The variation of pad sizes was tested and it was noticed that the larger pads caused short-circuits due to paste spreading. The spreading was caused by a high uniaxial lamination pressure. On the other hand, the wet paste dried too quickly in smaller pads reducing the effective assembly time. Also the cavity size was varied in the tests. In Fig. 3 a flexible demonstrator matrix containing 5 x 7 green LED devices is shown.

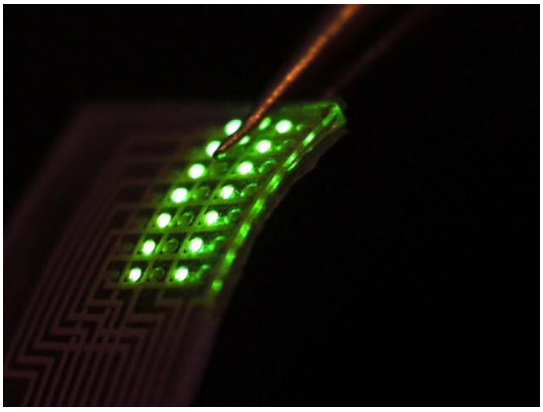

**FIGURE 3**. A Flexible 5 x 7 LED Matrix with Green LED Chips

In Fig. 4 a demonstrator matrix containing 3 x 3 blue LED devices is shown.

**FIGURE 4**. A LED Matrix Containing 3 x 3 Blue Chips

During the experiments it was noticed that the maximum amount of chips which was possible to assemble onto wet paste was about 50 pieces. The paste needed to be wet during chip assembly in order to achieve enough attaching force for chip bonding. The number of the assembled chips can be increased by using high speed pick and place bonding machine instead of manual bonder utilized in this case. In order to maximize yield, the amount of LED chips was beneficial to be smaller than 50 in this case. In the end of the development work, a demonstrator with 150 LED chips was fabricated. It was decided that the most optimal way would be to build it from 6 matrices, each of them having 5 x 5 devices. Each matrix was manufactured following the process described above. These matrices were then attached on the backplane with conductive adhesive Epotek H20E. The backplane contained the electrical connections implemented by screen printing. In Fig. 5 the assembled backplane comprising 6 modules is shown.

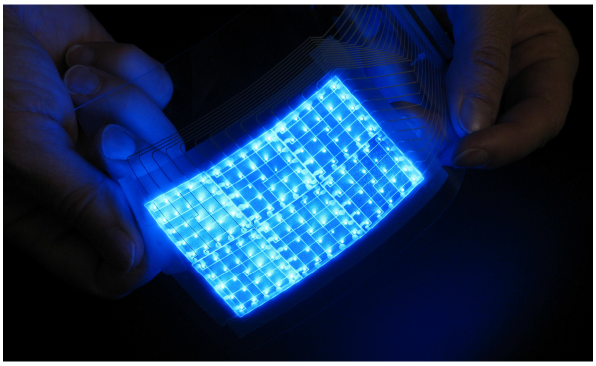

**FIGURE 5**. Assembled Backplane Comprising Six 5 x 5 LED Chip Modules

For demonstration purposes, a screen printed phosphor film was placed above the backplane to illustrate white light backlight illumination structure. The base of processed phosphor paste was commercially available yttrium aluminates ($Y_3Al_5O_{12}$:Ce) phosphor particles supplied by Phosphor Technology, USA. The phosphor particle size distribution was 95% and 5% for particles below 6µm and 2.1µm, respectively. Phosphor particles were added into UV hardenable varnish and mixed with Turbomix blender (10 000 rpm) and ultrasound. The viscosity of the paste was lowered by toluene. Compounded paste was screen printed on a 100 µm thick polycarbonate foil and hardened using UV exposure (1000 W, 20 s). In the hardening process the polymer was cross-linked and became unmoldable for heat and insoluble to chemicals. In Fig. 6 the screen printed phosphor polycarbonate film is placed above the demonstrator backplane.

