# Understanding the Global Semiconductor R&D Landscape

*Hassan Khan, YY Ahn, Filipi Nascimento Silva, Afonso Amaral,*

## Background

In the aftermath of the Covid-19 pandemic, the semiconductor industry has undergone two major shifts. The first is a policy shift driven by increasing geopolitical competition and a focus on supply chain resiliency. The second is a technology shift driven by the emergence of Artificial Intelligence as the largest demand driver for the industry.

Both of these shifts are also beginning to re-shape the global R&D landscape. Nations have launched ambitious programs to reshore manufacturing and upskill their workforces. Across the US, EU, South Korea, and Japan these programs have allocated billions of dollars to both manufacturing and R&D. Additionally, the private race to create large-scale AI systems has fueled capacity expansions and new technology approaches (e.g. advanced packaging, backside power delivery, high-bandwidth memory).

At the same time, emerging workloads are driving demand for wide-bandgap power electronics and more performant photonic integrated circuits. These emerging platforms receive far less attention but are potentially critical areas of investment for clean energy, electric vehicles, and datacenter scale-out.

This report will provide an overview of the global semiconductor R&D landscape taking into account the ongoing impact of the two epochal shifts highlighted above. The report will focus on activities in the US, EU, and east Asian allies  It will also provide selected data-driven deep dives on specific technologies to highlight capabilities that can be expanded in future work.

# Study Aims and Approach

The request is for this presentation to address the below three items:

- Mapping of the areas where academia, industry, U.S. government programs, foreign governments, and other major R&D institutions are making, or are planning to make, semiconductor R&D investments.
- Identify the areas for additional investment that would have the greatest potential to further USG mission, recognizing that advancements in some technology areas may require broad collaboration that can be effectuated by USG.
- To the extent feasible within the timeframe and resources available, the study could include neutral assessment of potential future scientific and industrial trajectories in semiconductors; the potential military, economic, and social implications of those trajectories, and the opportunities and bottlenecks to realizing those futures.

Given the expedited study timeframe, the primary focus of the work will be on the first two bullets above. However, it is expected that this work will also begin to elucidate information about potential future trajectory that is relevant to the funding agency.

This study will combine two primary approaches. First a qualitative survey of published research program goals and agendas. This survey will primarily focus on publications from public agency and consortia groups given that firms do not highlight their research agendas due to competitive concerns.

The second is a quantitative review of publishing and patenting behavior in semiconductors. By definition this will be backwards looking but will indicate trends in research. We will combine high-level overviews with deep-dives on specific emerging technologies that are known to be relevant to future product roadmaps (e.g. advanced packaging, high-bandwidth memory, backside power delivery, etc.) to show how these technologies mature from scientific research to commercial products.

**Qualitative survey of major R&D research programs in semiconductors across US, EU, South Korea, Japan, and Taiwan**

- Focus is on understanding how research focus has evolved over time (e.g. what areas were hot 5 years ago, what areas are programs focusing on now, where were needs identified previously and how are current research programs addressing or not addressing)
- Explore the differences in structure of R&D research programs from different global regions which would include the organizations/institutions/agencies either channeling funding, or interacting with industry - and their objectives. (besides the differences in focus areas, what are the different ways funding is getting channeled?)
- Particular focus on where there is overlap between stated research goals and where there is not (e.g. are all USG agencies funding the same things? Do their funding programs align with the White House Microelectronics Research Strategy?

**Quantitative review of semiconductor R&D trends**

- Publication mapping by semiconductor R&D sub-area grouped by country and institution type over the years
- Explore potential links between funding agency focus areas and performance
- Specific focus on industry R&D themes - what are leading firms publishing in research journals and conferences (e.g. explosion in advanced packaging + silicon photonics), how does this tie to their patenting efforts?
- Highlight specific areas of focus rather than just broad data (e.g. evolution on number of patents and number of publications)
- [potential] Venture Capital investment themes: What types of firms are raising semiconductor funding from Venture Capitalists (focus on the US)? What does this tell us about technology trends and how they're tied to R&D focus programs

