Building Active Matrix By Additive Manufacturing (BAMBAM)

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Abstract

The overall objective of the BAMBAM project is to demonstrate the feasibility of an active-matrix µLED display without TFT on glass consisting. It will represent an advanced in flexible display solution, having promise for improved brightness, power consumption, and robustness relative to other flexible displays. The project will result in key technologies for the growing flexible µLED industry, which will open doors for a display industry in Europe and to fit within circular economy principles.

Author Keywords

Microled, Active Matrix, Display, Flexible, Mass Transfer, Printing, Additive Manufacturing, Pixel, Driver, µIC.

1. Display manufacturing standards

In standard displays (for smartphone, IT, TV) based on Organic Light Emitting Diodes (OLEDs) (Figure 1), all the active elements, providing the current to the emissive elements in pixels, are manufactured together by successive coatings and structuring by photolithography of thin film layers to build an active matrix of thin film transistors (TFT) on huge glass substrates.

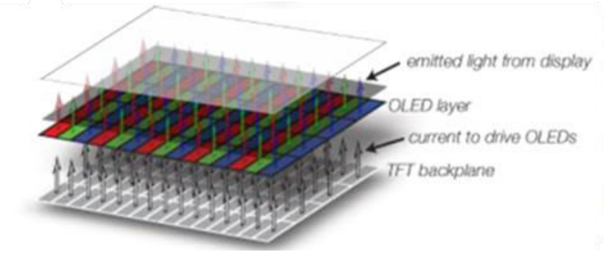

Figure 1: Principle of an OLED display

The TFT technology induces high market barrier to any entrant and has a tremendous energy consumption. In the case of TFT/LCD, OLED or TFT/µLED, the TFT active matrix is made on very large glass substrates, up to 10m², with a 2 to 4µm resolution limit and at the cost of expensive semiconductor factories with the size of several soccer fields and mainly located in Asia.

These factories have a very high electrical energy consumption (≈500MWh/yr./factory) (1). They are not a sustainable solution for an overall reduction of humanity's ecological energy-related footprint. And following China's 20B$/year investment in several new factories since 2017, each production line, requiring an investment of a few billion euros, this manufacturing and environmental footprint will continue. Besides, this huge figure prevents any newcomer from entering the market unless it is fully financially supported by local governments. It is thus very difficult for Europe to re-enter this market without a technical disruption.

Other drawbacks of the thin film layer-based technologies on glass are the rather high input impedance of the metal coatings that are used for the current supplies to the pixels and the very limited availability of through glass vias (TGV). Though through-glass vias are being developed (2), they are very expensive for display technologies (3) hence preventing any direct contact from the rear side of the glass to the center of the display area and any opportunity to optimize the voltage drop on the power supplies.

When operating the display, each emissive pixel is driven by a small electrical current. On glass, considering the lack of TGV, this current can only be supplied from the edges of the display area. Then, considering the impedance of the metal layers, from the edges of the display area to the central pixel element, there can be a significant drop in the power supply voltages to the LED due the joule effect. To compensate for the voltage-drop on the power bus lines, the designer must increase the power supply voltage, leading to very significant increase in power consumption.

For OLED and LCD, there is a need for a seal ring to protect the liquid crystal or the OLED from moisture or oxygen. It adds another constraint on the periphery of the display as shown on Figure 2. It is impossible to design a seamless display on glass. Large video walls made of assembled LCD or OLED panels are always showing a tiny but visible dark area between each single display element. Thus, large OLED or LCD displays have to be manufactured on single pieces of glass which both limits the display area or extends the mother glass size thus the factory cost.

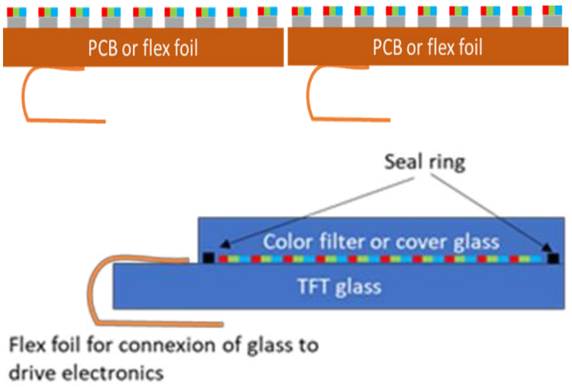

Figure 2: Edge of a LCD or an OLED panel

2. Display opportunity with µLEDs

A new display technology is emerging. The principle of this technology is to have a µLED at each pixel of the picture. On the other end, µLEDs (Figure 3) are manufactured on a separate substrate and cut into single elements which are then transferred on the display substrate.

