Combined Modeling of Electromigration, Thermal and Stress Migration in AC Interconnect Lines

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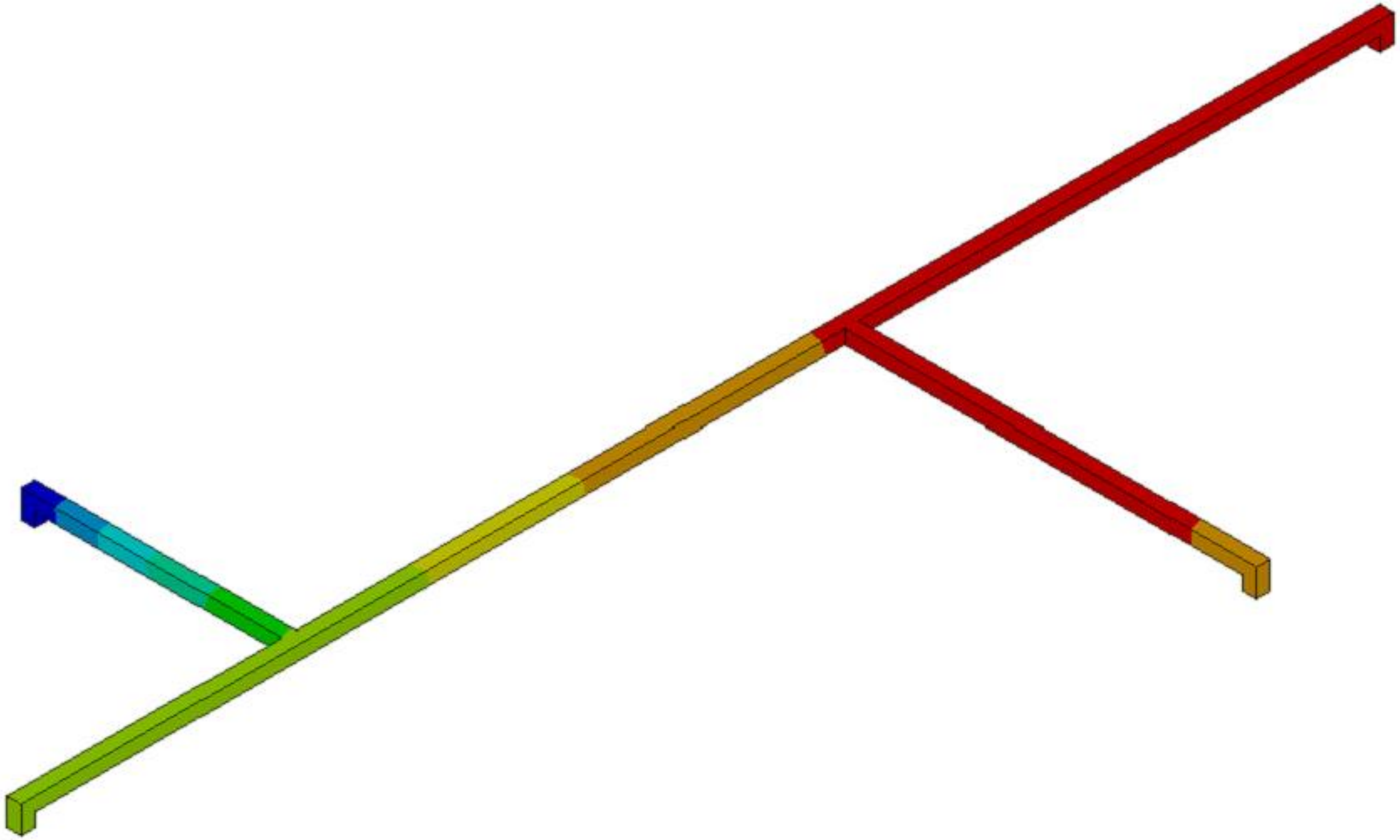
Outline

Introduction
- Motivation
- Basics of EM, TM, and SM
- Migration in AC Nets

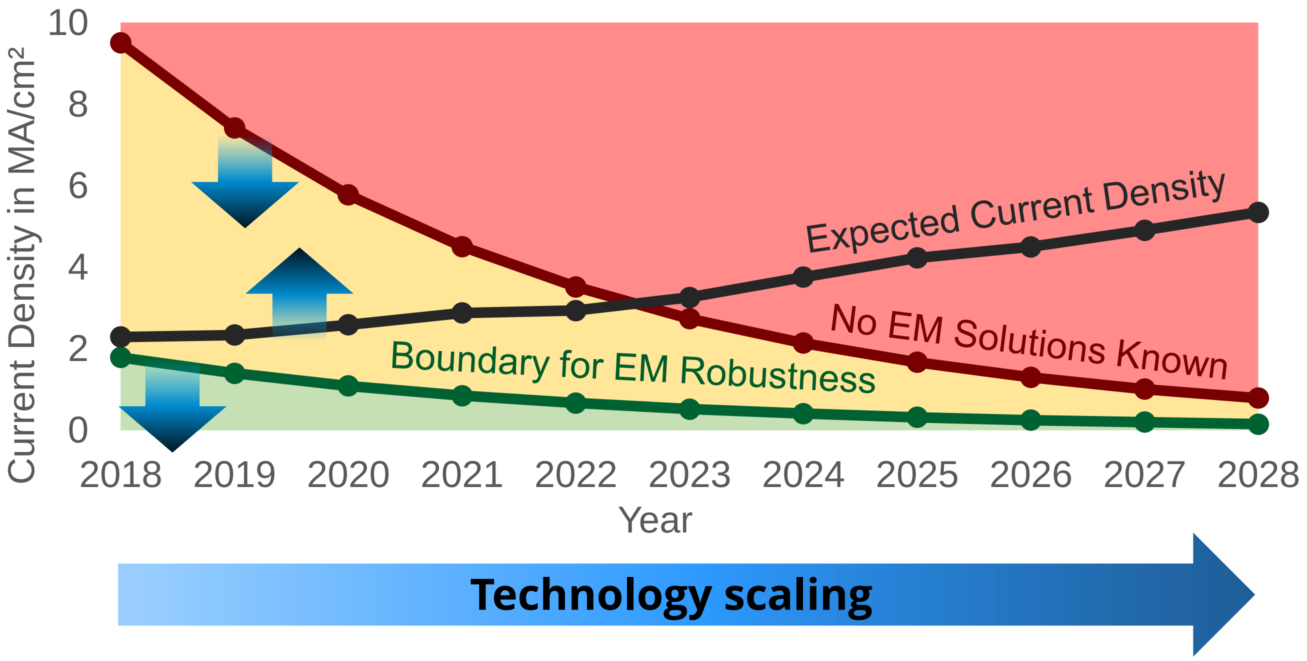
Novel FEM Models
- General Concept
- Results
- Verification
- Outlook

