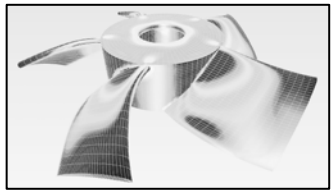
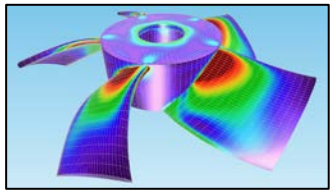
Analog Computing with Inverse-Designed Metastructures

Caio Silva and Giuseppe Romano

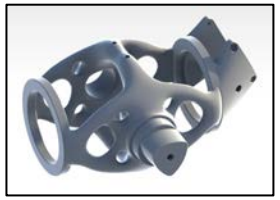
Massachusetts Institute of Technology

Geometry → Simulator → Results





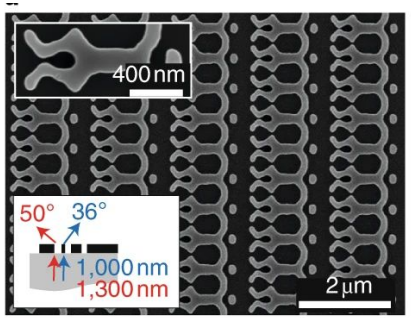
Forward problems



Topology optimization ← Target performances

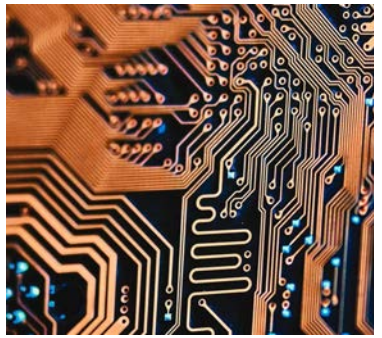
Inverse problems

J. of Aeron. 34.1 (2021): 91-110.



Nat. Photon. 12.11 (2018): 659-670.

Qatar Education City Convention Centre



Physics for AI

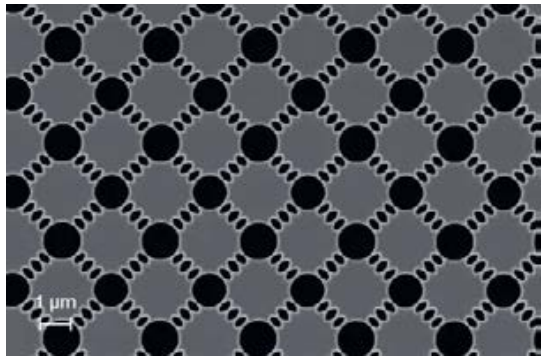
G. Romano and S. G. Johnson, Struct. and Multid. Optim. 65.10 (2022): 297.
S. G. Johnson "Notes on adjoint methods for 18.335." Introduction to Numerical Methods (2012).

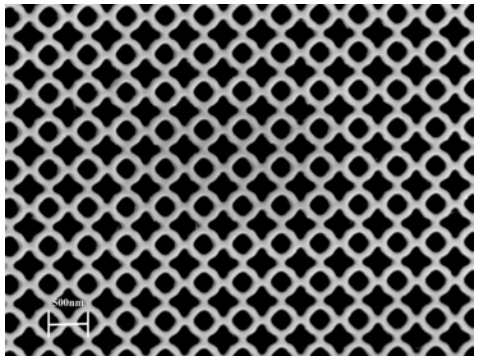
What is topology optimization (TopOpt) ?

It enables to differentiate through the physics of the problem, thus allowing for gradient-based optimization. No training needed.

The key mechanism is the “adjoint method,” also known as reverse-mode automatic differentiation or backpropagation.