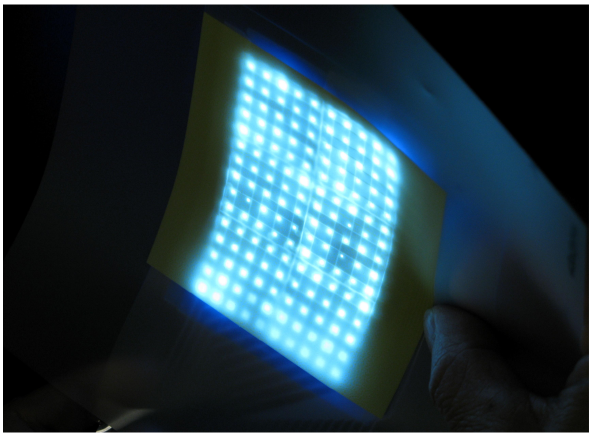

**FIGURE 6**. Screen Printed Phosphor Polycarbonate Film Placed above the Demonstrator

The phosphor film lamination onto the backplane structure was also successfully demonstrated. In addition, a 5 x 5 test matrix structure was used as an insert in injection molding process. The structure successfully tolerated the injection molding process stresses and LED chips were still operational after the embedding process. In Fig. 7 an injection molding embedded test structure is shown.

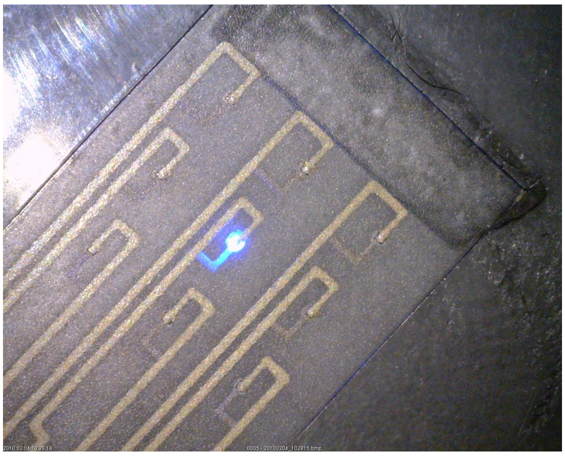

**FIGURE 7**. Injection Molding Embedded Test Structure

## CHARACTERIZATION OF THE STRUCTURE

The characterization of the BLIS demonstrator was performed using 500 mm diameter integrating sphere, model UMLA-C manufactured by Gigaherzt-optik and equipped with X4 light analyzer. The characterized BLIS was put in contact to the 38.1 mm diameter input aperture of the sphere for the light analysis. The integrating sphere system is shown in Fig. 8.

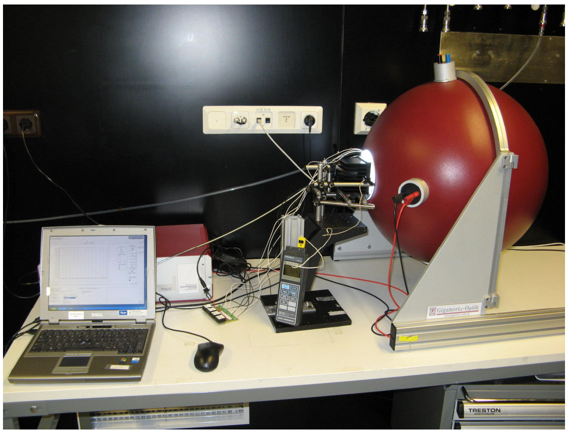

**FIGURE 8**. UMLA-C Integrating Sphere with X4 Light Analyzer

The characterization set-up for illumination uniformity measurement set-up of the 2 x 3 module LED BLIS is shown in Fig. 9. The used camera was PixeLink monochrome CMOS camera with Fujinon HF9HA-1B 1:1.4/9 mm camera objective. Light shaping diffuser of Luminit with 80° diffuser angle was used to further diffuse the light from the led.

