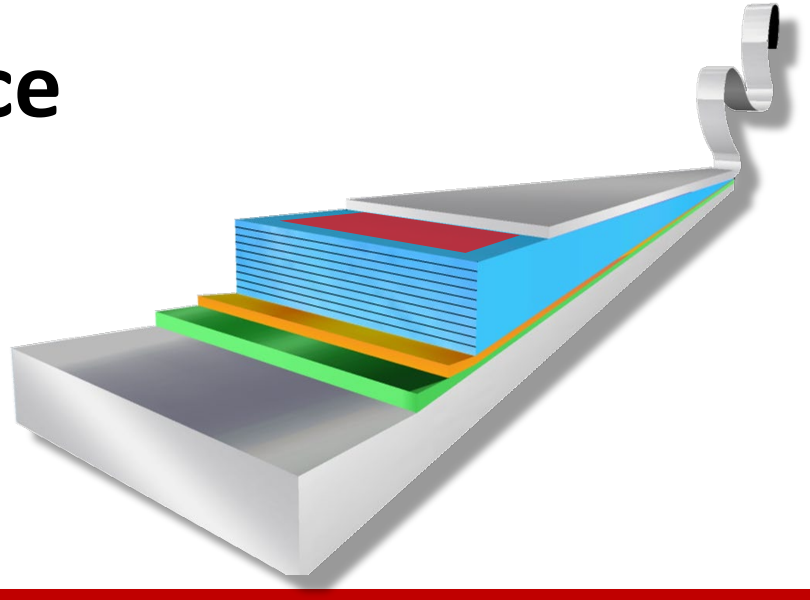
EUCAS2023
Bologna, Italy
3rd-7th September

ICMAB
INSTITUT DE CIÈNCIA DE MATERIALS DE BARCELONA
EXCELENCIA SEVERO OCHOA

Customizing coated conductors to enhance normal zone propagation velocities



Author: Pedro Barusco[3]
Presenter: Pedro Barusco[3]
Contributors : X. Obradors[1], X. Granados[1], T. Puig[1], C. Lacroix[2], F.Sirois[2]

1 - Institut de Ciència de Materials de Barcelona (ICMAB-CSIC) Campus de la UAB, 08193 Bellaterra, Barcelona, Spain
2 - Chemin de Polytechnique 2500, Montréal, Canada
3 - Renaissance Fusion, 22 Rue Jean Pierre Timbaud, 38600 Fontaine, France

P. Barusco – 4-MO-QC-02I – 16th European Conference of Applied Superconductivity
Bologna – Italy, September 7th 2023

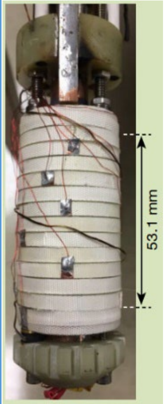
IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 55, January, 2024. Invited presentation given at EUCAS 2023, September 7, 2023, Bologna, Italy

Presentation Summary

- **Introduction**
  - HTS –tapes & Quench
- **Motivation**
  - The hot-spot issue
  - The Current Contact size
  - The Current Flow Diverter (CFD)
- **Fabrication routes:**
  - 1st proposal: Local Annealing
  - 2nd proposal: Yttria CFD
  - 3rd proposal: IMC CFD
  - 4rd proposal: Sulfide b-CFD
- **Conclusion & outlook**

High Temperature Superconducting (HTS) Tape

Superconducting High field magnets



Compact 45T+ magnet

Nature **570**, 496-499 (2019)

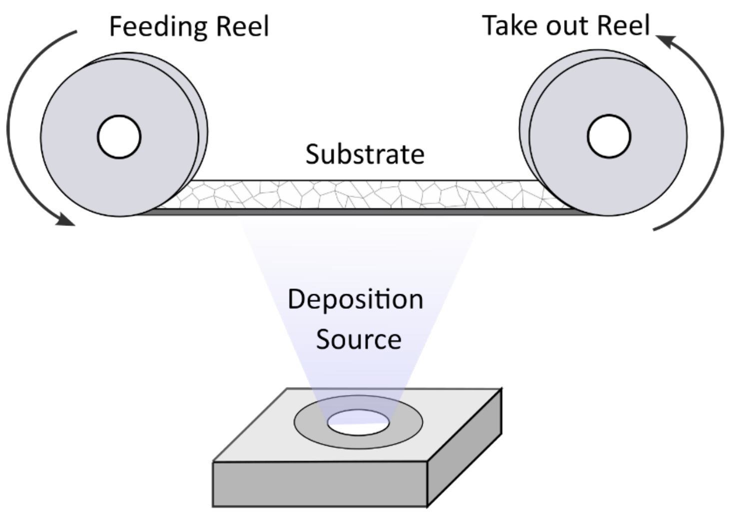
(HTS 12 pancake coils in a 31.1 T background fie

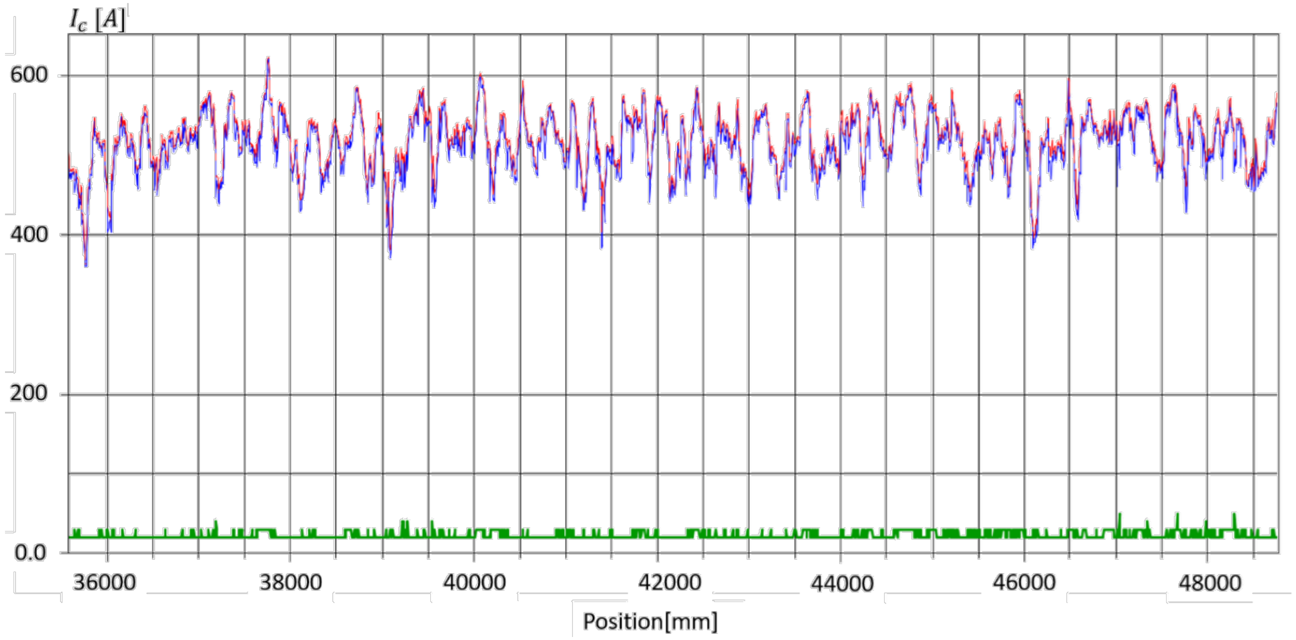
NATIONAL HIGH MAGNETIC FIELD LABORATORY

Little Big Coil (LBC) series

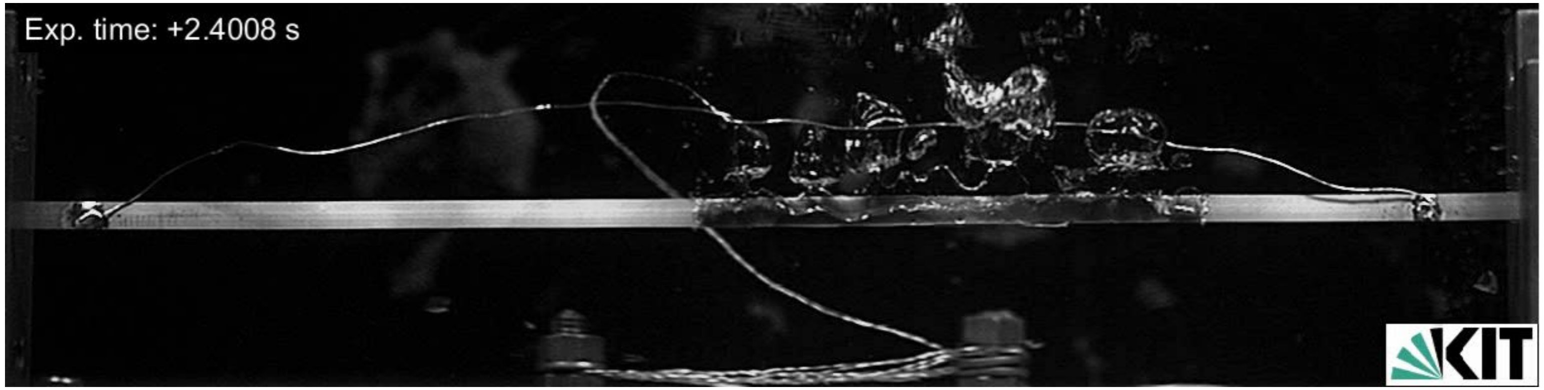
Superconducting Fault current limiters (SFCL)

Motivation: The *hot-spot* regime





Video from Sebastian Hellmann – 3M-LS-O2.7 – EUCAS 2015



Superconductor 4mm, Superpower ReBCO-tape 40 µm Cu-stabilization

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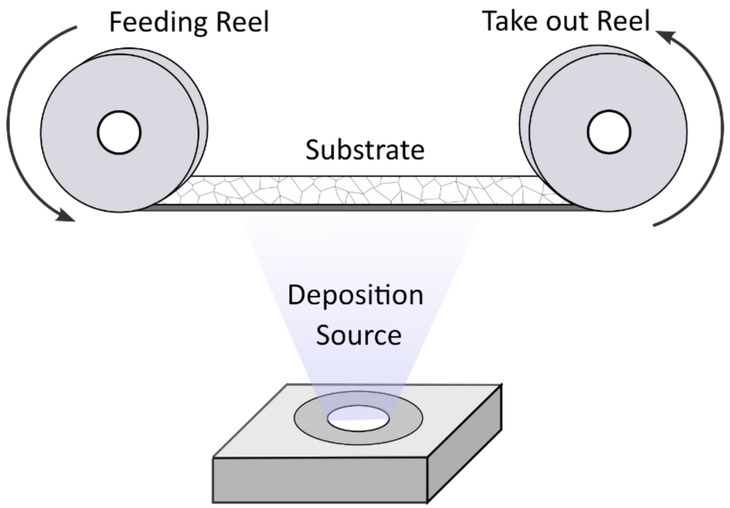

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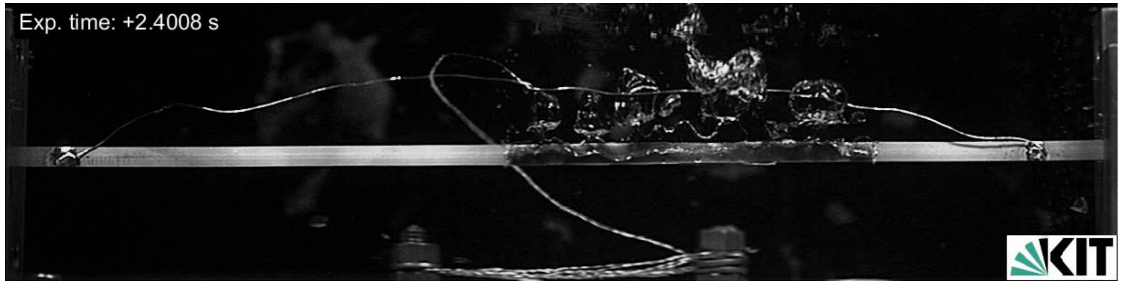
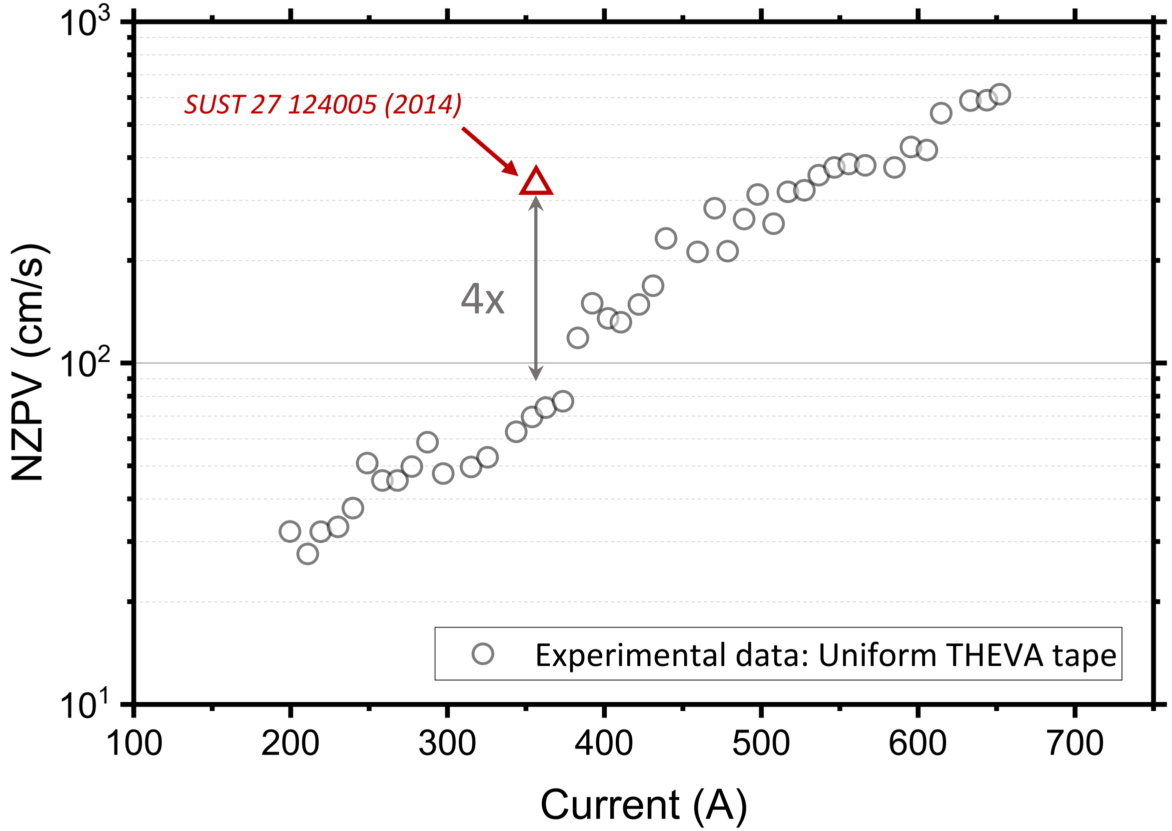


Superconductor 4mm, Superpower ReBCO-tape 40 µm Cu-stabilization

"… with an NZPV greater than 300 cm s−1, it is possible to achieve a satisfying local thermal stability with relatively short HTS-CCs …" (* at 365 A)

- Daniele Colangelo and Bertrand Dutoit Supercond. Sci. Technol. 27 124005 (2014)



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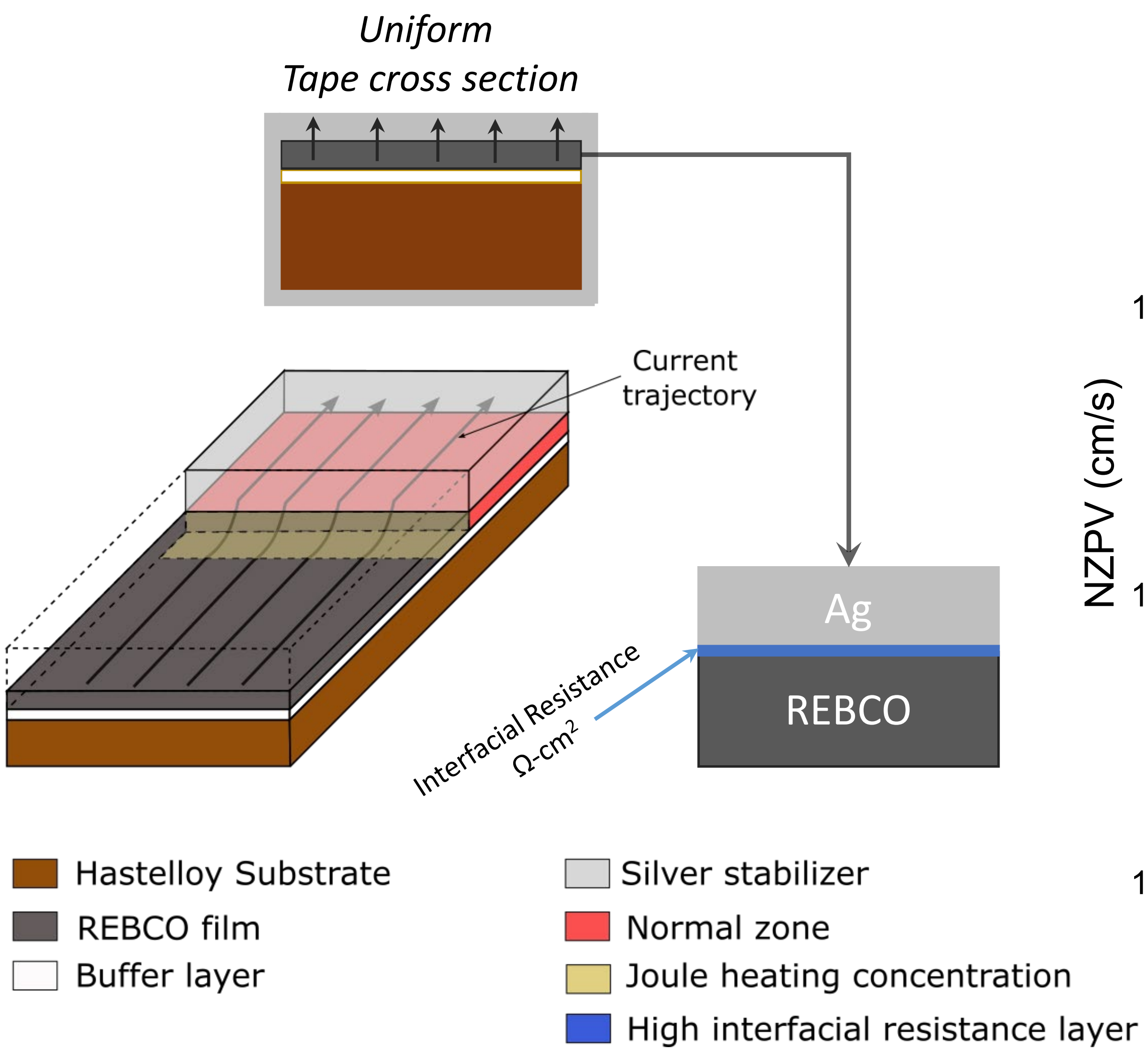
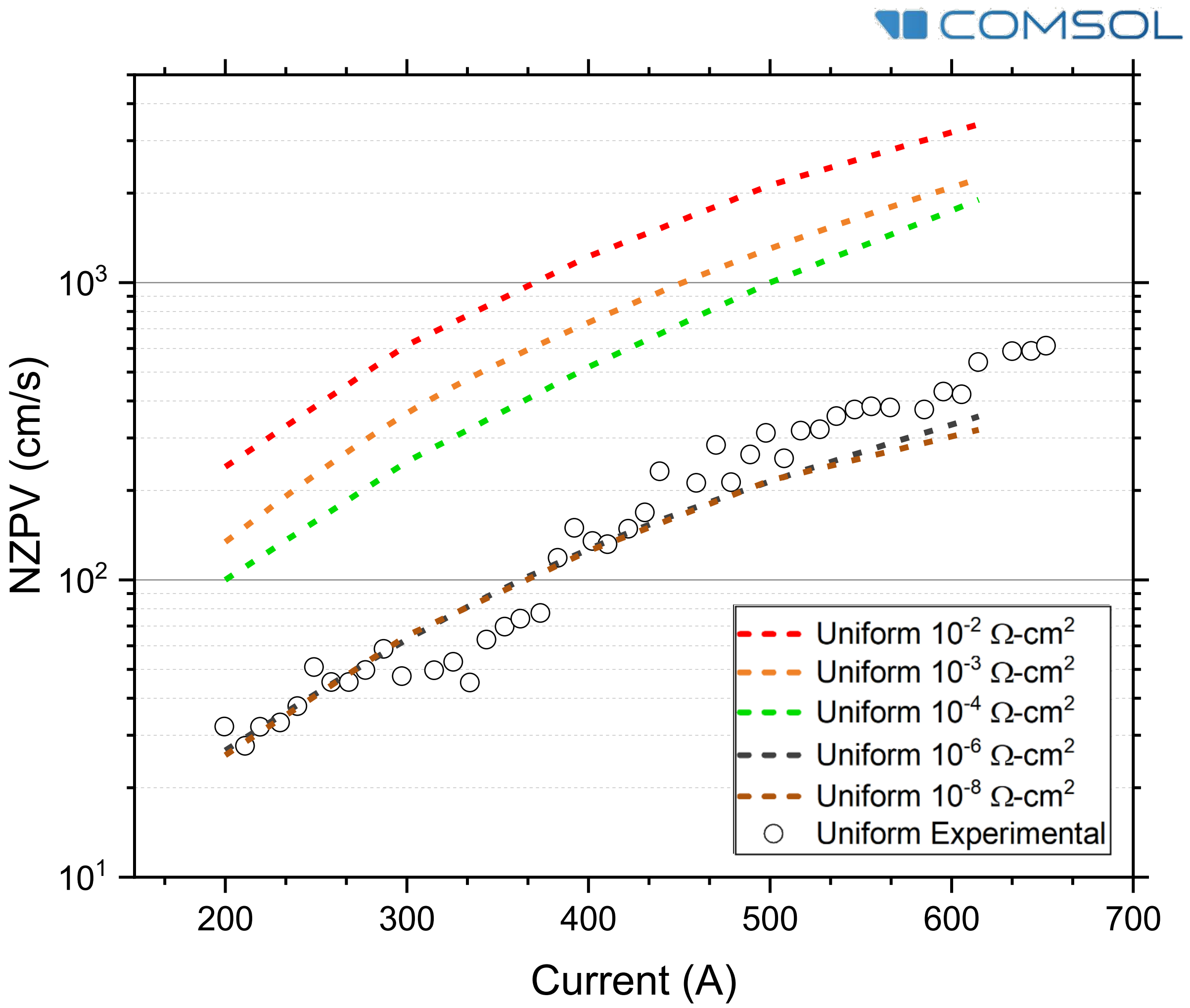
Motivation: Increasing the NZPV via the Interfacial Resistance





