Materiais e Dispositivos Magnéticos e Supercondutores
Profa. Dra. Cristina Bormio Nunes

SPINTRÔNICA

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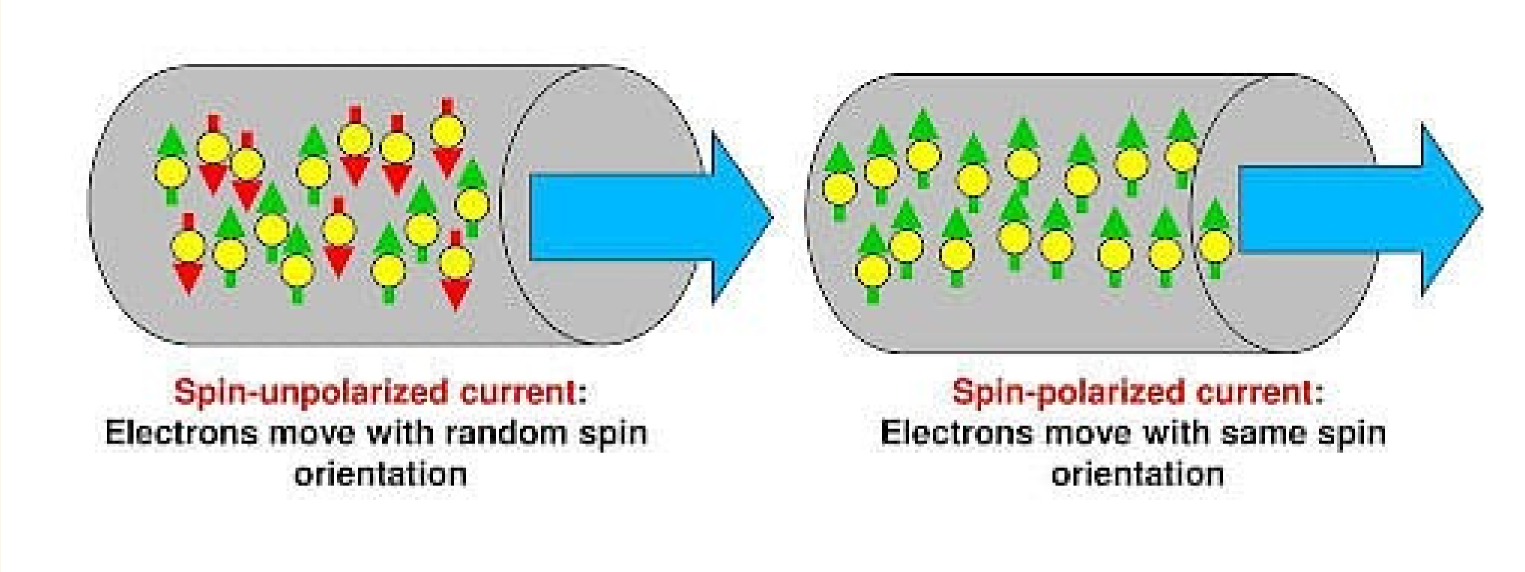
TÓPICOS

O QUE É SPINTRÔNICA?

- Definição de spintrônica
- Breve história do spin
- Motivação para compreendê-la

O QUE É SPINTRÔNICA?

- A spintrônica é uma área dedicada ao estudo das propriedades dos materiais derivadas do spin do elétron. Ao utilizar o spin do elétron como portador de informação surgem muitas possibilidades de aumentar a eficiência e de incrementar as funcionalidades dos dispositivos eletrônicos convencionais.

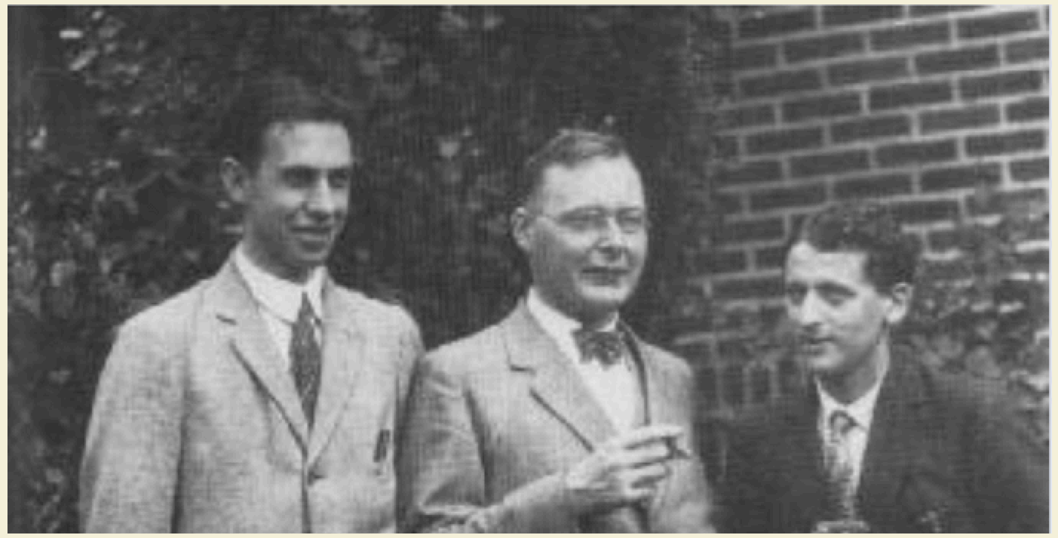


Fonte - Insightsonindia.com

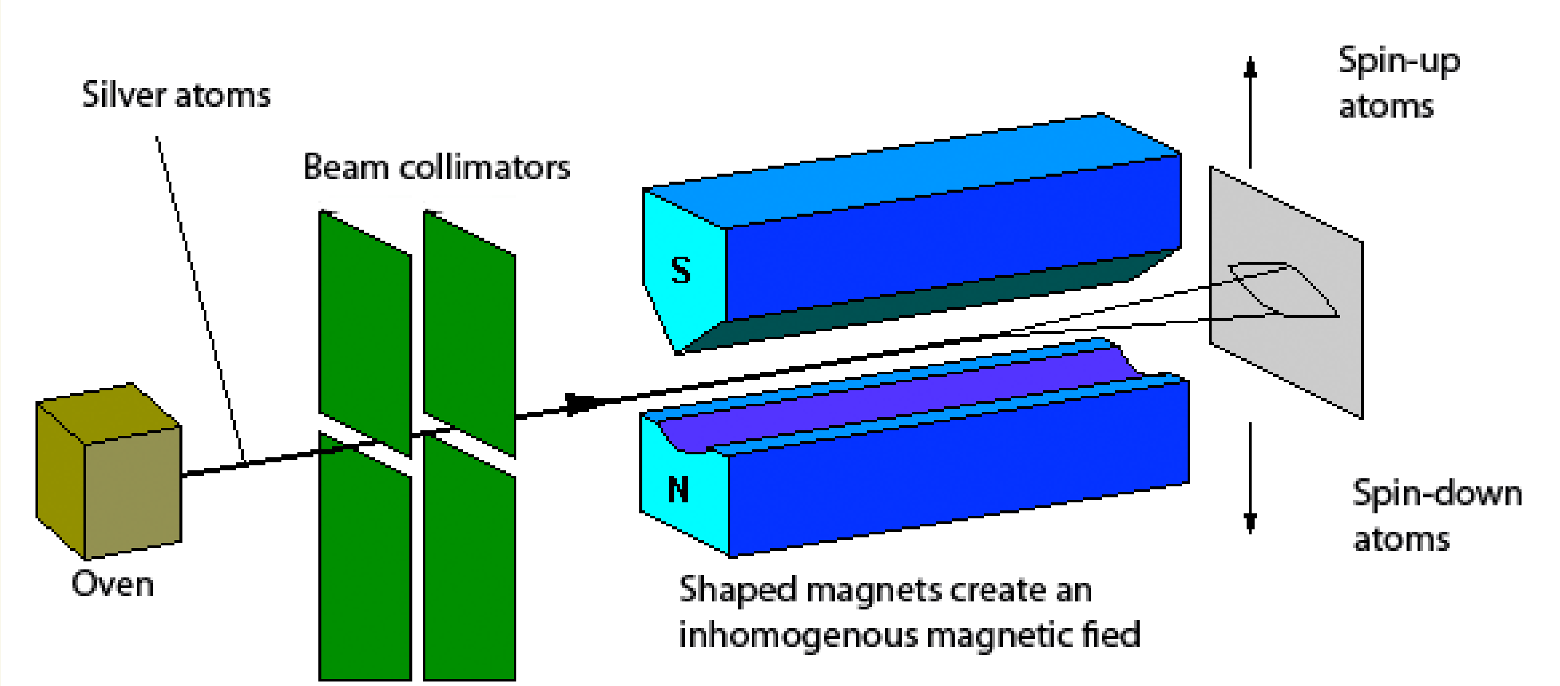
BREVE HISTÓRIA DO SPIN

- **1925** – George Uhlenbeck e Samuel Goudsmit propõem o conceito de spin do elétron: um momento angular intrínseco, apoiados por Ehrenfest.

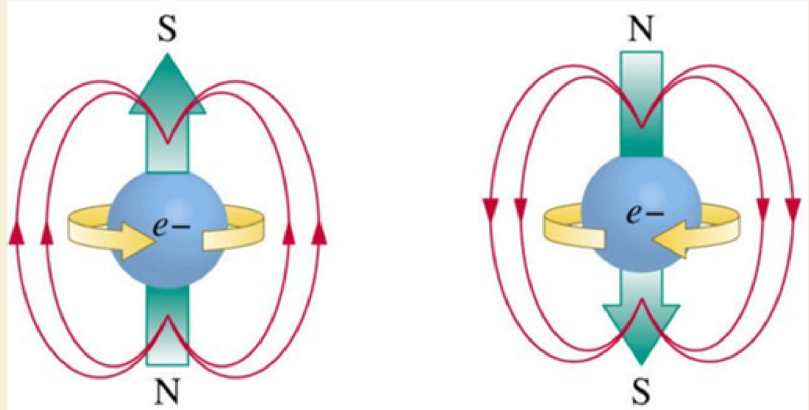
- **1930s–1940s** – Experimento de Stern-Gerlach confirma que o elétron possui propriedades magnéticas discretas e existência do spin.



Fonte - Instituut-Lorentz, Universidade de Leiden



Fonte - Informationphilosopher.com



Fonte - Müller K., Spin Explained in 5 Minutes

BREVE HISTÓRIA DO SPIN

- **1928** – Paul Dirac desenvolve sua equação relativística que prevê a existência do spin ½.
- **1988** – Albert Fert e Peter Grünberg descobrem a magnetorresistência gigante (GMR). A resistência elétrica muda drasticamente dependendo da orientação do spin dos elétrons.

$$(i\hbar\gamma^{\mu}\partial_{\mu}-mc)\psi=0$$

Fonte - Shutterstock

Fonte - The Independent

MOTIVAÇÃO

- **Limites da Eletrônica Convencional**

Alto consumo de energia e aquecimento por transporte de carga.

- **Spin como Novo Canal de Informação**

Uso da orientação do spin (↑ ou ↓) para representar bits.

.

- **Dispositivos Mais Eficientes**

Menor dissipação de calor, maior velocidade e memórias não voláteis.

