U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

ASI Advanced Sensors and Instrumentation

Advanced Sensors and Instrumentation (ASI) Annual Program Webinar

November 4, 6-7, 2024

Fiber-Embedded Wireless Sensors

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Joseph Pegna

10 Cady Hill Boulevard, Saratoga Springs, New York, 12866

www.fffibers.com

Acknowledgments:

Award DE-SC0023772, P.M.: Dr. Daniel Nichols

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Acknowledgments:
Award DE-SC0023772, P.M.: Dr. Daniel Nichols

Additive Manufactured Wireless Sensors

1. Template: Integrated Electronics
    - Most advanced form of AM
    - Proven track record on costs
2. State of the art 3-D Printed fuels
3. 3-D Printing vs. AM vs MAAM
4. 1 ½ -D Printing
5. 1 ½ -D Printed fiber-integrated sensors: Smart fuels
6. Transducer demonstration & characterization
7. Conclusions / Questions

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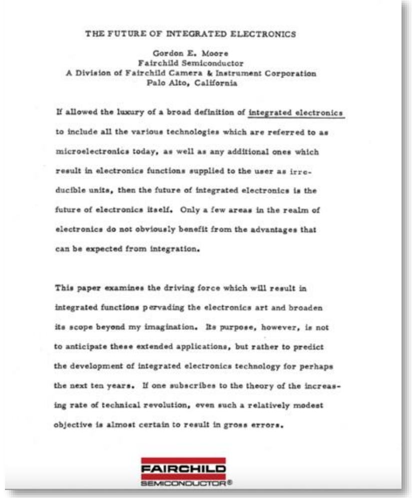
INTEGRATED ELECTRONICS MODEL

Gordon E. Moore, The Future of Integrated Electronics, Electronics Magazine, April 19, 1965



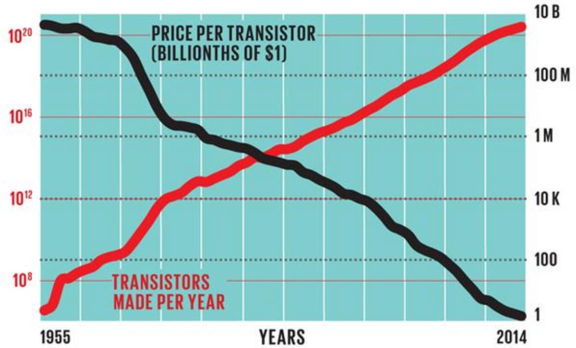
THE FUTURE OF INTEGRATED ELECTRONICS

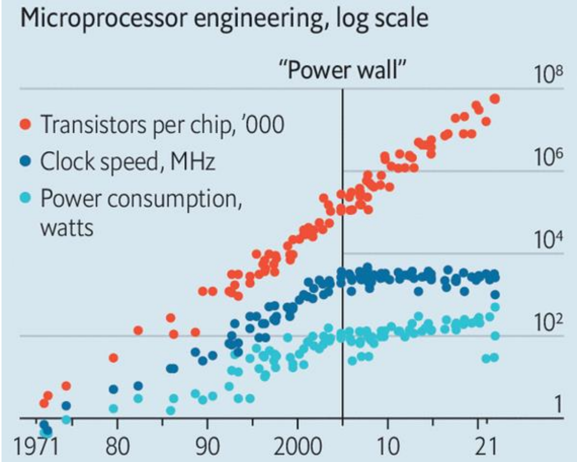
Gordon E. Moore
Fairchild Semiconductor
A Division of Fairchild Camera & Instrument Corporation
Palo Alto, California

If allowed the luxury of a broad definition of integrated electronics to include all the various technologies which are referred to as microelectronics today, as well as any additional ones which result in electronics functions supplied to the user as irreducible units, then the future of integrated electronics is the future of electronics itself. Only a few areas in the realm of electronics do not obviously benefit from the advantages that can be expected from integration.

This paper examines the driving force which will result in integrated functions pervading the electronics art and broaden its scope beyond my imagination. Its purpose, however, is not to anticipate these extended applications, but rather to predict the development of integrated electronics technology for perhaps the next ten years. If one subscribes to the theory of the increasing rate of technical revolution, even such a relatively modest objective is almost certain to result in gross errors.

FAIRCHILD SEMICONDUCTOR®

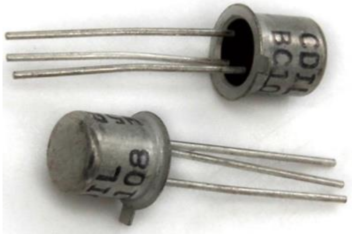




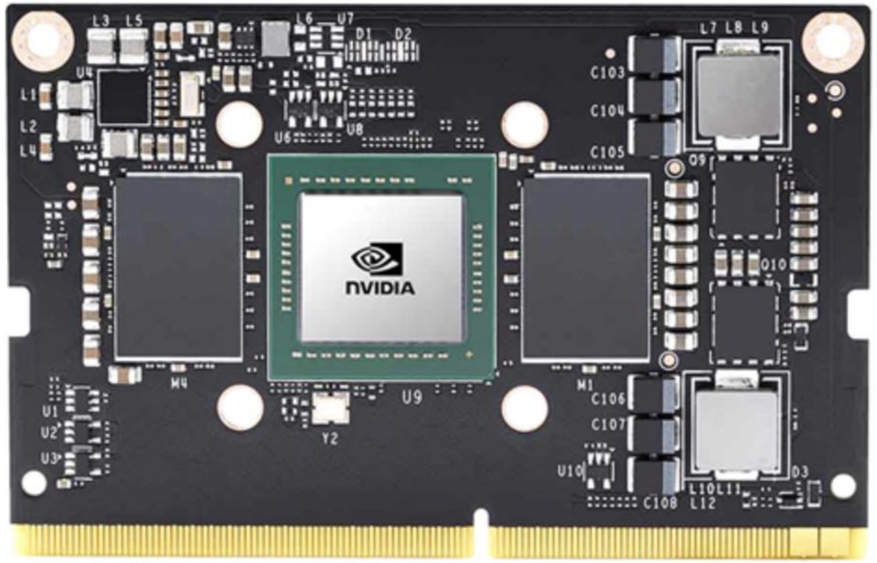
K. Rupp et al., Fifty years of microprocessor trend data, IMEC, 2022

1940: Vacuum Tubes **1950: Solid State Transistors**
ENIAC Computer **Printed Circuit Boards**

1960: Integrated Electronics **Present day: NVDIA**



SEMINAL TRANSITION: 1965
Photolithography
2½-D Multimaterial
Additive
Micromanufacturing



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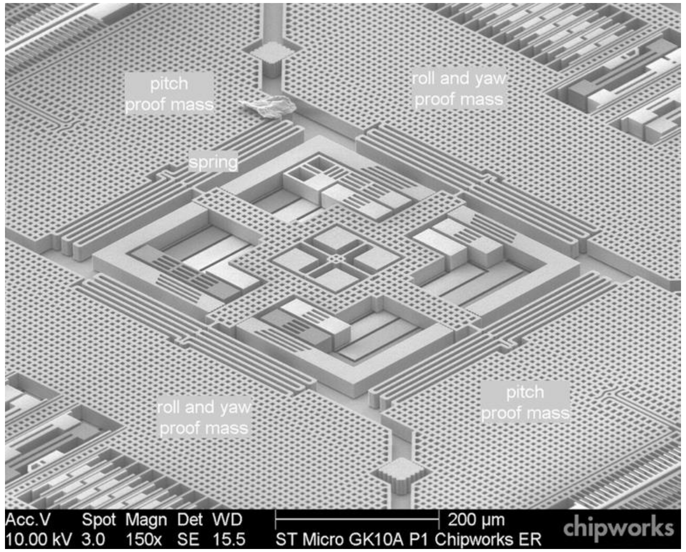
MEMS MODEL

Feynman, Richard P. (1960) *There's Plenty of Room at the Bottom.* Engineering and Science, 23 (5). pp. 22-36.


There's Plenty of Room at the Bottom

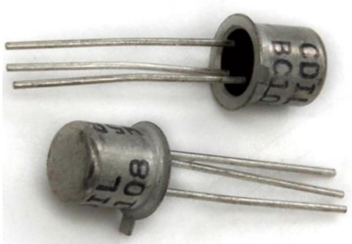
An invitation to enter a new field of physics.

by Richard P. Feynman



1940: Vacuum Tubes
ENIAC Computer

1950: Solid State Transistors
Printed Circuit Boards



1960

1960: Integrated Electronics

Present day: NVDIA

SEMINAL TRANSITION:
1965
Photolithography
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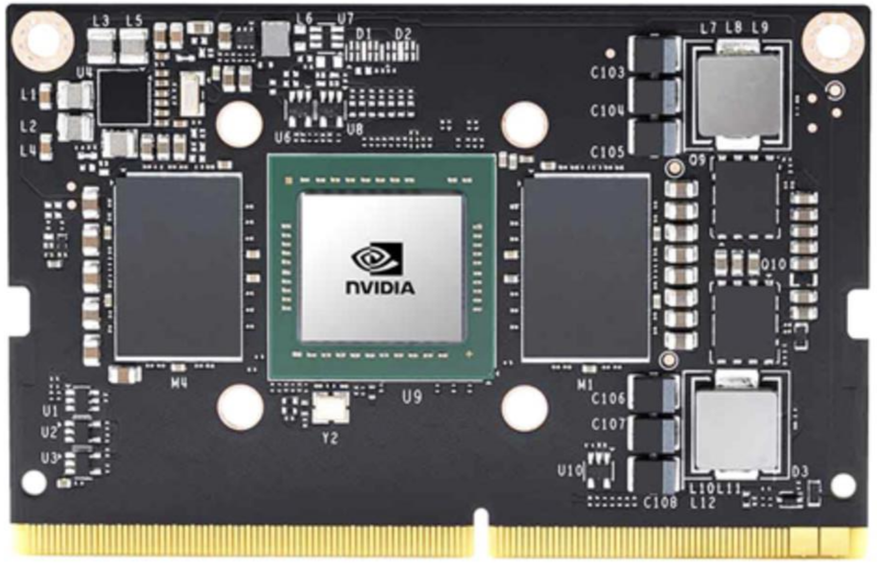

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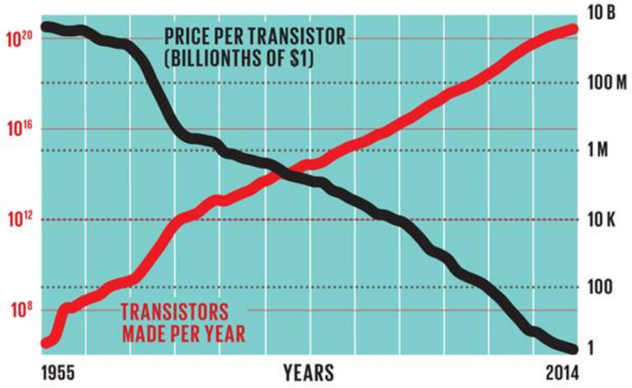
COMPARATIVE STATE OF NUCLEAR FUEL FAB ON THE INTEGRATED ELECTRONICS / MEMS TIMELINE



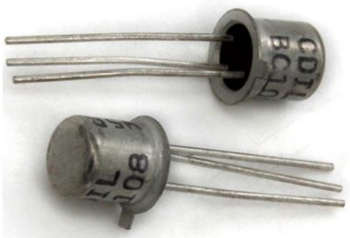
Are there similar curves in the future of fuel?