# Databases and capabilities

## Academic publications

Academic publications are tracked using two primary datasets: Web of Science and OpenAlex. We use a curated version of the Web of Science (WoS) publication database, hosted at Indiana University, to analyze scientific investment patterns in physical sciences and semiconductor-related fields. Our dataset includes internationally indexed journal and review articles published between 1960 and 2024 (included), filtered for completeness of institutional address and disciplinary classification. The OpenAlex dataset is a comprehensive, open-access catalog of scholarly metadata, encompassing over 250 million records on publications, authors, institutions, venues, and topics. It is designed as a successor to the Microsoft Academic Graph (MAG) and provides structured, interlinked data via a graph-based model and is updated monthly. We have access to two processed funding datasets. The first funding dataset documents the country-paper link. It was drawn from WoS metadata, which has the most comprehensive coverage), and cleaned by removing erroneous or rare entries. We assigned funding sources to countries with high accuracy. This data has been used in our preprint (Miao et al., 2025, under review in *Nature Communications,* https://arxiv.org/abs/2308.08630). The second dataset links, while not as comprehensive as the first, each funding instance to a standardized funding identifier (ROR: Research Organization Registry), allowing analysis based on the types of funders.

We also employ a pre-processed dataset of cutting-edge semiconductor publications as well as a semi-automated pipeline for producing the dataset. This dataset was originally drawn from IRDS post-CMOS roadmap publications. For each technology, we obtained the key publications cited in the IRDS report as well as their intellectual sources (references) and derivatives (future citations). This dataset captures the publications that led to the key breakthroughs as well as the current progresses on each front.

## Patents

Patents data are obtained from a curated dataset derived from the USPTO patent dataset, provided by PatentsView. This covers over 7 million patents published in the U.S. until the end of 2025. The dataset provides metadata, content, such as titles and abstracts, and citation relationships among patents.

## Interactive visualization platform

We will deploy interactive visualizations built on our prior work with Helios-Web (heliosweb.io), a scalable system for exploring large-scale networks and embeddings, including scientific and technological landscapes. The platform will enable real-time, dynamic navigation of semiconductor research data across countries, institutions, and technologies by integrating publication, patent, and funding records into a unified semantic map. This will be achieved by embedding the textual content of publications and patents using transformer-based models fine-tuned for the scientific language, such as SPECTER. Users will be able to navigate these semantic spaces and apply filters to explore specific institutions, technologies, or time periods. The resulting visualizations will reveal how technologies emerge, evolve, and cluster within the global R&D landscape.

Our preliminary map, shown in Figure X, was generated using the SPECTER model employing data from both the MAG (for training) and WoS (for inference). This embedding captures the full spectrum of scientific research, producing a structured landscape where distinct regions correspond to different disciplines. In Figure Y, we zoom into a region of this space to examine the placement of two post-CMOS technologies: 2D material channel FETs and topological insulators. The density gradient indicates the relative prevalence of publications funded by the U.S. and China, highlighting geographic differences in research emphasis.