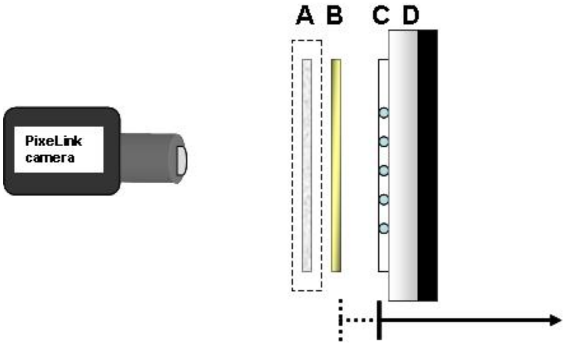

**FIGURE 9**. Illumination Uniformity Measurement Set-up

Set-up for uniformity measurement was as follows: A light shaping diffuser, B phosphor layer, C led module, D back reflector of white $BaSO_4$ or aluminum. The dotted line illustrates the measurement set-up with both diffuser and phosphor layer.

The PixeLink camera was fixed on the focus of the phosphor layer and the LED BLIS demonstrator in touch with back reflector was moved further from the phosphor layer. When the interaction of the diffuser and phosphor layer were measured, the camera was focused on the diffuser surface and the phosphor layer in contact with led device was moved.

The measured characteristic values of the BLIS demonstrator are listed in Table 1.

| Characteristic | Measured value |
|---|---|
| Brightness (cd/m$^2$, $I_{LED}$=2 mA) | 11600 |
| Luminous efficiency (lm/W) | 22 |
| Color temperature (K) | 5550 |
| CIE values (x, y) (Ø 38.1 mm area) | 0.33, 0.41 |
| CRI (25 mm x 25 mm area) | >70 |
| Total power conversion efficiency (%) | 6.3 |
| Blue light to white light power conversion efficiency (%) | 62.4 |

**Table 1.** BLIS Demonstrator Characteristic Values

We evaluated the required device pitch for uniform illumination by the PixeLink camera system by moving the led foil in contact with back reflector away from the phosphor surface, see Fig. 10. The distance between phosphor and led foil was measured by a slide caliper.

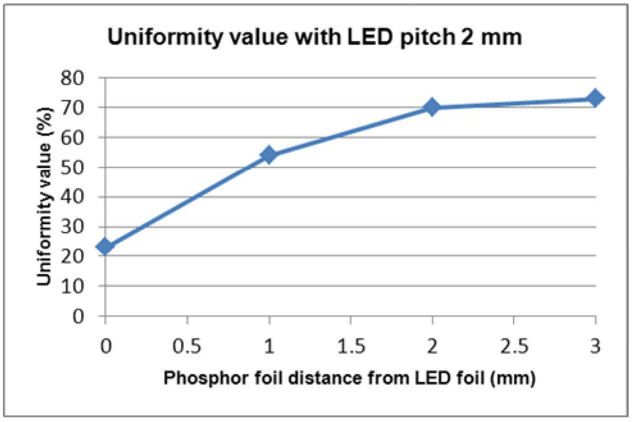

**FIGURE 10**. Achieved Illumination Uniformity when Moving LED Foil Away from Phosphor Foil, Device Pitch 2 mm

From Fig. 10 we can derive that the required pitch to achieve uniformity over 70% with minimum structure thickness is achieved, when the LED device pitch is equal to the allowed structure thickness. In order to achieve better uniformity or brightness for the BLIS, the straightforward approach is to decrease LED device pitch (increase the number of LED devices per surface area). With our present technology the minimum pitch of LED devices is about 500 µm, which leads to minimum thickness of 500 µm for the backlight illumination structure, when the uniformity of the illumination ≥ 70 is required. The brightness of the surface is possible to increase by increasing operating current for the LED devices in addition to just increase the number of LED devices. The measured average brightness of 11600 cd/m$^2$ was achieved using 2 mA individual LED device operating current. We can increase the operating current value five- to ten-fold in the present structure, which in principle results equivalent increase to the brightness value resulting brightness value of 58000-116000 cd/m$^2$. In addition, the luminous efficiency value can be greatly improved by using high efficiency LED devices, more efficient phosphor and decreasing the resistivity of the wires and contacts. It is also possible to improve uniformity of the illumination by implementing variable individual LED device driving electronics. The integration of efficient individual device driving electronics enables low resolution large area display applications, also.

