# Digital Fabrication of – Oxide Electronics

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## Abstract

*The ink-jet printing technology is one of the most promising alternatives to photolithographic and masking technology allowing additive patterning of functional materials such as conductors, insulators, and semiconductors on a substrate. This approach enables the fabrication of cost-effective electronics. In particular, printable amorphous oxides have some advantages compared to other solution processable organic materials like atmospheric and temperature stability and relatively high field-effect mobility, which make them competitive candidates to be integrated in functional devices and smart systems.*

*Here we report on the fabrication of basic electronic building blocks (e.g. a diode, resistor, capacitor) based on ink-jet printed amorphous oxides and metal contacts as active and passive device layers. Printed components are based on originally synthesized amorphous semiconductive oxides and metallic inks. After printing, low temperature sintering method developed by NovaCentrix® (PulseForge®) was performed in order to form the device active and passive layers. This was accomplished by using proprietary high-intensity flash lamps at very short pulse durations allowing us to use a low-cost Polyethylene terephthalate (PET) plastic film as the substrate material.*

*Obtained results may open novel routes for the development of a next generation of Large Area Printed Electronics based on printed amorphous oxides.*

## Introduction

The ink-jet printing technology allows direct patterning of functional materials such as conductors, insulators, and semiconductors onto the substrate. Amorphous oxides have numerous advantages due to their atmospheric and temperature stability, relatively high field-effect mobility, which make them competitive candidates to be integrated in functional devices and smart systems [1]. Employing printable amorphous oxides and processing them by digital fabrication is a promising route which may enable fabrication of high-end and cost-effective printed electronics. Here we report fabrication of functional electronic layers and a basic building block e.g. Schottky diode, based on ink-jet printed cadmium sulfide (CdS) nanocrystalline film and copper-oxide (CuO) as active and passive device layers.

## Experimental

In the last decade, colloidal nanocrystals (NCs) have been widely investigated due to their possible applications in fields as optoelectronic, photocatalysis and biological labeling [2-4]. Semiconductor quantum dots can be fabricated via several techniques [5-6]. Highly luminescent CdSe/CdS and CdSe/ZnS core-shell nanocrystals have been prepared through organometallic approaches [7]. However, organometallic reactions are carried out in organic phase or aqueous phase. Therefore, both nucleation and growth of the nanocrystals only were happened in a homogeneous system. It is very difficult for organic-phase approaches to synthesize oil-soluble nanocrystals by using various water-soluble precursors [7]. Pan et. al. reported two phase method which occurs under mild conditions and results in highly luminescent nanoparticles.

In this study the CdS, synthesized in two phase synthetic routes to obtain oil soluble nanoparticles, was employed as Schottky diode active layer. This method allows very slow particle growth and thus crystal size and quality can be controlled easily. The nucleation and particle growth occurs at the interface between toluene and water. Toluol phase consists of Cd source and capping agent (oleic acid) and water phase consists of S precursor, generally thiourea. Thiourea undergoes a hydrolysis reaction and release S very slow. This type of synthesis can be carried out both in autoclave (under high pressure) and also at atmospheric conditions. For this purpose, synthesis was carried out at 170°C in autoclave. High quality CdS nanoparticles with average size of 7 nm were obtained after 6 hours.

CdS was ink-jet printed (Autodrop Professional Positioning System MD-P-801, nozzle having a diameter of 50 µm) from toluene solution (2.1 wt%) on the top of the CuO stripe. After printing CdS films were wet-chemically treated by potassium hydroxide (KOH) (1 M) to form the device active layer. Basic approach to neutralized oleic acid (capping agent) by basis (KOH) allows us to obtain functional CdS thin films at the room temperature and under ambient conditions.

CuO-ink (Metalon ICI-003) from NovaCentrix was ink-jet printed from water based solution by Epson C88+ Photo Stylus desktop ink-jet printer and sintered in order to form the diode cathode-contact. That was accomplished by using photonic sintering PulgeForge® tool in ambient conditions by applying light pulse with energy of 7,6 J/cm$^2$ in app. 10 milliseconds allowing us to use low-cost plastic film, such as Polyethylene

terephthalate (PET) as substrate material. The resulting CuO stripe shows 100 mΩ/sq resistance, which is equivalent to 1/3 of Cu bulk conductivity.

Finally, the device fabrication was finished by sputtering of Al through the shadow mask to form ohmic-contact [8].

Diodes electrical characterization was performed by using Keithley 2616 SourceMeter in ambient conditions.

