Ultra-Precise Deposition Technology for High-Resolution Flat Panel Displays

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ABSTRACT

We demonstrate a novel ultra-precise deposition (UPD) technology for next-generation displays. UPD allows maskless deposition of highly-concentrated silver and copper inks (even 85% wt. of metal content) and the printed feature size is as small as 1 micrometer with the electrical conductivity up to 45% of bulk value.

1 INTRODUCTION

We demonstrate a novel ultra-precise deposition (UPD) technique [1] for printing of advanced metallization schemes in next-generation, high-resolution displays. This includes fabricating arbitrarily-shaped planar interconnectors on challenging substrates, as well as making highly-transparent/low resistivity electrodes [2].

The unique feature of the UPD technology is that it allows maskless deposition of highly-concentrated silver and copper inks (even 85% wt. of metal content) to obtain repeatable structures (conductive lines, meshes, arbitrary shapes, crosses, microdots) with feature size as small as 1 micrometer, which is order of magnitude less, compared to state-of-the-art methods using inks with similarly high viscosity. The conductivity of printed structures is up to 45% of the conductivity of bulk metal. Moreover, height-to-width aspect ratio of printed structures is up to 1:1 in a single pass. This allows precise printing on complex topographies, which is required for high-resolution displays.

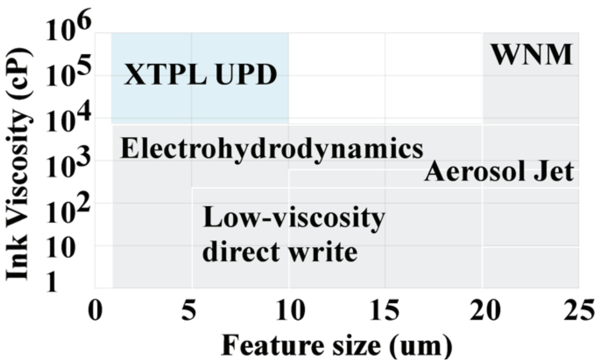

Figure 1 Comparison of different technologies for printed electronics.

The combination of high-viscosity inks (10'000 to 1'000'000 cP) and fine printed features (1 to 10 μm) defines a unique operating range for the UPD technology. On the opposite end of the scale there is inkjet printing [3], that allows to print low-viscosity inks with feature size larger than 20 μm. Aerosol jet [4], [5] typically uses inks characterized by viscosity up to 1000 cP and allows to print structures with feature size larger than 10 μm. Electrohydrodynamic printing [6] allows to print features as small as 1 μm, but uses low-viscosity inks and obtaining a reasonable aspect ratio requires multiple passes, which significantly slows down the process. Despite significant progress in direct writing process [7]–[9], reliable printing using micrometer nozzles still has not been demonstrated, and conductivity of printed structures is far below the conductivity of bulk material. Comparison of different technologies for printed electronics is summarized in Figure 1.

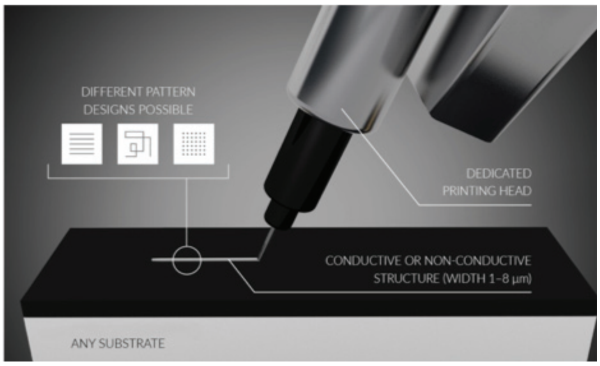

Figure 2 Sketch of the XTPL approach: ultra-precise dispensing (UPD), which is an additive manufacturing technology to print nanomaterials.

Moreover, compared to competitive approaches [6], [10], [11], UPD does not require electric field and therefore there is no risk of damaging the substrate or other electrical components. Finally, there are no artifacts at the beginning or at the end of the structures.

2 ULTRA-PRECISE DEPOSITION PROCESS

In Figure 2 we show sketch of the UPD technique. The printing head deposits in-house formulated ink, i.e., nanoparticles in a liquid solution, on a substrate, such as glass or flexible foil. In Figure 3 we show a variety of structures printed using the UPD method, including lines, dots, and crosses.

