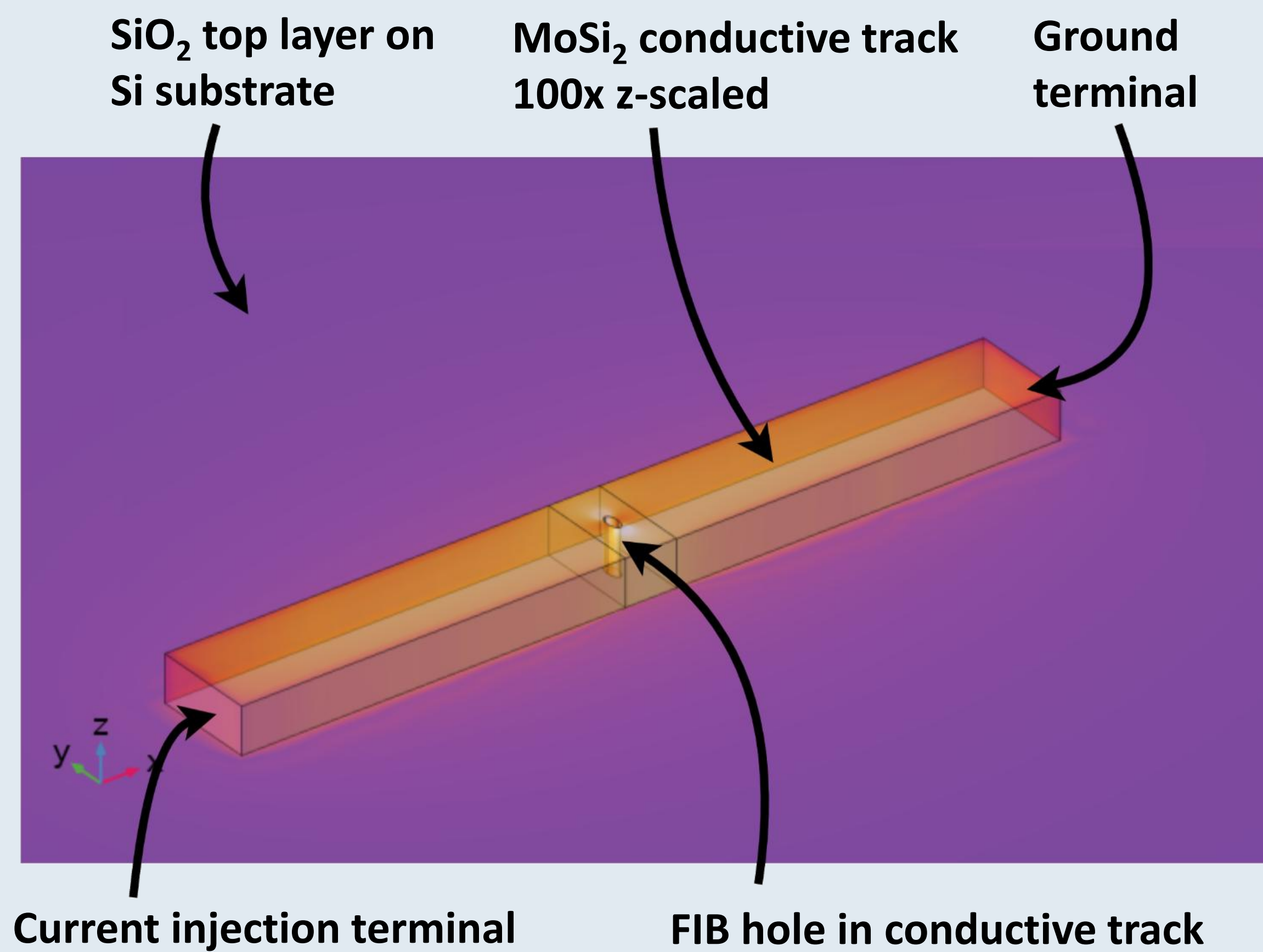




Stabilized Multiphysics Modeling of Electromigration in MEMS IR Emitters

A test line for infrared emitters fails when a damage front creeps for minutes, then runs away in the final second. One variable transformation makes that a single, stable solve.

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Introduction & Goals

MEMS infrared emitters are the radiation sources in non-dispersive infrared (NDIR) gas sensing. Operated at high current density and several hundred degrees Celsius, their conductive tracks age by electromigration: conductor material is displaced and a hotspot forms that ultimately destroys the track.