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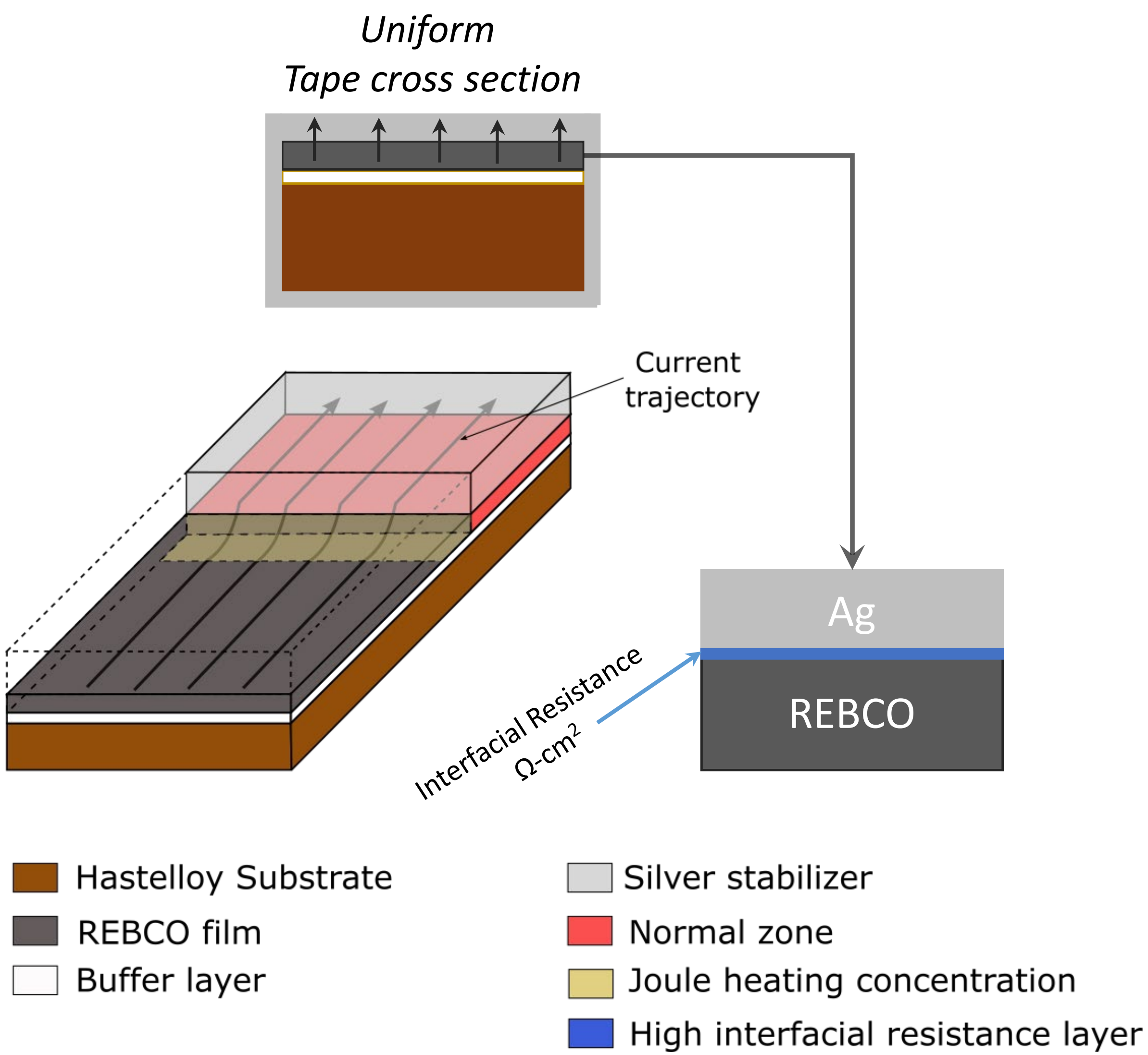
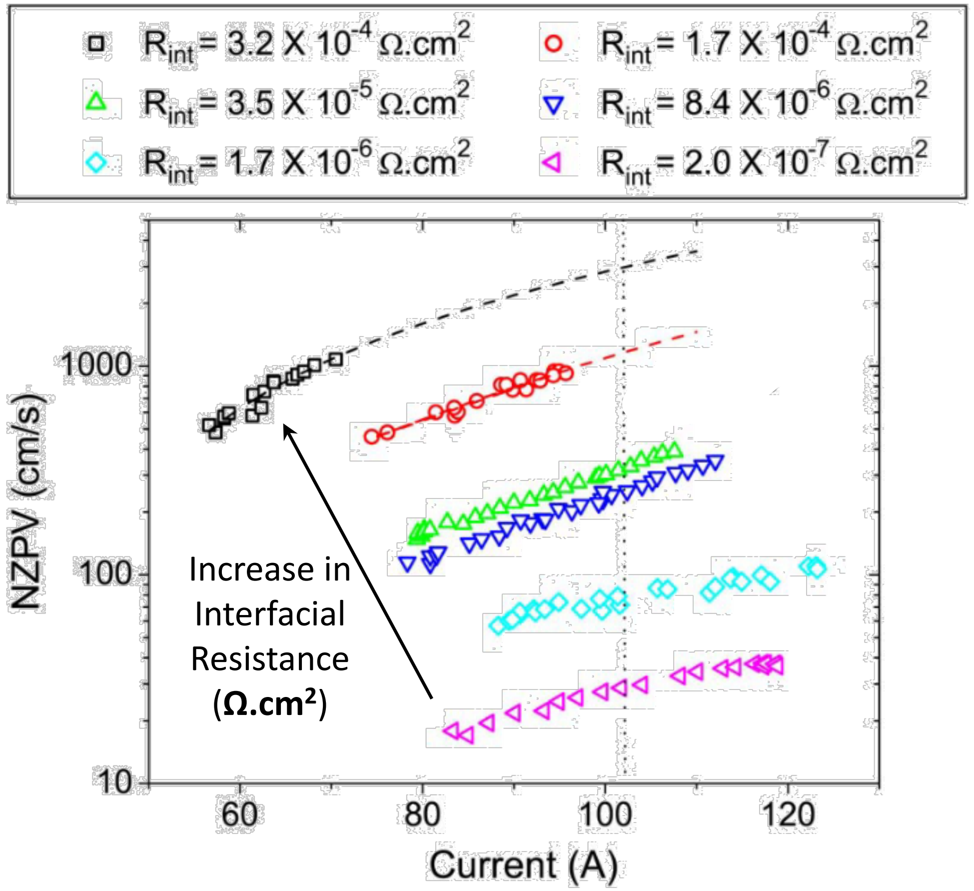


Lacroix et al., IEEE Trans. Supercond. Vol.23 No. 3 (2013)



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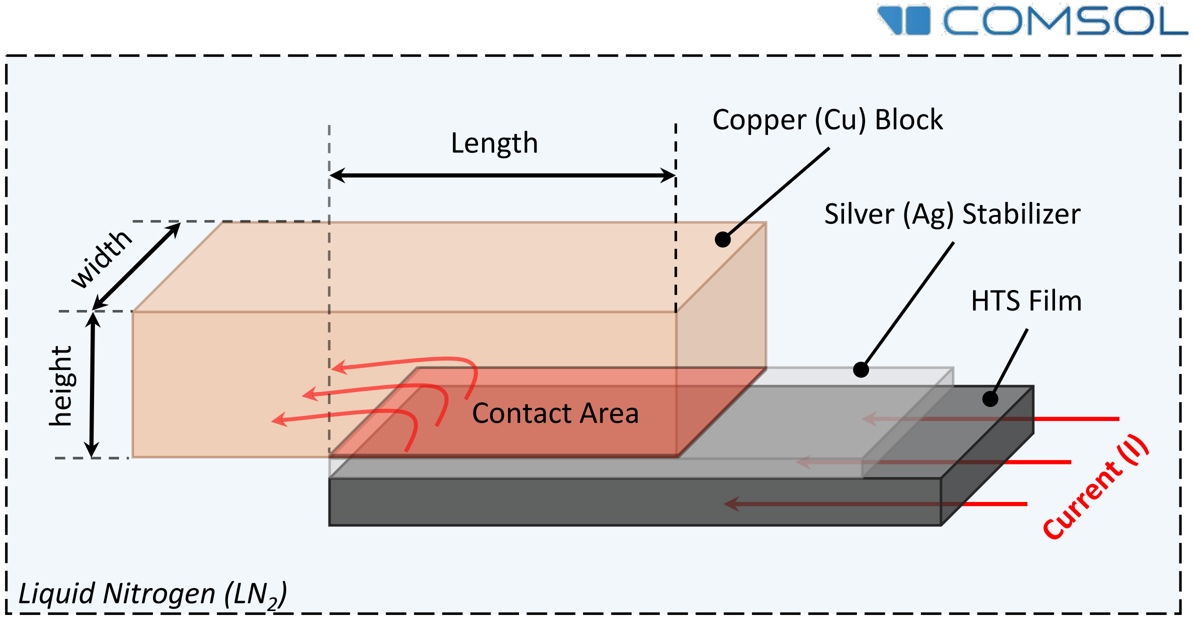
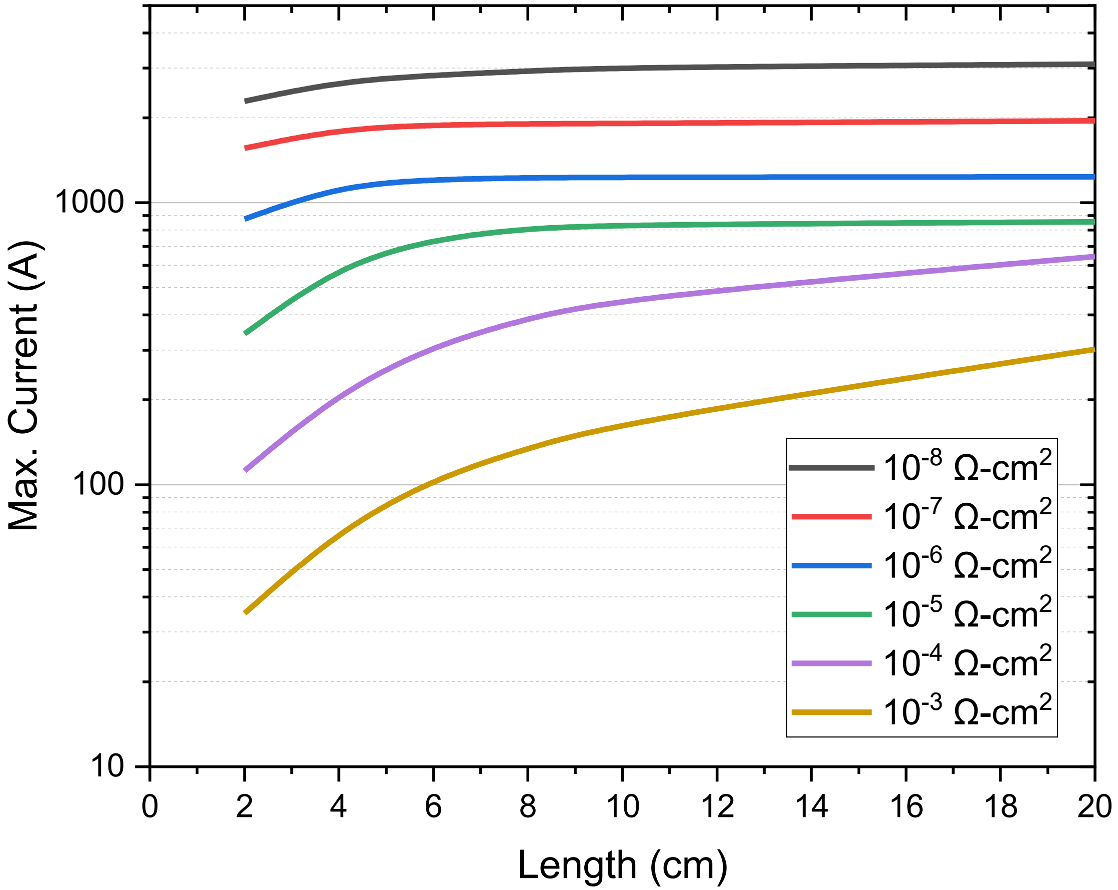
Motivation: Designing the Current Contacts Size



- Heights: h_{cu}= 1 cm, h_{Ag}= 1 µm, h_{HTS} = 100 nm
- Width: $w_{cu} = w_{ag} = w_{hts} = 12$ mm
- Length sweep: $2 \leq L \leq 100\ cm$
- Transport Current sweep: $1 \leq I \leq 5000\ A$
- Interfacial Resistance : $10^{-8} \leq \rho \leq 10^{-3}$ Ω-cm²
- Criteria for Min. Cont. Area: Maximum **decrease of 5% in I_c**



⚠ **Current Contacts above 10 cm in length start to become impractical.**

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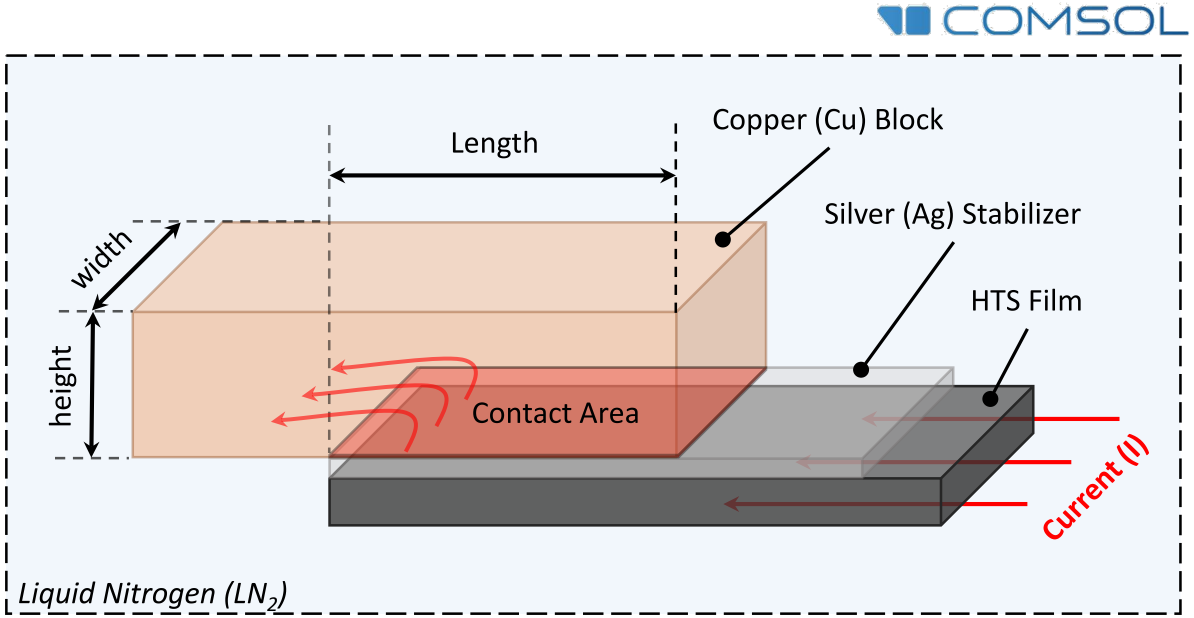

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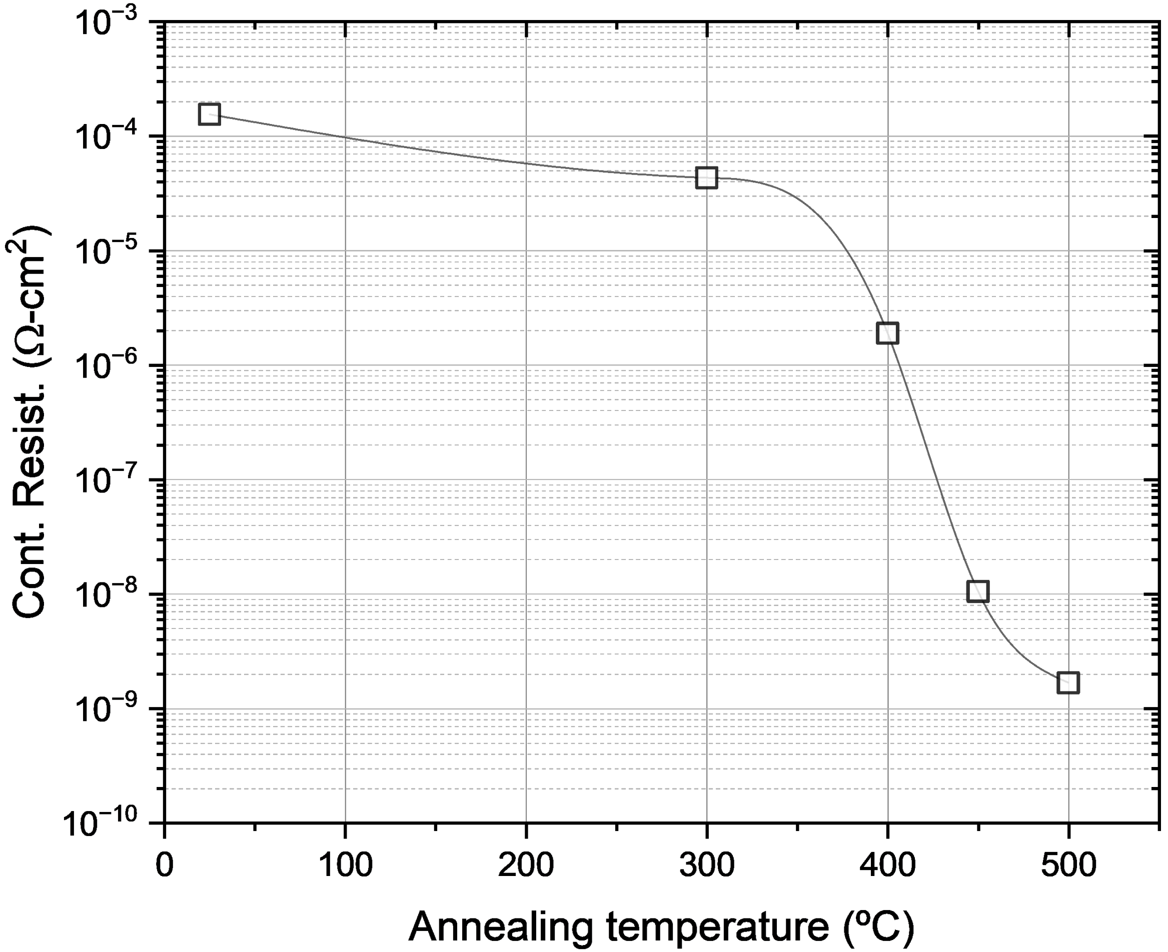
Silver-GdBCO contact resistance versus Annealing temperature (T plateaus of 2 hours)



