Program MSE
MSE Day 18.11.2022

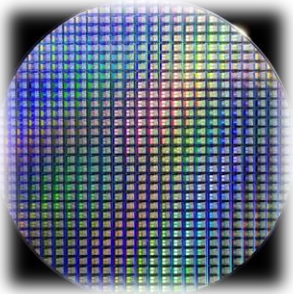
Printed Electronic Devices and Circuits

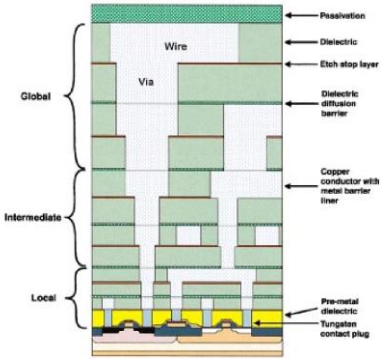
M. Sc. Hongrong Hu
RU Aghassi

HELMHOLTZ

Why printing electronics?

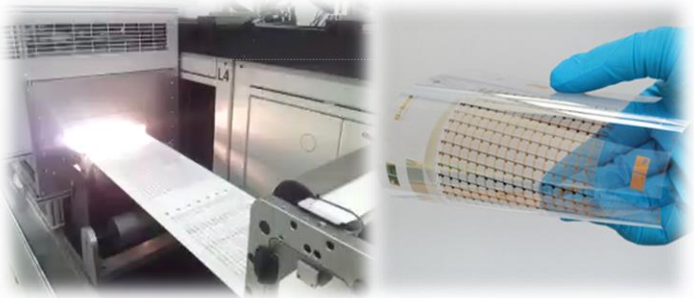
Silicon Technology





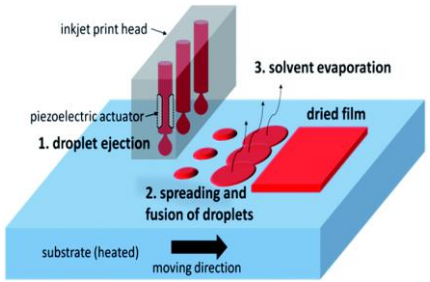
- nm-technology
- Performance up to ~GHz
- Substractive processes needed
- Modern CMOS requires 37 masks and ~300 process steps

Digital Printing Technology

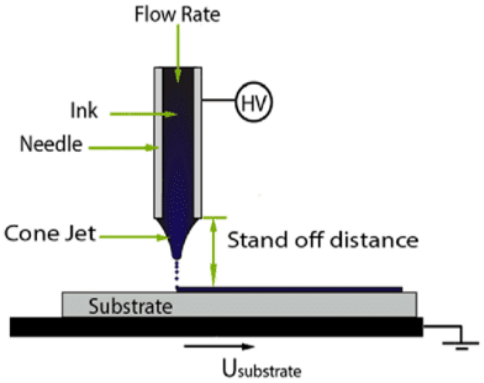


- µm-technolgy
- Performance Hz-kHz, maybe MHz achievable
- Only needed materials are deposited
- Maskless, additive, large area, low cost