1940: Vacuum Tubes
ENIAC Computer

1950: Solid State Transistors
Printed Circuit Boards

1960: Integrated Electronics

Present day: NVDIA



1960

SEMINAL TRANSITION:

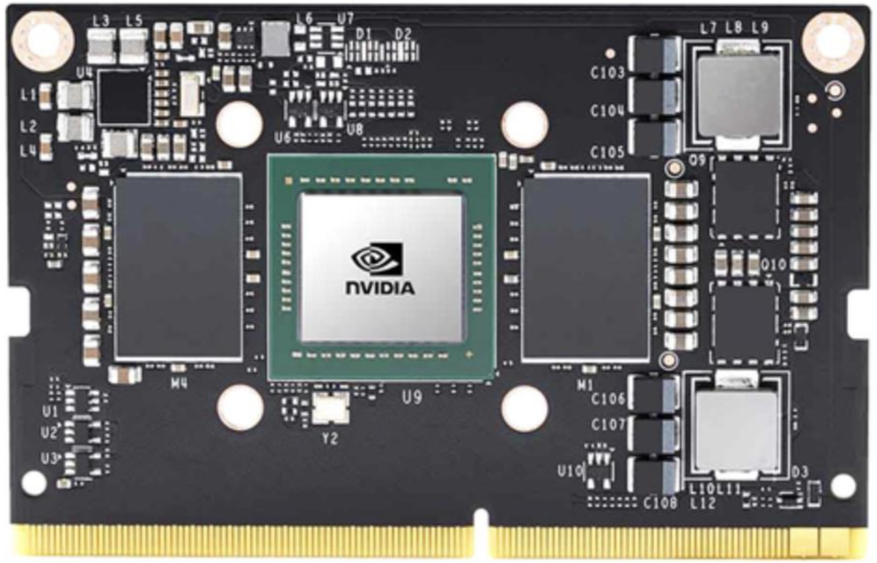
1965

Photolithography

2½-D Multimaterial

Additive

Micromanufacturing



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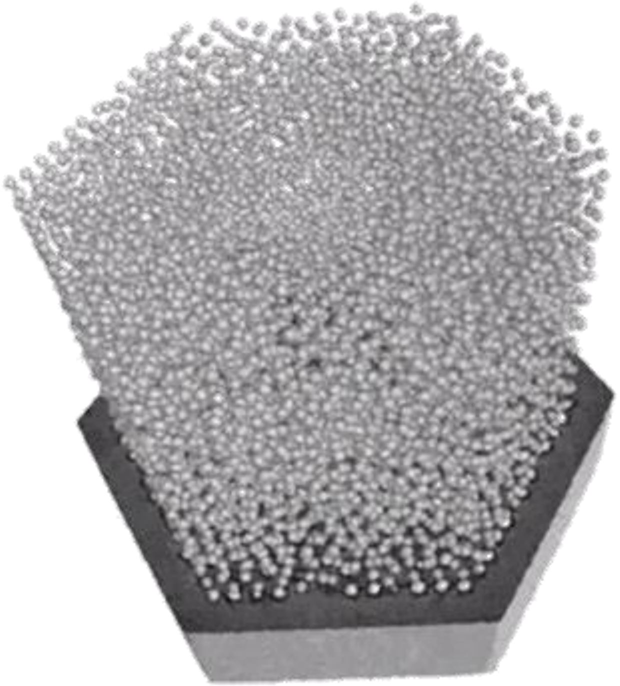
STATE OF THE ART 3-D PRINTED NUCLEAR FUEL



Source: ORNL Transformational Challenge Reactor Program

- **Monolithic SiC powder, 3-D printed layer-by-layer,**
- **With TRISO particles inclusions**
- **Consolidated by skin-deep SiC CVI**
- **Conformal geometry and topology only achievable by 3-D Printing**

MISSING FOR SEMINAL TRANSITION:

- **STILL *'PICK AND PLACE APPROACH'***
- **POWDER BED DISRUPTION**
- **MATERIAL AGNOSTIC PROCESS**

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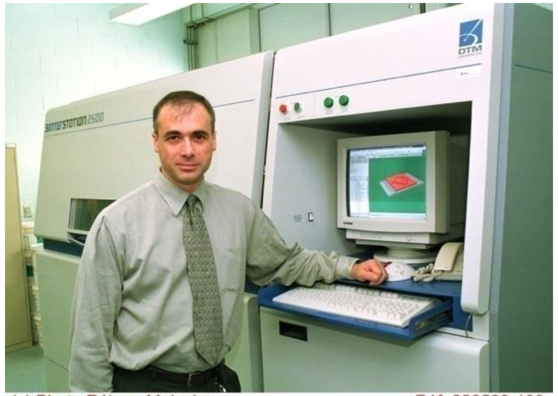
Additive Manufacturing vs 3-D Printing

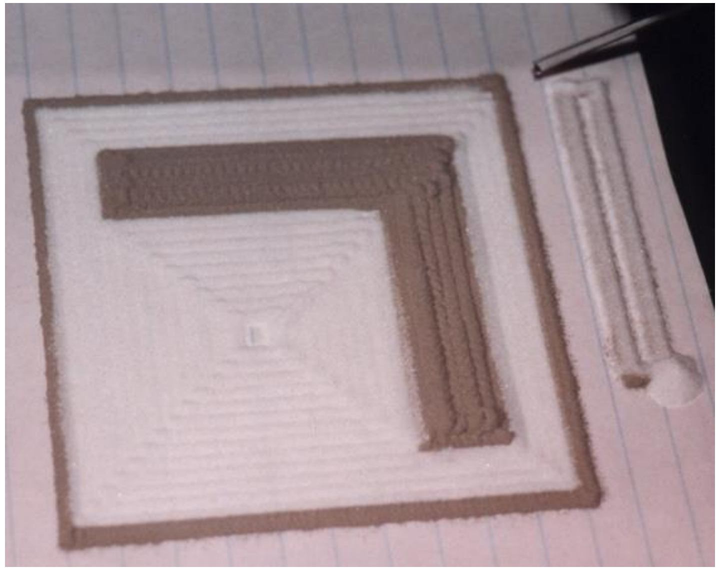


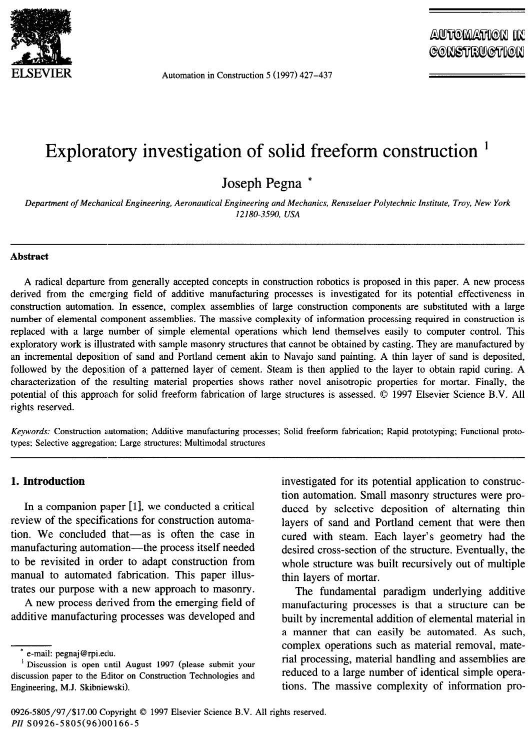
(c) Photo Réjean Meloche Réf: 220523-109

3-D Printing: Flat Layer-by-flat layer

- Opens vast new geometries and topologies
- Intimately tied to few materials

Additive Manufacturing vs 3-D Printing





ELSEVIER

Automation in Construction 5 (1997) 427–437

AUTOMATION IN CONSTRUCTION

Exploratory investigation of solid freeform construction [1]

Joseph Pegna *

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Abstract

A radical departure from generally accepted concepts in construction robotics is proposed in this paper. A new process derived from the emerging field of additive manufacturing processes is investigated for its potential effectiveness in construction automation. In essence, complex assemblies of large construction components are substituted with a large number of elemental component assemblies. The massive complexity of information processing required in construction is replaced with a large number of simple elemental operations which lend themselves easily to computer control. This exploratory work is illustrated with sample masonry structures that cannot be obtained by casting. They are manufactured by an incremental deposition of sand and Portland cement akin to Navajo sand painting. A thin layer of sand is deposited, followed by the deposition of a patterned layer of cement. Steam is then applied to the layer to obtain rapid curing. A characterization of the resulting material properties shows rather novel anisotropic properties for mortar. Finally, the potential of this approach for solid freeform fabrication of large structures is assessed. © 1997 Elsevier Science B.V. All rights reserved.

Keywords: Construction automation; Additive manufacturing processes; Solid freeform fabrication; Rapid prototyping; Functional prototypes; Selective aggregation; Large structures; Multimodal structures

1. Introduction

In a companion paper [1], we conducted a critical review of the specifications for construction automation. We concluded that—as is often the case in manufacturing automation—the process itself needed to be revisited in order to adapt construction from manual to automated fabrication. This paper illustrates our purpose with a new approach to masonry.

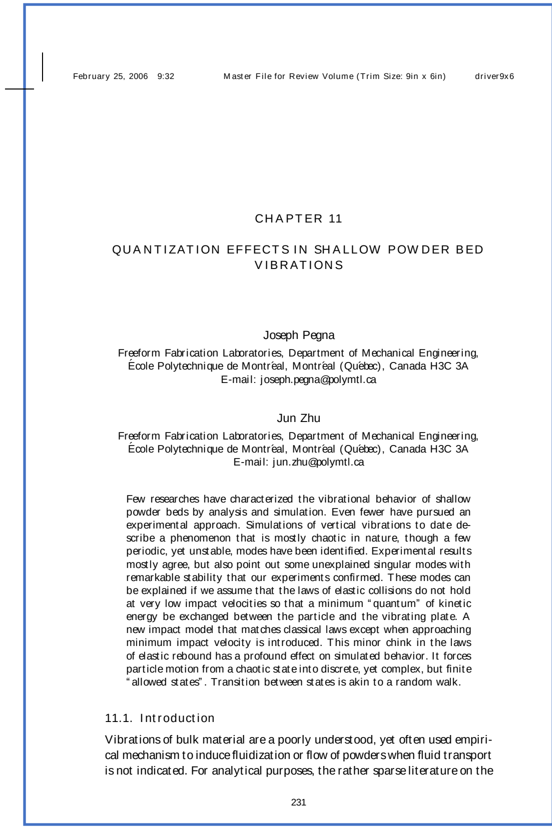
A new process derived from the emerging field of additive manufacturing processes was developed and investigated for its potential application to construction automation. Small masonry structures were produced by selective deposition of alternating thin layers of sand and Portland cement that were then cured with steam. Each layer's geometry had the desired cross-section of the structure. Eventually, the whole structure was built recursively out of multiple thin layers of mortar.