Summary



Motivation

ITRS Roadmap (2015)

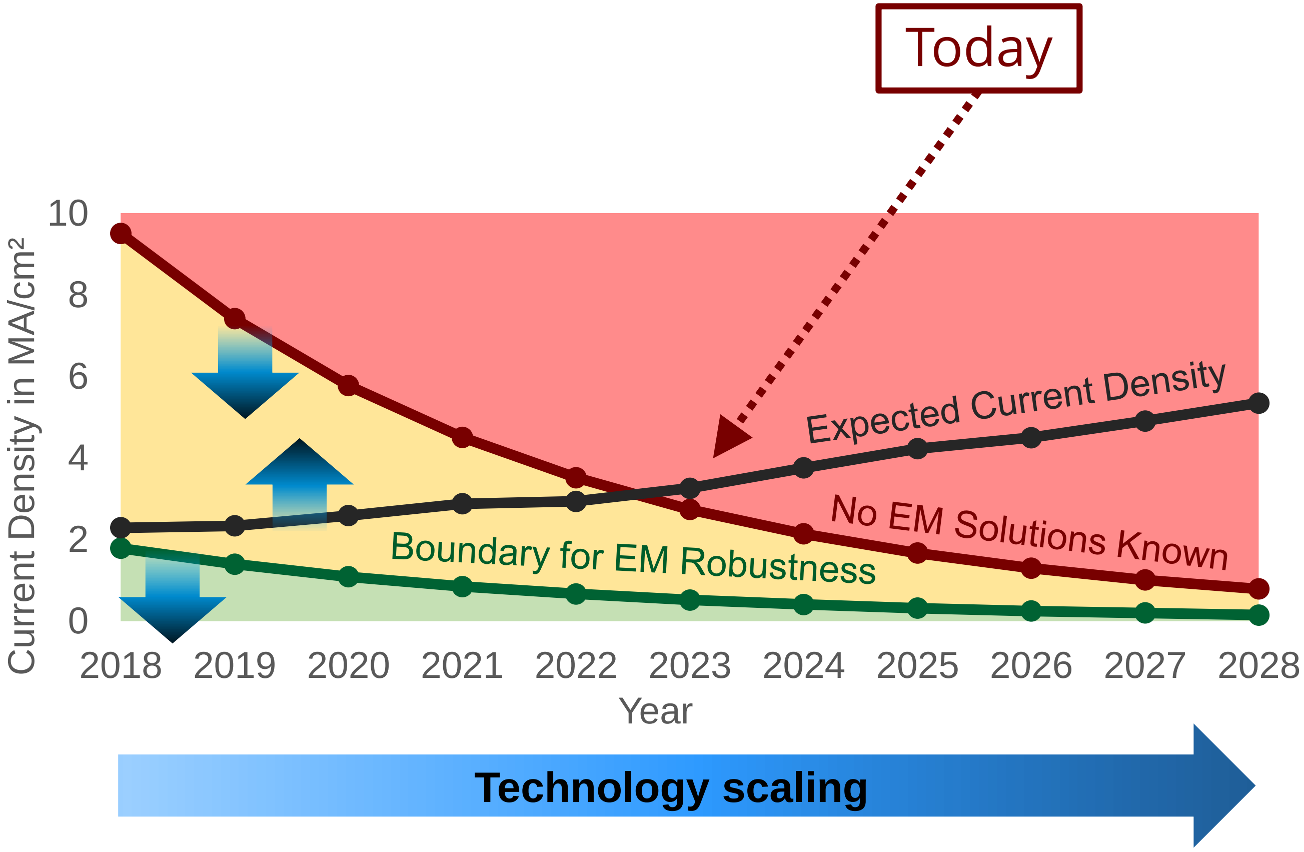


Additional Trends:

- Rising number of nets
- Higher complexity of migration mechanisms:
  - Temperature dependency
  - Interconnect scaling → surface effects
- AC nets are increasingly affected by migration-induced degradation

Motivation

ITRS Roadmap (2015)

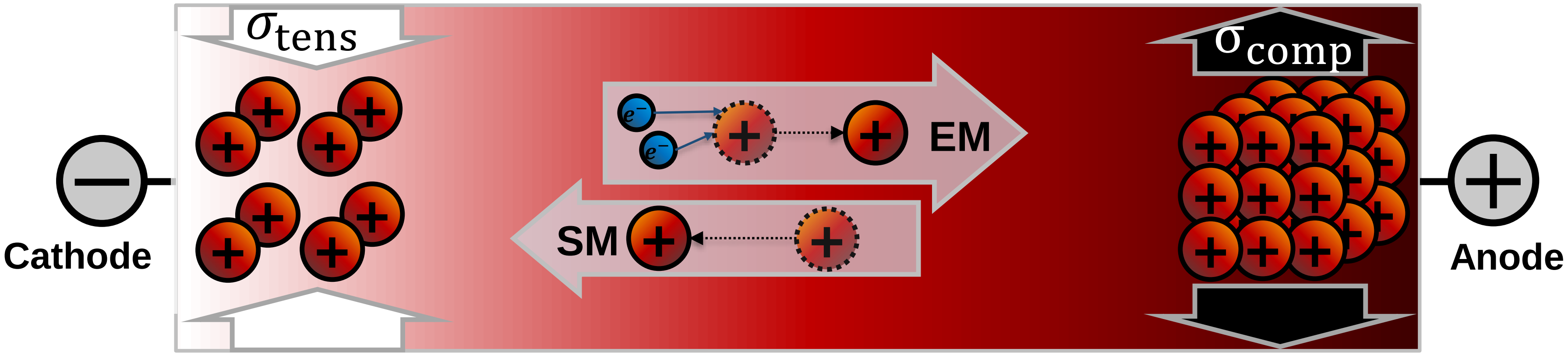


How have these issues been addressed?

