Eliminating TFT backplanes in microLED displays using ultra precise deposition (UPD) printed interconnects

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ABSTRACT

Developing microLED processes compatible with the production of fine pitch displays of TV size is one of the main challenges to exceed their limitation to small screens such as found on microLED based smartwatches. The EU funded project “Building Active matrix MicroLED displays By Additive Manufacturing” (BAMBAM) develops unique manufacturing technologies for realizing fine pitch displays based on active microLED pixels which can be mass transferred. One of the key technologies is printing of electrical and optical structures with an Ultra Precise Deposition (UPD) technique. This paper presents first results of UPD printed Ag wires realizing the interconnections between pixel driver ICs and microLEDs. Therefore, the influence of different substrate types, such as Glass, PCB and flex PCB, on the printing processes were evaluated. Additionally, a sidewall insulation process by insulator printing was developed to enable Ag ink wire printing on chips with non-insulated sidewalls. The BAMBAM technology developments shall enable a renewal of the European display industry by removing the need for thin film transistor arrays for addressing large size, fine pitch microLED displays.

Keywords: Additive Manufacturing, Ultraprecise Printing, Digital Pixel, microLED

1. INTRODUCTION

The BAMBAM project is an EU funded project driven by a consortium of seven members: Aledia, XDisplay, X-Celeprint, XTPL, QustomDot, Barco and the Institute of Large Area Microelectronics (IGM) at the University of Stuttgart. The project is dedicated to address the fine pitch video wall (VW) market segment with a pitch equal to 390 µm (home theater video wall). The main goal in BAMBAM is to use additive manufacturing technologies to build a microLED display without using Thin Film Transistor (TFT)-backplanes. This opens the doors for a display industry in Europe which is in addition more sustainable than conventional display manufacturing due to the elimination of the high energy consuming TFT backplane fabrication [1].

This paper presents the general BAMBAM process, first results made by the BAMBAM consortium and more specific the investigations at the IGM. The scope for the IGM was to elaborate the influence of different substrates (Glass, PCB and flex PCB) to the UPD printing with Ag nanoparticle ink. Especially their effect on the printing process, the resolution, the temperature budget and the possible need for planarization were defined to find the best suitable substrate for the BAMBAM process. After defining the process parameter, a first batch of microLEDs and microICs were successfully connected through UPD printing. An additional special requirement for the microLED interconnect was to insulate the chip walls to avoid short circuits on that early batch of diced microLEDs.

2. BACKGROUND

This chapter describes the role of TFT backplanes in microLED displays and the related issues which will be solved through the BAMBAM approach described in the second section of this chapter.

2.1 TFT backplanes in microLED displays

The principle of a conventional microLED manufacturing process relies on a TFT backplane which controls each subpixel. This is because the microLEDs must be manufactured on a different substrate than the controlling structure. The microLEDs are mounted on the top of the backplane by mass transfer. The minimum pitch is therefore driven by the mass transfer and wire bonding rules. The TFT backplane is usually made on glass because of the higher achievable resolution than on rigid or flexible PCB. One drawback in using a backplane made with thin film technology is the high impedance of metal layers. This high impedance is then reducing the efficiency of each microLED depending on the position on the display [1]. Another issue of this conventional approach comes up when single pixels are not working because of defective LEDs on the wafer [2]. In this case a lot of effort is required to remove a not working pixel or repairing it [3].

2.2 The BAMBAM Pixel

Additive manufacturing through UPD printing of Ag nanoparticle ink is the key technology of the BAMBAM concept. This deposition method was developed by XTPL [4] and is realized in the so-called Delta Printer which was for the first time commercially sold to the University of Stuttgart in 2021. This printing method has a positioning accuracy of ± 2 µm and is able to print structures down to a width of 1 to 10 µm. In comparison to bonding with a conventional wire bonding system, this technology makes it possible to use similar design rules like lithography on glass. Based on this process the BAMBAM consortium designed a new innovative microLED pixel integration (**Figure 1**).

