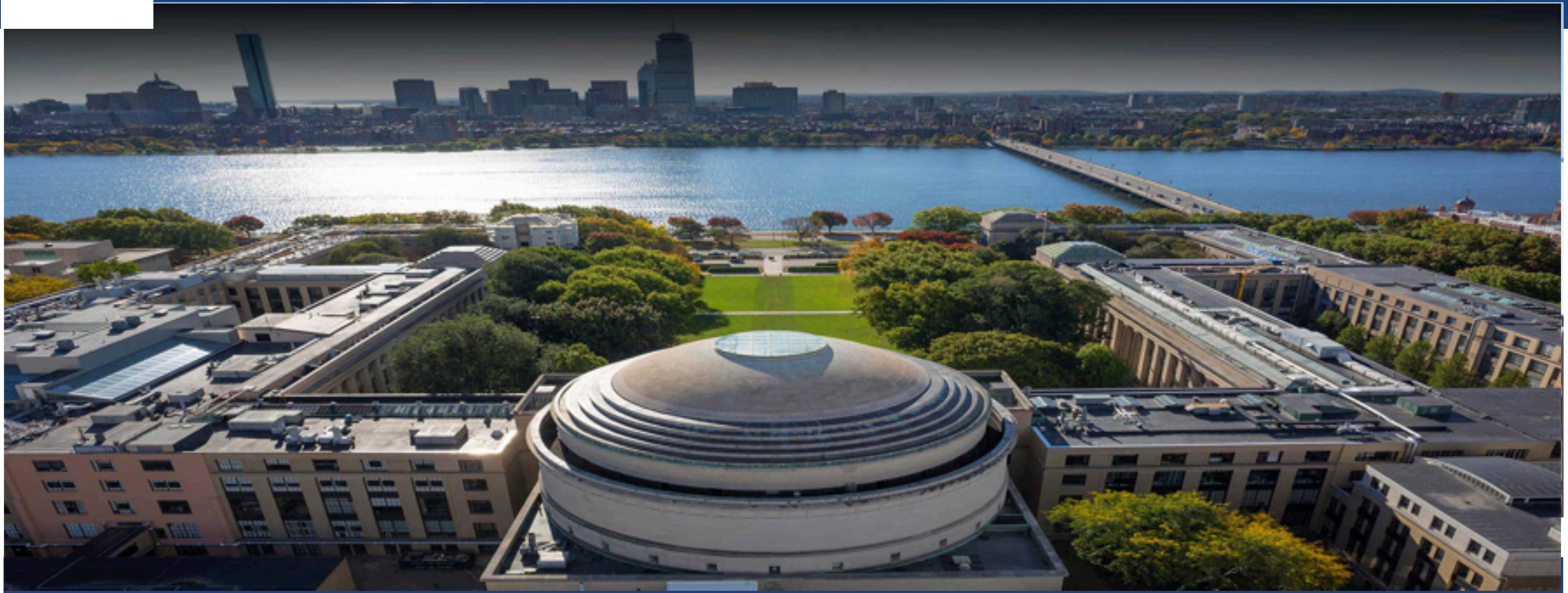


Engineering Ceramic and Glass-Materials for Energy Storage, Sensing and Computing

Jennifer L.M. Rupp

Electro-**C**hemical **M**aterials Group

Massachusetts Institute of Technology, MIT

Green&Smart: Transfer and Storage of Energy and Information

energy storage of renewables

autonomous mobility

energy efficient cities + resiliant infrastructures

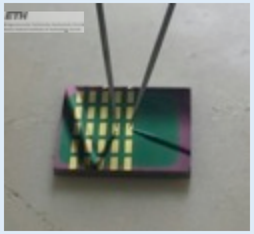
"smart electronics & sensing"

Innovation for sustainable energy and information supply

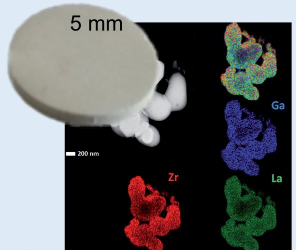
…. is based on novel material and device concepts.

Rupp group: Solid State Materials for Energy & Information Devices

Novel All Solid State Li Batteries + CO_2 Environmental Trackers



CO_2 environmental + medical sensing based on Li^+



Novel solid state Li battery with high capacities

I Garbayo et al. JLM Rupp, Advanced Energy Materials 2017
J Van den Broek et al. JLM Rupp, Advanced Energy Materials, 2016
C Haensel et al. JLM Rupp, Nanoscale 2016
M Rawlance et al. JLM Rupp, Nanoscale 2016
S Afyon et al. JLM Rupp, J of Materials Chemistry 2015

Ionic memory and computing logics: memristors

information storage + non-binary computing

S Schweiger et al. JLM Rupp, Advanced Materials 2017
R Schmitt et al. JLM Rupp, ACS Nano 2017
M Kubicek, F Messerschmitt et al JLM Rupp, ACS Nano 9, 2015
F Messerschmitt, et al. JLM Rupp, Adv Funct Mater. 25, 2015
F Messerschmitt, et al. JLM Rupp, Adv Funct Mater. 24, 2014

Renewable Solar Fuels (Hydrocarbons)

CO_2
H_2O

in

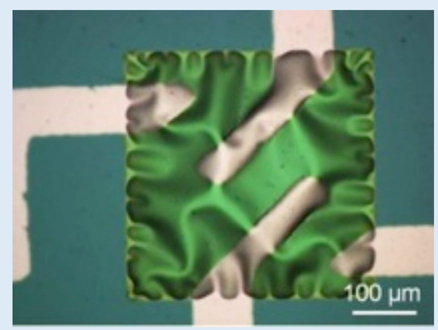
out

syngas
Storage
Or
Chemicals

clean energy storage with no material`s capacity limitations

AH Bork et al., JLM Rupp, Advanced Energy Materials, 2016
AH Bork, et al. JLM. Rupp, J. of Mat Chem A, 2015

Micro-energy convertor designs



grid-independent energy conversion for autonomous electronics

Y Shi, AH Bork, S Schweiger, JLM Rupp, Nature Materials 14, 2015
Y Shi et al. JLM Rupp, Adv Mat, 2016

Outline

Energy Storage: All Solid State Li^+ Batteries

- Cheap Ceramic Processing: Mass Storage
- Low Temperature Microbatteries

Environmental Monitoring: CO_2 Sensing

- Novel Li^+-Garnet-based CO_2 Sensor Architectures

Neuromorphic Computing: Memristors

- Strained Memristor Concept

Energy Storage: Material Limitations of Liquid based Batteries

Renewable Energies

Solar

Wind

↑

energy storage

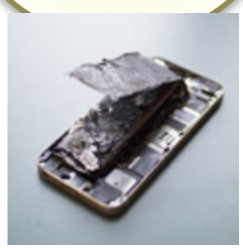
↓

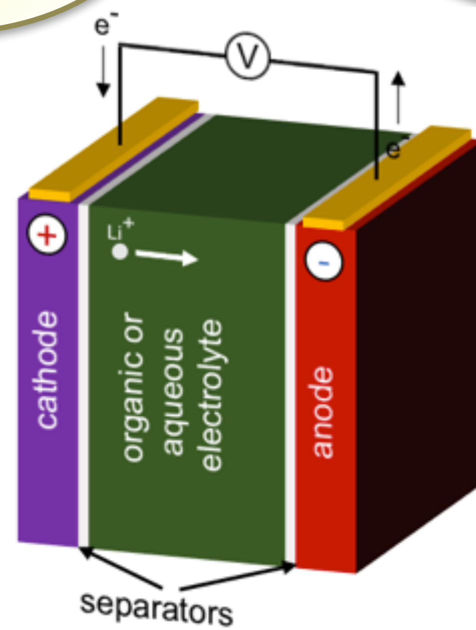
challenges

instable electrolyte/electrodes interfaces

low temperature window (<120° C)

safety: inflammable batteries





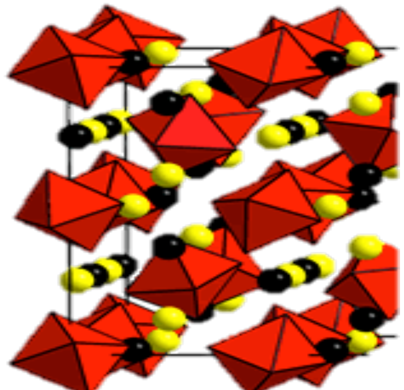
limited scalability + V-window

damage: Li dendrites

Today`s liquid-based Li-ion batteries have severe safety, stability and scaling limitations. New Material architectures and cell designs needed.

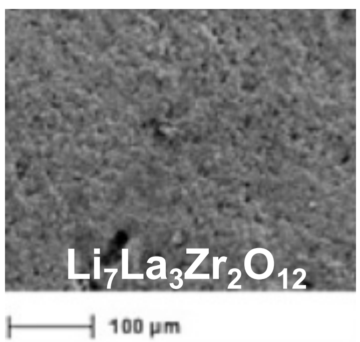
Literature: All Solid State Battery Electrolytes based on Li-Garnets

structure

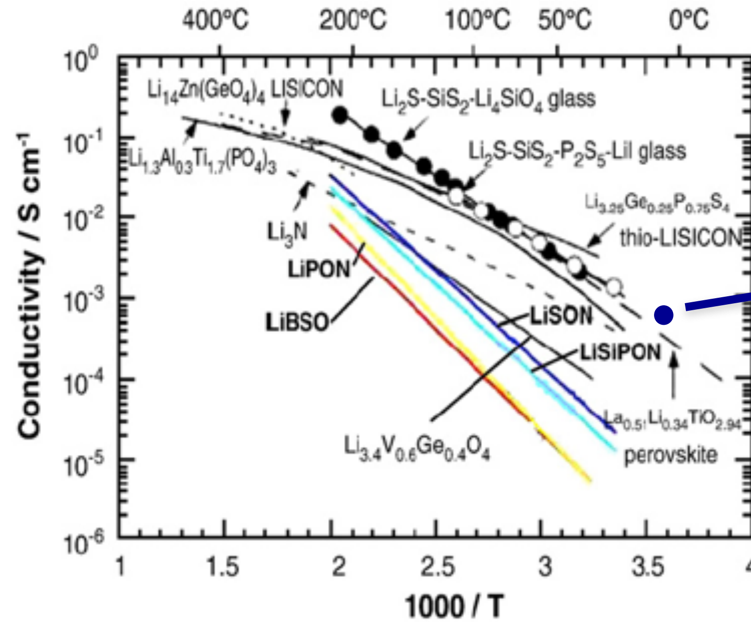


$Li_7La_3Zr_2O_{12}$

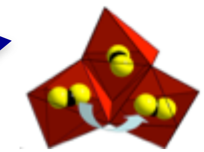
dense ceramic



Li^+ ionic transfer



Li-Garnets
$Li_7La_3Zr_2O_{12}$



structural Li^+ diffusion

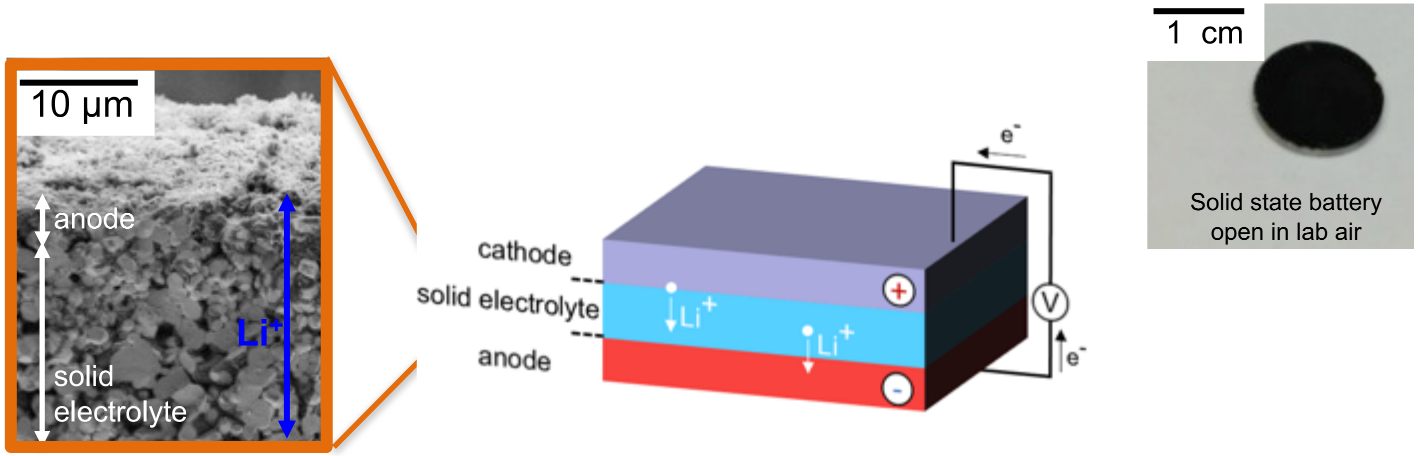
Knauth et al., Solid State Ionics 180, 2009
H El Shiwari amd J Janek, J. of Power Sources 2013

Young field, since 2012:
First macro ceramic Li-garnet electrolytes pellets: comparable Li conduction by one order to classic liquids → advantage: solid state nature

(1) Reviewed Li-garnet battery performance: J van den Broek, S Afyon, JLM Rupp, Advanced Energy Materials, 2016
(2) S Afyon et al. JLM Rupp, J. of Materials Chemistry A 3, 2015

All Solid State Li^+ batteries without Liquids

Innovation: Non-inflammable Li^+ battery up to 1000°C in air.



energy storage of renewables

electric vehicles

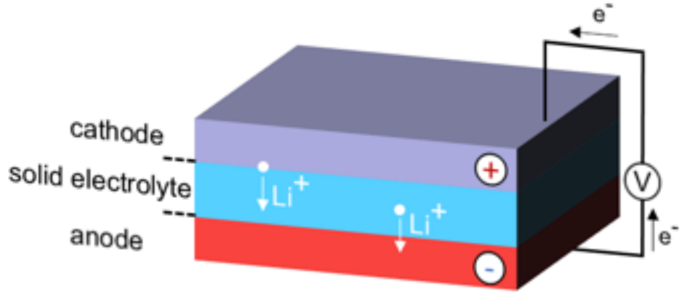
"smart electronics & sensing"

Rupp group research: All solid state batteries based on Li-Garnets. Cheap manufacturing, high V cathodes, understanding interface reactions, tuning power characteristics and charging.