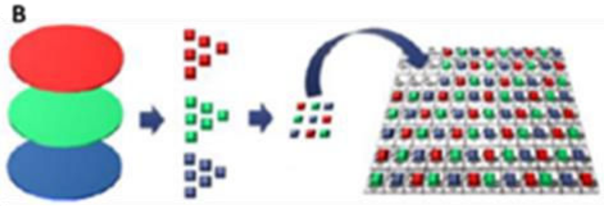

Figure 3: Principle of a µLED display

Such high-resolution displays require transferring very small LEDs down to a size of 15µm or less, to reduce µLED display costs which mostly dependent on µLED sizes and quantity.

µLED are not grown on the same substrate as their control electronics. Printed circuit boards (PCB), rigid or flexible, are made of successive lamination of insulating layer and rather thick metal layers. They offer interesting solutions as a backplane on which to assemble the µLED. Compared to glass, many metal layers with very low resistivity and through PCB vias are available. They enable low impedance and easy transfer of any equipotential to the rear face of the panel. Thus, they offer solutions to several issues the displays on glass are facing. They also offer, with same or even better design rules, the opportunity to have flexible panels. Flexible TFT displays are on polyimide or on ultra-thin glass are complex to manufacture, with lower yield and therefore significantly more expensive.

With LEDs on PCB, as shown on Figure 4 , since through PCB vias are available it is possible to put each display element next to each other within a pixel pitch. LEDs on PCB therefore dramatically improve the visual experience (uniform pixels, no edge between panels) while tremendously reducing energy consumption at the same time.

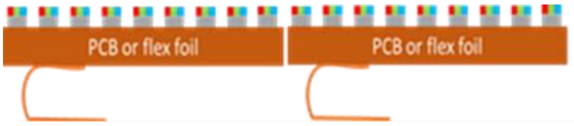

Figure 4: PCB tiling for large displays

Being able to assemble LED displays on PCB or flex foils to build bigger displays with the very aggressive pixel pitch enabled by the micro printing solution paves the way to a new era in the consumer electronics world.

3. The BAMBAM project: making active µLED printing on flexible foil possible.

All displays on glass, LCDs, and OLEDs, use thin film transistors (TFT) to control the amount of light emitted by each pixel. When moving from glass to PCB substrates, the TFTs are not available anymore. To cope with this issue and to offer even more functionalities in each pixel, ALEDIA has been developing the concept of the active µLED pixel, or Smart PIXEL. Each LED is physically attached to a driving circuit on CMOS in a wafer-to-wafer process prior to the transfer on the display surface. This is possible due to ALEDIA's patented process to grow LED nanowire GaN directly on silicon, making the wafer-to-wafer process industrially feasible. It is indeed much more difficult to assemble two different materials in a wafer-to-wafer process while it is very common to have 2D LED on sapphire and a CMOS circuit on silicon. ALEDIA can therefore propose active µLED pixel elements that do not require the use of TFTs on glass.

For standard OLED displays, the cost of the display is directly related to the surface of the displaying area: the cost of the active matrix on glass and OLED is almost the same for 65" full HD and a 65" 4K. For a µLED displays the cost of the display is defined by the quantity of µLEDS and the size of each µLED (the smaller the µLEDs, the more can be manufactured from a single wafer, the cheaper they are). Thus, at first glance, the cost of the LEDs for a 65" 4K TV display will be 4 times the cost of the LEDs of a 65" full HD, considering that it is possible to use the same LEDs per pixel in both cases and that luminance is sufficient. It is a major challenge of the display LED manufacturers to reduce the size of the LED to make the cost of displays compatible with the market trends and expectations.

However, PCBs, which can offer very low impedance bus lines or power planes, cannot achieve very tight design tolerances. The typical trace width and spacing that can be manufactured on large size PCBs on high volumes and low cost, is bigger than 50µm. It is one order of magnitude larger than the tolerances routinely achievable on glass. Considering a 4 contacts RBG chip (1R, 1G, 1B and 1 common) or an active pixel with 4 contacts (Row, Column, VDD and GND), it would be possible to consider a 15x15µm chip for transfer on an active matrix on glass while using a PCB requires a chip of at least 150x150µm². Although an RGB chip of 150x150µm² is almost good enough to serve all display sizes above 12" in full HD standard, when changing the size of the LED from 15x15µm² to 150x150µm², the cost per LEDs is multiplied by 100 (not considering the dicing street impact and the yield impact).