The fundamental paradigm underlying additive manufacturing processes is that a structure can be built by incremental addition of elemental material in a manner that can easily be automated. As such, complex operations such as material removal, material processing, material handling and assemblies are reduced to a large number of identical simple operations. The massive complexity of information pro-

* e-mail: pegnaj@rpi.edu.

[1] Discussion is open until August 1997 (please submit your discussion paper to the Editor on Construction Technologies and Engineering, M.J. Skibniewski).

PII S0926-5805(96)00166-5



CHAPTER 11

QUANTIZATION EFFECTS IN SHALLOW POWDER BED VIBRATIONS

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Few researches have characterized the vibrational behavior of shallow powder beds by analysis and simulation. Even fewer have pursued an experimental approach. Simulations of vertical vibrations to date describe a phenomenon that is mostly chaotic in nature, though a few periodic, yet unstable, modes have been identified. Experimental results mostly agree, but also point out some unexplained singular modes with remarkable stability that our experiments confirmed. These modes can be explained if we assume that the laws of elastic collisions do not hold at very low impact velocities so that a minimum "quantum" of kinetic energy be exchanged between the particle and the vibrating plate. A new impact model that matches classical laws except when approaching minimum impact velocity is introduced. This minor chink in the laws of elastic rebound has a profound effect on simulated behavior. It forces particle motion from a chaotic state into discrete, yet complex, but finite "allowed states". Transition between states is akin to a random walk.

11.1. Introduction

Vibrations of bulk material are a poorly understood, yet often used empirical mechanism to induce fluidization or flow of powders when fluid transport is not indicated. For analytical purposes, the rather sparse literature on the

Functionality demands more:

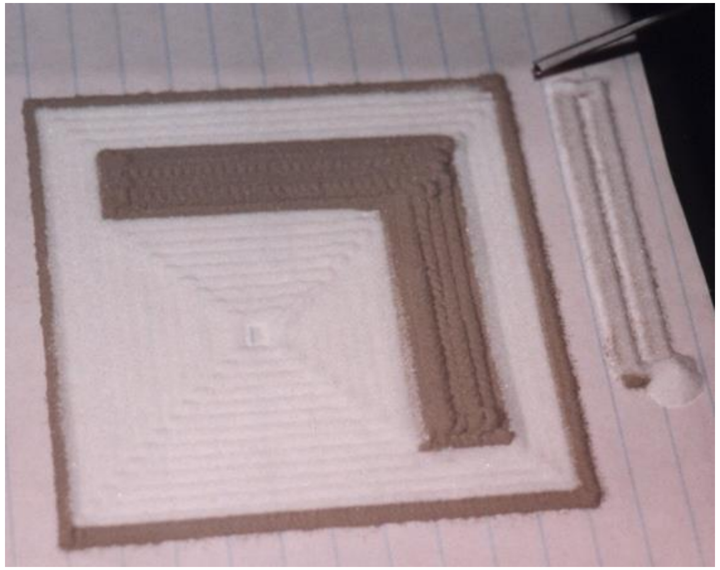
- Multiple materials

Material-Agnostic Additive Manufacturing

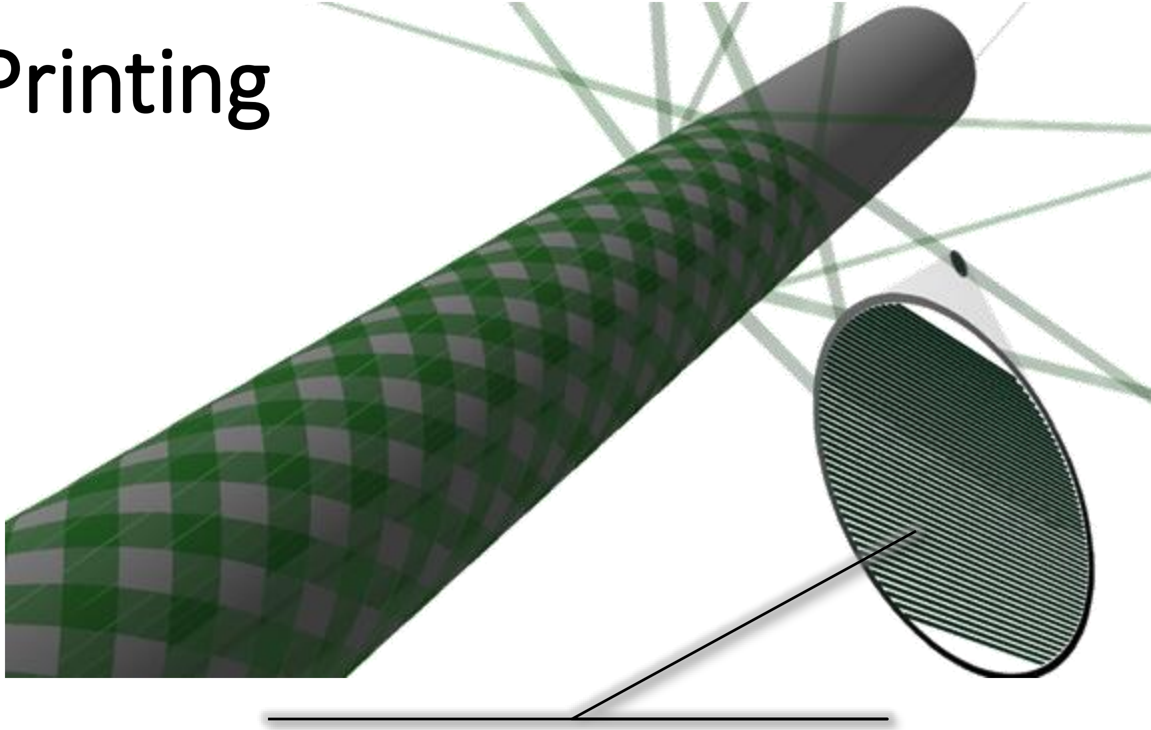
Pegna, J.; Exploratory Investigation of Solid Freeform Construction, Automation in Construction, Vol. 5, no.5, pp. 427-437 (Mar. 97)

Pegna, J. and Zhu, J.; Quantization effects in shallow powder bed vibrations, Advances in Mechanics of Solids. August 2006, 229-257

Additive Manufacturing vs 3-D Printing




Material-Agnostic Additive Manufacturing



Magnified view of ribbon of 51 functionally coated ß-SiC 0.001” filament ribbon

Feinroth, H. et al. (2010) Ceramics in Nuclear Applications (eds Y. Katoh, et al.), doi: 10.1002/9780470584002.ch4

Additive Manufacturing:

- Not necessarily flat
- Not necessarily layers

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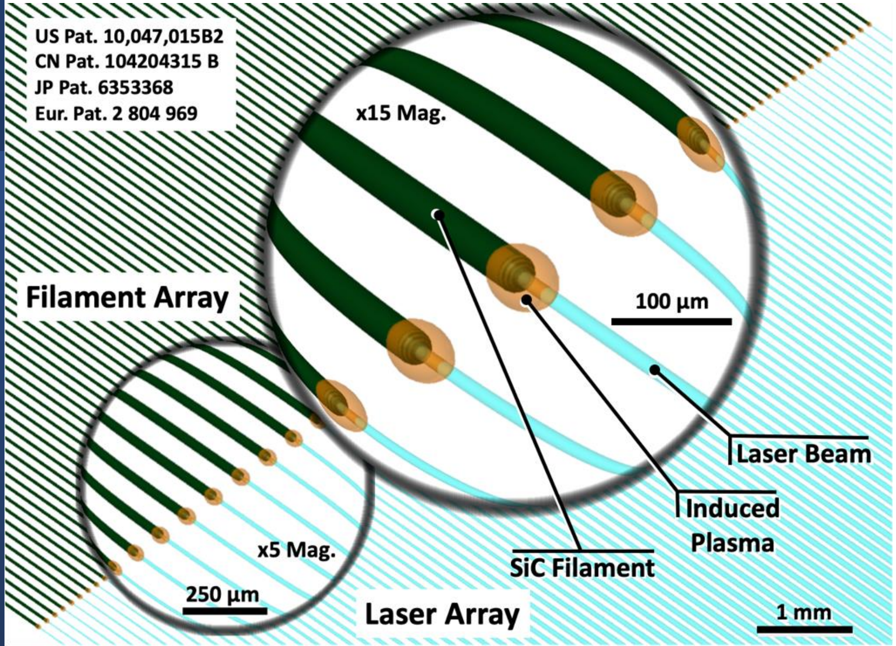
Additive manufacturing of fibers

- LCVD-Based Fiber Laser Printing: Material-Agnostic AM
- Proprietary Technology

(with certain government rights)



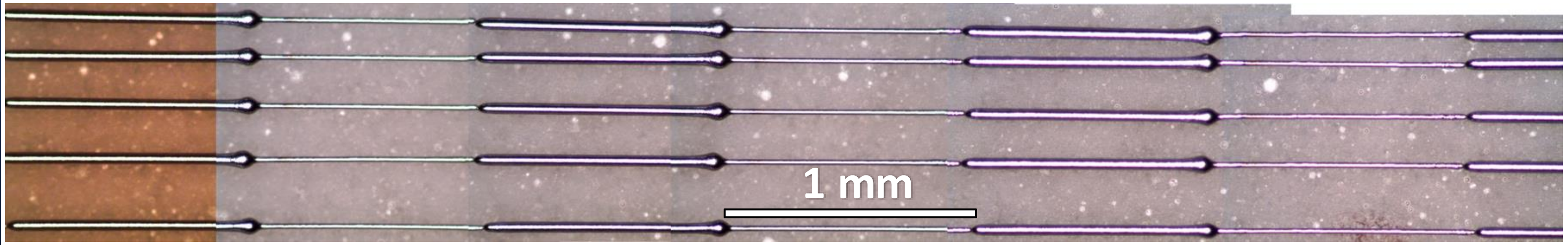
Features:

- Multi-material & Functionally graded materials
- Variable diameter profile

Maxwell, J.L., Pegna, J., DeAngelis, D., Messia, D.; Three-Dimensional Laser Chemical Vapor Deposition of Nickel-Iron Alloys, Materials Research Society. Vol. 397, Advanced Laser Processing of Materials, pp. 601-606 (1996)

FFF has the only facility in the world dedicated to production of fibers using LCVD.

https://youtube.com/shorts/CERn_DdPhWA



Composite Optical Microscope picture of 5 SiC filaments “as printed”