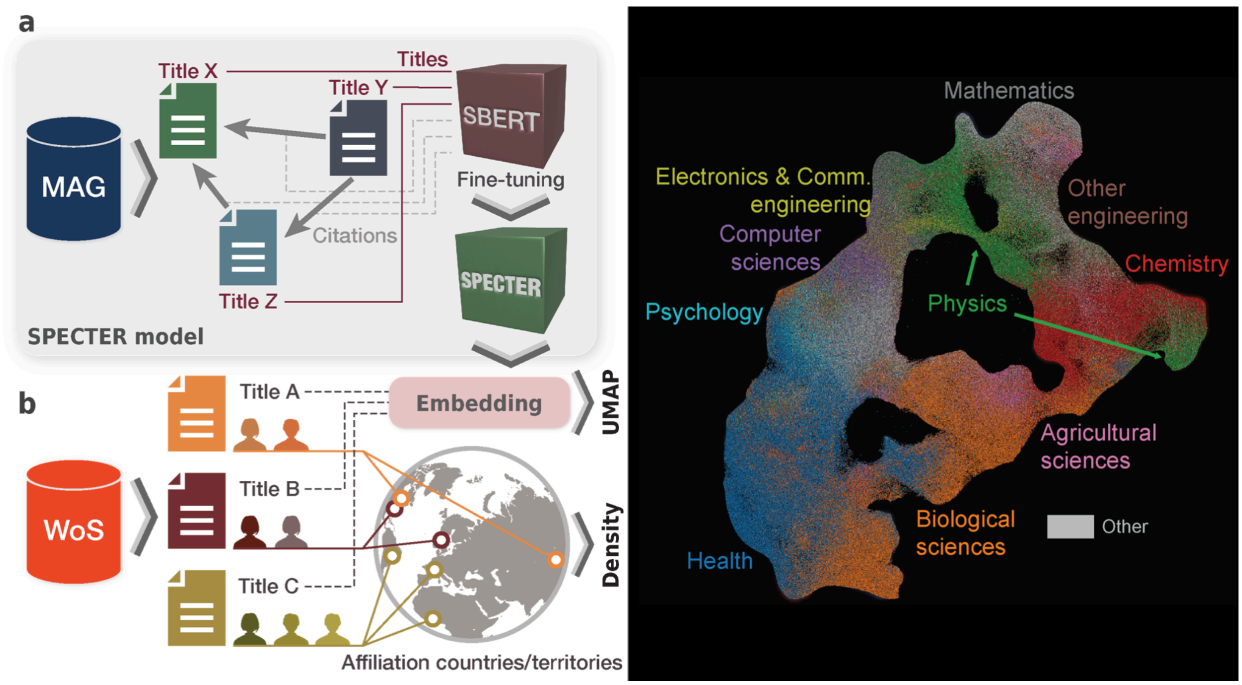


Figure X - Semantic landscape of science based on SPECTER embeddings, projected into two dimensions using UMAP. Colors represent NSF-assigned disciplines associated with each paper.

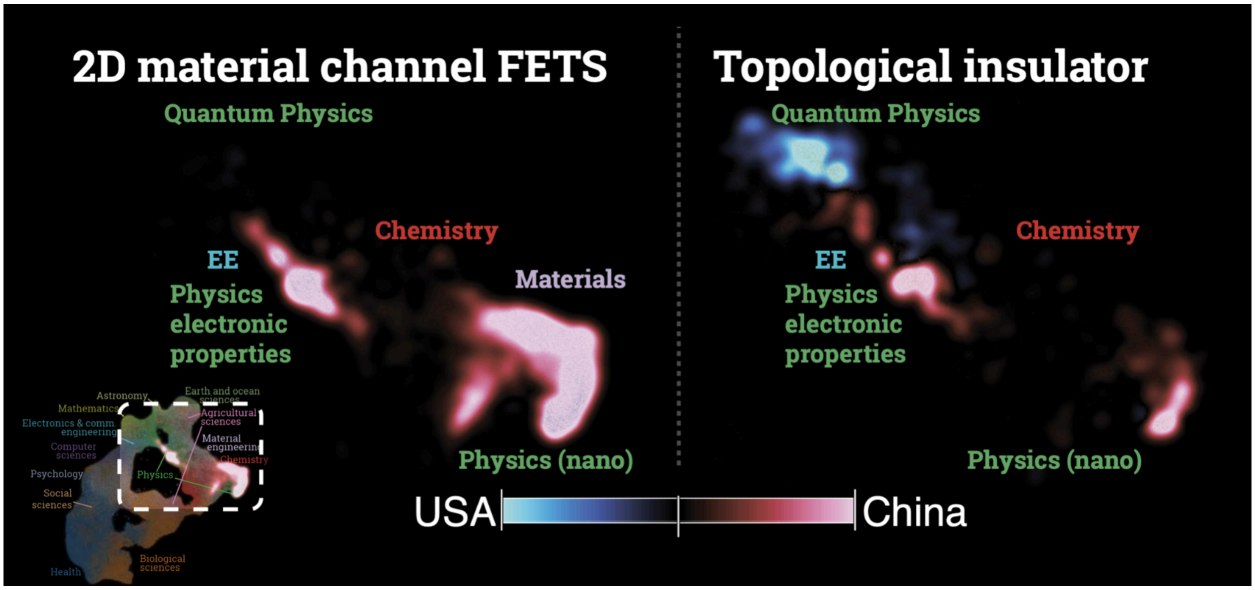


Figure Y - Distribution of publications related to two post-CMOS technologies, illustrating their placement within the scientific landscape and the funding contributions from the U.S. (blue) and China (red).