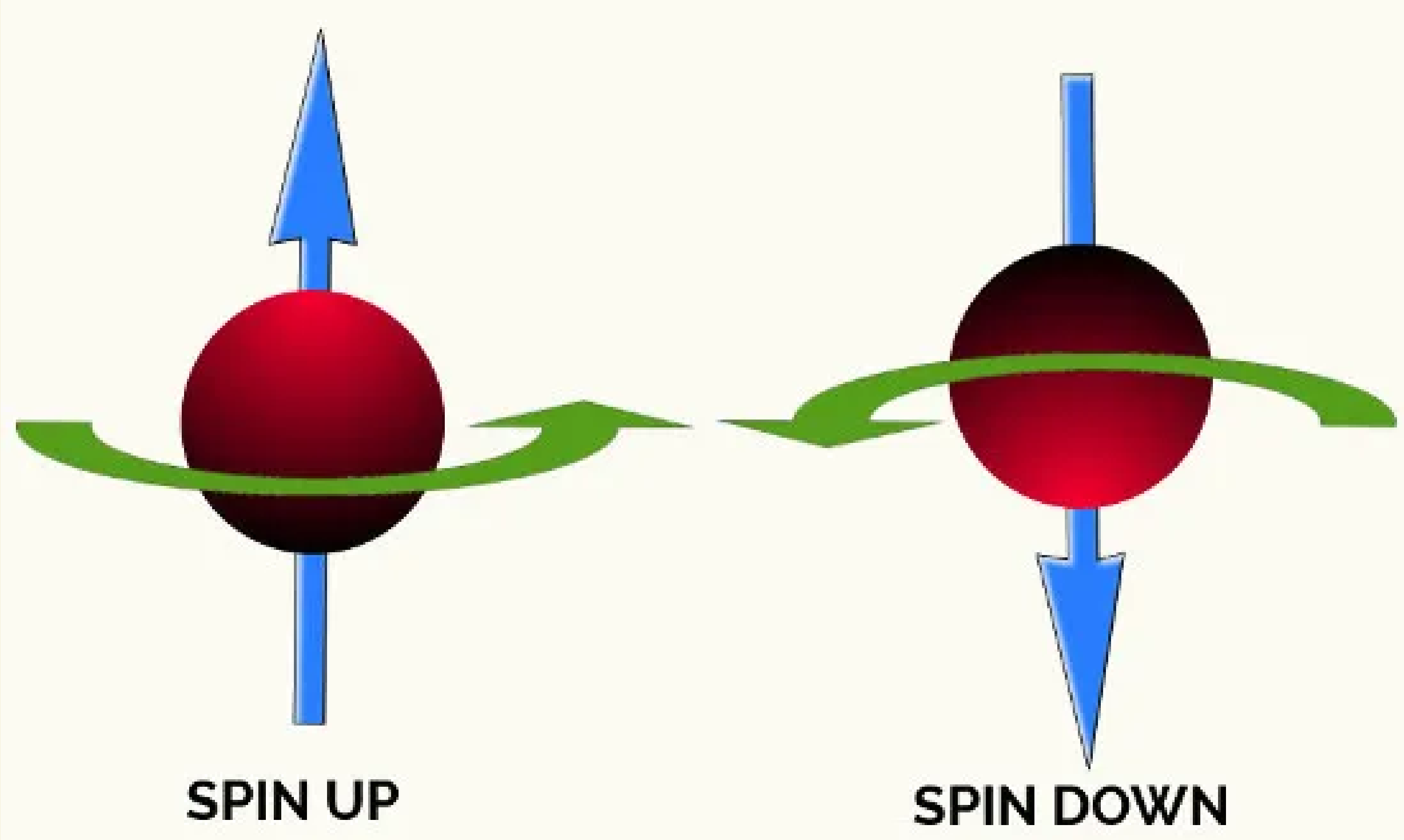
- **Novas Funcionalidades e Tecnologias Futuras**

Sensores magnéticos avançados, computação quântica e inteligência artificial.

PRINCÍPIOS FÍSICOS

SPIN

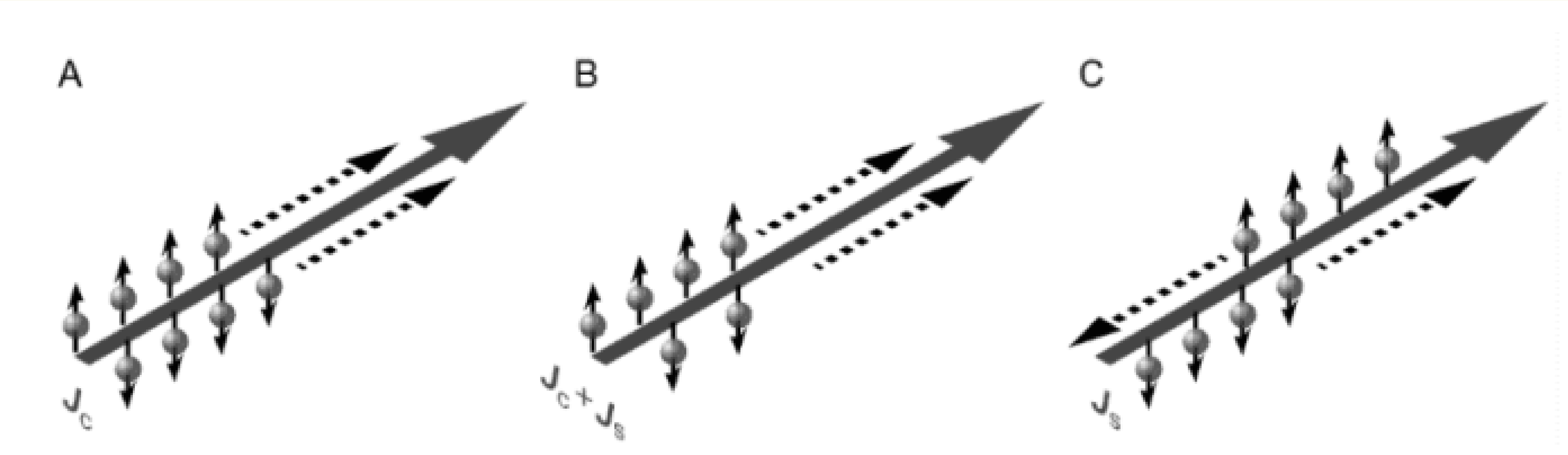
- Momento angular do elétron
- Propriedade intrínseca e quantizada
- Momento magnético associado
- Portador de informação na spintrônica



Fonte - Preparaenem.com

PRINCÍPIOS FÍSICOS

CORRENTE DE SPIN



Fonte - Abraão Neto

A - Corrente não polarizada

B - Corrente de carga polarizada em SPIN

C - Corrente pura de SPIN

Js - Corrente de SPIN

Jc - Corrente convencional de carga

$$\vec{J}_s = \frac{\hbar}{2q}\frac{\sigma_e}{q}\nabla\mu_s.$$

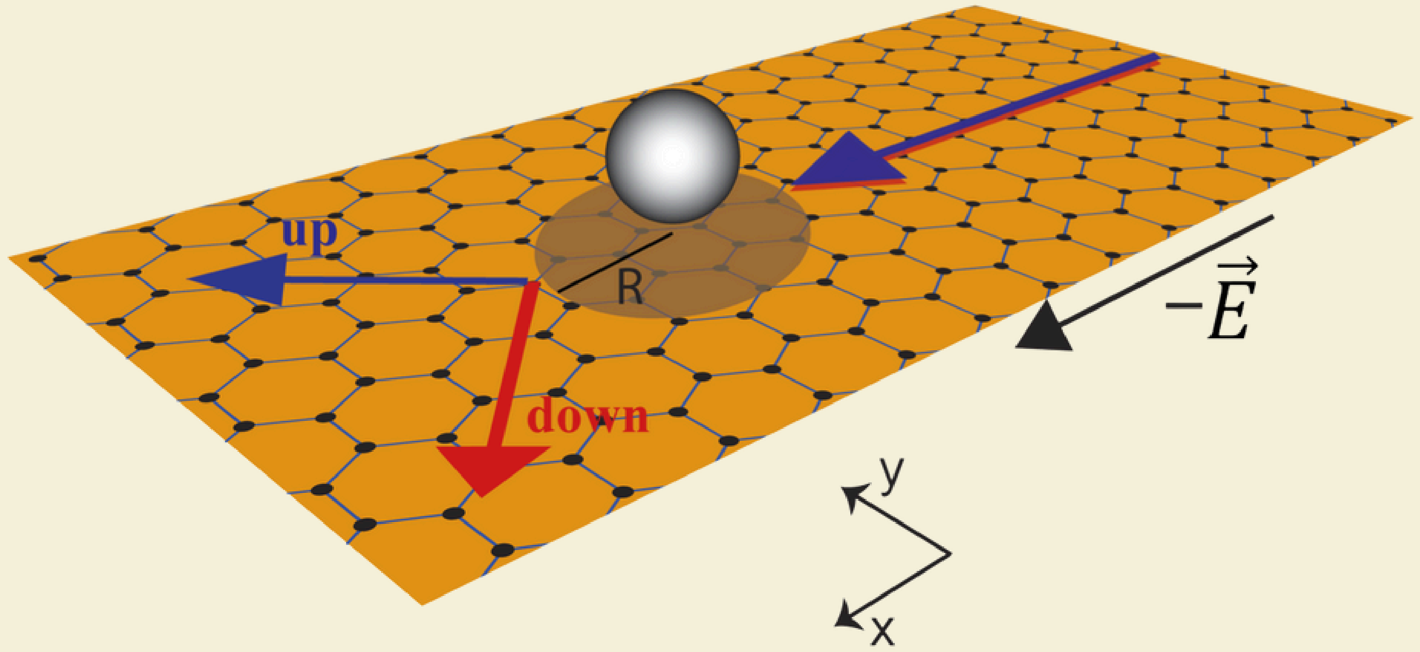
Fonte - Abraão Neto

PRINCÍPIOS FÍSICOS

EFEITO SPIN HALL

Geração de uma corrente de spin a partir de uma corrente de carga.

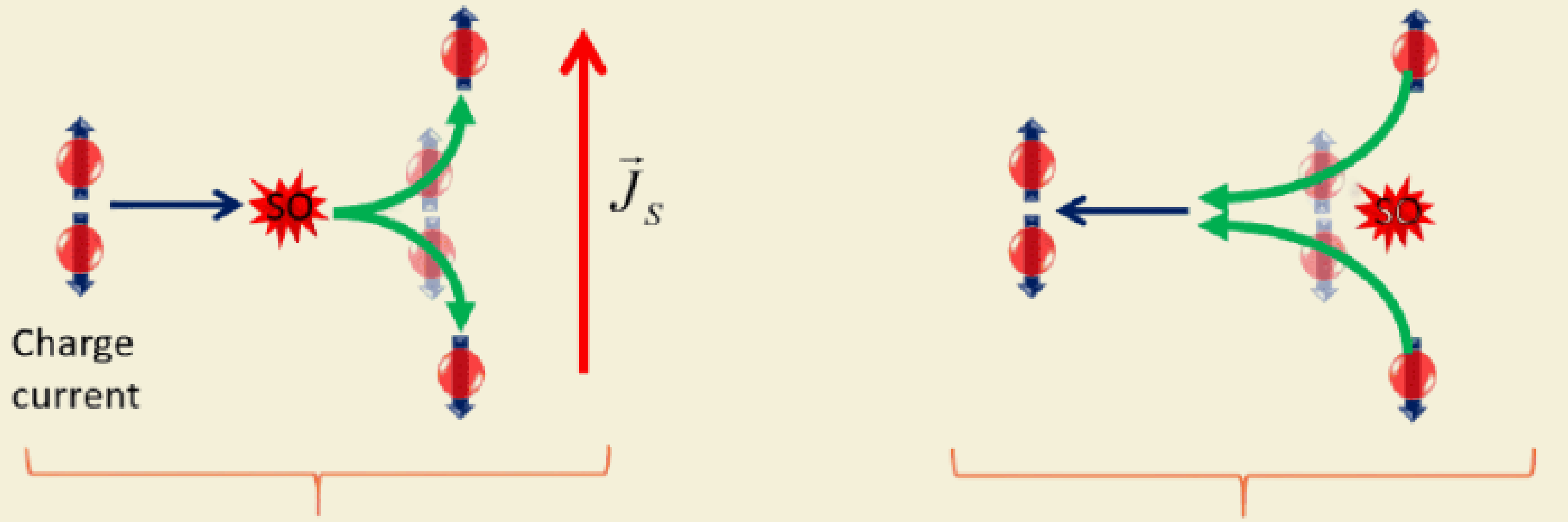
- “Current-induced spin orientation of electrons in semiconductors” - Dyakonov e Perel
- Origem na interação spin-óribita: separa os elétrons do material de acordo com a sua polarização de spin.
- Ocorre em materiais que possuem forte interação spin-órbita



Fonte - if.ufrj.br

PRINCÍPIOS FÍSICOS

EFEITO SPIN HALL



Spin Hall Effect (SHE)

Charge current

⇩

spin current

$$\vec{J}_S = \frac{\hbar}{2e}\theta_{SH}(\vec{\sigma}\times\vec{J}_C)$$

Inverse Spin Hall Effect (ISHE)