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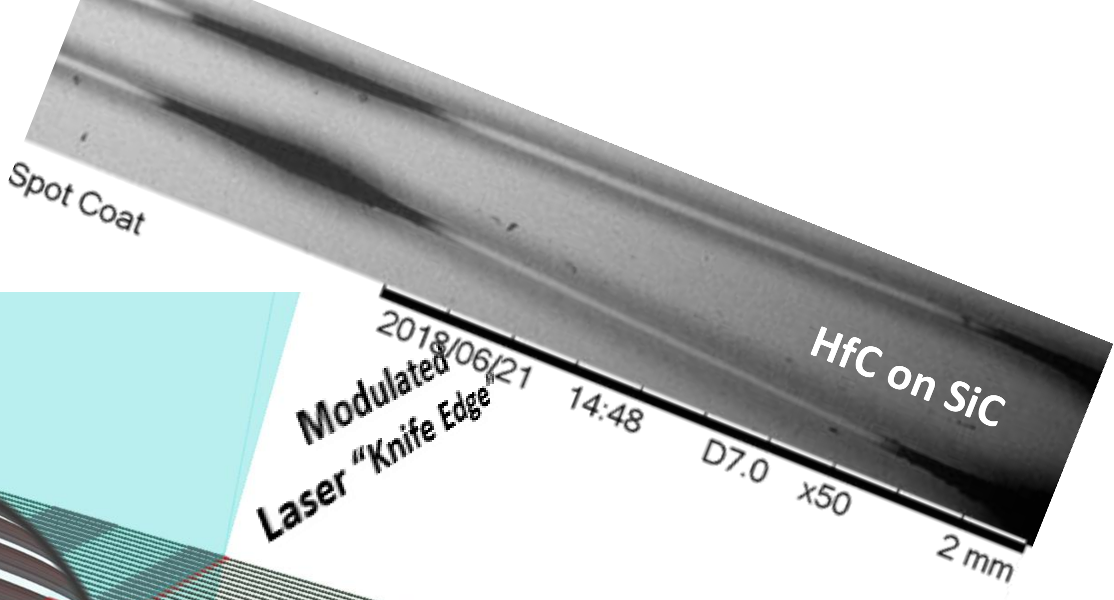
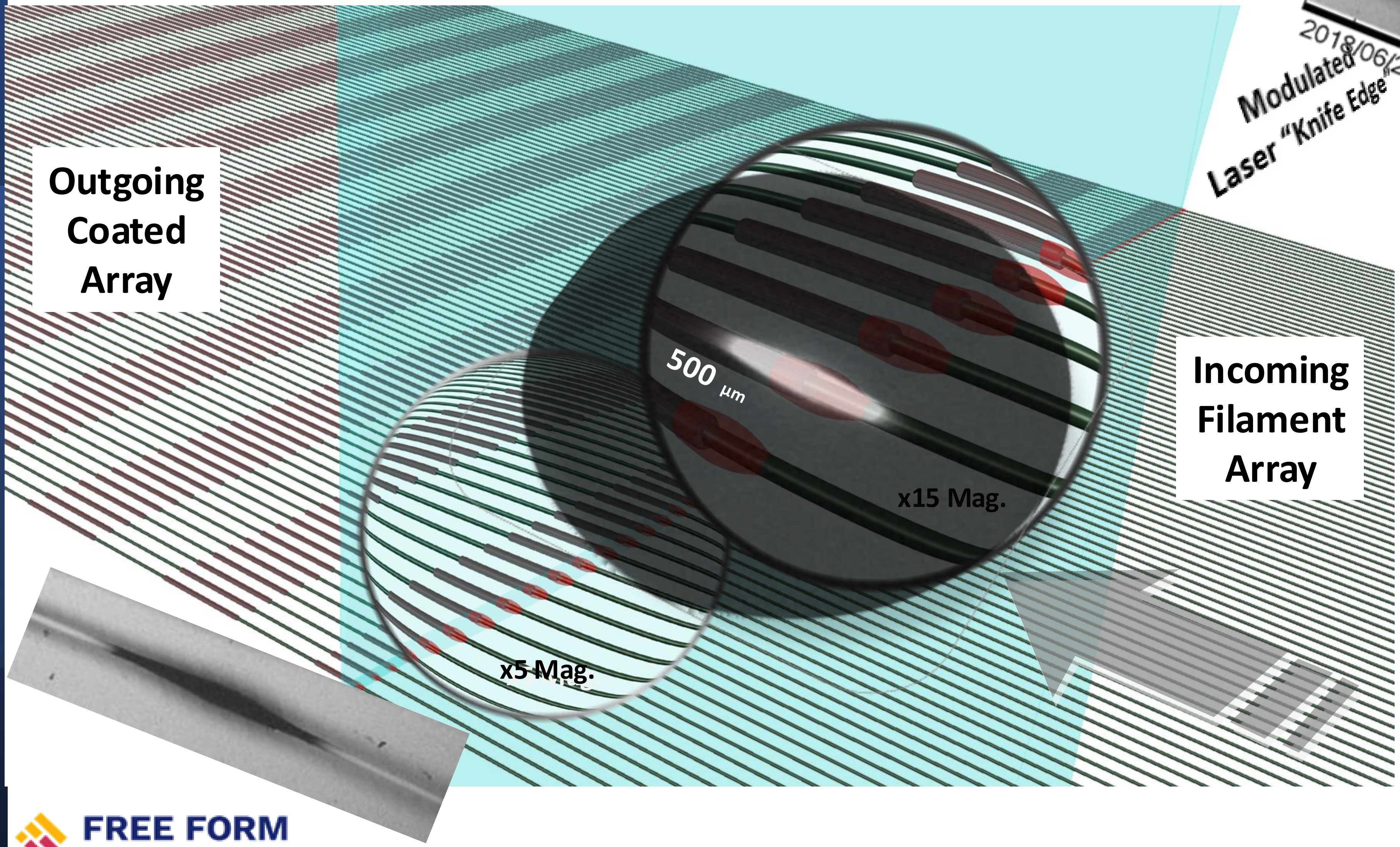
Laser CVD Spot Coating





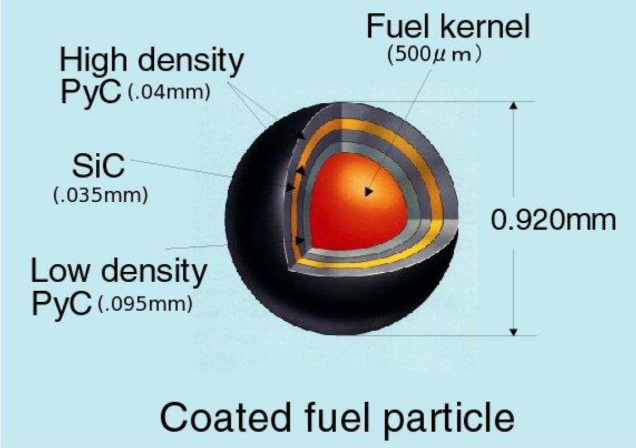
Fiber Laser Printing
+
Spot Coating
=
1 ½ D Printing

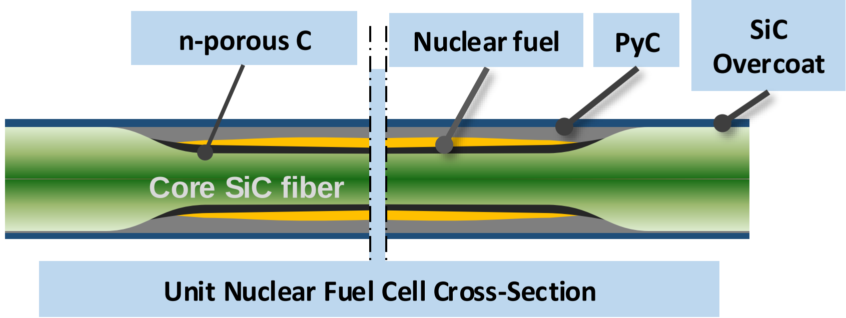
Multi-material fibers

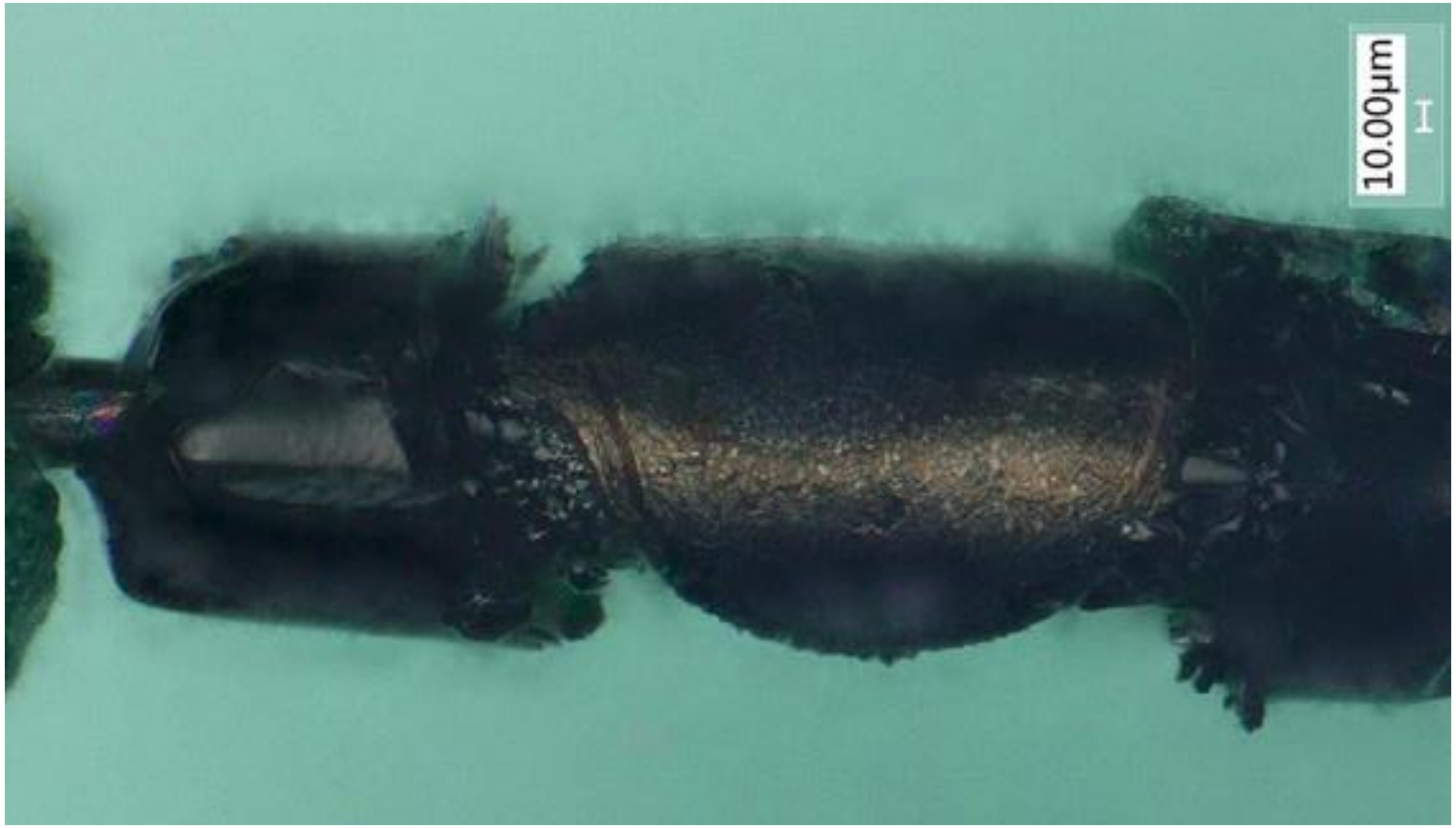
Opening for Integrated multifunctional fiber reinforcement in composite materials

Example: Fuel-in-Fiber:
1 ½ D Printed Fiber-Embedded TRISO-like fuel

TRISO-inspired multifunctional SiC fiber providing fuel containment and structural reinforcement to a SiC CMC.