The BAMBAM project will bring to TRL4 the additive processes to print active µLEDs (ALEDIA's Smart Pixels) displays on flexible foils. This will be achieved through each partners' fields of expertise to develop a new disruptive display technology consisting of the following key-elements:

- ✓ ***Epitaxially grown blue GaN µ-LED on Si-wafer****, allowing unprecedented wafer-to-wafer bonded to CMOS driving circuitry (active µ-LED) though known and mastered processes in foundries. [Aledia, XDisplay]*
- ✓ ***Mass-transferable** by elastomer stamps compatible with different substrates (**flexible/rigid**) after wafer-dicing [Aledia, XCeleprint]*
- ✓ *Contacted by **µ-printing** with Ag-infused ink (both for power and signal distribution) by developing (i) dedicated ink formulations compatible with µLED application and flexible foils and (ii) expanding printing process to µLED displays [XTPL, University of Stuttgart]*
- ✓ *Color-conversion by **µ-printing** with QD infused ink (both for red and green) through the development of a process-stable and RoHS-compliant QD-ink that enables outstanding wide-color gamut micro displays with an efficient color conversion of the blue µLEDs to red and green. [XTPL, University of Stuttgart, QustomDOT]*
- ✓ ***Having a strong foothold in, and understanding of, the professional b2b visualization market** allowing to implement as soon as TRL3 and 4 the eco-design of the display to ensure the minimal environmental impact [Barco]*

The micro printing solution proposed by XTPL(4) and the University of Stuttgart offers the opportunity to have very narrow metal lines, down to 1µm in width, but also to have a very accurate positioning of the lines with respect to the structures they are interconnecting. They should provide similar design tolerances as photolithography on glass but they can be used on PCB. Micro printing of narrow metal lines could also be compared to wire bonding (Figure 5) of components placed on a PCB (COB technology for Chip On Board). However, the minimum size of the wires is 15µm and the size of the bonding pads cannot be lower than 40µm which does bring a significant improvement compared to standard PCB design tolerances. and gives another benefit of the narrow silver wires.

With µprinting of narrow metal lines on PCBs, it is possible to:

- ✓ *Have very small µLED dimensions, down to the range of 30µm to 60µm size for RGB components (ie 10 to 20µm)* *size is not limited anymore by the design rules of the PCB*

- ✓ *Take advantage of the low impedance of metal layers on PCBs*
- ✓ *Have access to tiling with seamless tiles (which is not possible on glass) thus enable the manufacturing of large displays but based on smaller elements, requesting smaller machines footprint for manufacturing*
- ✓ *Have access to substrates and entire displays without the huge CAPEX of a TFT display fab.*

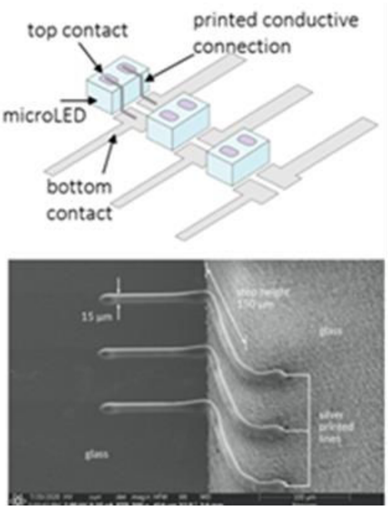

Figure 5: contact between µLED and substrate

It the purpose of the BAMBAM project to consider all additive solutions: electrical, optical or assembly to manufacture large flexible active µLEDs displays on standard PCBs or flex foils.

4. Active MLEDs to save energy.

Saving energy during manufacturing. TFT factories are not a sustainable solution for an overall reduction of humanity's ecological energy-related footprint. Each plant has a very high energy consumption: a Gen 6 TFT-LCD panel plant uses 506GWh. This corresponds to the electricity consumption of a 100 000 inhabitants city. The new display design developed in BAMBAM removes the need for TFT panels and consequently the need for fully TFT-dedicated plants, to regular foundries used throughout the micro-electronics sectors, therefore inducing scale economies by allowing a single plant to manufacture several types of devices. A typical IC foundry consumes half the energy of an average TFT plant. The increase in energy consumption by a foundry manufacturing µLED displays will be marginal compared to the fixed energy consumption that will happen anyway (with or without the added display manufacturing activity).