## SIMULATION TOOL FOR SYSTEM DESIGN AND OPTIMIZATION

A simulation tool was developed capable to demonstrate the achievable illumination uniformity and brightness of the system. The simulation tool was implemented using Matlab$^{TM}$ software. The idea in the simulation tool was to define maximum allowed LED pitch to achieve required brightness, uniformity and thickness values for a specific application. The main objective of the simulation tool was to enable optimization of the backlighting system performance against the cost. The cost evaluation of the

BLIS was performed using Cost-of-Ownership (COO) modeling [9].

### Optical Performance Simulation Tool

The optical simulation tool development was based on the characterization results of single led test structure. Characterizations showed the scattering properties of a single test multilayer structure equipped with different diffuser and phosphor film at different distances. The uniformity of the illumination was considered as a main performance parameter of the BLIS system. The idea in the optical performance simulation was to combine the individually produced illumination beams together along the optical axis towards fictitious LCD element in order to compare the achieved uniformity along the optical axis. In Fig. 11 an example of simulated light distribution is shown.

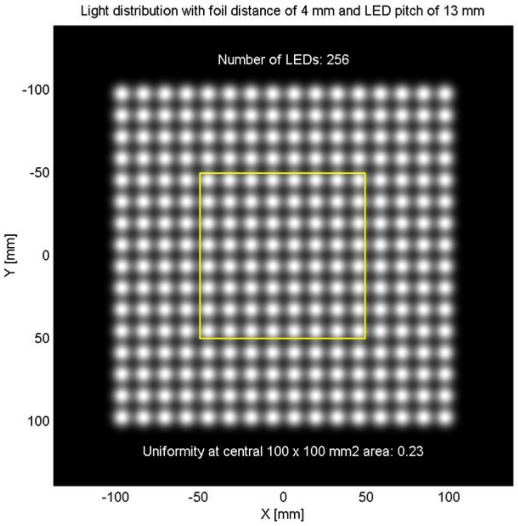

**FIGURE 11.** Example of Simulated Light Distribution

The headline in Fig. 11 shows the distance of the diffuser element (4 mm) from the 200 x 200 $mm^2$ area multilayer LED structure and LED pitch (13 mm). The total number of LEDs is 256 with 13 mm pitch. The simulated uniformity value (0.23) is calculated inside a 100 x 100 $mm^2$ area in order to avoid edge effects.

In Fig. 12 an example of simulated intensity profiles over LED row and between two LED rows is shown.

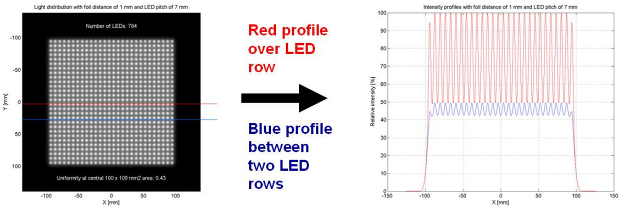

**FIGURE 12.** Example of Simulated Intensity Profiles Over LED Row and Between Two LED Rows

The diffusing effect structures increase light beam mixing and improve illumination uniformity. We used three different components, with diffusing effects, namely a white $BaSO_4$ coated plate, a mirror and an yttrium aluminate ($Y_3Al_5O_{12}$:Ce) phosphor. $BaSO_4$ paint reflectance, when properly applied, is 0.992±0.001. In addition, $BaSO_4$ material is a good diffuser [10]. Mirror was purely a reflective component and it was not producing diffuse scattering. However, mirror introduced a diffusing effect so that increasing the distance between the back reflector mirror and the LED substrate, the uniformity of the illumination in forward direction was slightly improved. The phosphor small particle size and large difference in refractive indices between phosphor and polymer substrate resulted in diffuse scattering of incident and emitted light [11]. In Fig.13 the simulation result of BLIS element LED pitch vs. uniformity with white diffuser at different foil distances is shown.