- New interconnect materials
- Layout design with EM countermeasures
- Novel (stress-based) migration models → especially for PDNs

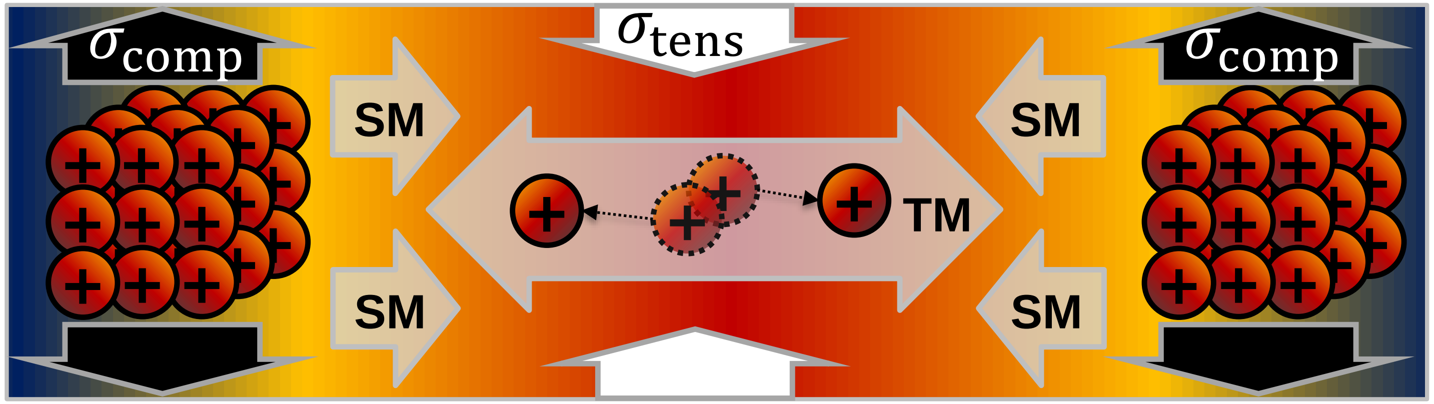
Electromigration

- Atomic motion driven by an electric current
- Cathode: tensile stress (voids)
- Anode: compressive stress (hillocks)
- Counteracting force: stress migration (SM, driven by stress gradients)



Thermal Migration

- Atomic motion driven by temperature gradients due to
  - Joule heating
  - Devices with high power dissipation
- Often neglected compared to EM, but gains significance



Stress Evolution

- Combined EM, TM, and SM cause stress profile within an interconnect
- Stress evolution is described by the Korhonen equation (originally EM and SM, expanded by TM)
- Stress distribution eventually reaches a steady state (for constant current density and temperature profile)
- Minimum/maximum occurring stress: decisive parameters for migration robustness

$$\frac{\partial \sigma}{\partial t} = \frac{\partial}{\partial x}\left[\frac{DB\Omega}{k_{\mathrm{B}}T}\left(\frac{\partial \sigma}{\partial x} - \frac{e\rho Z j}{\Omega} - \frac{Q}{\Omega T}\frac{\partial T}{\partial x}\right)\right]$$