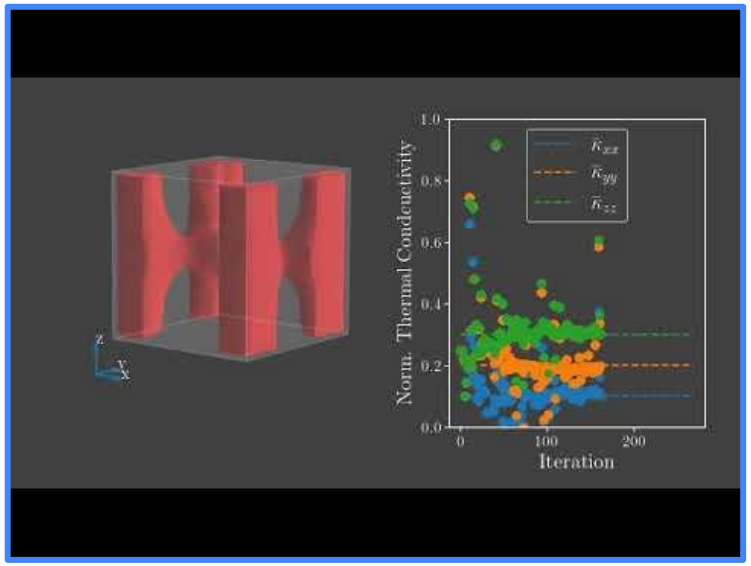
Nanoscale energy harvesters





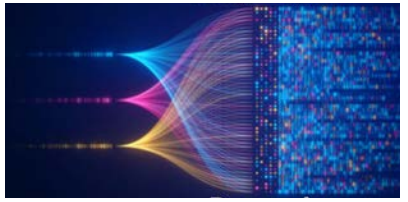
Includes features constraints

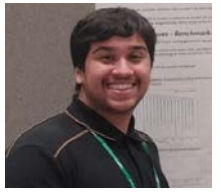
Example of optimization for a thermal orthotropic material



G. Romano and S. G. Johnson, Struct. and Multid. Optim. 65.10 (2022): 297.
S. G. Johnson "Notes on adjoint methods for 18.335." Introduction to Numerical Methods (2012).

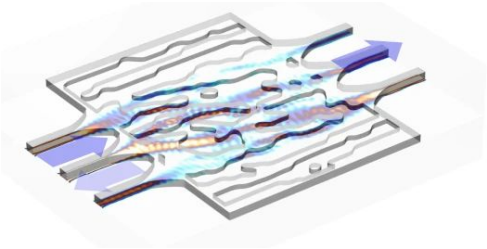
Matrix-vector multiplication (MVM) is at the core of modern applications

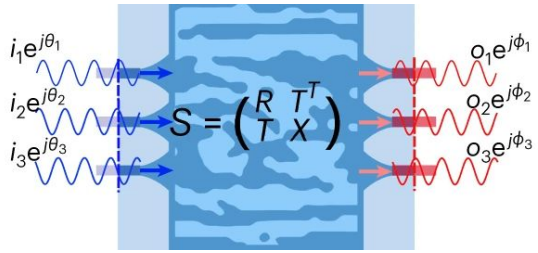




Caio Silva

MVM have been implemented in photonic metamaterials



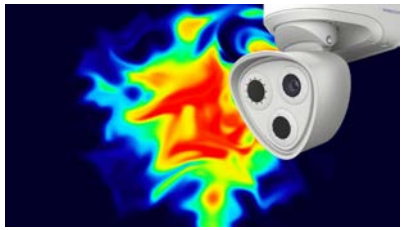


Nikkhah, Vahid, et al. Nature Photonics 18.5 (2024): 501-508.

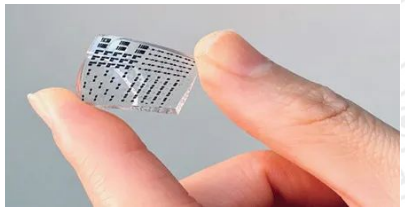
We implement inverse-design MVM using heat as signal carrier.