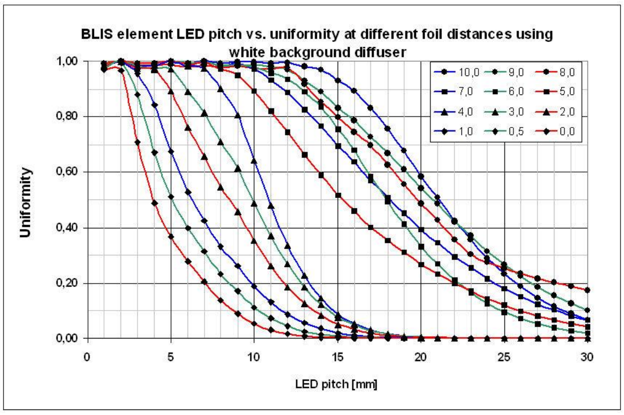

**FIGURE 13.** Simulation Result of BLIS Element LED pitch vs. Uniformity with White Diffuser at Different Foil Distances

In Fig.14 the simulation result of BLIS element LED pitch vs. uniformity with mirror at different foil distances is shown.

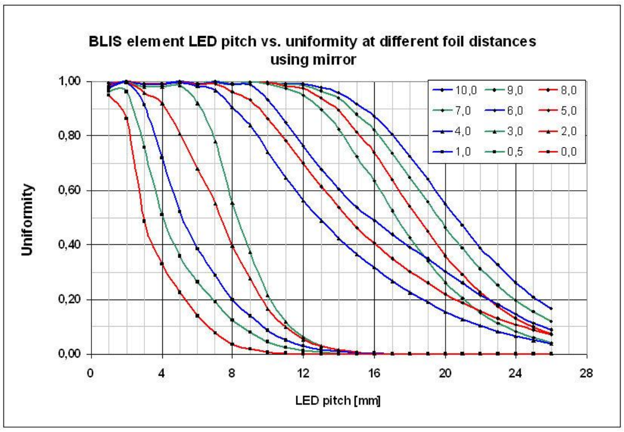

**FIGURE 14.** Simulation Result of BLIS Element LED pitch vs. Uniformity with Mirror Background at Different Foil Distances

In Fig.15 the simulation result of BLIS element LED pitch vs. uniformity with phosphor at different foil distances is shown.

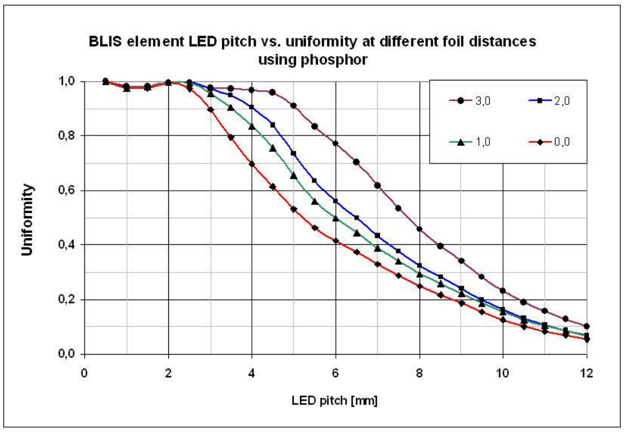

**FIGURE 15.** Simulation Result of BLIS Element LED pitch vs. Uniformity with Phosphor at Different Foil Distances

In Fig. 16 a LED pitch comparison at different foil distances at uniformity value of 80% is shown.