Charge current

⇧

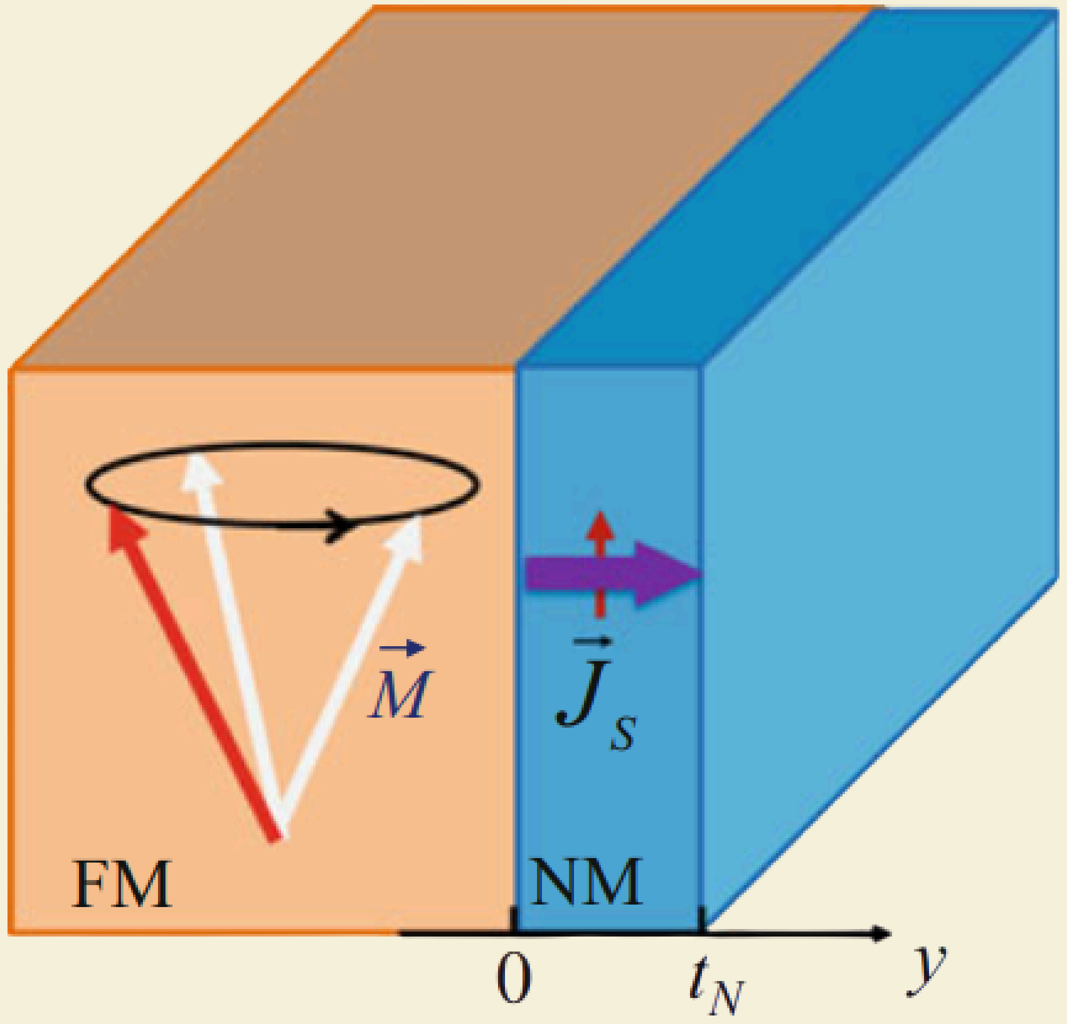
spin current

$$\vec{J}_C = \frac{2e}{\hbar}\theta_{SH}(\vec{J}_S\times\vec{\sigma})$$

Fonte - Abraão Neto

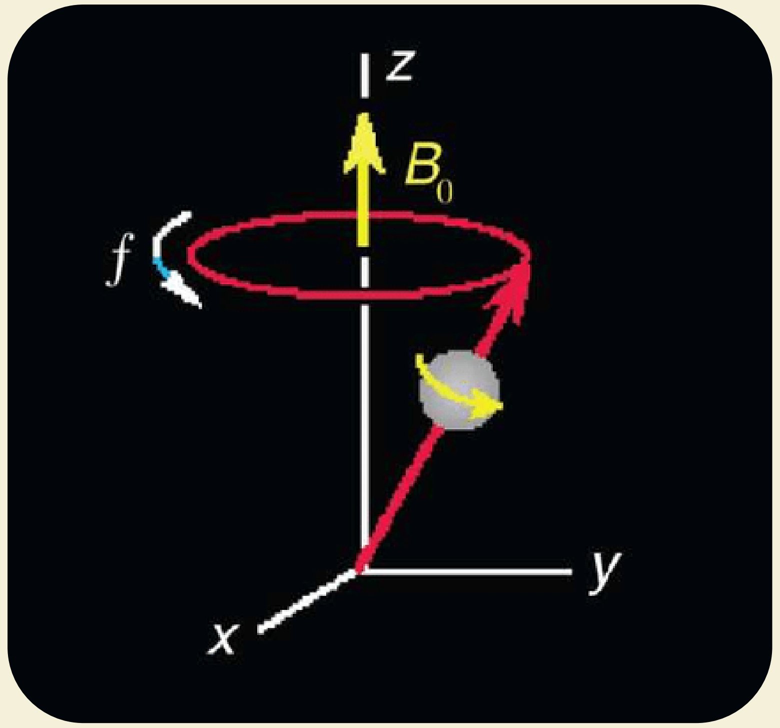
PRINCÍPIOS FÍSICOS

Spin pumping



Fonte - Fundamentals of Magnonics (M. Rezende)

- Precessão da magnetização em ferromagnetos (FM) pode transferir um fluxo de spins para um meio metal normal (MN) adjacente, sem a aplicação de um campo externo.

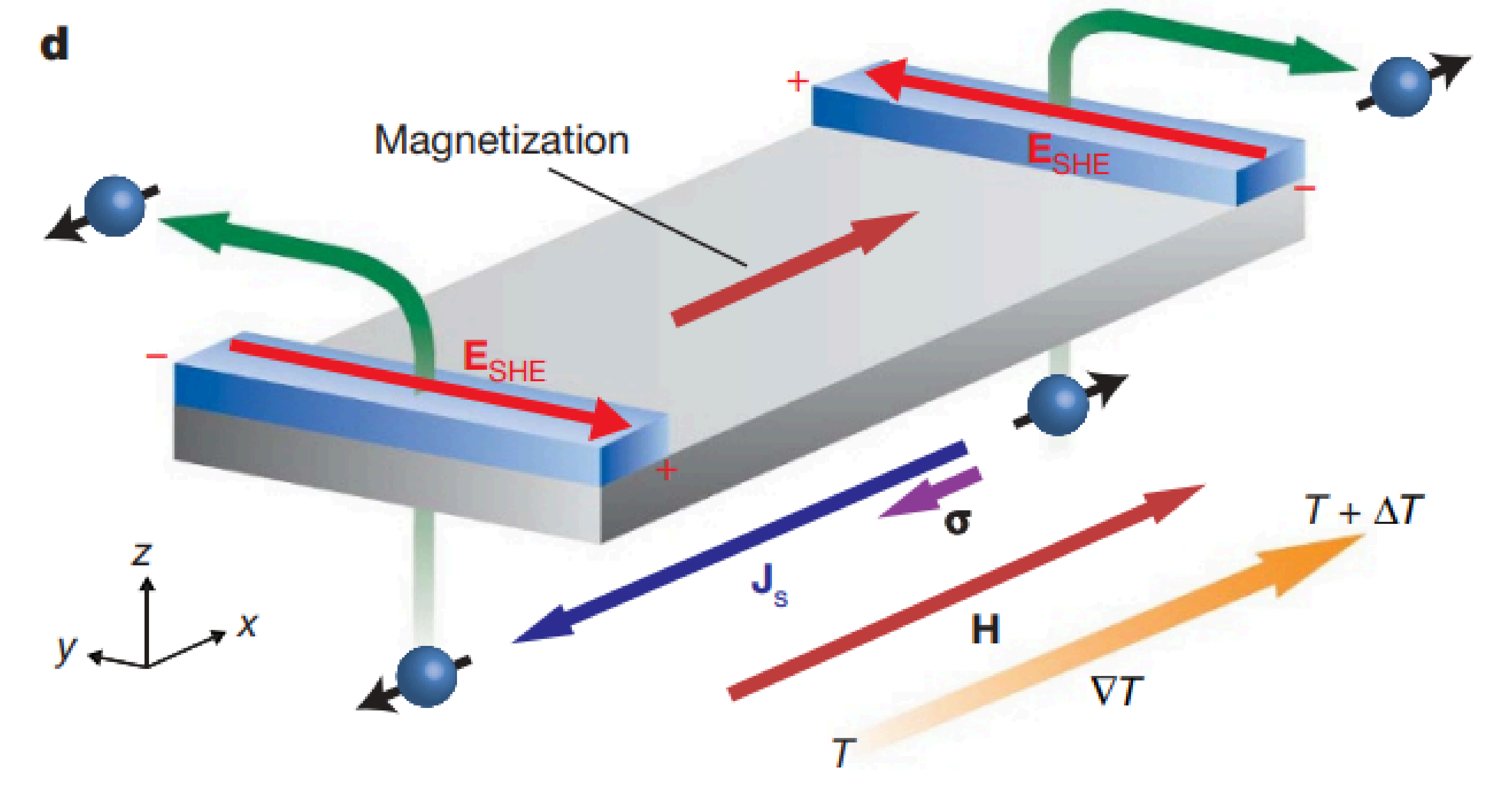


Fonte - researchgate.net

PRINCÍPIOS FÍSICOS

EFEITO SEEBECK

- Em um material magnético submetido a uma diferença de temperatura surge uma corrente de spin, que pode ser convertida em tensão elétrica via o efeito Hall de spin inverso (ISHE).



Fonte - Observation of the spin Seebeck effect (K. Uchida)

MATERIAIS RELEVANTES

01 Ferromagnéticos

02 Condutores “não magnéticos”

03 Materiais semicondutores com spin

04 Isolantes magnéticos e isolantes topológicos

MATERIAIS RELEVANTES

Ferromagnéticos

Geram naturalmente uma polarização de spin

- Forte interação de troca
- Fe (ferro), Co (cobalto), Ni (níquel)
- Ligas como CoFeB (muito usada em MRAM)

- Usos principais:
    a. Eletrodos injetores de spin em dispositivos;
    b. “Filtros” de spin.

MATERIAIS RELEVANTES

Condutores “não magnéticos”

Transporte de corrente spin-polarizada com menor espalhamento

↓

Perda de informação

- **Diamagnéticos** e paramagnéticos (interação de troca);
- Fraca interação spin-fônon;
- Alto grau de pureza e ordem da estrutura cristalina;
- Baixo acoplamento spin-órbita.

MATERIAIS RELEVANTES

Semicondutores com spin

Podem ser manipulados eletricamente e integrados a chips

Sem a necessidade de um
campo externo

- Lógicas spintrônicas, controle elétrico de spin via efeito Rashba;
- GaAs (Arseniato de Gálio) – base para estudos de transporte de spin;
- InSb (Antimoneto de Índio) – forte acoplamento spin-órbita.

Caminho para "transistores de spin"

MATERIAIS RELEVANTES

Isolantes magnéticos e isolantes topológicos

YIG (Yttrium Iron Garnet) e Bi_2Se_3 (isolantes topológicos)

Granada de ferro ítrio

YIG

- Ferrimagnético
- Isotante elétrico, mas transmite excitações de spin (magnons)

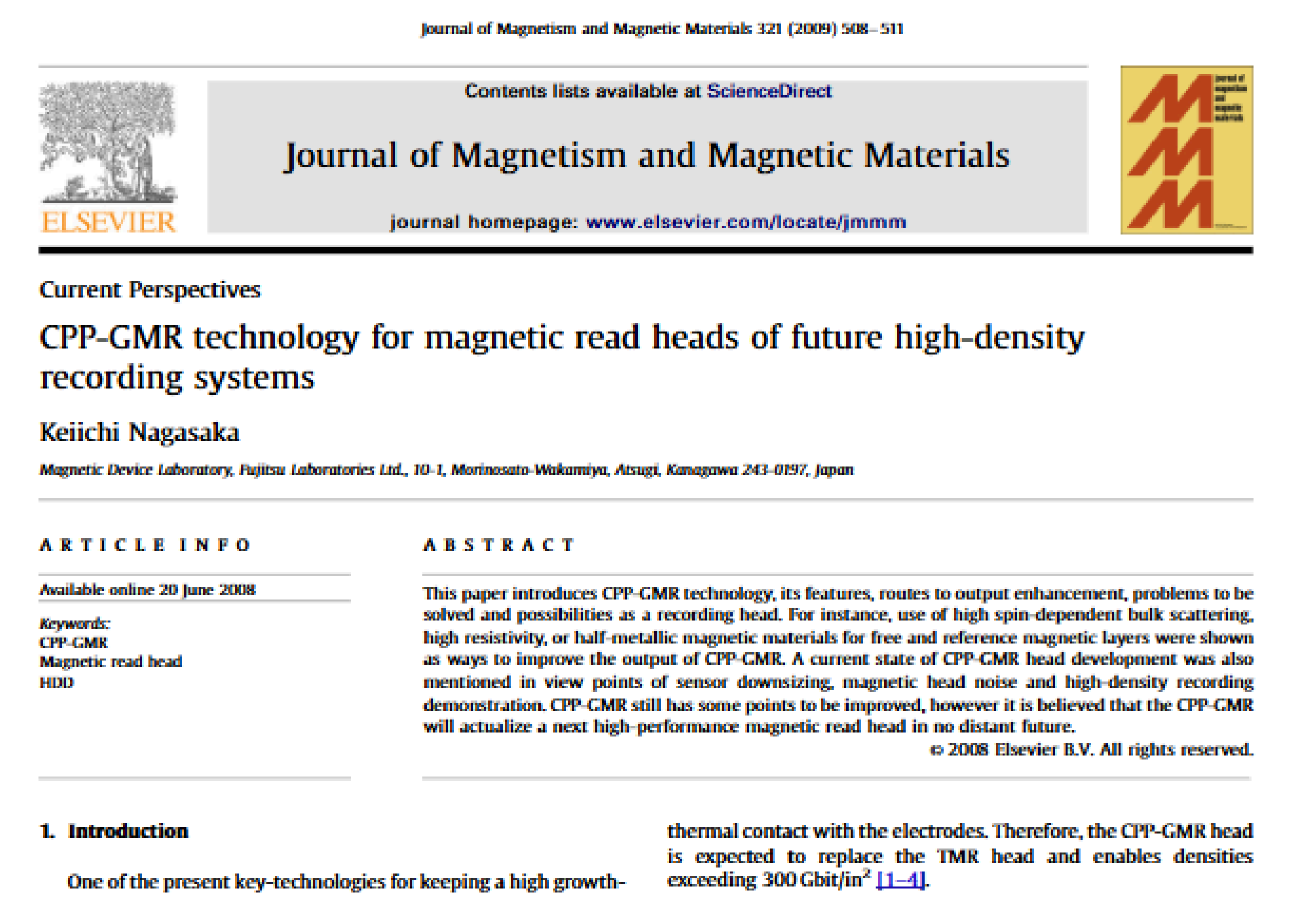
Isolantes topológicos

- Condução de spin com baixíssima dissipação

ESTADO DA ARTE

O que já está consolidado

Cabeças de leitura de HDs



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Current Perspectives

CPP-GMR technology for magnetic read heads of future high-density recording systems

