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

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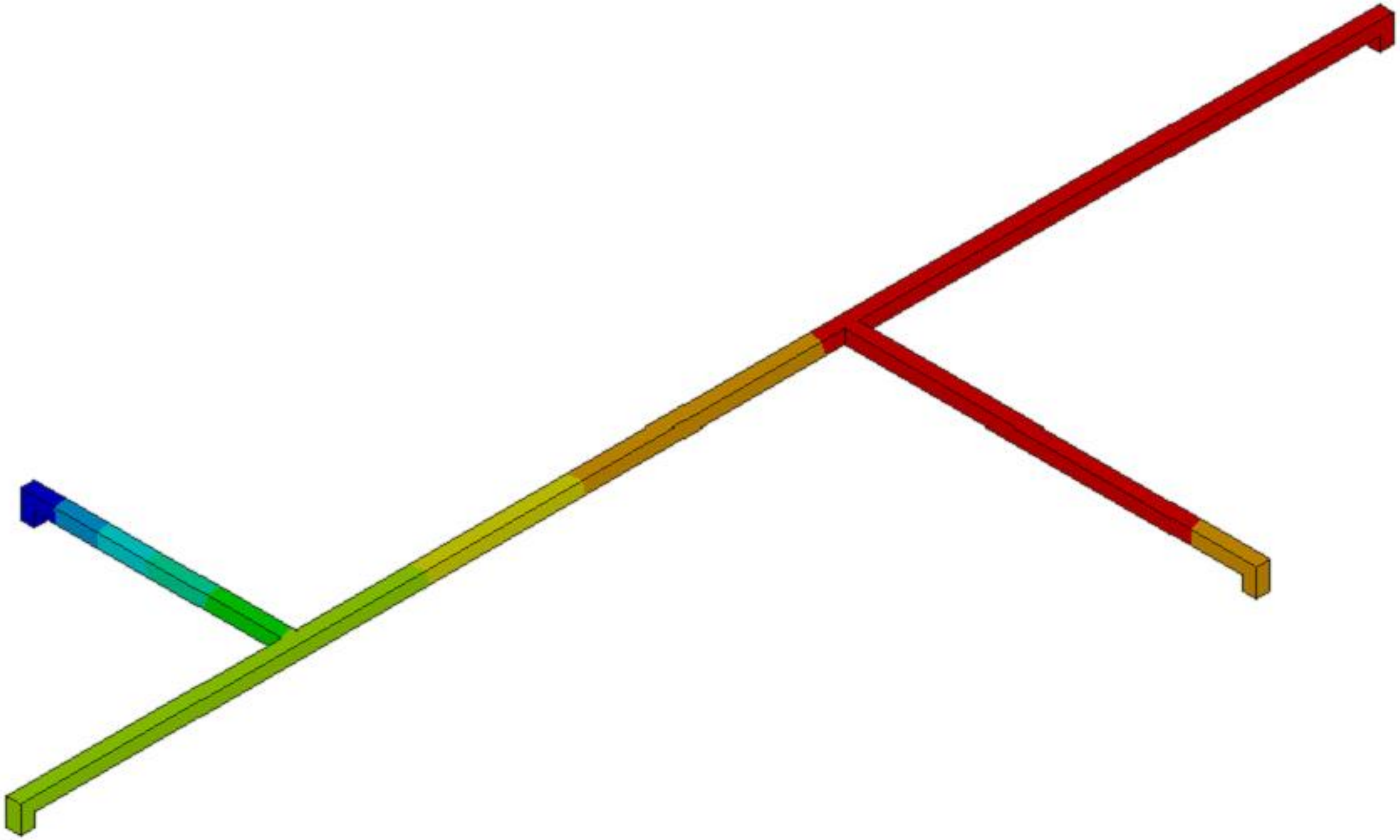
Outline



Introduction

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

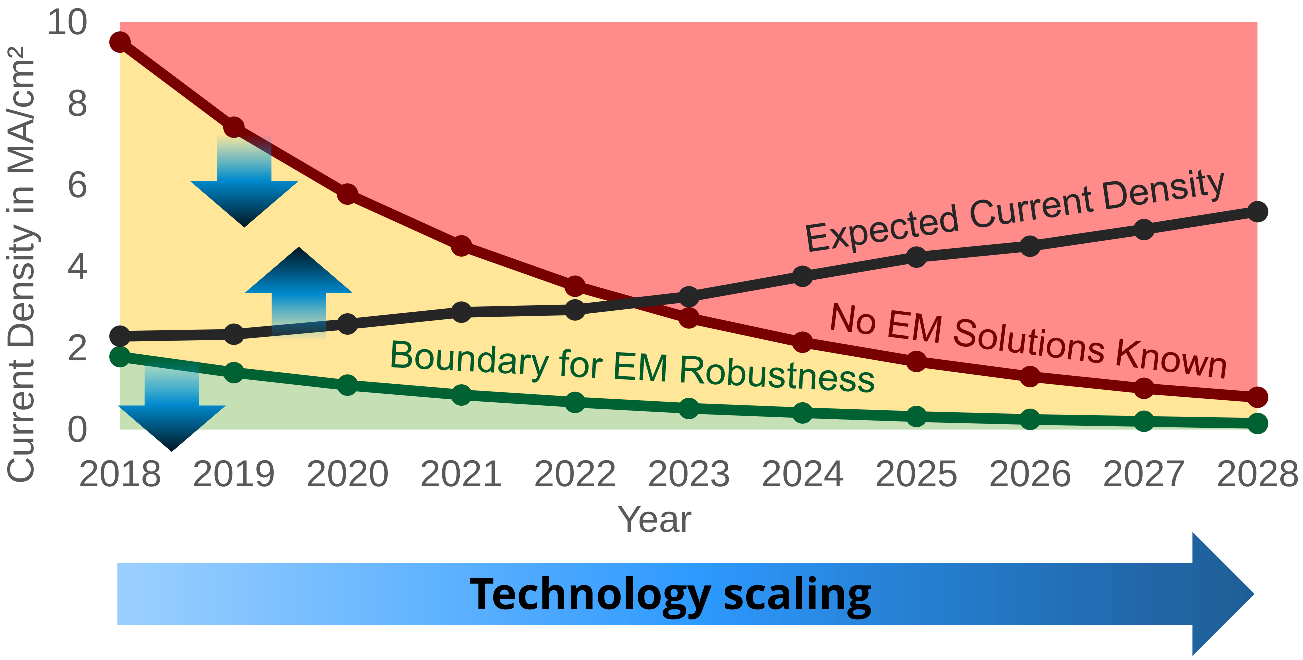
Novel FEM Models

- General Concept
- Results
- Verification
- Outlook

Summary

Motivation

ITRS Roadmap (2015)