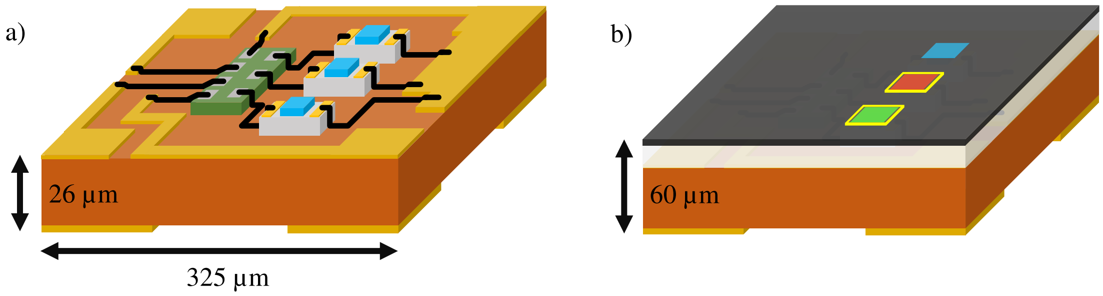

Figure 1: MicroPackaged RGB Digital Pixel by Additive Manufacturing, a) after printing Ag interconnects b) after color conversion layer-stack

The pixel is realized by X-Celeprint's mass transfer of nanowire microLEDs from Aledia and driver microICs from XDisplay to a polyimide flex PCB, the so-called microPackage [5]. After that connection lines are printed by the UPD printer from XTPL with a process developed by the IGM. To create a RGB pixel on three mass transferred blue microLEDs, a patterned black matrix filled with quantum dots developed by QustomDot using XTPL's UPD system will be realized on top of the microLEDs (**Figure 1**). Afterwards, this microPackage is diced into 325x325 µm^2 pixels that are compatible to pick and place on a fine pitch flexible tile which has a strongly simplified structure due to the active driving of the pixel (**Figure 1 a)).** This approach opens the possibility of pre-testing each pixel before pick and place, which increases the yield and removes the need of repairing pixels of the microLED display.

3. RESULTS

This section describes first results of the BAMBAM project after one year of development. Before the integration on the microPackage, all individual process steps are investigated separately for debugging purposes.

3.1 Nanowire microLED

The microLED produced by Aledia is based on a GaN nanowire array grown on a Si-wafer [6]. Compared to LCDs and OLEDs they offer higher brightness levels and lower energy consumption. The development regarding to the microPackage aims to realize a size before dicing of 90 µm x 50 µm and after dicing of 70 µm x 30 µm (**Figure 2**). The active area for light emission will be 30 µm x 40 µm. The BAMBAM microLED is designed for two front side pads which will be compatible with micro printing of Ag interconnects.

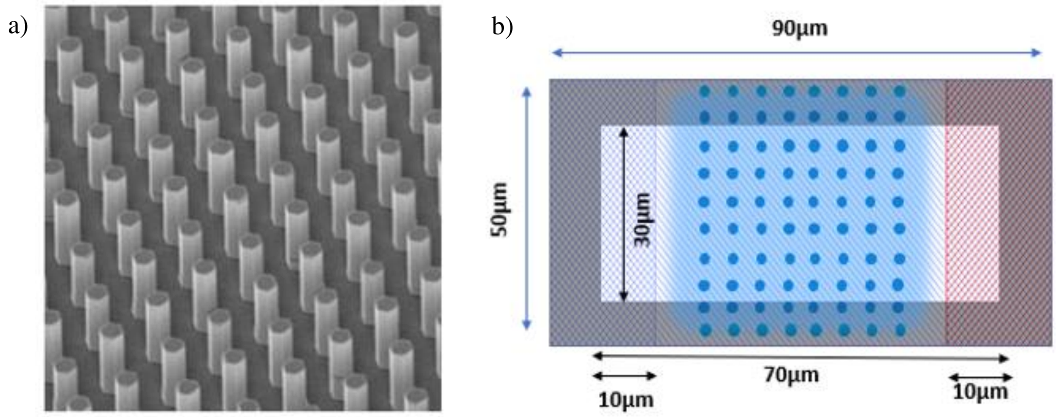

Figure 2: a) SEM picture of the nanowire µLED b) BAMBAM microLED device

3.2 Mass transfer of microIC pixel driver and microLEDs

Transferring the microLEDs and microICs is based on X-Celeprints existing technology to mass transfer microIC pixel driver. The microLED transfer process is based on using elastomer stamps to pick and place a large amount of devices at the same time [7]. The mass transfer of the microICs from XDisplay is based on the anchor and tether method, which uses a sacrificial layer below the die (**Figure 3**). After attaching the die, the stamp force causes the tether to break and releases the device. This allows to transfer the microIC with an accuracy of ± 1.5 µm [8].