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1^{st} Proposal: Local Annealing after air exposure

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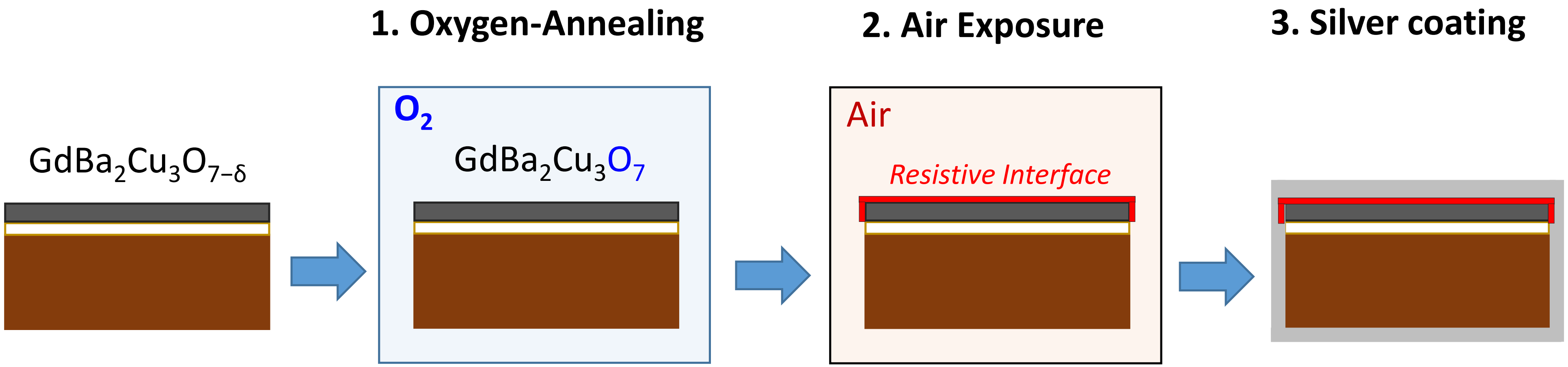
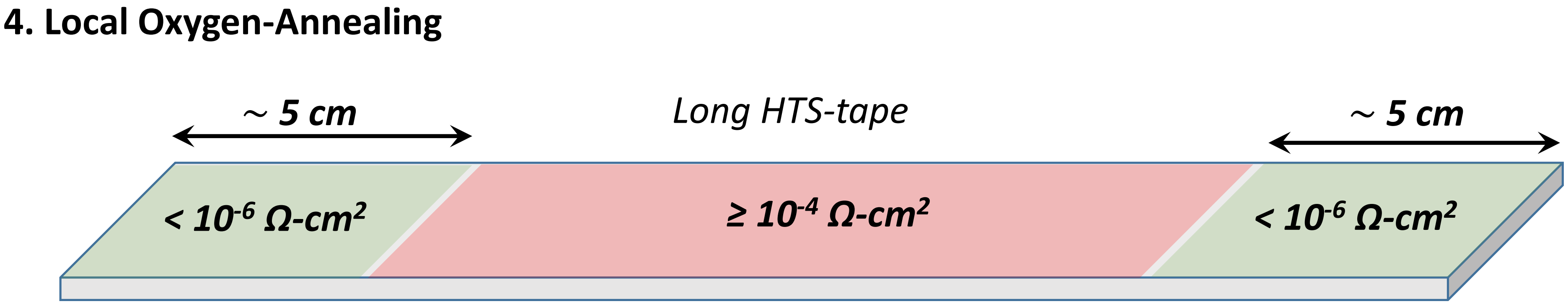
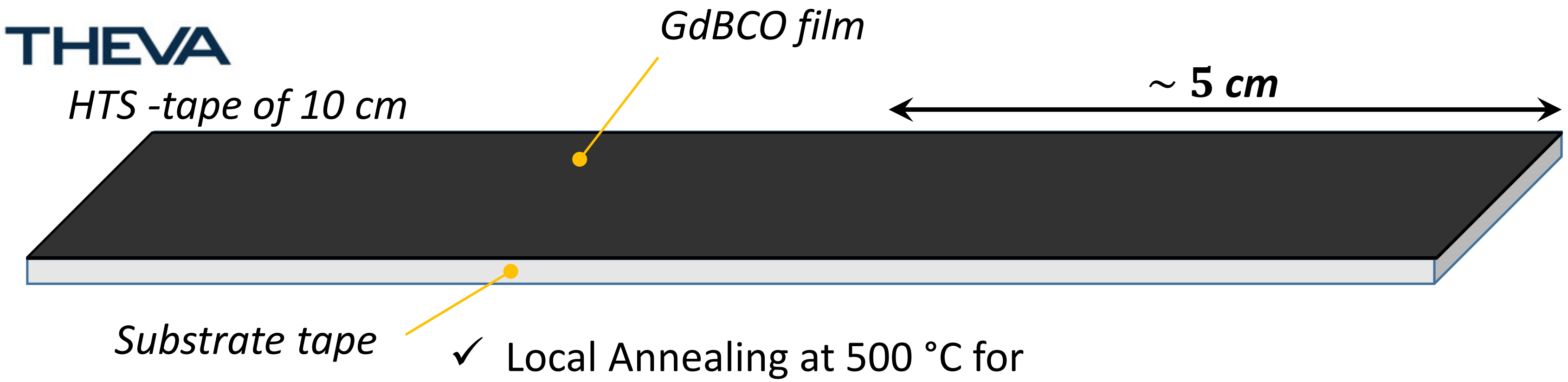




P. Barusco et al. To be published

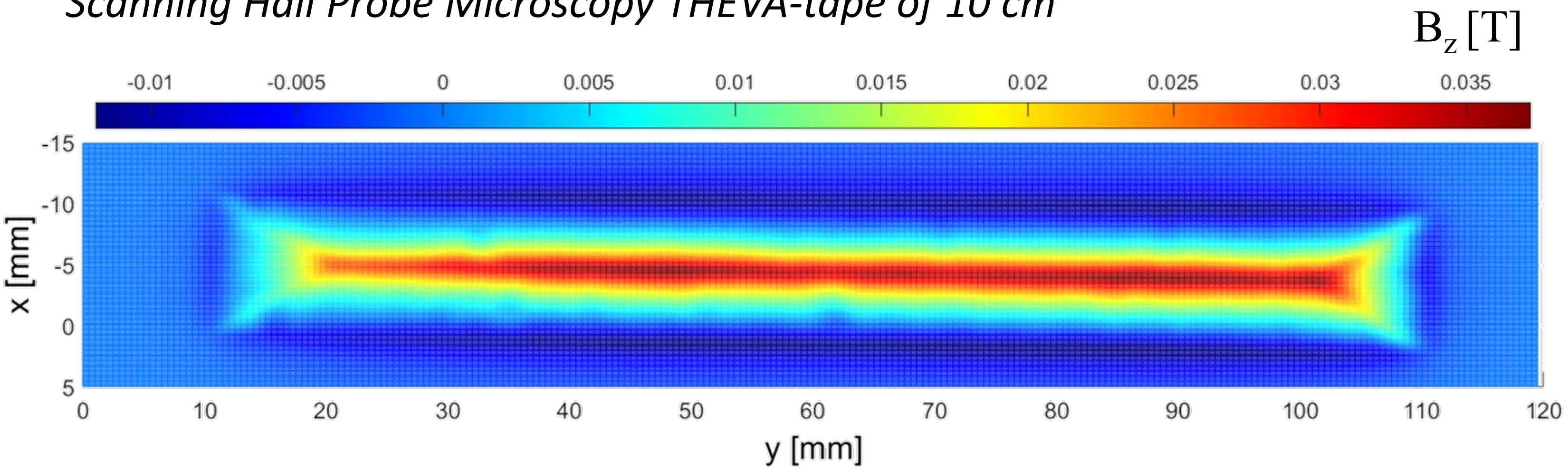
1^{st} **Proposal:** Local Annealing – The Experiment

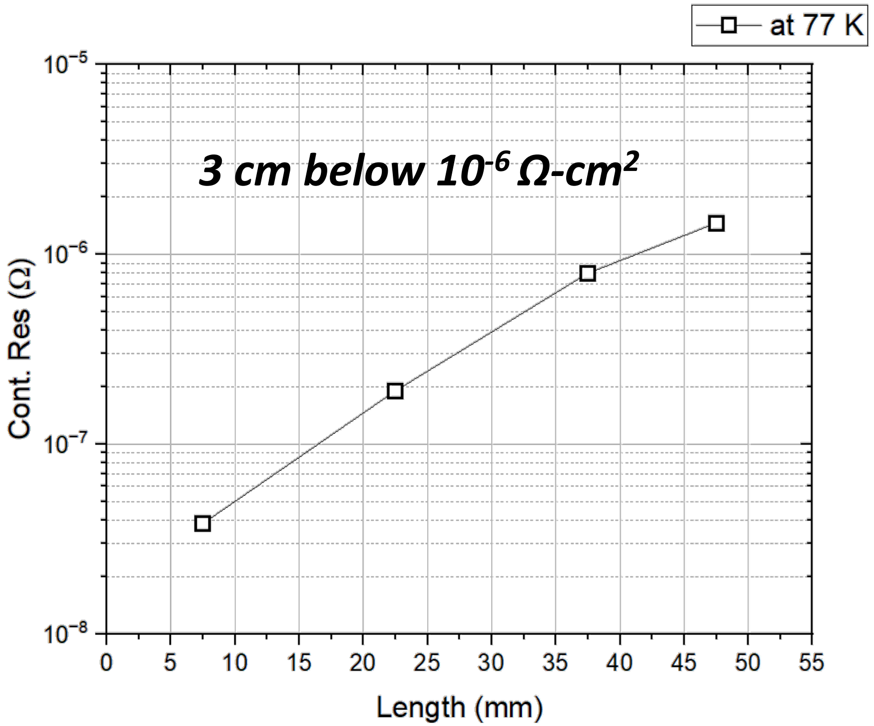
THEVA



✓ Local Annealing at 500 °C for 2h in 0.6 L/min of O_2 flow

Scanning Hall Probe Microscopy THEVA-tape of 10 cm





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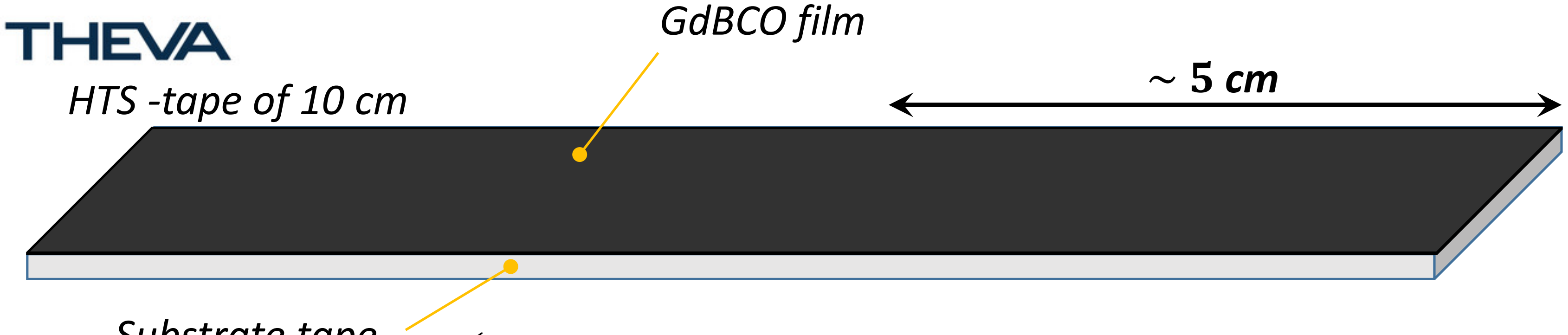

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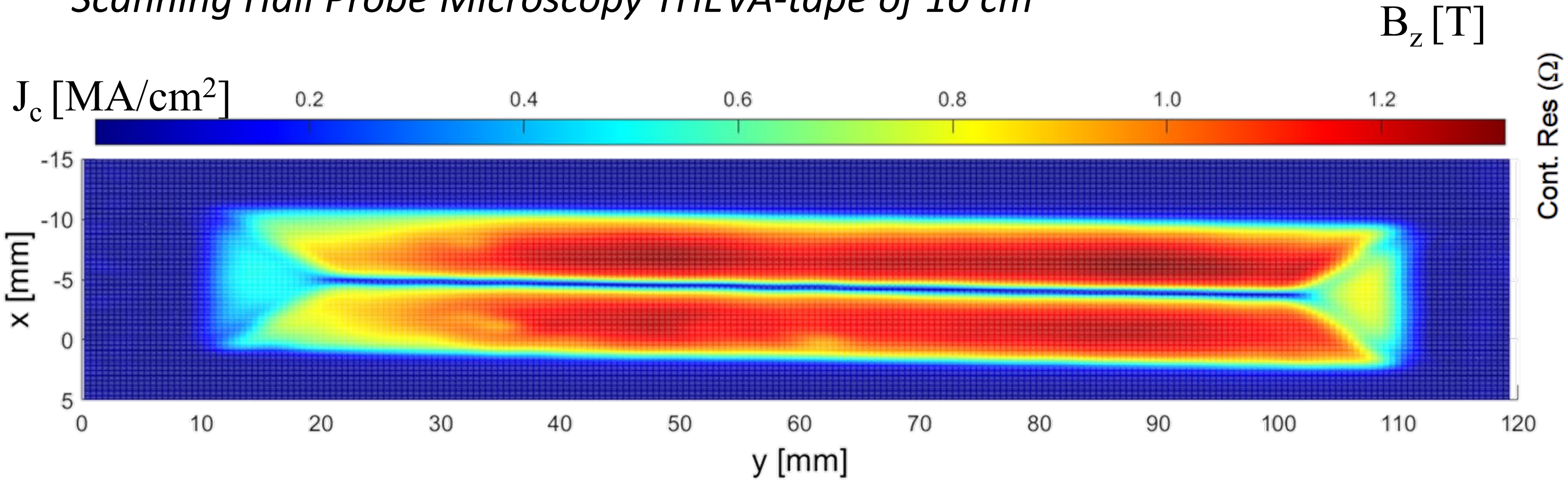

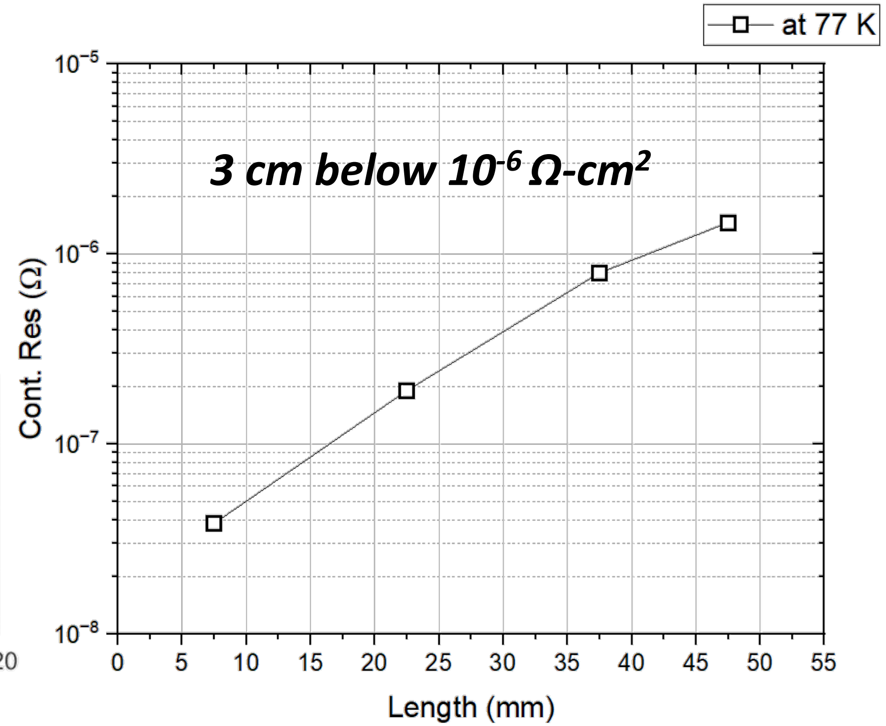

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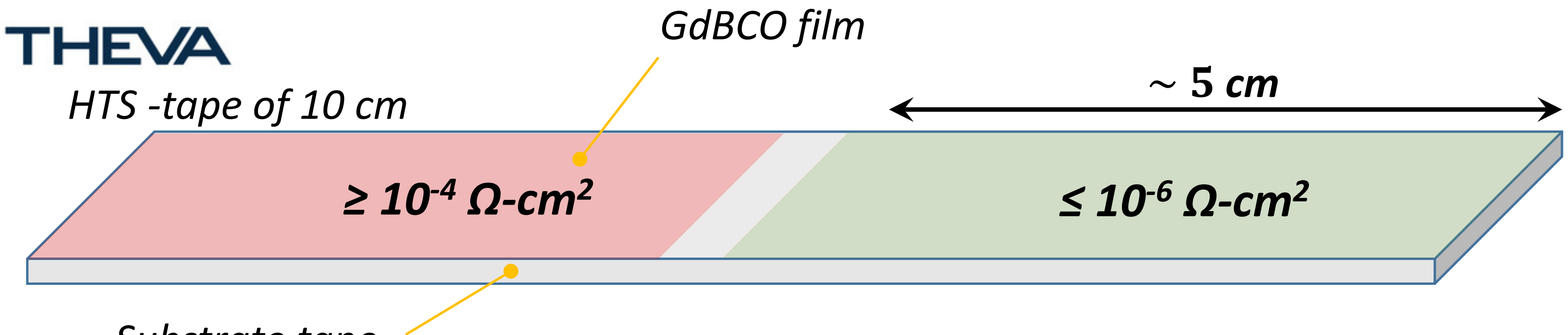

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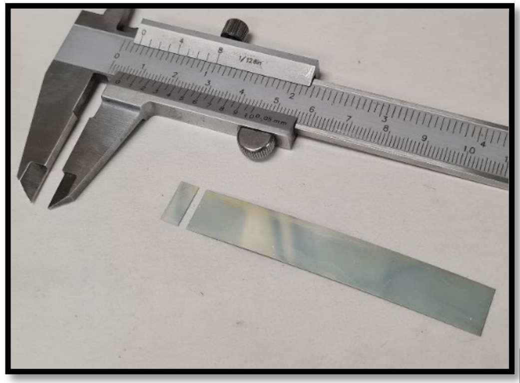

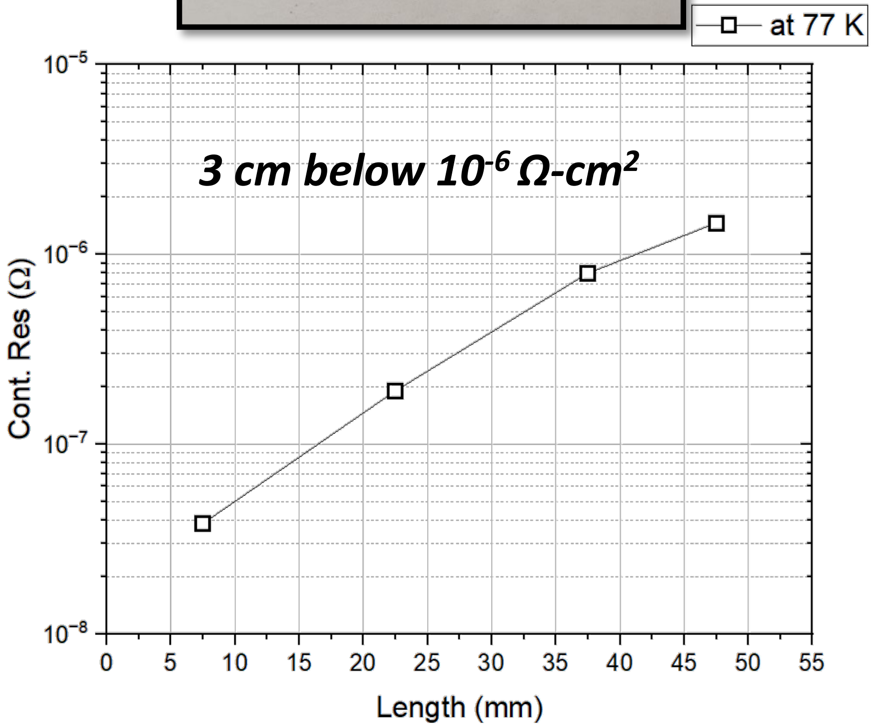

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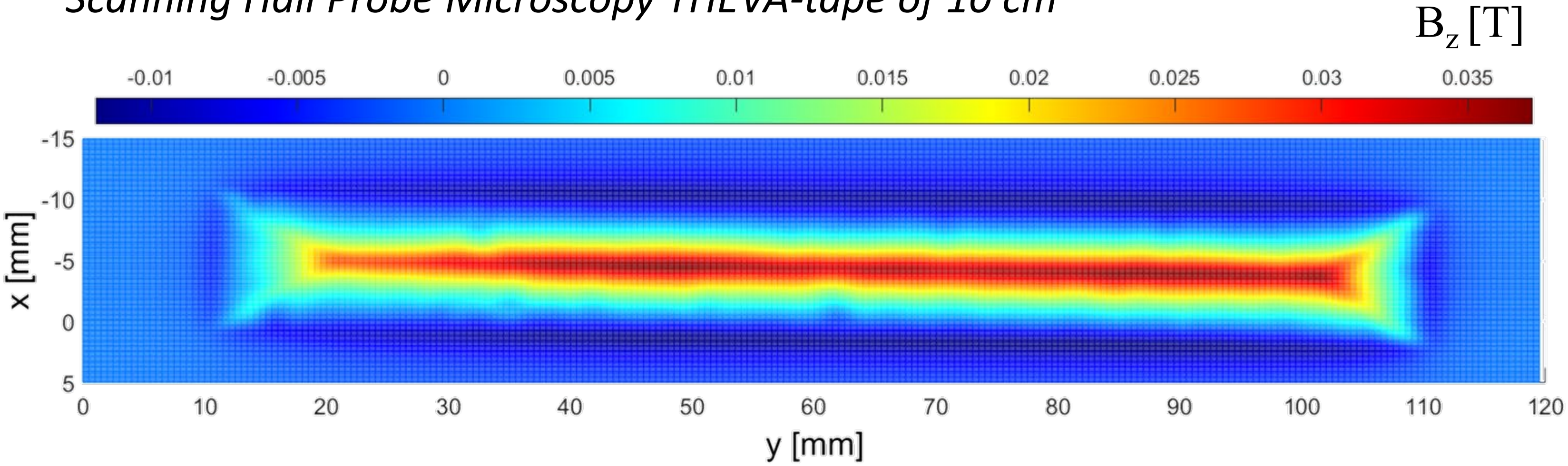