S Afyon, F Krumeich, JLM Rupp, J of Mateials Chemistry A, 2015 - Featured in Green Car News
JLM Rupp, M Streiff, patent EP 15000536.1, 2015

Solid State Electrolyte Li-Garnet/Cathode Interfaces

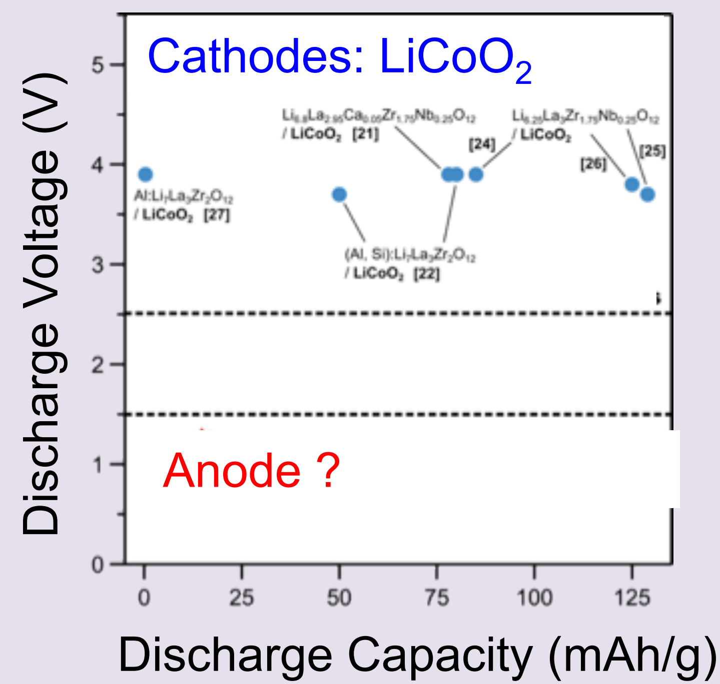
Integration of $Li_7La_3Zr_2O_{12}$ Solid Electrolytes to Batteries



What are suitable electrodes?
Power?

young field: first battery in 2012

Li-Garnet Battery: Electrode Materials



Ceramic processing and solid state battery engineering:

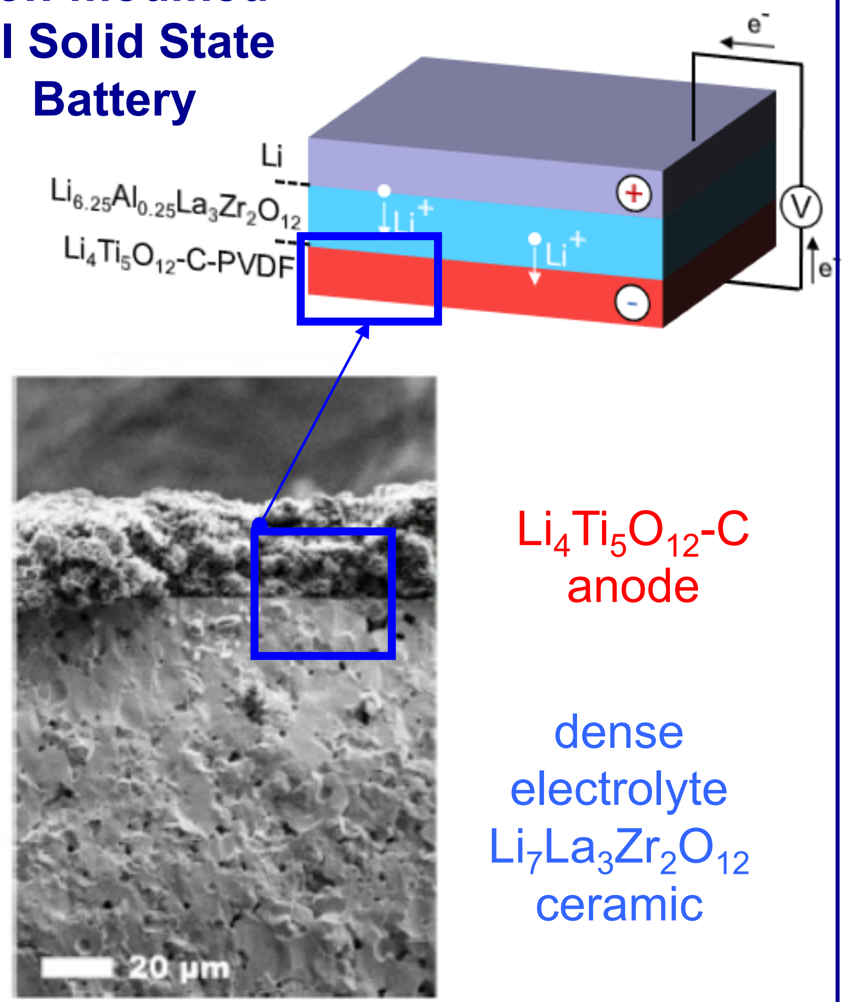
Electrodes compatible with Li-garnets needed

→ First cathodes reported (cells[1] + Ceder group MIT: MD modeling[2])

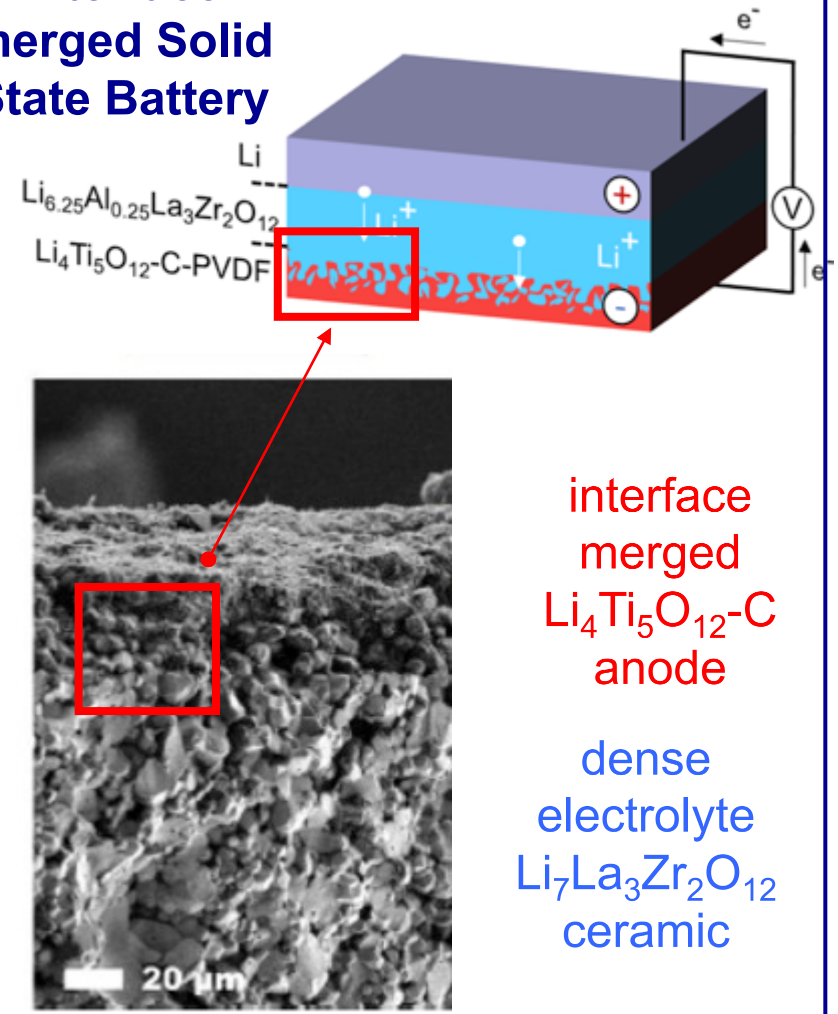
(1) Reviewed Li-garnet battery performance: J van den Broek, S Afyon, JLM Rupp, Advanced Energy Materials, in press 2016
(2) LJ Miara, G Ceder et al,Chem of Materials, 27, 2015
(3) X Tong, V Thangadurai, E Wachsman, Inorganic Chemistry 54, 2015
(4) S Afyon et al. JLM Rupp, J. of Materials Chemistry A 3, 2015

Solid Li^+ batteries the role of ceramic/interface manufacturing

Non-modified All Solid State Battery



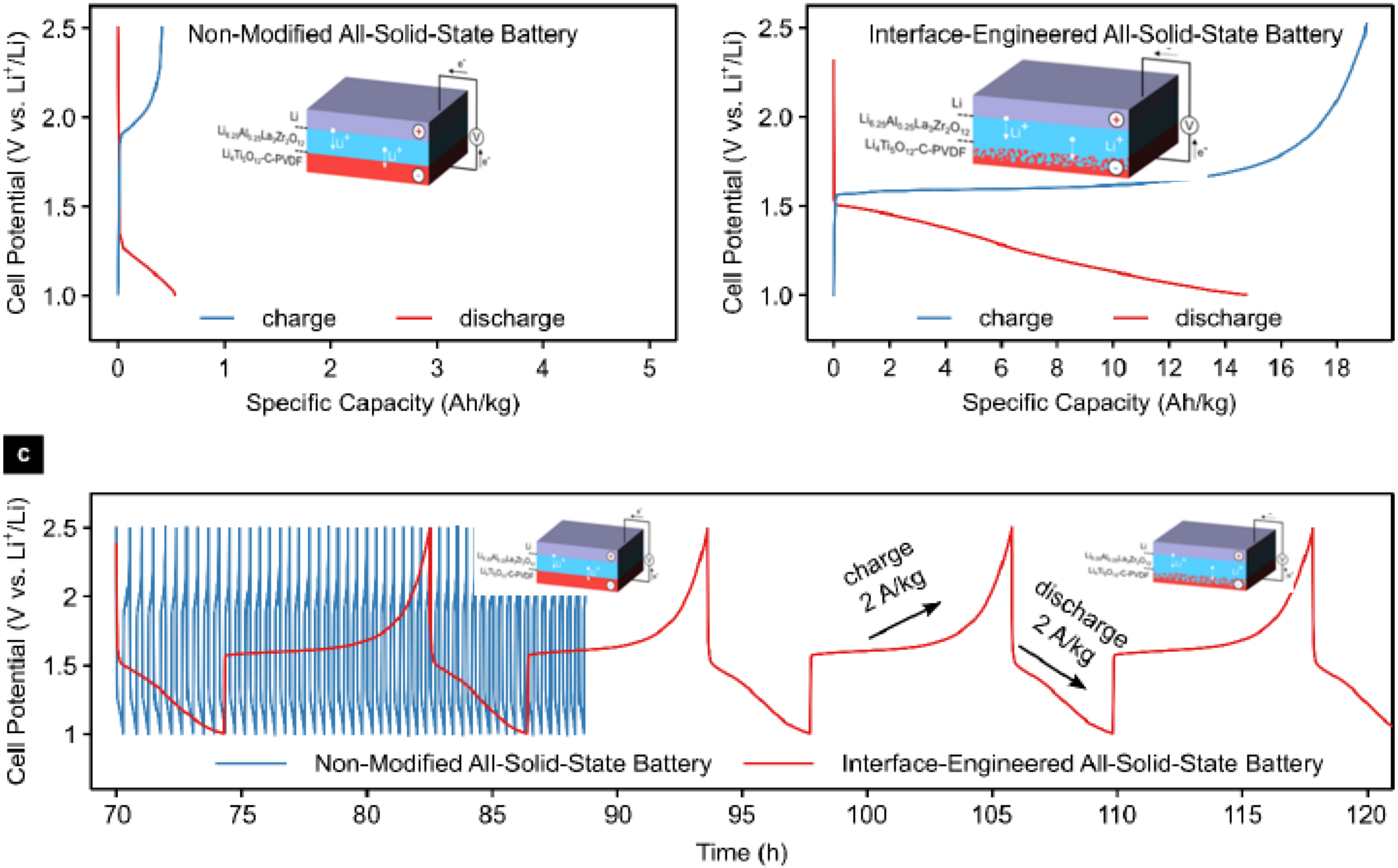
Interface merged Solid State Battery



Model experiment:
Influence of solid-solid anode-electrolyte interface coagulation on electrochemistry?

J van den Broek, S Afyon, JLM Rupp, Advanced Energy Materials, 1600736 (2016)

Solid Li^+ batteries the role of ceramic/interface manufacturing

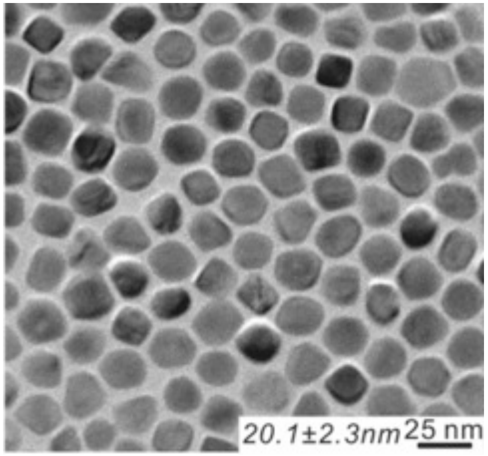


First metal oxide-based anode operated successfully in Li-Garnet battery cell.
Higher specific capacitances are reached for the interface engineered cells.

J van den Broek, S Afyon, JLM Rupp, Advanced Energy Materials, 1600736 (2016)

Solid State Li^+ Garnet Electrolyte Battery with Antimony Anode

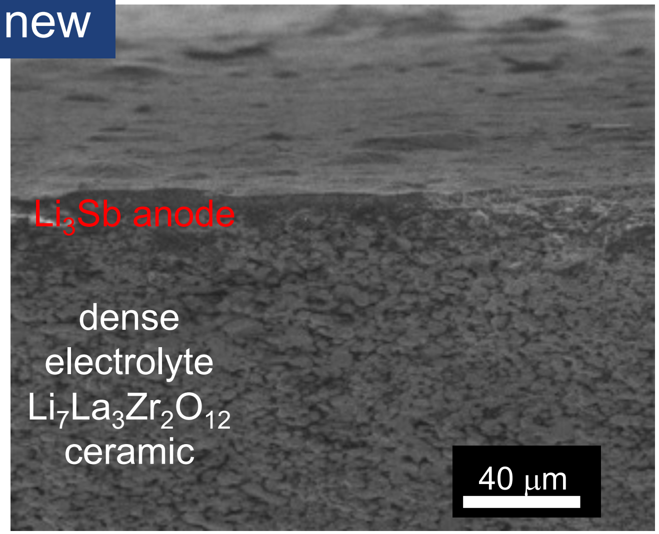
Sb nanoparticles
liquid Li standard battery

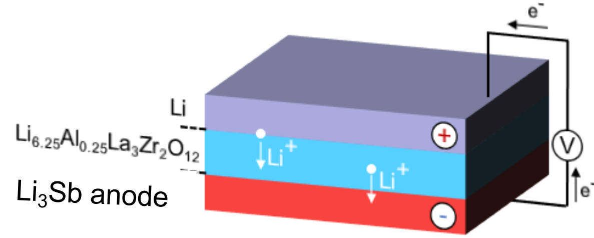


$Sb+3Li^++3e^- \leftrightarrow Li_3Sb$
(660 mAh g^{-1}, ΔV=135%)

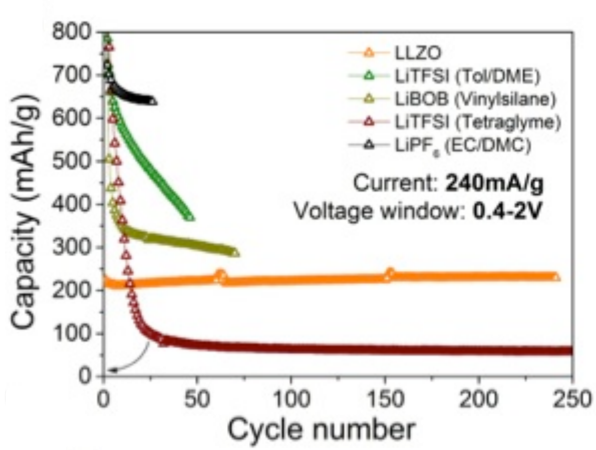
M. He, M Kovalenko et al, *Nano Letters*, **2014**, *14*, 1255

new





Sb anode + $Li_7La_3Zr_2O_{12}$
solid electrolyte ceramic
→ 230 mAh/g

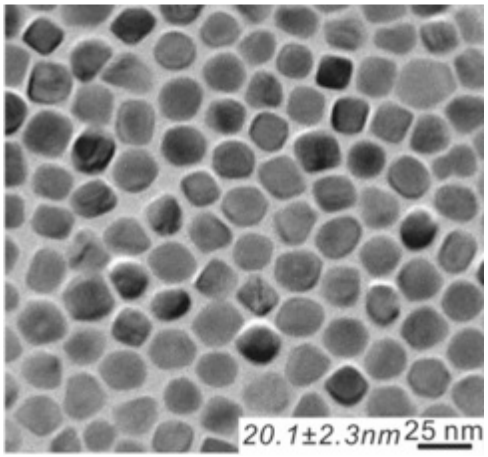


High stability for solid state battery cell based on solid Li-garnet electrolyte compared to classic commercially available liquid type electrolytes in batteries.