Predicting that endpoint is a reliability question — and a hard numerical one. The damage stays local at first, but then accelerates suddenly and the solver steps from 10 s down to 9 ms.

Solved directly, the damage variable exceeds $D = 1$. The usual remedies both fail: clipping puts a non-smooth constraint at exactly the moment of interest, and artificial diffusion buys stability by smearing out the very localization under study.

We present a fully coupled 3D electro-thermal-damage model — a silicon volume with a shell-formulated track — whose empirical damage variable stays bounded by construction, so that the transient runs without spatial or temporal smoothing, benchmarked against in-situ microscopy of the same structure.

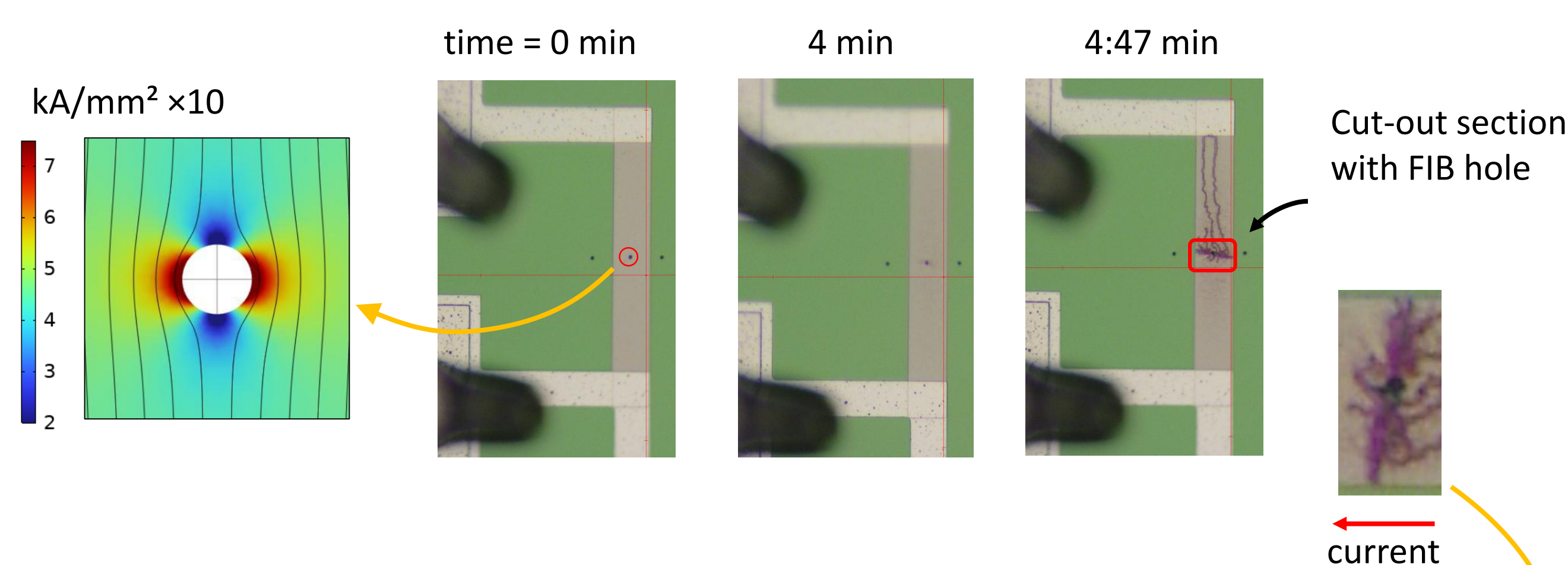


FIGURE 1. Experimental test structure for electromigration and simulated temperature and current flow around the hole made with a focused ion beam (FIB). Amorphous MoSi₂ 57 nm, track 120 × 20 μm on 500 nm SiN_x / 70 nm SiO₂ over silicon. The 1 μm FIB hole fixes where current crowding and the hotspot appear.

Methodology

The model couples Electric Currents in Shells (ecis), Heat Transfer in Shells (htlsh) and in the silicon die via Heat Transfer in Solids (ht), and a Coefficient Form Boundary PDE (cb) carrying the damage field D . Electromigration mass flux is mapped to a damage rate of Huntington form,

$$\underbrace{\frac{dD}{dt}}_z = k \underbrace{\left(\frac{E}{k_B} \right) e^{-\frac{E_A}{k_B T}} (1 - D)}_f, \quad \text{transformation: } D = 1 - e^{-z}$$

and the damage feeds back on conductivity, $\sigma = \sigma_0(T) \cdot (1 - D)^2$.