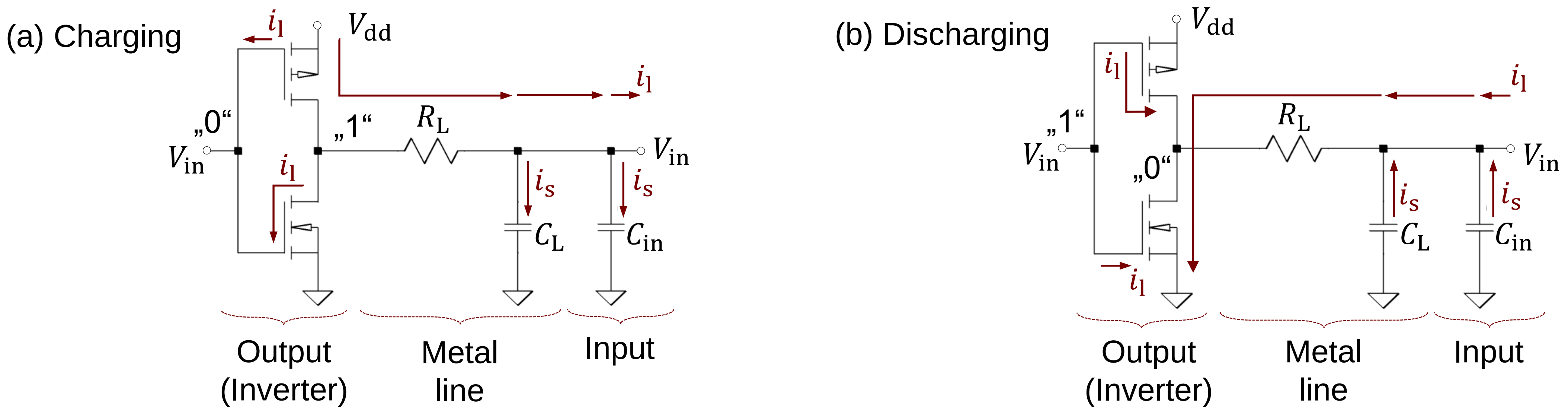
SM **EM** **TM**

Migration in AC Nets

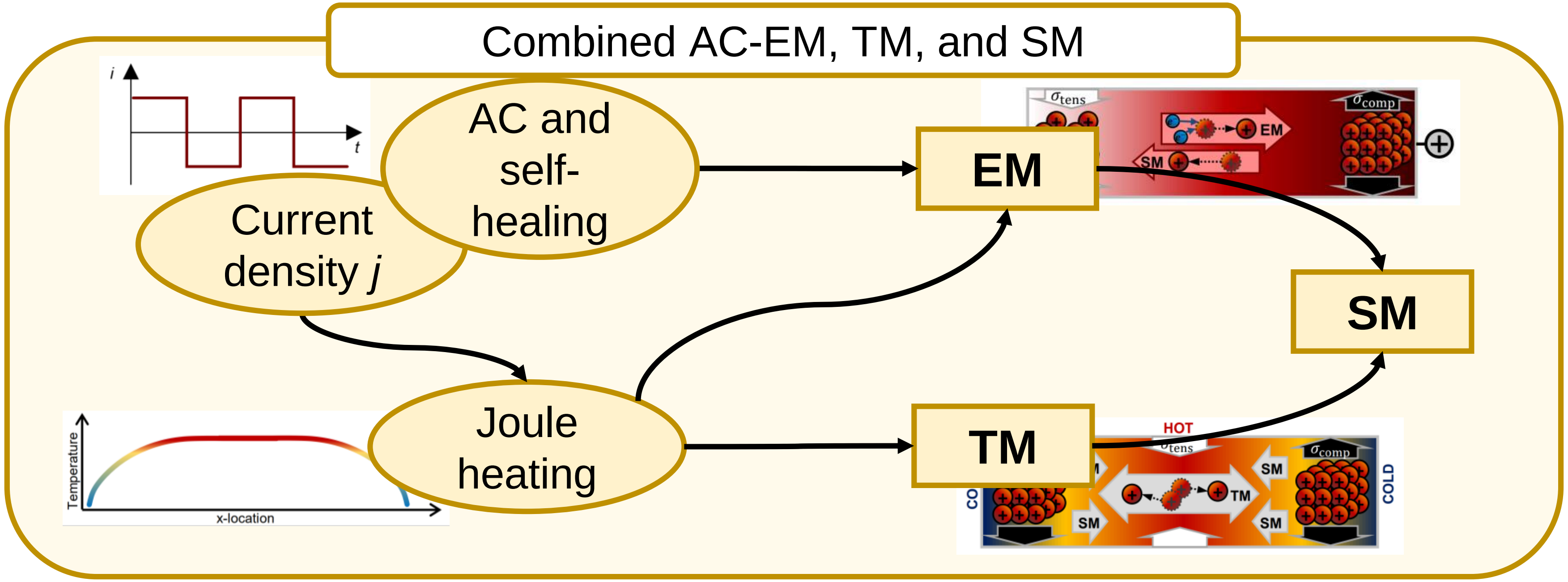
Signal lines are stressed with **alternating currents** due to

- (static) leakage power
- (dynamic) switching power

EM: Effect of self-healing



Migration in AC Nets



- Self-healing is imperfect and can be modeled by a factor *r* (≈0.7-0.9)
- Joule heating and TM are independent from current direction