S Afyon, J van den Broek, C Haensel, S Wang, K Kravnchik, M Kovalenko, JLM Rupp, in review 2017

Solid State Li^+ Garnet Electrolyte Battery with Antimony Anode

Sb nanoparticles
liquid Li standard battery



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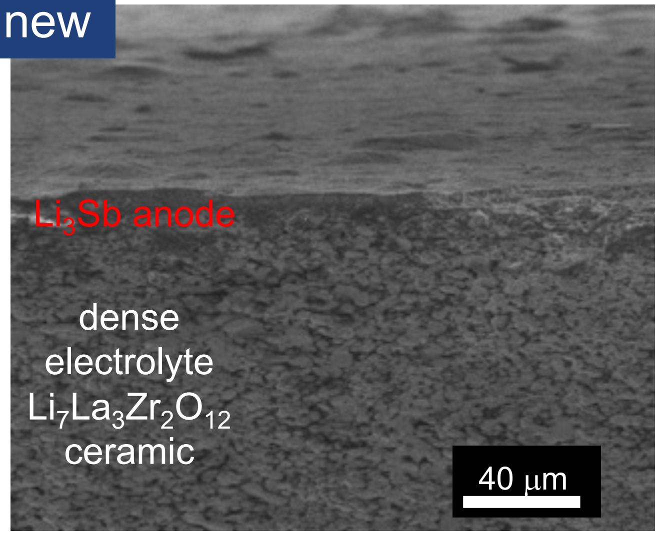

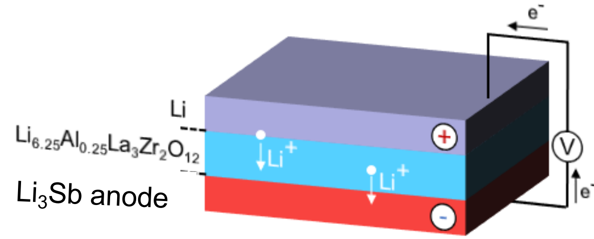

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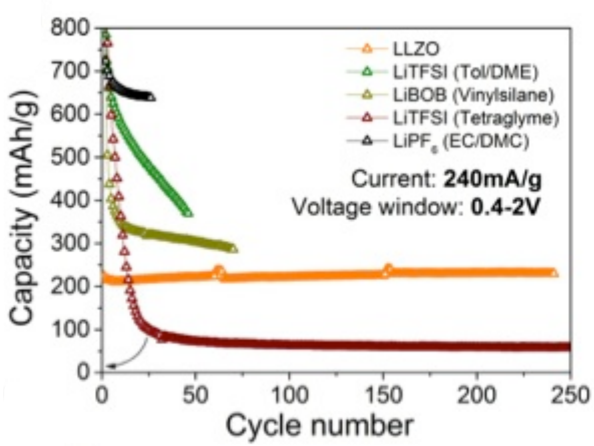

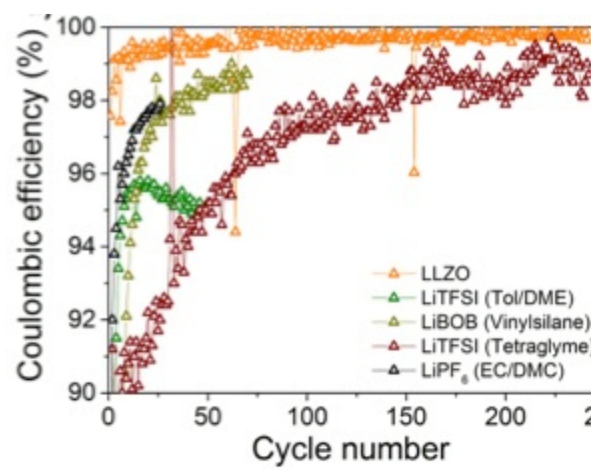

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S Afyon, J van den Broek, C Haensel, S Wang, K Kravnchik, M Kovalenko, JLM Rupp, in review 2017

What is next? A Fair and Green Solid State Li Battery

Co mines in Congo

Cathode of battery:
i.e.$LiCoO_2$, LiMnNiCo (NMC) …

90 % of today`s batteries are based on political and socio-economic critical elements such Co in their cathodes (i.e. Tesla, Duracell, …)

→ Amnesty International: violation of human rights[1]

→ U.S. trade group Electronic Industry Citizenship Coalition:
60% world share of Co Congo are problematic[2]

Innovation: Make a first solid state battery without politically critical elements

1) Amnesty International Report, Child labor behind smart phone and electric car batteries, retrieved 2016-01-19
2) Electronic Industry Citizenship Coalition, a practical approach to greening electronics supply chain, June 2010
3) African mineral Production, British Geological Survey, Retrieved 2009-0930

Outline

Energy Storage: All Solid State Li^+ Batteries

- Cheap Ceramic Processing: Mass Storage
- Low Temperature Microbatteries

Environmental Monitoring: CO_2 Sensing

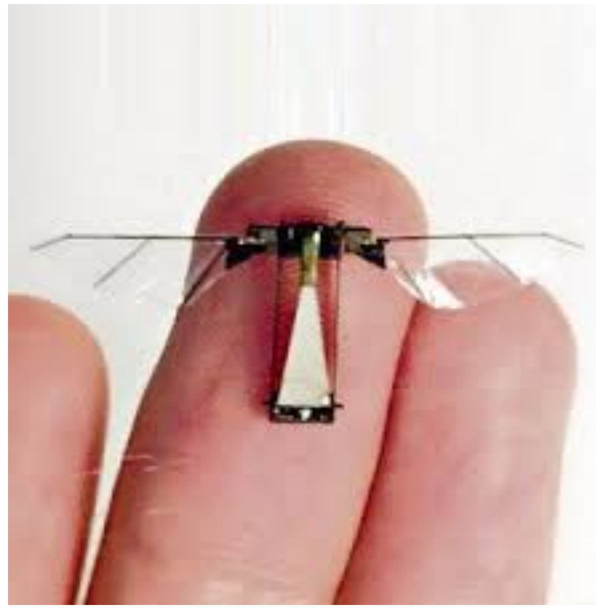
- Novel Li^+-Garnet-based CO_2 Sensor Architectures

Neuromorphic Computing: Memristors

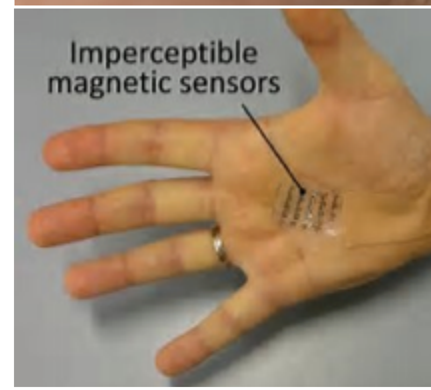
- Strained Memristor Concept

Microbattery: Energy Supply for Sensing and Transmitters

sensing dust:
environmental monitoring



miniaturized drones,
sensing,
transmitting devices,
reconnaissance technology



human implants

powered pills
controlled substance release

autonomous energy supply → “pre-processing sensing data” →

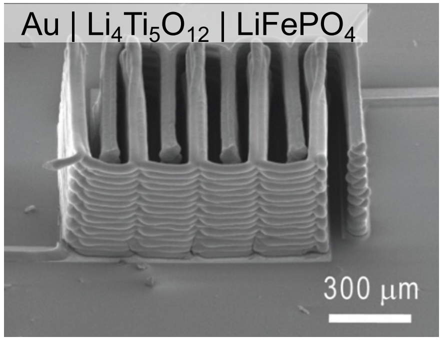
Autonomous sensors are required for future health and environmental sensing and sensing for efficient energy use:

→ thin film microbatteries required

State-of-Technology & Challenges: Thin Film Microbatteries

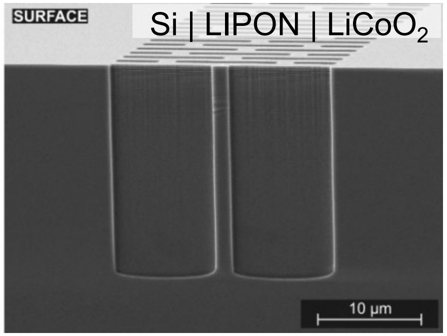
Academia: Microbattery Research

3D printed architectures



Sun, Lewis et al., Adv. Mater., 25(33), 2013, 4539.

Si integrated



Notten et al., Adv. Mater., 19(24), 2007, 4564.

Product: Thin Film Microbattery

Si integrated thin film battery

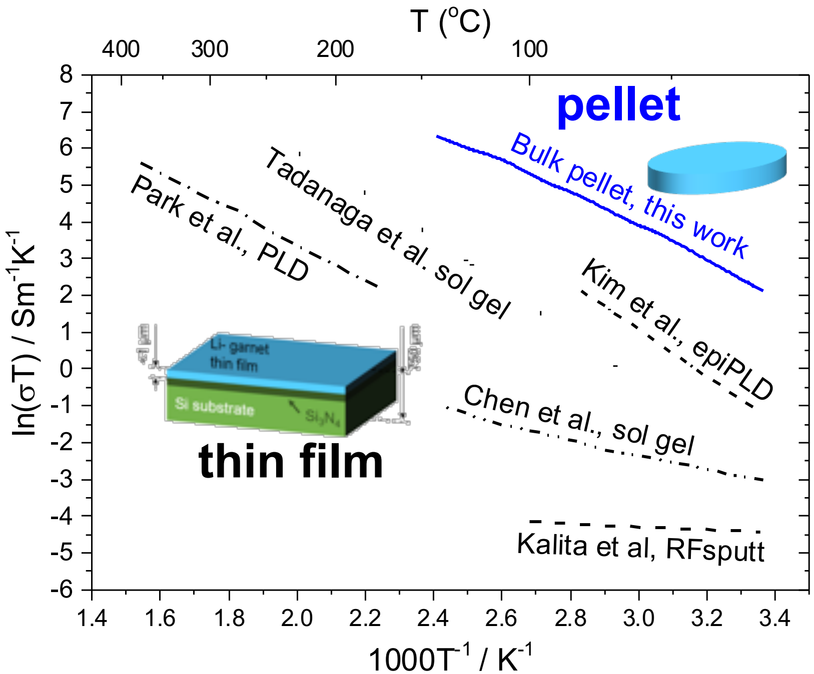
Oak Ridge "Bates" cell

Challenges

- Reduced Li conductivity electrolyte
- Limited T-operation window
- High V cathode integration challenging
- Safety & stability for high cycle life

Thin Films vs. Macro-Pellets of Li Garnet Electrolytes: $Li_7La_2Zr_3O_{12}$

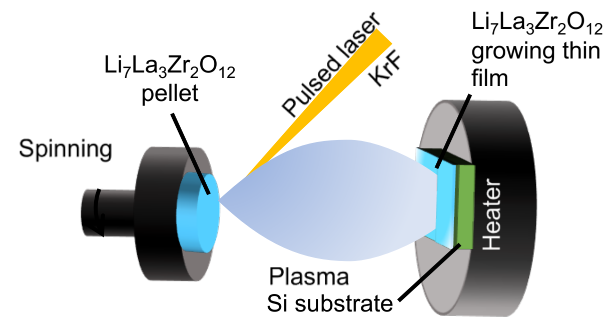
Literature: $Al{:}Li_7La_2Zr_3O_{12}$

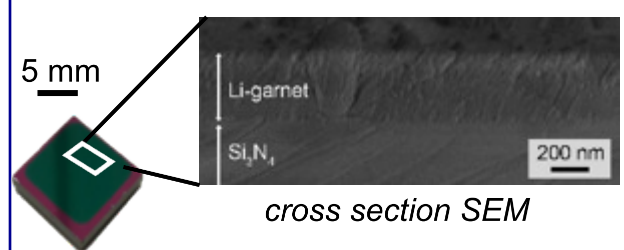


Li-conductivity variation 10^{-7}-10^{-3} S/cm !

[1] Tan et al., ECS Solid State Letters 1(6), 2012.
[2] Kim et al., Dalton Trans. 42, 2013.
[3] Park et al., Thin Solid Films, 576, 2015.
[4] Kalita et al., Solid State Ionics, 229, 2012.
[5] Nong et al. Materials Letters 154: 167, 2015.
[6] Tadanaga et al., J Power Sources, 273, 2015.
[7] Chen et al., J Mater Chem A 2(33): 13277, 2015

Example MIT: Pulsed Laser Deposition $Ta{:}Li_7La_2Zr_3O_{12}$





cross section SEM

dense+crack-free electrolyte films

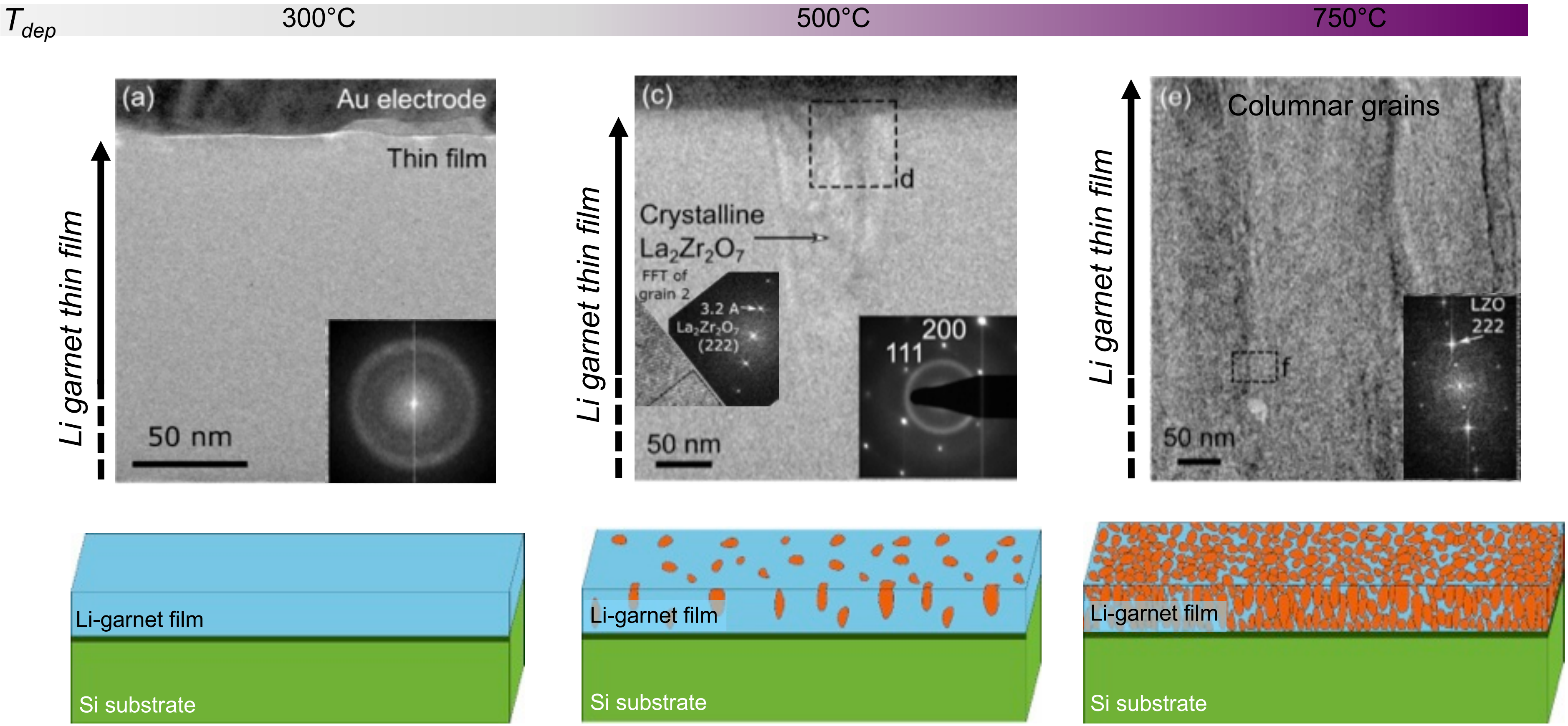
I Garbayo, JLM Rupp, to-be-submitted

Open question for thin film electrolytes and future microbatteries:

How does processing affect the Li concentration, phase, density? Ionic conductivity? Can we design low temperature microbattery processing?