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Keywords:
CPP-GMR
Magnetic read head
HDD

ABSTRACT

This paper introduces CPP-GMR technology, its features, routes to output enhancement, problems to be solved and possibilities as a recording head. For instance, use of high spin-dependent bulk scattering, high resistivity, or half-metallic magnetic materials for free and reference magnetic layers were shown as ways to improve the output of CPP-GMR. A current state of CPP-GMR head development was also mentioned in view points of sensor downsizing, magnetic head noise and high-density recording demonstration. CPP-GMR still has some points to be improved, however it is believed that the CPP-GMR will actualize a next high-performance magnetic read head in no distant future.

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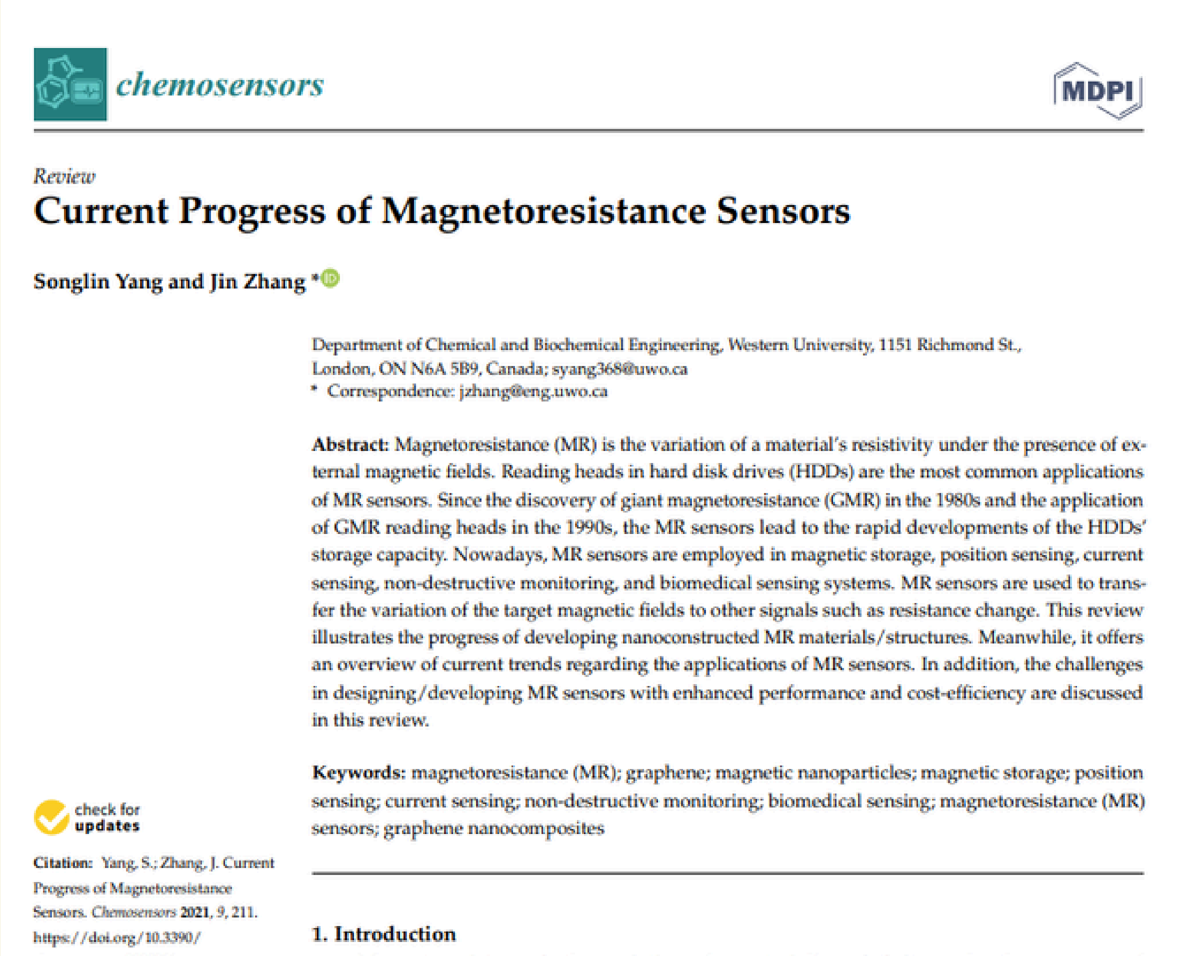
1. Introduction

One of the present key-technologies for keeping a high growth-rate of magnetic recording density in hard disk drive (HDD)

thermal contact with the electrodes. Therefore, the CPP-GMR head is expected to replace the TMR head and enables densities exceeding 300 Gbit/in^2 [1–4].

In this paper, I take a general view of several methods for



chemosensors

MDPI

Review

Current Progress of Magnetoresistance Sensors

Songlin Yang and Jin Zhang *

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Abstract: Magnetoresistance (MR) is the variation of a material's resistivity under the presence of external magnetic fields. Reading heads in hard disk drives (HDDs) are the most common applications of MR sensors. Since the discovery of giant magnetoresistance (GMR) in the 1980s and the application of GMR reading heads in the 1990s, the MR sensors lead to the rapid developments of the HDDs' storage capacity. Nowadays, MR sensors are employed in magnetic storage, position sensing, current sensing, non-destructive monitoring, and biomedical sensing systems. MR sensors are used to transfer the variation of the target magnetic fields to other signals such as resistance change. This review illustrates the progress of developing nanoconstructed MR materials/structures. Meanwhile, it offers an overview of current trends regarding the applications of MR sensors. In addition, the challenges in designing/developing MR sensors with enhanced performance and cost-efficiency are discussed in this review.

Keywords: magnetoresistance (MR); graphene; magnetic nanoparticles; magnetic storage; position sensing; current sensing; non-destructive monitoring; biomedical sensing; magnetoresistance (MR) sensors; graphene nanocomposites

check for updates

Citation: Yang, S.; Zhang, J. Current Progress of Magnetoresistance Sensors. *Chemosensors* **2021**, 9, 211. https://doi.org/10.3390/chemosensors9080211

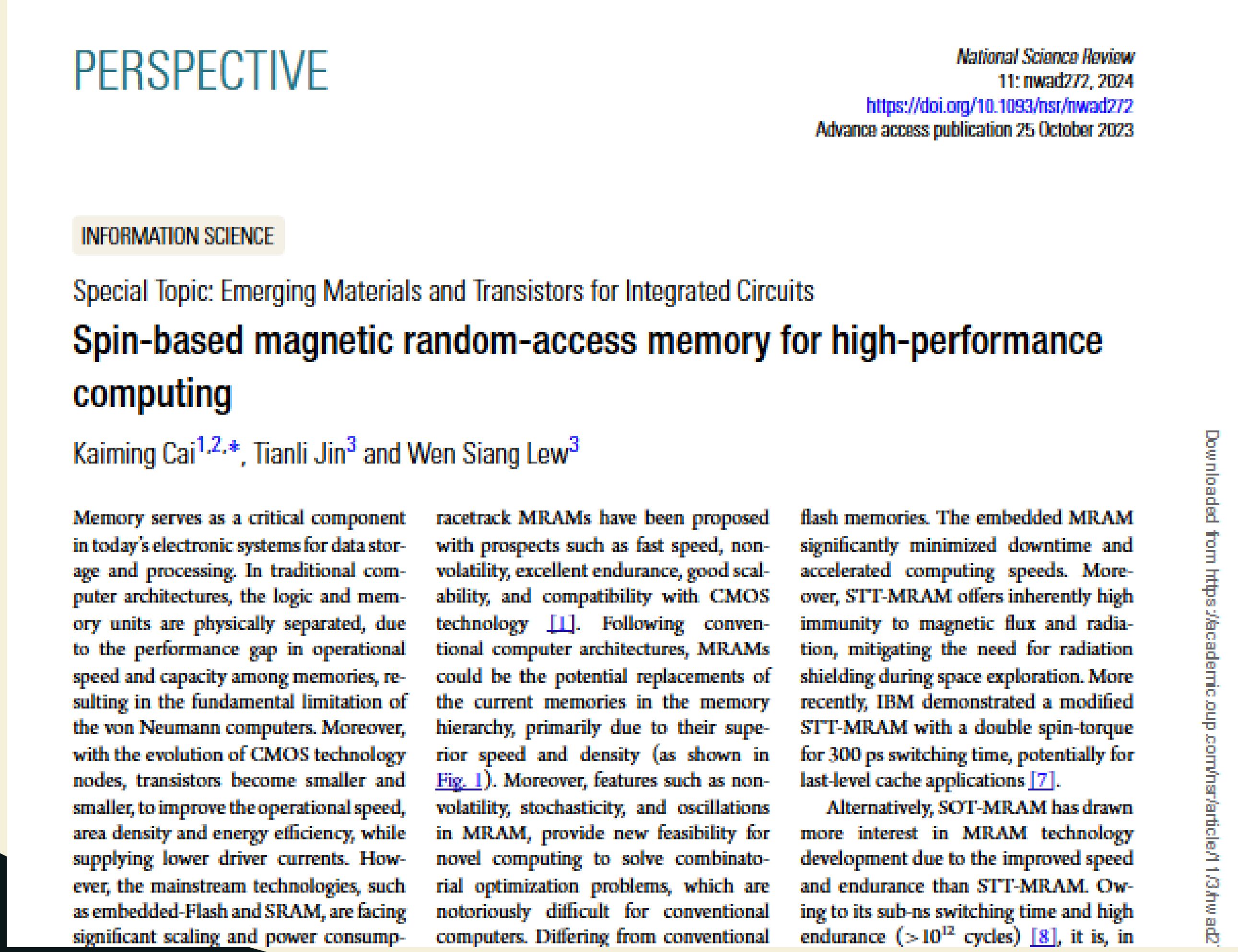
1. Introduction

Magnetoresistance is the variation of a material's resistivity under the presence of

ESTADO DA ARTE

O que já está consolidado

MRAM (Memória Magnética de Acesso Aleatório)



PERSPECTIVE

National Science Review
11: nwad272, 2024
https://doi.org/10.1093/nsr/nwad272
Advance access publication 25 October 2023