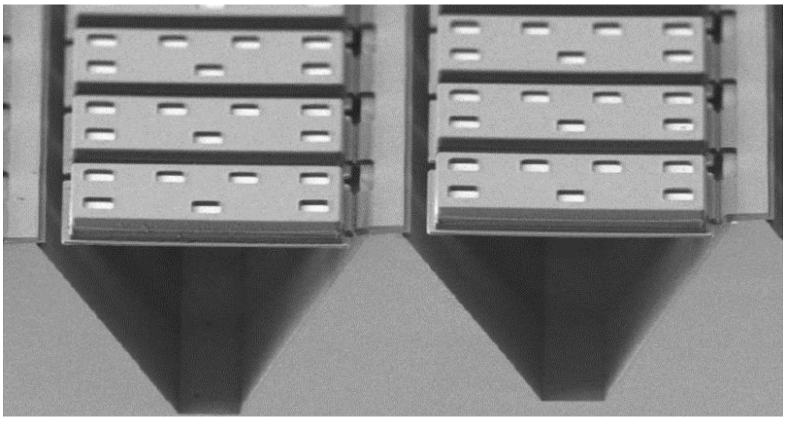

Figure 3: Cross-Sectional micrograph of microICs after formation of the anchors and tethers

To verify the BAMBAM Ag wire printing approach and transferring accuracy, a Glass test vehicle with gold contacts was designed (**Figure 4**). The test vehicle provides a substrate contact for each microIC port. The size of each port is 5x5 µm^2 and has a minimum pitch of 25 µm. After printing each microIC port to its substrate connection it is possible to verify the functionality of a single chip.

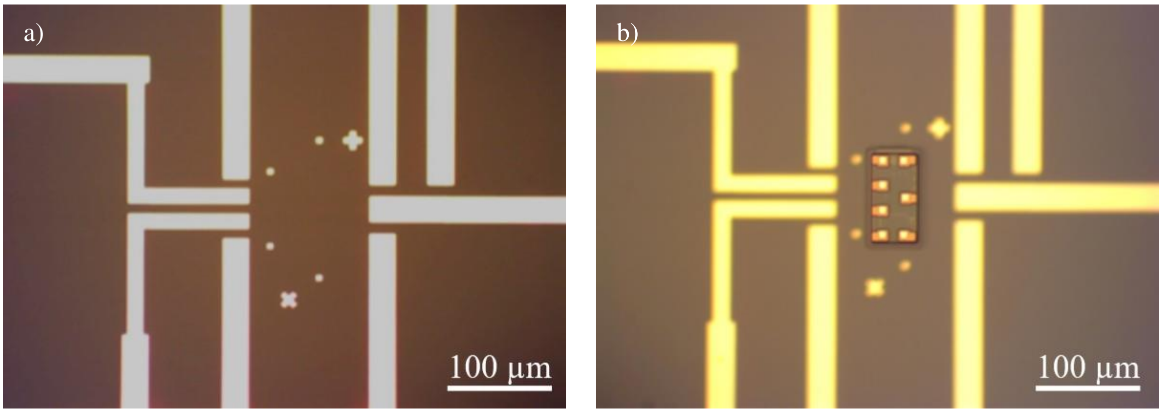

Figure 4: Glass test vehicle with gold contact pads a) before and b) after transferring the microIC

3.3 Color conversion by printed quantum dot ink

To build a full RGB pixel out of blue GaN microLEDs, quantum dot inks will be filled into an array of cavities on top of the microLED structure (**Figure 1 b)**). The filling process is done by XTPLs UPD system with quantum dot inks from QustomDot (**Figure 5**). These inks are InP-based and offer high absorption coefficients with narrow and size-tunable emission properties. In addition, the toxicity is much lower than by Cd/Pb based quantum dots which makes it to the only sustainable solution for display industry for now [9]. During the development in the BAMBAM project printable quantum dot inks were formulated and tested. The main criteria for this process was the reproducibility and nozzle clogging of the printing process. XTPL and QustomDot were able to achieve printed quantum dot structures down to a minimal size of 4 µm. They also successfully filled 40 µm x 40 µm x 7 µm cavities with the developed quantum dot ink as shown in **Figure 5 b), c)**.