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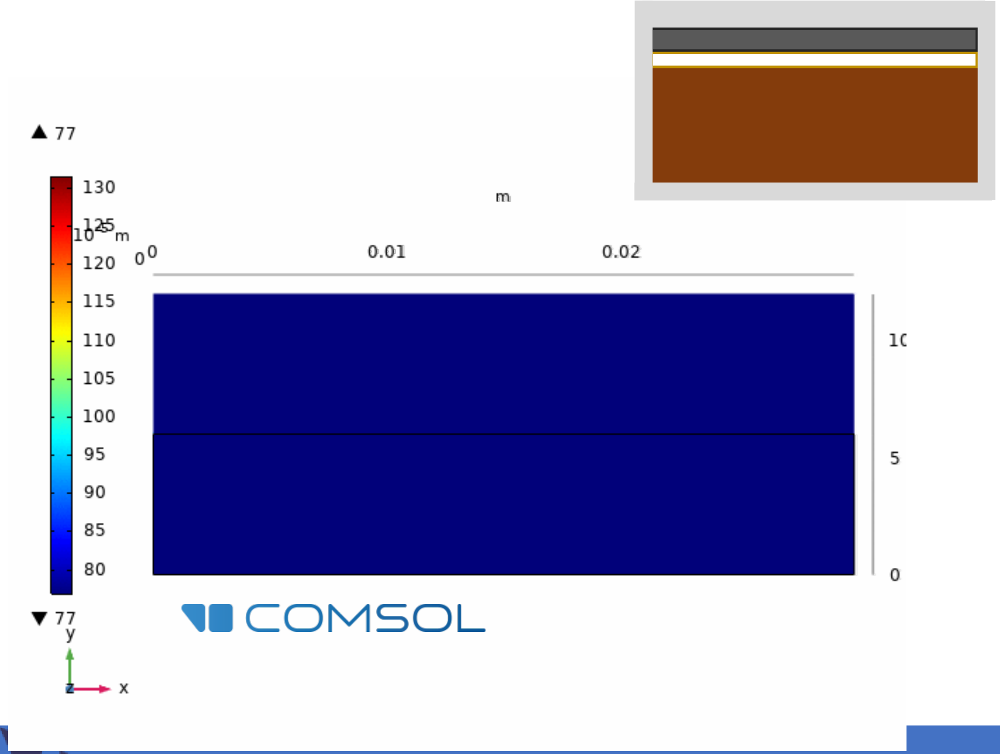
2nd Proposal: The Current Flow Diverter (CFD)

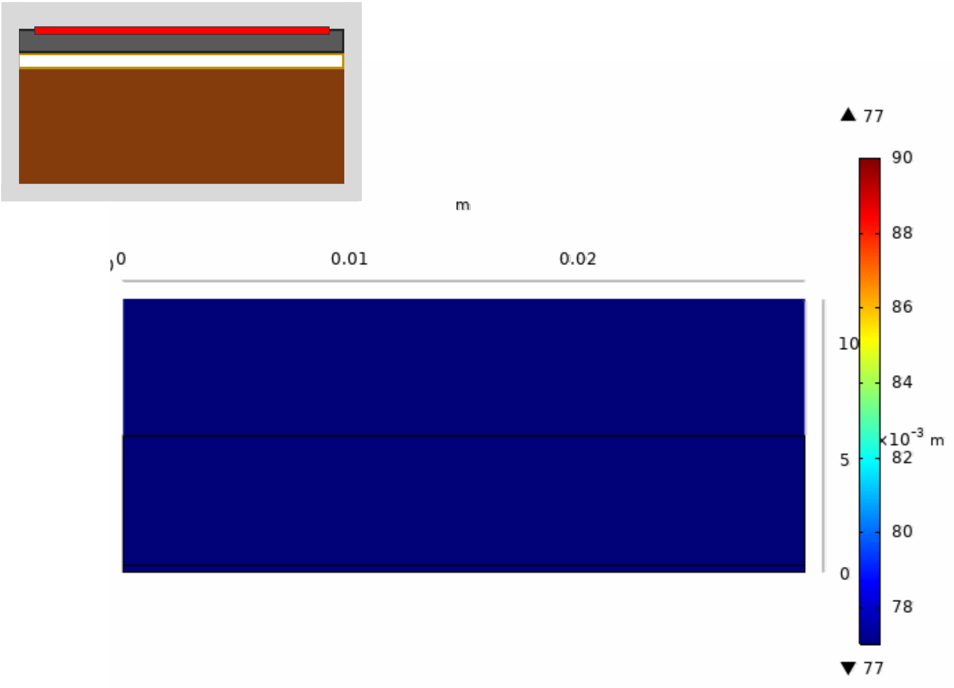
POLYTECHNIQUE MONTRÉAL

- Uniform Interface vs. CFD
  - Steady current 300 A
  - For 10 ms Duration

Hastelloy Substrate	Silver stabilizer
REBCO film	Normal zone
Buffer layer	Joule heating concentration
	High interfacial resistance layer

Lacroix et al., SUST 27 035003 (2014)
Lacroix et al., SUST 27 055013 (2014)
Lacroix et al., SUST 30 064004 (2017)





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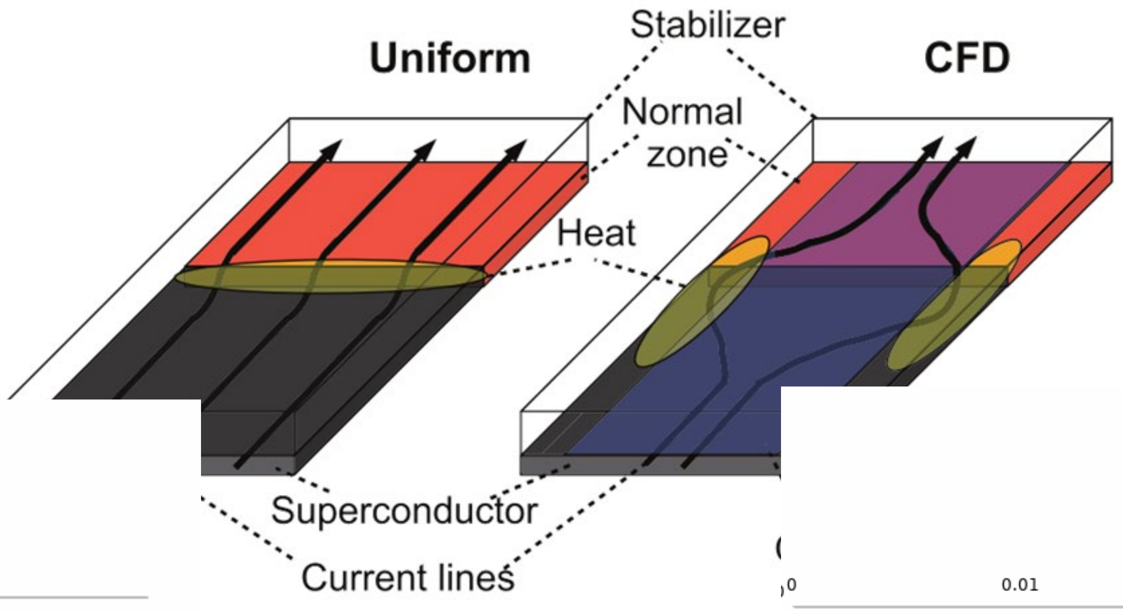

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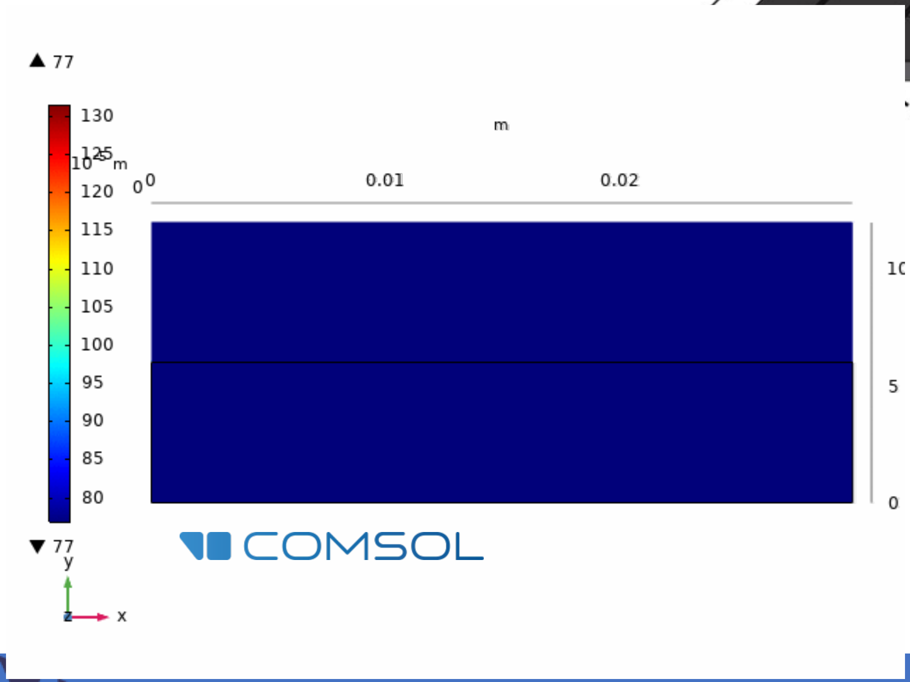

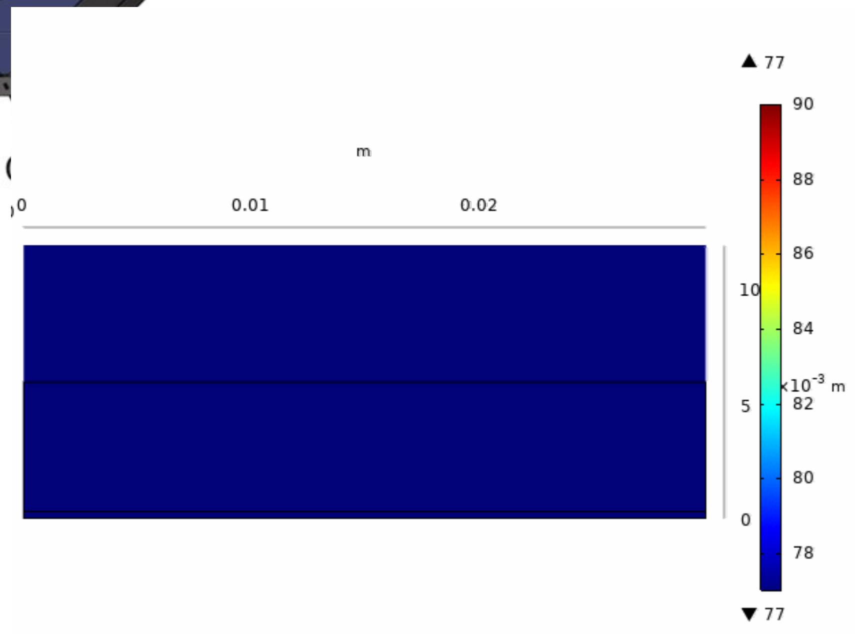

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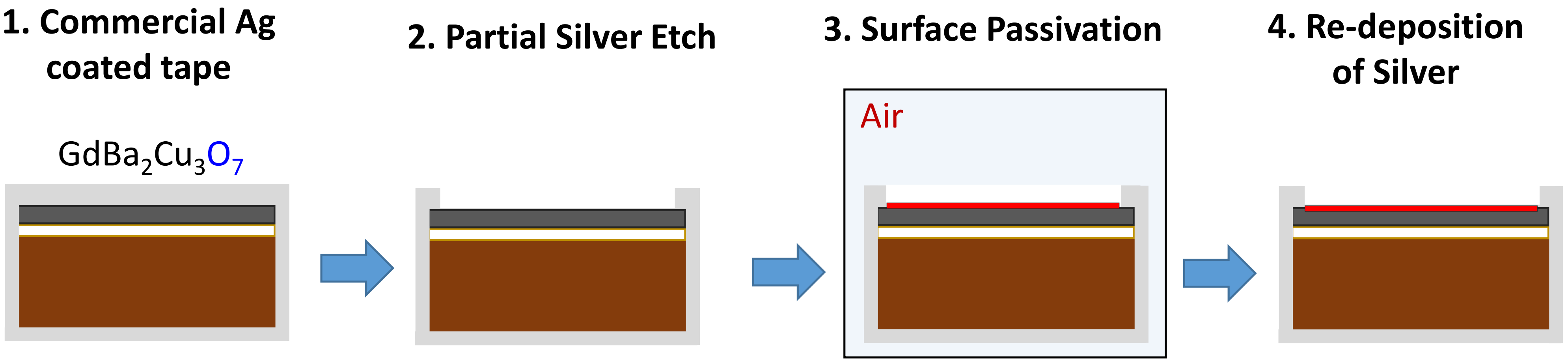
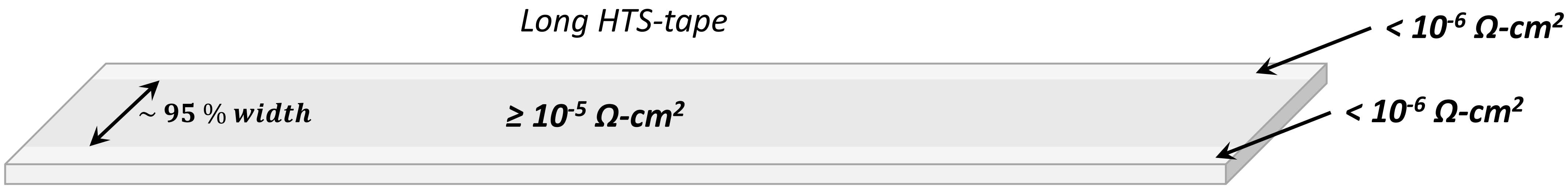
2^{nd} **Proposal:** The Classic CFD



4. Final CFD



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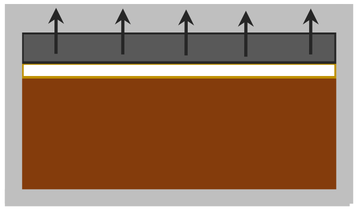
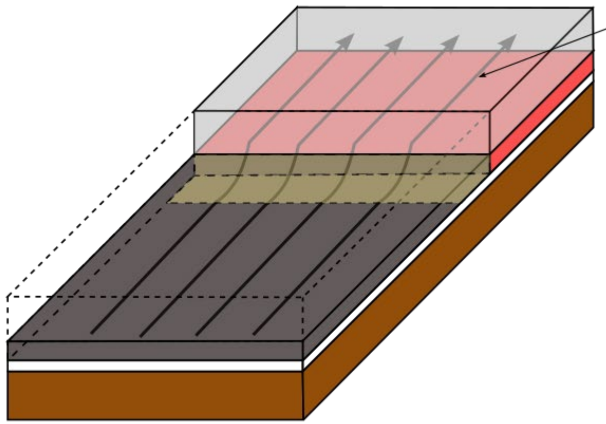
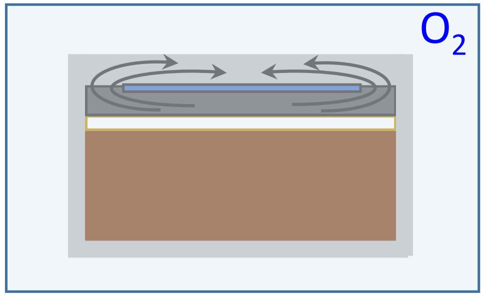
2nd Proposal: CFD with Amorphous Y_2O_3

Uniform
Tape cross section





4. Final O_2 Annealing for CFD



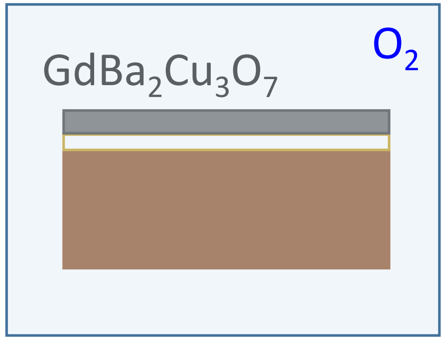
Barusco et al., ACS Omega 7, 15315 (2022)
Lacroix et al., SUST 35 055009 (2022)

0. Grown HTS film (NOT oxygenated)

$GdBa_2Cu_3O_{7-\delta}$

3. Silver Coating

1. Oxygen Annealing



2. Yttria Chemical Solution Disposition

POLYTECHNIQUE MONTRÉAL

Lacroix et al., SUST 27 035003 (2014)
Lacroix et al., SUST 27 055013 (2014)
Lacroix et al., SUST 30 064004 (2017)

- Hastelloy Substrate
- REBCO film
- Buffer layer
- Silver stabilizer
- Normal zone
- Joule heating concentration
- High interfacial resistance layer

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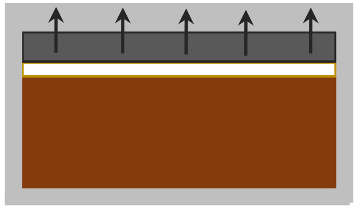

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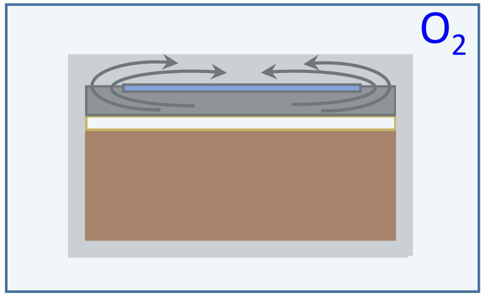