INFORMATION SCIENCE

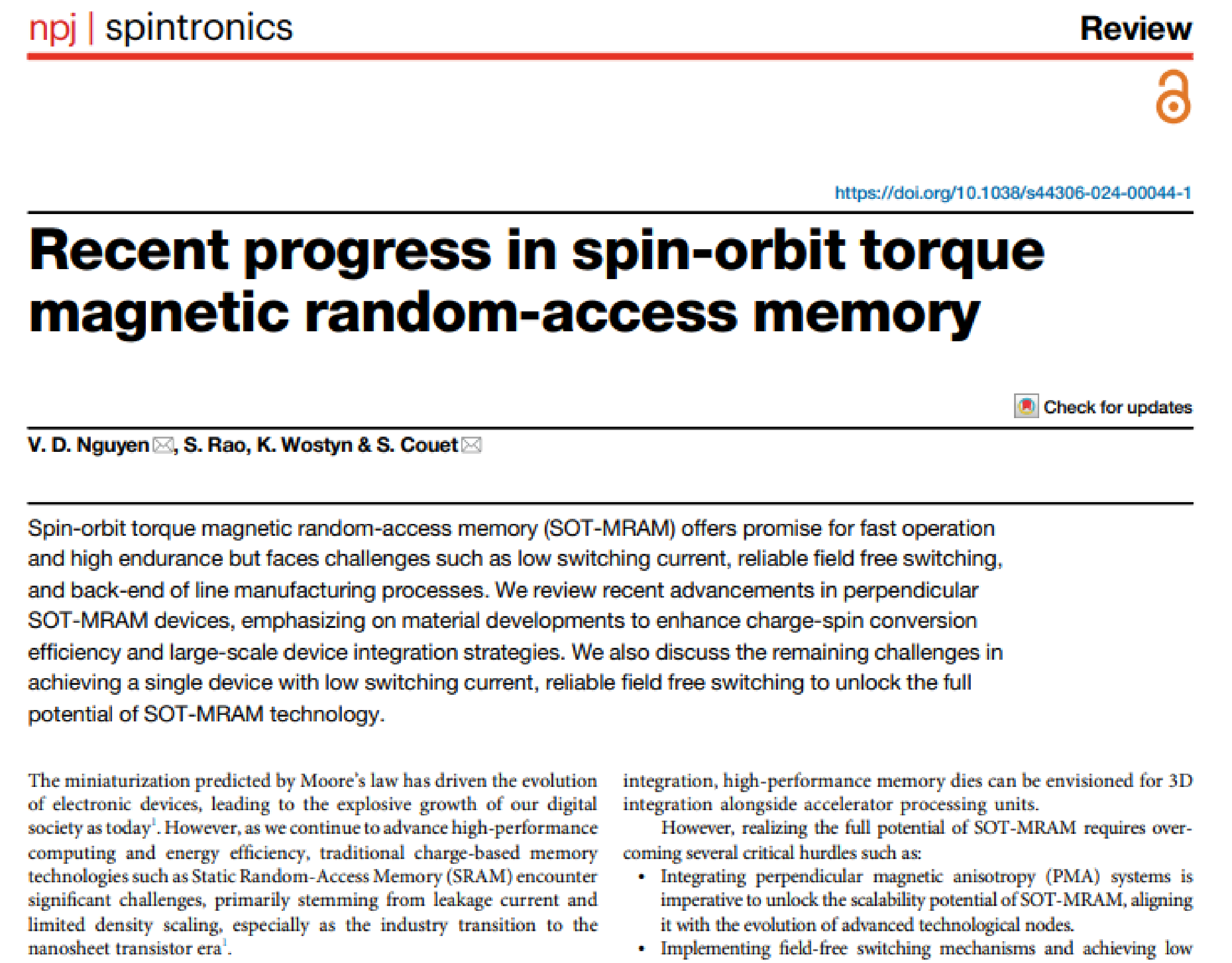
Special Topic: Emerging Materials and Transistors for Integrated Circuits

Spin-based magnetic random-access memory for high-performance computing

Kaiming Cai[1,2,*], Tianli Jin[3] and Wen Siang Lew[3]

Memory serves as a critical component in today's electronic systems for data storage and processing. In traditional computer architectures, the logic and memory units are physically separated, due to the performance gap in operational speed and capacity among memories, resulting in the fundamental limitation of the von Neumann computers. Moreover, with the evolution of CMOS technology nodes, transistors become smaller and smaller, to improve the operational speed, area density and energy efficiency, while supplying lower driver currents. However, the mainstream technologies, such as embedded-Flash and SRAM, are facing significant scaling and power consump- racetrack MRAMs have been proposed with prospects such as fast speed, non-volatility, excellent endurance, good scalability, and compatibility with CMOS technology [1]. Following conventional computer architectures, MRAMs could be the potential replacements of the current memories in the memory hierarchy, primarily due to their superior speed and density (as shown in Fig. 1). Moreover, features such as non-volatility, stochasticity, and oscillations in MRAM, provide new feasibility for novel computing to solve combinatorial optimization problems, which are notoriously difficult for conventional computers. Differing from conventional flash memories. The embedded MRAM significantly minimized downtime and accelerated computing speeds. Moreover, STT-MRAM offers inherently high immunity to magnetic flux and radiation, mitigating the need for radiation shielding during space exploration. More recently, IBM demonstrated a modified STT-MRAM with a double spin-torque for 300 ps switching time, potentially for last-level cache applications [7].

Alternatively, SOT-MRAM has drawn more interest in MRAM technology development due to the improved speed and endurance than STT-MRAM. Owing to its sub-ns switching time and high endurance ($>10^{12}$ cycles) [8], it is, in



npj | spintronics

Review

https://doi.org/10.1038/s44306-024-00044-1

Recent progress in spin-orbit torque magnetic random-access memory

Check for updates

V. D. Nguyen ✉, S. Rao, K. Wostyn & S. Couet ✉

Spin-orbit torque magnetic random-access memory (SOT-MRAM) offers promise for fast operation and high endurance but faces challenges such as low switching current, reliable field free switching, and back-end of line manufacturing processes. We review recent advancements in perpendicular SOT-MRAM devices, emphasizing on material developments to enhance charge-spin conversion efficiency and large-scale device integration strategies. We also discuss the remaining challenges in achieving a single device with low switching current, reliable field free switching to unlock the full potential of SOT-MRAM technology.

The miniaturization predicted by Moore's law has driven the evolution of electronic devices, leading to the explosive growth of our digital society as today[1]. However, as we continue to advance high-performance computing and energy efficiency, traditional charge-based memory technologies such as Static Random-Access Memory (SRAM) encounter significant challenges, primarily stemming from leakage current and limited density scaling, especially as the industry transition to the nanosheet transistor era[1].

Magnetic random-access memory (MRAM), leveraging the spin integration, high-performance memory dies can be envisioned for 3D integration alongside accelerator processing units.

However, realizing the full potential of SOT-MRAM requires overcoming several critical hurdles such as:

- Integrating perpendicular magnetic anisotropy (PMA) systems is imperative to unlock the scalability potential of SOT-MRAM, aligning it with the evolution of advanced technological nodes.
- Implementing field-free switching mechanisms and achieving low switching currents in PMA systems are also critical for practical

ESTADO DA ARTE

O que já está consolidado

Torque de transferência de spin (STT) e torque órbita-spin (SOT)

Condensed Matter > Mesoscale and Nanoscale Physics

[Submitted on 23 Apr 2021 (v1), last revised 6 May 2021 (this version, v2)]

Roadmap of spin-orbit torques

Qiming Shao, Peng Li, Luqiao Liu, Hyunsoo Yang, Shunsuke Fukami, Armin Razavi, Hao Wu, Kang L. Wang, Frank Freimuth, Yuriy Mokrousov, Mark D. Stiles, Satoru Emori, Axel Hoffmann, Johan Åkerman, Kaushik Roy, Jian-Ping Wang, See-Hun Yang, Kevin Garello, Wei Zhang

Spin-orbit torque (SOT) is an emerging technology that enables the efficient manipulation of spintronic devices. The initial processes of interest in SOTs involved electric fields, spin-orbit coupling, conduction electron spins and magnetization. More recently interest has grown to include a variety of other processes that include phonons, magnons, or heat. Over the past decade, many materials have been explored to achieve a larger SOT efficiency. Recently, holistic design to maximize the performance of SOT devices has extended material research from a nonmagnetic layer to a magnetic layer. The rapid development of SOT has spurred a variety of SOT-based applications. In this Roadmap paper, we first review the theories of SOTs by introducing the various mechanisms thought to generate or control SOTs, such as the spin Hall effect, the Rashba-Edelstein effect, the orbital Hall effect, thermal gradients, magnons, and strain effects. Then, we discuss the materials that enable these effects, including metals, metallic alloys, topological insulators, two-dimensional materials, and complex oxides. We also discuss the important roles in SOT devices of different types of magnetic layers. Afterward, we discuss device applications utilizing SOTs. We discuss and compare three-terminal and two-terminal SOT-magnetoresistive random-access memories (MRAMs); we mention various schemes to eliminate the need for an external field. We provide technological application considerations for SOT-MRAM and give perspectives on SOT-based neuromorphic devices and circuits. In addition to SOT-MRAM, we present SOT-based spintronic terahertz generators, nano-oscillators, and domain wall and skyrmion racetrack memories. This paper aims to achieve a comprehensive review of SOT theory, materials, and applications, guiding future SOT development in both the academic and industrial sectors.

Comments: an invited paper in the "Advances in Magnetics" series
Subjects: **Mesoscale and Nanoscale Physics (cond-mat.mes-hall)**; Applied Physics (physics.app-ph)
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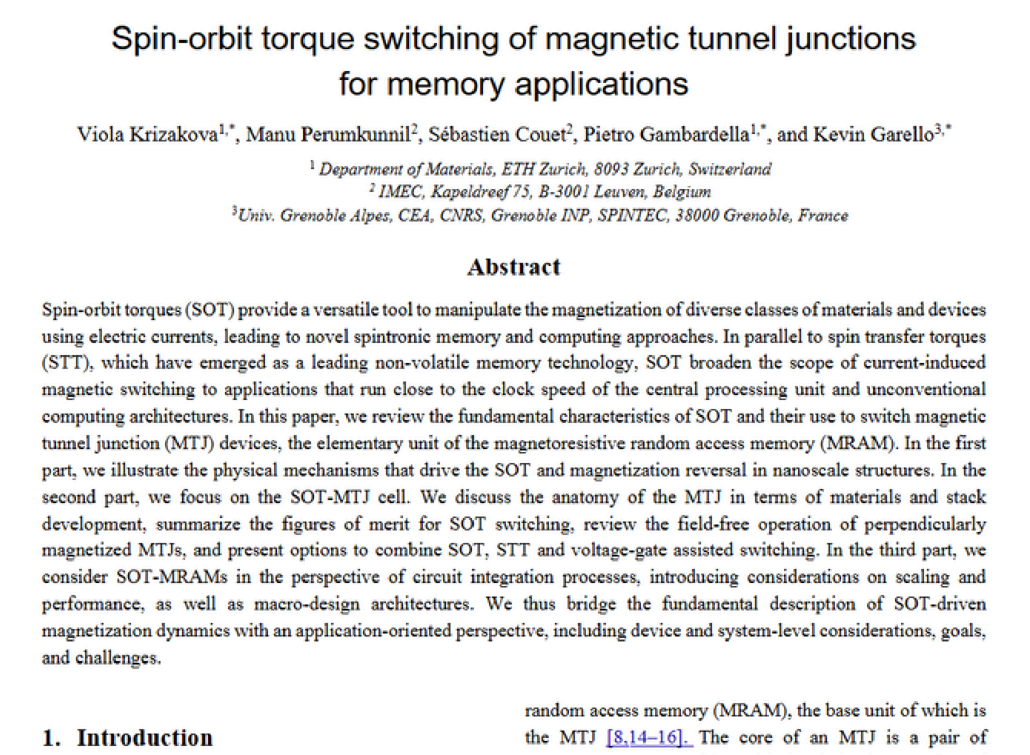

Spin-orbit torque switching of magnetic tunnel junctions for memory applications

Viola Krizakova[1,*], Manu Perumkunnil[2], Sébastien Couet[2], Pietro Gambardella[1,*], and Kevin Garello[3,*]

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Abstract

Spin-orbit torques (SOT) provide a versatile tool to manipulate the magnetization of diverse classes of materials and devices using electric currents, leading to novel spintronic memory and computing approaches. In parallel to spin transfer torques (STT), which have emerged as a leading non-volatile memory technology, SOT broaden the scope of current-induced magnetic switching to applications that run close to the clock speed of the central processing unit and unconventional computing architectures. In this paper, we review the fundamental characteristics of SOT and their use to switch magnetic tunnel junction (MTJ) devices, the elementary unit of the magnetoresistive random access memory (MRAM). In the first part, we illustrate the physical mechanisms that drive the SOT and magnetization reversal in nanoscale structures. In the second part, we focus on the SOT-MTJ cell. We discuss the anatomy of the MTJ in terms of materials and stack development, summarize the figures of merit for SOT switching, review the field-free operation of perpendicularly magnetized MTJs, and present options to combine SOT, STT and voltage-gate assisted switching. In the third part, we consider SOT-MRAMs in the perspective of circuit integration processes, introducing considerations on scaling and performance, as well as macro-design architectures. We thus bridge the fundamental description of SOT-driven magnetization dynamics with an application-oriented perspective, including device and system-level considerations, goals, and challenges.