Always available in computing systems

Thermal image processing



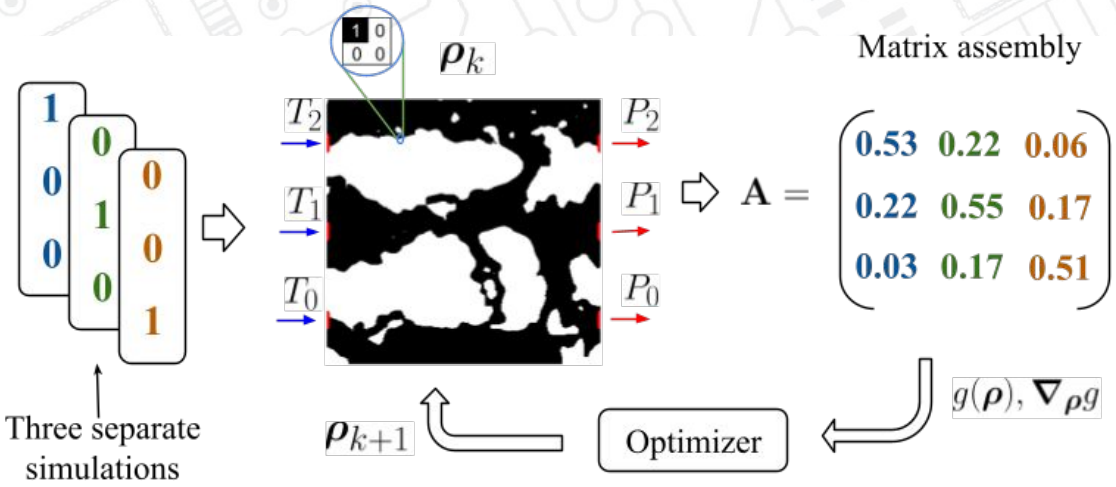
Electronic Skin

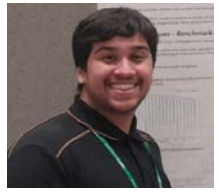


C. Silva and G. Romano, https://arxiv.org/abs/2503.22603

Target Matrix:

$\bar{\mathbf{A}}$





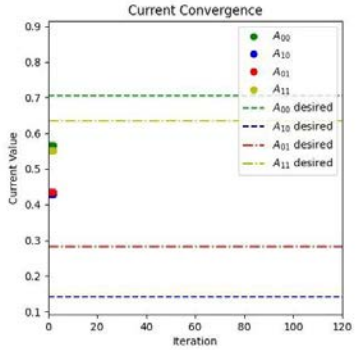
Caio Silva

Cost function:

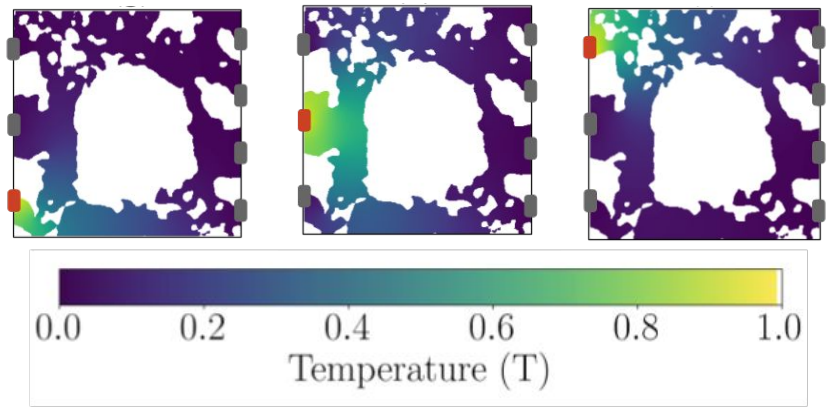
$$g(\boldsymbol{\rho}) \approx ||\mathbf{A}(\boldsymbol{\rho}) - \bar{\mathbf{A}}||$$

We build upon our in-house code MatInverse, a differentiable thermal transport code.