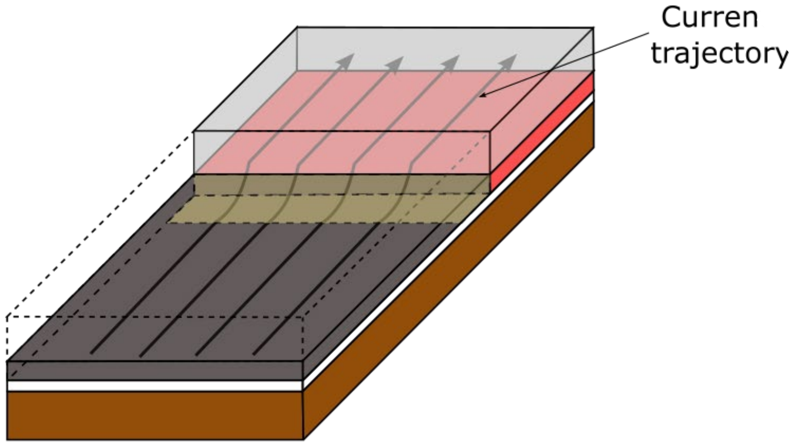

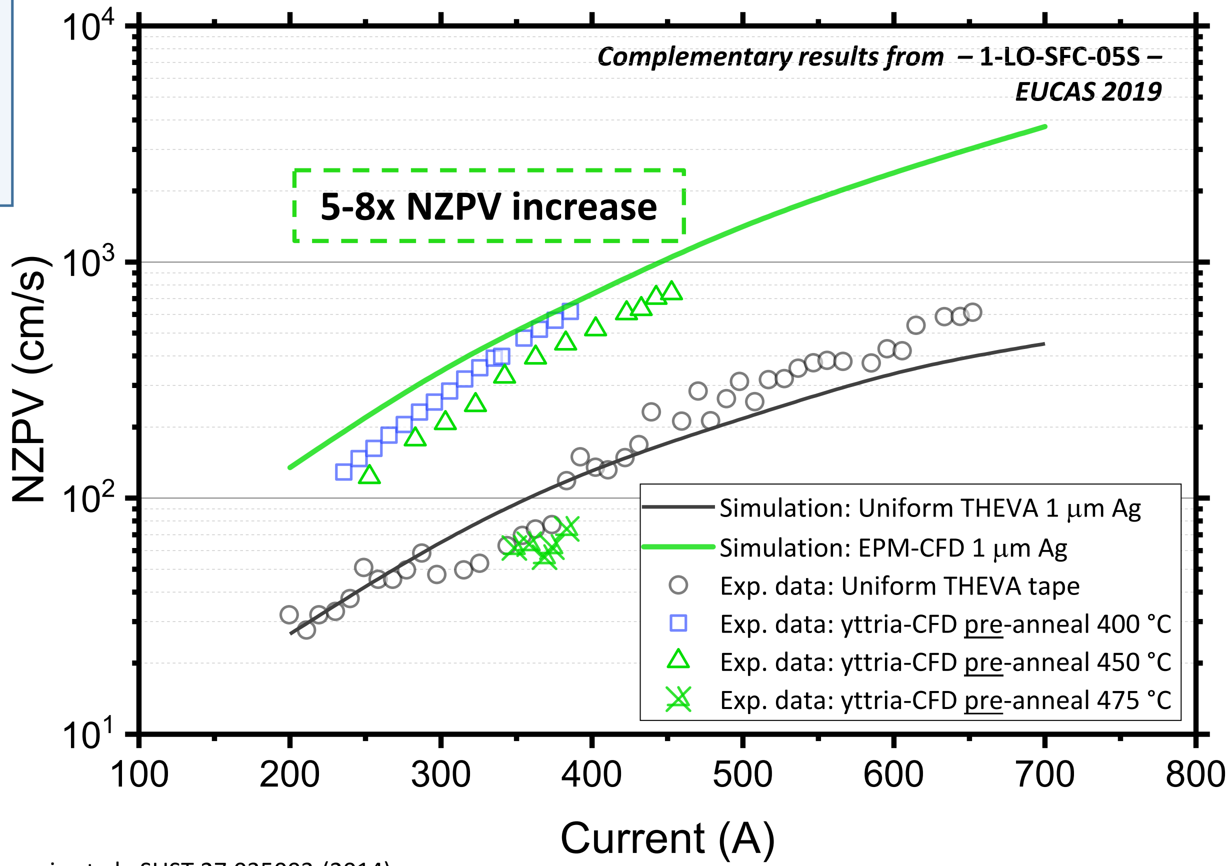

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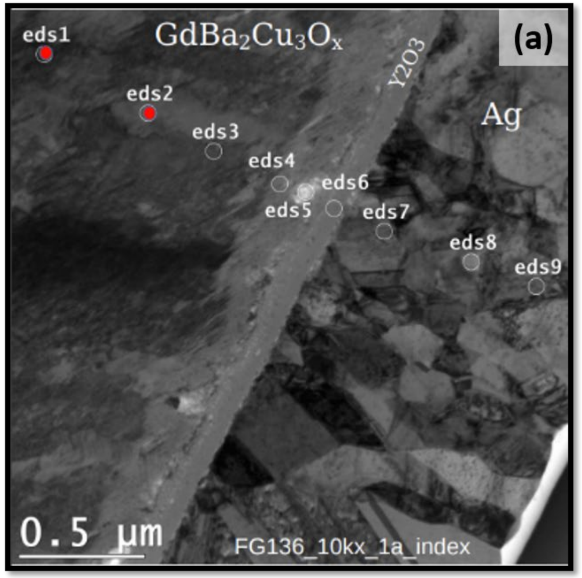
POLYTECHNIQUE MONTRÉAL

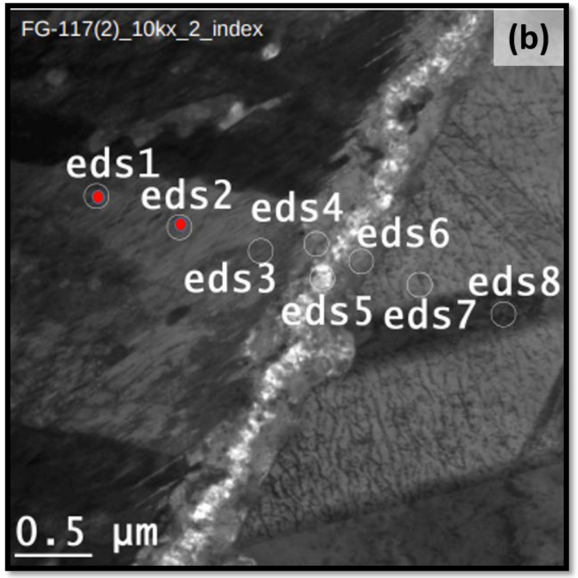
Lacroix et al., SUST 27 035003 (2014)
Lacroix et al., SUST 27 055013 (2014)
Lacroix et al., SUST 30 064004 (2017)

2^{nd} Proposal: TEM analysis of the Yttria-CFD interface

Yttria-CFD Before Oxygen Annealing

Yttria-CFD After Oxygen Annealing





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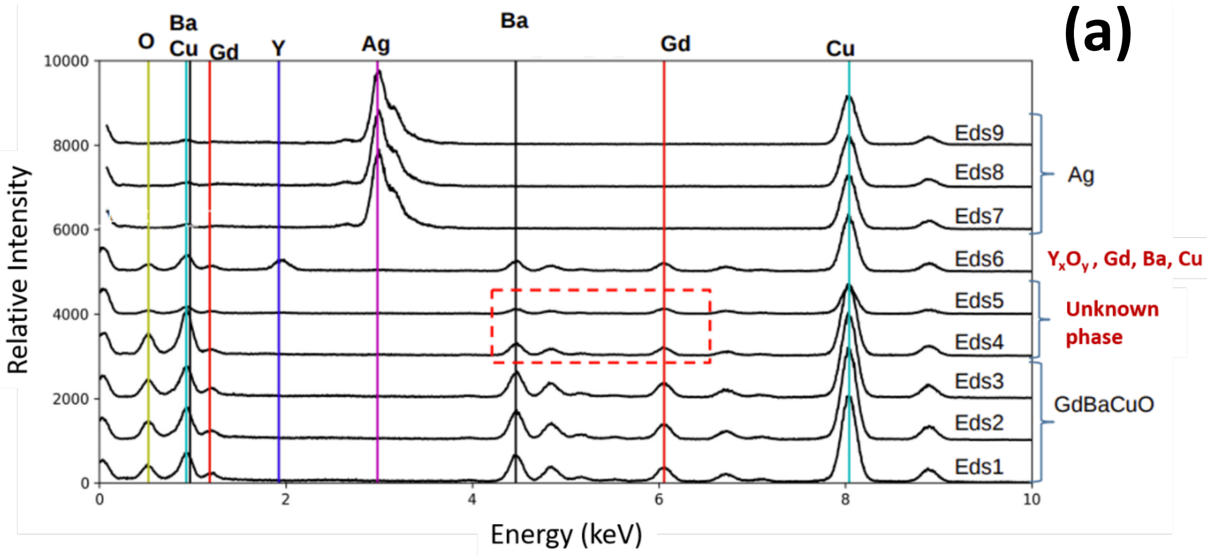

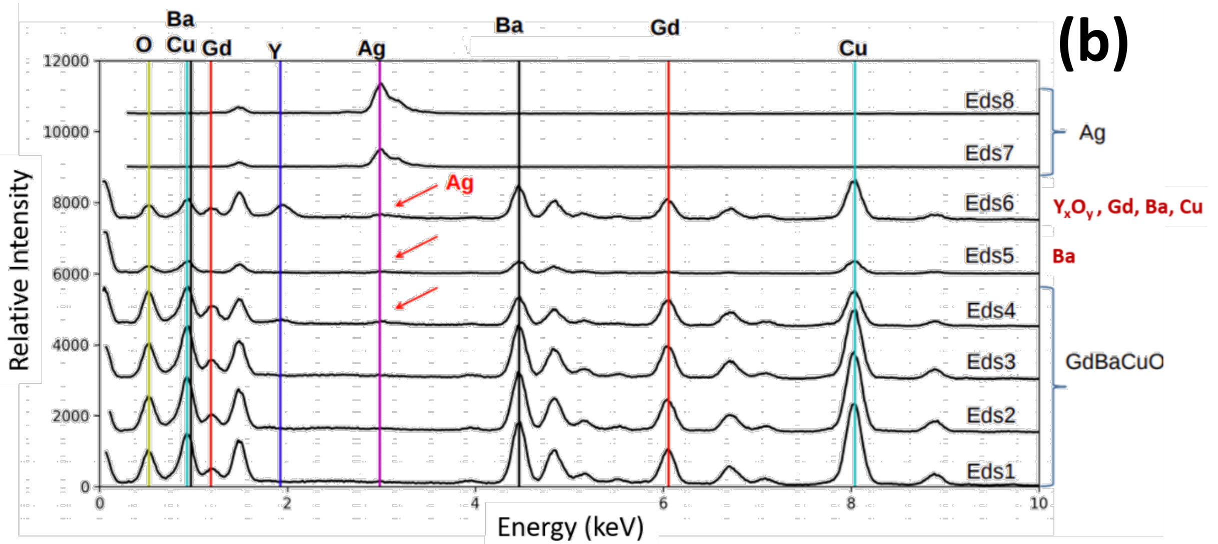

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3rd Proposal: CFD with intermetallic compounds (IMC)

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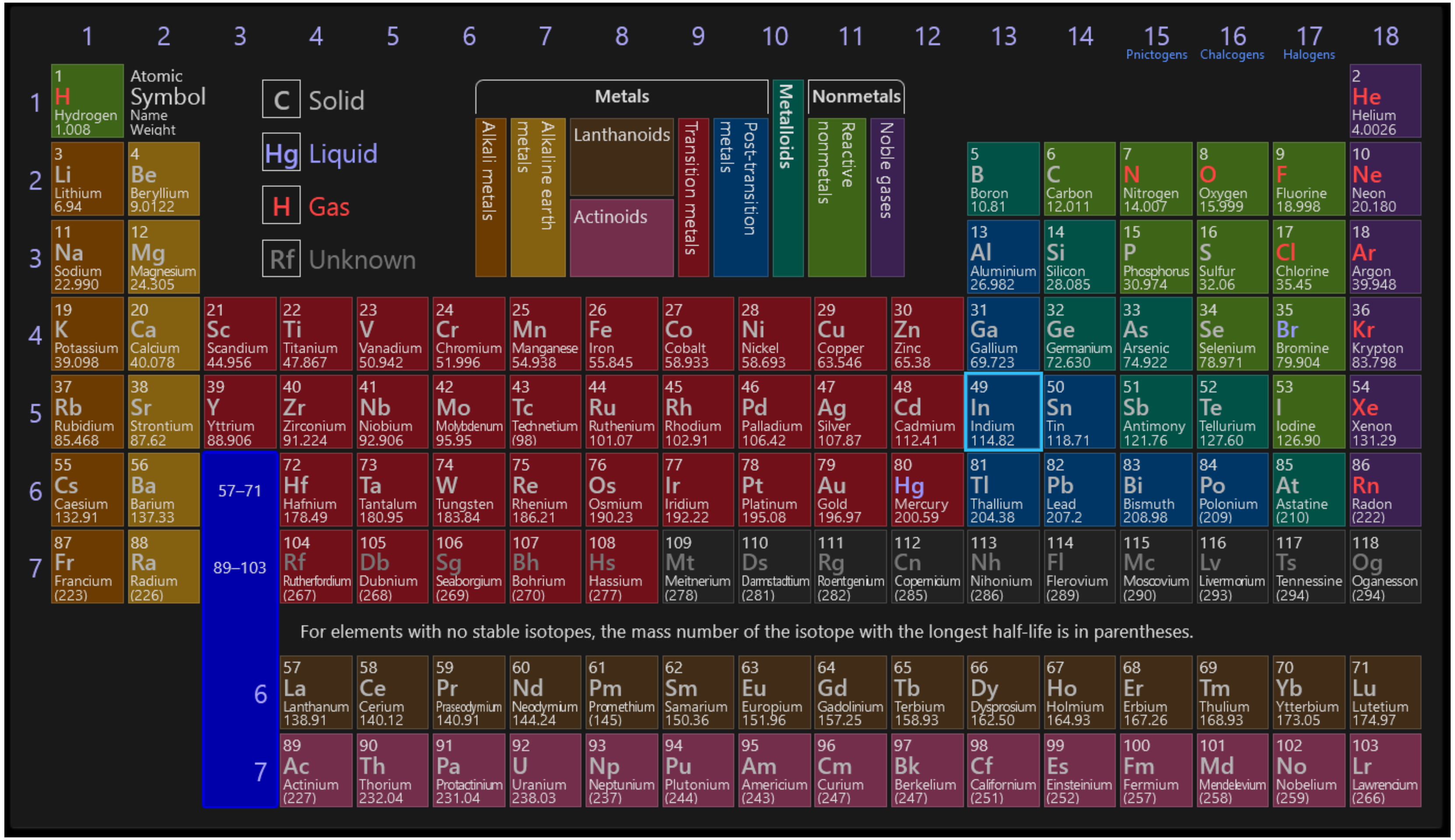
V. Simić and Z. Marinković, "Room Temperature Interactions in Ag-Metals Thin Film Couples", *Thin Solid Films, 61* (1979) 149-160



Binary System Ag and ...	Bulk difusion	Thin film interdiffusion at Room T
Al	+	-
Au	-	-
Bi	-	-
Cd	+	+
Cr	-	-
Cu	-	-
Ga	+	+
In	+	+
Pb	-	-
Sn	+	+

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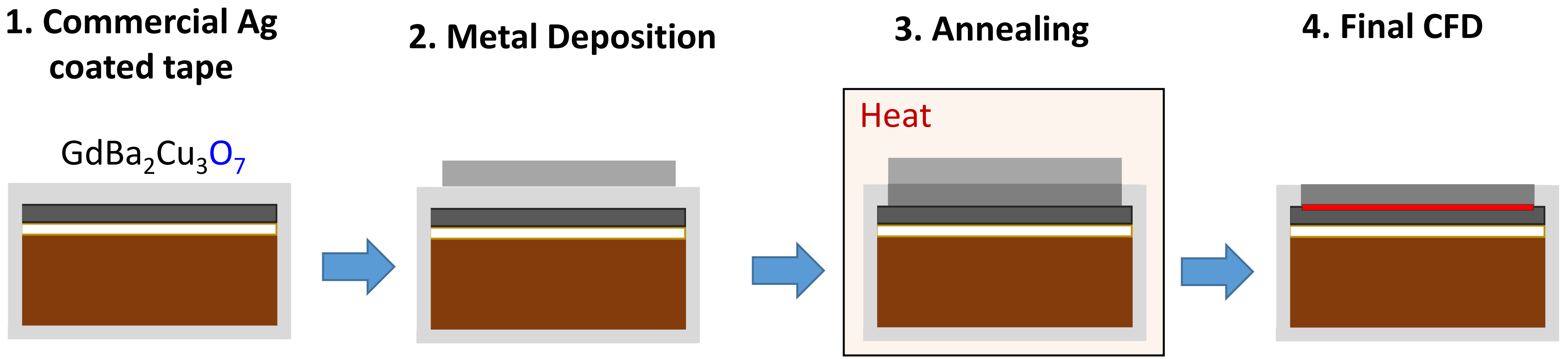
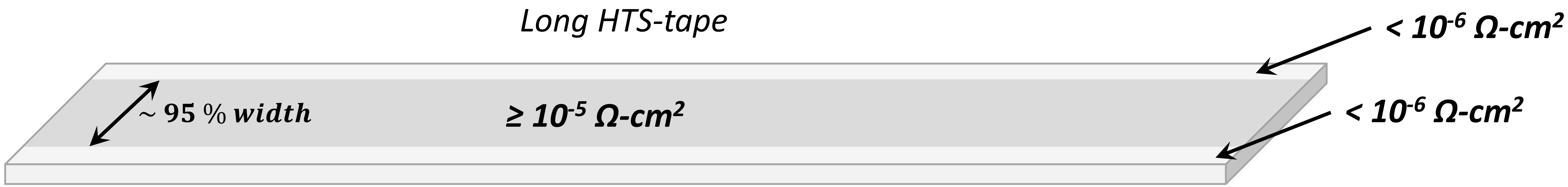
3rd Proposal: Can we use another metal to create the CFD?



4. Final CFD



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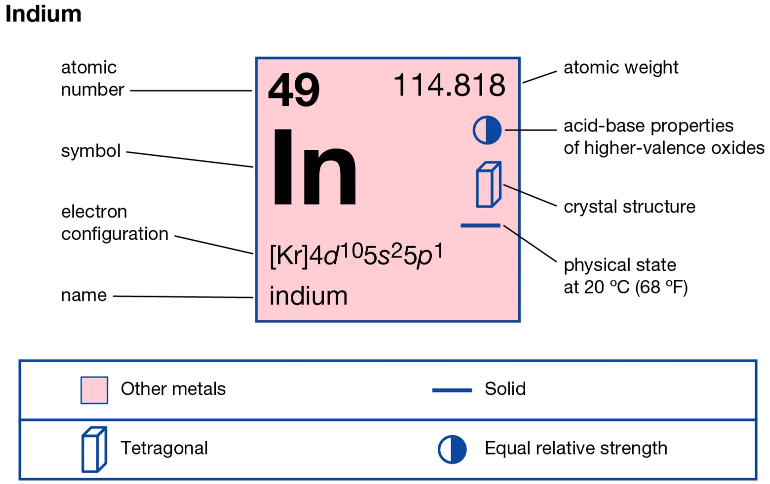
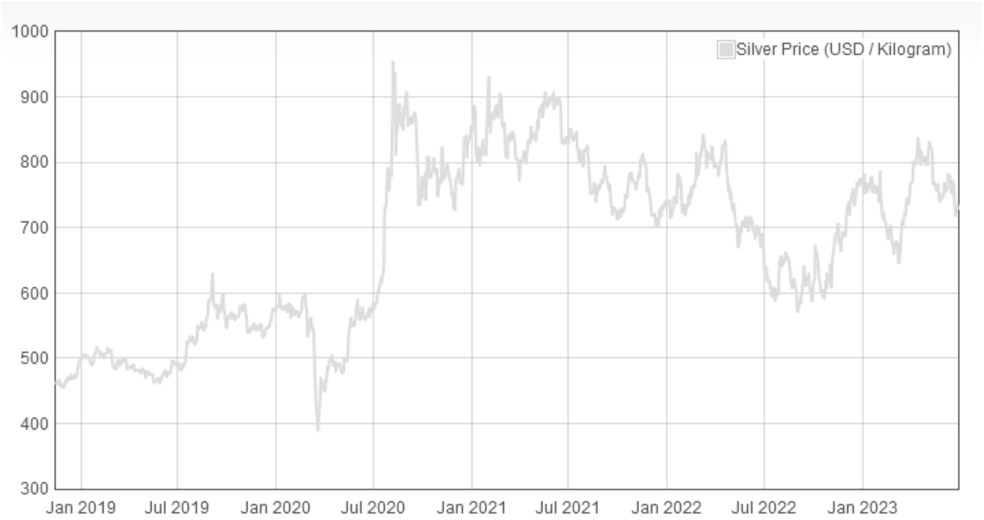
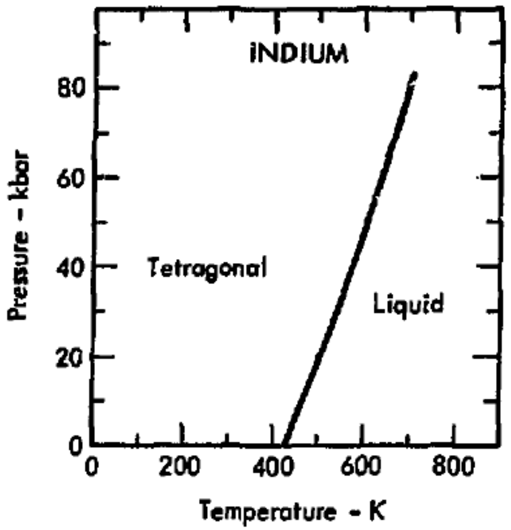
3rd Proposal: CFD with Indium (In)

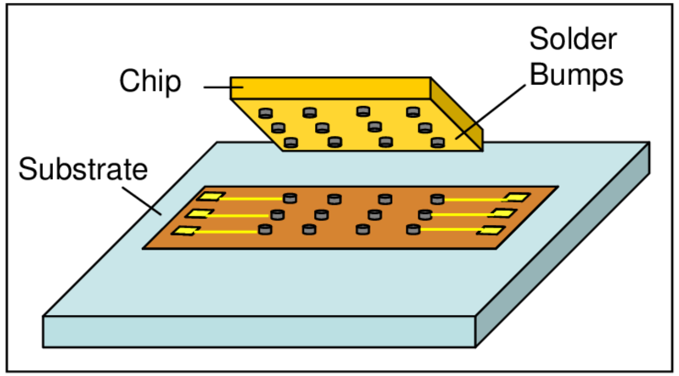
EUCAS2023 Bologna, Italy 3rd-7th September

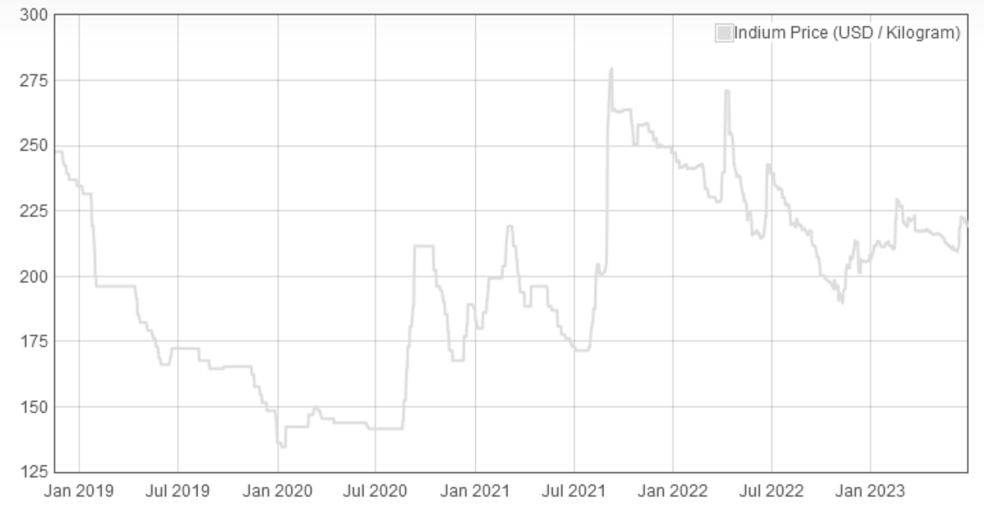






In flip-chip bonding





3rd Proposal: How much Indium do we need?