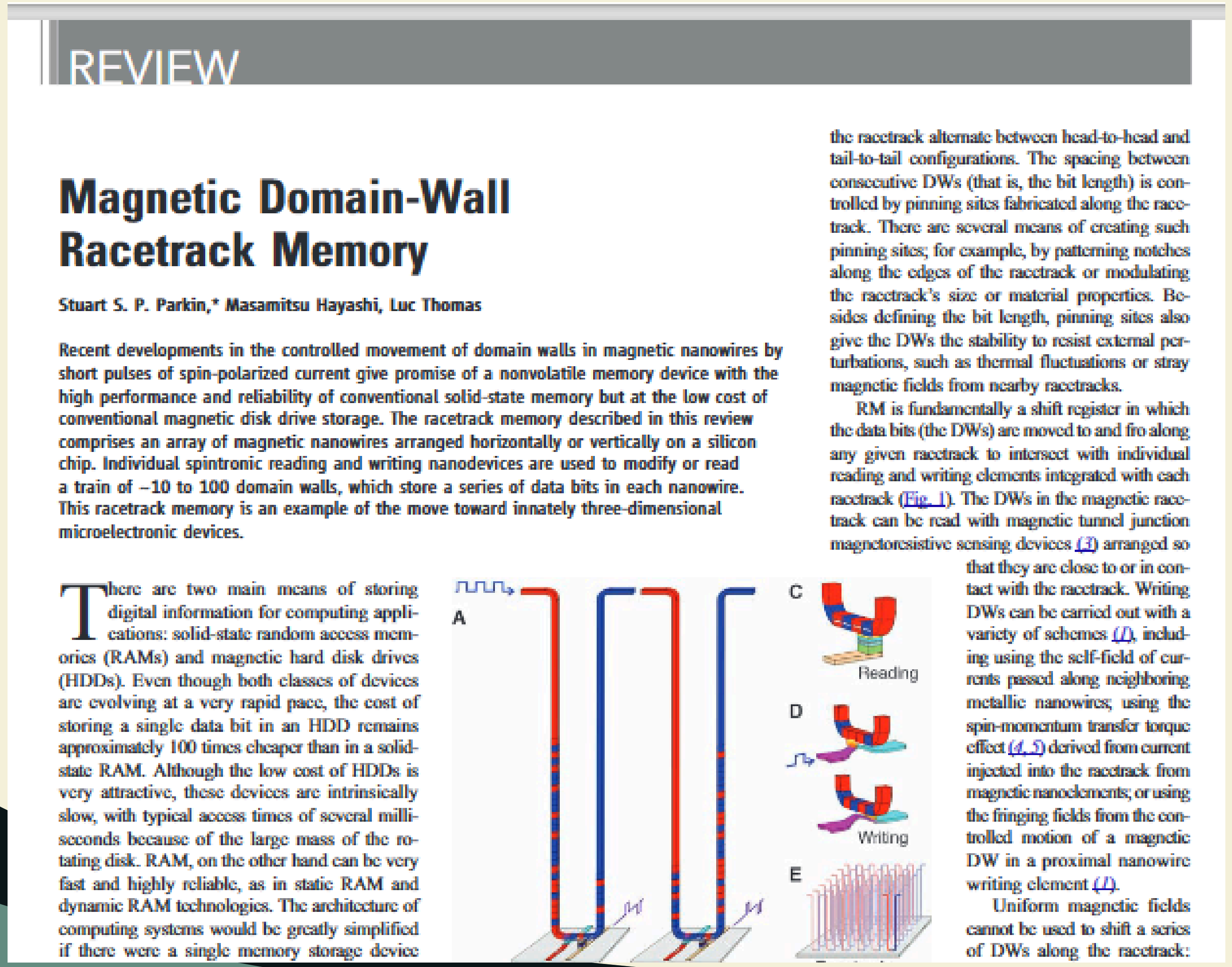
1. Introduction

random access memory (MRAM), the base unit of which is the MTJ [8,14–16]. The core of an MTJ is a pair of nanomagnets separated by a thin insulating barrier. One of

ESTADO DA ARTE

Avanços recentes em pesquisa

Racetrack memory



REVIEW

Magnetic Domain-Wall Racetrack Memory

Stuart S. P. Parkin,* Masamitsu Hayashi, Luc Thomas

Recent developments in the controlled movement of domain walls in magnetic nanowires by short pulses of spin-polarized current give promise of a nonvolatile memory device with the high performance and reliability of conventional solid-state memory but at the low cost of conventional magnetic disk drive storage. The racetrack memory described in this review comprises an array of magnetic nanowires arranged horizontally or vertically on a silicon chip. Individual spintronic reading and writing nanodevices are used to modify or read a train of ~10 to 100 domain walls, which store a series of data bits in each nanowire. This racetrack memory is an example of the move toward innately three-dimensional microelectronic devices.

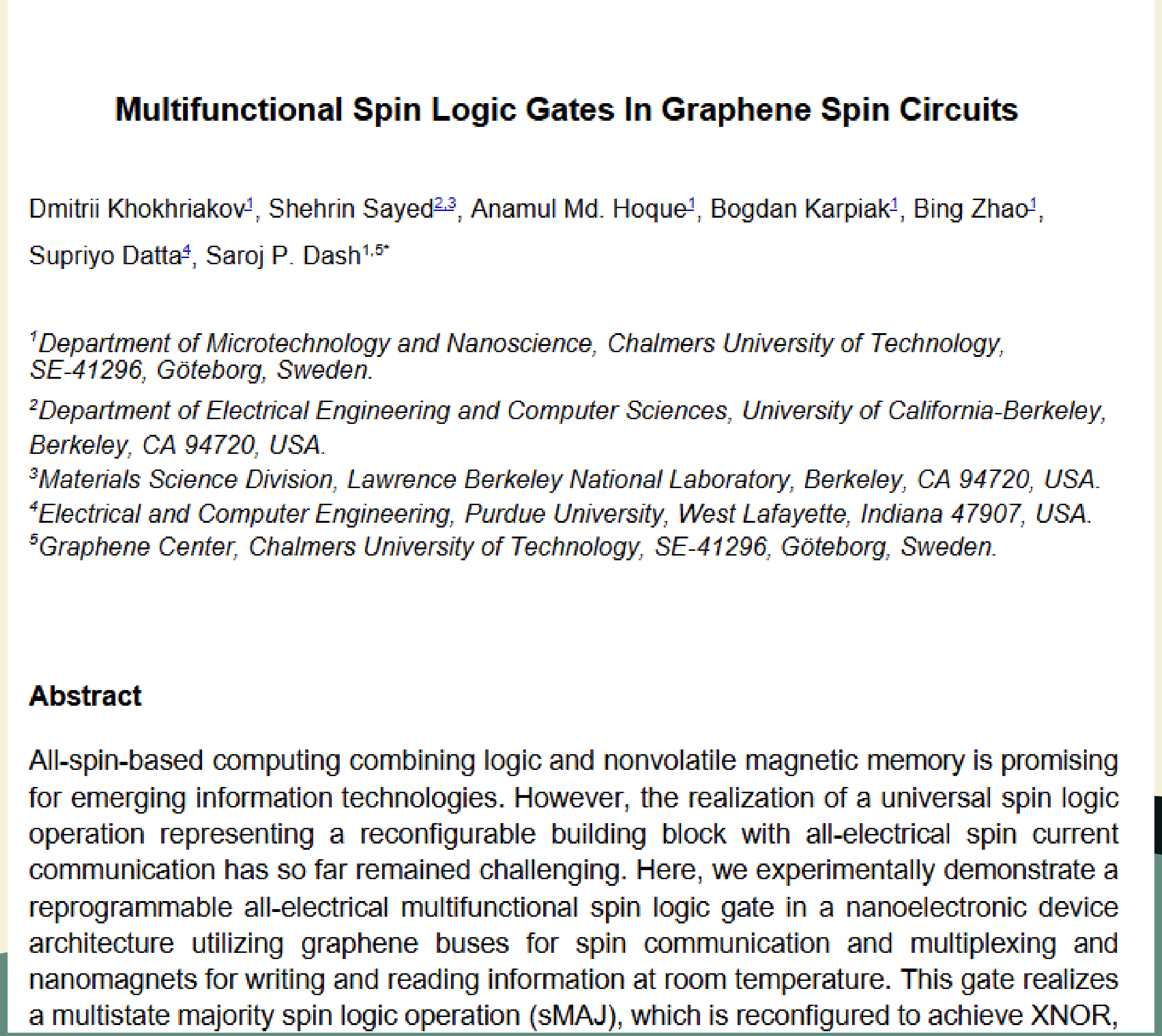
There are two main means of storing digital information for computing applications: solid-state random access memories (RAMs) and magnetic hard disk drives (HDDs). Even though both classes of devices are evolving at a very rapid pace, the cost of storing a single data bit in an HDD remains approximately 100 times cheaper than in a solid-state RAM. Although the low cost of HDDs is very attractive, these devices are intrinsically slow, with typical access times of several milliseconds because of the large mass of the rotating disk. RAM, on the other hand can be very fast and highly reliable, as in static RAM and dynamic RAM technologies. The architecture of computing systems would be greatly simplified if there were a single memory storage device

the racetrack alternate between head-to-head and tail-to-tail configurations. The spacing between consecutive DWs (that is, the bit length) is controlled by pinning sites fabricated along the racetrack. There are several means of creating such pinning sites; for example, by patterning notches along the edges of the racetrack or modulating the racetrack's size or material properties. Besides defining the bit length, pinning sites also give the DWs the stability to resist external perturbations, such as thermal fluctuations or stray magnetic fields from nearby racetracks.

RM is fundamentally a shift register in which the data bits (the DWs) are moved to and fro along any given racetrack to intersect with individual reading and writing elements integrated with each racetrack (Fig. 1). The DWs in the magnetic racetrack can be read with magnetic tunnel junction magnetoresistive sensing devices (3) arranged so that they are close to or in contact with the racetrack. Writing DWs can be carried out with a variety of schemes (1), including using the self-field of currents passed along neighboring metallic nanowires; using the spin-momentum transfer torque effect (4, 5) derived from current injected into the racetrack from magnetic nanoelements; or using the fringing fields from the controlled motion of a magnetic DW in a proximal nanowire writing element (1).

Uniform magnetic fields cannot be used to shift a series of DWs along the racetrack:

Computação Spintrônica



Multifunctional Spin Logic Gates In Graphene Spin Circuits

Dmitrii Khokhriakov[1], Shehrin Sayed[2,3], Anamul Md. Hoque[1], Bogdan Karpiak[1], Bing Zhao[1], Supriyo Datta[4], Saroj P. Dash[1,5*]

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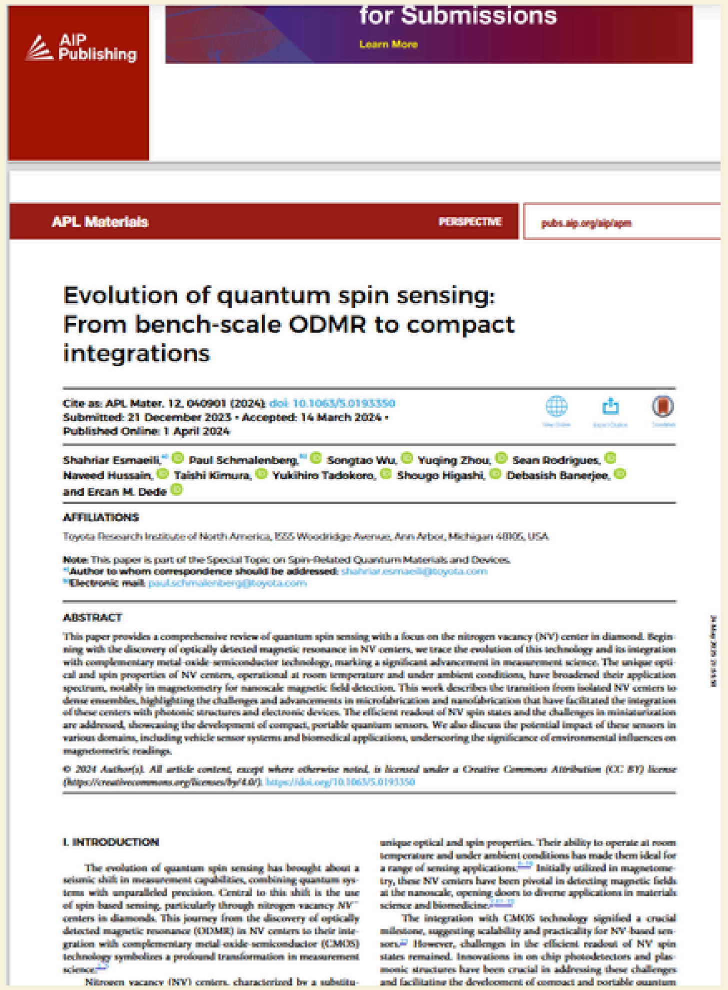
Abstract