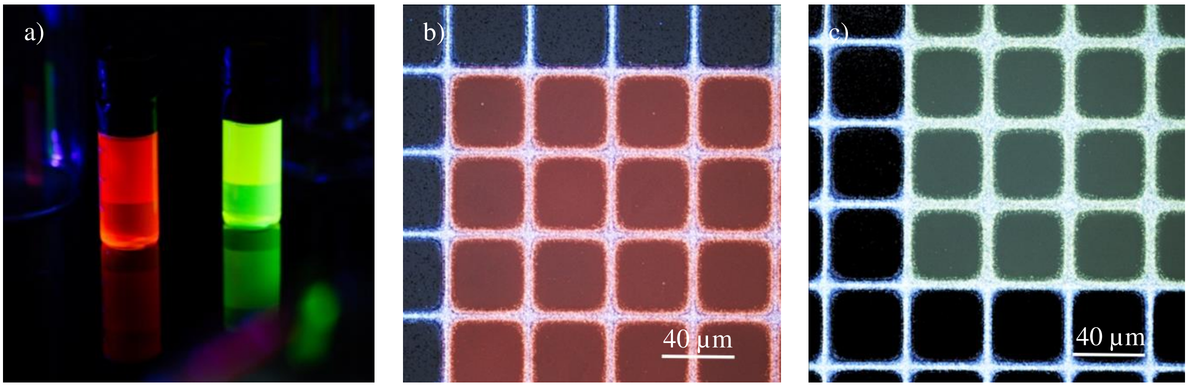

Figure 5: a) Red and Green quantum dot inks b) cavities filled with red and c) green quantum dots

3.4 Substrate related UPD printing results

Manufacturing conductive wires with a Ag nanoparticle-based ink is based on a sintering process to reach a conductivity of up to 40 % of the bulk value [4]. The University of Stuttgart investigated the influence of substrate related properties to the BAMBAM process. Therefore, three substrate types were investigated: display glass (Corning 1737), polyimide foil (KCL 2-17/50 FR) and PCB (FR4).

Optimum sintering parameter were determined for each substrate type to reach the best possible conductivity. To meet the specification of the final BAMBAM devices, the printing process always aimed to reach printed linewidths of 5 µm ± 1 µm. For rough surfaces a planarization layer with photopatternable negative tone dielectric (DOW Intervia 8023-10) had to be used to achieve high-resolution printing results (**Figure 6**).

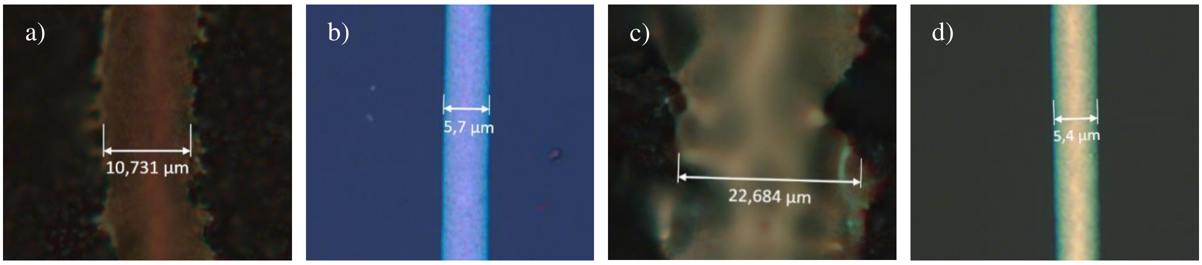

Figure 6: Printed Ag ink on different surface roughness (a) raw polyimide (17 µm copper removed), b) planarized polyimide, c) raw PCB (34 µm copper removed), d) planarized PCB

Printing on Glass has the fewest restrictions regarding the printing process. For Glass the optimum sintering temperature is 250°C leading to a wire resistance of 30 ± 5 Ω/mm at a line width of 5 µm after 20 min of sintering. Sintering on PCB and polyimide foil (copper removed on both substrates) is limited by the capability of the used planarization layer. For the investigated material the maximum sintering temperature was at 200°C which leads after 60 min to a resulting resistance of 75 ± 25 Ω/mm at a line width of 5 µm.