D must remain within $[0, 1]$. Rather than clipping it, we solve for $z = -\ln(1 - D)$ and recover D by transformation. Since z lies in $[0, \infty)$, the bound holds exactly — every Newton iteration, every time step. The equation collapses into $\partial z / \partial t = f$. The bound holds by construction, no artificial diffusion, no temporal smoothing.

Results

Under constant current (40 mA) the model reproduces the sequence seen by in-situ microscopy: incubation at the FIB rim through $\frac{3}{4}$ of the life → lateral spreading from 4 min → runaway. In the final 31 ms the hotspot rises from 499 to 894 °C and the damage band reaches both track edges; resistance drifts 490.4 → 642.1 Ω.

$E_A = 0.8$ eV (estimated by machine learning); k from one measured time to failure (4:47 min). Saturation is not reached: at constant current the ligament power density diverges.

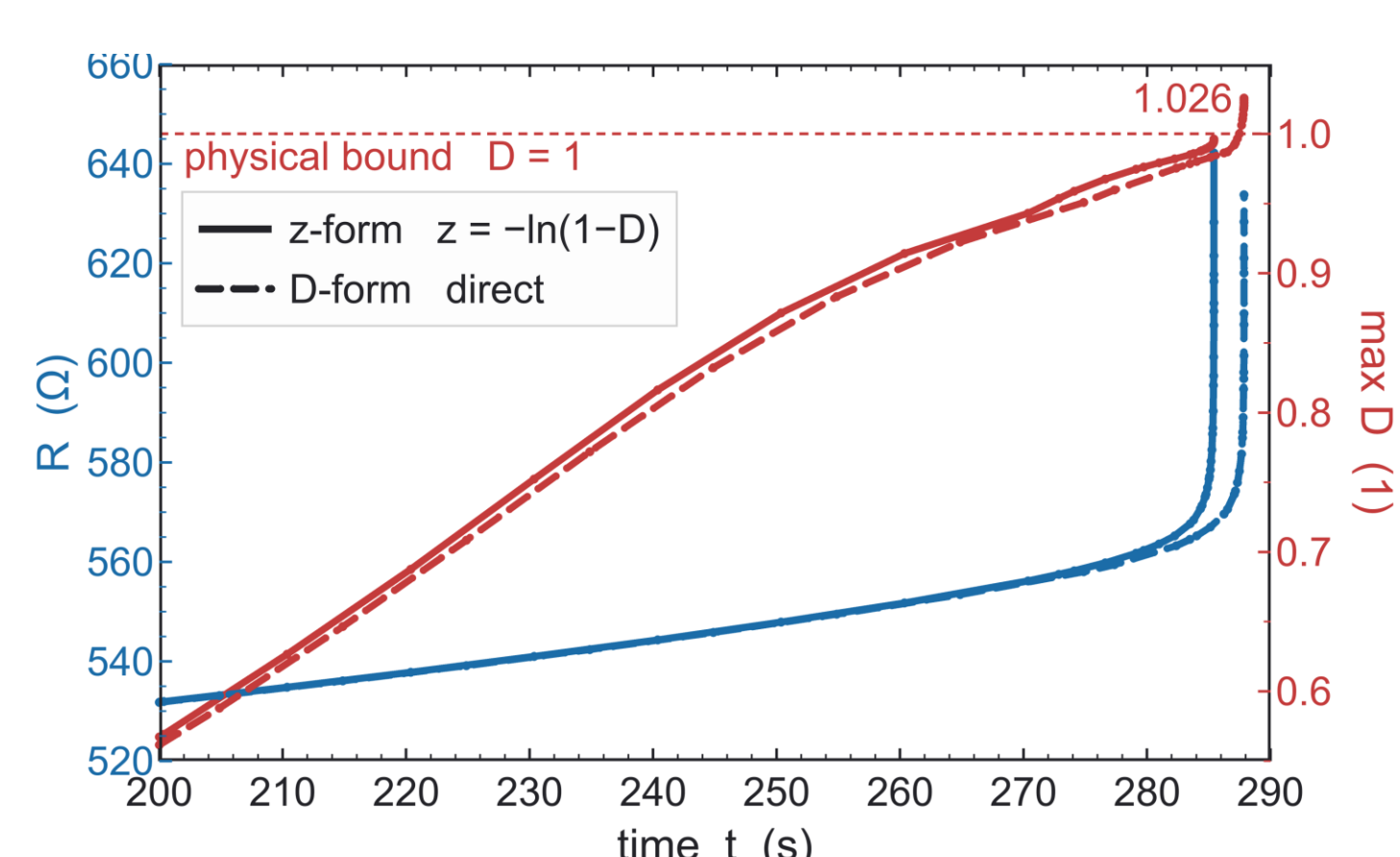