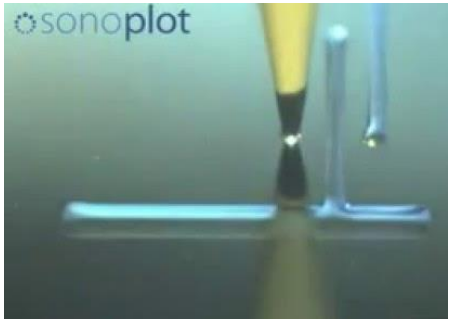
Printing techniques



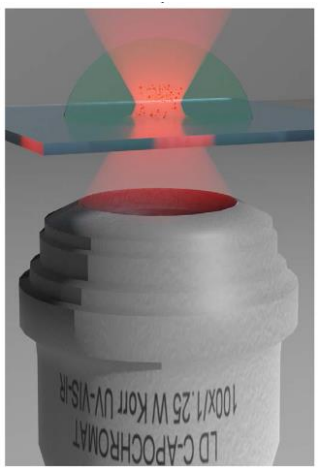
Inkjet



Electrohydrodynamic

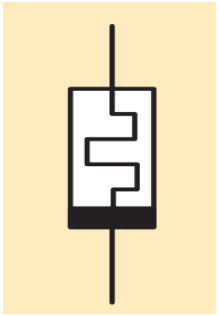


Capillary



Laser

Printed memristors

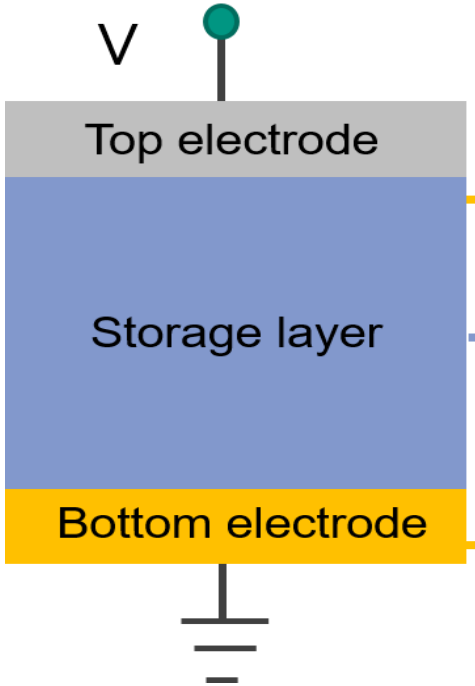


Memristor symbol

2 terminal electronic device realized in many nanoscale systems

- 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



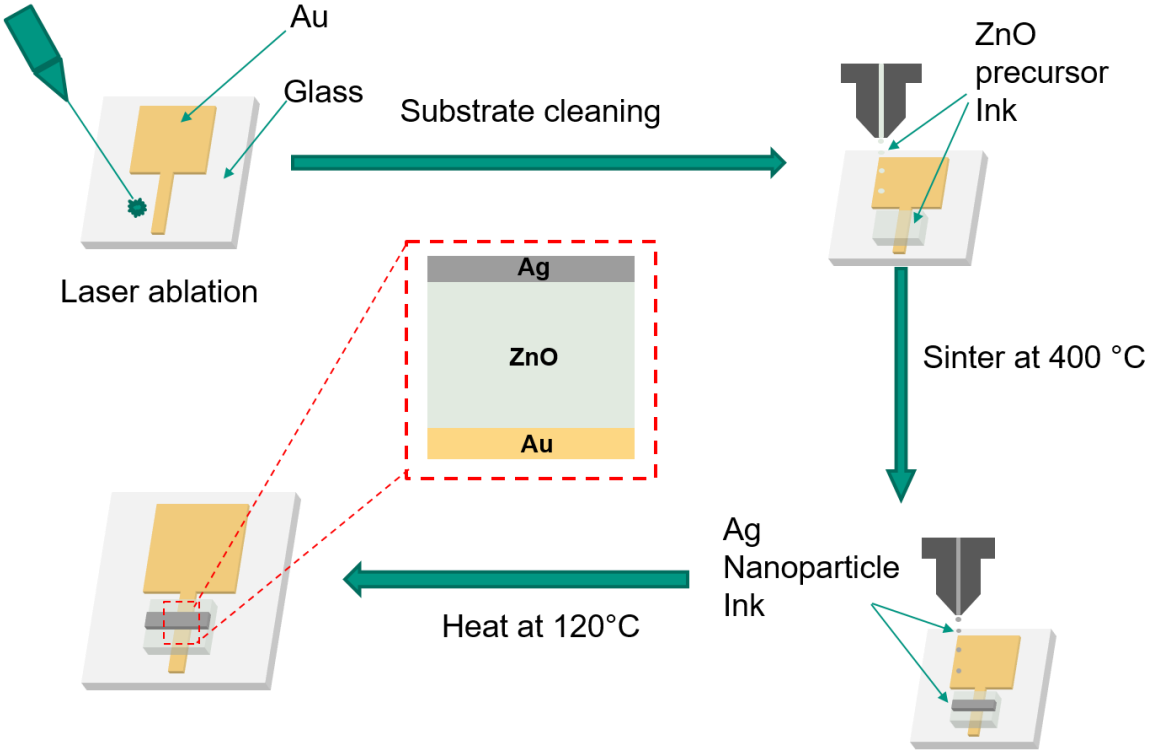
Materials for electrode:

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

Materials for storage layer:

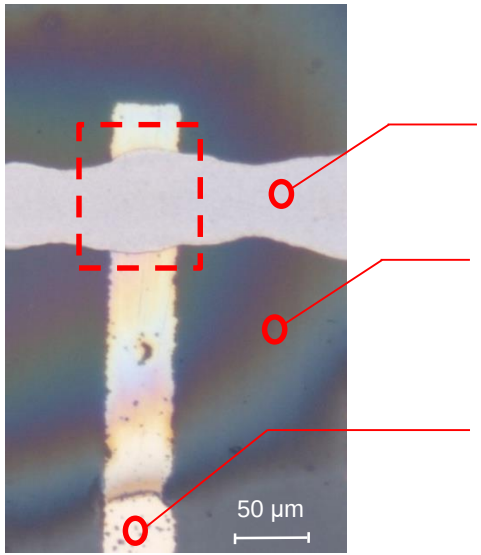
- Binary oxide:
  ZnO, WO_{3-x}, CuO, TiO_2, NiO
- Metal-organic framework:
  HKUST-1, UIO-66