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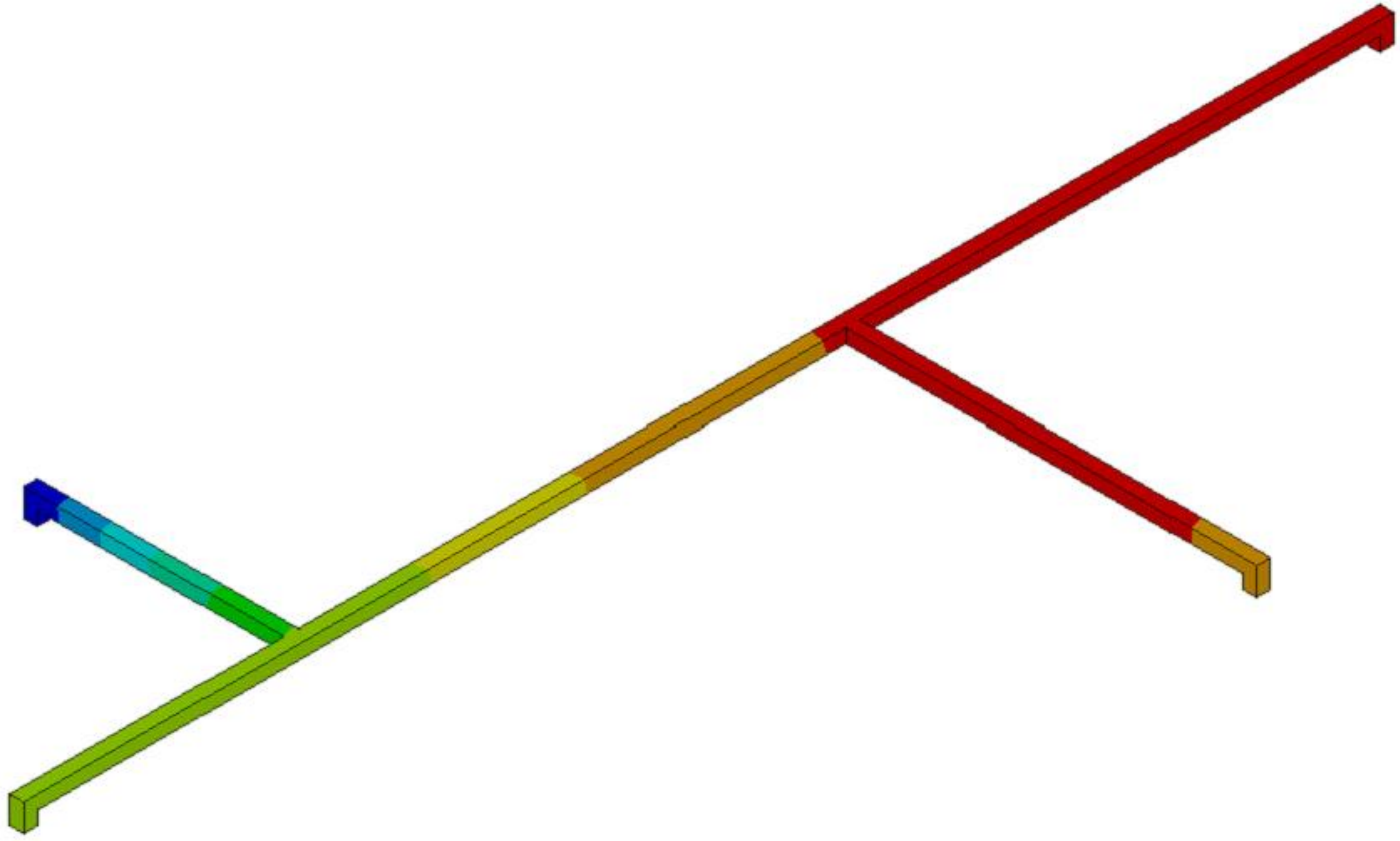
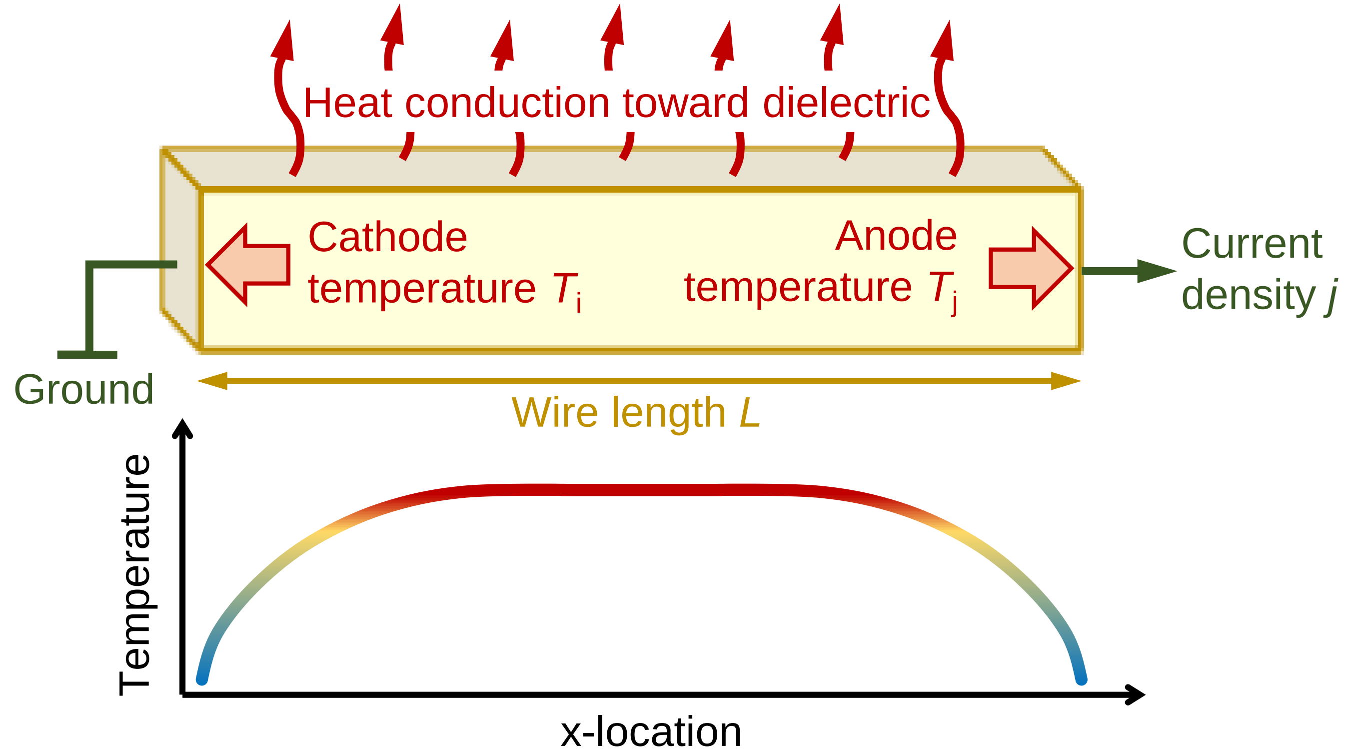
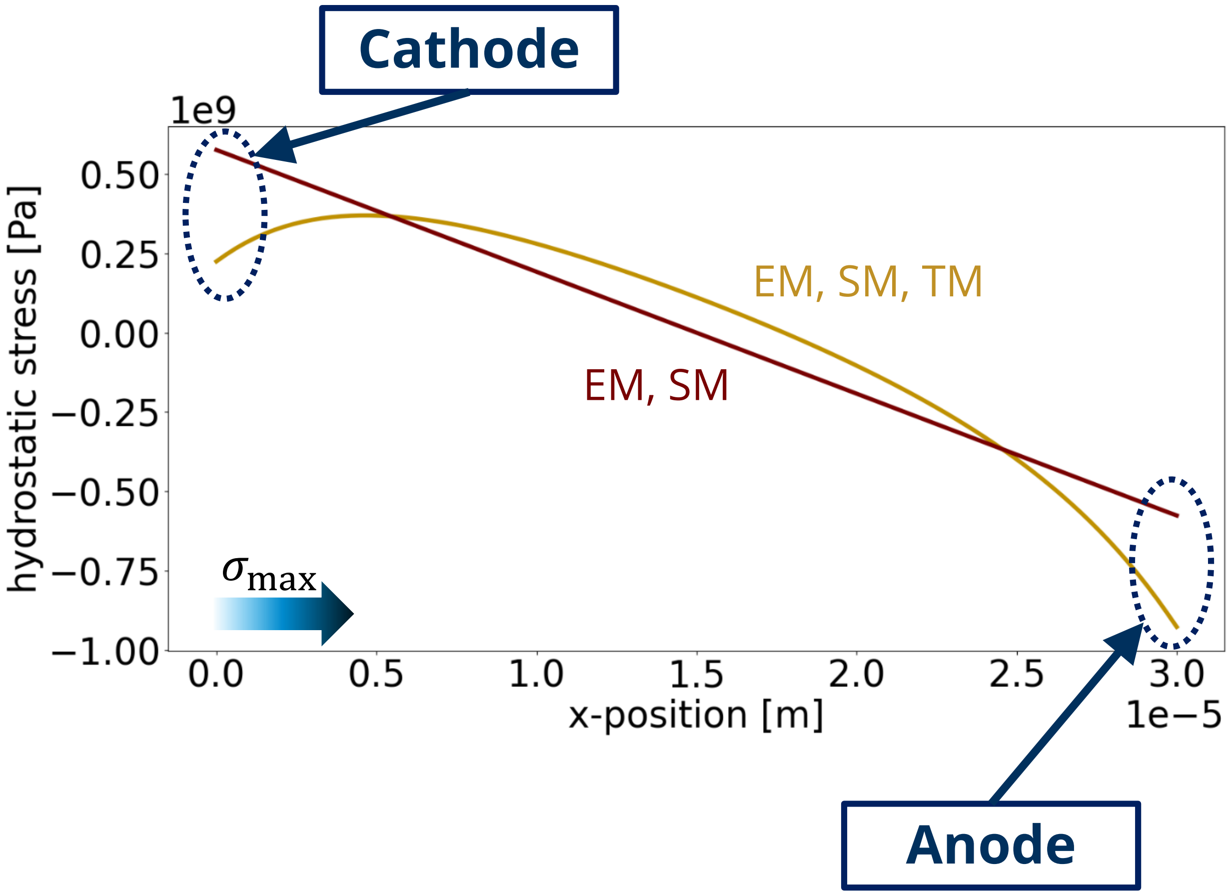


