Printed Electronic Devices and Circuits

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Why printing electronics?

• nm-technology
• Performance up to ~GHz
• Subtractive processes needed
• Modern CMOS requires 37 masks and ~300 process steps

• µm-technology
• Performance Hz-kHz, maybe MHz achievable
• Only needed materials are deposited
• Maskless, additive, large area, low cost
Printing techniques

Inkjet

Electrohydrodynamic

Capillary

Laser
Printed memristors

- Fundamental device (similar to L, C, R) postulated in 1971 by Leon Chua and found in 2008 (Strukuov et al., Nature 2008 and others)
- Physical concept relies on solid-state electronic and ionic transport coupled under an external bias voltage
- Resistance can be switched under an applied electrical field (direction & magnitude)
- Most promising application: non-volatile memory, neuromorphic computing, Hardware security
Memristor structure

Materials for electrode:
- Cu, Ag, Ti, W, Pt, Au
- Graphene
- ITO
- PEDOT:PSS

Materials for storage layer:
- Binary oxide: ZnO, WO$_{3-x}$, CuO, TiO$_2$, NiO
- Metal-organic framework: HKUST-1, UIO-66
Fabrication process of inkjet-printed memristor

1. Substrate cleaning
2. Laser ablation
3. Heat at 120°C
4. Sinter at 400 °C
5. ZnO precursor ink
6. Ag Nanoparticle Ink
7. Au
8. Glass
Inkjet-printed memristor

Top view (optical photo)

Cross-section (FIB-SEM)

Width of electrodes: ~50 μm

Thickness:
- Ag: ~100 nm
- ZnO: ~250 nm
- Au: 50 nm

Resistive switching mechanism

Inkjet-printed memristor performance

High uniformity

Endurance under dynamic pulse voltage mode over 500 cycles

Excellent retention performance over $10^4$ s (non-volatile)

Multi-photon multi-material laser printing

Polymers, metals, and semiconductors can be laser printed

Yang, Liang, et al. Light: Advanced Manufacturing 2.3 (2021)
Yang, Liang, et al. Laser & Photonics Reviews 16.3 (2022)

Work from AG Wegener, T2
Laser-printed semiconductor: ZnO

- Size of ZnO hemisphere can be controlled by laser power and exposure time
- ZnO can be fast laser printed in arbitrary form (speed of 100 μm/s)

Joint work (AG Wegener, AG Aghassi, AG Blasco, and AG Barner-Kowollik)

Liang et. al. submitted
Laser-printed Pt-ZnO-Ag memristors

- Novel recipe for ZnO
- Laser is used to write and simultaneously sinter the semiconductor
- Feature size below 1 μm

Liang et. al. submitted
Laser-printed memristor performance

- Bipolar resistive switching
- Small voltage variability
- Retention over $10^4$ s
- Endurance over 700 cycles
Memristive crossbar array for security circuit
Physically unclonable function (PUF)

Hardware security

6 x 6 crossbar structure consisting of 36 memristors, fabricated within one setup

Liang et. al. submitted
Memristive crossbar arrays for security circuits

Activation of 36 memristors

I_{\text{read}} of 36 activated memristors

Low noise of I_{\text{read}}

Liang et. al. submitted
Security keys out of stochastic currents

Circuit architecture around memristor-PUF

Bit-array distribution

No bit errors over 300 cycles

Liang et. al. submitted
Summary

• Inkjet-printed memristor

• Laser-printed memristor

• Laser-printed memristive crossbar array as hardware security circuit
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