We develop and control the essential parts of the process:

1. Ink synthesis,
2. Nozzle preparation and printhead design,
3. Process development.

Optimization of physico-chemical properties of the inks include: 1) nanoparticle synthesis and sintering process, to achieve required resistivity; 2) solvents and adhesive additives, to achieve required adhesion to the substrate (the printed structures pass 10x scotch-tape test).

There are also no intrinsic limitations with respect to materials to be printed and substrates. Therefore, it is possible to print on materials with very different wetting properties, such as oxides (e.g. SiO2), nitrides (e.g. SiNx), metals, glass, and foils (e.g. PI, Kapton), as well as to print on junctions (metal/semiconductor/insulator) and cover vertical steps. Both printing on hybrid substrates, as well as traversing steps, will be demonstrated in the next section.

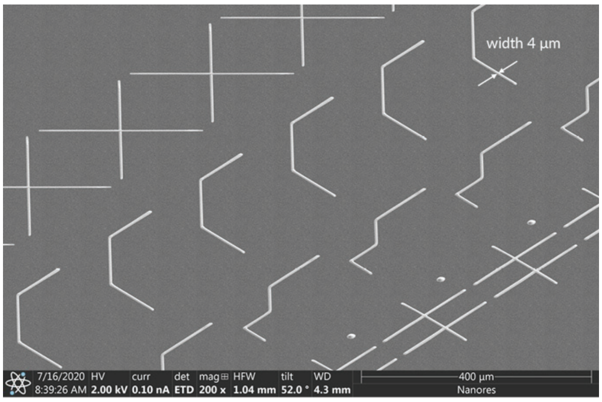

Figure 3 Variety of structures printed using the UPD method, including lines, dots, and crosses. The width of the lines is 4 µm.

3 RESULTS

In this section we present results pivotal for fabricating and repairing next generation, high-resolution displays: printing on steps, which is a robust alternative for standard wire bonding; printing on hybrid substrates, consisting of materials characterized by different wetting properties; open-defect repair in OLEDs; and finally, deposition of microdots.

3.1 Printing on steps

In Figure 4 we show a set of continuous silver lines with a width of 15 µm, printed on the step with the height of 150 µm. Therefore, the step is ten times higher compared to the width of the line.

Such interconnectors are a robust alternative for a standard wire bonding and can be used, among other applications, for metallization schemes and repair processes in micro-LED arrays [12].

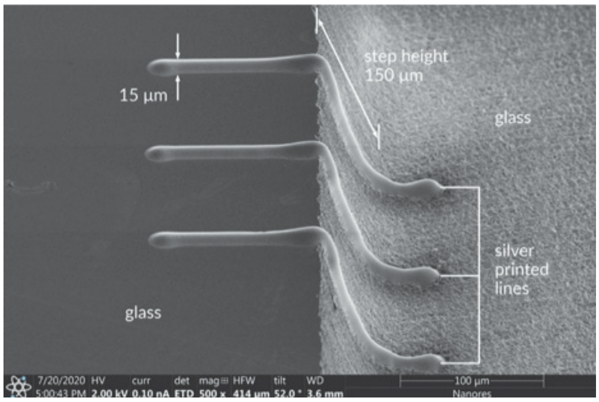

Figure 4 Repeatable and continuous silver lines with a width of 15 µm printed on the step with the height of 150 µm.

In Figure 5 we demonstrate repeatable and continuous silver lines with a width of 4 µm printed on the series of steps with the height of 15 µm. It can be seen that the printed lines traverse this set of steps while staying uniform.

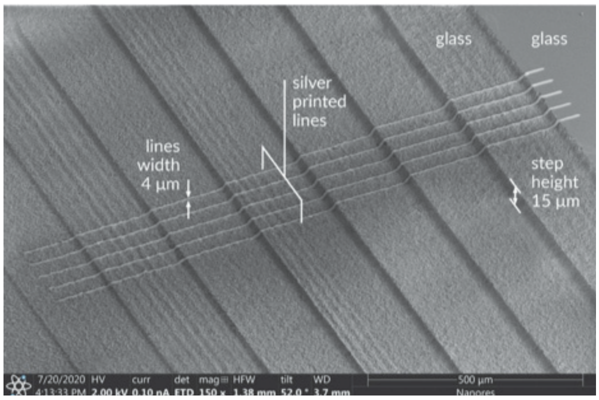

Figure 5 Repeatable and continuous silver lines with a width of 4 µm printed on the series of steps with the height of 15 µm.