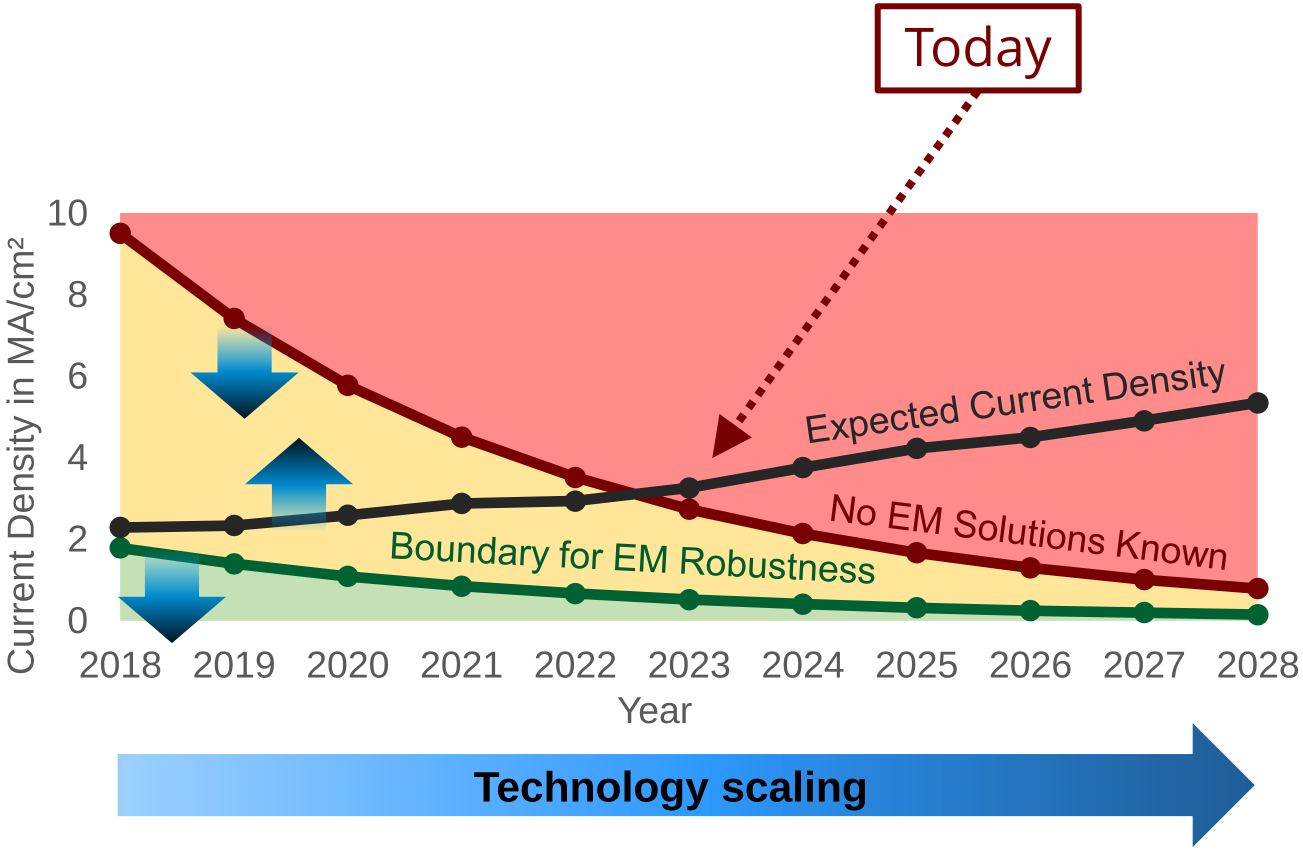


Additional Trends:

- 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)

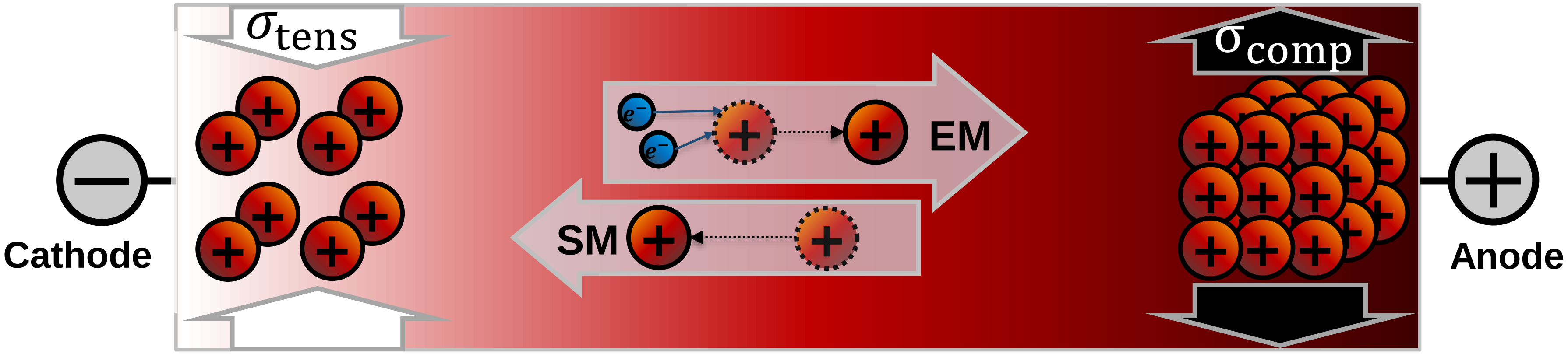


How have these issues been addressed?

