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Bridging academia and industry for the future of spintronics

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The future of spintronics hinges on the effective collaboration between academia and industry. Here we explore the crucial role of partnership in advancing research and innovation, highlighting how these collaborations can drive technological breakthroughs in the field of spintronics and facilitate their transition to practical applications.

Spintronics, or spin-based electronics, utilizes both the spin and charge of electrons for information processing and has emerged as a key contender in fields such as data storage, computing, and other traditionally semiconductor-driven technologies. The origins of spintronics date back to the 1920s, when Samuel Goudsmit and George Uhlenbeck discovered electron spin as a fundamental quantum property. This understanding was further advanced by Wolfgang Pauli's development of the Pauli exclusion principle, which, together with progress in quantum mechanics, provided crucial insights into electron behaviour in solids and the nature of magnetism.

The practical applications of spintronics began to take shape in the 1970s and 1980s. One of the key theoretical developments was the spin Hall effect, proposed in 1971 by Jairo Sinova and M. I. Dyakonov, which described the accumulation of electron spin on the edges of a conductor when an electric current flows through it. However, the real breakthrough came in 1988 when Albert Fert and Peter Grünberg independently discovered giant magnetoresistance (GMR), demonstrating that small changes in magnetic field could lead to significant variations in electrical resistance. This discovery earned both scientists the Nobel Prize in Physics in 2007 and marked the birth of modern spintronics. GMR became foundational in the development of hard disk drive (HDD) read heads, with IBM introducing the first GMR-based read heads in 1997, enabling a substantial increase in data storage capacities.

In parallel, the tunnelling magnetoresistance (TMR) effect, a similar phenomenon based on electron tunnelling through an insulating barrier, became crucial in magnetic tunnel junctions (MTJs), further enhancing data storage technologies. The 2000s witnessed more advanced spintronic technologies, such as spin-transfer torque (STT), discovered early in the decade. STT enabled the control of magnetization through spin-polarized currents rather than external magnetic fields, leading to the development of spin-transfer torque magnetoresistive random-access memory (STT-MRAM), a promising non-volatile memory technology[1]. These devices excel in non-volatile memory applications, offering high speed and low power consumption[2]. In addition, spintronics holds potential for ultra-efficient embedded memory, advanced vehicle sensors, and neuromorphic computing applications, offering enhanced performance and efficiency[3–5].

Advancements in emerging memory technologies such as resistive RAM (ReRAM), phase-change RAM (PCRAM) and ferroelectric RAM (FeRAM) are intensifying competition in the memory technology market, driving the need for ongoing innovation and enhanced performance. Spintronics faces considerable challenges in this landscape. From the physics standpoint, ongoing university research is focused on improving the efficiency of spin injections, spin detection and extending spin lifetime and spin coherence — all of which are crucial for the advancement of spintronic devices. Technologically, spintronics must address several key issues, including integrating spintronic devices with existing semiconductor technologies and CMOS processes, scaling up production while optimizing manufacturing techniques, reducing power consumption, and improving switching speeds. Ensuring high reliability and endurance is also essential for long-term device performance. Addressing these challenges effectively will be key to establishing spintronics as a competitive force in the rapidly evolving memory market. Collaboration between academia and industry is crucial in this effort, as it enables the fusion of cutting-edge scientific discoveries with industrial manufacturing processes and standards.

The gap between academia and industry

However, several gaps between academia and industry limit the potential for spintronics technology to become mainstream. A primary difference lies in the focus of each sector: academia typically emphasizes fundamental research, aiming to uncover novel materials and the underlying physics of spin phenomena. Here, success is typically driven by the number of high-impact publications. Although these breakthroughs are scientifically important, they often lack immediate commercial relevance. By contrast, industry prioritizes the practical application of these discoveries, with an emphasis on manufacturability, cost-efficiency and scalability. To bridge this gap, academia must place greater emphasis on applied research, ensuring that innovations are not only novel but also feasible for large-scale production and aligned with the real-world needs of industry.