Fabrication process of inkjet-printed memristor

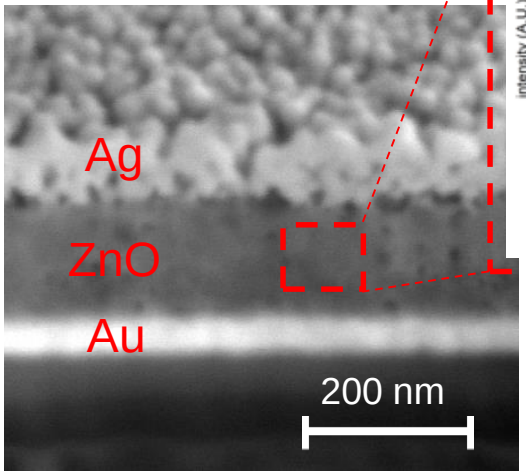


Inkjet-printed memristor

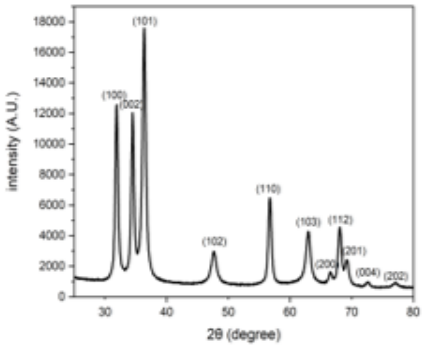
Top view
(optical photo)



Cross-section
(FIB-SEM)



XRD



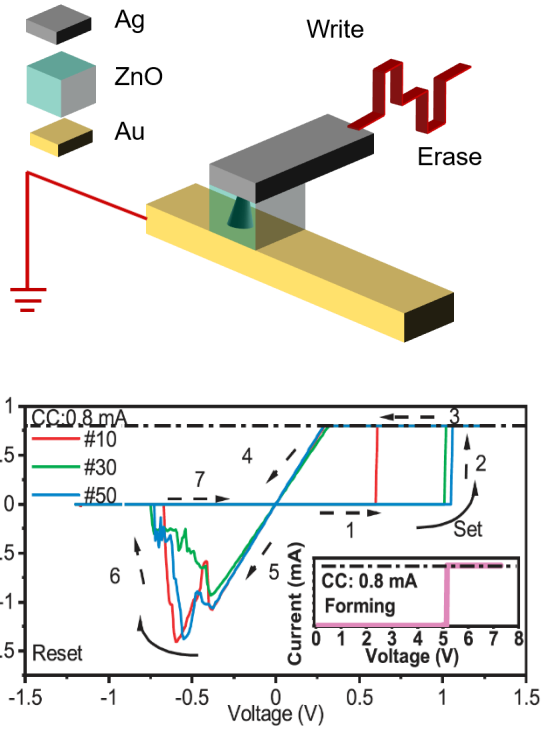
Thickness:

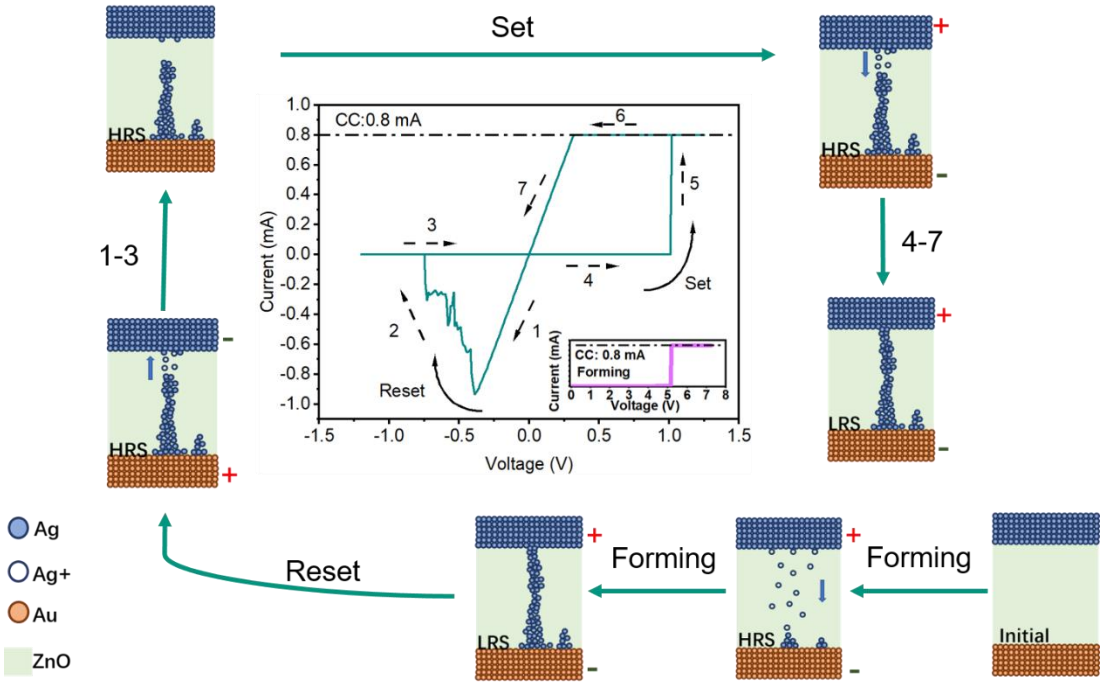
- Ag: ~100 nm
- ZnO: ~250 nm
- Au: 50 nm

Width of electrodes: ~50 µm

Hu, et al. Applied Physics Letters 119.11 (2021)

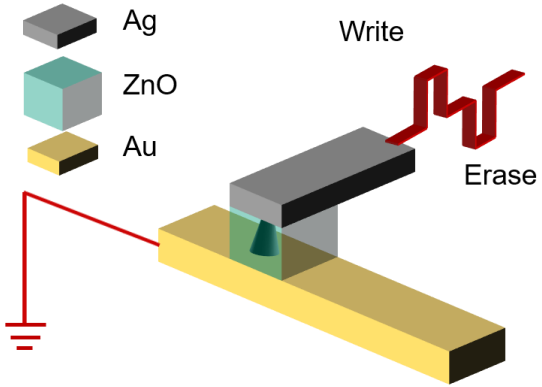
Resistive switching mechanism



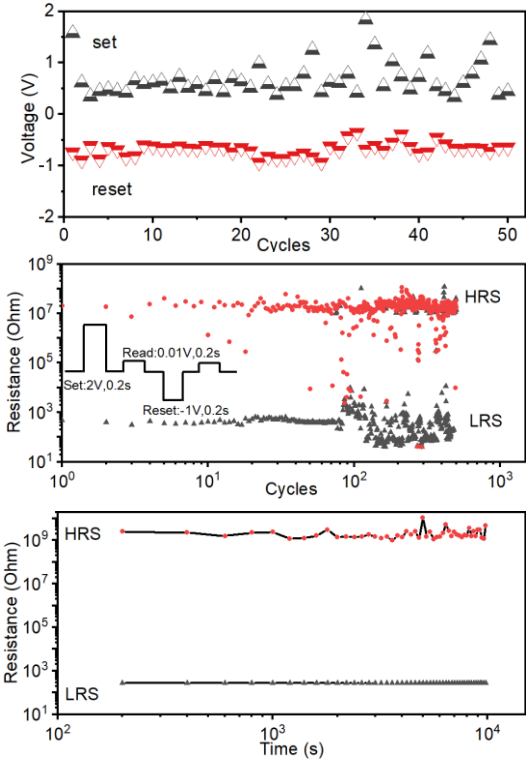


Hu, et al. Applied Physics Letters 119.11 (2021)

Inkjet-printed memristor performance



Hu, et al. Applied Physics Letters 119.11 (2021)