FEM Models: General Concept



- Temperature rise is caused by Joule heating (no external heat sources)
- Self-healing is modeled by reducing the effective charge number Z in the diffusion equation of EM

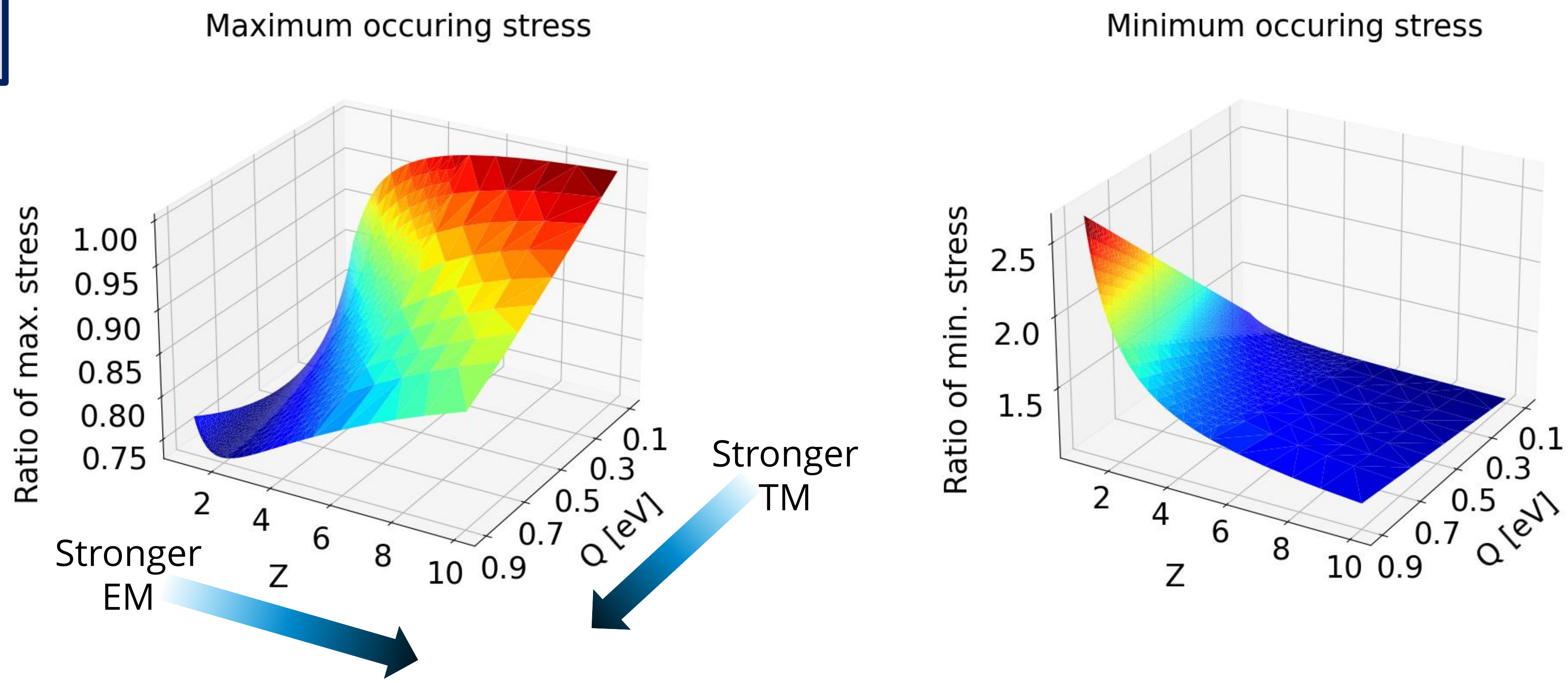
FEM Models: Results



- TM consideration results in non-linear stress profile
- Cathode: reduced tensile stress
- Anode: increased compressive stress
- Stress maximum is not located at the cathode, but shifted toward the middle of the wire