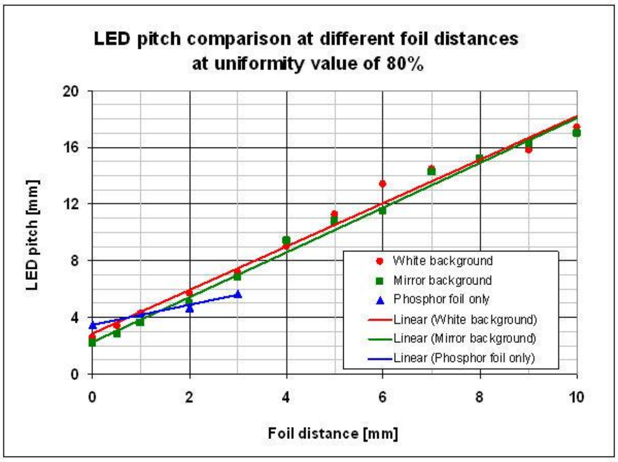

**FIGURE 16.** LED Pitch Comparison at Different Foil Distances Uniformity Value of 80%

From Fig. 16 one can notice that phosphor foil is a very efficient diffuser at short foil distances.

The main advantages of the implemented system compared to traditional light guiding system are easy optical coupling with high efficiency in an integrated and thin package. The uniformity of the illumination can be optimized with variation of LED pitch and the thickness of the structure without any complicated diffractive optics design and especially implementation. The structure is also easily scalable in size and geometry. The developed technology seems to be suitable to produce backlight illumination structures for applications in which thin, high brightness, lightweight, efficient and cost-efficient backlight illumination structure is essential, such as, hand-held devices. In addition, the developed technology seems to be possible to apply in several other applications, such as, information tables, signboards and displays.

### Manufacturing Cost Modeling Using COO

Manufacturing cost per produced module can be evaluated using COO modeling, in which the investments to processing and manufacturing machines, facilities like production floor, accessories, labor and other recurring costs during the lifetime of the equipment are summed up. The cost per produced good module is simply achieved by dividing all the manufacturing costs by a number of produced Good Modules (GMs). Thus COO depends on the production throughput rate, equipment acquisition cost, equipment reliability, maintenance, equipment utilization, throughput, yield, rework and scrap cost and useful life-time of the system. The basic COO is calculated by the following equation:

COO per unit = total cost/number of good-quality products.

COO = (FC + VC + YC)/(L x THP x Y x U)

Where,

FC= Fixed costs (amortized for the period under consideration)

VC = Operating costs (variable or recurring costs, labor costs)

YC= Yield loss costs (scrap and rework)

L = Life of equipment

THP = Throughput rate

Y = Composite yield

U = Utilization

The basic equation for calculating the COO was originally developed for wafer fabrication tools and has become a common reference between equipment suppliers and equipment users in the semiconductor industry [12]. Use of the COO is an implementation of Activity-Based Costing (ABC) that helps in understanding all costs associated with a decision. It improves decisions by relating costs to the products, processes, and services that drive cost. The COO modeling is extremely simple tool and it is very easy to apply. The real challenge in the modeling is to attain the accurate parameter values. Manufacturing speed and yield are extremely important parameters and inaccuracy in these parameter values create inaccuracy in the final modeling result. Especially the yield is a very critical parameter, because the scrap cost increases the cost of a GM very intensively, if the value added in the package is high. Manufacturing cost estimation of a BLIS 25 x 25 $mm^2$ module consisting 5 x 5 LED chips, achieved by COO modeling, is showed in Fig. 17.