3.2 Hybrid substrates

Hybrid substrates, composed of materials characterized by different wetting properties, are common in novel electronic devices. An example of printing on such a hybrid substrate is shown in Figure 6. The substrate consists of aluminum (Al) layer deposited on a PECVD silicon nitride (SiNx) with a vertical step of 0.35 µm. The printed silver lines are characterized by the width of 2 µm and the height of 350 nm. Despite different contact angles of Al and SiNx, the printed structures are uniform, also at the interface of both materials. Moreover, the lines cover the step without discontinuities and the proper sintering ensures a full adhesion to both materials. In Figure 7 we show cross-section of the printed line on a glass substrate, demonstrating dense packaging of the nanoparticles.

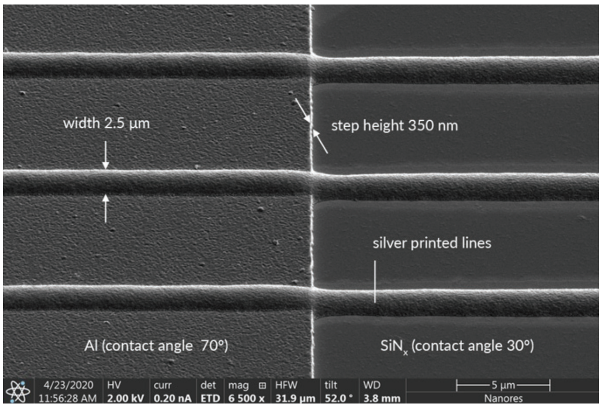

Figure 6 Example of printing on a hybrid substrate consisting of aluminum (Al) layer deposited on a PECVD silicon nitride (SiNx) with a vertical step of 0.37 µm.

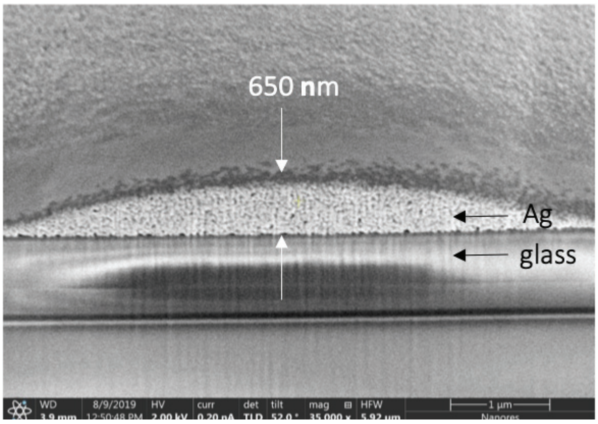

Figure 7 Cross-section of the printed line on a glass substrate, demonstrating dense packaging of the nanoparticles.

3.3 Open-defect repair in complex OLED TFT arrays

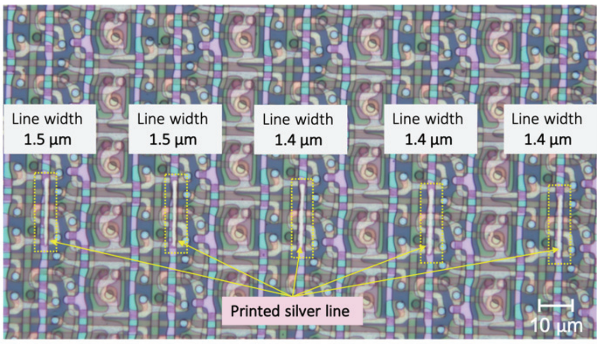

Figure 8 Repeatable and continuous silver lines with a width of around 1.5 µm, length of 20 µm printed on a complex OLED TFT array.

Open defects, defined as local lack of conductive material in conductive paths, may occur in OLED arrays. Such defects may appear at the production stage and usually result in the product rejection. The problem is becoming even more significant in the context of ongoing miniaturization of electronic devices: significant increase in resolution and size of displays.