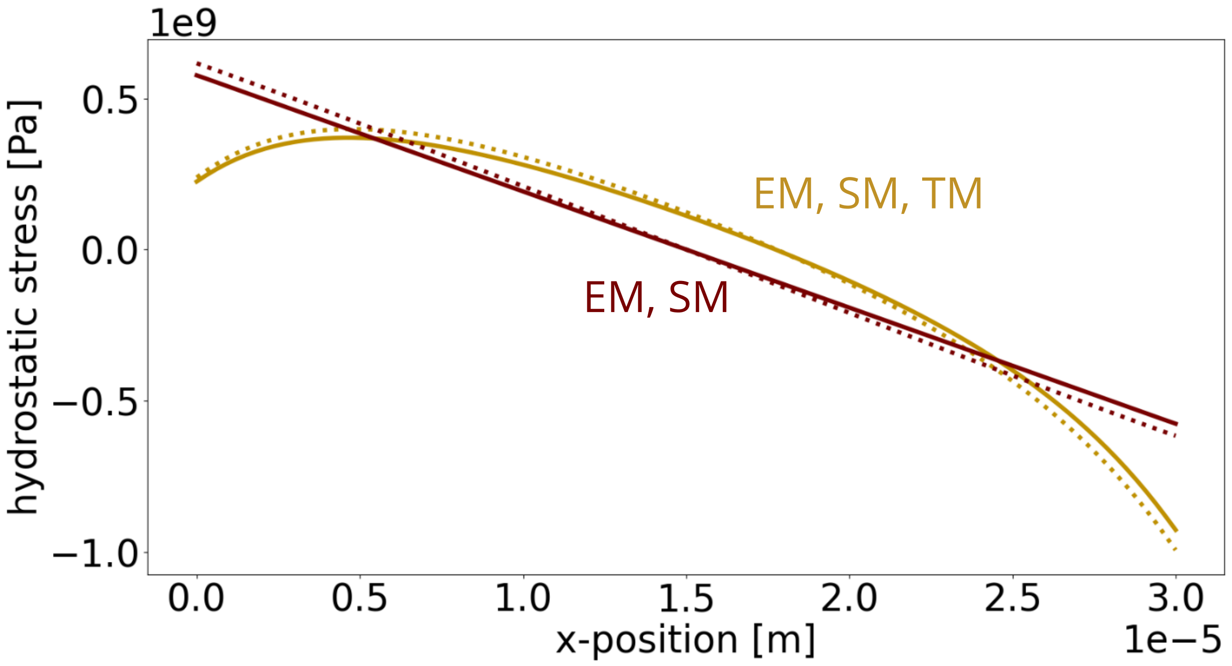
FEM Models: Results

Ratio of TM/EM

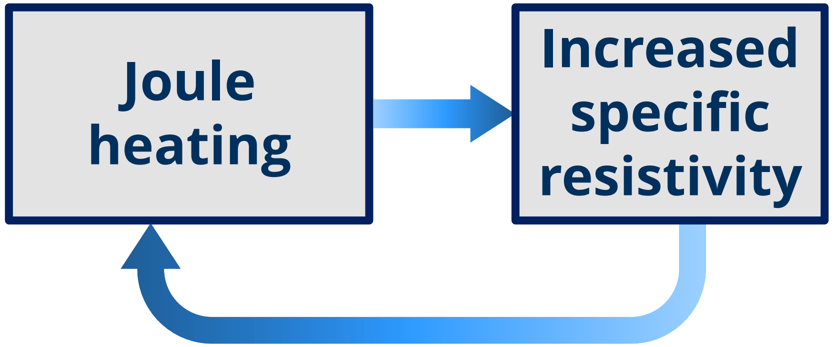


- Impact of TM varies depending on the values of Z (effective charge number) and Q (heat of transport)

FEM Models: Results

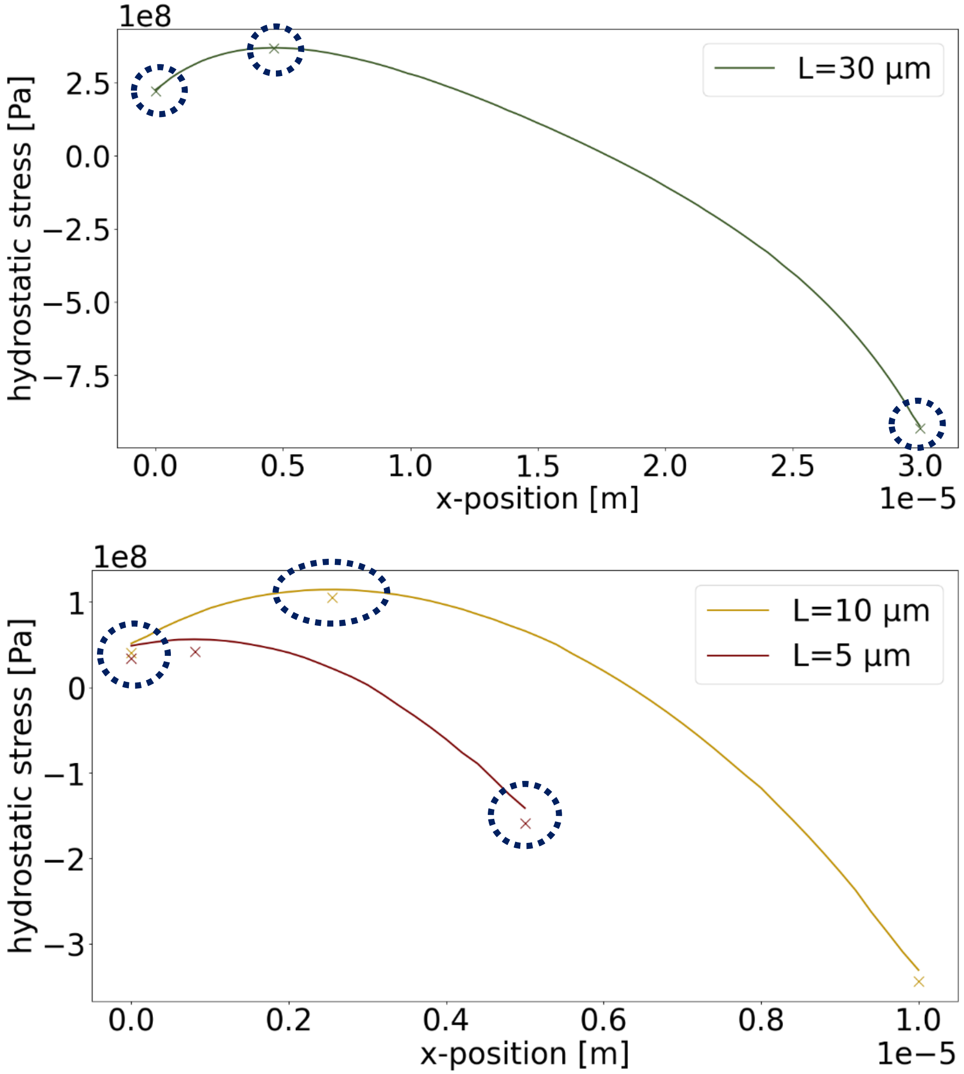


- Dotted lines: stress profile with consideration of temperature-dependent resistivity