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

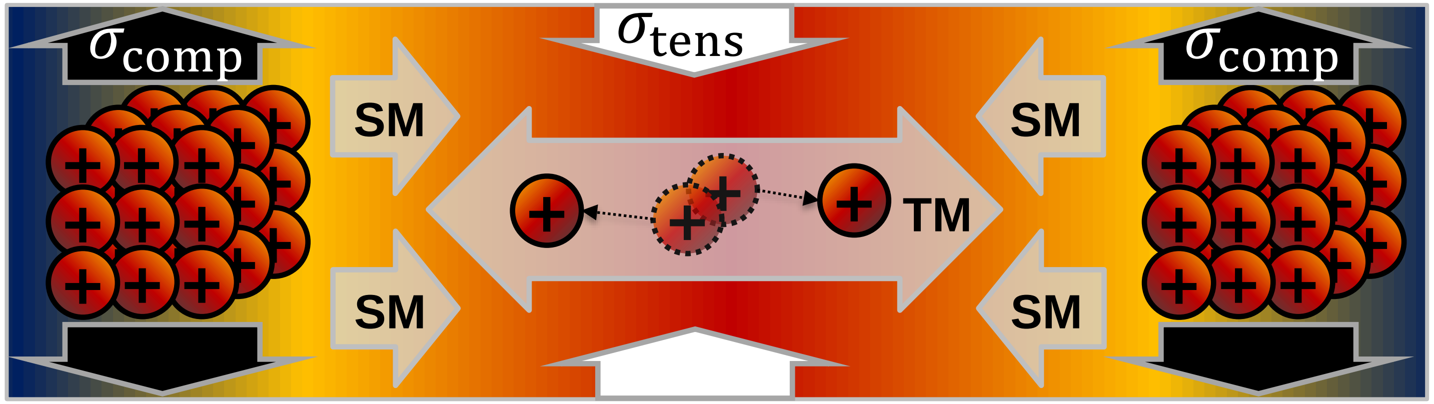
Electromigration

- 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

$$\frac{\partial \sigma}{\partial t} = \frac{\partial}{\partial x}\left[\frac{DB\Omega}{k_{\mathrm{B}}T}\left(\underbrace{\frac{\partial \sigma}{\partial x}}_{\textbf{SM}} + \underbrace{\frac{e\rho Z j}{\Omega}}_{\textbf{EM}} + \underbrace{\frac{Q}{\Omega T}\frac{\partial T}{\partial x}}_{\textbf{TM}}\right)\right]$$

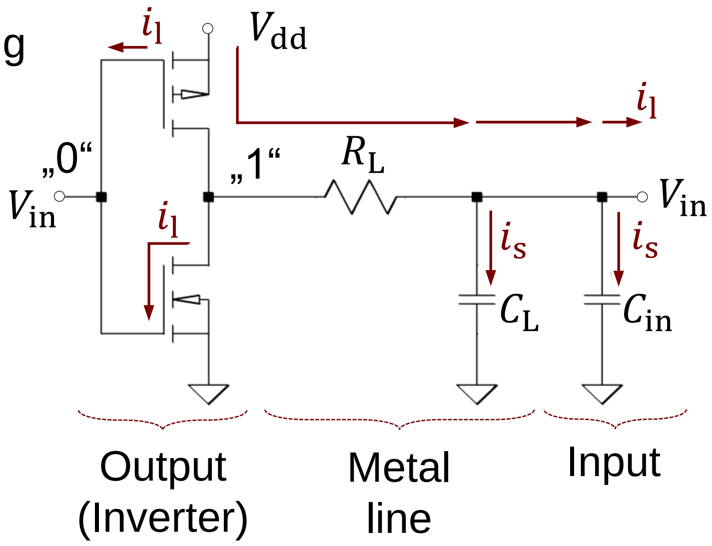
Migration in AC Nets

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

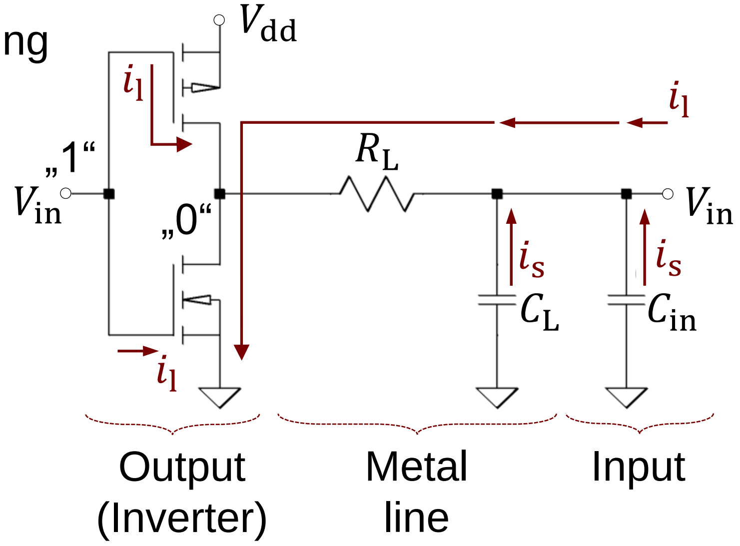
- (static) leakage power
- (dynamic) switching power