FIGURE 3. Resistance R (blue, left axis) and maximum damage $\max D$ (red, right axis) for the same model, same mesh, same current — only the damage formulation differs. Solid: z-form, $z = -\ln(1 - D)$. Dashed: direct D-form, which overshoots the physical bound $D = 1$ (max 1.026). Shown from 200 s; earlier the two runs coincide.

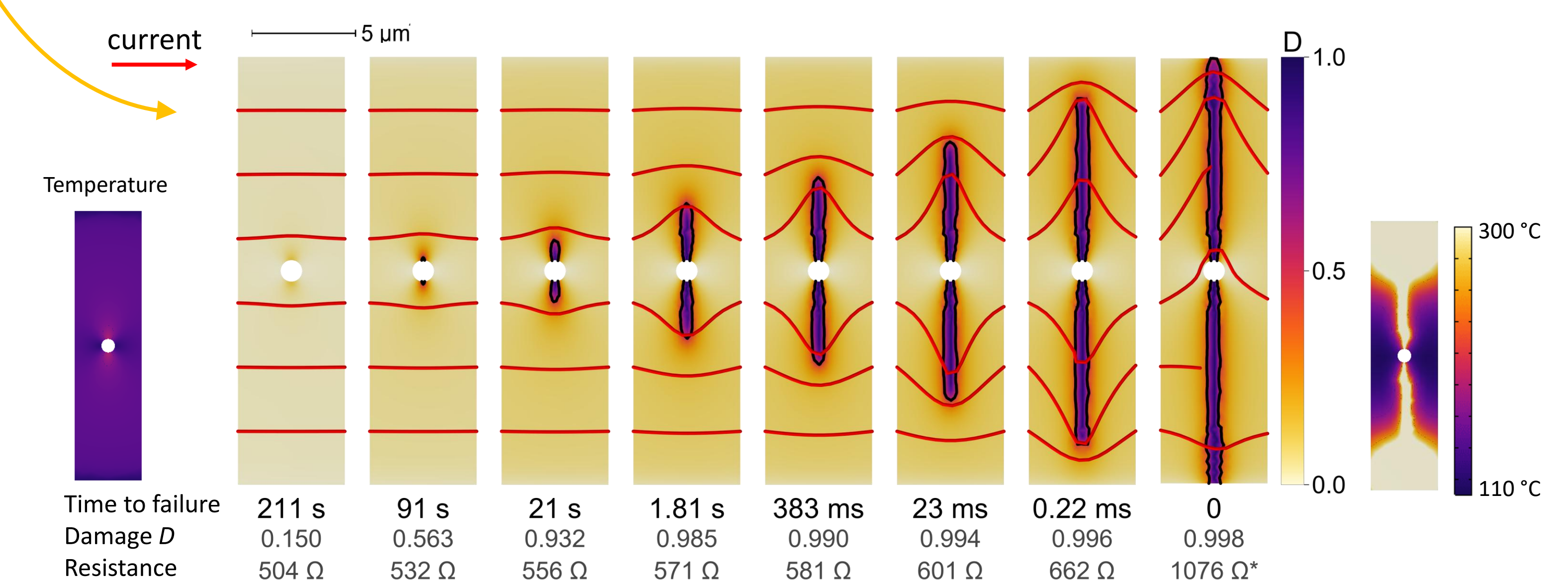


FIGURE 2. Damage field D at eight instants of one 40 mA transient, showing the full 20 μm track width over 5 μm of its length. The fields are spaced roughly logarithmically in time to failure, from 215 s down to 0.32 ms — the span a single solve has to cover. Black contour: $D = 0.5$. Labels give time to failure, max D , and resistance. *Solver terminates here at the failure point, with the damage band across the full width; R and peak temperature diverge and are not converged values.

Flanking panels: temperature over the same area at the start (left) and 0.32 ms before failure (right), own colour scale, clipped at 300 °C (peak 894 °C).

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