The results made on the three test substrate types have been evaluated to choose the best substrate for the BAMBAM microPackage. To fulfill the requirement of the digital Pixel described in **Section 2.2** a polyimide-based flex PCB with low roughness and 7 µm copper structures was chosen as substrate. Printing tests on this substrate mounted on a rigid carrier substrate proved that the printed structure is as uniform as on planarized polyimide and is able to meet the BAMBAM requirements. In this case the temperature is not limited by the planarization material which leads to similar sintering properties as on glass.

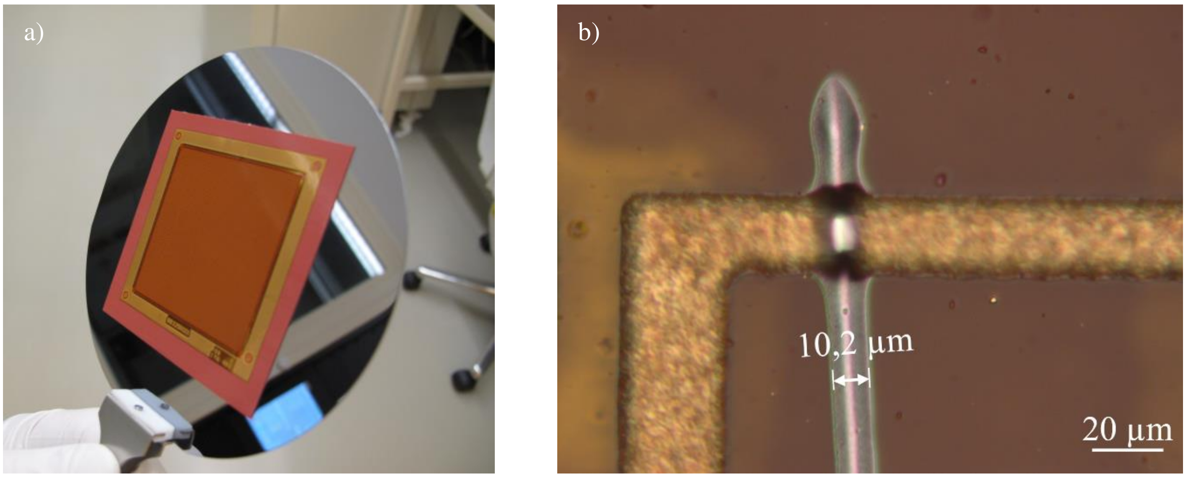

Figure 7: a) Laminated microPackage on rigid carrier substrate b) printing test on microPackage

3.5 UPD printed insulation and interconnects on microLEDs

Before printing interconnects on microLED devices, the printing over chip edges in the range of 100 µm was analyzed. Because of the chip height the printing process itself becomes more complex and additionally on each 90° edge a potential weak point under current load is introduced. Therefore, first tests have been done on chip dummies manufactured out of thick photostructurable epoxy (SUEX 125 µm).

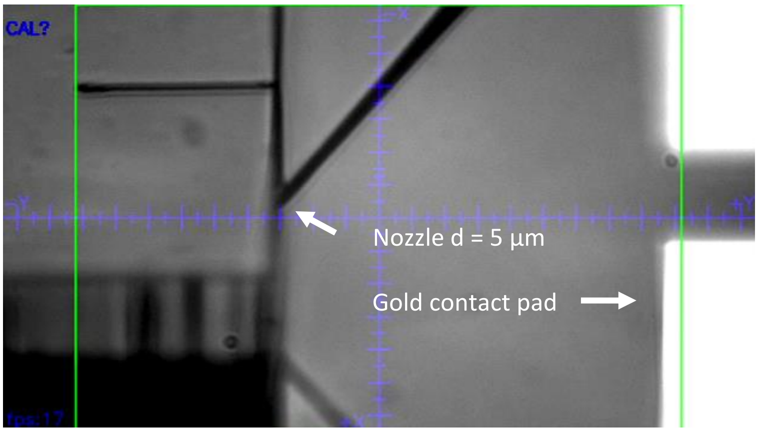

Figure 8: Printing process of a 125 µm height dummy chip test structure

The chip dummy in **Figure 8** is fabricated on a glass substrate with gold contacts which are connected by UPD printing over the dummy structure. Current load tests showed a maximum current of 50 mA before damaging the wire. A more detailed SEM analysis showed that the weak spots after the current load test of this printed structure are at the chip edges (**Figure 9**). This is the case because of the different thermal expansion of the epoxy and the glass substrate when sintering the ink which causes stress at the transitions. The weak points can therefore be compensated by adding more ink to the corners to compensate for small cracks caused by sintering.