## Results

Figure 1(a) show an optical image of printed CuO stripe, whereas Figure 1(b) and 1(c) shows SEM images of as-printed and photonic cured CuO stripe by PulseForge®, respectively. Resulting CuO features semi porous structures with no sharp surface. In general, lack of sharp interface between metal and semiconductor layer may cause poor device properties due to disturbed charge transport properties and presence of the trap states at the interface.

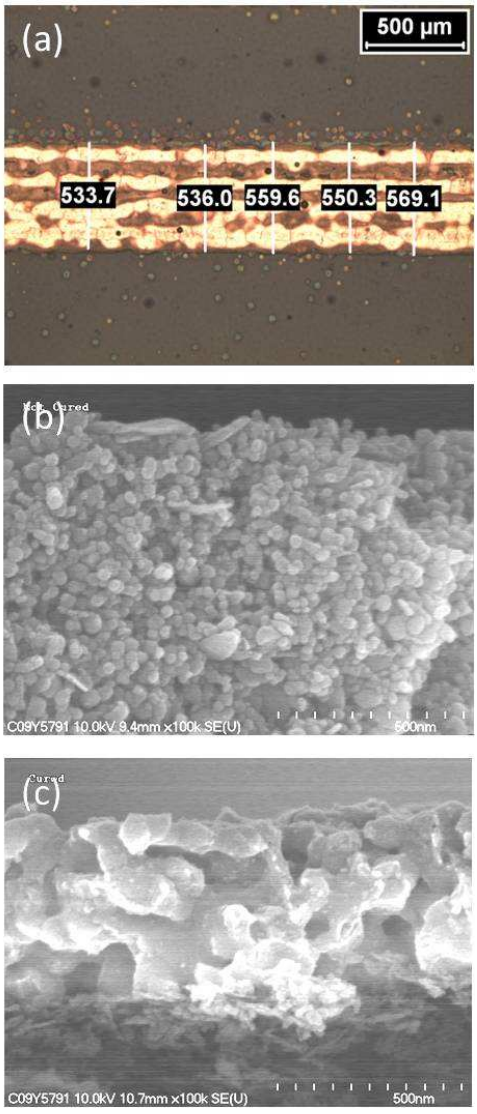


**Figure 1**. *(a) Optical image of printed CuO lines, (b) SEM image of as printed CuO ink, and (c) SEM image of CuO photonic cured by PulseForge® photonic sintering tool*

Figure 2(a) and 2(b) shows a device structure and optical image of fabricated diode. In a case of fabricated CdS based Schottky diode, in forward direction, i.e. biasing the CuO contact with positive with respect to the Al contact, electron current is injected into CdS. Figure 2(c) shows *J-V* characteristic of CdS based Schottky diode in a semi-logarithmic and linear representation (inset).

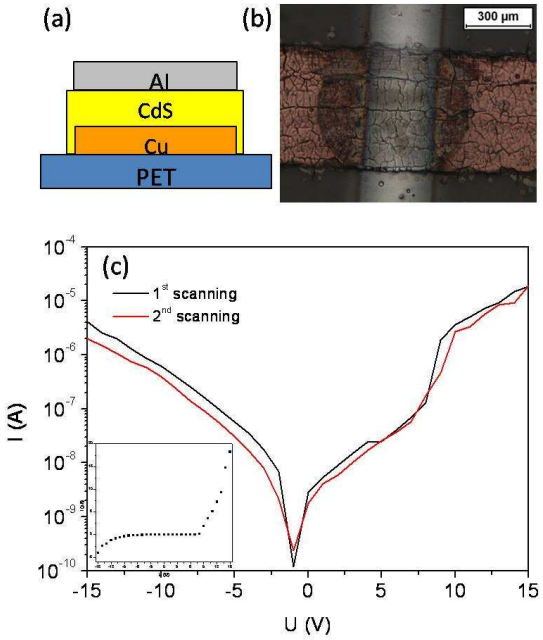


***Figure 2**. (a) Device structure, (b) optical image of diode, and (c) J-V characteristic of CdS based Schottky diode in semi-logarithmic and linear representation (inset)*

Poor rectification ratio, as seen from the logarithmic J-V curve, can be attributed to the poor interface between CuO and CdS, as well as to the non-optimized sintering process. Further optimization of the printing and sintering process is under progress.

Nevertheless, resulting working Schottky diode based on CdS film obtained at room temperature and under ambient conditions shows potentially new approach and open a novel routes for the development of a next generation of Large Area Printed Electronics based on printed amorphous oxides.

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