High throughput R2R printing, testing and assembly processing of flexible RGB LED displays

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***Abstract*—This paper introduces high throughput processing of hybrid flexible RGB LED displays. Processing consists of conductive tracks printing on PET substrate, verification of printed substrate quality by specific characterization equipment and assembly of individually addressable RGB LEDs on substrate using adhesive bonding process. High throughput in manufacturing of flexible displays is achieved utilizing roll-to-roll processes in all steps of the manufacturing process. Utilization of seamless printing tool doubled printing process throughput compared to traditional printing process requiring two printing tools and steps.**

Implemented roll-to-roll automated electrical test equipment enabled high throughput testing and verification of printed substrate web functionality. Testing was a very important step to verify that printed wiring on the web fulfilled quality requirements for the assembly process.

Required SMD components electrically bonded on substrate with R2R assembly machine by utilizing Isotropic Conductive Adhesive (ICA). In addition, Non-Conductive Adhesive (NCA) utilized to provide mechanical support of component, when flexible system bended to smaller than 20 mm radius. Dispensing process noticed to be the most time consuming process in flexible LED display manufacturing, when numerous adhesive dots applied on the substrate. In order to increase throughput in manufacturing, decrease of time used in dispensing process needed. Throughput increase by a factor of ten was possible to achieve by utilizing high speed dispensing process. Increase of more dispenser units in the dispensing process furthermore increase achievable throughput in the manufacturing process.

Two meter long flexible display system demonstrator was designed, manufactured and tested based on processed flexible display element.

Keywords—roll-to-roll printing, characterization, assembly, RGB LED, flexible, display

I. INTRODUCTION

Thin, flexible, large area and possibly transparent platform is aspired for signage and display solutions for several applications. Large area flexible electronics technology provides an attractive possibility for making flexible element to apply in flexible or conformal display applications. Technology enables manufacturing of very thin, potentially large area display elements that can be bent and shaped and enable curved forms for illumination and display applications.

Organic Light Emitting Devices (OLEDs) [1] enable implementation of flexible display elements [2]. Flexible OLED package structure has called as FOLED in the literature [2]. Sensitivity of utilized organic materials to oxygen and water vapor, however, limits the lifetime of FOLED based lighting displays [2][3]. Traditional technology to provide efficient shield to OLED devices has based on placing OLED device between glass plates. Glass as a hermetic material provides adequate shield against these gases. Glass materials, however, are typically rigid and brittle, which hinders their utilization in FOLED systems. A specific flexible barrier films have pursued to provide efficient shield against mentioned gases. Performed research work so far has led to remarkable improvement of the flexible barrier films. The achieved permeation level, however, has not reached level provided by glass, ceramic and metal materials, which considered as hermetic.

Material technologies and packaging solutions applied with inorganic LEDs enable long lifetime of components even in harsh environmental conditions. Inorganic materials are intrinsically much more tolerant to moisture and oxygen than organic materials typically applied in FOLEDs. In addition, applied packaging technologies with inorganic LEDs based on hermetic materials and joints provide effective shielding against moisture and oxygen. In order to construct durable, flexible, large area display system, we have applied roll-to-roll printed plastic substrates equipped with roll-to-roll adhesive bonded individually addressable RGB and RGBW SMD LEDs. Applying roll-to-roll process in both printing and bonding, we achieve high throughput and cost efficiency for hybrid flexible system manufacturing [4]. Testing of printed substrate roll provides verification of substrate for assembly process. Testing of assembled roll after bonding process generate information about assembly process yield and

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provide closing a feedback loop to assembly process control. In addition, testing provide verification of flexible LED display roll final quality.

II. Flexible Display element

A. Design of Flexible Display Element

Design of continuous display substrate layout originates from the performed concept design of the display system in which main targeted characteristics of the display, such as measures (200mm x 2000mm) and pixel pitch (25mm) specified. Display element layout design depicted in Fig.1.

Continuous display substrate in case means that several meters long flexible display element introducing alfa-numeric information can be implemented based on substrate design. In addition, preliminary material, component and production methods selections performed. Specific individually addressable RGB SMD LED, type SK6812B, selected for display element design. This component enable displaying alfa-numeric and graphical video information. Component is available in two package sizes 3535 and 5050. Both LED types utilized in this study. 3535 package was selected to be applied in flexible alfa-numeric display element due to its smaller size, see Fig.2. Smaller size component potentially enable smaller mechanical stresses to ink layer and bonding materials when substrate is bend. In addition, a 1206 size 33µF SMD capacitor by TDK utilized in system also (Fig. 2).

Both of these SMD components are possible to assemble on substrate using both soldering and adhesive bonding processes. Utilization low-cost flexible plastic substrate means that standard reflow soldering process is not possible to apply due to material low thermal properties and adhesive bonding processes based on Anisotropic Conductive Adhesive (ACA) or Isotropic Conductive Adhesive (ICA) need to be applied instead. Display element layout design based on thin and flexible polyethylene terephthalate (PET) substrate equipped with silver ink printed conductive tracks and RGB SMD LEDs.