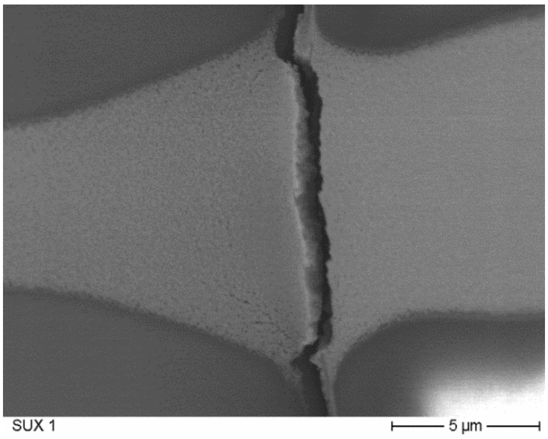

Figure 9: Bottom edge of chip dummy after current load test at 50 mA

This behavior is not considered as an issue for the BAMBAM approach because the maximum reached current is far above the specification of a microLED.

To investigate the compatibility of Aledia's microLEDs with the wire printing solution a RGB light up setup was designed. Preliminary tests were conducted on older microLEDs which differ from the final devices of the BAMBAM project in their thickness of 100 µm instead of 30 µm and larger footprint. After dicing the die to single microLEDs conductive layers on the chip sidewall can be shorted when printing conductive material on them. Therefore, the IGM developed a workaround to insulate the chip before wire printing by depositing dielectric materials such as UV curable glues, thermal curable glues and photoresists with the XTPL Delta printer. Afterwards the conductive Ag nanoparticle ink was printed on top (**Figure 10**) and a modified sintering process was used based on the results in **Section 3.4** and adding a slow temperature ramp for heating and cooling to avoid cracks due to thermal expansion of the glue.

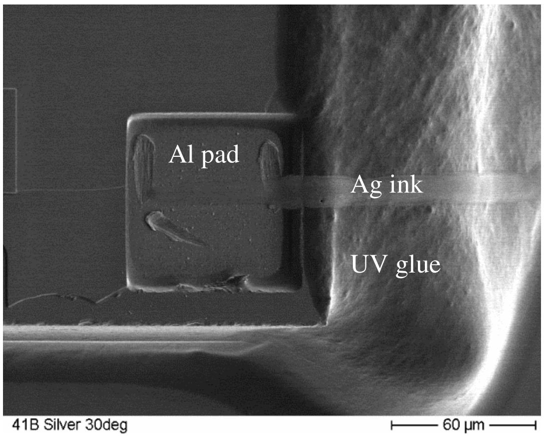

Figure 10: SEM picture of an Ag printed interconnect on top of the UV glue insulation

Figure 11 shows the light up of the connected microLEDs through connecting the gold contacts on the glass substrate. Due to the use of Aluminum contact pads on the microLEDs a native oxide is introduced between the pad and the silver ink. Hence, a voltage of roughly 15 V for the first light up was necessary which can be decreased to normal microLED operating voltage afterwards. This is because the formed metal-insulator-metal structure must be broken through once to get a conductive interconnect. Because of this behavior the BAMBAM consortium decided to use a gold pad for the microLEDs instead to avoid this initial break through which also could have an influence to the microLEDs lifetime.