$$A = \begin{bmatrix} 0.705 & 0.282 \\ 0.141 & 0.635 \end{bmatrix}$$



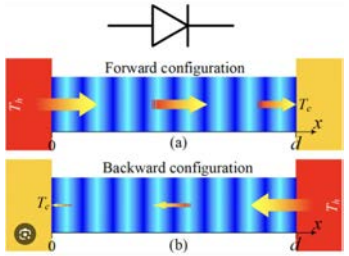
Approximate MVP with accuracy of 96 %



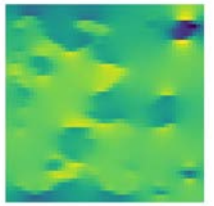
(video courtesy by C. Silva)

C. Silva and G. Romano, https://arxiv.org/abs/2503.22603

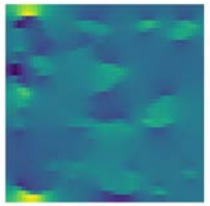
The adjoint method enable differentiating through non-linear simulations



Forward

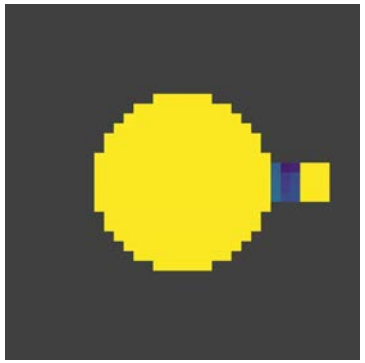


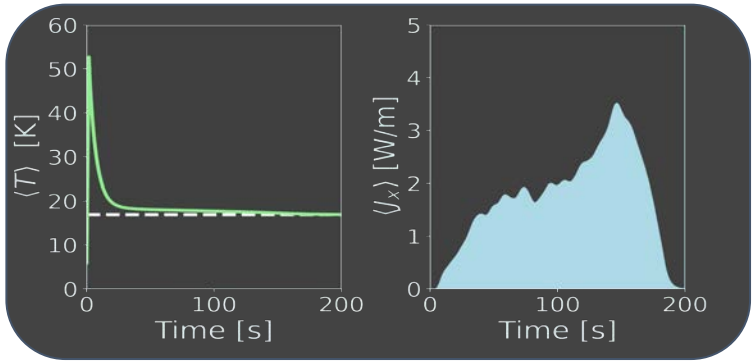
Backward



Greta Lawer

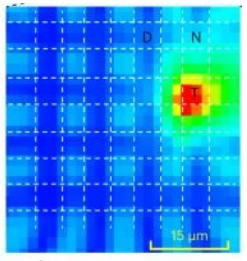
The adjoint method can also be applied in time: It entails running the simulation backward.