US Patents 10,546,661 B2 and 11,518,719 B2
DE-SC0018734, Dr. Frank Goldner, PM

Li, W., Shirvan, K., Harrison, S. and Pegna, J.; *Innovative accident tolerant fuel concept enabled through direct manufacturing technology*, Applied Energy, Vol. 264 (2020) https://doi.org/10.1016/j.apenergy.2020.114742

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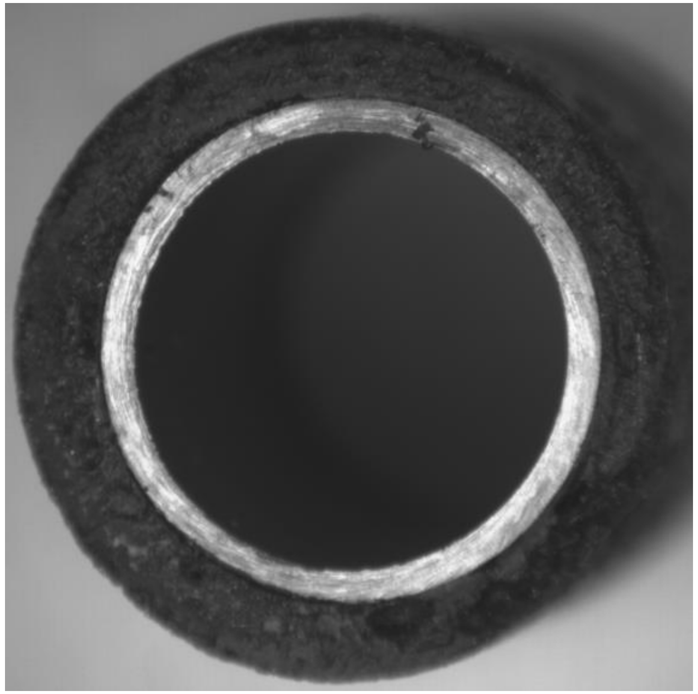
Embedded Wire CVD (EWCVD):
Direct Deposition of SiC-SiC CMCs onto Zircalloy cladding

Optical Microscope Views:

Zone 1 Diamond sawed

Diamond ground lateral surface



Zone 2 Diamond sawed

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Homogeneous Joining of SiC-SiC Composites

ORNL supplied 1” long SiC/SiC CMC tube samples

Tube pairs homogeneously joined by SiC-SiC CMC

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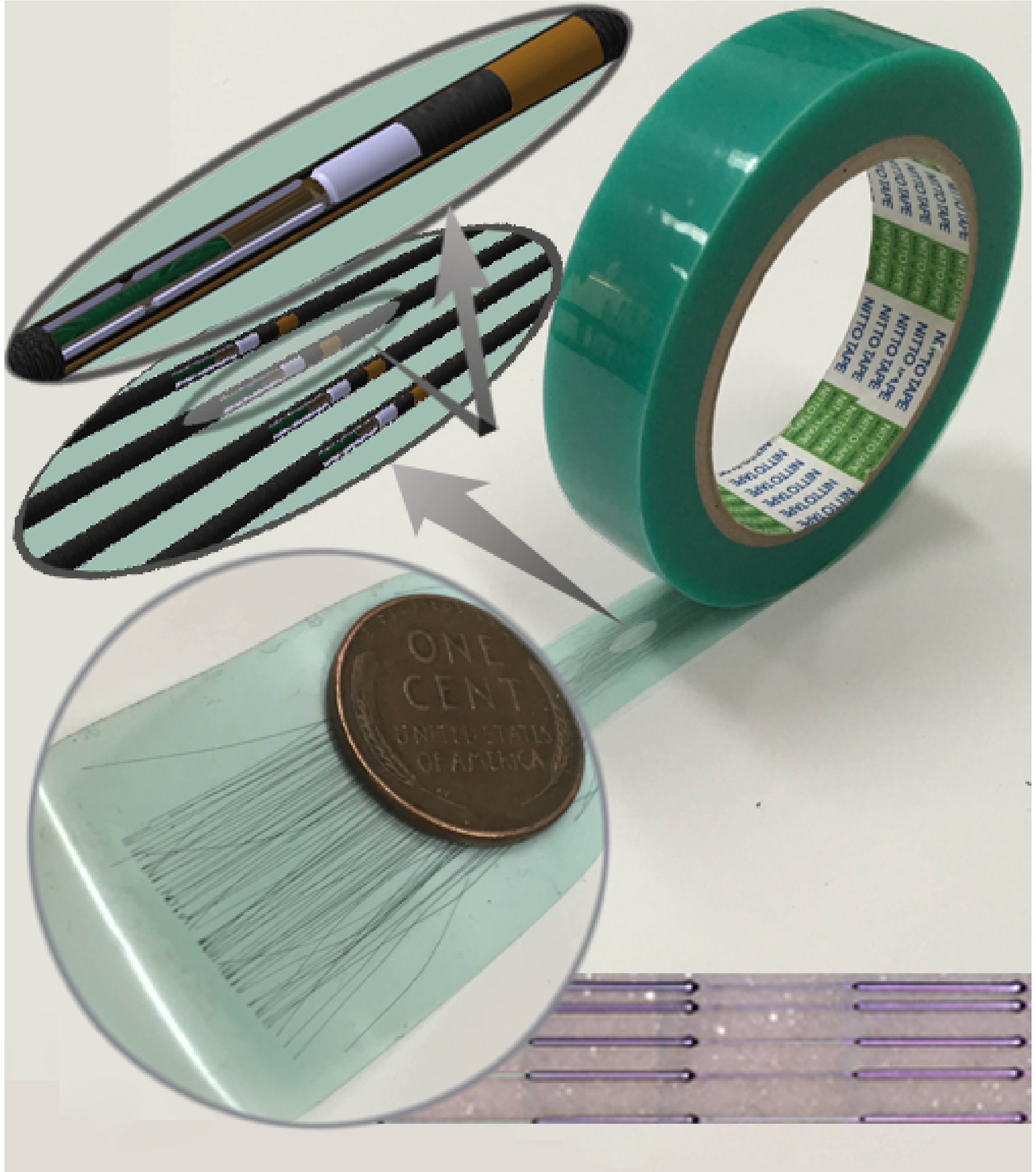
DE-SC0021665, Dr. Chuck Wade, PM.

US Patent Application: 17/661,059

Methodology

Smart structural fibers make intelligent composites



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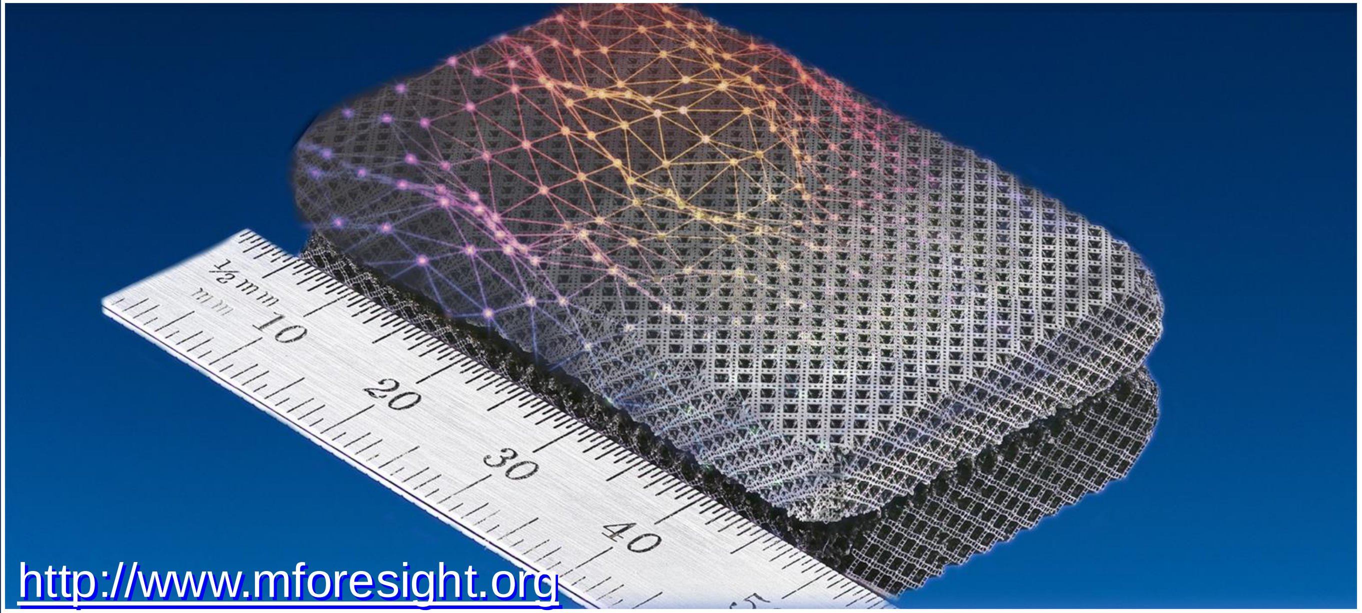
Intelligent Composite ⇔ Smart Fibers



DATA COLLECTION

DIGITAL TWIN

MACHINE LEARNING & AI

BIG DATA

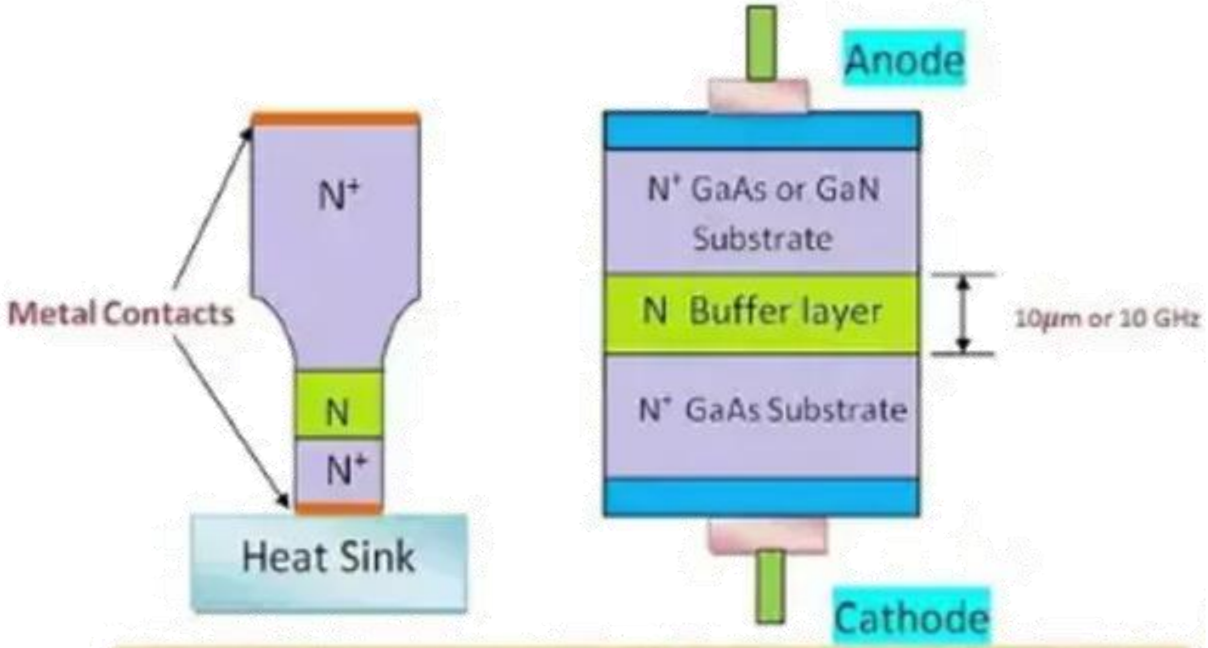
Bio-equivalent: Skin nerve endings.
Fingertip: $241/cm^2$
Fingers: $81/cm^2$
Foot: $21/cm^2$