EM: Effect of self-healing

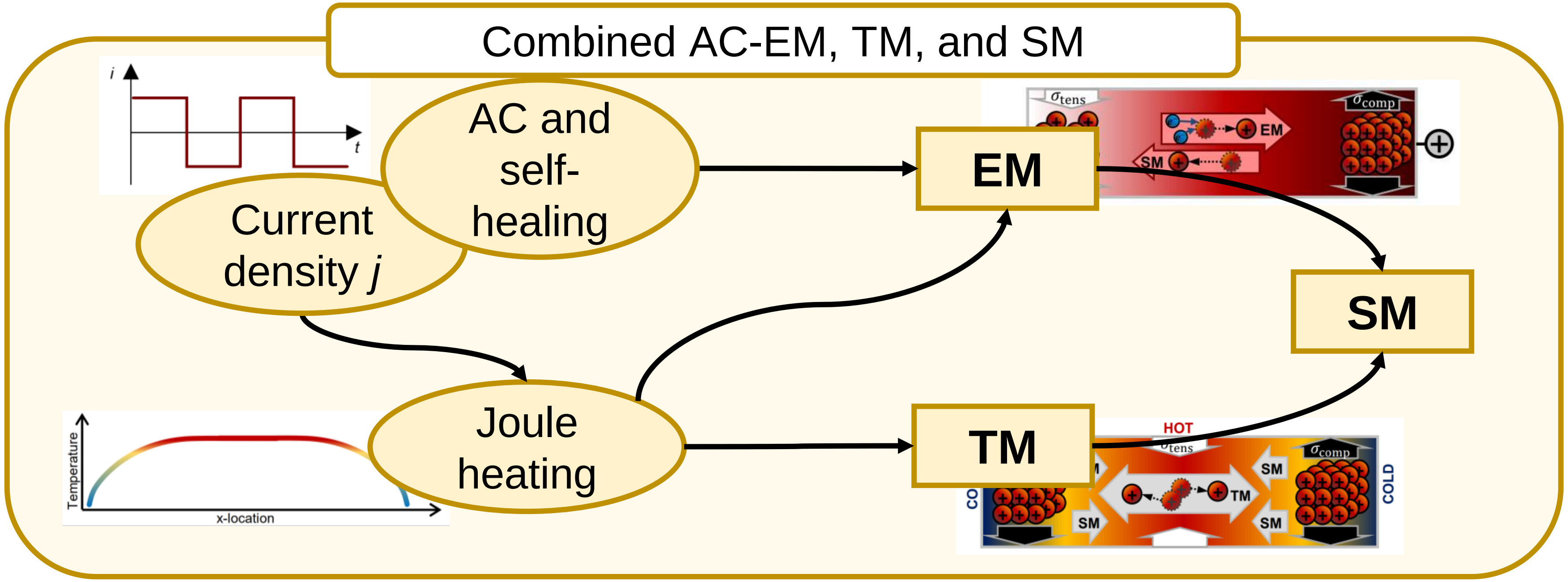
(a) Charging



(b) Discharging



Migration in AC Nets



Combined AC-EM, TM, and SM

AC and self-healing

Current density *j*

Joule heating

EM

SM

TM