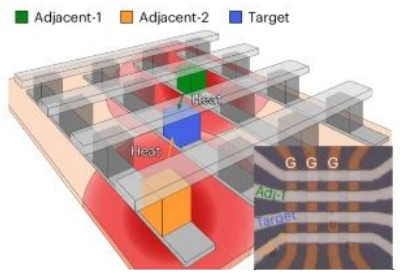


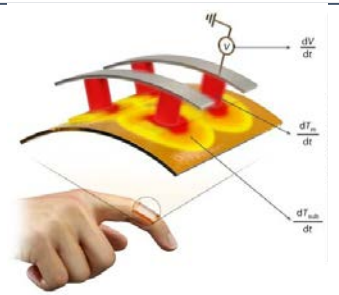


Challenge

Transient + Nonlinearity
=
Neuromorphic heat-assisted computing



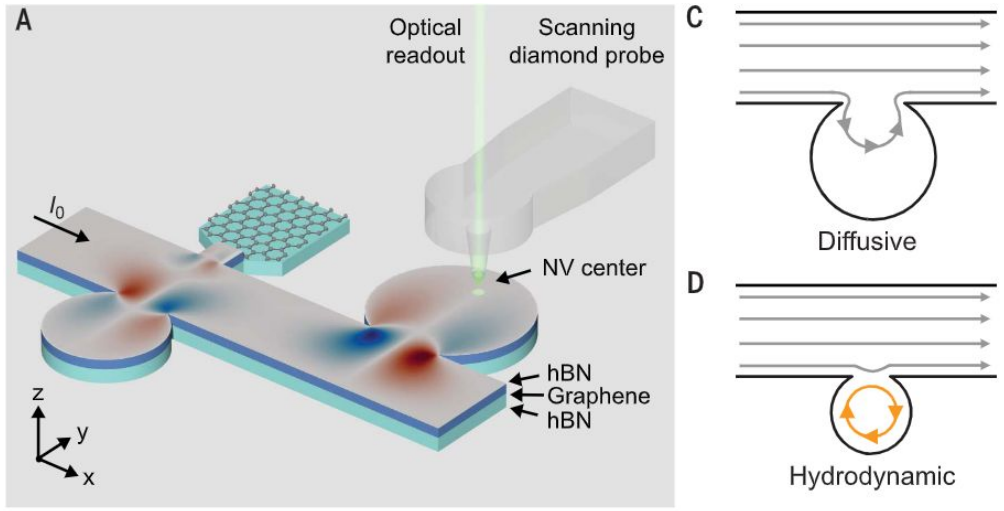




Kim, Gwangmin, et al. Nat. Mat. 23.9 (2024): 1237-1244.

Challenge: Nanoscale Analog Computing

At the nanoscales the diffusive theory fail. Phonon dynamics need to be taken into account.

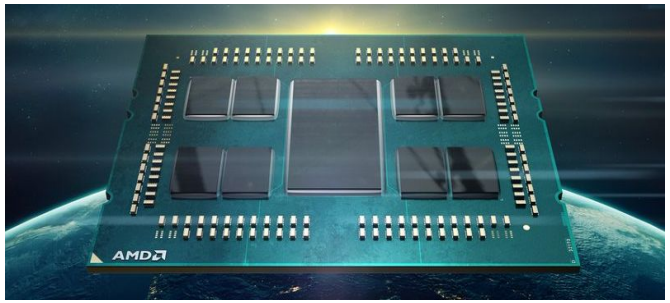


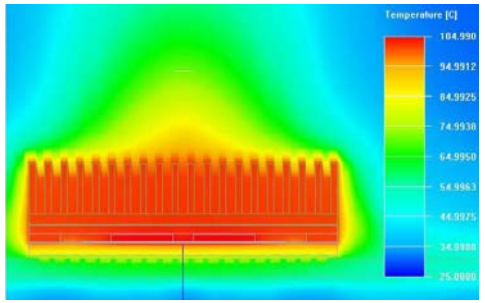
Palm, Marius L., et al. "Observation of current whirlpools in graphene at room temperature." Science 384.6694 (2024): 465-469.

G. Romano and S. G. Johnson, Struct. and Multid. Optim. 65.10 (2022): 297.
G. Romano, OpenBTE, https://arxiv.org/abs/2106.02764

Chiplets are the building block of modern architectures.

Dense packing creates hot spots.





Zhou, Minghao, et al. 12.6 (2022): 956-963.