I Garbayo, et al. JLM Rupp, Advanced Energy Materials, in press 2017

TEM: Glassy to Crystalline Ta-$Li_7La_3Zr_2O_{12}$ Films



Pseudo-amorphous Li-garnet network

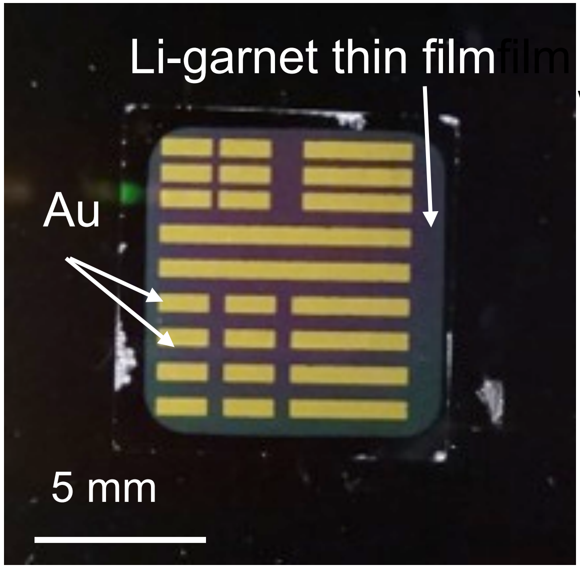
$La_2Zr_2O_7$ grains in Li-garnet amorphous network

Crystalline $La_2Zr_2O_7$ dominates over amorphous Li-garnet

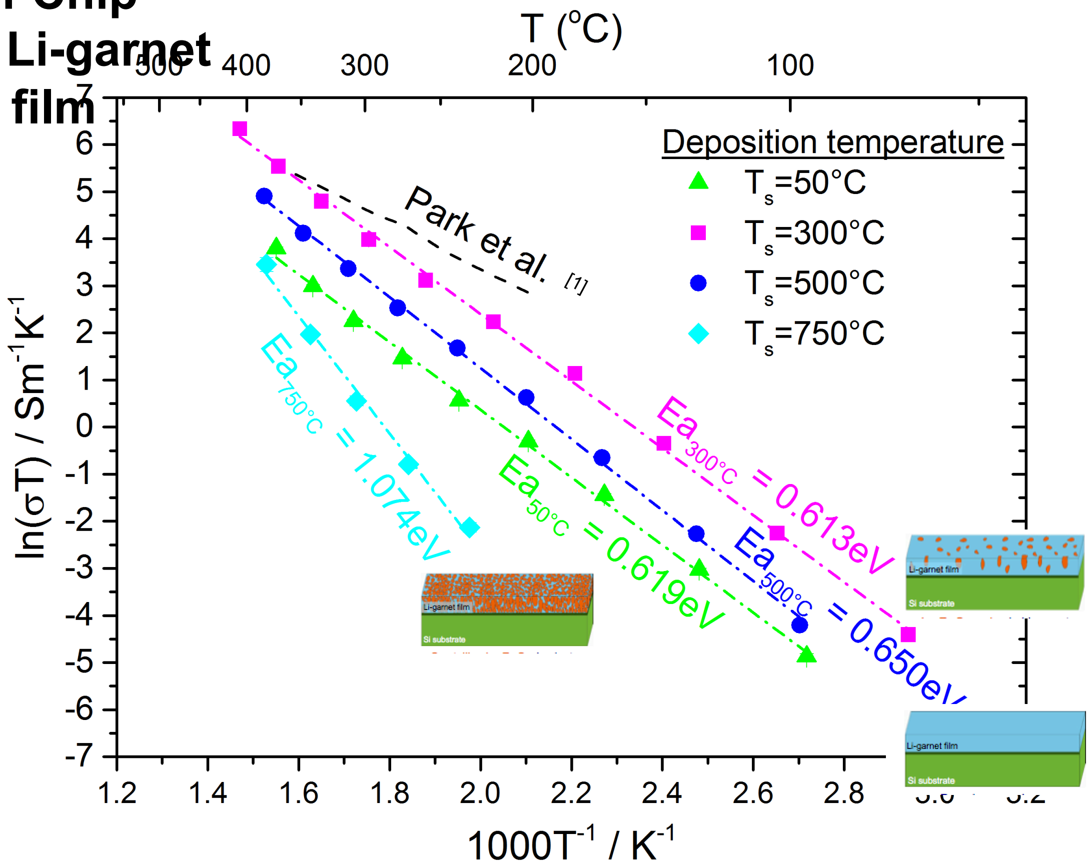
"Glass-like" Li rich garnet films can be created: Cost reduction
→ low processing temperature → new strategy to avoid Li-dendrites

I Garbayo, et al. JLM Rupp, Advanced Energy Materials, in press 2017

Li-transport Garnet Electrolyte Thin Films vs. Nanostructure



Si-Chip with Li-garnet film



Highest Li^+ mobility at 300° C deposition temperature for glass-type Li garnet films.

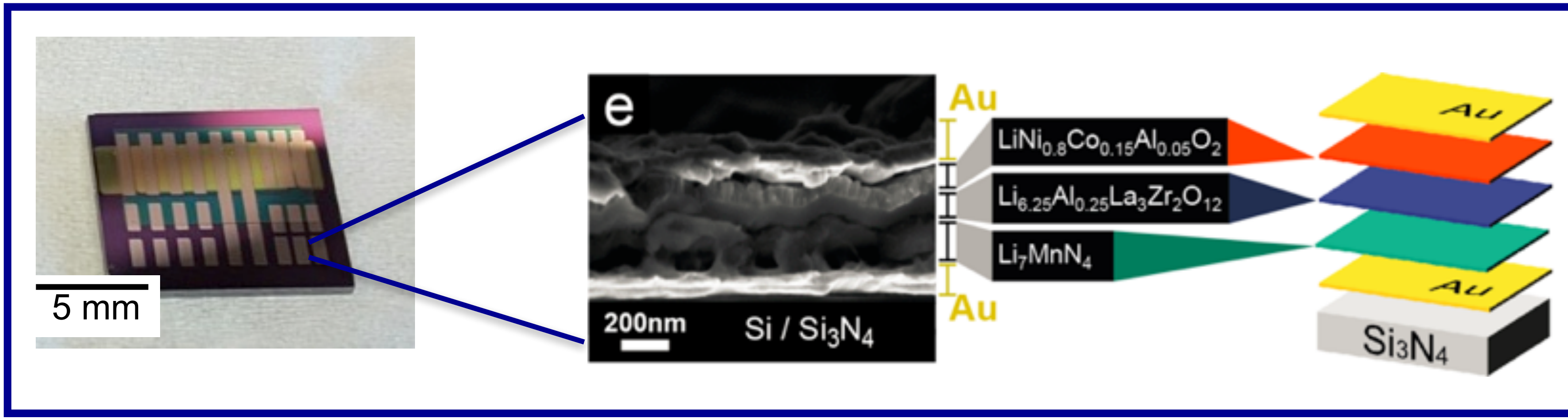
Opportunities:

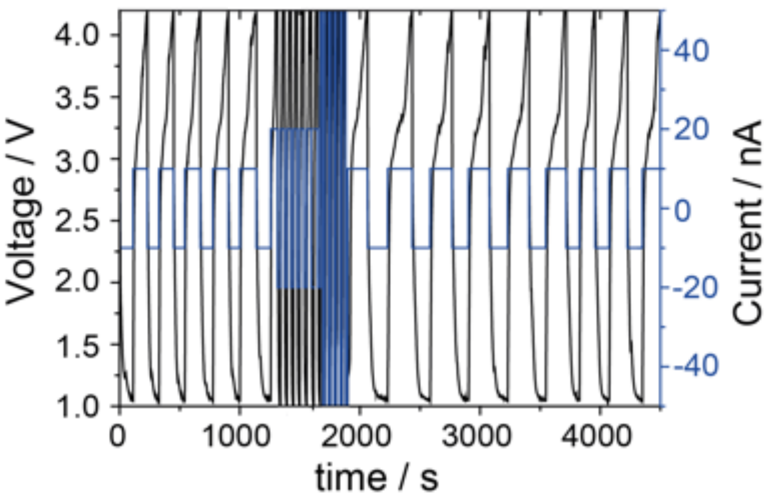
- Low temperature processing → new glass electrolytes
- Fast Li conductivity / increased T window → unclear: integration?

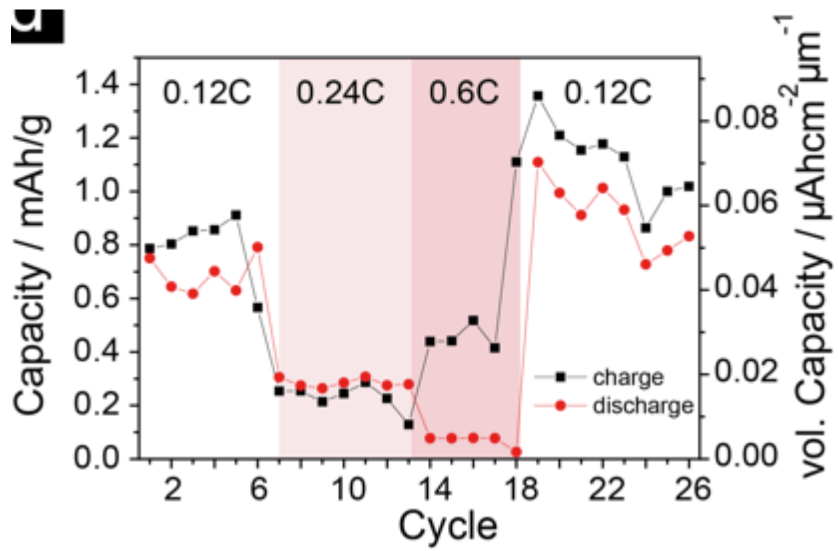
[1] Park et al., Thin Solid Films, 576, 2015.

I Garbayo, et al. JLM Rupp, Advanced Energy Materials, in press 2017

Low Temperature Processed Glassy Thin-Film Microbattery







- Stable Cycling Achieved for first Garnet-based All Solid State Thin-Film Microbattery. Whole cell stable in air and processed at low temperature.

I Garbayo, et al. JLM Rupp, Advanced Energy Materials, in press 2017

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Neuromorphic Computing: Memristors

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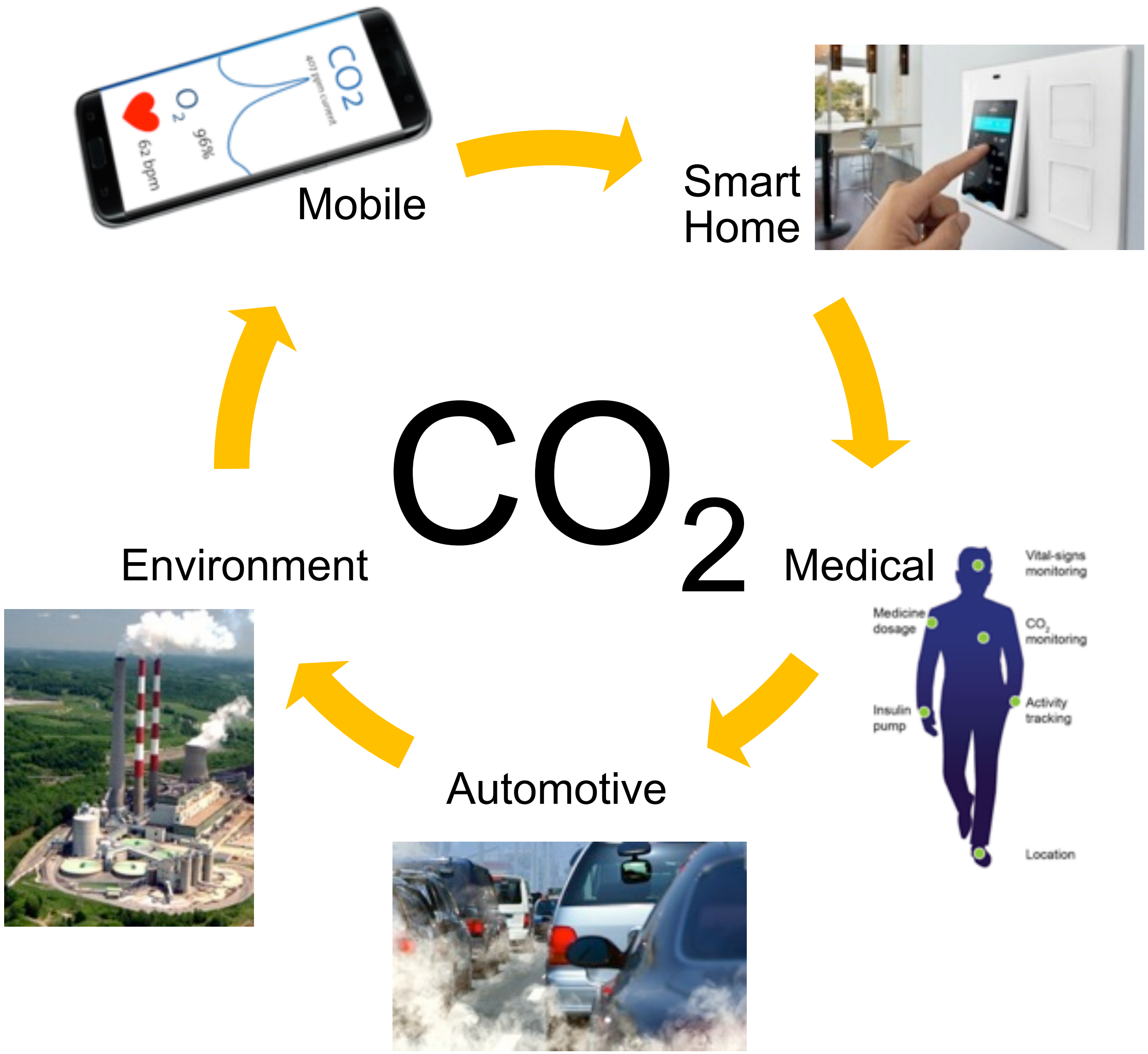
Relevance of CO_2 tracking for society and energy management

IR Sensor

Electrochemical Sensor

Needs for products:

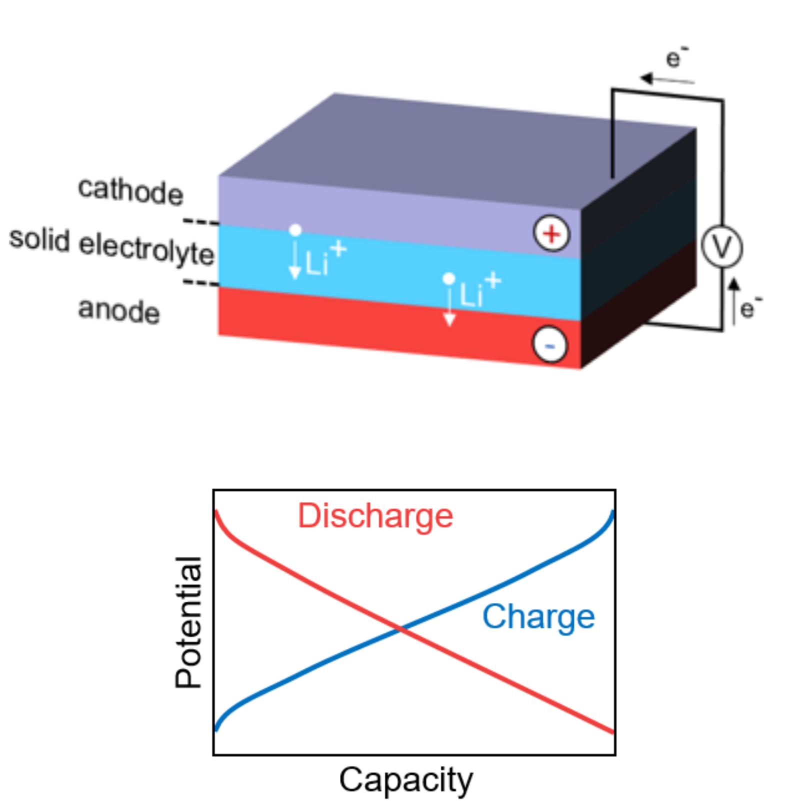
- Power efficient
- Small
- Low cost
- Chip integration



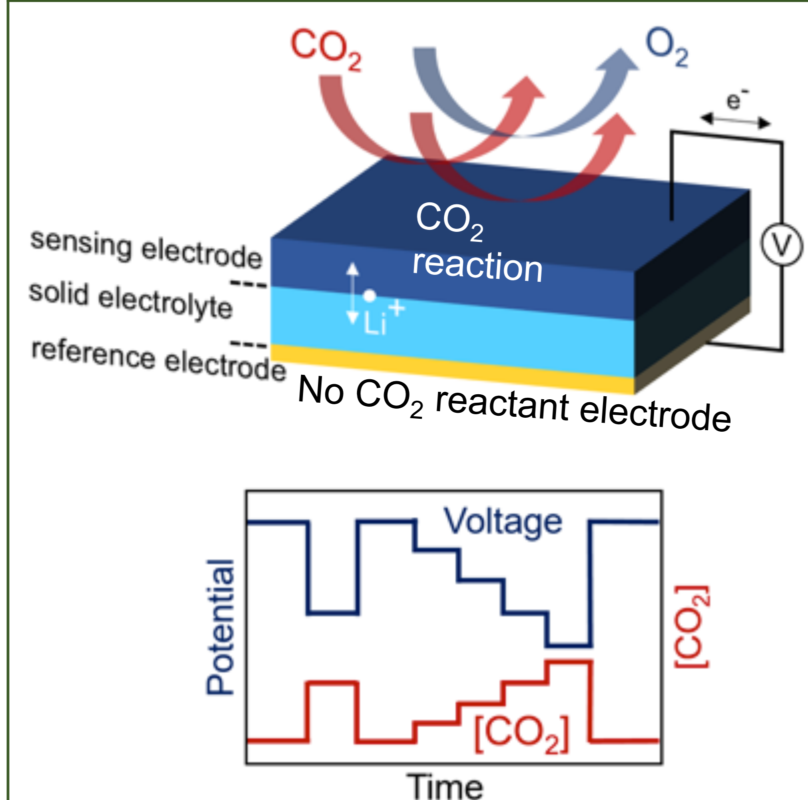
M Struzik, JLM Rupp et al, to-be-submitted

Solid State Energy Storage and Tracking Devices Based on Li^+

Energy Storage Devices



Electrochemical CO_2 sensors

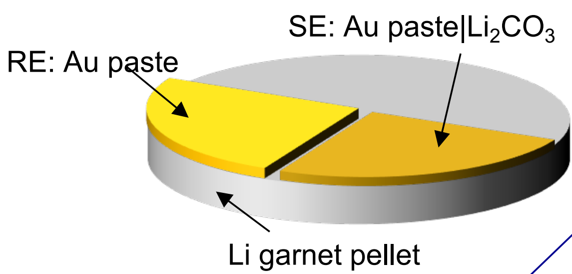


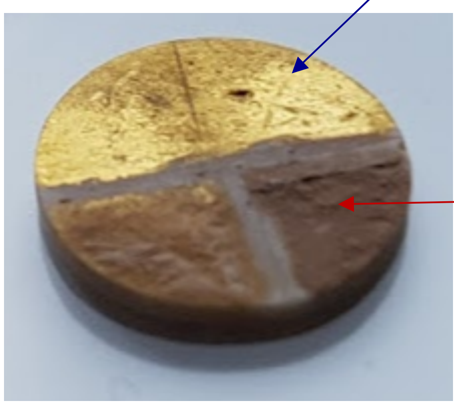
Replacing liquids by solid state electrolytes improves safety and stability

Challenges: fast, dense and thin Li-electrolytes needed with low interfacial resistances towards electrodes !