Saving energy during the use phase. With active matrix LTPS TFTs, it is estimated that the power loss in the TFTs reaches almost 70%. In such displays, only 30% of the power goes to the emitter material or device. Even if µ-LEDs are twice as efficient as OLEDs, then the whole display will only get to be around 15% more efficient" The disruptive technology proposed in BAMBAM will not suffer from these TFT losses as (a) the CMOS driving electronics is integrated in the µ-LED, and (b) the considered substrates (RF4, flex foil) allow power supplies planes and through substrate vias with a resistivity much lower than ITO by a factor of 100 to 1000.As such, the technology developed in BAMBAM is expected to have a power consumption of 0.2W/dm2 (@ 300nit) or lower by 2030, roughly halving the Specific energy use in W/dm2 of new TVs by 2030(5).

An eco-designed approach for the European display industry. Besides energy savings, BAMBAM will positively impact the environment through two major levers: a better reusability and the reduction of F-gas consumption, all of them resulting from the removal of the TFT layer. 98% of a current TV can be recycled. However, this is far from easy regarding the LCD and OLED panels, which are complex sandwiches (Figure 6) (6) which are thermally treated in incineration plants to recover the small amount of contained metal.

The glass fraction, accounting for 85% of the panel, ends up in the slag together with oxidized metals, and no recycling process is yet available at industrial scale. The intrinsic design proposed by the BAMBAM project, allow µLEDS removal from the substrate for example through abrasion, to be recycled to recover materials of interest (Si, Ga notably if the Ga concentration is >100ppm). Consequently, the substrate (glass, PCB, flexible foil…) does not suffer from a thermal treatment and can be reused and resubmitted for micro-printing of µLEDS, silver wires and color conversion.

In BAMBAM, LED contacts to the backplane are made through silver wires directly printed on the metals (Cu) on the substrates (flex foil or PCB), thus removing the need for conductive layers of indium-tin oxide (figure 6). Indium (6) is still used in the LED manufacturing process but for a 10% of the previous coated surface. It is considered as a strategic material mostly used for displays since production boomed from 149 tons in 1994 to 819 tons in 2014. While QDs used for color conversion are based on InP core material, they are covered with II-VI shells, as ZnSe or ZnS. Indium content in QD material is thus very low.

Figure 6: ITO layers in LCD

Finally, F-gas are considered super greenhouse gas. SF6 for example is considered 23500 times more harmful to the climate in terms of its global warning potential than CO2 and has an estimated lifetime in the atmosphere of 3200 years. The technology developed in the BAMBAM project will contribute to the further reduction in the use and emission of these super greenhouse gasses as dictated by EU-legislation as the total surface area that will need to be etched for the same display area (i.e., Si-wafer for densely packed µ-LED and driving electronics) will be significantly less than for the current TFT/LCD, and emerging TFT/µ-LED technology (i.e., LTPS wafer must be etched at the same size as the final display). This implies a lower need for the use and consumption of these chemicals.

At the core of the BAMBAM concept is the reconciliation of the developed technologies with the end-users needs and requirements as well as with existing and upcoming environmental regulations. To ensure that this is achieved, specifications that are an optimal compromise between end-user needs and requirements, environmental performances and technical constraints will be defined early in the project. As a first step, the material and processes will be developed, and their performance and compatibility will be assessed through test vehicles. In a second step, the processes will be further developed and integrated into display demonstrators. The targeted test vehicle will be sufficiently representative of the final demonstrator to decouple the process development aspects from more system related aspects that will be required for the full demonstrator. The technical and environmental performance of the developed processes and materials will be continuously assessed during the project and the combination of both will be considered to design the final display design and operational architecture. The main component of the targeted display, the targeted processes and the associated challenges are described below.

5. Acknowledgment

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6. Conclusion

BAMBAM will combine the development of cutting-edge materials with the development of processes for the additive manufacturing of µLED displays. This includes:

- The development of a high-resolution printing process to enable contacting of smaller µLEDs onto new substrates
- The development of µLED of reduced size and their compatibility with silver micro-wiring.
- The development of a new printing technology for the patterning of a QD-based color conversion module (CCM) at a lower pitch both at wafer and chip level
- The integration of these technologies into fully functional display demonstrators

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