- Impact is dependent from material parameters
- Always increases stress

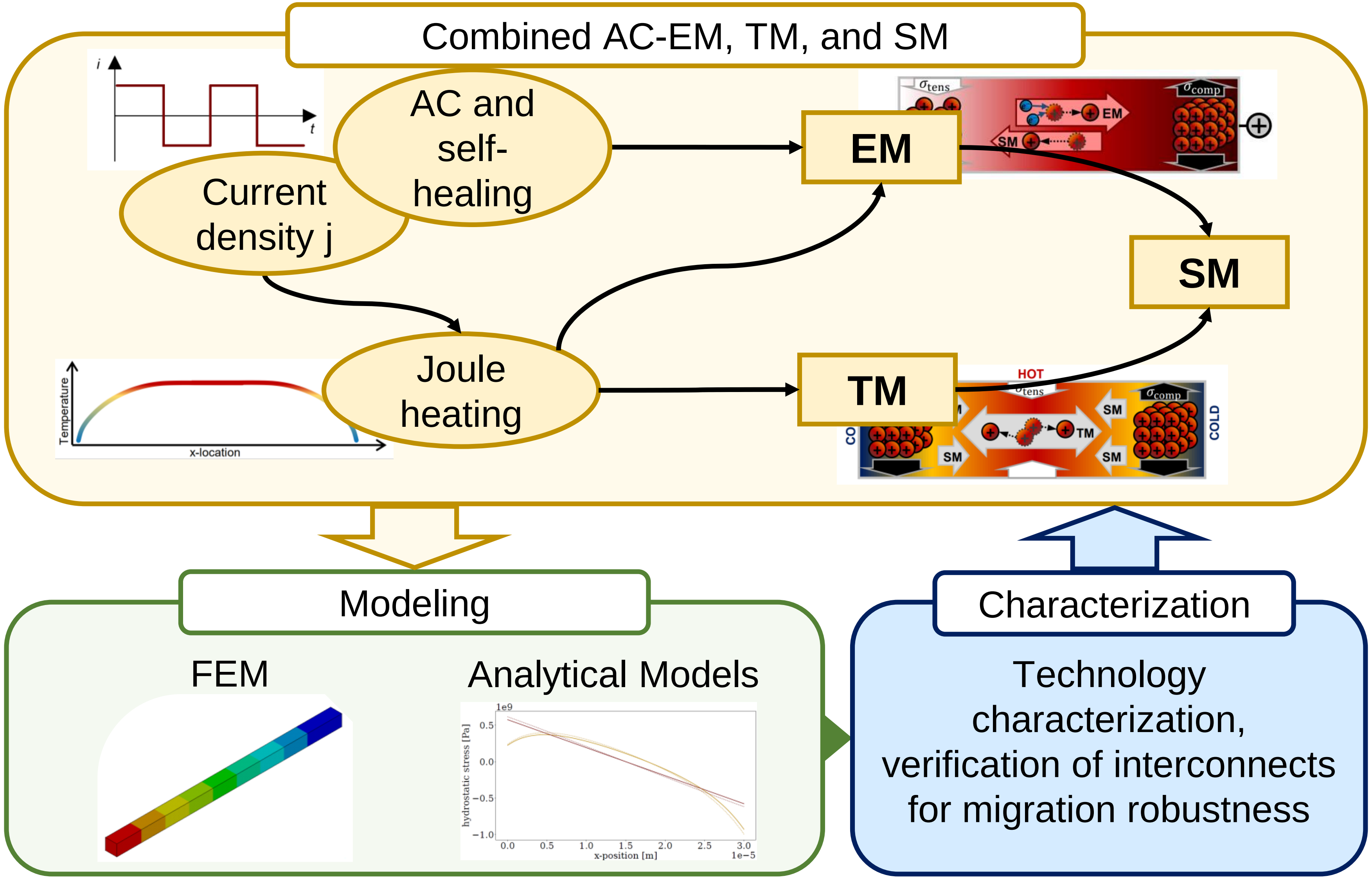
FEM Models: Verification



Comparison with analytical models by Chen (2020)

- Good agreement for long wires
- Relative error gets bigger for shorter wires due to simplifications made in the analytical models
  - Tensile stress is underestimated
  - Compressive stress is overestimated
- New equation for location of stress maximum derived
  - Precise results for short wires (stress is still underestimated)

FEM Models: Outlook



FEM Models: Outlook

More precise modeling will require experimental validation

- FEM models can act as design guidelines
- Material parameters need to by specified by technology characterization
- Temperature profile of wires within a realistic chip context needs to be obtained

AC nets need to be designed in a migration-robust manner

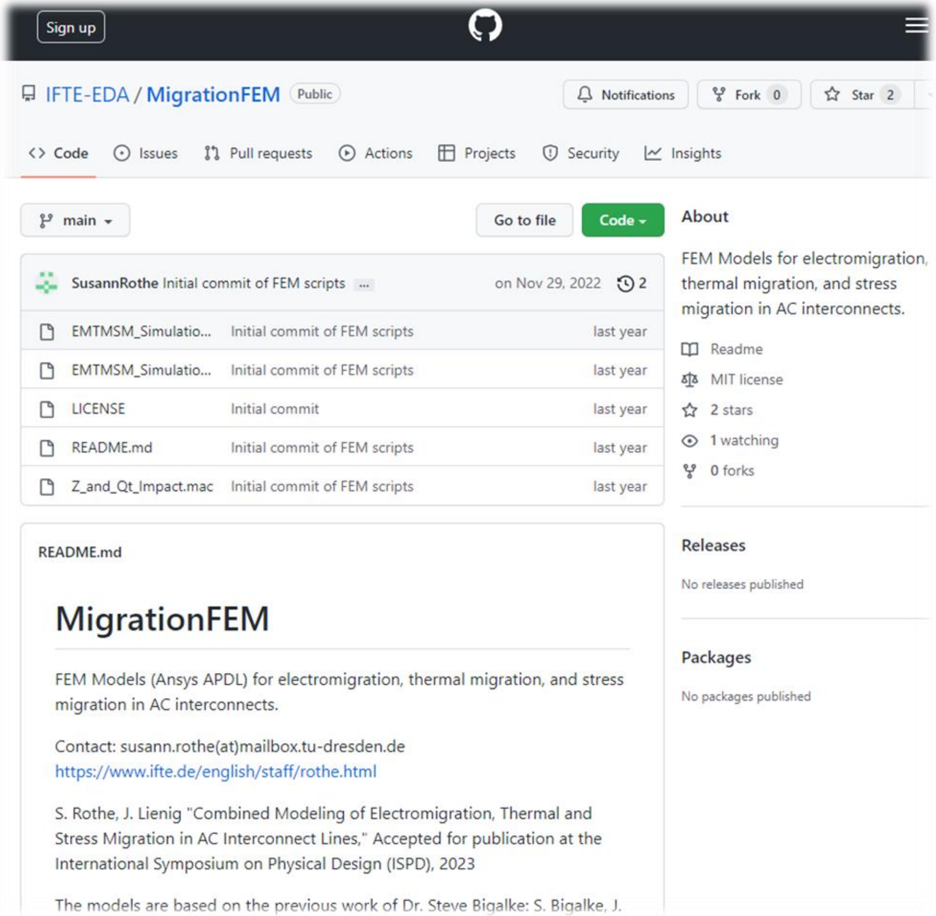
- Full-chip FEM verification will be too time-consuming
- FEM models can be used to derive routing constraints and migration-inhibiting measures

Summary

In this work, we developed:

- FEM models (Ansys® APDL) available on GitHub
  - Simulation of straight wires and more complex interconnect structures
  - Analysis of the impact of material parameters and temperature on AC-EM and TM

- An analytical model to
  - Find location of stress maximum
  - Calculate temperature along a wire considering temperature-dependent resistivity



https://github.com/IFTE-EDA/MigrationFEM

Thank you for your attention!

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FEM models available on https://github.com/IFTE-EDA/MigrationFEM