Another notable challenge is the issue of scalability and manufacturing feasibility. Whereas academic research often focuses on small-scale experiments or individual devices, industry requires these innovations to be scaled for mass production. Tools, facilities and criteria differ considerably between research and industry. Academic tools are typically designed for small-batch processing, usually on coupons or up to 4-inch wafers, whereas industry-grade tools emphasize high-throughput, high-yield production on 12-inch wafers. Moreover, the industry's stringent yield requirements are driven by the need to meet consumer demands efficiently and cost-effectively. Establishing joint research platforms where academia and industry share resources — such as fabrication facilities and characterization tools — is essential. These platforms enable the rapid development and testing of spintronic devices under real-world conditions, addressing practical specifications such as long retention times (such as over

10 years at 85 °C for memory applications) and high write endurance (10^{15} cycles or greater). Such collaborations pool expertise and resources, accelerating the innovation cycle and improving R&D efficiency.

In addition, the issue of commercial viability and cost remains a barrier. Many materials and techniques explored in academic spintronic research are either too expensive or too complex for integration into existing semiconductor manufacturing processes. As a result, a close working partnership between academia and industry is crucial for aligning research with the economic realities of industrial production, especially in lowering costs while maintaining high performance standards.

A further challenge lies in the technology transfer process, in which moving spintronic innovations from university labs to commercial settings can be slow due to intellectual property (IP) issues and differences in approaches to patenting and licensing. Overcoming these barriers requires streamlining the technology transfer process and fostering open communication between both sectors. Collaboration between academia and industry has a pivotal role in addressing these gaps. Joint research initiatives and public-private partnerships enable the sharing of expertise and resources. Academia can benefit from the industry's experience with large-scale manufacturing and product development, while industry gains access to cutting-edge research, facilitating a more efficient and aligned innovation process.

Potential solutions

To enhance industry-academia collaborations in spintronic technologies, several key strategies can be implemented, including government-backed funding initiatives, the establishment of dedicated research hubs and consortiums, long-term funding models, industry involvement in talent development, and multinational collaborative projects:

Government bodies, funding agencies, and private sponsors play a pivotal role in fostering spintronics partnerships. By offering tax incentives, financial support, and incentivizing industry-academia partnerships, they create an attractive environment for industries to invest in these collaborations. Programs such as Singapore's Industry Alignment Fund – Industry Collaboration Projects (IAF-ICP), administered by A*STAR, and various initiatives from the US National Science Foundation (NSF), are instrumental in driving innovation and promoting the commercialization of spintronic technologies. These initiatives often involve multiple governing agencies that work together to steer research through targeted grants, helping to build a robust spintronics R&D ecosystem.

The creation of collaborative platforms, such as spintronics innovation hubs and research centres, offer companies, universities and research institutions a shared infrastructure, including cleanrooms, microfabrication labs, and characterization facilities. Consortiums such as Semiconductor Manufacturing Technology (SEMATECH) and the Singapore Spintronics Consortium (SG-SPIN) help to foster long-term research collaboration, provide access to shared knowledge, and align research goals with industry needs.

Short-term research funding can be unstable and less appealing to industry partners. To ensure continuity in industry-academia collaborations, governments and industry stakeholders should focus on multi-year grants that enable researchers to address complex challenges requiring sustained effort. These funding models should emphasize outcome-based objectives, such as proof-of-concept demonstrations, prototype development, patent filings, and the continuous engagement of industrial partners. This approach encourages academic researchers to work closely with companies to develop commercially viable spintronic solutions.

Furthermore, universities and companies should collaborate with government agencies overseeing education and the economy to launch specialized training programs, internships, and curricula focused on spintronics. This will equip students and researchers with the necessary skills for industrial R&D. Industry fellowship programs, such as the Economic Development Board Industrial Postgraduate Programme (EDB-IPP)[6], enable PhD students to split their time between university research and industry placements. Such arrangements further strengthen industrially relevant research and innovation in spintronic technologies.

Lastly, the initiation of multinational research programs can foster collaborations between countries with leading spintronics research capabilities. Grants co-funded by agencies such as the European Commission, the US NSF, and Singapore's A*STAR would support global cooperation and accelerate progress in the field. International exchanges enable students, researchers, and industry partners to gain valuable experience through placements at global research centres and fabrication plants. Furthermore, international spintronics conferences provide a platform for academia and industry leaders to network, share research and establish collaborative partnerships.

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Competing interests

The authors declare no competing interests.

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