Source: Tactile innervation densities across the whole body, Giulia Corniani and Hannes P. Saal, 19 Oct 2020 https://doi.org/10.1152/jn.00313.2020

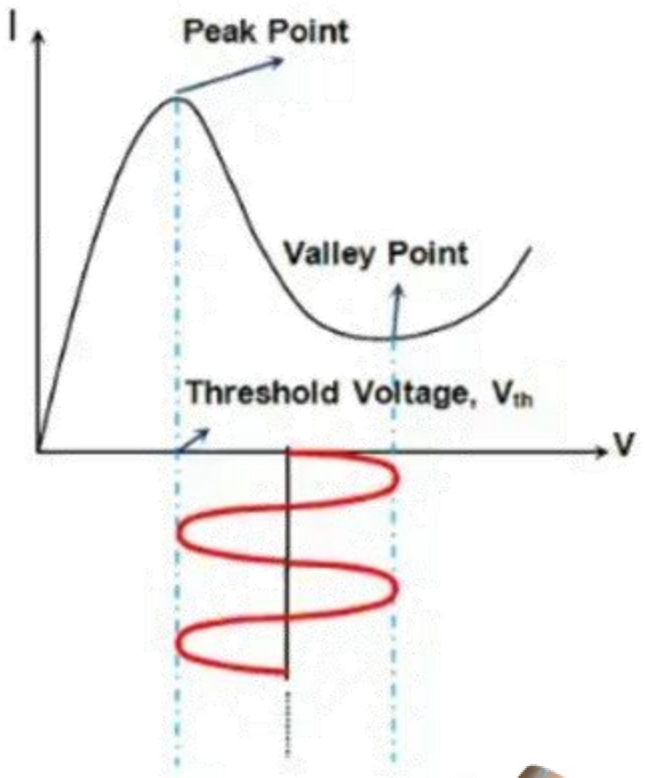
Sample Fiber-*Integrated* Device

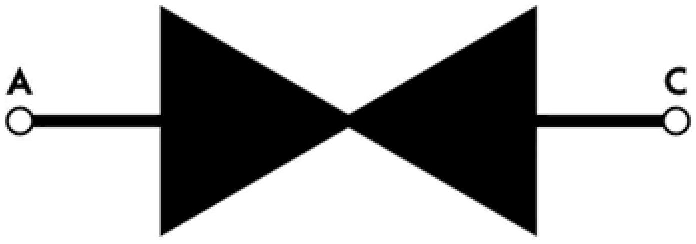
Wireless Thermocouple / Thermal flux Sensor

- **2 functional components:**
  - **Transducer (thermocouple) – Phase I**
  - **Transmitter (Gunn Diode) – Phase II**

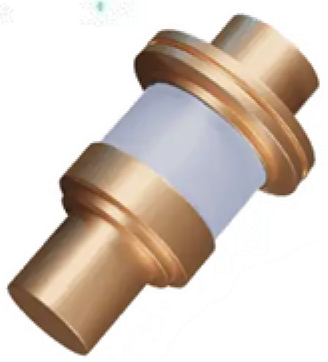


Construction of Gunn Diode





Symbol of Gunn Diode



Nuclear Tech justification:

- GaN or GaAs device: Robust under Gamma and neutron irradiation.
- Working principle only depends on doping differential.

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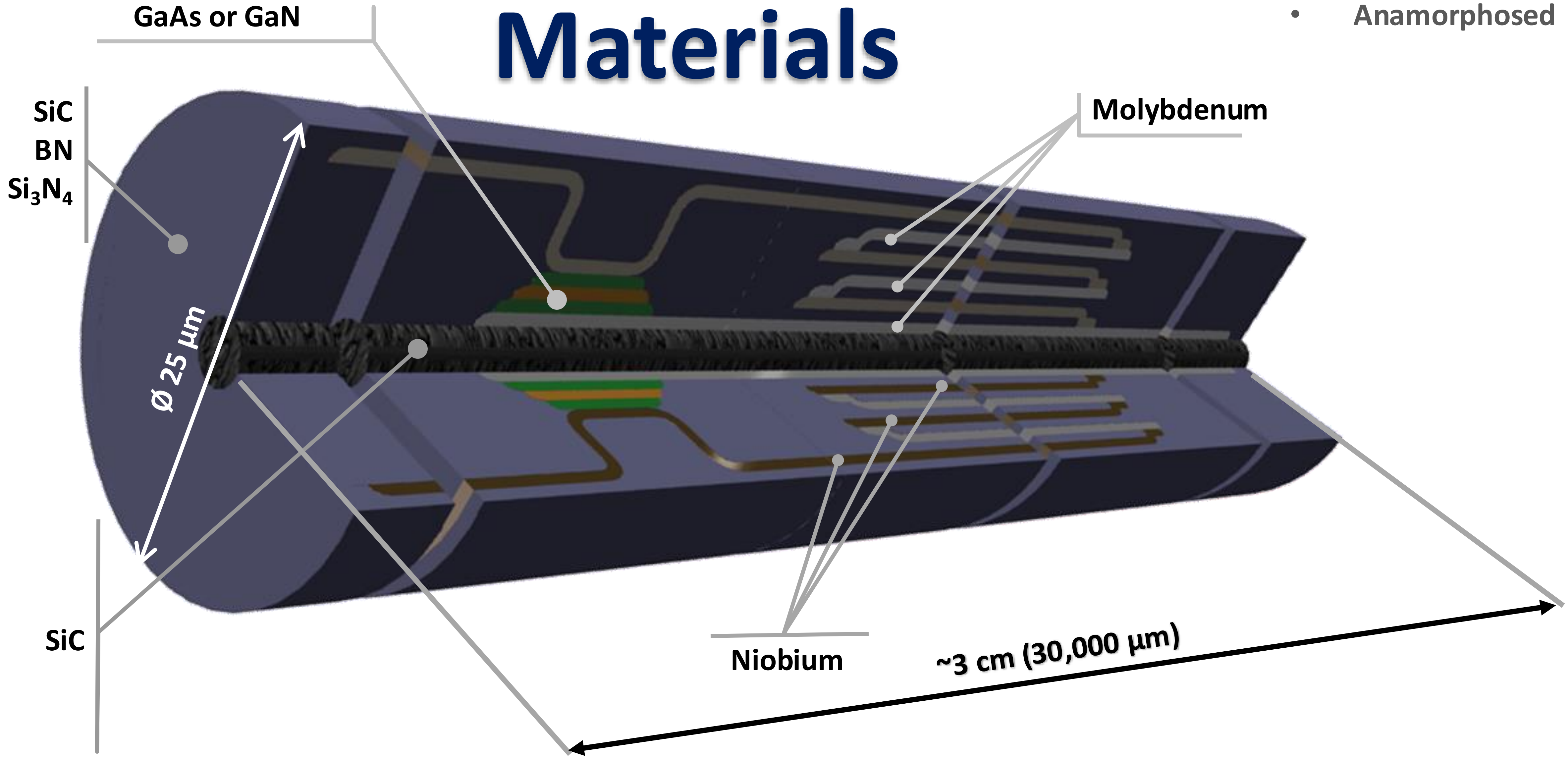
Sample Fiber-*Integrated* Device *