The embeddings will also be analyzed along meaningful dimensions, such as comparing research and patents from institutions receiving VC investments versus those funded solely by public or other sources. These semantic axes can reveal patterns in the knowledge space, highlighting technologies that are more likely to attract private investment, as well as identifying gaps or untapped areas that may benefit from increased support.

## Researcher Bios

**Hassan Khan**
Hasasn Khan was most recently the Director of Economic Security at the CHIPS Program Office at the Department of Commerce. At CHIPS he oversaw the development of their strategic investment portfolio and worked alongside investment teams on nearly every deal. He also worked with the Department of Treasury on implementation of the AMIC. Prior to CHIPS, he was a member of the National Network for Critical Technology Assessment at CMU. He also previously worked at Apple and McKinsey focused on global manufacturing initiatives. He received his PhD from Carnegie Mellon's department of Engineering and Public Policy where his dissertation examined the policy programs behind finding a successor to silicon CMOS. He was the recipient of the NSF GRFP.

**Yong-Yeol "YY" Ahn**
Yong-Yeol (YY) Ahn is a Quantitative Foundation Distinguished Professor at the University of Virginia School of Data Science. He was previously a Professor at the Indiana University School of Informatics, Computing, and Engineering and a Visiting Professor at MIT during 2020–2021. He worked as a postdoctoral research associate at the Center for Complex Network Research at Northeastern University and as a visiting researcher at the Center for Cancer Systems Biology at the Dana-Farber Cancer Institute after earning his PhD in Statistical Physics from KAIST in 2008. His research focuses on data science, spanning methodological work in network science, machine learning, and AI, as well as their applications to computational social science, computational neuroscience and biology, and the science of science. He serves as an expert in the National Network for Critical Technology Assessment, a major initiative of the NSF Technology, Innovation and Partnerships (TIP) Directorate. He is the recipient of several awards, including the Microsoft Research Faculty Fellowship and the LinkedIn Economic Graph Challenge.

**Filipi Nascimento Silva**
Filipi N. Silva is an Associate Research Scientist at the Observatory on Social Media (OSoMe) — Indiana University. He obtained his Ph.D. in Computational Physics from the São Carlos Institute of Physics at the University of São Paulo. Dr. Silva's research centers around science of science, innovation analysis, and the dynamics of scientific discovery. He develops and employs advanced computational methods, including complex network analysis, embedding techniques, and interactive data visualization, to reveal hidden structures and patterns within scientific ecosystems. His interdisciplinary approach aims to understand how innovation emerges, propagates, and influences scientific trajectories. Recent projects include mapping the evolution of research fields through semantic embedding spaces, analyzing the strategic alignment and impact of science funding, and developing new frameworks for identifying and measuring scientific novelty and innovation. Dr. Silva also creates interactive visualization tools designed to facilitate the exploration and interpretation of large-scale scientific data, contributing actionable insights into the mechanisms driving scientific progress and innovation.

**Afonso Amaral**

Afonso Amaral leads international alliances research at the Critical Technology Initiative at Carnegie Mellon University, focusing on technology and manufacturing policy and regulation. His research specializes in advanced manufactured products, trade, innovation, and industrial mobilization strategies aimed at addressing current product shortages and future technology trajectories. His work focuses on European industries such as semiconductors, drones, green (net-zero) technologies, and medical products and devices. Afonso Amaral has been exploring the global semiconductor landscape and technological paradigm shift, by studying the potential of different technological pathways (More-Moore, More-than-Moore, Beyond CMOS devices). Afonso Amaral also collaborates with European institutions, for instance, he co-developed an early warning mechanism for monitoring supply chain disruptions with the Chief Economist team at the European Commission's Directorate-General for Internal Market, Industry, Entrepreneurship, and SMEs. This mechanism is currently employed for several critical and green technologies as well as semiconductors supply chains. Furthermore, Afonso has been collaborating with other departments within the European Commission to investigate structural vulnerabilities and arising risks in semiconductor supply chains, assess global industrial capabilities, and evaluate targeted domestic policies.