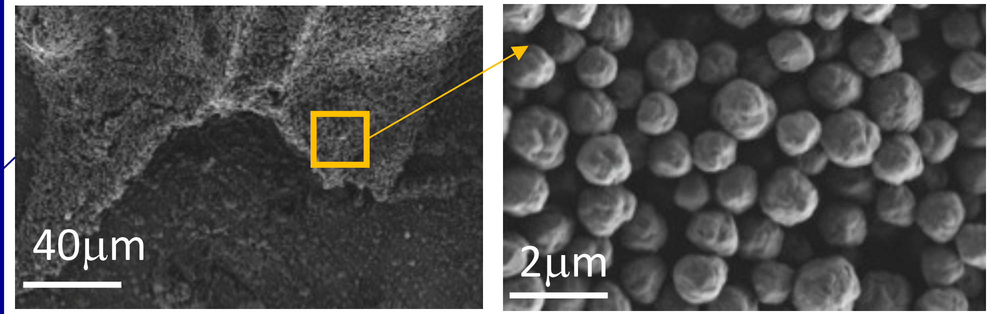
Li-Garnet based in-plane structure for CO_2 sensing

In-plane pellet based cell

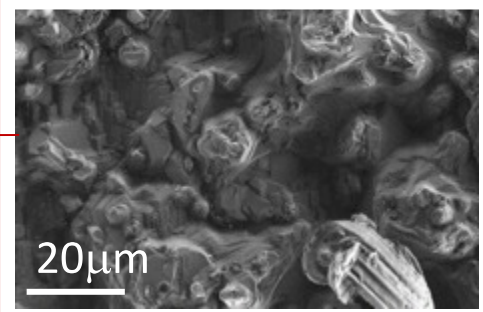




Reference electrode Au paste



Auxiliary phase – Li_2CO_3+Au



Porous morphology with access to the electrolyte

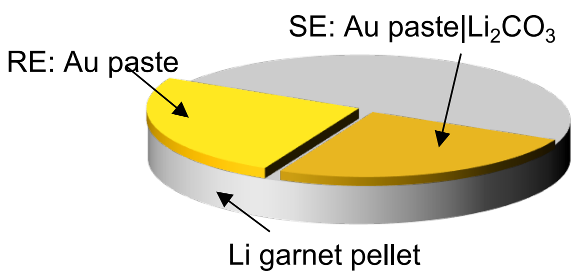
Good contact with LLZO

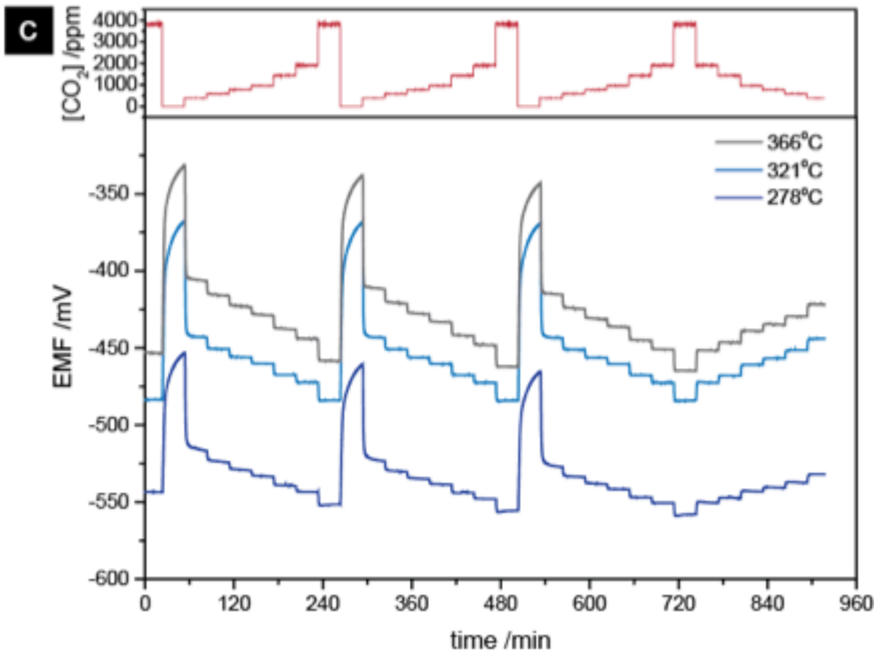
Successful integration of porous reference electrode and the auxiliary phase confirmed with SEM

M Struzik, JLM Rupp, in review 2017

Li-Garnet based in-plane structure for CO_2 sensing

In-plane pellet based cell





First successful CO_2 sensor device with $Li_7La_3Zr_2O_{12}$-based solid electrolyte

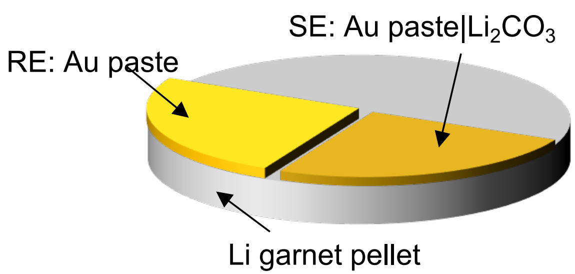
EMF: Sensor detects changes in $[CO_2]$, stable cyclability in a range 400-4000ppm

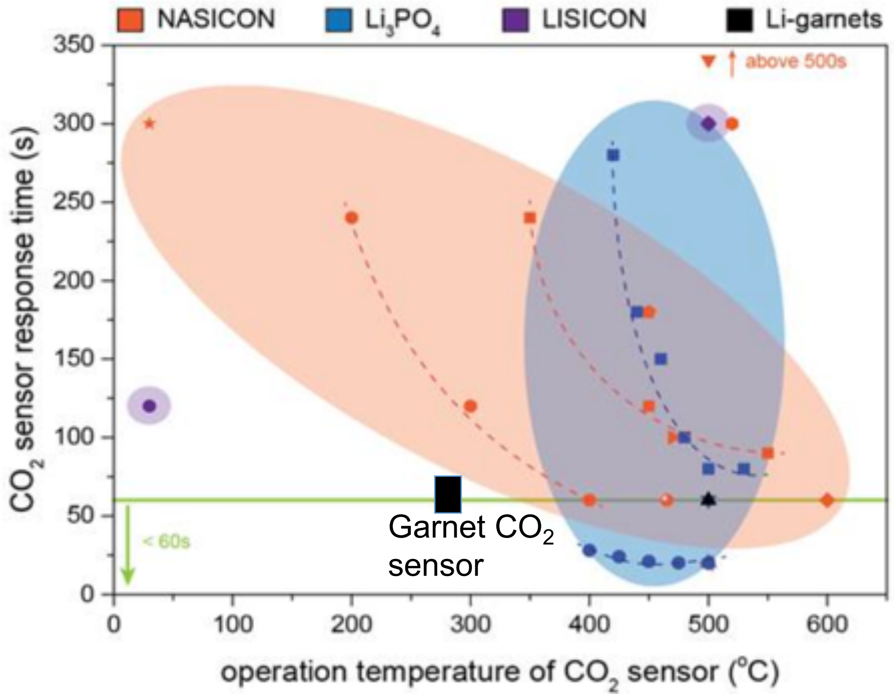
Sensitivity: ~32 mV **Response time:** <1 min at 280°C

M Struzik, JLM Rupp, in review 2017

Novel Li-Garnet CO_2 Sensors based on Battery Technology

In-plane pellet based cell





Comparison to state-of-technology shows fastest response time < 60sec at lowest temperature >300°C for newly proposed CO_2 Sensors based on $Li_7La_3Zr_2O_{12-d}$

M Struzik, JLM Rupp, in review 2017

Outline

Energy Storage: All Solid State Li^+ Batteries

- Cheap Ceramic Processing: Mass Storage
- Low Temperature Microbatteries

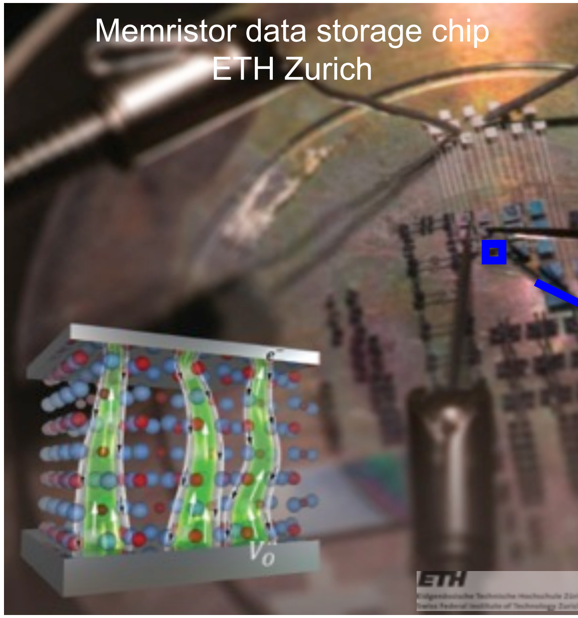
Environmental Monitoring: CO_2 Sensing

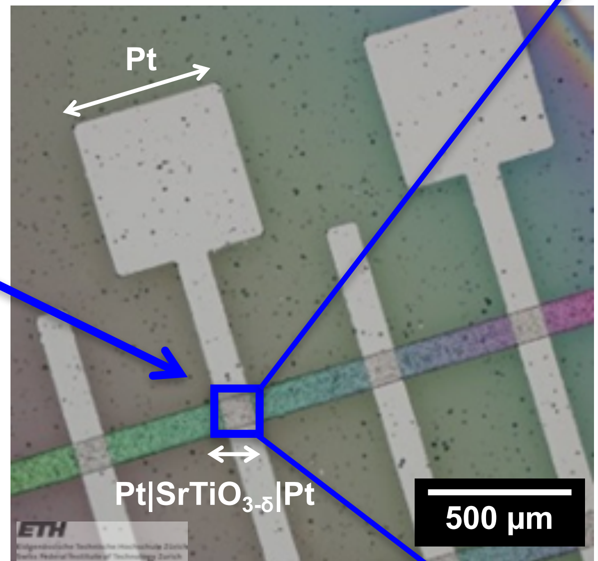
- Novel Li^+-Garnet-based CO_2 Sensor Architectures

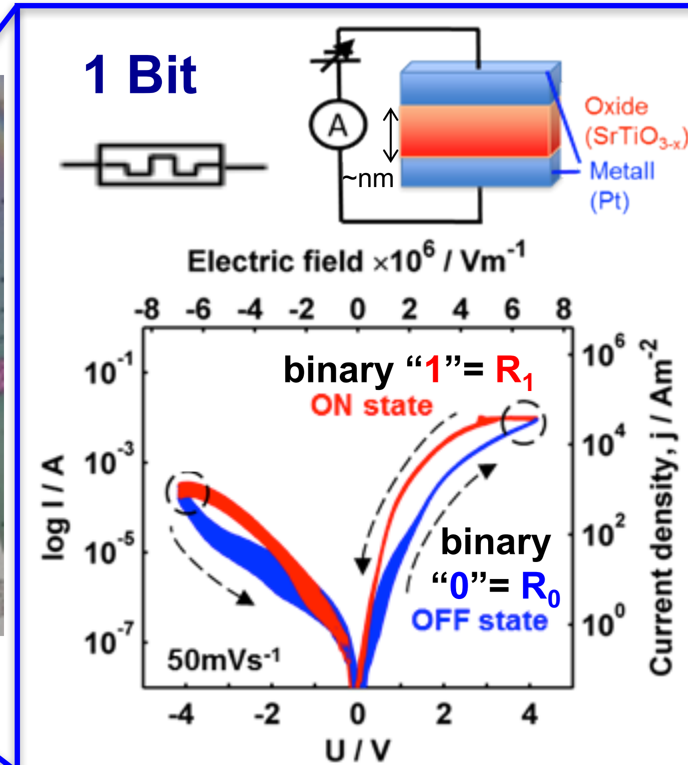
Neuromorphic Computing: Memristors

- Strained Memristor Concept

What is a Memristor / Resistive Switch?