All-spin-based computing combining logic and nonvolatile magnetic memory is promising for emerging information technologies. However, the realization of a universal spin logic operation representing a reconfigurable building block with all-electrical spin current communication has so far remained challenging. Here, we experimentally demonstrate a reprogrammable all-electrical multifunctional spin logic gate in a nanoelectronic device architecture utilizing graphene buses for spin communication and multiplexing and nanomagnets for writing and reading information at room temperature. This gate realizes a multistate majority spin logic operation (sMAJ), which is reconfigured to achieve XNOR,

ESTADO DA ARTE

Avanços recentes em pesquisa

Spintrônica E Mecânica Quântica



APL Materials PERSPECTIVE pubs.aip.org/aip/apm

Evolution of quantum spin sensing: From bench-scale ODMR to compact integrations

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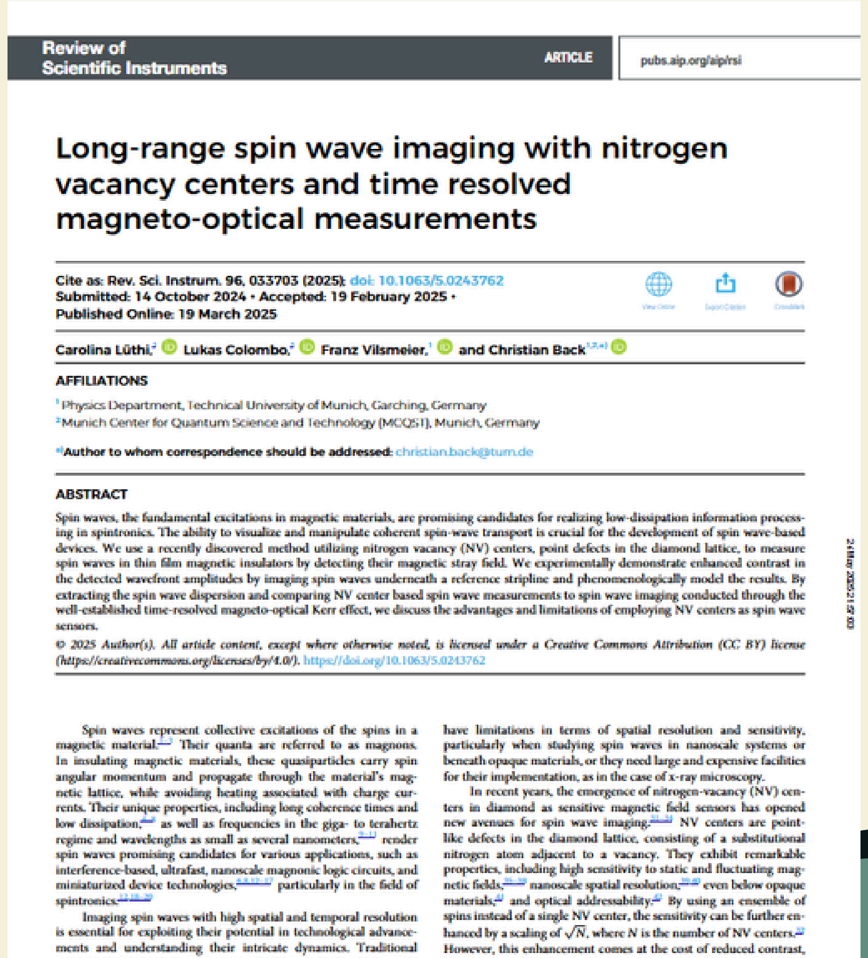
ABSTRACT

This paper provides a comprehensive review of quantum spin sensing with a focus on the nitrogen vacancy (NV) center in diamond. Beginning with the discovery of optically detected magnetic resonance in NV centers, we trace the evolution of this technology and its integration with complementary metal-oxide-semiconductor technology, marking a significant advancement in measurement science. The unique optical and spin properties of NV centers, operational at room temperature and under ambient conditions, have broadened their application spectrum, notably in magnetometry for nanoscale magnetic field detection. This work describes the transition from isolated NV centers to dense ensembles, highlighting the challenges and advancements in microfabrication and nanofabrication that have facilitated the integration of these centers with photonic structures and electronic devices. The efficient readout of NV spin states and the challenges in miniaturization are addressed, showcasing the development of compact, portable quantum sensors. We also discuss the potential impact of these sensors in various domains, including vehicle sensor systems and biomedical applications, underscoring the significance of environmental influences on magnetometric readings.

I. INTRODUCTION



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Long-range spin wave imaging with nitrogen vacancy centers and time resolved magneto-optical measurements

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ABSTRACT

Spin waves, the fundamental excitations in magnetic materials, are promising candidates for realizing low-dissipation information processing in spintronics. The ability to visualize and manipulate coherent spin-wave transport is crucial for the development of spin wave-based devices. We use a recently discovered method utilizing nitrogen vacancy (NV) centers, point defects in the diamond lattice, to measure spin waves in thin film magnetic insulators by detecting their magnetic stray field. We experimentally demonstrate enhanced contrast in the detected wavefront amplitudes by imaging spin waves underneath a reference stripline and phenomenologically model the results. By extracting the spin wave dispersion and comparing NV center based spin wave measurements to spin wave imaging conducted through the well-established time-resolved magneto-optical Kerr effect, we discuss the advantages and limitations of employing NV centers as spin wave sensors.

APLICAÇÕES

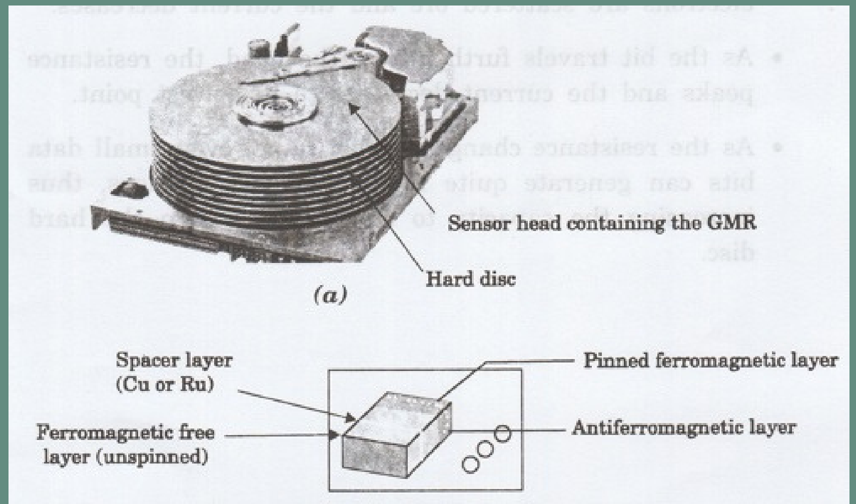
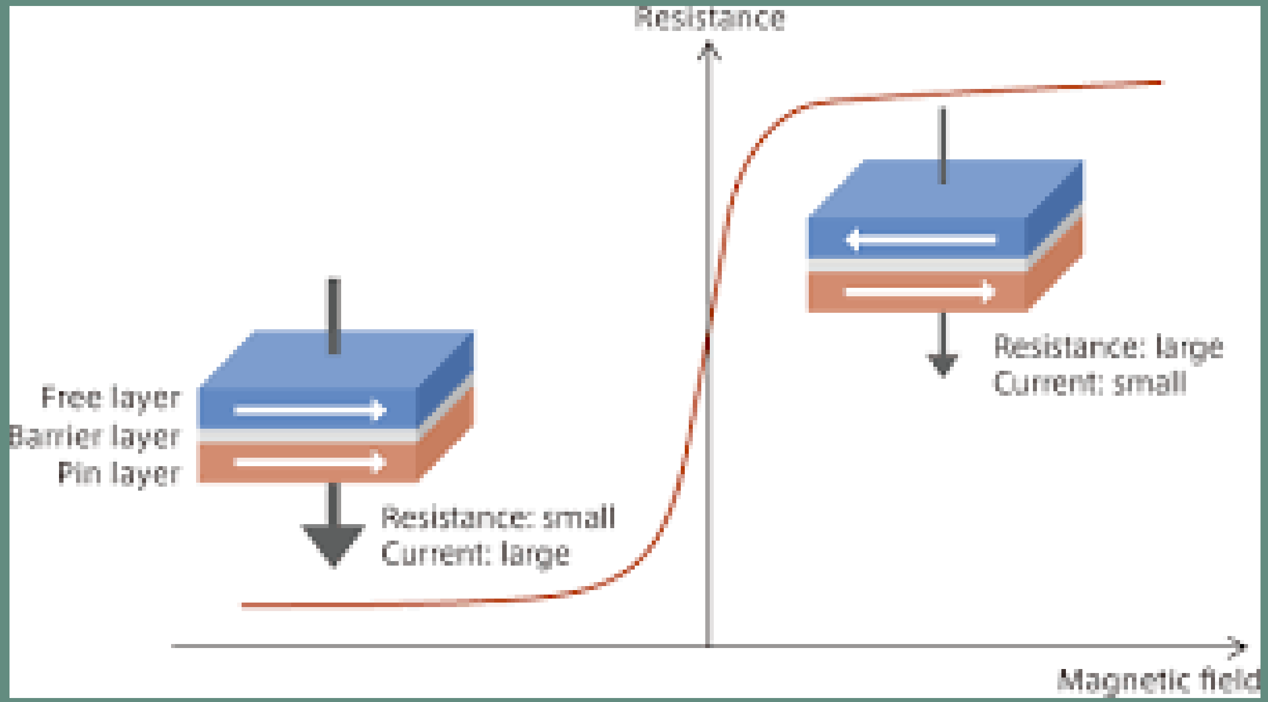


Fig. 2.35 (b) Spin valve

Sensores Magnéticos

Analisando a variação de resistência em um semicondutor (multicamadas) com propriedade de Magnetorresistência Gigante, é possível detectar campos magnéticos com uma precisão superior a sensores de Efeito Hall

- Eficientes em temperatura ambiente
- Melhoria no desempenho dos cabeçotes de leitura de discos rígidos
- Detectores de corrente e voltagem independentes
- Uso amplo em sensores de eficiência.

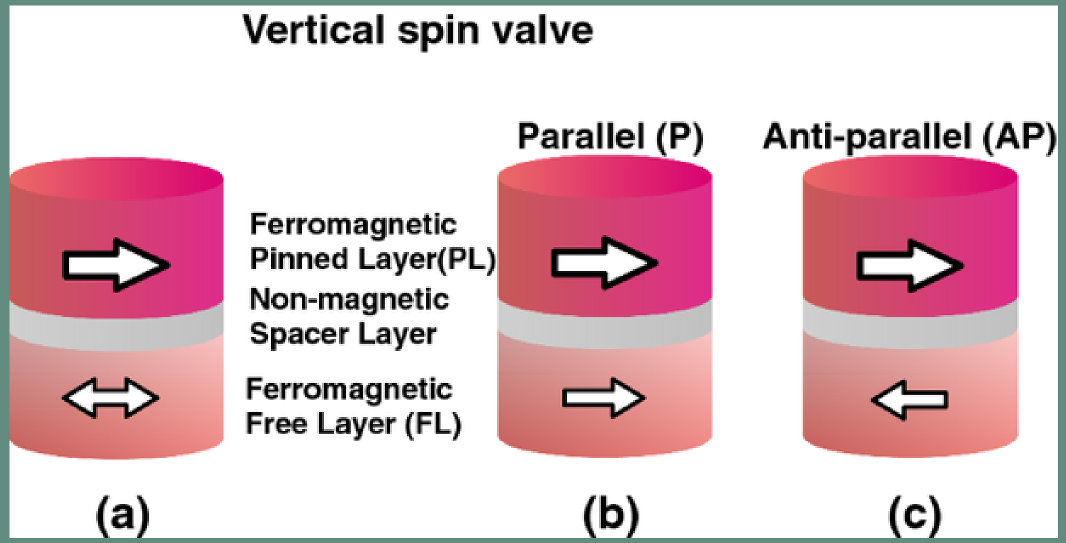


APLICAÇÕES

Transistor de Spin e Informação Magnética

Outra aplicação consiste na utilização de uma interface similar (camadas magnéticas entre não=magnéticas) para alternar a magnetização de uma de suas interfaces sob corrente, oferecendo uma espécie de transistor de baixo gasto energético.