A.N. Campbell, Canadian Journal of Chemistry. **48**(11): 1703-1715.

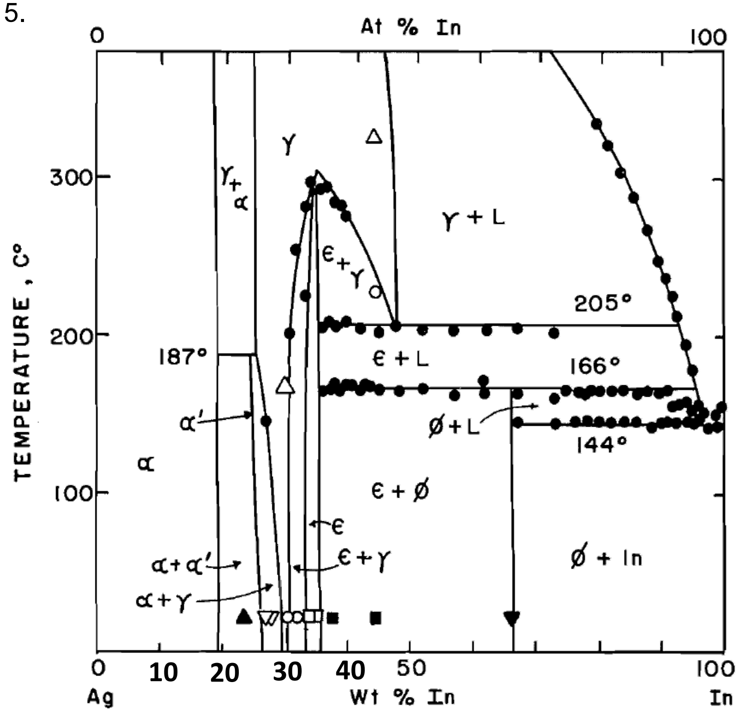
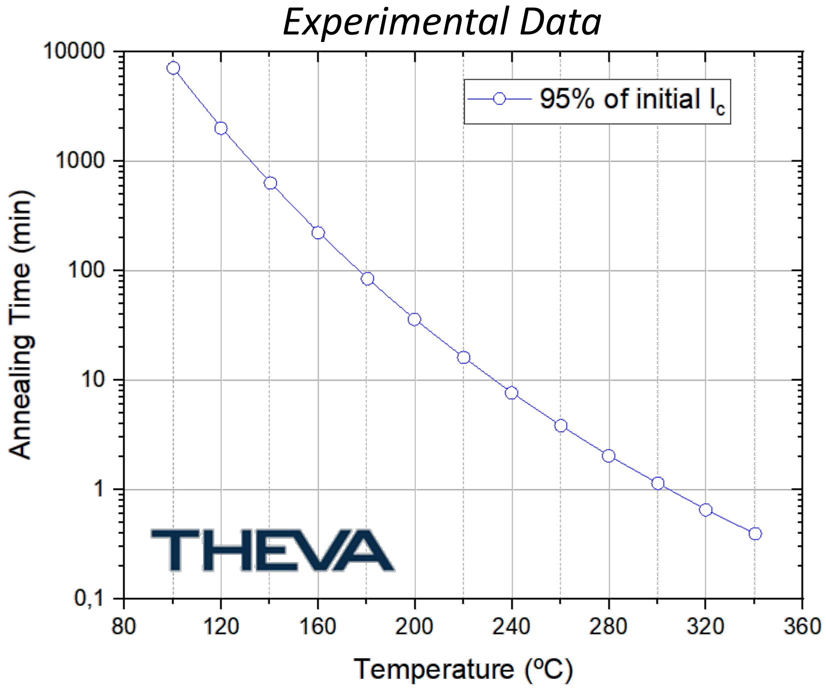
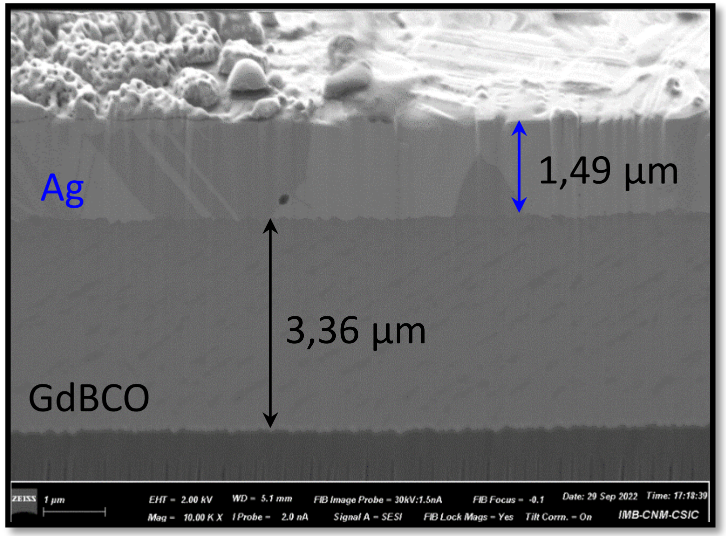


FIG. 5. Phase diagram of Ag–In below 300 °C: ▽, α + γ; ○, ε + γ; □, ε; ■, ε + ϕ; △, γ; ▲, α + α′ (γ phase metastable); ▼, ϕ; ●, DTA.





SEM-FIB cross-section image of THEVA tape

- ❑ BCT $AgIn_2$ (φ-phase) → ;
- ❑ Cubic Ag_2In (ε-phase) → 32,8 wt% - 36,82wt%
- ❑ Hexagonal Ag_3In (γ-phase) → 29 wt% - 29.7 wt%
- ❑ Cubic Ag_3In (α'-phase, aka alpha-prime)

⚠ **The $AgIn_2$ has a high Ductility coefficient. Unsuitable for the HTS's shunt coating.**

1) Pure Ag_2In (ε-phase)

2) Ag_3In + Ag_2In phase (ε + γ)

3) Pure Ag_3In (γ-phase)

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3rd Proposal: How fast Indium Diffuses in pure Silver?

R. Roy, "The kinetics of formation of Intermetallics in In/Ag thin film couples", *Thin Solid Films, **197**(1991) 303-318*

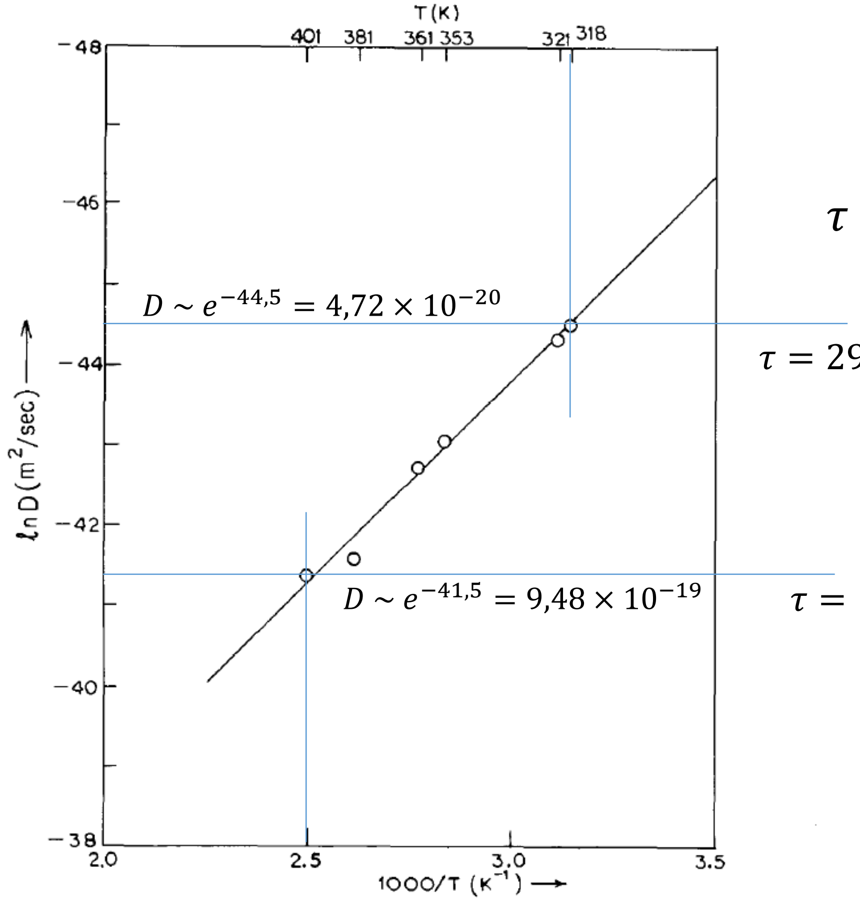


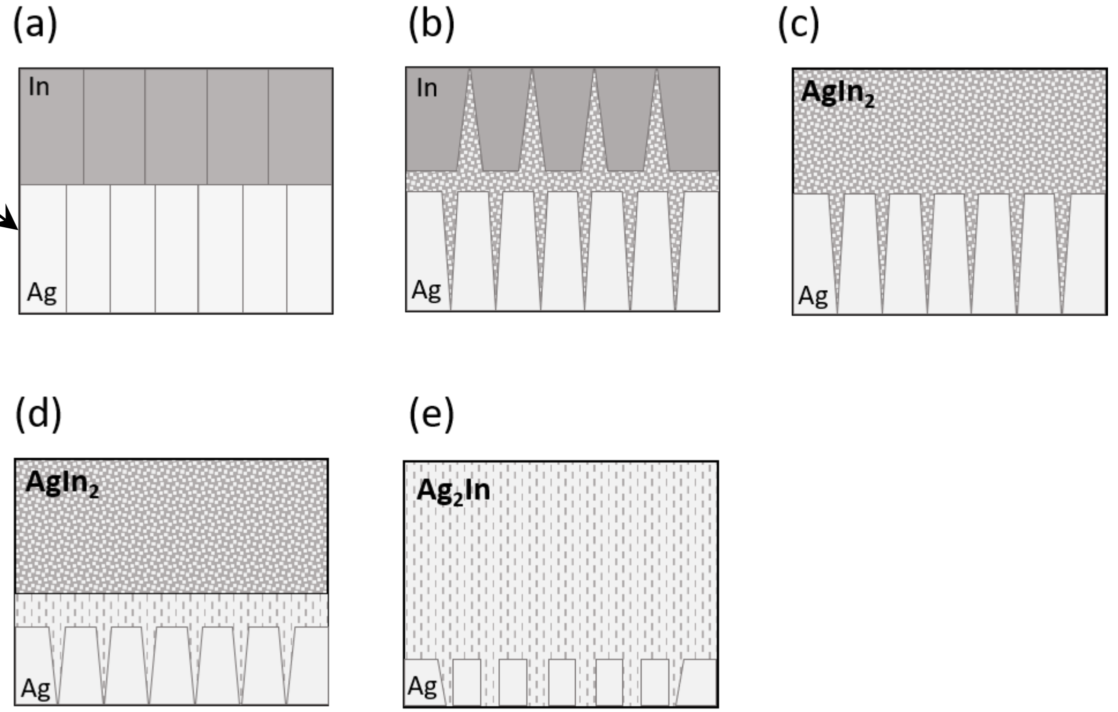
Fig. 3. Variation in diffusion coefficient $\ln D(t)$, as obtained from the plots presented in Fig. 2, with reciprocal absolute temperature $1/T$.

$L = 1\ \mu m$

$$\tau = \frac{L^2}{2\pi^2 D}$$

$\tau = 298\ h = 12\ days$

$\tau = 14\ hours$



Schematic model of the sequence of reaction and compound formation in Ag/In bilayer polycrystalline film (In < Ag): (a) as deposited; (b) AgIn$_2$ layer due to ambient diffusion; (c) growth of Ag$_2$In layer near the interface and at the silver grain boundaries at ambient temperature with aging or at higher temperature; (d) further growth of Ag$_2$In throughout the specimen and on the silver underlayer.

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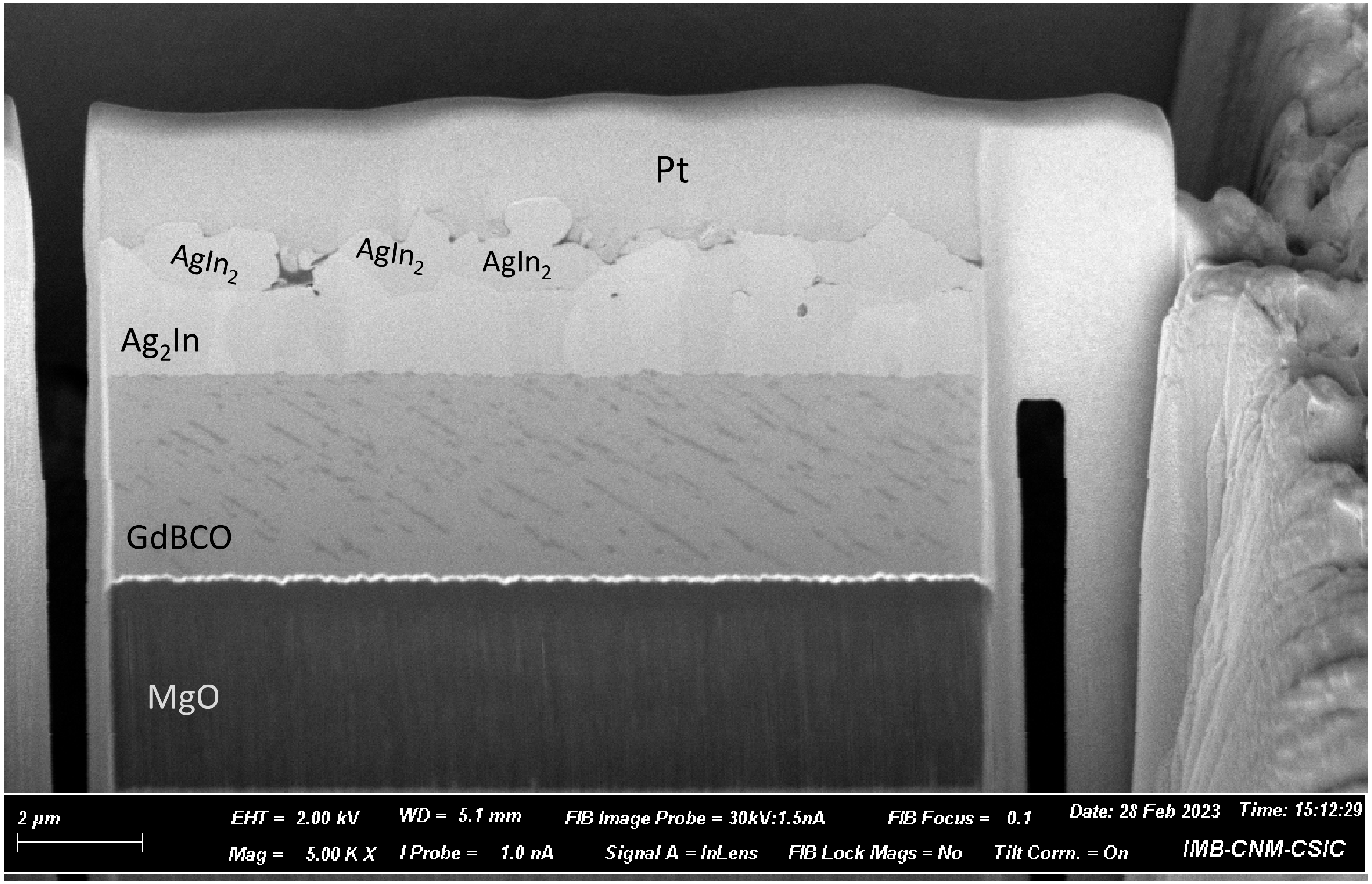
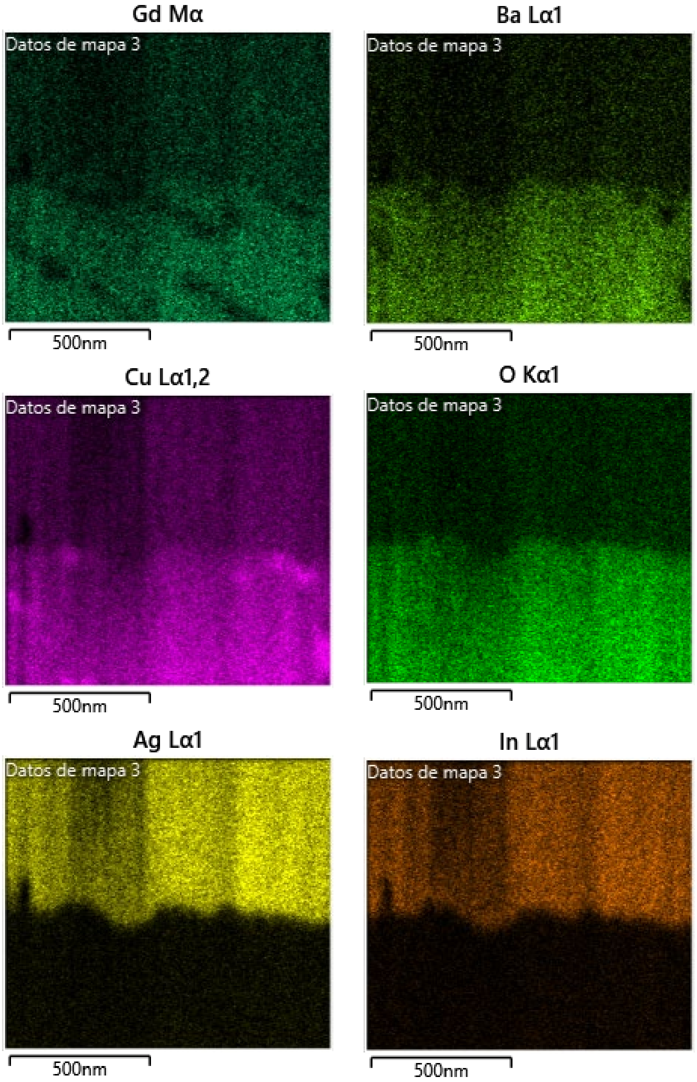
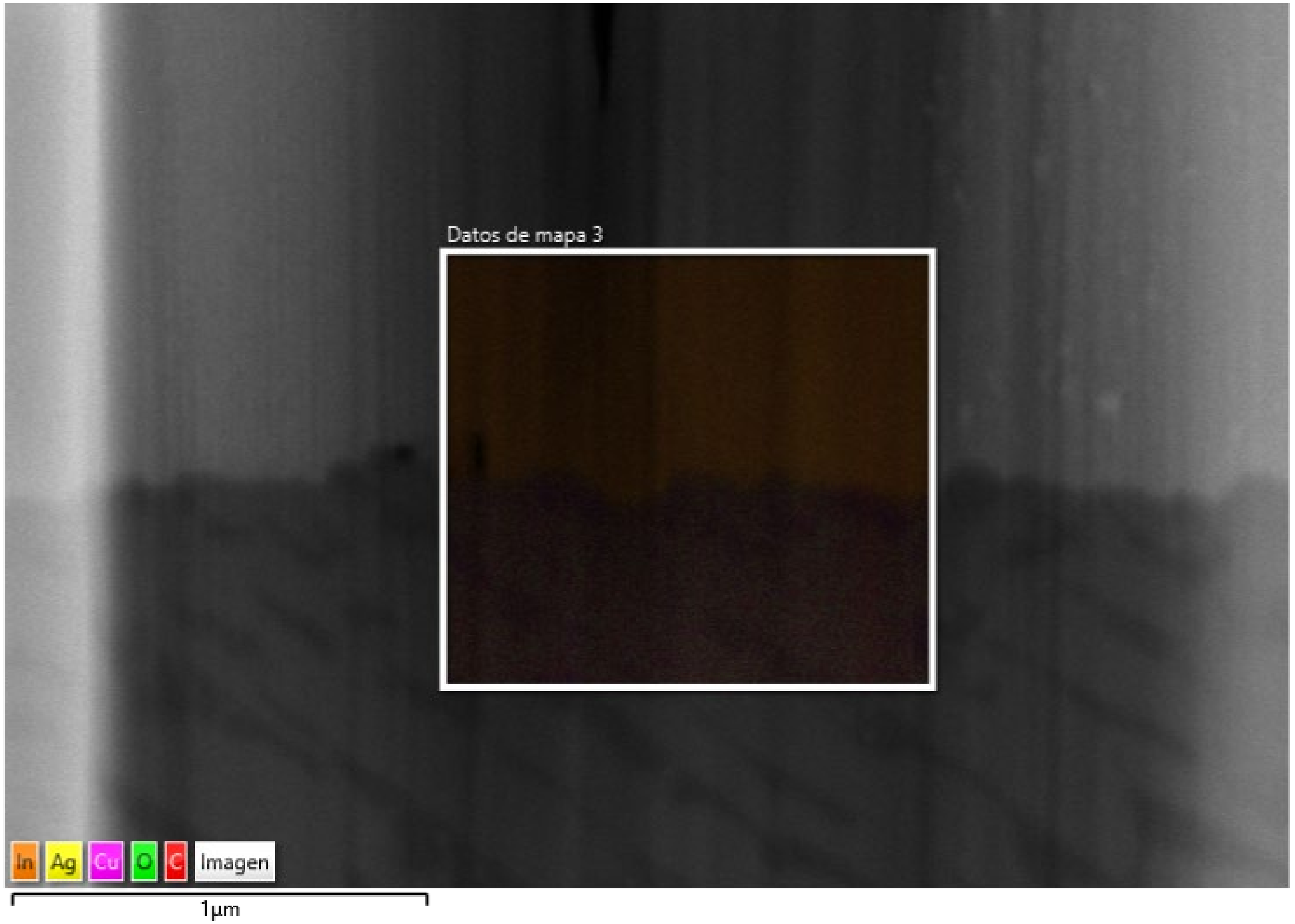
3rd Proposal: Map-EDX Analysis of Indium IMC-CFD