Example: first Pt-$SrTiO_{3-\delta}$-Pt-based memristor cross-bar arrays[1,3]

Memristor = "Memory + Resistor": the 4th basic circuit element

Potential application: data storage

Young field: active start 2008[7,8] → driven by electrical engineers

Team: oxide defect kinetic to device performances described for memristors[1-6] + new strained material building blocks as bit storage architectures[4]

1) Messerschmitt F, Rupp JLM, Advanced Functional Materials, 24, 2014
2) Schweiger S, et al. Rupp JLM. ACS Nano, 8, 2014
3) Messerschmit F, Kubicek M, Rupp JLM, Advanced Functional Materials, 2015
4) Schweiger S, Bowman W, Aschauer U, Rupp JLM, Advanced Materials, 2017
5) Schweiger et al. Rupp JLM, patent WO2014170023, 2014
6) Kubicek M, et al. Rupp JLM, ACS Nano, 2015
7) Yang et al. DB Strukov Nature Nanotechnology 3, 2008
8) Waser et al., Advanced Functional Materials, 21, 2009

Memristor for Binary Information Storage

memristor computer storage:
Hewlett Packard

Ref. 1,2	**Memristor**	**Flash**	**DRAM**	**FeRAM**
write time (ns)	5	1000	10	10
write operation (V)	<1.5	15	2.5	1.5
retention (yrs)	>10	>10	64ms	>10
write cycles	10^{16}	10^{5}	10^{16}	10^{14}
smallest feature size F (nm)	25	36	50	180
cell area, F^2	4	5	6	22

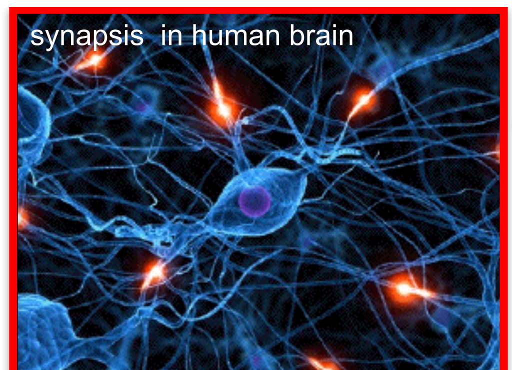
Vision: Memristive Logics for Neuromorphic Computing

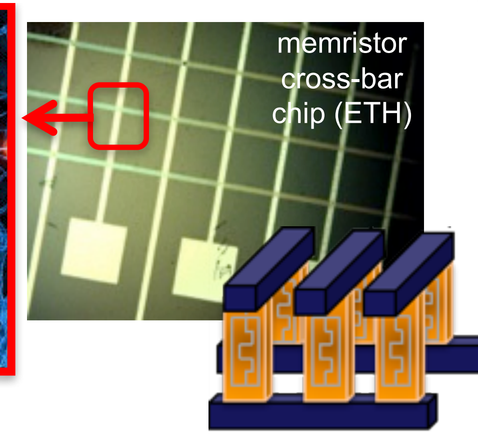
synapsis (brain) ~ memristor bits (chip)

→ similar density $10^{10}/cm^3$

→ ionically controlled hysteretic response (e.g. synaptic time spike responses)

→ multi-level: non binary-response



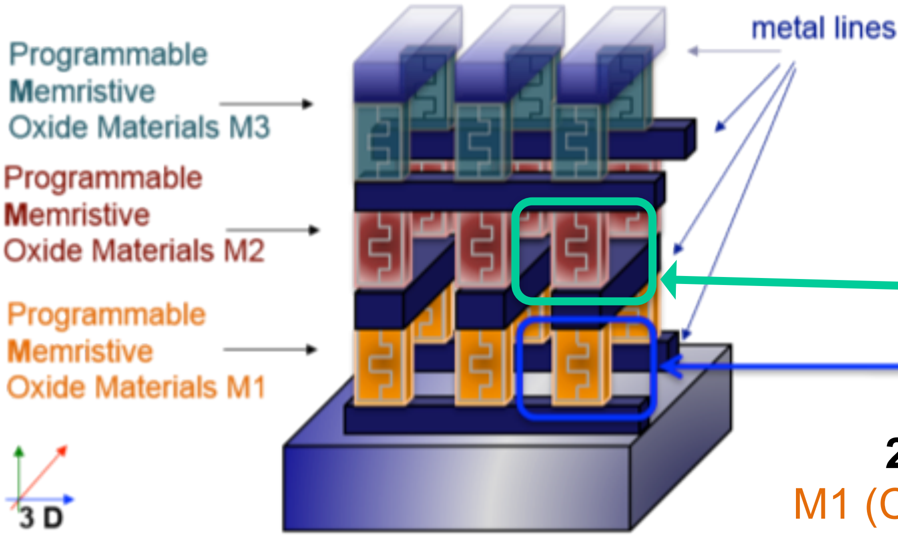


SNSF (ERC) Starting Grant, JLM Rupp 2015-2020

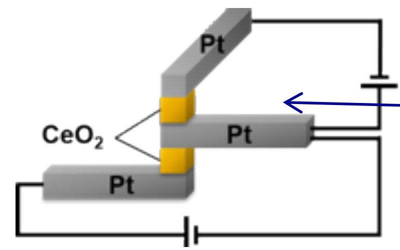
Material challenges: Defect chemical descriptions? Surface vs. bulk kinetics? Best oxide architecture? → base of memristor hardware

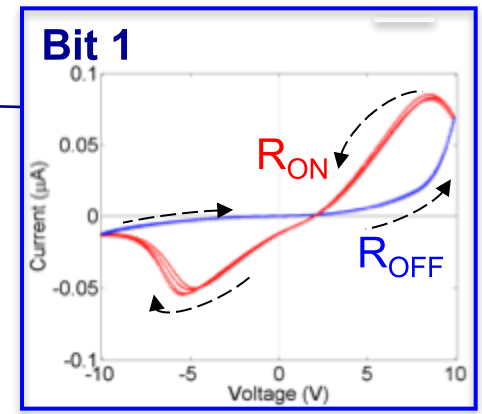
1) Peschkin and Ventra, Adv. in Physics 60, 2011   2) International Technoloy Roadmap for Semiconductor Industry (ITRS) 2012

Let's design First Oxide-based Memristive Logics

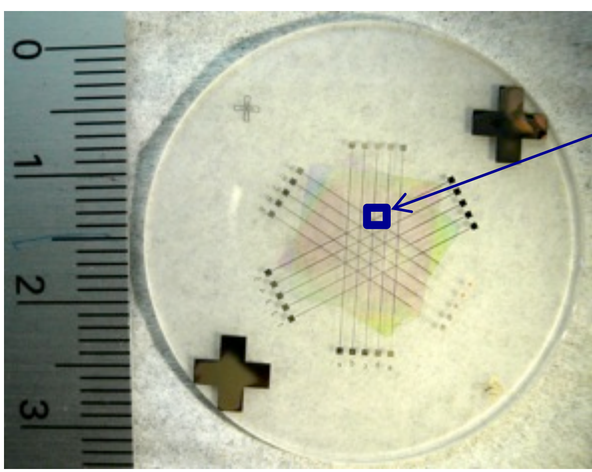


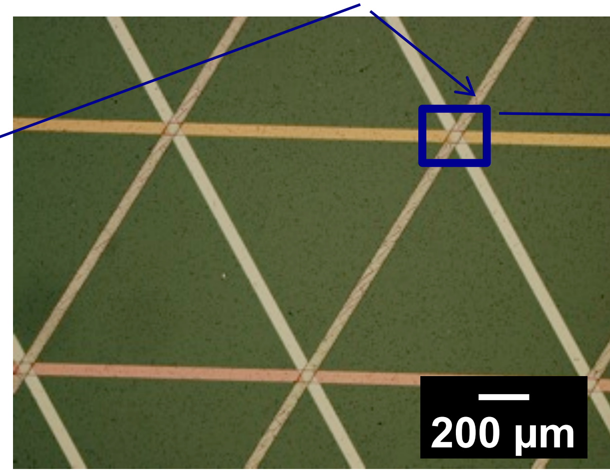
Example: 1st serial connection of 2-Bits based on bipolar switching CeO_{2-x} oxide memristors. (ETH)

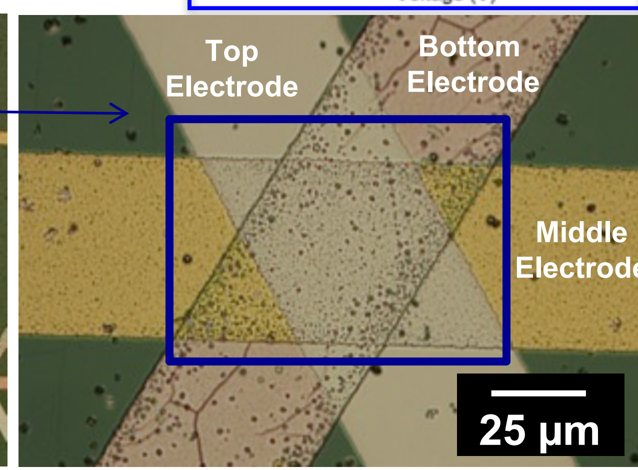




2 Bits (series):
M1 (CeO_{2-x})+M2 (CeO_{2-x})







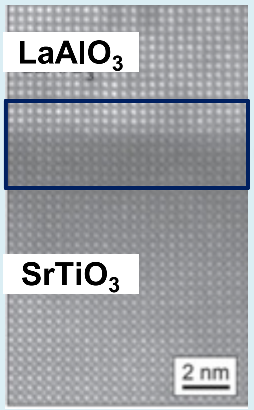
Make and study serial connections of the resistive switches
Material engineering of new ionic controlled oxide computing hardware beyond binary.

PhD Thesis Rafael Schmitt, Electrochemical Materials, MIT/ETH

State-of-the-art: Altering Strain Fields in “Electronics” and “Ionics”?

Electronics

Electronic heterostructure oxide as building blocks for devices



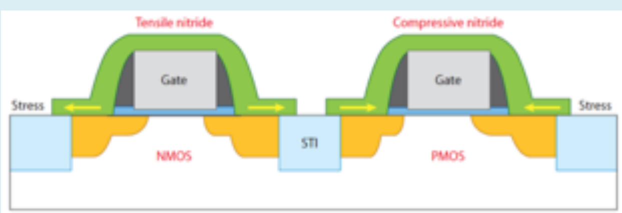
insulator

fast conducting electronic interface

insulator

JM Triscone, J Mannhart et al. Science (2007)

Strained Transistor

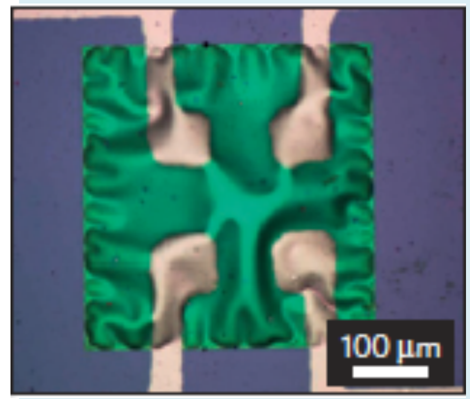


T Ghani, Intel Logic,www.intel.com 2009

strain → enhances electronic mobility

Ionics

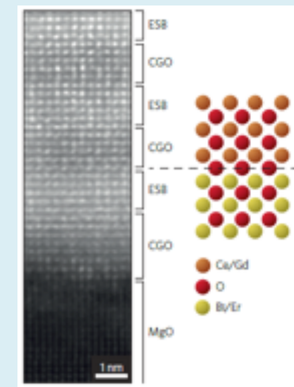
Strain-ionic defect interaction: micro-devices



Y Shi et al. and JLM Rupp, Nature Materials (2015)

Controlling strain patterns to modify transport

Ionic heterostructures

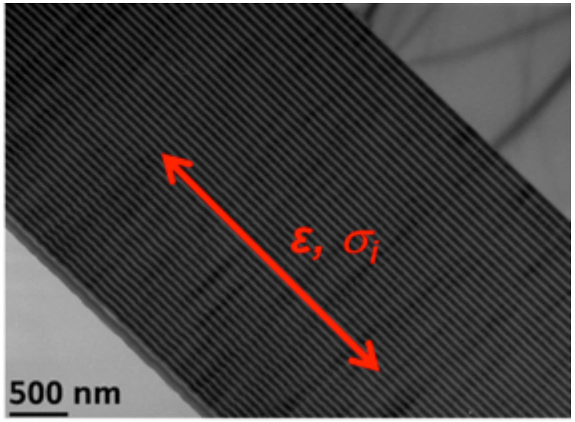


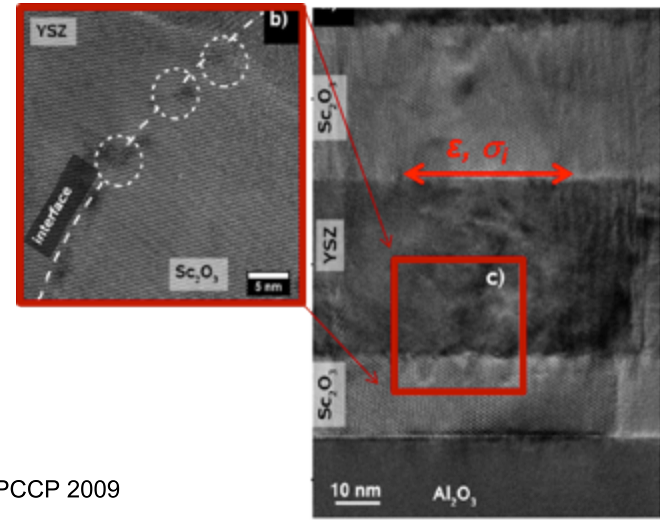
S Schweiger et al. JLM Rupp, ACS Nano (2014)
S Schweiger et al. JLM Rupp, Advanced Materials (2016)
Sata, Maier et al., Nature (2000)
Sanna, Esposito et al.,Pryds Nat Mat (2015)
Song, Gregori, Maier et al., APL Mat (2014)
Schichtel, Korte, Janek, PCCP (2009)
Korte, Janek et al., PCCP (2014)
Perkins, Kilner, McComb et al., AFM (2010)

Strain and space charges at interfaces

Strained oxide materials and concepts are needed for novel ionic devices !

What is known about strained oxide ionic heterostructures?





Schichtel et al., PCCP 2009

Changed conductivity σ_i due to strained multilayer ε interfaces
No device integration so far!

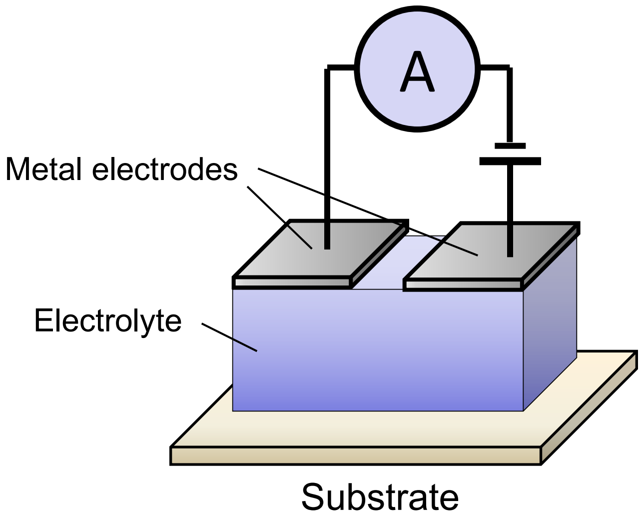
Material	T(K)	Relative change in conductivity	Remarks	Authors
YSZ/Y_2O_3	623 - 973	10^1	Multilayer	Korte et al.
$Sm{:}CeO_2/YSZ$	673 – 1073	10^1	Multilayer	Sanna et al.
$YSZ/Gd_2Zr_2O_7$	550 – 750	10^2	Multilayer	Li et al.
$Gd{:}CeO_2$ on MgO/STO	723 – 1123	10^1-10^2	Thin film	Kant et al.
YSZ on MgO	423 - 773	10^3	Thin film	Sillassen et al.

Reviews:
JLM Rupp, SSI 2012
B Yildiz, MRS Bulletin 2014

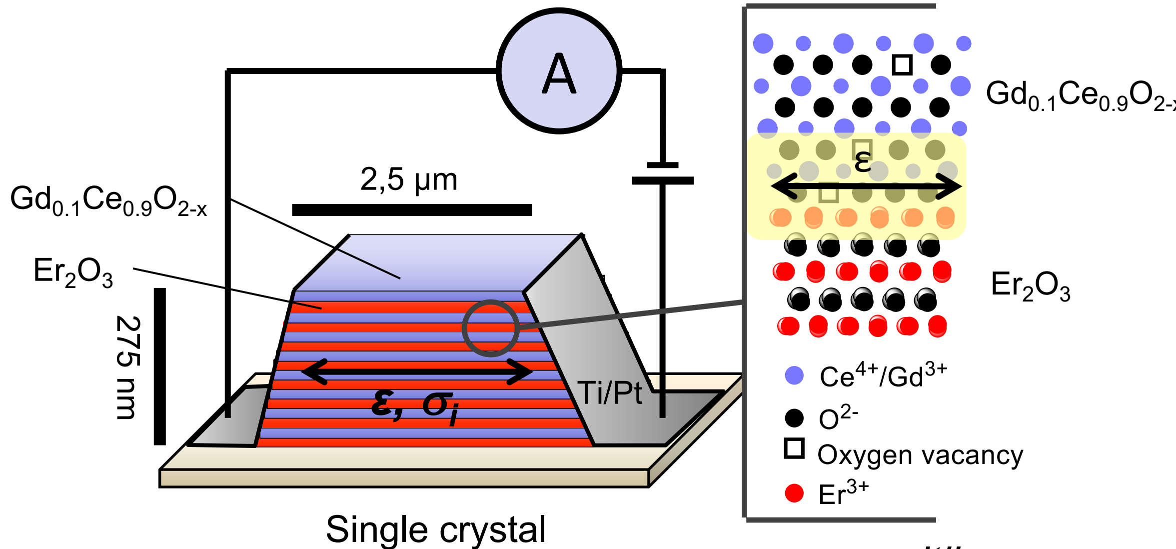
Theory:
A Kushima and B Yildiz, J of Mat Chem 2010
RA DeSouza et al. PRL, 2013

Strained multilayers - alternative to doping in resistive switches?

State-of-the-art



New micro-dot electrode concept



multilayer $Er_2O_3/Ce_{0.9}Gd_{0.1}O_{2-x}$

Change in classic top-electrode contacting: sideways electrode micro-dot contacting for strained oxides?