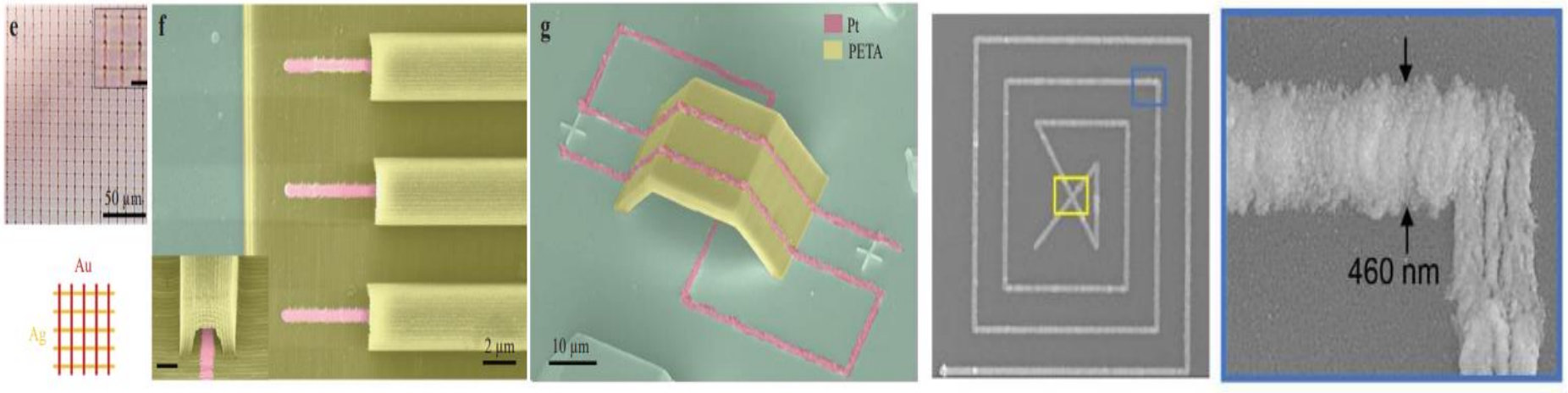
High uniformity

Endurance under dynamic pulse voltage mode over 500 cycles

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

Multi-photon multi-material laser printing

Polymers, metals, and semiconductors can be laser printed

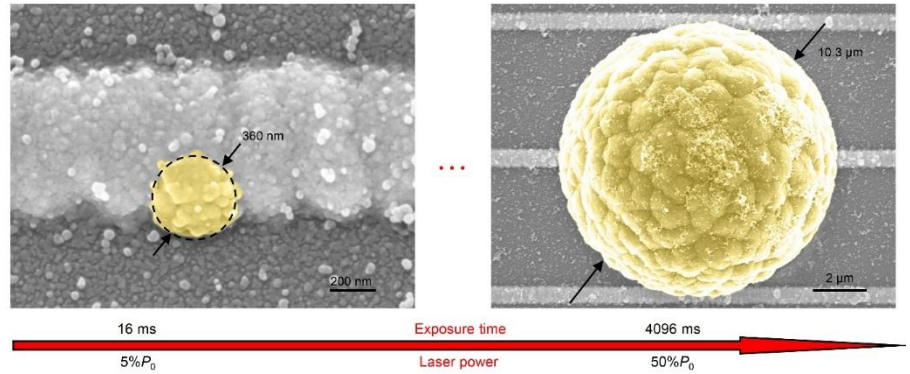


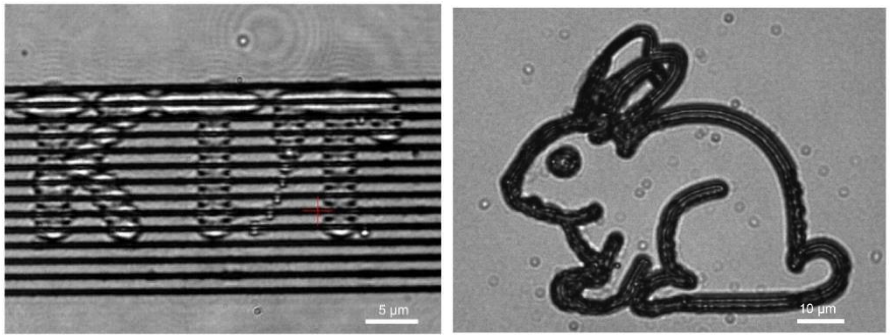
Yang, Liang, et al Light: Advanced Manufacturing 2.3 (2021)

Yang, Liang, et al. Laser & Photonics Reviews 16.3 (2022)