**Fernando Portilla** (under Dr. Afonso Amaral supervision)

Fernando is a software engineer and Engineering and Public Policy graduate student with a dual background in industrial and computer engineering, bridging cloud-scale systems, governance, and global supply chain resilience. Led development of an interoperable electronic health record platform at Snappi, advancing automation and AI adoption across clinical settings. At Microsoft, contributed to Azure Policy's enforcement and reporting architecture, supporting regulatory compliance across millions of cloud resources. Technical scope spans generative AI systems, back end services, and data analysis. Current work includes mapping semiconductor manufacturing equipment and developing replicable methods to identify sourcing risks across regions and contribute to evidence-based industrial policy.

## Previous relevant work:

- Miao, Lili, Vincent Larivière, Feifei Wang, **Yong-Yeol Ahn**, and Cassidy R. Sugimoto. "Cooperation and interdependence in global science funding." Under review in *Nature Communications*, arXiv preprint arXiv:2308.08630 (2023).
- Kim, Munjung, Marios Constantinides, Sanja Šćepanović, **Yong-Yeol Ahn**, and Daniele Quercia. "The Potential Impact of Disruptive AI Innovations on US Occupations." Under review, arXiv preprint arXiv:2507.11403 (2025). https://arxiv.org/abs/2507.11403
- Miao, Lili, Dakota Murray, Woo-Sung Jung, Vincent Larivière, Cassidy R. Sugimoto, and **Yong-Yeol Ahn**. "The latent structure of global scientific development." Nature Human Behaviour 6, no. 9 (2022): 1206-1217.
- Peng, Hao, Qing Ke, Ceren Budak, Daniel M. Romero, and **Yong-Yeol Ahn**. "Neural embeddings of scholarly periodicals reveal complex disciplinary organizations." Science Advances 7, no. 17 (2021): eabb9004.
- **Khan, Hassan**, Erica Fuchs, and David Hounsehll. "Science and Research Policy at the End of Moore's Law" [https://www.nature.com/articles/s41928-017-0005-9](https://www.nature.com/articles/s41928-017-0005-9)
- Kim, Seongwoon, **Yong-Yeol Ahn**, and Jaehyuk Park. "Labor space: A unifying representation of the labor market via large language models." In Proceedings of the ACM Web Conference 2024, pp. 2441-2451. 2024.
- Constantino, Isabel, Sadamori Kojaku, Santo Fortunato, and **Yong-Yeol Ahn**. "Representing the disciplinary structure of physics: a comparative evaluation of graph and text embedding methods." Quantitative Science Studies 6 (2025): 263-280.
- Frank, Morgan R., **Yong-Yeol Ahn**, and Esteban Moro. "AI exposure predicts unemployment risk: A new approach to technology-driven job loss." PNAS nexus 4, no. 4 (2025): pgaf107.
- Kim, Munjung, Sadamori Kojaku, and **Yong-Yeol Ahn**. "Uncovering simultaneous breakthroughs with a robust measure of disruptiveness." Under review in Science Advances, arXiv preprint arXiv:2502.16845 (2025).
- **A Amaral**, MG Morgan, J Mendonça, E Fuchs, 2023, National core competencies and dynamic capabilities in times of crisis: Adaptive regulation of new entrants in advanced technology markets, Research Policy 52 (4), 104715
- **A Amaral**, W Connell Garcia, F Di Cometi, C Herghelegiu, 2022, 'SCAN'(Supply Chain Alert Notification) Monitoring System, Single Market Economics Papers, Directorate-General for Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs, Chief Economist Team
- Ana C. M. Brito, Maria C. F. Oliveira, Osvaldo N. Oliveira Jr., **Filipi N. Silva**, and Diego R. Amancio. "History of Chemistry of Materials According to Topic Evolution Based on Network Analysis and Natural Language Processing." Chemistry of Materials 36 (2024): 1–7.
- Jaromír Klarák, Ana C. M. Brito, Luan F. Moreira, **Filipi N. Silva**, Diego R. Amancio, Robert Andok, Maria C. F. Oliveira, Mária Bardošová, and Osvaldo N. Oliveira Jr. "Using Network Analysis and Large-Language Models to Obtain a Landscape of the Literature on Dressing Materials for Wound Healing: The Predominance of Chitosan and Other

Biomacromolecules: A Review." International Journal of Biological Macromolecules 306 (2025): 141565.