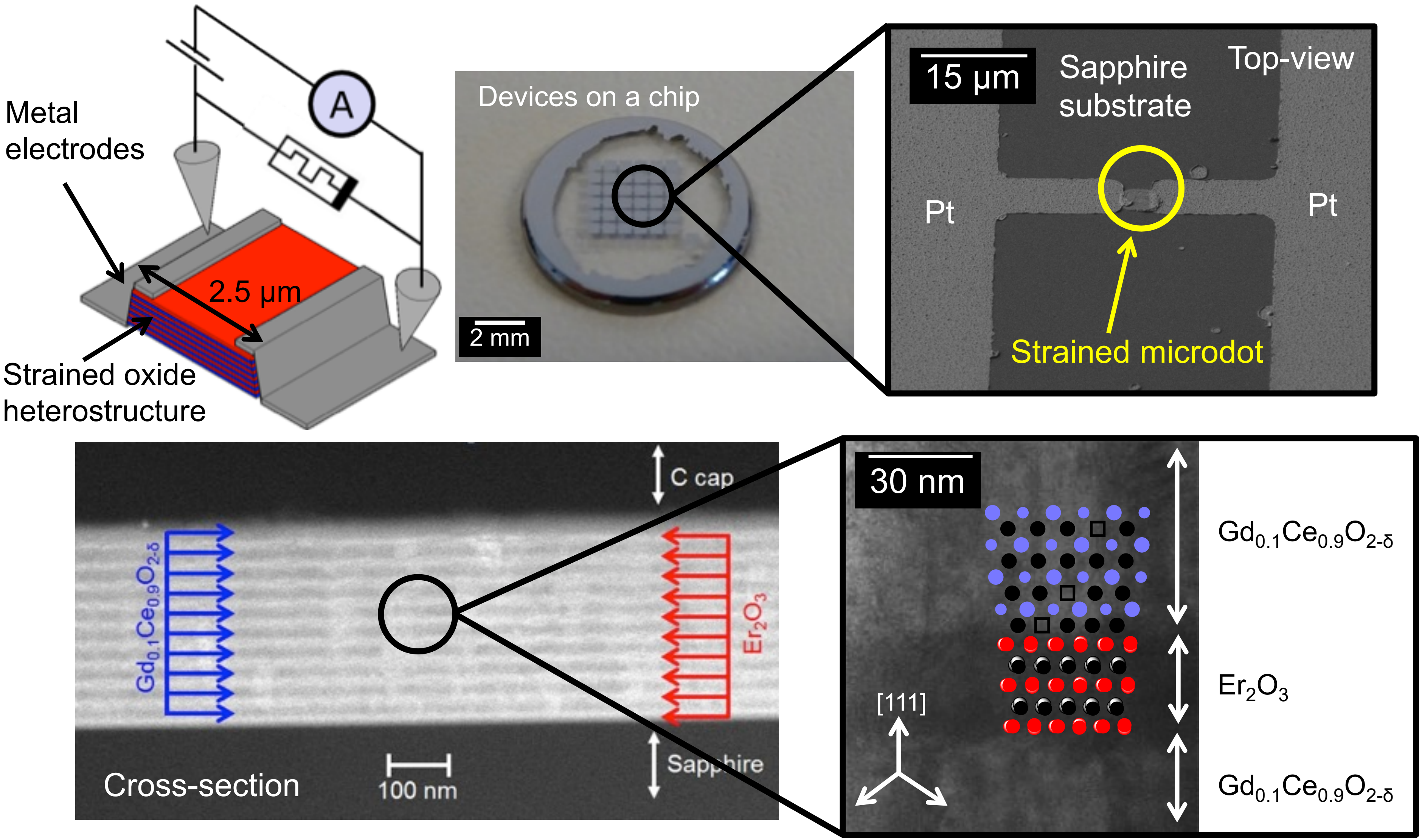
→ Replace top-electrode contacting of single oxide films

→ Electric conductivity of multilayers is variable by far more than pure monolayer characteristics. No device integration so far.

(1) J.L.M. Rupp, S.Schweiger, F. Messerschmitt; Patent WO2014170023

(2) S Schweiger, JLM Rupp et al., ACS Nano, 8, 5, 5032 (2014)

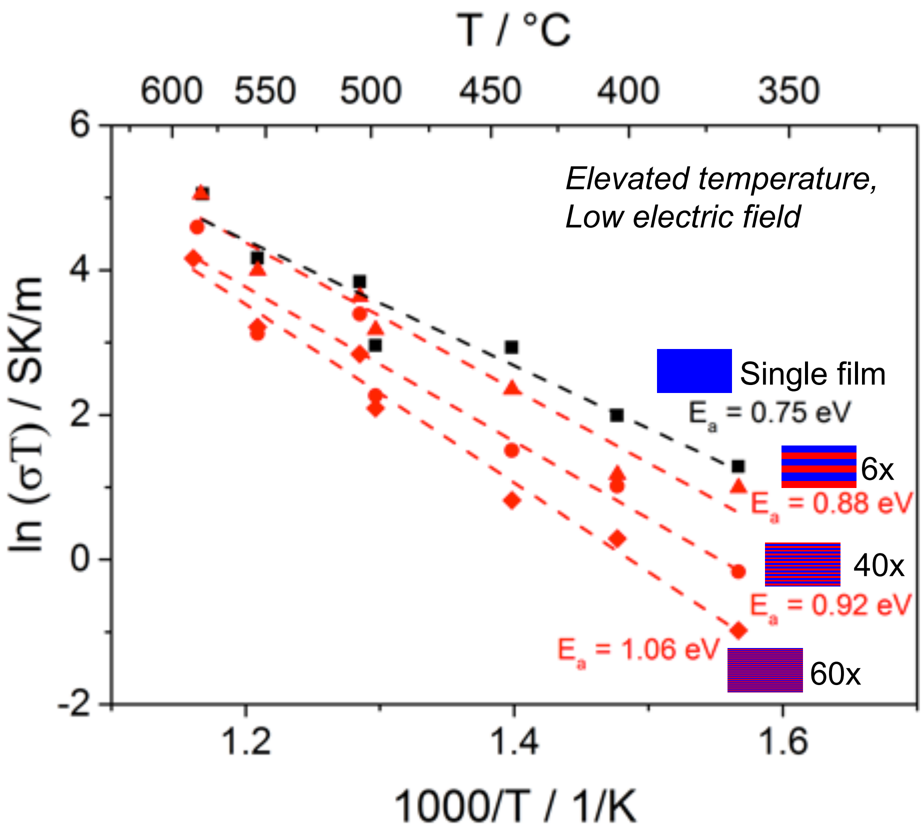
Strained ionic heterostructure microdots

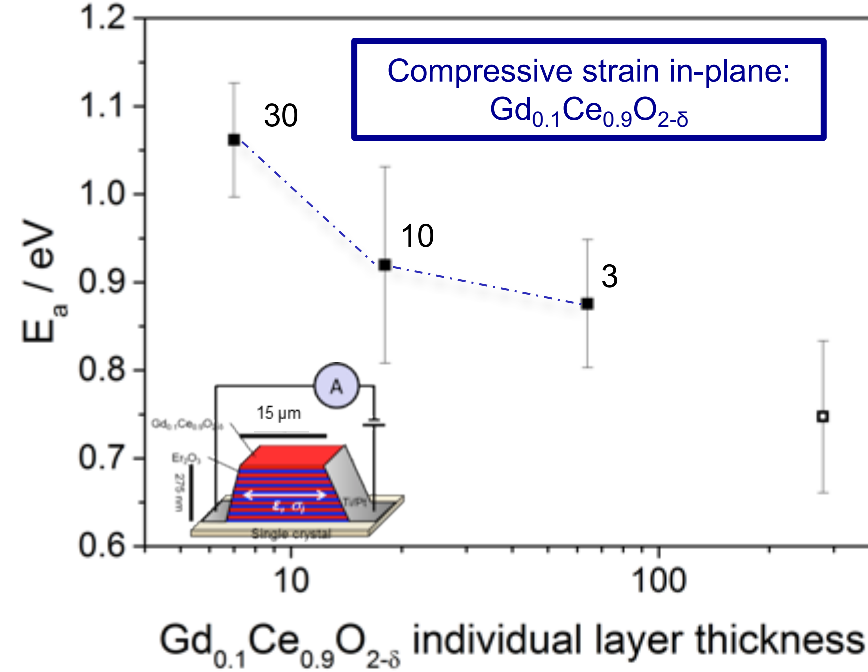


Sucessful manufacturing of strained mulitlayer microdot arrays for first devices.

S Schweiger, R Pfenninger, W Bowman, U Aschauer, JLM Rupp, Advanced Materials, 2017

Transport properties of microdot device

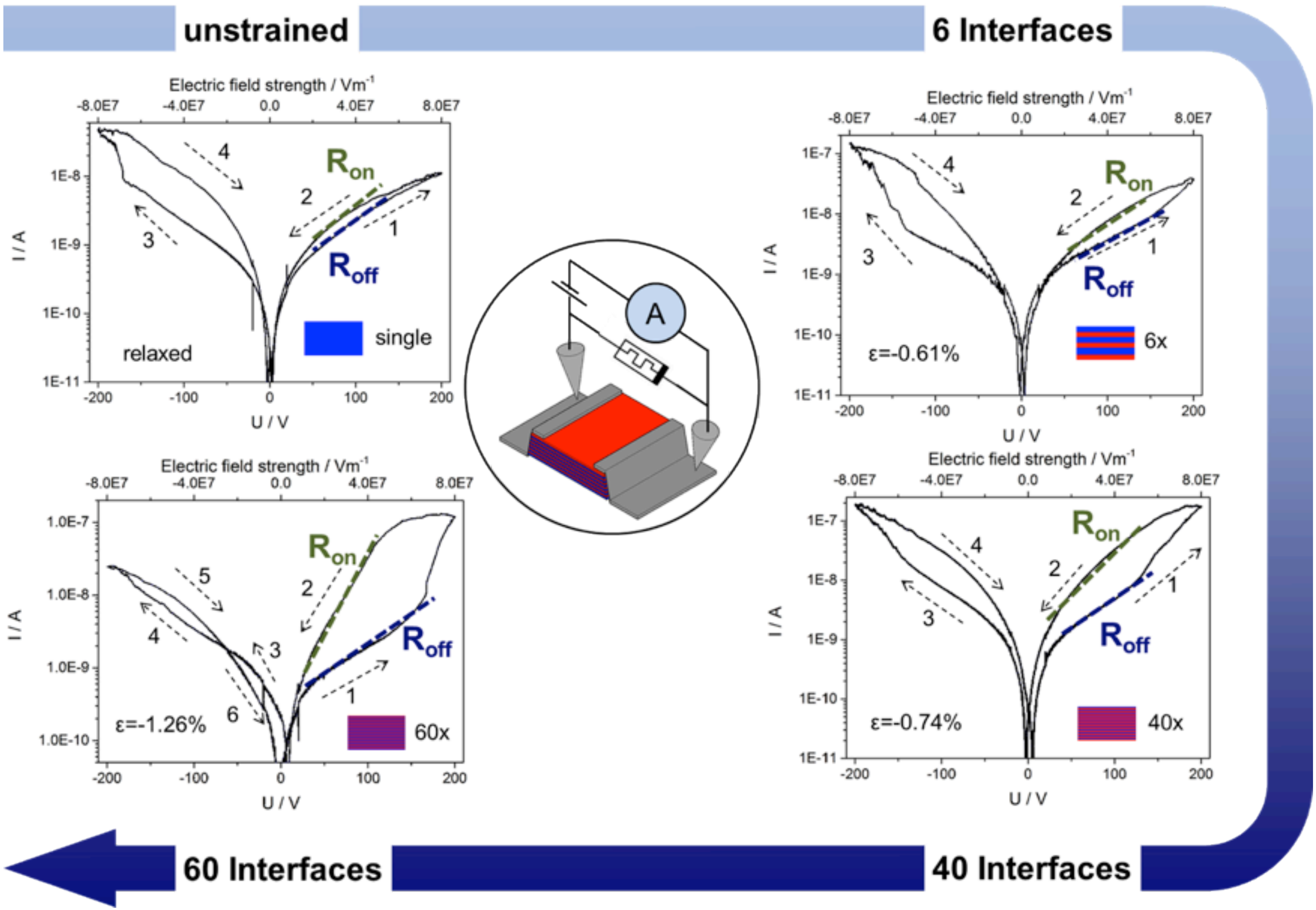




- Compressive in-plane strain of -1.16% in conducting phase.
- Decreasing the film thickness from 280 nm to 7 nm (increasing number of interfaces) → increase of E_a = Δ0.31 eV.

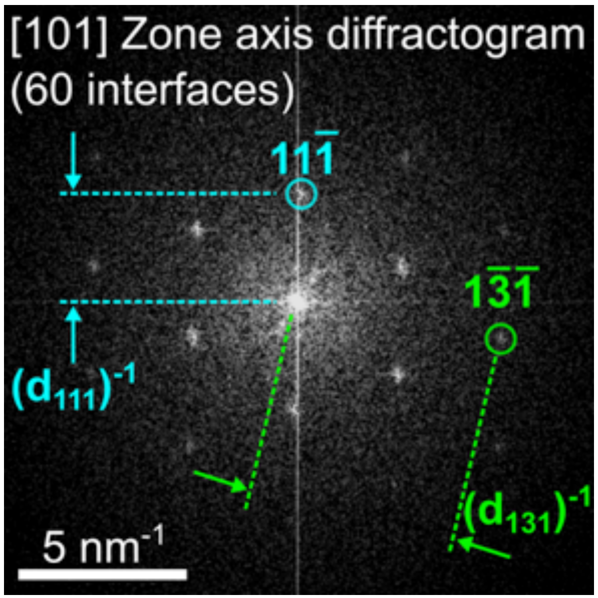
S Schweiger, R Pfenninger, W Bowman, U Aschauer, JLM Rupp, Advanced Materials, 2017

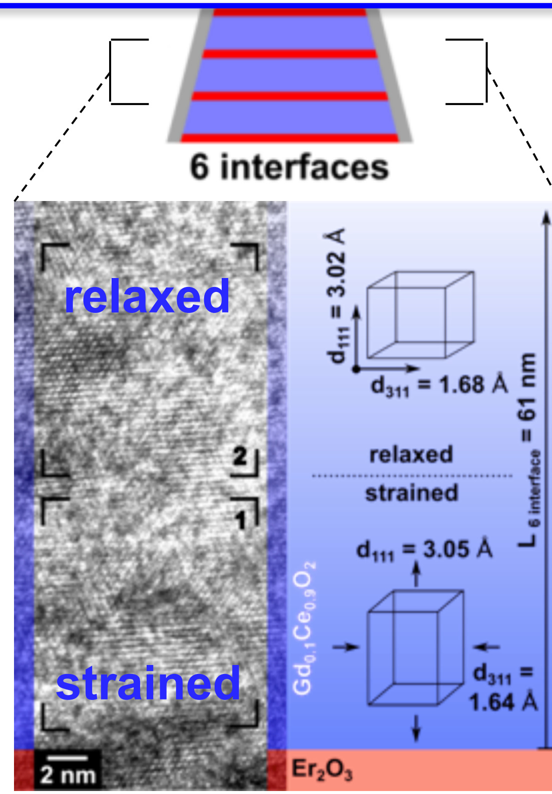
Influence of strain on memristance: Cyclic voltammetry

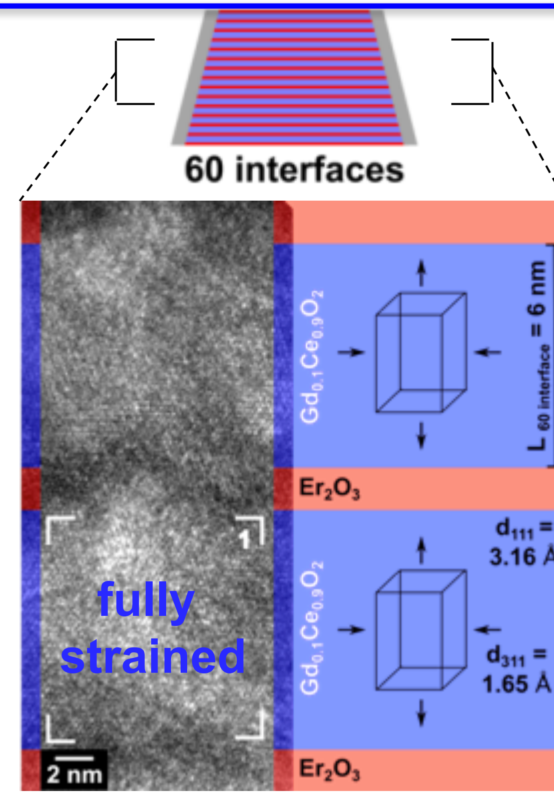


S Schweiger, R Pfenninger, W Bowman, U Aschauer, JLM Rupp, Advanced Materials, 2017