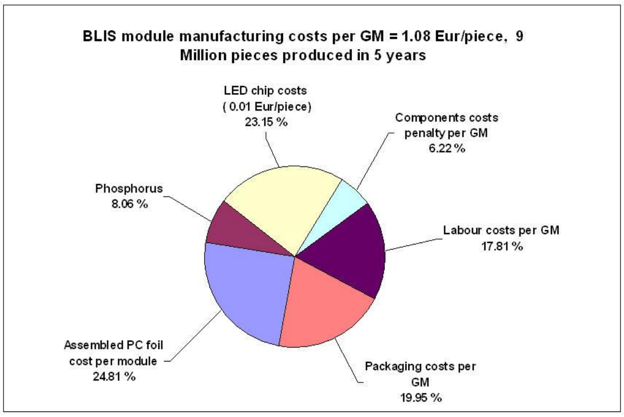

**FIGURE 17.** Estimation of BLIS Element Manufacturing Cost by COO Modeling

From Fig. 16 we can see that the estimated BLIS element cost according to the COO modeling is 1.08 Eur/piece, when 9 Million pieces are manufactured during 5 years. This COO modeling result was achieved using following assumptions: a new production line with new machines is invested, the investments to the machines are amortized during 5 years, the utilization rate of the production line was 0.80 and the yield value used in the modeling was 0.90. The performed simulation result clearly suggests that the assembled PC foil cost and LED chip cost are the most important factors in the manufacturing cost of the final BLIS module.

## DISCUSSIONS

The dominant technology for manufacturing BLIS is typically based on the use of individually packaged SMD LEDs, LGP and diffuser films. Organic Light Emitting Diodes (OLEDs) are offering a competing solution providing thin and conformable backlighting and lighting structures in the future. At the moment the brightness, efficiency and lifetime of OLEDs, however, are not as high as in our proposed solution based on multilayer polymer structures and embedded inorganic LED chips. Therefore it seems that there could be an opportunity for the suggested BLIS technology. The developed technology at the moment allows versatile tuning of characteristics of the BLIS element including tuning of dimensions, brightness, color temperature, CRI and uniformity. One way to transfer excess heat from the LED devices is to use as thin polymer substrate as possible against the heat sink structure. In addition, by using etched copper patterning in the layer L1 in Fig. 1. as a heat spreading layer, the excess heat transfer away from the LED devices can be improved. The achieved lower operating temperature of the LED devices means longer life time for the devices.

The luminous efficiency value can be greatly improved by using high efficiency LED devices, more efficient phosphor and decreasing the resistivity of the wires and contacts. The required number of LED devices is increasing, when the structure thickness is decreasing. On the other way, a thicker structure requires less devices in order to achieve required uniformity. It is also possible to improve uniformity of the illumination by implementing diffractive structures on the foil surfaces applying printing technologies, such as nanoimprint technology [13]. In addition, uniformity of the illumination can be improved by implementing variable individual LED chip driving electronics paving the way towards information signboards and low resolution displays. The work is continued in the future by developing a R2R production capability utilizing fast LED chip alignment and attachment technology. In order to achieve high speed R2R production system a single foil substrate structure solution is required.

## CONCLUSIONS

The requirements for modern backlighting illumination structure are typically high brightness and luminous efficiency achieved in thin and light structure. We have implemented multi-layer polymer structure based on embedded LED devices and a phosphor layer. The demonstrated backlight illumination structure consists of six modules containing 5 x 5 LED chips each, resulting total number of 150 LED devices with 5 mm pitch. The measured key characteristics of the demonstrator were as follows: average brightness was 11600 cd/m$^2$ ($I_{LED}$=2 mA), luminous efficiency 22 lm/W, color temperature 5550 K, CIE values (x=0.331, y=0.411), CRI $\geq$ 70 and total power conversion efficiency of 6.3%.

The developed technology allows versatile tuning of characteristics of the BLIS element including tuning of dimensions, brightness, color temperature, CRI and uniformity. The luminous efficiency value can be greatly improved by using high efficiency LED devices, more efficient phosphor and decreasing the resistivity of the wires and contacts. It is also possible to improve uniformity of the illumination by implementing variable individual LED device driving electronics paving the way towards low resolution large area displays.

Combination of the developed Matlab$^{TM}$ performance simulation tool and the COO tool enables us to estimate the manufacturing cost of a specific BLIS element against the required performance, assisting decision making in different applications and specific individual customer cases.

## AKNOWLEDGEMENTS

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