- 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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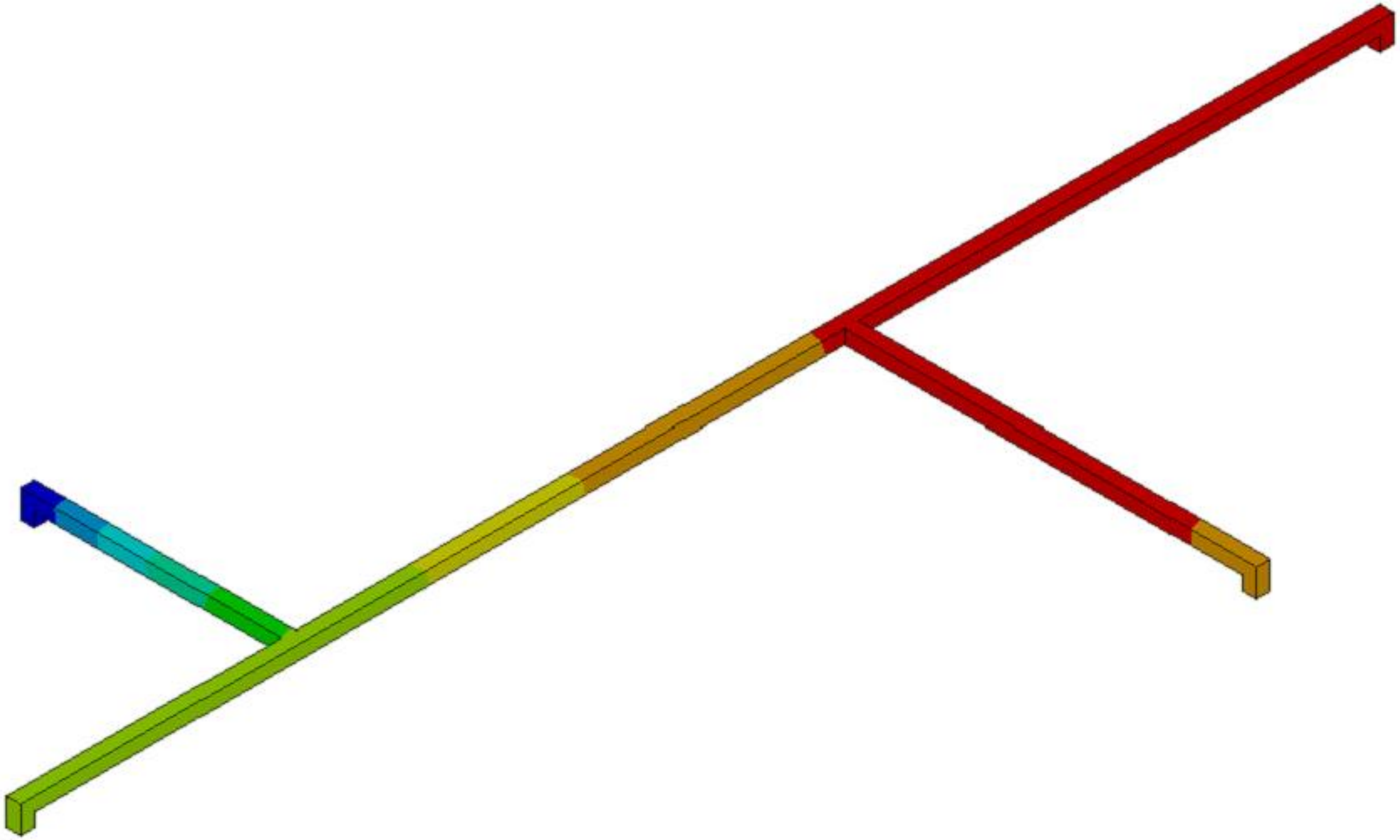
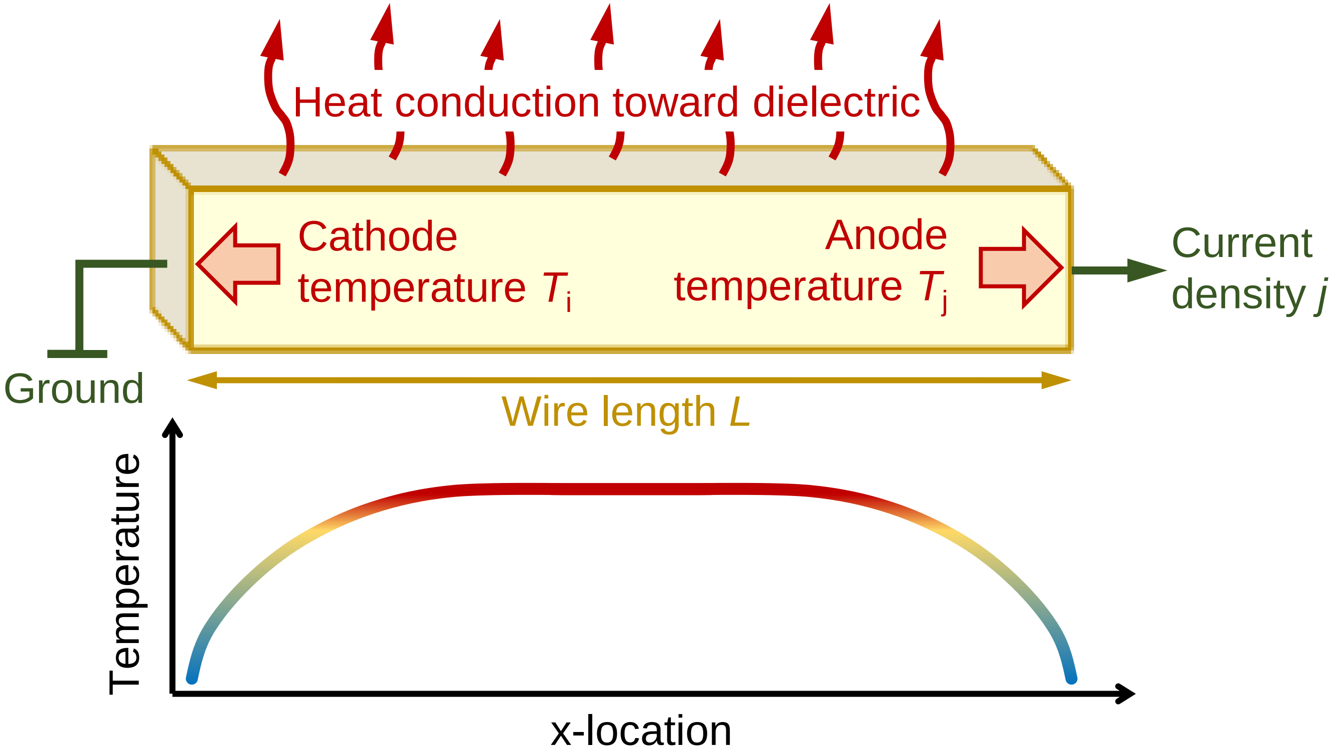
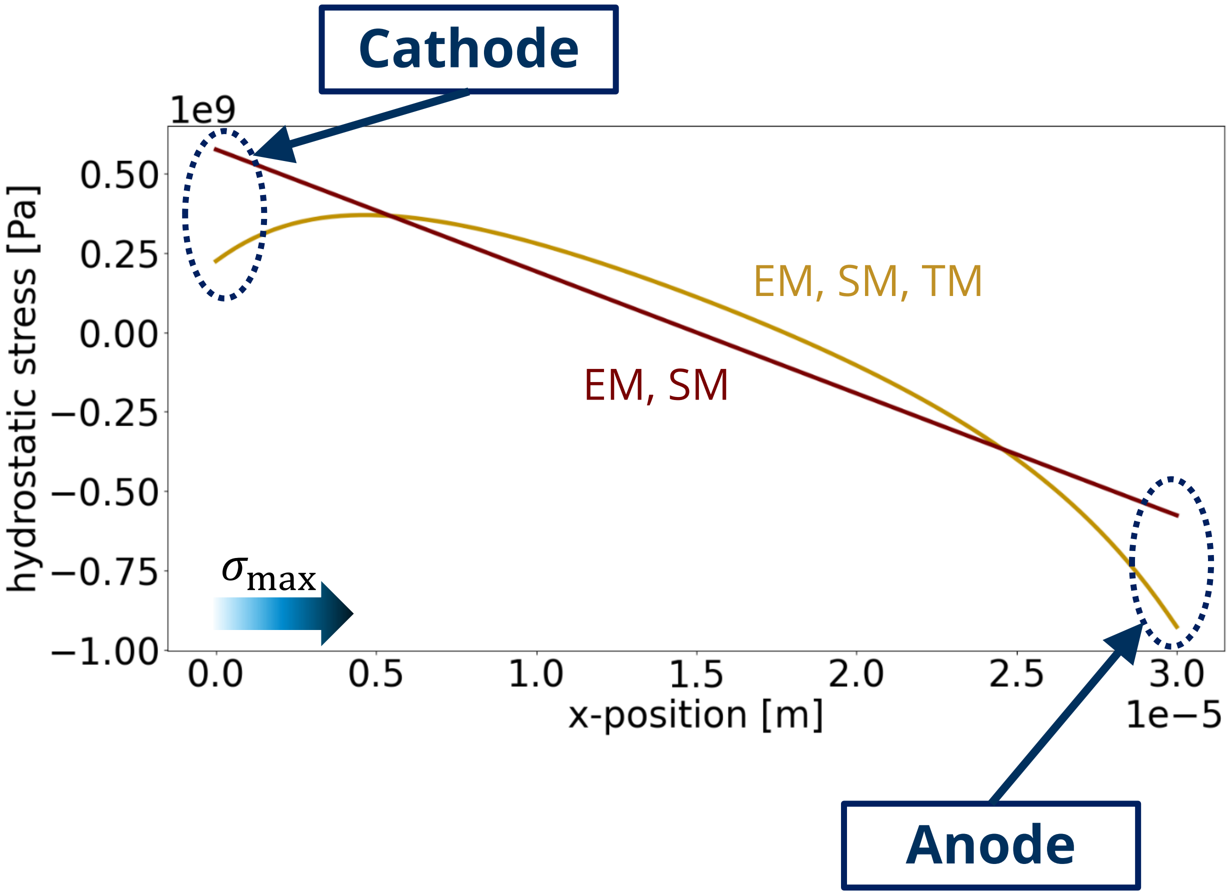