Heterostructure oxide thin films: TEM investigations







Strain relaxation in the $Gd_{0.1}Ce_{0.9}O_{2-\delta}$ layers for 6 interfaces

→ in-plane compression Δ = 0.04Å

→ out-of-plane tension Δ = 0.03Å

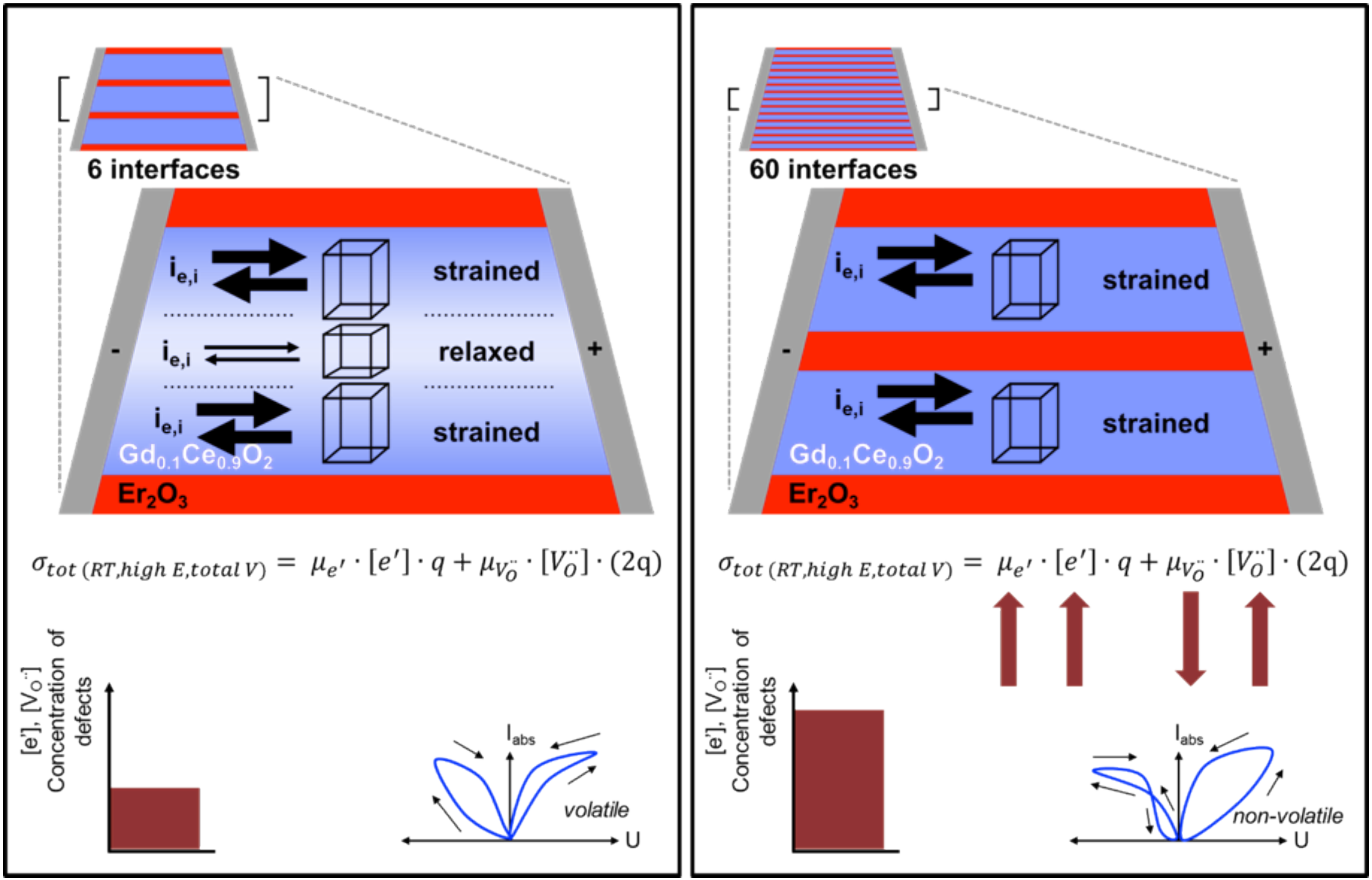
Fully strained $Gd_{0.1}Ce_{0.9}O_{2-\delta}$ layers for 60 interfaces no relaxation,

Δout-of-plane = 0.14Å

Increasing anisotropy with decreasing $Gd_{0.1}Ce_{0.9}O_{2-\delta}$ layer thickness

S Schweiger, R Pfenninger, W Bowman, U Aschauer, JLM Rupp, Advanced Materials, 2017

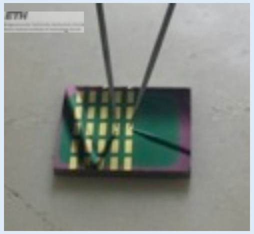
The strained memristor: defect transport model



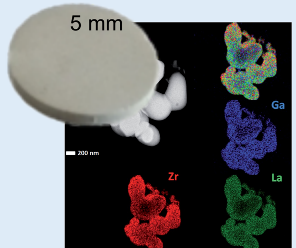
S Schweiger, R Pfenninger, W Bowman, U Aschauer, JLM Rupp, Advanced Materials, 2017

Rupp group: Solid State Materials for Energy & Information Devices

Novel All Solid State Li Batteries + CO_2 Environmental Trackers



CO_2 environmental + medical sensing based on Li^+



Novel solid state Li battery with high capacities

J Van den Broek et al. JLM Rupp, Advanced Energy Materials, 2016
C Haensel et al. JLM Rupp, Nanoscale 2016
M Rawlance et al. JLM Rupp, Nanoscale 2016
S Afyon et al. JLM Rupp, J of Materials Chemistry 2015

Ionic memory and computing logics: memristors

information storage + non-binary computing

S Schweiger et al. JLM Rupp, Advanced Materials 2017
M Kubicek, F Messerschmitt et al JLM Rupp, ACS Nano 9, 2015
F Messerschmitt, et al. JLM Rupp, Adv Funct Mater. 25, 2015
F Messerschmitt, et al. JLM Rupp, Adv Funct Mater. 24, 2014

Renewable Solar Fuels (Hydrocarbons)

CO_2
H_2O

in →

→ out

syngas
Storage
Or
Chemicals

clean energy storage with no material`s capacity limitations

AH Bork et al., JLM Rupp, Advanced Energy Materials, 2016
AH Bork, et al. JLM. Rupp, J. of Mat Chem A, 2015

Micro-energy convertor designs

grid-independent energy conversion for autonomous electronics

Y Shi, AH Bork, S Schweiger, JLM Rupp, Nature Materials 14, 2015
Y Shi et al. JLM Rupp, Adv Mat, 2016

Electrochemical Materials MIT USA

Memristive Information Storage & Logics

Dr. Andreas Nenning

Dr. Felix Messerschmitt

Dr. Juan Carlos Gonzalez Rosillo

Thomas Defferriere

Eva Sediva

Solid State Li-Ion Batteries + Sensors

Dr. Michal Struzik

Michael Rawlence

Reto Pfenninger

ECM

Prof. Dr. Jennifer Rupp

Fuel Cells

Philipp Simons

Solar-to-Fuel Materials

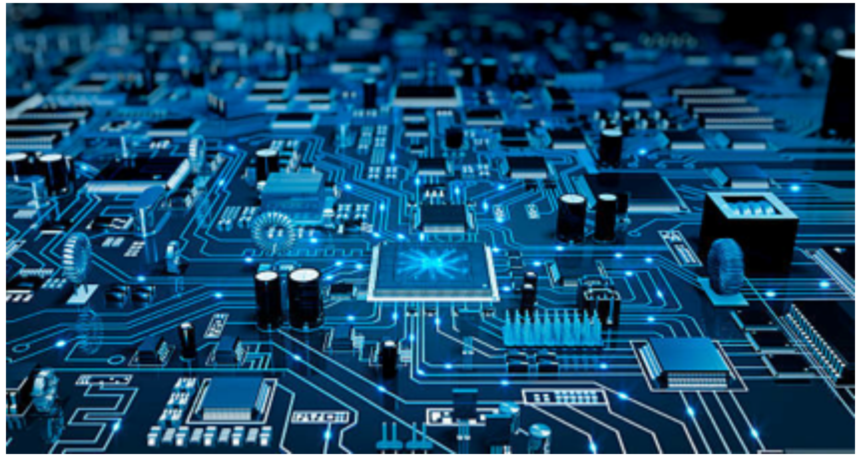
Dr. Alexander Bork

Dr. Kunjoong Kim

Dr. Alfonso Carrillo

What is next ? Prof Rupp`s dream list

Socio-economic acceptable energy storage: Fair batteries

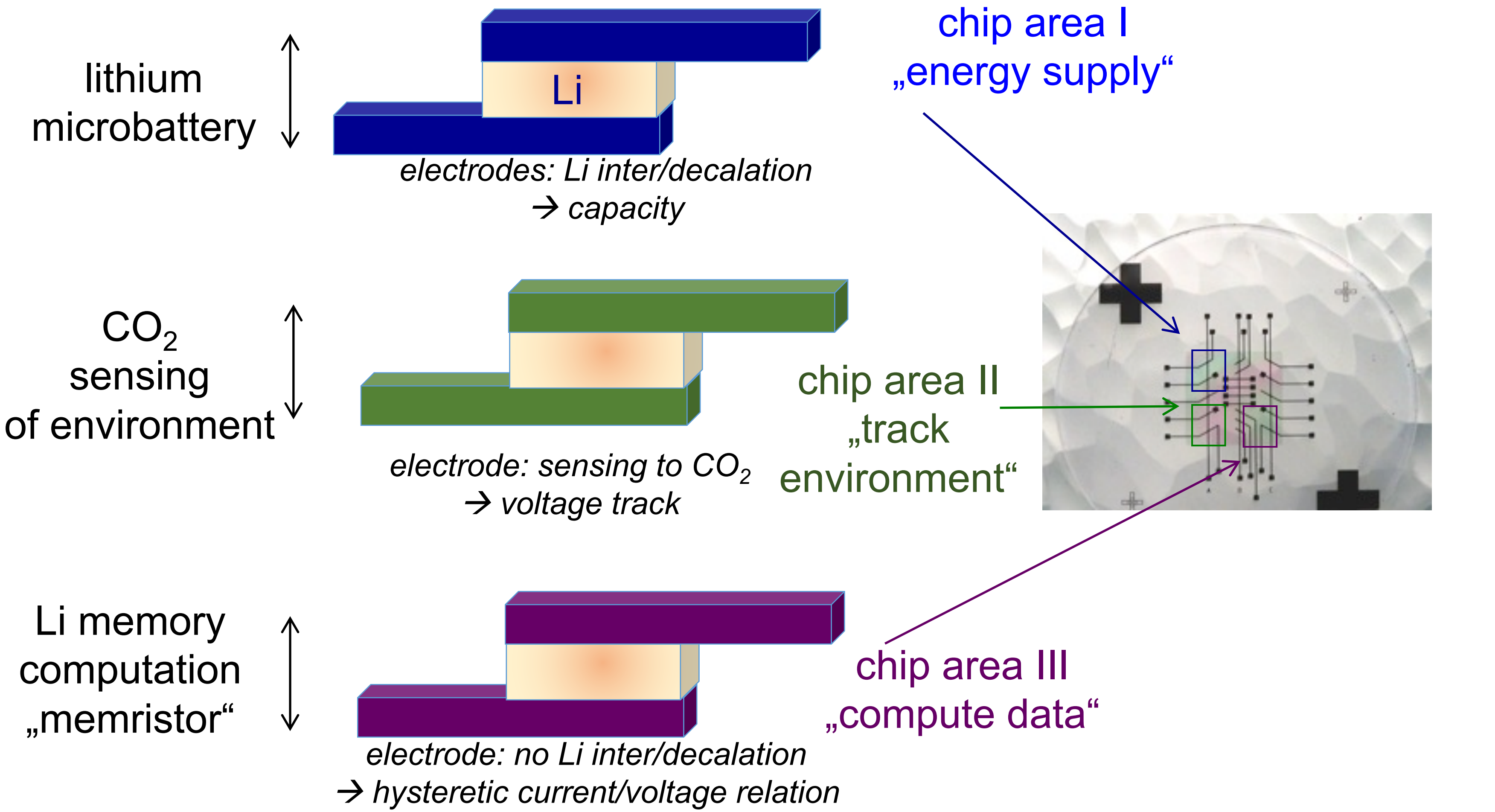


New Li circuits: storage, sensing, data computing

Solar fuel + plastics (cars, …)

- Make 1st Solid State Fair Trade Battery Concepts
- Lithium Oxide Circuits for Energy Storage, Sensing and Computing Units: Lithium are the next electrons ☺
- Make fully Glass-Type Batteries
- Power Efficiently Human Implants

What`s next? “Lithionic Emulator Chips”

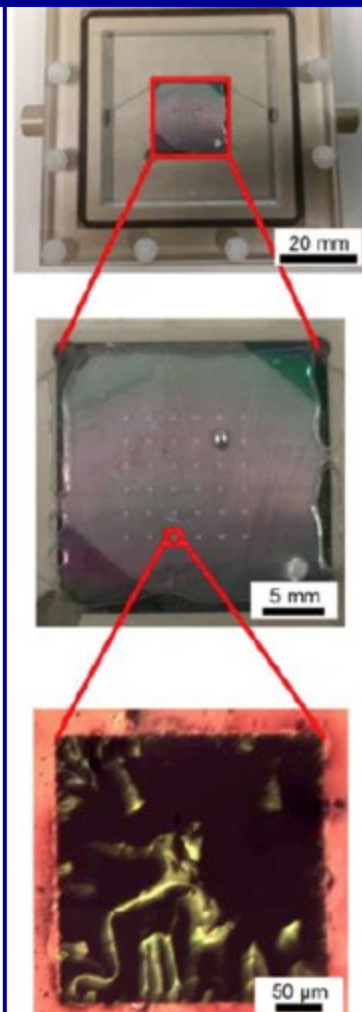


One Li-electrolyte thin film material enables by electrode choice superior functions:
→ Use Li motion to sense, store energy and compute data

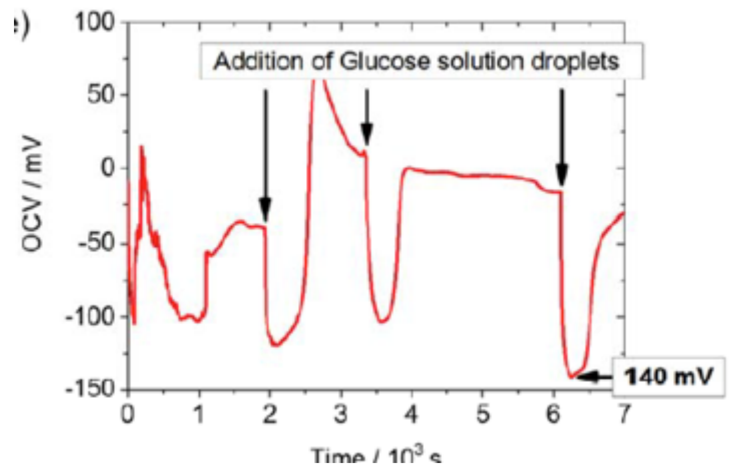
A Sugar Fuel Cell to Power Implants in Humans

human body requires on-board power supply ...
... to power sensors, pacemakers, ...
... to connect wirelessly for monitoring...

new device concept



1st solid state sugar-to-power converting chip for human blood flow



Examples: 1st Si-chips with integrated glucose fuel cell membranes + proof-of-prioncipleoperation for solid state materials, developed by Rupp team MIT

New energy harvesting device to convert sugar to energy as implant to human blood circuit to power e.g. sensor chips →study materials & power devices

confidential