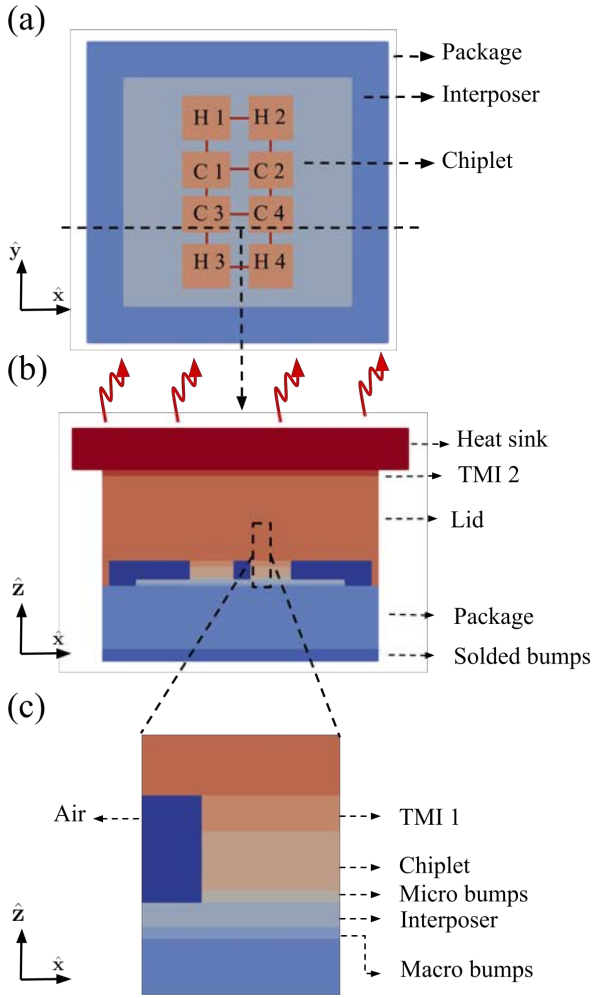
What is the chiplet locations that minimize the total wirelength while keeping the maximum temperature below a threshold?

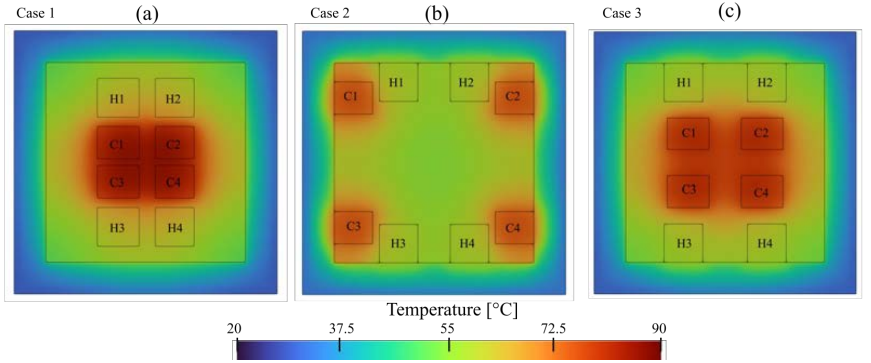
We developed a end-to-end differentiable pipeline, which includes several regularizations

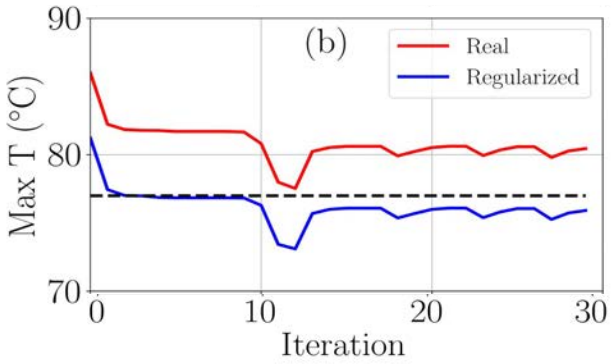
$$T_{\max} \approx \left(\frac{1}{N} \sum_{n=0}^{N-1} T_i^p \right)^{1/p}$$

MIT-IBM Watson AI Lab

G. Romano et al. 2025 Proceedings 75th Electronic Components and Technology Conference (ECTC), https://arxiv.org/abs/2502.16633