FEM Models: General Concept



- 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

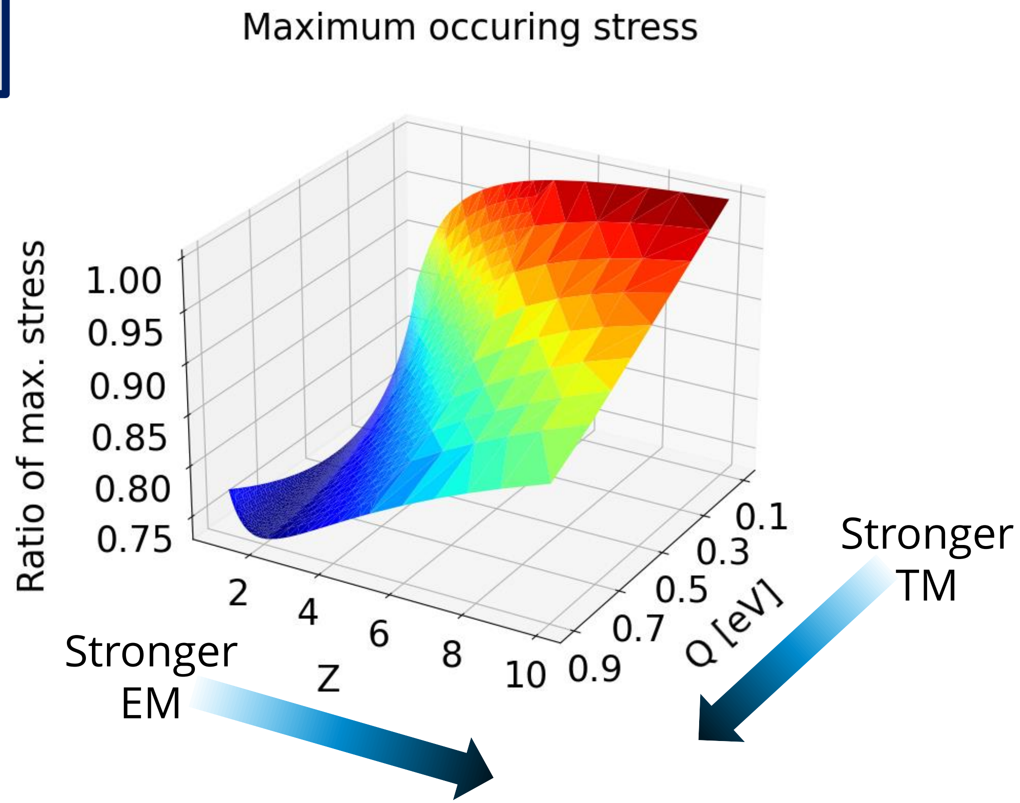
FEM Models: Results

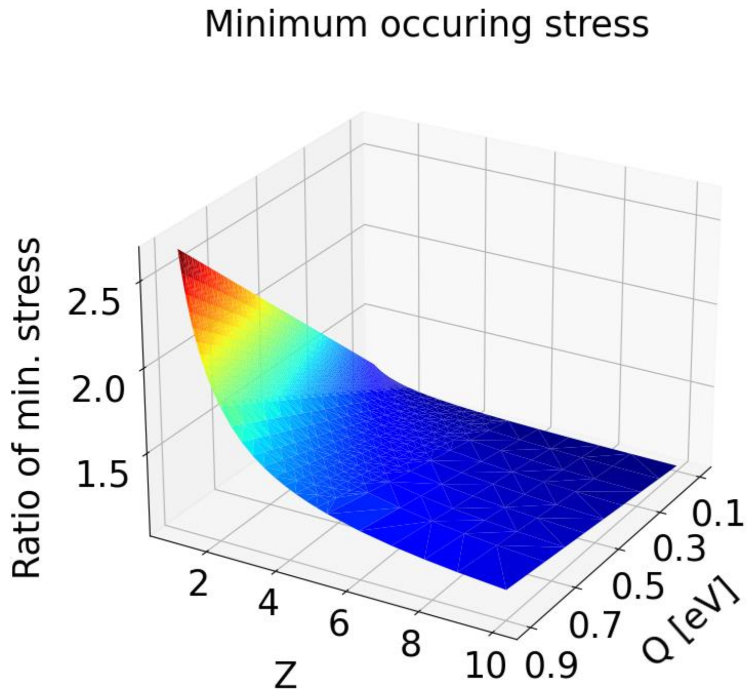


- TM consideration results in non-linear stress profile
- Cathode: reduced tensile stress
- Anode: increased compressive stress
- Stress maximum is not located at the cathode, but shifted toward the middle of the wire