- Broken view
- Not to scale
- Anamorphosed



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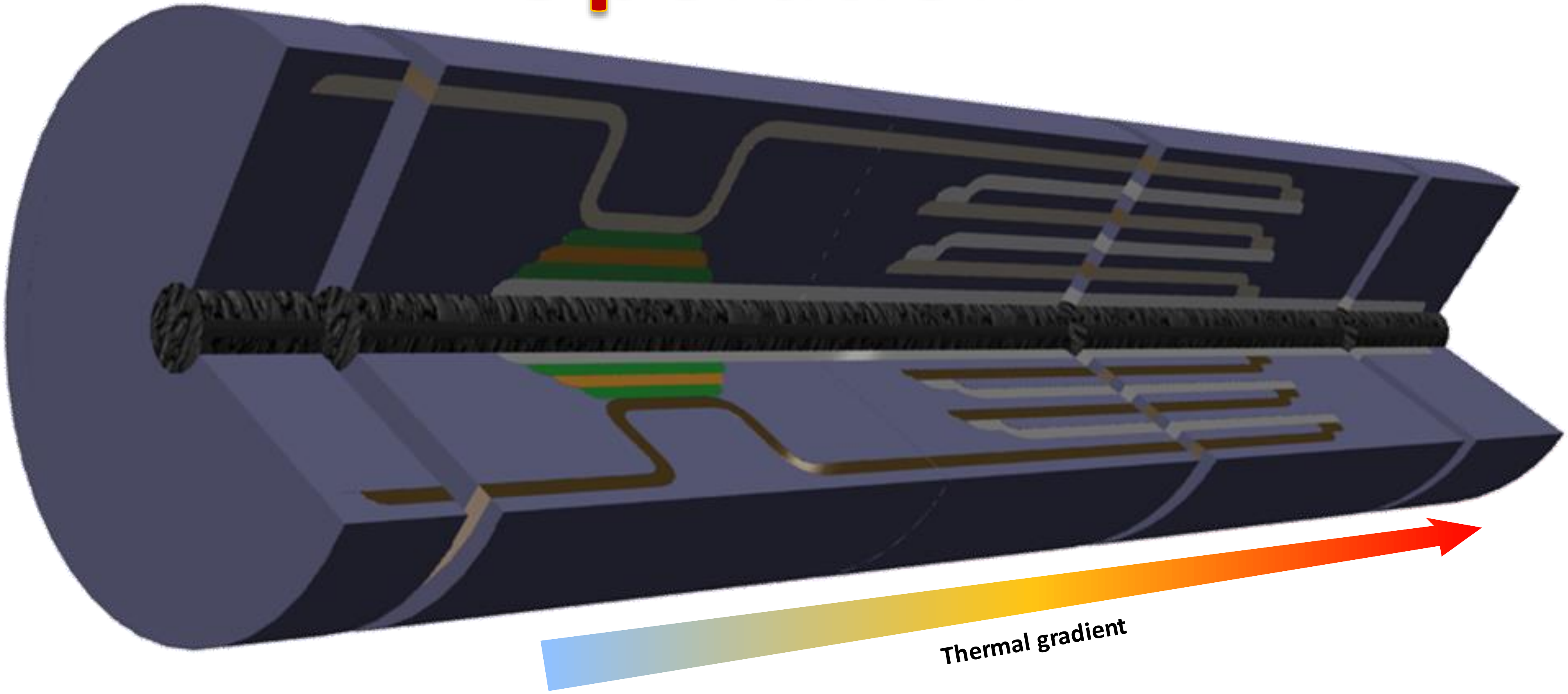
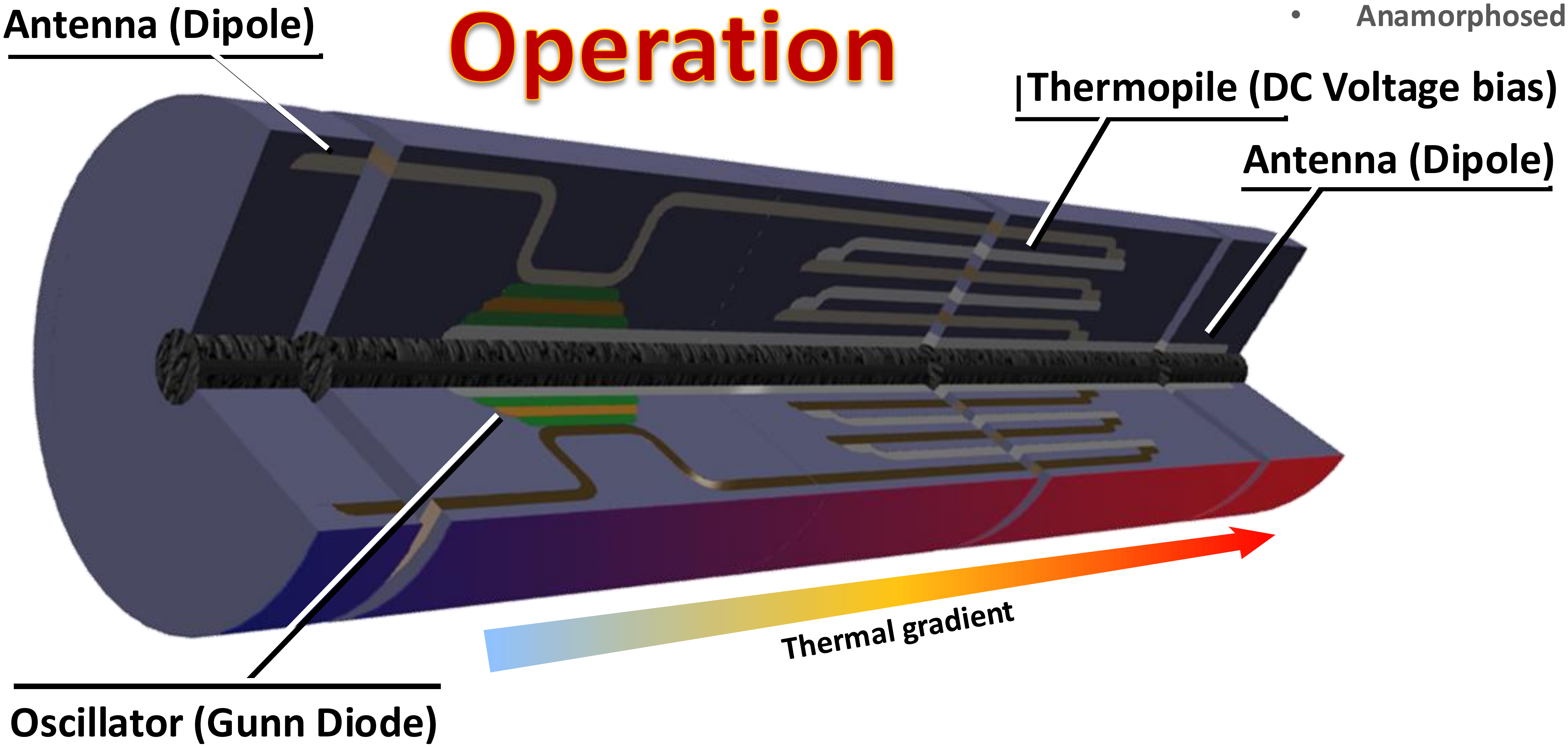
Sample Fiber-*Integrated* Device

Operation



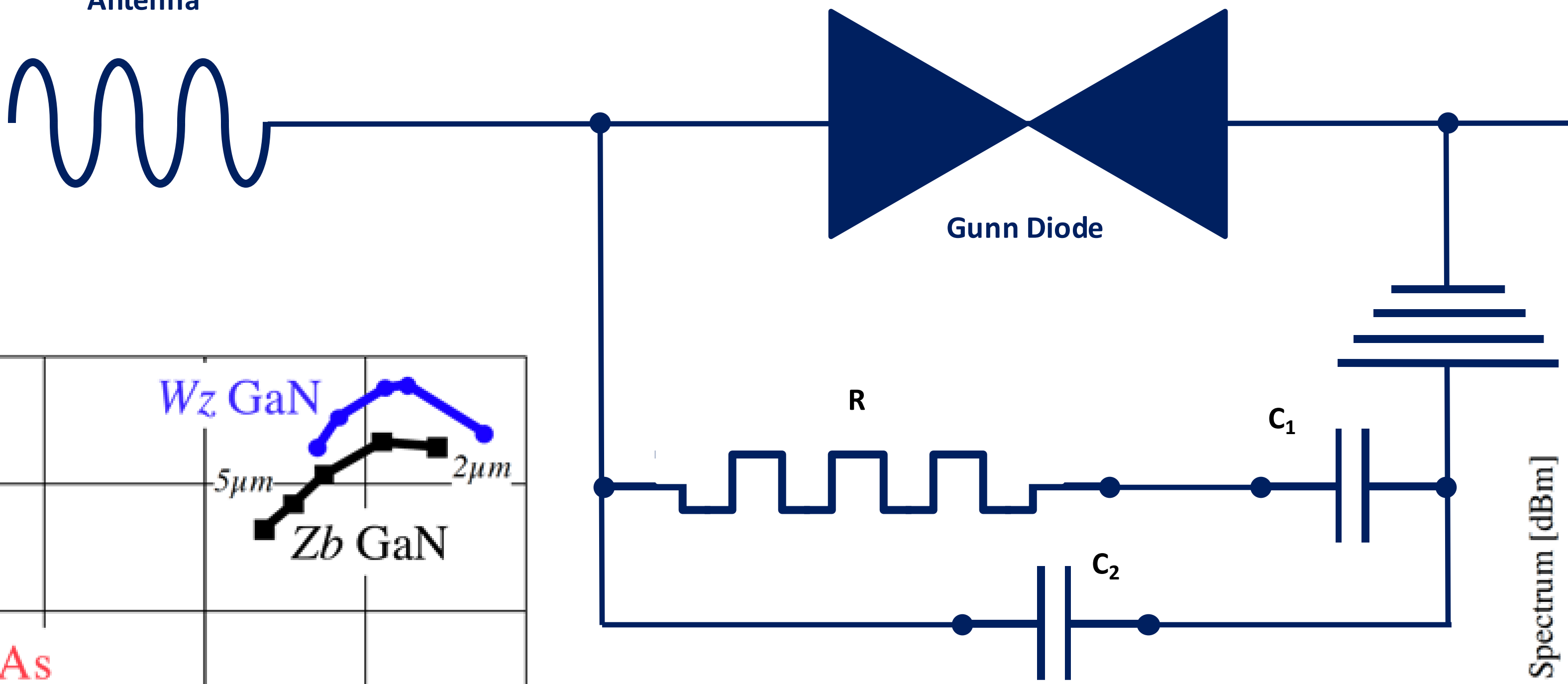
Sample Fiber-*Integrated* Device

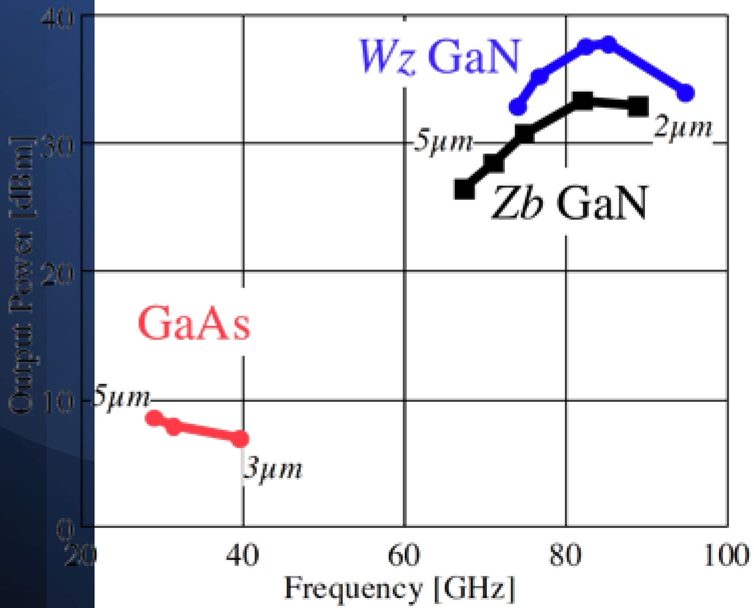
- Broken view
- Not to scale
- Anamorphosed



Sample 1½-D Printed Device

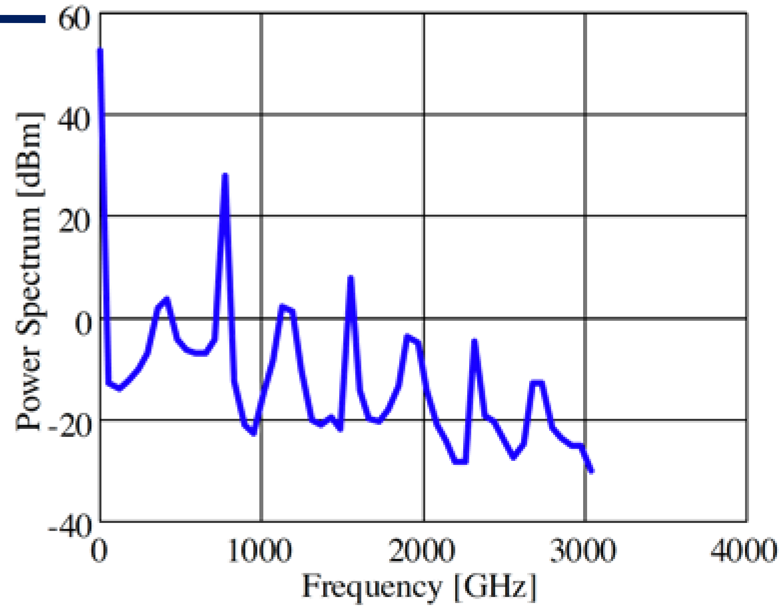
Equivalent Circuit





Example of calculated power output

Example of calculated power spectrum



Source: Alekseev, E., Pavlidis, D., Sutton, W.E., Piner, E., Redwing, J.; IEICE Trans. on Electronics Vol. E84C No.10 pp.1462-1469 (2001)