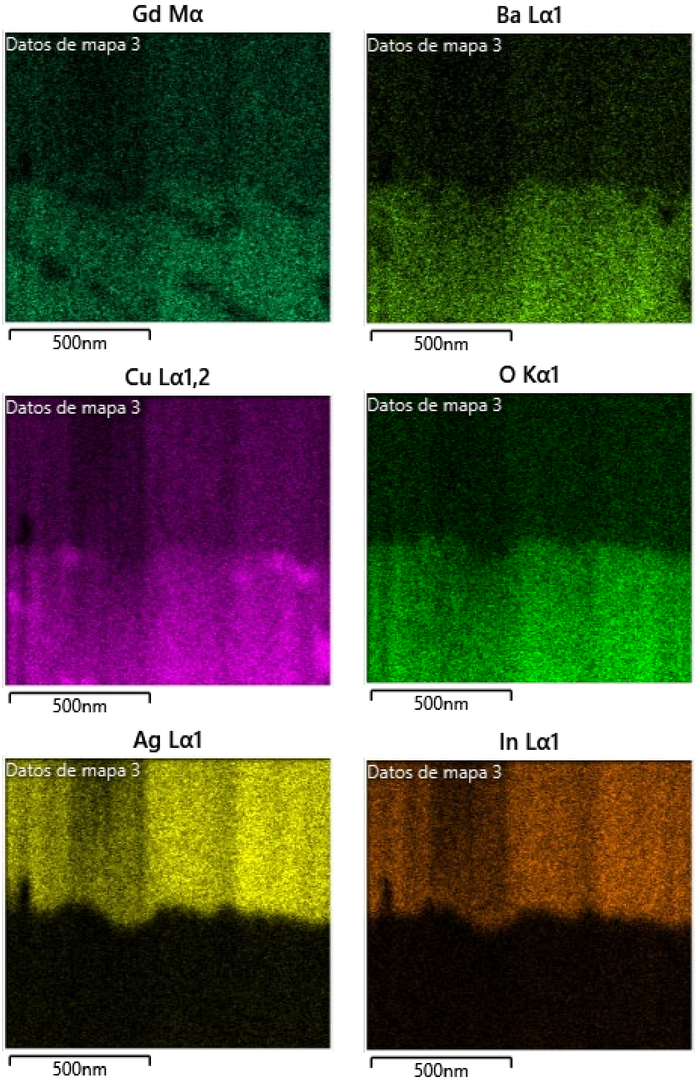
SEM-FIB image of the IMC-CFD In cross-section





3rd Proposal: Map-EDX Analysis of Indium IMC-CFD





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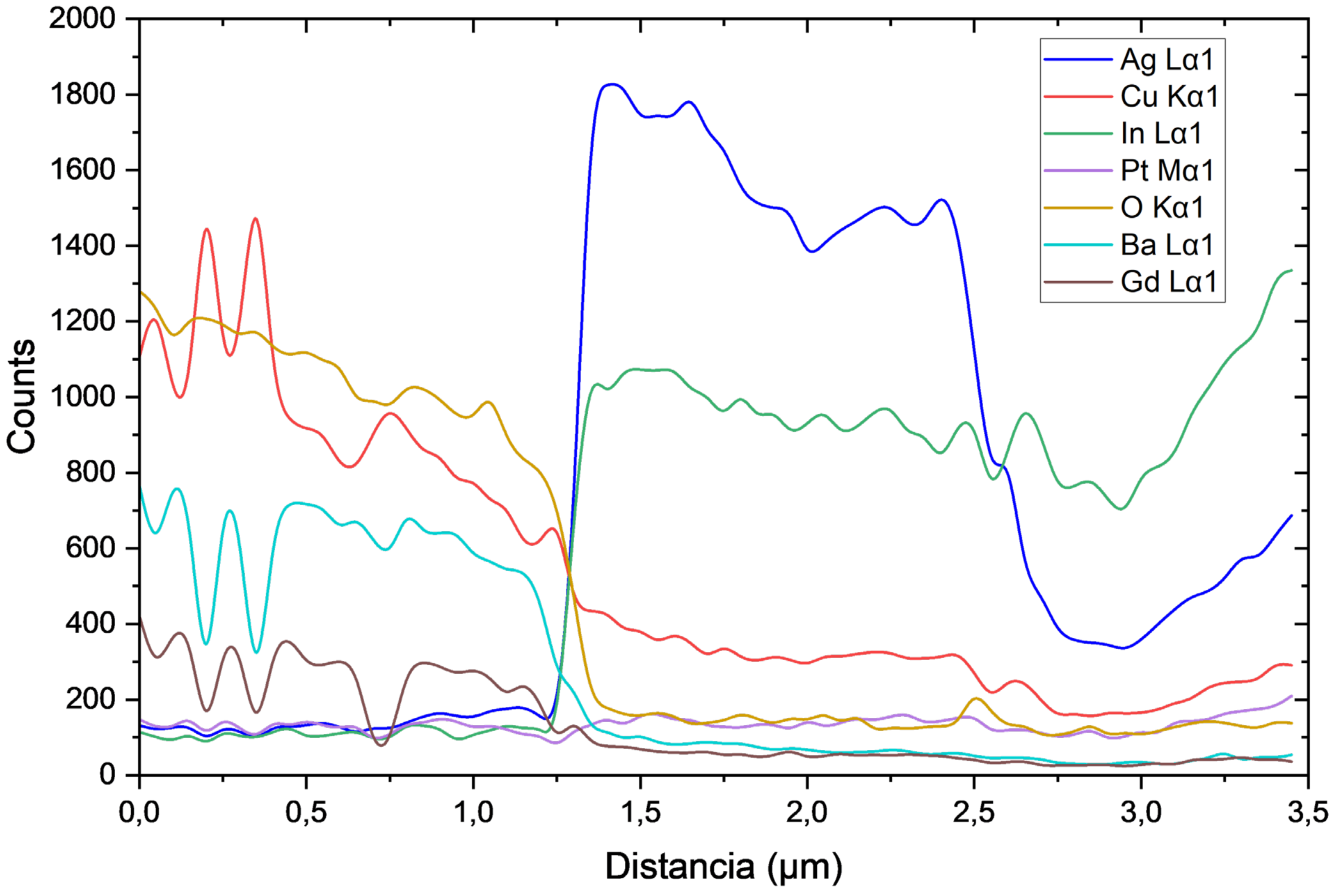
3rd Proposal: Line-EDX Analysis of Indium IMC-CFD

- ✓ Minimal diffusion of the In into the GdBCO layer (< 5 nm).



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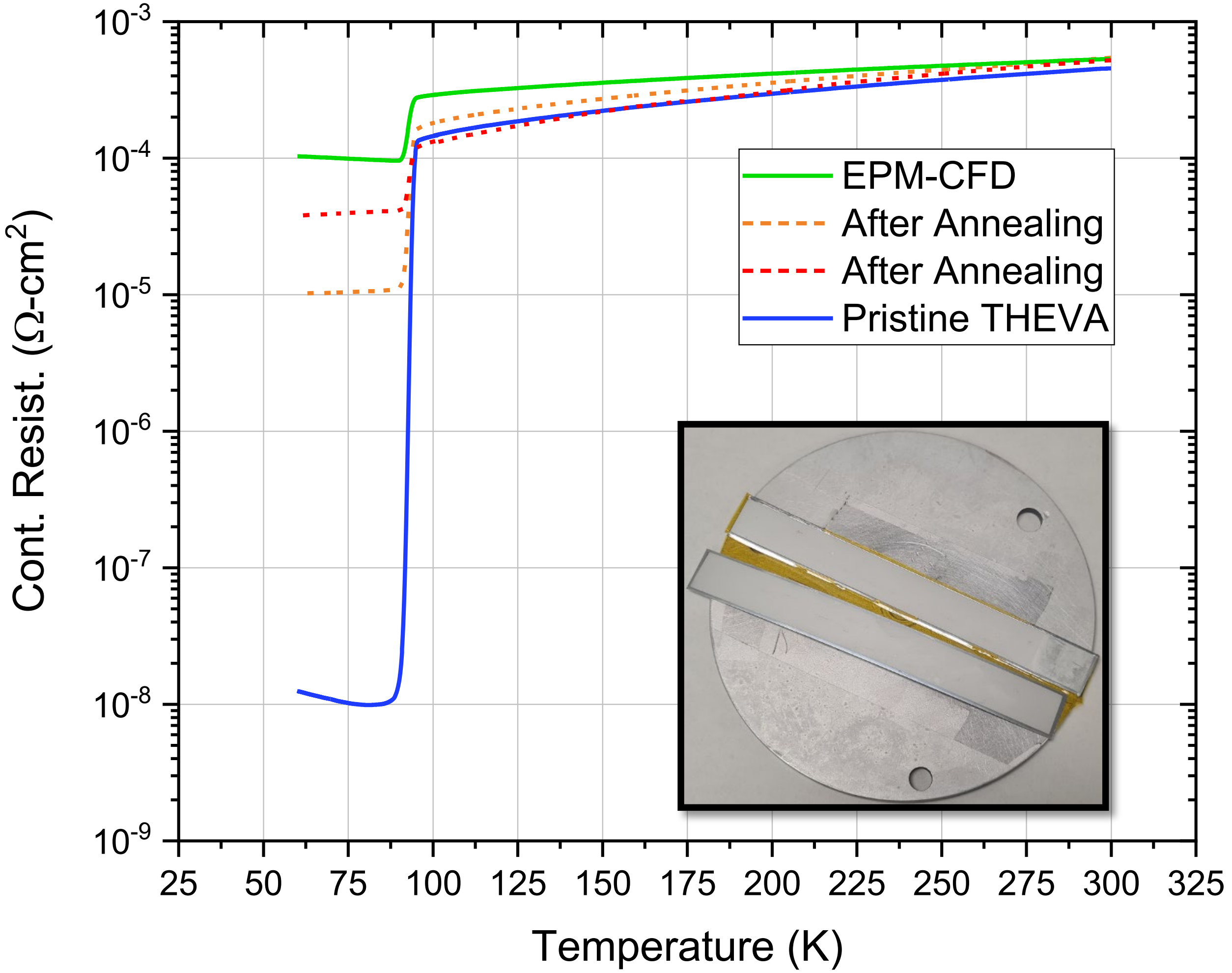
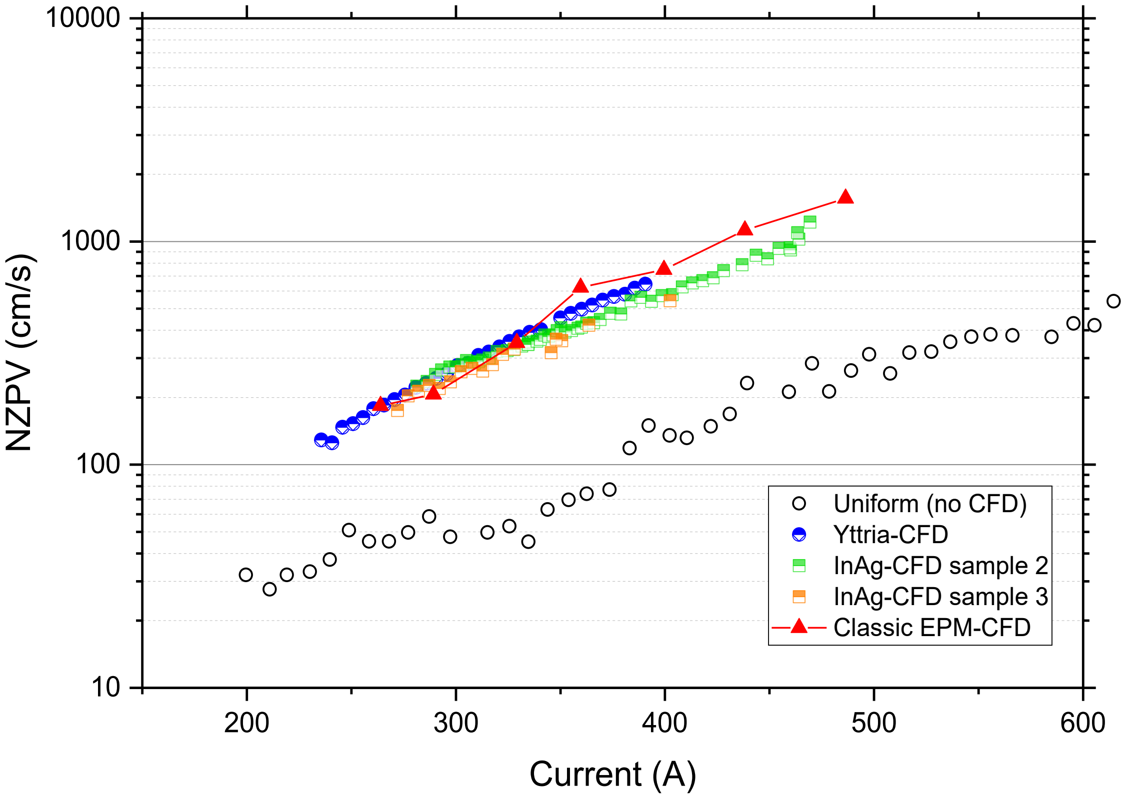
3rd Proposal: Interfacial resistance & NZPV tests





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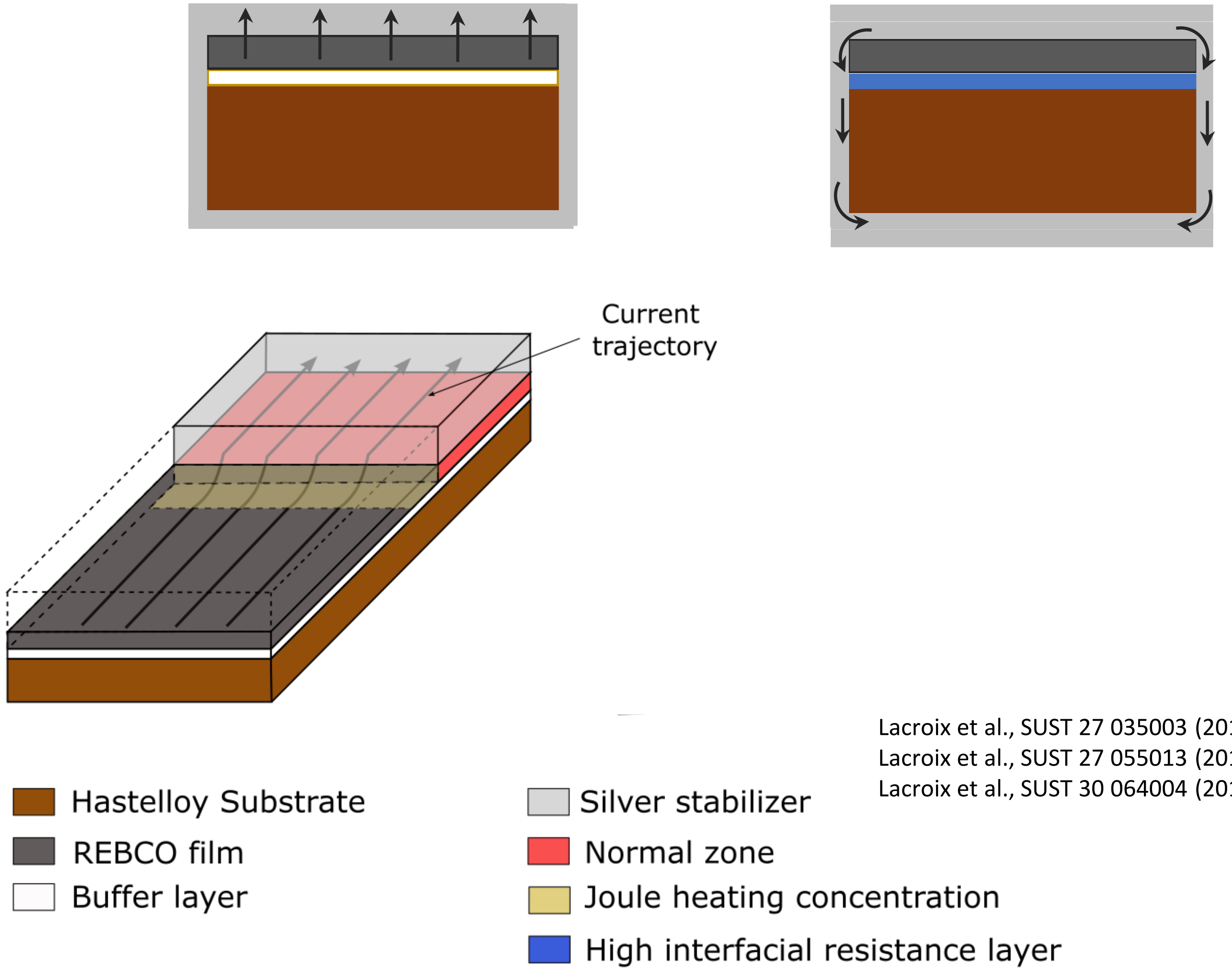
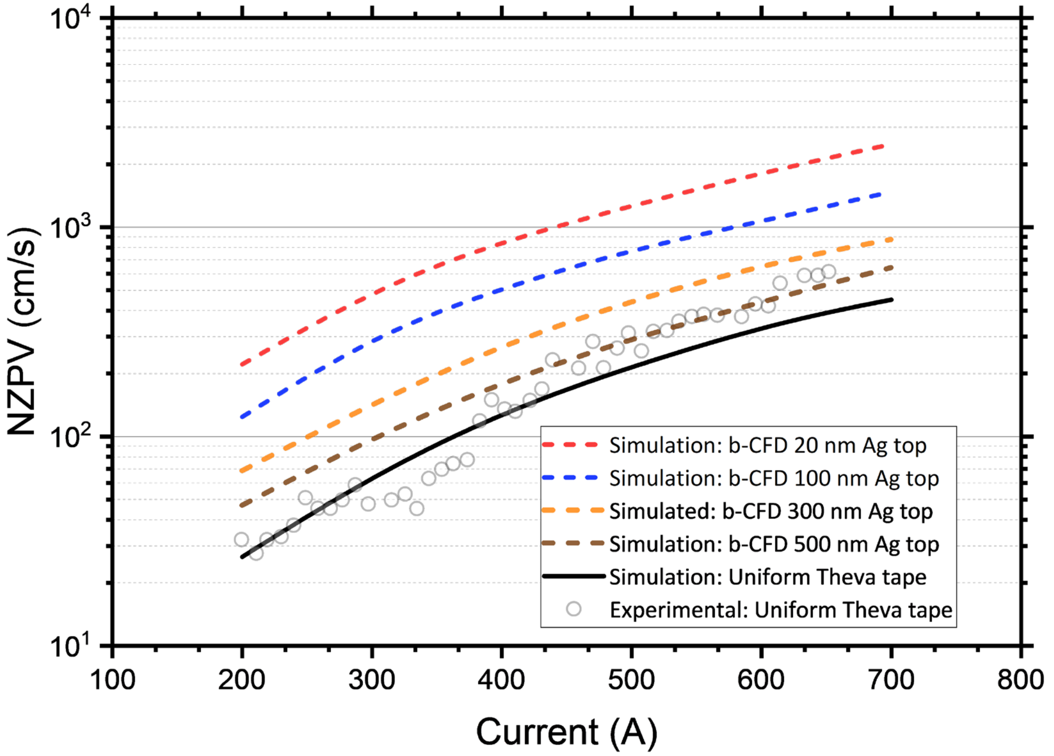
4th Proposal: b-CFD via silver sulfidation