- Jin Ai, Richard S. Steinberg, Chao Guo, and **Filipi N. Silva**. "Triadic Novelty: A Typology and Measurement Framework for Recognizing Novel Contributions in Science." arXiv preprint arXiv:2506.17851 (2025).
- Attila Varga, Sadamori Kojaku, and **Filipi N. Silva**. "Measuring Research Interest Similarity with Transition Probabilities." Quantitative Science Studies (2025): 1–40.
- Katy Börner, **Filipi N. Silva**, Stasa Milojević, Visualizing big science projects, Nature Reviews Physics 3 (11), 753-761

## Possible journals for tracking publications:

These journals were selected based on their scientific impact, peer recognition, and strong alignment with the semiconductor device roadmap (including logic, memory, and materials):

**1. Nature Electronics**
Premier interdisciplinary journal focusing on devices, materials, and systems for electronics. Frequently publishes state-of-the-art work on spintronics, ferroelectric memory, topological materials, and neuromorphic architectures.
Impact Factor >25 (among the highest in applied physics and materials science).

**2. IEEE Transactions on Electron Devices (T-ED)**
Flagship IEEE journal for semiconductor devices. Excellent for CMOS extensions and commercial feasibility studies of new FETs and memory architectures (e.g., STT-MRAM, ReRAM, CBRAM).
Strong industry-academic mix, often includes reliability and scalability studies.

**3. Journal of Applied Physics (JAP)**
High-quality journal with strong coverage of materials and device physics, especially for magnetoelectric, ferroelectric, and Mott-based devices.
Frequently cited in the IRDS and beyond-CMOS community. Ideal for foundational science informing commercial paths.

**4. Japanese Journal of Applied Physics (JJAP)**
Actively publishes Beyond-CMOS roadmap articles (including the 2022 roadmap by An Chen). Strong focus on Asia-based developments (Japan, Korea) which makes it good for comparative tracking.

**5. Nature Nanotechnology**
Covers breakthroughs in 2D materials, nanoelectromechanical systems, and neuro-inspired computing, all core elements of beyond-CMOS.
Often publishes commercialization roadmaps or spin-off company analyses (to be confirmed).

Conferences: ECTC, VLSI, Hot Chips

[DOE Basic Research Needs]
[SRC MAPT]
[EU SRIP REPORT]
[Digital EU]

| Institution | Report / Strategy | Key R&D Focus Areas |
|---|---|---|
| **SRC** | Decadal Plan for Semiconductors / MAPT Roadmap | Analog compute, memory fabrics, advanced packaging, secure systems, energy efficiency |
| **IMEC** | 20-Year Semiconductor Roadmap / imec Highlights 2023 | High-NA EUV, forksheet/CFET devices, 3D stacking, sustainable scaling, 2nm+ nodes |
| **EU Commission** | European Chips Report / SRIP Report / R&D Policy Brief | Node shrink, pilot lines, IP, talent, EU-level R&D funding mechanisms |
| **IITP** | ICT R&D Strategy (via IITP) | AI chips, logic/memory leadership, ecosystem funding, public-private partnerships |
| **LSTC / METI** | LSTC / METI Strategy | Domestic 2nm R&D, materials, design, Rapidus-led pilot line efforts |
| **ITRI** | TSMC R&D Overview / Ecosystem reports | Advanced logic (2nm), 3D packaging, specialty SoCs, new memory, platform R&D |
| **ASPI** | ASPI Semiconductor Moonshot Report / ANFF Overview | Compound semiconductors, pilot fabs, mature-node CMOS, research translation, skill pipelines |
| **OSTP** | National Strategy on Microelectronics Research | Foundational research, infrastructure, workforce, R&D-to-manufacturing ecosystem |
| **DOE** | Basic Research Needs for Microelectronics | Materials R&D, novel architectures, extreme environments, edge computing |
| **NSF** | NSF–NIST Microelectronics Workforce MOU / National Chip Design Center Proposal | Education pipeline, chip design tools, design centers, workforce inclusion |
| **DARPA** | Electronics Resurgence Initiative / Microsystems Technology Office | High-risk innovation: photonics, RF, energy-efficient logic, heterogeneous integration, secure ICs |