FEM Models: Results

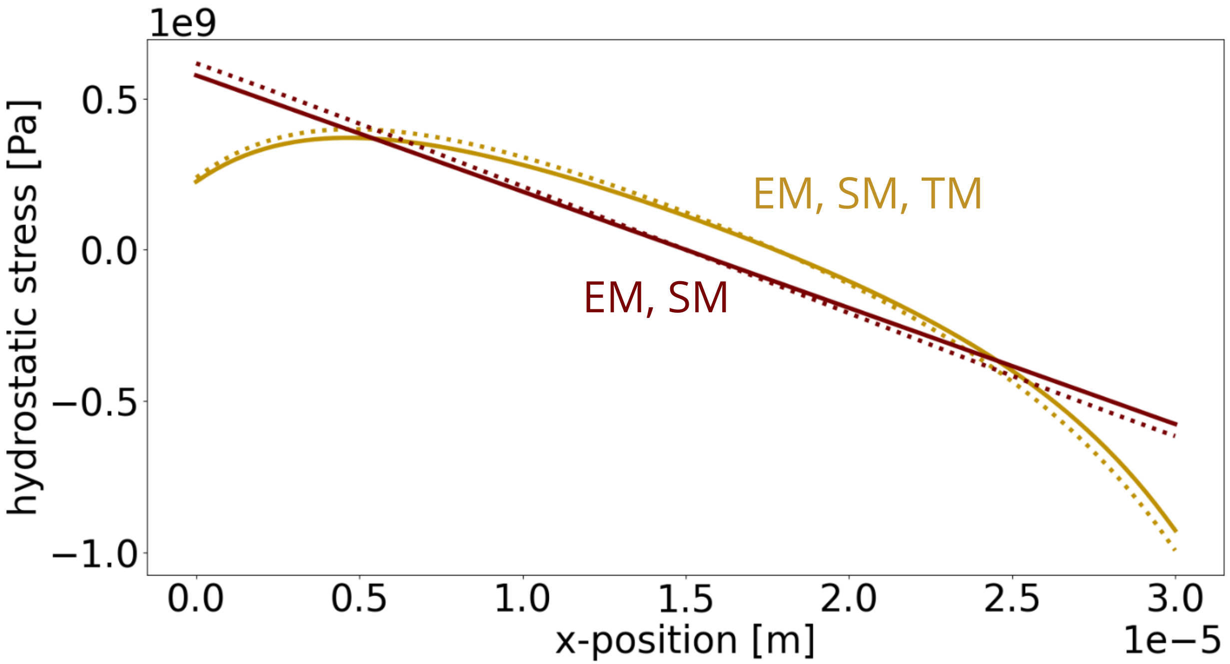
Ratio of TM/EM



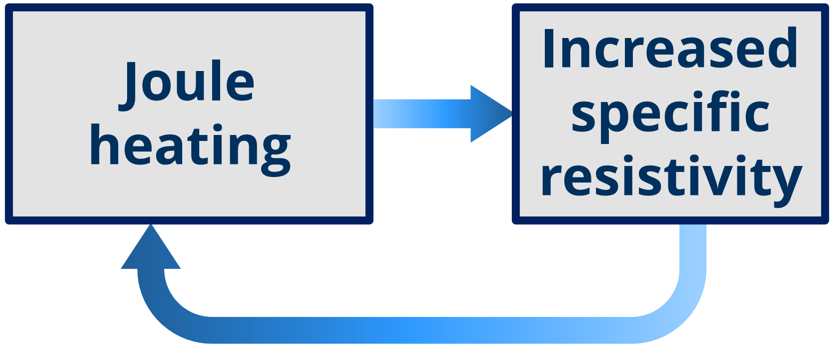


- Impact of TM varies depending on the values of Z (effective charge number) and Q (heat of transport)