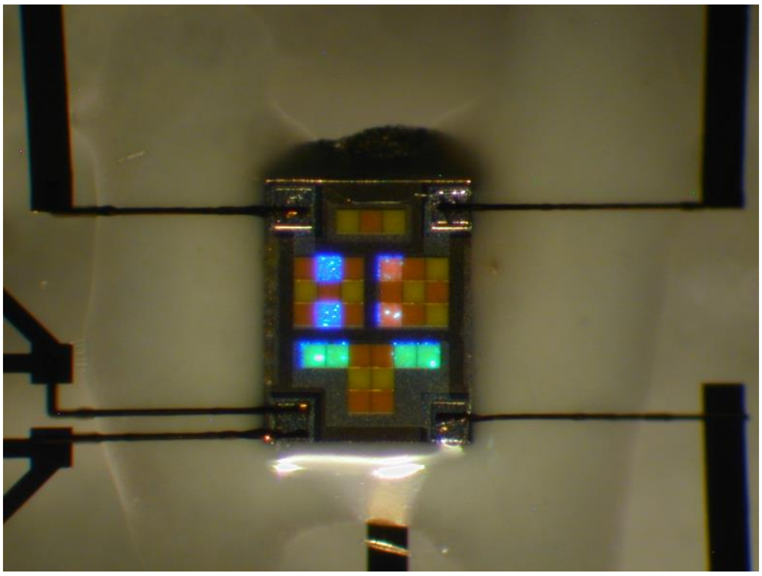

Figure 11: Light up of an insulated R&D microLED after Ag wire print

The bottom left contact pad of the microLED in **Figure 11** is a dummy contact. It is used for characterizing the printed interconnect regarding wire resistance, contact resistance and material compatibility.

3.6 First UPD printed interconnects on microIC driver

To verify the additive interconnecting approach on the microICs for pixel driving, glass test vehicles as shown in **Figure 4** have been used for UPD printing tests. Because the microIC is natively insulated at the chip sidewall it can be connected without an insulation layer. However, due to the small pitch of the contact pads and the multi-step structure of the chip, another challenge regarding the printing process appeared. On each edge of the chip structure capillary forces have an effect on the Ag ink directly after printing. These forces cause a spreading of the ink which is problematic in combination with the small pad pitch and lead to the risk of shorting the interconnects. Nevertheless, through proper modification of the surface energy on the substrate, the printed structure showed almost none spreading at the chip edges (**Figure 12**) and therefore no shorted interconnects.

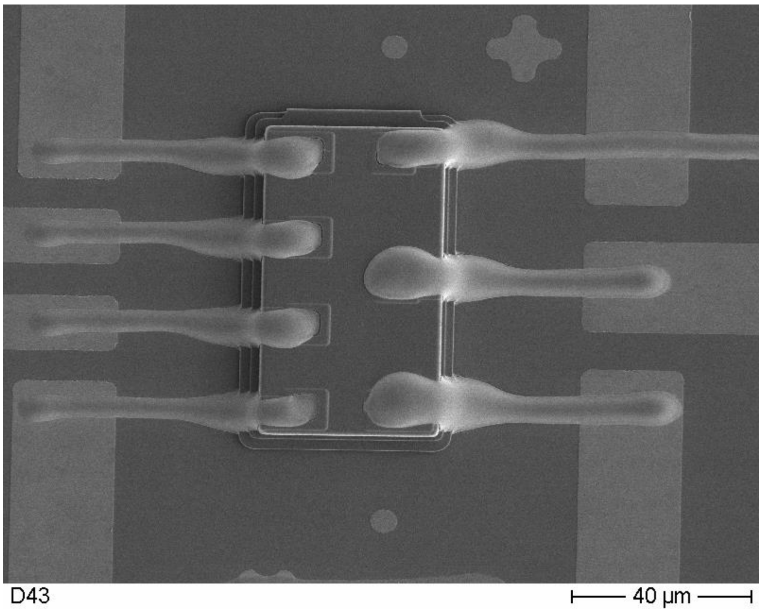

Figure 12: Interconnected microIC by UPD printing of Ag nanoparticle ink

4. SUMMARY

The BAMBAM project aims for Europe's entry into the display industry with an innovative approach for creating an active matrix microLED display without a TFT backplane. The BAMBAM consortium was able to make progress in many different sections of the pixel integration which can be summarized as:

- Developing a microLED pixel driven by a microIC integrated into a final pixel size of 325x325 µm^2
- Designing a blue microLED based on Aledia's GaN nanowire technology compatible with UPD printing of interconnects
- Verification of X-Celeprint's mass transferring approach of XDisplays microIC on a glass test vehicle ready for interconnection tests
- Developing UPD printable quantum dot inks by QustomDot and XTPL for color conversion on pixel level
- Defining Ag wire printing processes on different substrate types
- Successfully lighting up a microLED by UPD printing at the University of Stuttgart
- Connecting a microIC by UPD printing and proper surface energy modification

After finishing the interconnection process developments for pixel drivers, the consortium will combine all processes into a 4x4 pixel demonstrator on Glass. A 40x40 pixel display will be designed and produced with the final BAMBAM process after verification of all process steps done in the 4x4 pixel demonstrator.

5. ACKNOWLEDGMENT

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