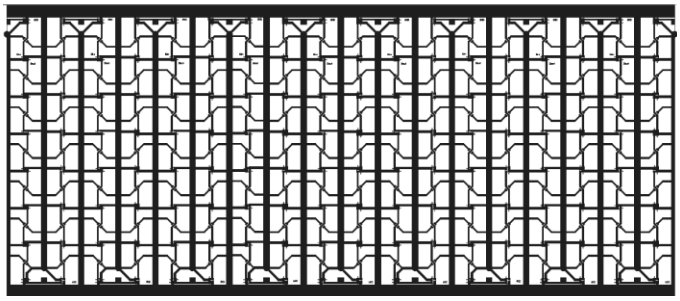

Fig. 1. Display element layout design

Fig. 2. Selected LED and capacitor components for LED display element

B. Printing of Display Element Substrate

Traditional rotary screen printing of continuous substrate requires two printing phases due to the fact that seam area in the traditional printing tool can’t be equipped with printing features and non-printed area between repetition lengths is generated. In order to form continuous circuitry for display element, another printing step with another tool need to apply to cover empty areas between repetition lengths. In order to increase cost efficiency and speed up rotary screen printing process, seamless tool designed to process continuous LED display substrate in single-phase printing process. Seamless tool enable printing of continuous circuitry in rotary screen printing process in single printing step, which potentially doubles printing process speed. In addition, tool cost decreased about 50%. In addition, used work time to tool washing and installing reduced about 50%, also.

Seamless tool designed, manufactured and assembled in MAXI pilot printing machine and continuous LED display substrate rotary screen printed on Melinex ST506 PET substrate using Asahi LS-411AW silver ink. LS-411AW silver ink selected to application due to its specified low sheet resistance (under 40mΩ/sq for 10µm thick layer) and flexibility (under 10% decrease to sheet resistance after 10 times 360 deg bending). These both characteristics, which both are very important characteristics in flexible LED display element.

Continuous LED display substrate enabled free adjustment of final display system length. In practice the maximum length of the display element limited by achievable resistance of current push bars. Display element length of two meters targeted in this case. In Fig.3 MAXI roll-to-roll pilot printing machine is shown and in Fig.4 rotary screen printed continuous display element printed with seamless tool are shown.

Fig. 3. MAXI roll-to-roll pilot printing machine

Fig. 4. Rotary screen printed continuous display element substrate

C. Assembly and Testing of Flexible Display Element

In order to verify the functionality of printed substrates with different functionalities, VTT has taken into practice an automatic functional roll-to-roll test platform (TESLA). Fig. 5 presents the automated roll-to-roll functional test system completely.

The main parts of TESLA are reeling unit, bed-of-nails fixture and electrical measurement equipment. The reeling unit consists of wind/unwind system and is dedicated to move the web containing printed electronic structures. It includes also machine vision features for automatic alignment of the web and bed-of-nails.

The bed-of-nails fixture is a layout-specific test board assembled with wired pogo-pins to provide physical contacts from the test equipment to the web.

The actual measurement operations is performed with an automatic functional tester including general-purpose test and measurement equipment such as LCR meter, DC power supplies and an electronic load. In addition to roll-to-roll operation mode, the same automatic functional test equipment and test fixtures is possible to use in sheet-to-sheet mode with manual alignment of sheets on dedicated measurement area.

Fig. 5. TESLA roll-to-roll test platform

Printed substrate sample printed for SK6812 5050 size RGB LED, which length was 70 meters, characterized with TESLA using layout-specific test fixture (Fig.6) and dedicated software running in an industrial PC installed in the test system. In the actual testing two possible failure types probed, namely short circuits in component bonding areas and defects in wiring between bonding areas. According to the performed tests, not a single short circuits nor wiring defects observed in the sample, so the sample was fully functional and verified for component assembly.

LEDs and capacitors assembly on two meter long printed substrate performed using Datacon 2200EVO roll-to-roll bonding machine, see Fig. 7. Component bonding performed in two steps. Component electrical bonding performed with EPO-TEK H20E ICA and mechanical support bonding with Loctite 3525 NCA. EPO-TEK ICA was heat cured and Loctite NCA UV cured. ICA adhesive used in electrical bonding because SMD component based on low thermal conductivity plastic package material did not support ACA bonding. Mechanical support bonding applied to improve reliability in cases, when substrate is bend below 20 mm bending radius. Transparent PET substrate enables visual inspection of component bonding from bottom side. In Fig. 8 an example of LED ICA bonding is shown from top and bottom side. In Fig. 9 an example of capacitor ICA bonding is shown from top and bottom side.

In case that speed of adhesive dots dispensing on substrate is the bottleneck in the manufacturing process throughput, it is obvious to tackle that specific bottleneck. We tested a new dispenser unit, which increased dispensing speed by a factor of ten compared to the original dispenser in Datacon 2200EVO bonding machine. By utilizing two dispenser units in the system, dispensing speed is possible to increase by factor of twenty compared to the original level.