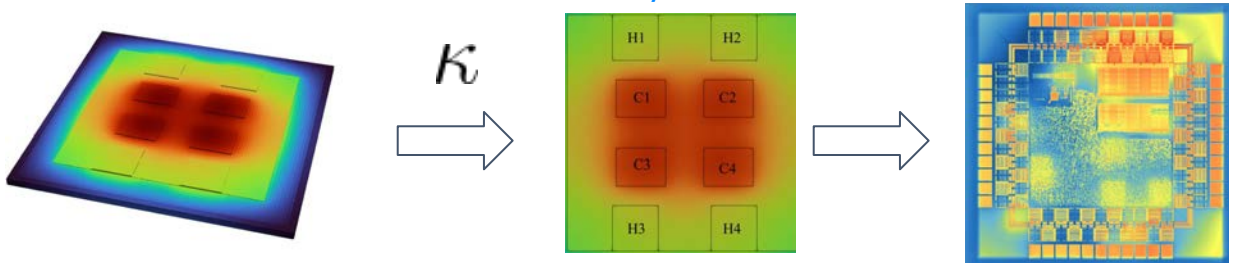




Validated against ANSYS

Challenge

Effective 2D thermal conductivity

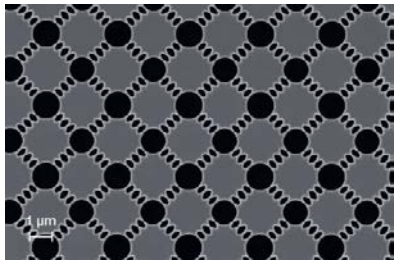


What is an equivalent 2D model that reproduces the 3D map?
Regression is enabled by differentiable programming

G. Romano et al. 2025 Proceedings 75th Electronic Components and Technology Conference (ECTC), https://arxiv.org/abs/2502.16633

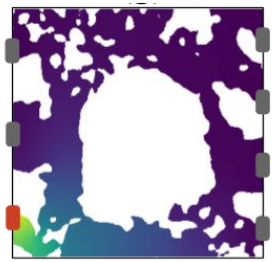
Toward multiphysics topology optimization

Nanoscale energy harvesters



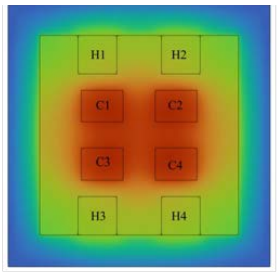
G. Romano and S. G. Johnson, Struct. and Multid. Optim. 65.10 (2022): 297.

Analog Computing



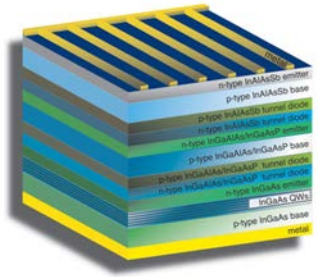
Caio Silva and G. Romano, https://arxiv.org/abs/2502.16633

Chiplets



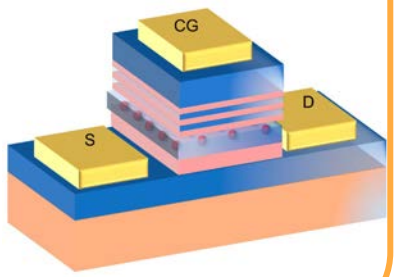
G. Romano et al. 2025 (ECTC '25)

Solar Cells



S. Mann, …, G. Romano Phys. Comm. 272 (2022): 108232.

CMOS



Modules

dTherm — Macroscale heat conduction

dBTE — Nanoscale heat conduction

dDD — Drift-Diffusion

dMech — Elasticity

⇩

MatInverse

Conclusions

- Heat-based analog computing is a potential opportunity for scenarios where temperature gradients arise naturally.
- Inverse design is a powerful tool for engineering materials and devices with prescribed properties.
- Automatic differentiation and differentiable solvers overcome the inefficiencies of try and error approaches
- Multiphysics topology optimization dramatically opens up possibility in the device/application space.

Collaborators

Steven G. Johnson (MIT/Math)
Caio Silva (MIT/Physics)
Alexei Maznev (MIT/Chemistry)
Keith A. Nelson (MIT/Chemistry)
Marco Colangelo (Northeastern U.)
Yang Yu (Raith America)
Nima Dehmamy (IBM)
Xin Zhang (IBM)