Work from AG Wegener, T2

Laser-printed seminconducor: ZnO



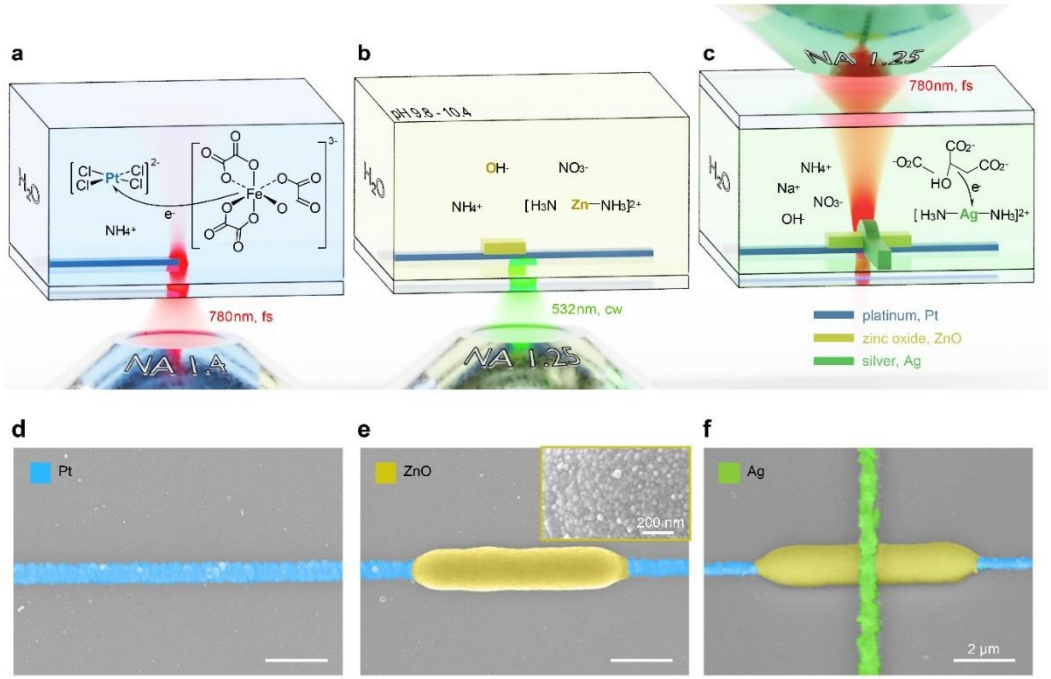


- Size of ZnO hemisphere can be controlled by laser power and exposure time
- ZnO can be fast laser printed in arbitrary form (speed of 100 µm/s)

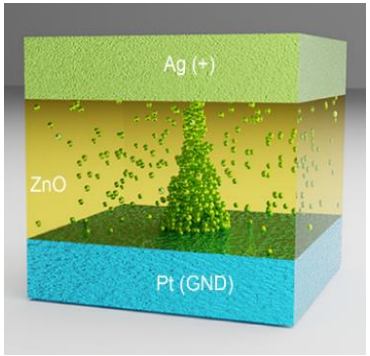
Joint work (AG Wegener, AG Aghassi, AG Blasco, and AG Barner-Kowollik)