Tape cross section



Lacroix et al., SUST 27 035003 (2014)
Lacroix et al., SUST 27 055013 (2014)
Lacroix et al., SUST 30 064004 (2017)



Lacroix et al., SUST 35 055009 (2022)
Barusco et al. To be published

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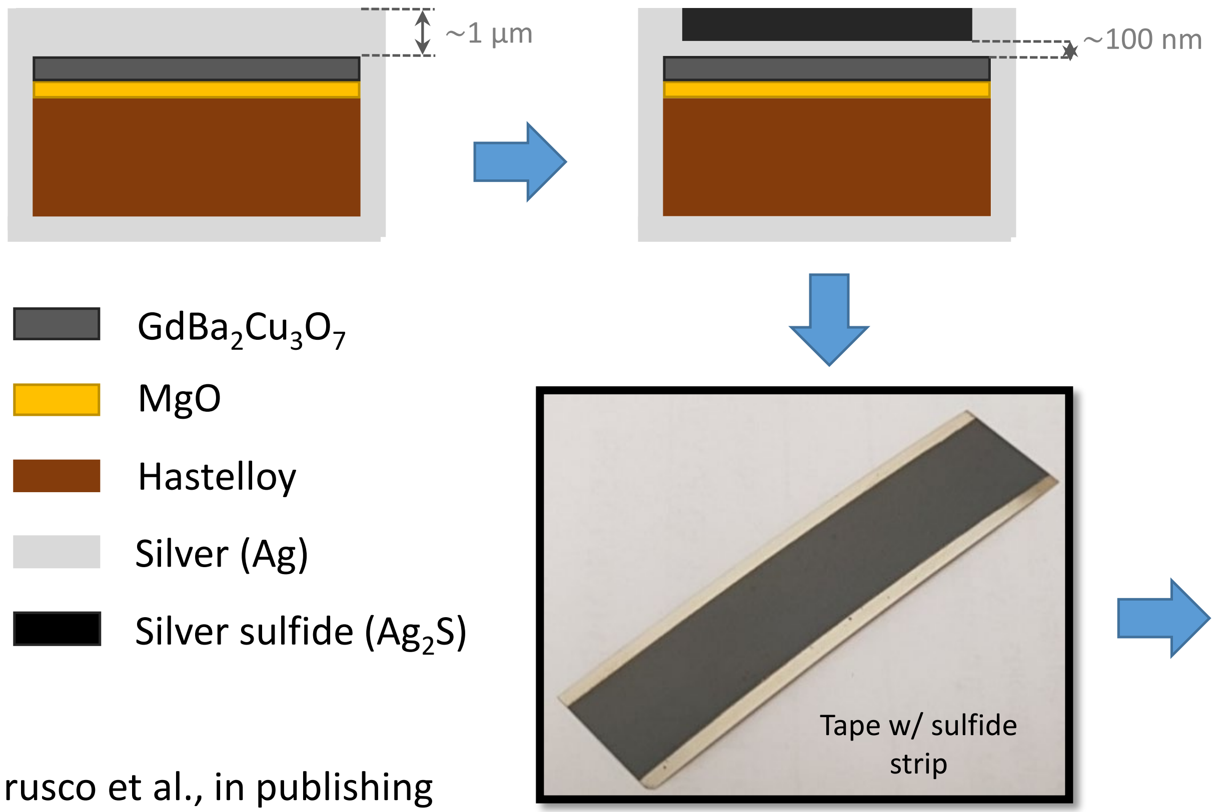
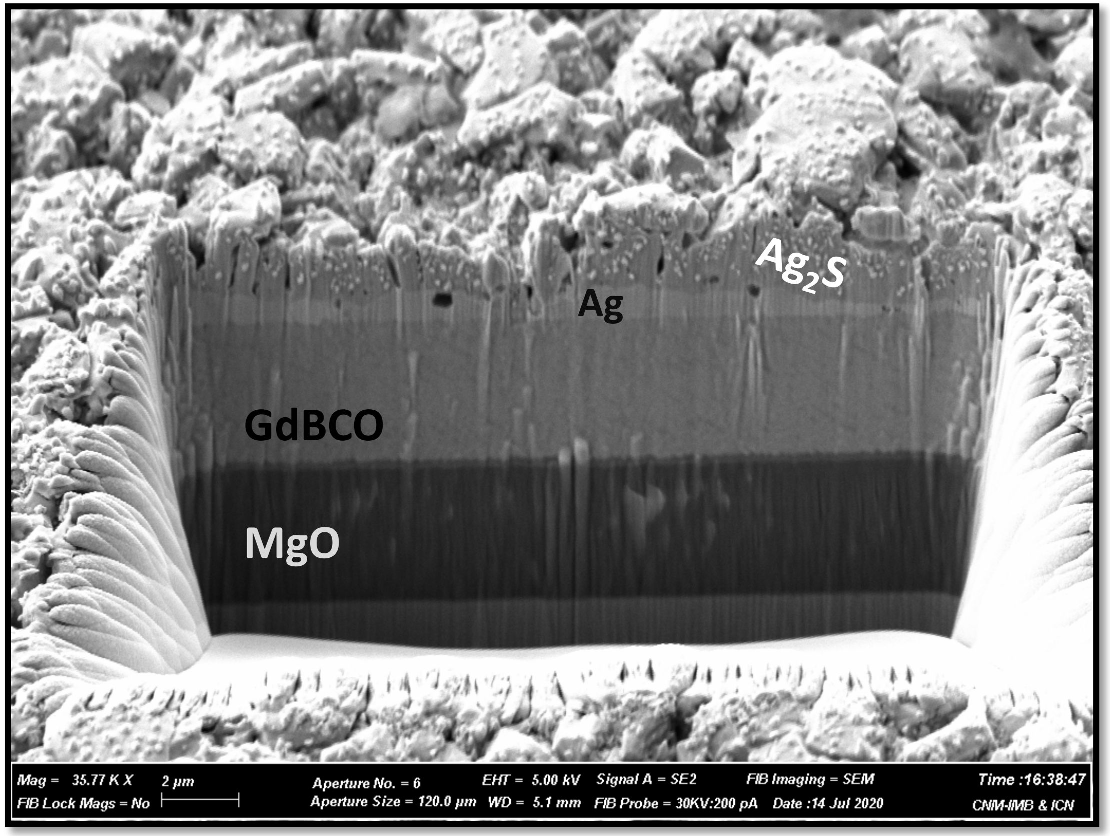
4th Proposal: The b-CFD architecture with sulfidation

- Partial **Sulfidation** of the Ag shunt:

$$2Ag(s) + S\,(g) \longrightarrow Ag_2S\,(s)$$



The sulfidation process can be controlled to avoid damaging the HTS



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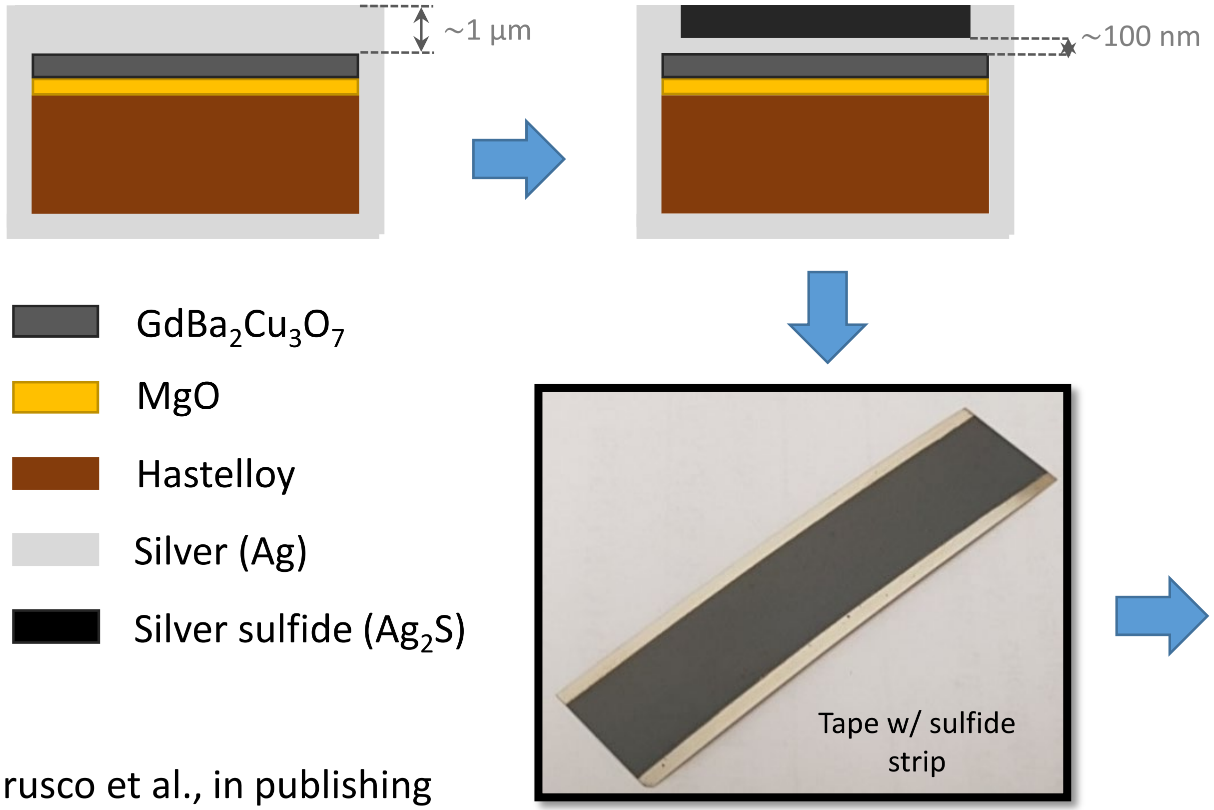

Barusco et al., in publishing

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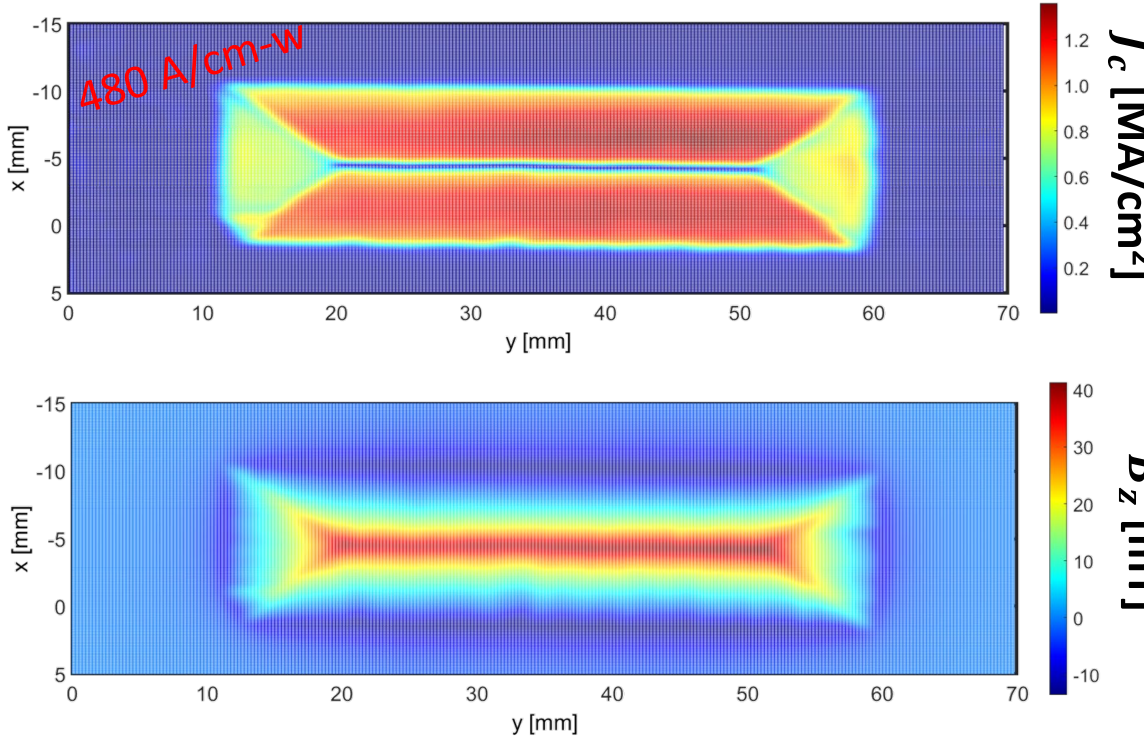

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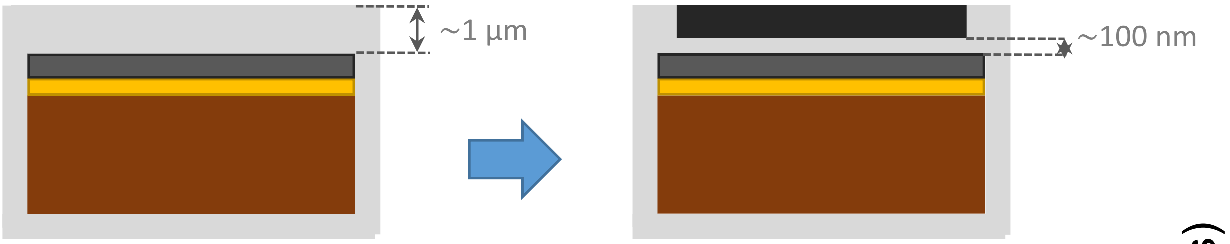

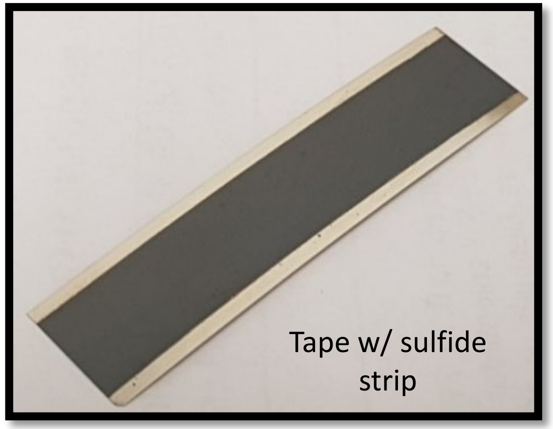

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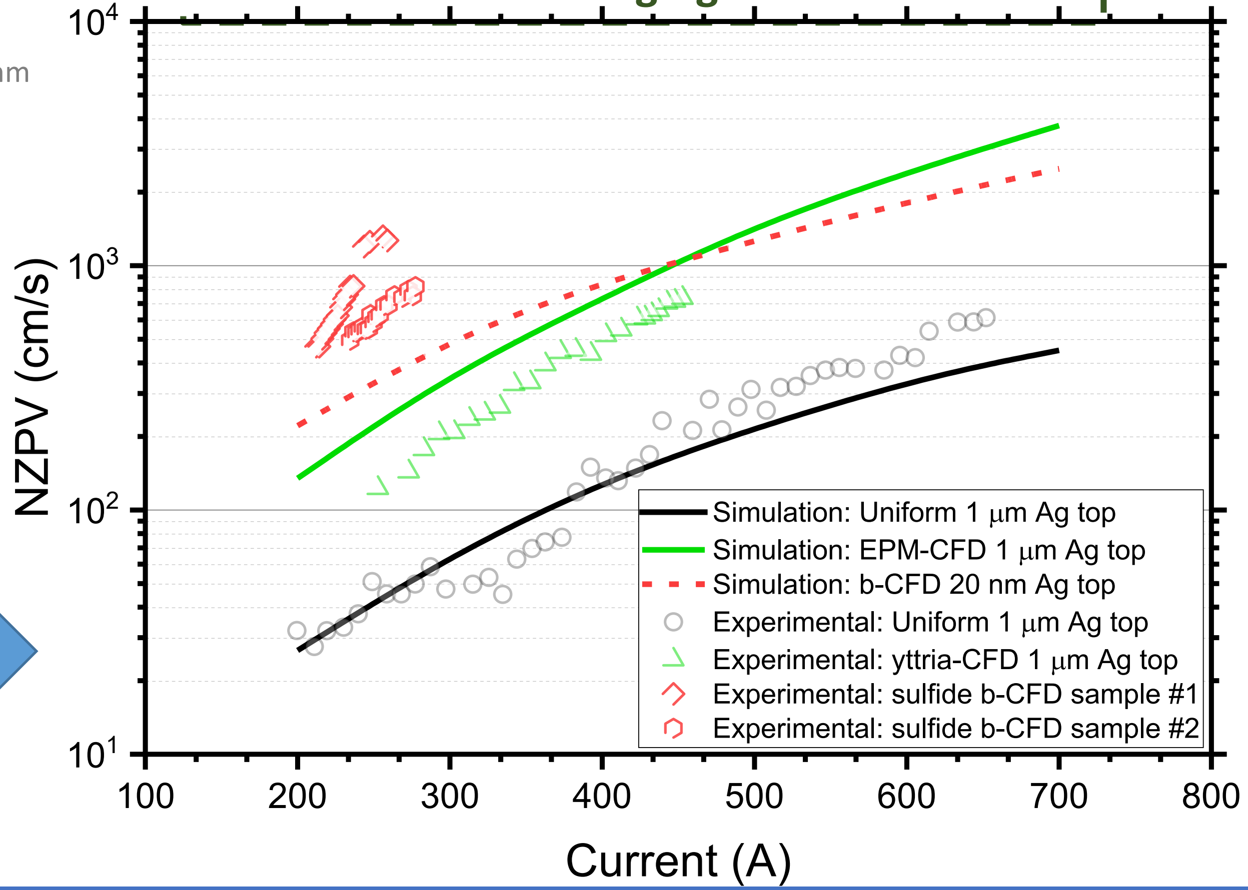

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Conclusions

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3rd-7th September

Technique	Pros	Cons
Local Annealing	• Extremely high NZPV • Ultra simple technique/ no extra machinery required	• Two Extra steps: Pre-oxygenation + Local Annealing • MUST customize the Tape's length
Classic CFD (CFD)	• 5-10x increase in the NZPV • No need to customize the length • Relatively simple implementation	• Two extra steps: Ag etch & Ag re-sputtering • Waste of expensive silver material
CFD-Yttria	• 5-8x increase in the NZPV • Cheap CSD process	• Two extra steps: Pre-oxygenation & Yttria-CSD • MUST Avoid silver diffusion during annealing
CFD-Indium	• 5-8x increase in the NZPV • Compatible with the standard silver-coated CCs	• Two extra steps: In deposition and annealing • Indium is cheaper than Ag but still pricy
bCFD-Sulfide	• Same performance as the bCFD • Cheap Sulfidation process • Compatible with the standard silver-coated CC	• Not yet compatible with a Cu shunt • Requires controlling the gas reaction in an R2R process

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- CNRS / Institut Neel (NEEL)

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- Theva Dünnschichttechnik GmbH

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- SUPERENERTECH (PID2021-127297OB)
- SUPERPOWER (TED 2021)