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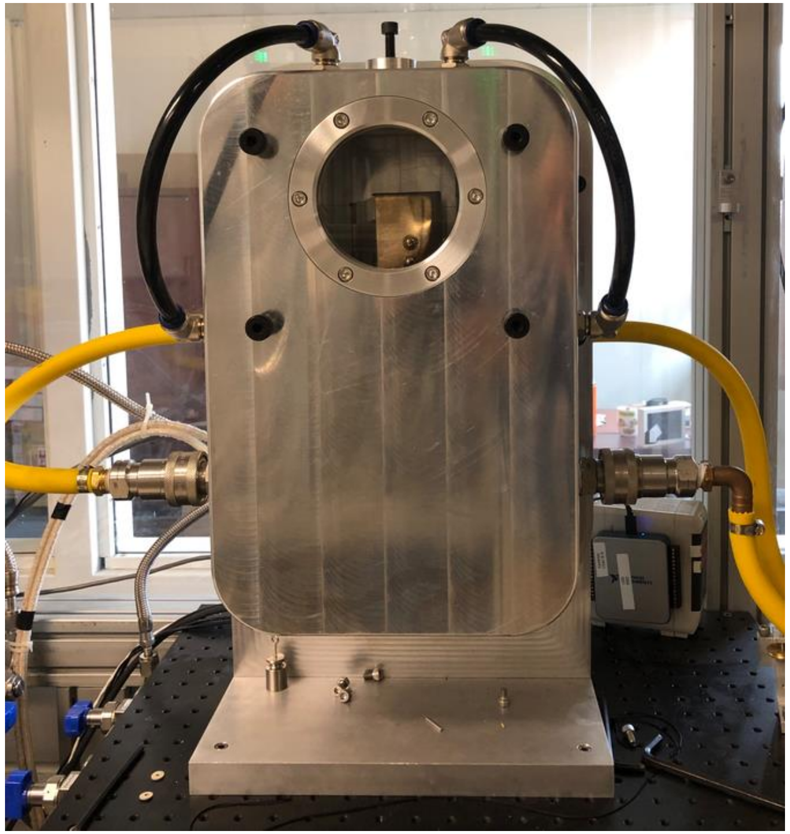
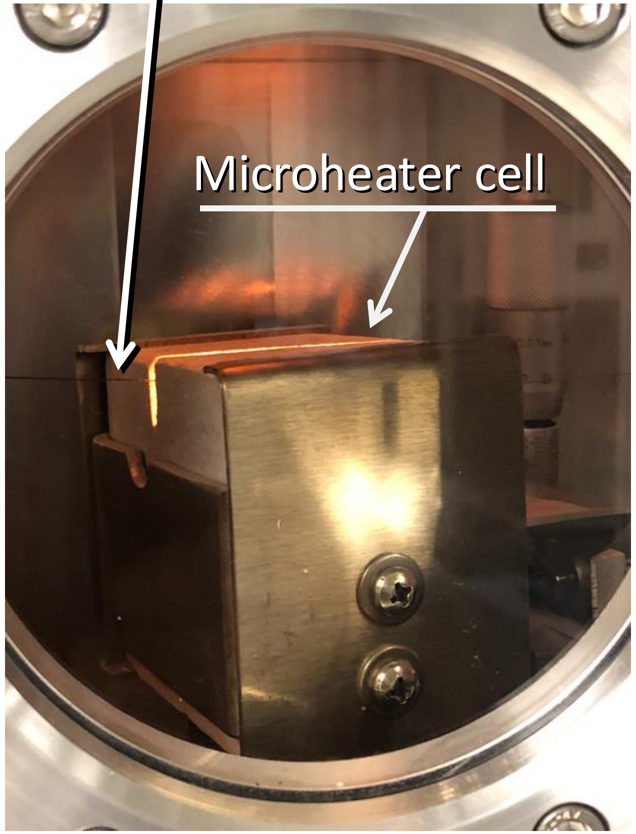
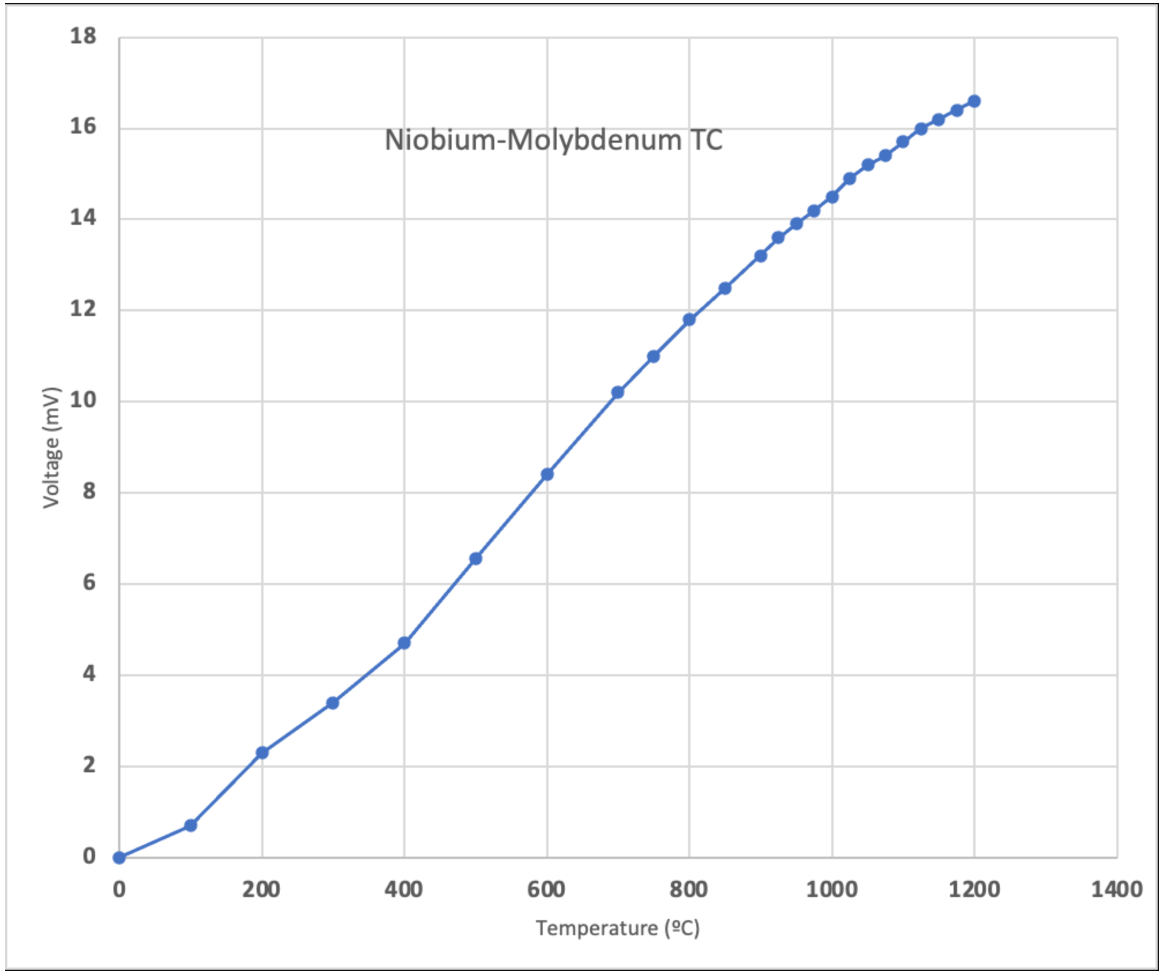
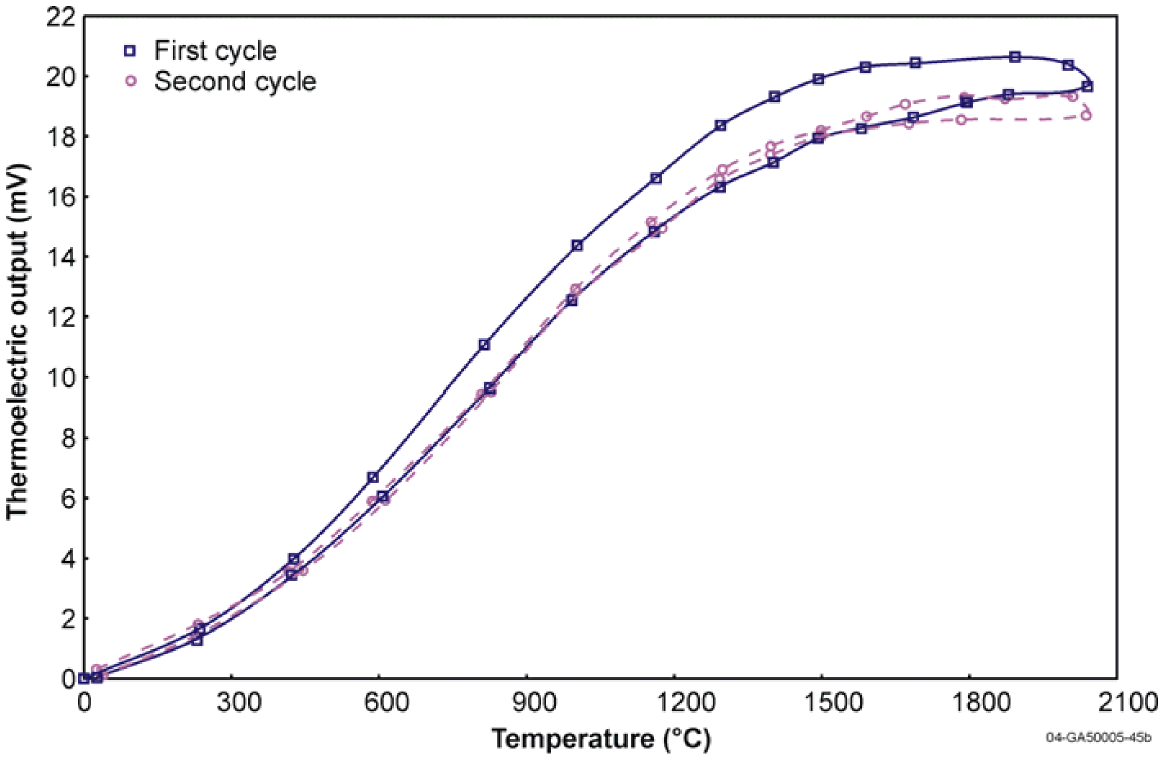
Fiber-Integrated Niobium-Molybdenum TC Demo & Characterization





Niobium-Molybdenum Thermocouple Demo & Characterization





Source:

S. C. Wilkins, “Characterization and Materials-Compatibility Tests of Molybdenum-Niobium Thermocouples,” Seventh International Symposium on Temperature: Its Measurement and Control in Science and Industry, Toronto, Ontario, Canada, April 28-May 1, 1992.

S.C. Wilkins, et al., “Low Cross-Section Mo-Nb Thermocouples for Nuclear Applications: The State-of-the-Art,” Fifth Symposium on Space Nuclear Power Systems, pp 499-502, Albuquerque, New Mexico, January 11-14, 1988.

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Conclusions & Ongoing Work

GOAL: Establishing Seminal Transition to Integrated Intelligent Fuel by AM.
ACHIEVEMENT: First demonstration of a fiber integrated thermocouple
CHALLENGE: Fiber-Integrated Gunn Diode remains to be demonstrated

TECHNOLOGICAL IMPACT:

1. *Supports feasibility of large density integrated low-cost sensors.*
2. *General approach to multifunctional fibers: e.g. Flexible devices in fiber-reinforced CMCs*
3. *Low-cost devices (~10's m¢/device)*

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