Liang et. al. submitted

Laser-printed Pt-ZnO-Ag memristors

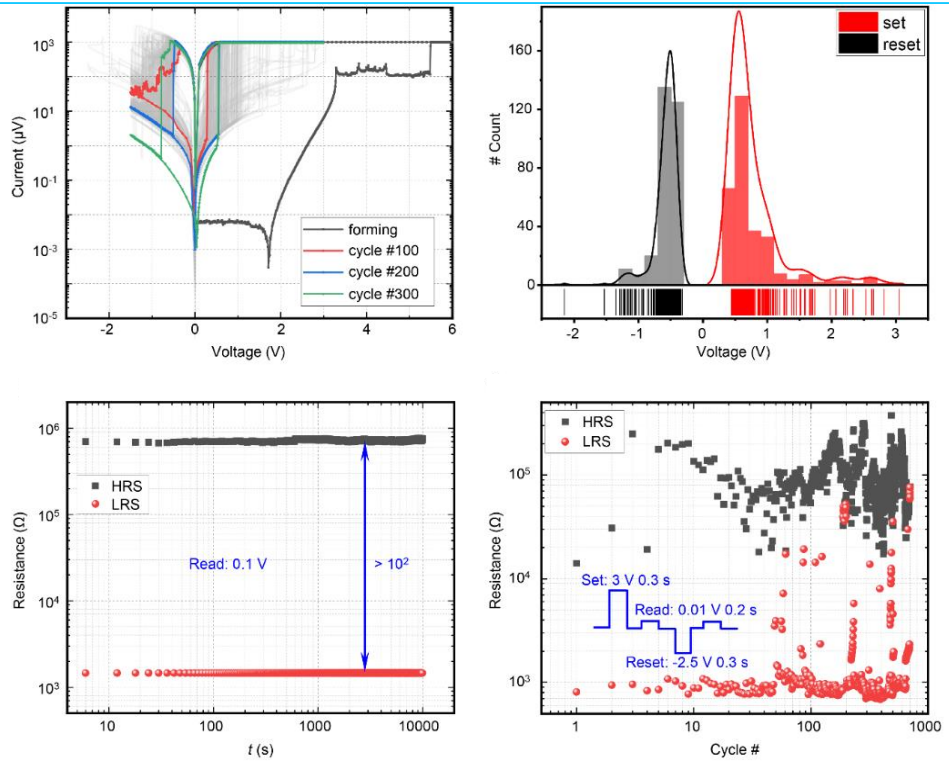


Liang et. al. submitted



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

Laser-printed memristor performance

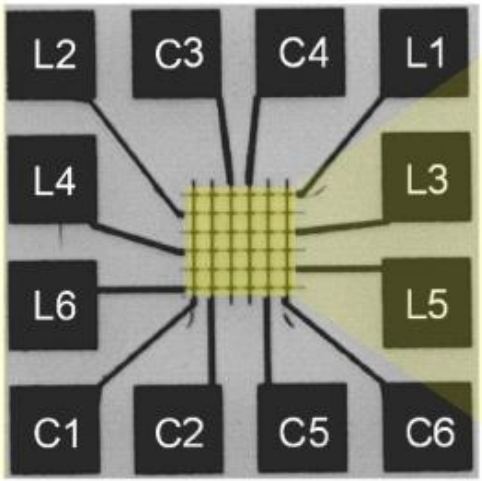


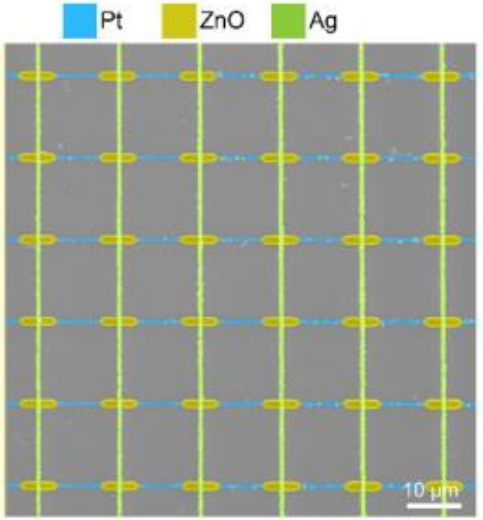
- Bipolar resistive switching
- Small voltage variability
- Retention over 10^4 s
- Endurance over 700 cycles

Liang et. al. submitted

Memristive crossbar array for security circuit Physically unclonable function (PUF)

Hardware security

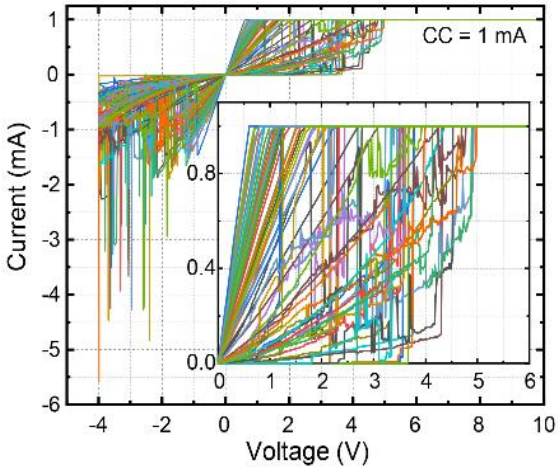




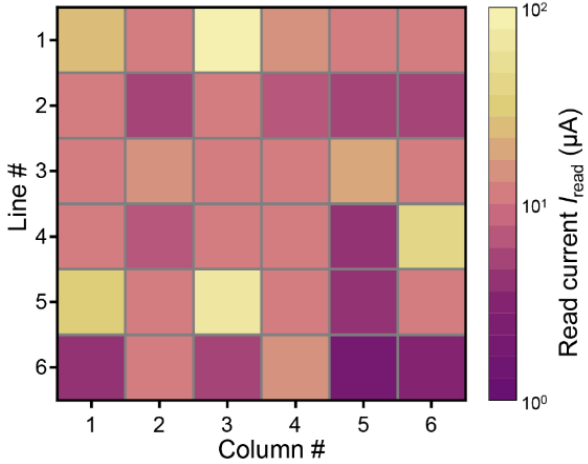
6 x 6 crossbar structure consisting of 36 memristors, fabricated within one setup

Liang et. al. submitted

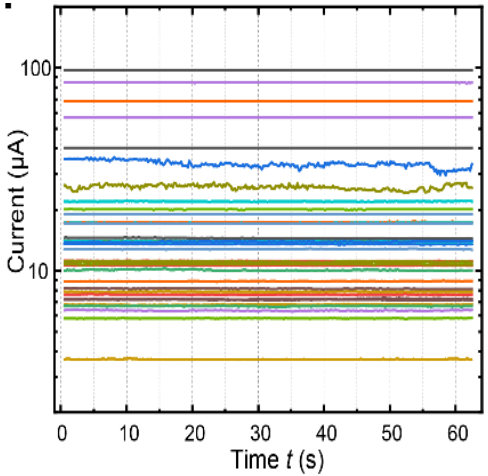
Memristive crossbar arrays for security circuits