Fig. 6. Test fixture for testing sample dedicated to SK6812 5050 size RGB LED foil testing

Fig. 7. Datacon 2200EVO roll-to-roll bonding machine

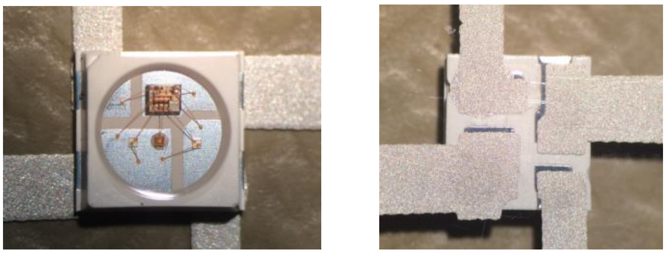

Fig. 8. Example of LED ICA bonding from top (left) and bottom (on right)

Fig. 9. Example of capacitor ICA bonding from top (left) and bottom (on right)

III. FLEXIBLE DISPLAY SYSTEM BASED ON FABRICATED ELEMENT

A flexible alpha-numeric display system demonstrator was designed, implemented and tested based on assembled flexible display element, see Fig. 10. A mechanical supporting system consisted of bottom plate, 3D printed bottom and top parts and up to 2 meters long metallic pole consisting of six short pieces. Display element assembled between 3D printed parts equipped with holes for pole. System relatively low total weight of below five kilograms and support system easy assembly and disassembly characteristics enabled system easy transfer and use as movable demonstrator system.

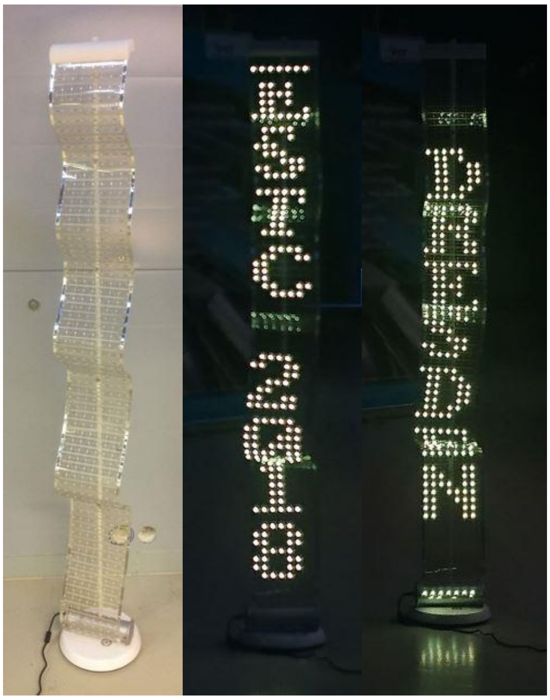

Fig. 10. Flexible display system non-operational (left) and operational (middle and on the right)

Specific power supply provided operational power to LED display element, wireless connection and control electronics of the display element. Displayed information transmitted wireless to the control electronics utilizing Android mobile phone Bluetooth™ connection to control electronics VTT's TinyNode V3.0. A JavaScript-powered webpage that utilizes the experimental Web Bluetooth API in Google Chrome browser designed and implemented to create user interface for the display system. Edited alpha-numeric scrolling information transmitted wireless on-the-fly to the display system. Refresh of new information to the display system occurred below one second using Android mobile phone. As a conclusion, operation of the flexible display system controlled by wireless user interface demonstrated successfully.

IV. CONCLUSION

The achieved test results showed that seamless rotary screen printing is beneficial to simplify and speed up printing process. Printing throughput doubled using seamless printing tool compared to use of traditional printing tool.

Automated roll-to-roll characterization of printed substrate web provides verification of substrate and enables automated processing and documentation of the measurement data.

Dispensing process, however, typically limits throughput in the flexible display element manufacturing process. The performed study proved that dispensing process speed is possible to increase by a factor of ten by using tested dispenser compared to Datacon 2200EVO dispenser. In addition, dispenser equipped with two dispenser heads increases dispensing process speed by factor of two resulting total dispensing process speed increase by a factor of twenty compared to speed achieved with Datacon 2200EVO.

Implementation of display system based on processed flexible display element demonstrated successfully. According to achieved result high throughput manufacturing of cost efficient large area flexible display systems seems feasible.

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REFERENCES

[1] C.W. Tang and S.A. VanSlyke, “Organic electroluminescent diodes”, App. Phys. Lett. 51, 1987, 913.

[2] P- E. Burrows et al., “Ultra berrier flexible substrates for flat panel systems”, Displays 22, 2001, 65-69.

[3] J. S. Lewis and M. S, Weaver, “Thin-film permeatition-barrier technology for flexible organic light-emitting devices”, IEEE J. Sel. Top. Quantum Electron. 1, 2004, 45-57.

[4] K. Keränen et al. “Roll-to-roll printed and assembled large area lighting element”, Int J Adv Manuf Technol (2015) 81:529–536.