FEM Models: Results



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

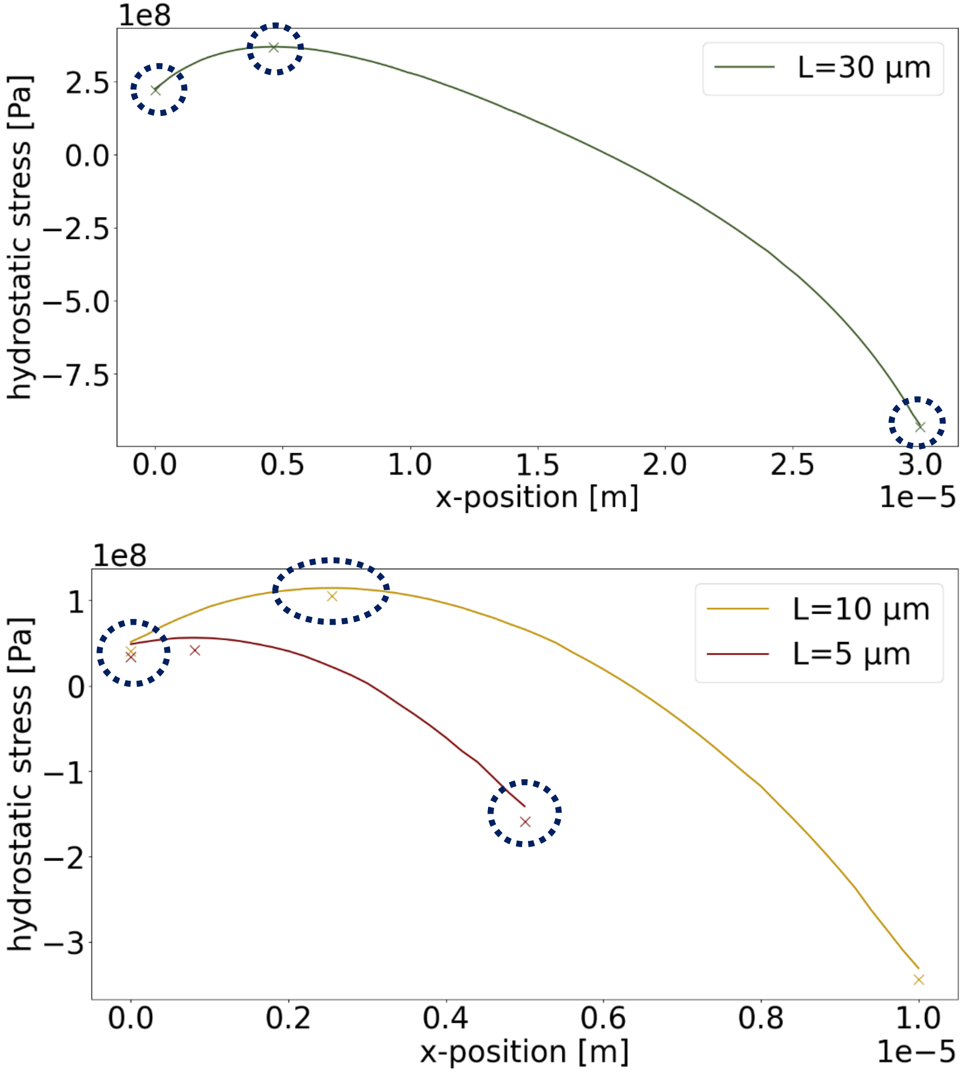


Joule heating

Increased specific resistivity

- Impact is dependent from material parameters
- Always increases stress

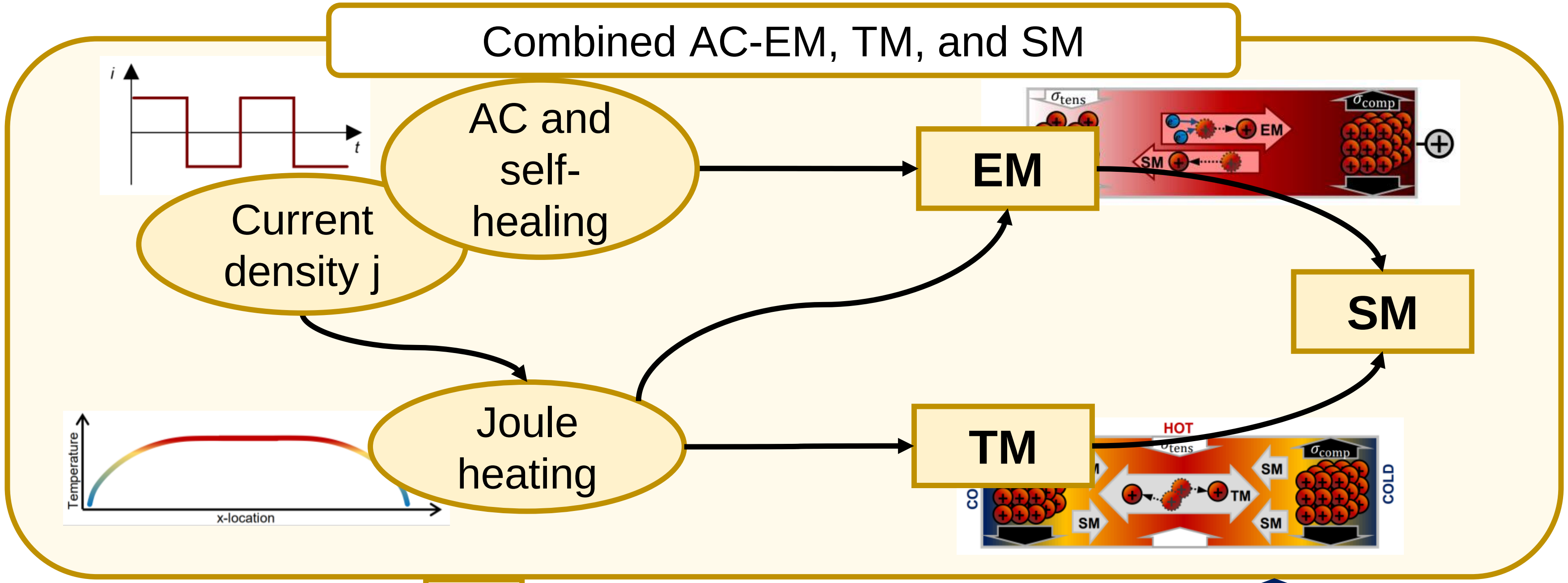
FEM Models: Verification



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



Combined AC-EM, TM, and SM

Current density j

AC and self-healing

Joule heating

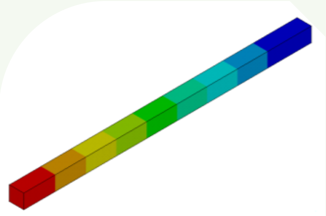
EM

TM

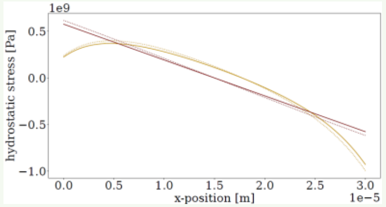
SM

Modeling

FEM



Analytical Models



Characterization

Technology characterization, verification of interconnects for migration robustness

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

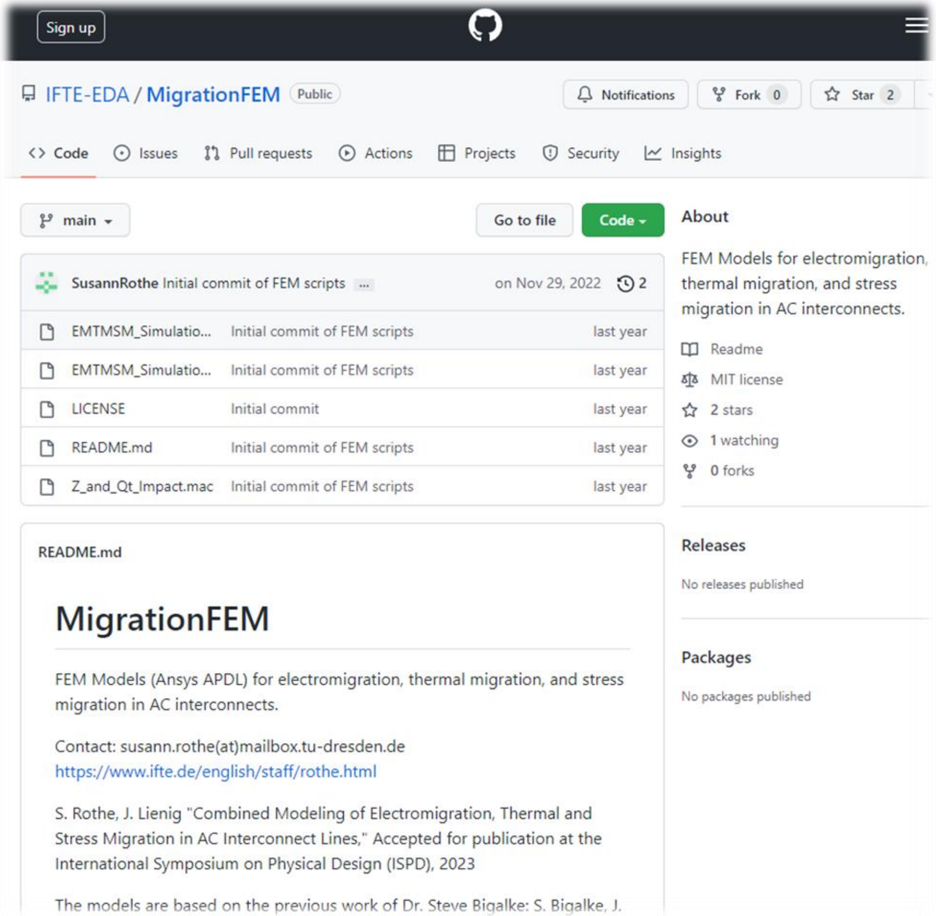
- Full-chip FEM verification will be too time-consuming
- FEM models can be used to derive routing constraints and migration-inhibiting measures

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



SusannRothe Initial commit of FEM scripts ... on Nov 29, 2022 2

EMTMSM_Simulatio...	Initial commit of FEM scripts	last year
EMTMSM_Simulatio...	Initial commit of FEM scripts	last year
LICENSE	Initial commit	last year
README.md	Initial commit of FEM scripts	last year
Z_and_Qt_Impact.mac	Initial commit of FEM scripts	last year

FEM Models for electromigration, thermal migration, and stress migration in AC interconnects.

MigrationFEM

FEM Models (Ansys APDL) for electromigration, thermal migration, and stress migration in AC interconnects.

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The models are based on the previous work of Dr. Steve Bigalke: S. Bigalke, J.

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

Thank you for your attention!

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www.ifte.de

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