Activation of 36 memristors



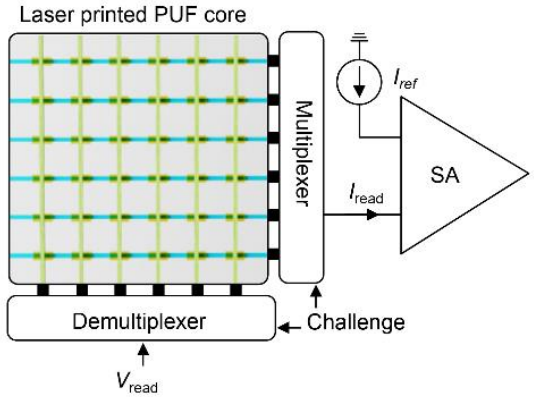
I_{read} of 36 activated memristors



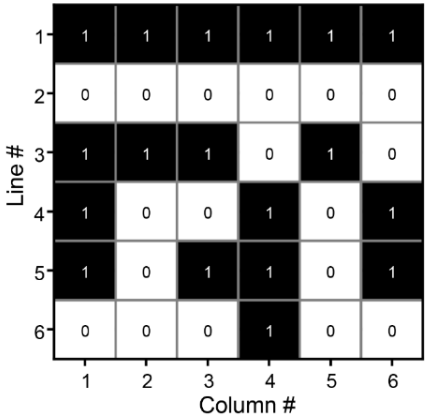
Low noise of I_{read}

Liang et. al. submitted

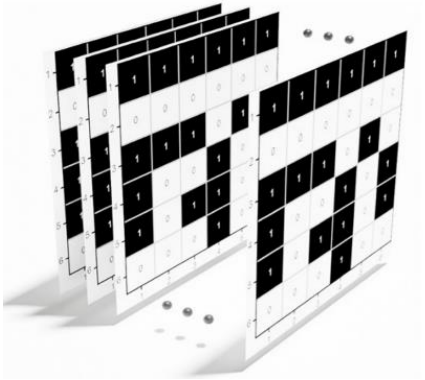
Security keys out of stochastic currents



Circuit architecture around memristor-PUF



Bit-array distribution

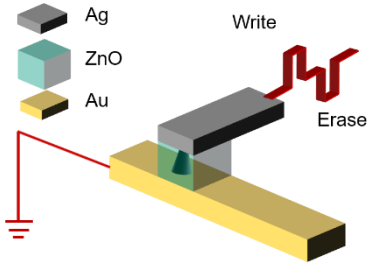


No bit errors over 300 cycles

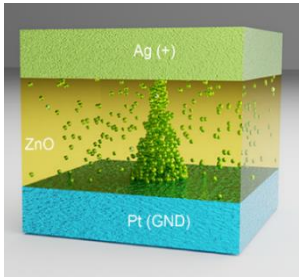
Liang et. al. submitted

Summary

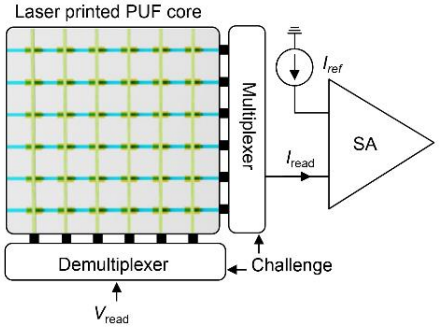
- Inkjet-printed memristor



- Laser-printed memristor



- Laser-printed memristive crossbar array as hardware security circuit



HELMHOLTZ

Acknowledgments

Prof. Jasmin Aghassi-Hagmann
Prof. Martin Wegener
Prof. Eva Blasco
Prof. Christopher Barner-Kowollik
Dr. Liang Yang
Dr. Alexander Scholz
Dr. Gabriel Cadilha Marques
Dr. Florian Feist
Dr. Niklas Maximilian Bojanowski
Steven Kraus

3D MATTER MADE TO ORDER

DFG Deutsche Forschungsgemeinschaft
Excellence Strategy,
EXC 2082/1 – 390761711

HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES
Excellence Networks, Phase 2 & 3

Carl Zeiss Stiftung

HEiKA
Heidelberg Karlsruhe
Strategic Partnership