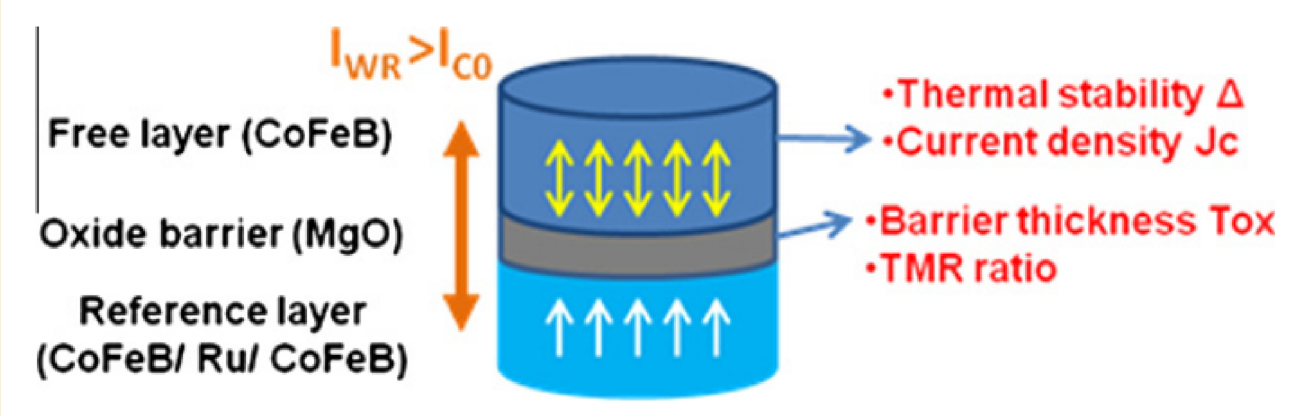
- Melhoria no desempenho dos cabeçotes de leitura de discos rígidos
- Uso amplo na indústria de armazenamento magnético (Spin Transfer Torque-MRAM ou STT-MRAM)



LIMITAÇÕES

As principais limitações destes aparelhos envolvem as proporções de suas dimensões e perturbações no alinhamento de spin desejado ou analisado

- Variações na barreira entre filmes pode causam erros no registro de informações
- Escalas de fabricação nanométricas encarecem seu custo
- Sujeito a flutuações térmicas no equipamento
- Despolarização sob campo externo



PERSPECTIVAS FUTURAS

Explorando três frentes emergentes com grande potencial para aplicações futuras

Spintrônica de Antiferromagnéticos

Materiais Topológicos na Spintrônica

Lógica Spintrônica (All-Spin Logic ASL)

PERSPECTIVAS FUTURAS

Spintrônica de Antiferromagnéticos: Visão Geral

Porque usar antiferromagnéticos?

- Ausência de campo externo → sem perturbação magnética
- Frequência de operação ultra-rápida (THz)
- Não volatilidade e estabilidade térmica

Vantagens sobre ferromagnéticos

- Imunidade a interferência magnética
- Alta densidade de integração

PERSPECTIVAS FUTURAS

AFM Spintronics: Funcionamento

Como se manipula o estado AFM?

- **Torque de spin para controle**
    - Corrente elétrica fica polarizada em spin
    - Flui através de um material com forte acoplamento spin órbita
    - Gera uma corrente de spin que exerce torque sobre a magnetização

PERSPECTIVAS FUTURAS

AFM Spintronics: Funcionamento

Como se lê o estado AFM?

- **Magnetoresistência anisotrópica (AMR)**
  - Variação da resistência elétrica com a orientação da corrente em relação à orientação dos momentos magnéticos antiferromagnéticos
- **Efeito Hall Anômalo**
  - Efeito Hall que ocorre na ausência de campos magnéticos externos

PERSPECTIVAS FUTURAS

AFM Spintronics: Funcionamento

Exemplos: CuMnAs, Mn_2Au → reversão de estados via corrente elétrica

Aplicações: memórias magnéticas ultrarrápidas, dispositivos tolerantes a radiação

PERSPECTIVAS FUTURAS

Materiais Topológicos na Spintrônica

O que são?

Um material topológico é aquele cujas propriedades na superfície são diferentes das propriedades no seu interior, e essas diferenças são preservadas mesmo com deformações ou torções do material.

Por que são úteis na spintrônica?

- Geração eficiente de corrente de spin
- Robustez contra imperfeições → transporte quase sem dissipação
- Integração com ímãs permite comutação por torque de spin topológico

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Tipos e Materiais Topológicos

Tipos relevantes

- Isolantes Topológicos (Bi2Se3, Sb2Te3)
- Semimetais de Weyl (TaAs, NbAs)
- Magnéticos topológicos (MnBi2Te4)

Aplicações: Memórias, conversores spin-carga, dispositivos lógicos de baixa dissipação

PERSPECTIVAS FUTURAS

Lógica Spintrônica (ASL): Conceito

O que é All-Spin Logic?

- Processamento puramente com corrente de spin
- Elimina a separação entre lógica e memória

Bit representado pela magnetização ↑↓ de nanoímãs

- Informação propagada por corrente de spin → sem corrente de carga

PERSPECTIVAS FUTURAS

Componentes e Funcionamento da ASL

Arquitetura básica:

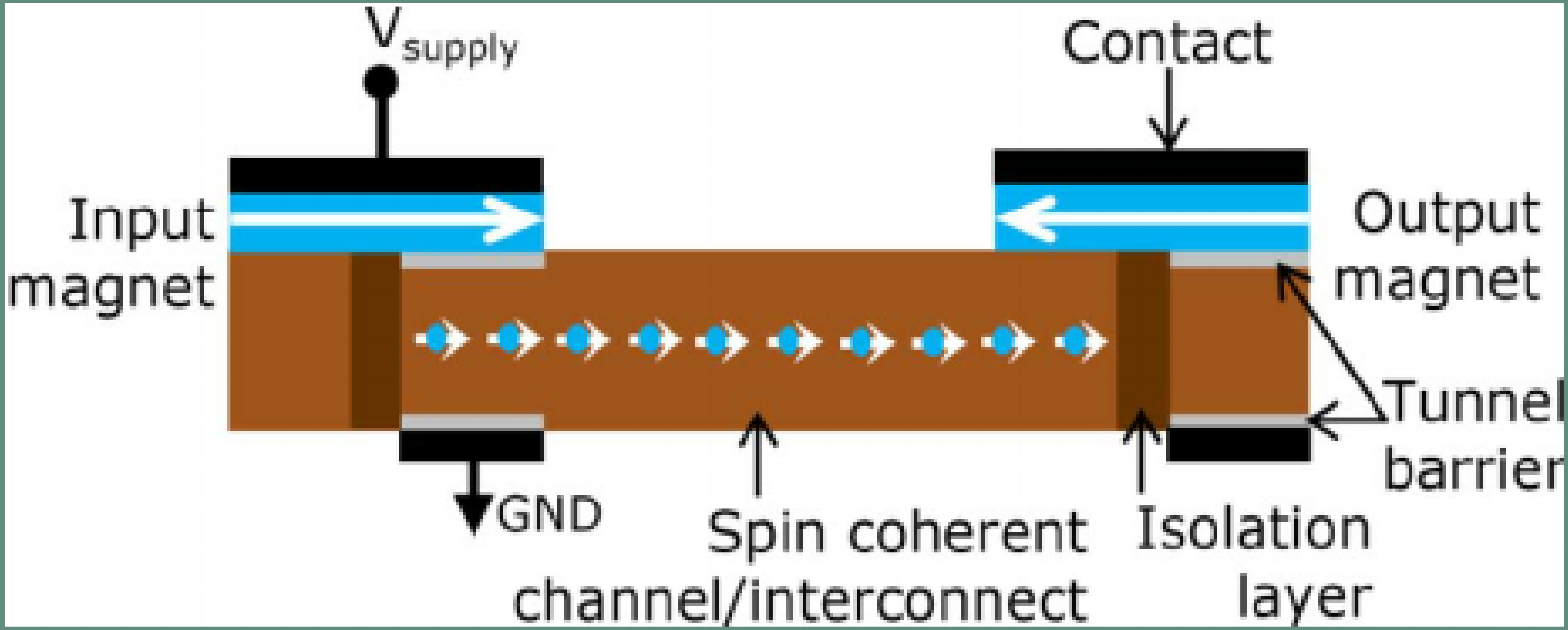
Nanoímã A → Canal de spin → Nanoímã B

- Injeção de spin → transporte → torque → comutação
- Canais de trasnporte: Cu, grafeno, semicondutores

Lógica não volátil, baixo consumo, escalável

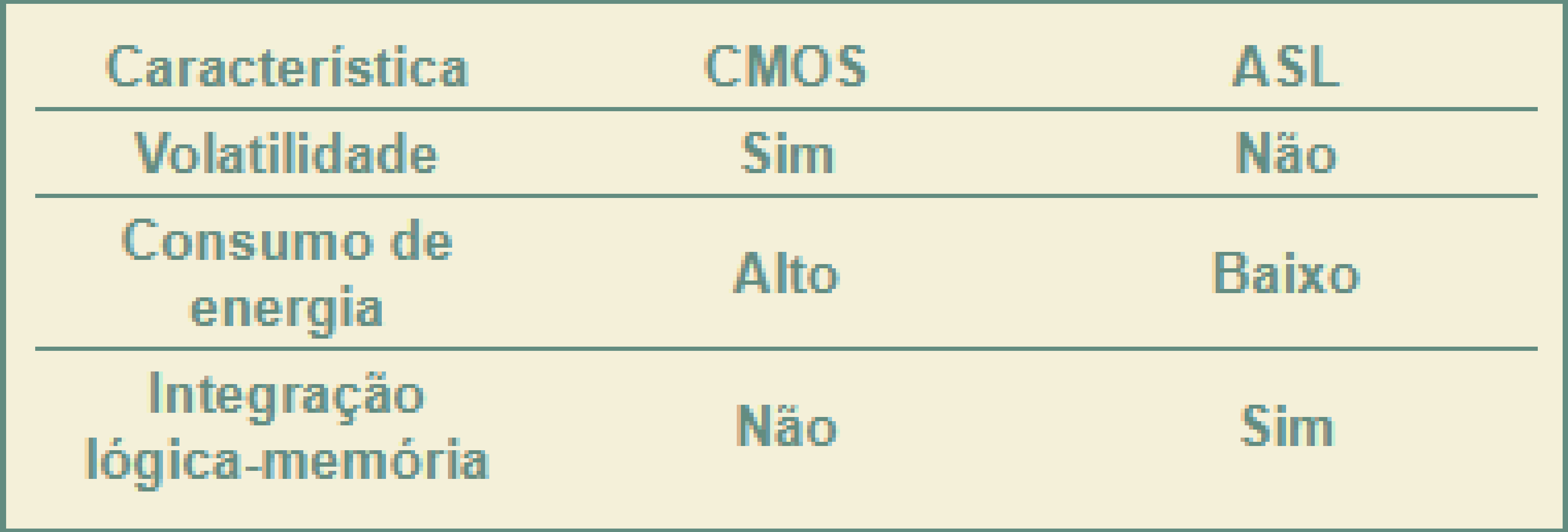
PERSPECTIVAS FUTURAS

Componentes e Funcionamento da ASL



PERSPECTIVAS FUTURAS

Comparativo e Desafios Atuais



Característica	CMOS	ASL
Volatilidade	Sim	Não
Consumo de energia	Alto	Baixo
Integração lógica-memória	Não	Sim

PERSPECTIVAS FUTURAS

Comparativo e Desafios Atuais

Desafios:

- Eficiência na injeção de spin
- Perdas por relaxação de spin
- Velocidade de comutação
- Escala de fabricação
- Tempo de comutação comparável ao CMOS

PERSPECTIVAS FUTURAS

Comparativo e Desafios Atuais

Eficiência na injeção de spin

Interface entre materiais → barreiras → reduzem eficiência

- Desenvolvimento de novos materiais
- Interfaces mais limpas
- Técnicas de engenharia em camadas atômicas

PERSPECTIVAS FUTURAS

Comparativo e Desafios Atuais

Relaxação de Spin

Tendência de perder a polarização ao longo do tempo e da distância

- Limita o alcance → restringe tamanho dos dispositivos
- Grafeno → baixo acoplamento spin órbita → reduz o efeito
- Limitações fabricação e integração

PERSPECTIVAS FUTURAS

Comparativo e Desafios Atuais

Velocidade de Comutação

Ainda precisa competir com os transistores tradicionais

Mesmo que prometa consumo menor de energia

Deve atingir tempo de resposta de nanossegundos ou menos

PERSPECTIVAS FUTURAS

Comparativo e Desafios Atuais

Escala de Fabricação

Demonstração em laboratório em escala nanométrica

Condições muito controladas, como baixas temperaturas

Larga escala precisa de:

- Reprodutibilidade
- Estabilidade térmica
- Compatibilidade com processos industriais

PERSPECTIVAS FUTURAS

Comparativo e Desafios Atuais

Integração com a tecnologia CMOS

Indústria eletrônica atual → baseada em CMOS

CMOS = Complementary Metal-Oxide-Semiconductor

Novas tecnologias necessitam ser compatível com esse ecossistema para serem usadas em larga escala

- Avançoes em materiais e dispositivos
- Arquiteturas híbridas
  - Lógica tradicional e spintrônica

CONCLUSÃO

Em resumo, a Spintronicâ se expressa como uma das principais aplicações tecnológicas da teoria de Spin na atualidade e um grande avanço na ciência de materiais e dispositivos eletrônicos, trazendo aplicações diretas de propriedades quânticas da matéria para a tecnologia do dia a dia.

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