State-of-the-art repair methods include [13], [14]: Focused Ion Beam (FIB), Laser Chemical Vapour Deposition (LCVD), and Direct Laser Deposition (DLD). The main disadvantages of these technologies are limited throughput and cost. Moreover, FIB can damage active electronic systems in integrated circuits (due to electrostatic discharge defects), LCVD and DLD provide only a limited possibility to obtain paths with a width below 10 µm, and LCVD uses toxic gases.

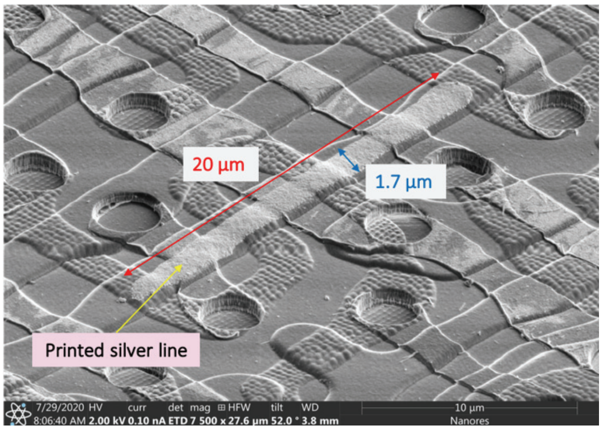

Figure 9 Continuous silver line with a width of 1.7 µm, length of 20 µm printed on a complex OLED substrate.

XTPL approach overcomes these limitations and allows to repair broken conductive lines already at the production stage. In Figure 8 and Figure 9 we show repeatable and continuous silver lines with a width of around 1.5 µm, length of 20 µm printed directly on an OLED substrate with complex topography. This image also demonstrates that UPD allows to print on substrates with significant complexity and that the printing process is characterized by micrometer precision.

3.4 Deposition of microdots

Color-filter layers based on quantum dots are currently produced using subtractive methods: the whole layer is deposited and the unnecessary material is removed. This approach has a number of limitations: it is expensive, complex, and slow.

XTPL technology allows to overcome these limitations. Quantum dots are directly deposited, which simplifies the whole process and reduces the overall manufacturing cost. Moreover, it allows to increase resolution: microdots currently obtained on the market usually have about 50 µm, the minimum is 20 µm – while XTPL currently achieves dots with diameter of 1 µm.

The UPD technique can be also used to print an array of uniform silver microdots, as shown in Figure 10. Number of more complex approaches to create such array have been presented in the literature [15], [16]. In this case, UPD allowed to deposit dots with diameter of 10 μm and height of 2.5 μm.

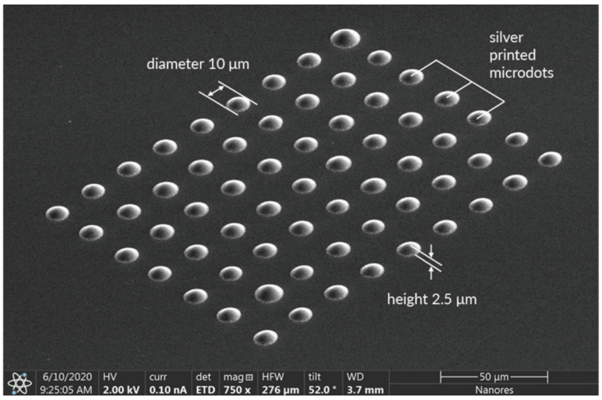

Figure 10 Printed array of uniform silver microdots.

4 CONCLUSIONS

In this contribution we demonstrate a novel ultra-precise deposition (UPD) technique developed by XTPL. UPD answers the growing needs for fabrication of high-density hybrid microelectronics and is particularly suitable for next-generation, high-resolution displays. Other existing technologies do not provide the required fine feature sizes. In this regard, UPD allows to precisely deposit high-viscosity conductive inks on complex substrates and obtain arbitrary shapes, inducing lines, dots, crosses, and meshes. The printed feature size is as small as 1 micrometer with the electrical conductivity up to 45% of bulk value.

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Figure 11 Printed array of uniform silver microdots.

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