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斯坦福新闻 May 5, 2023 Laura Castanon

一种新材料可能会使基于磁铁的计算机内存更加高效

工程师们发现了一种金属化合物，该化合物可能会使更高效的计算机内存更加接近商业化，从而降低计算的碳足迹，实现更快的处理速度，并允许在个人设备上进行 AI 训练，而不是在远程服务器上进行。

在过去的十年中，随着[日益复杂的]人工智能技术~~日益复杂~~的引入，对计算能力的需求呈指数级增长。新的、能源高效的硬件设计可以帮助满足这种需求，同时降低计算的能源消耗，支持更快的处理速度，并允许在设备本身内进行 AI 训练。

“在我看来，我们已经从互联网时代过渡到了 AI 时代，”斯坦福大学工程学院的 Leland T. Edwards 教授 Shan Wang 说道。“我们希望能够在边缘上实现 AI，也就是在您的家庭计算机、手机或智能手表上进行本地训练，以进行心脏病检测或语音识别等任务。为了做到这一点，您需要一种非常快速的、非挥发性[非易失性]的内存。”

Wang 教授和他的同事们最近发现了一种可能会使一种新型内存更接近商业化的材料。在一篇发表在 Nature Materials 上的新论文中，研究人员展示了一层名为锰钯三的金属化合物的薄层具有促进一种存储数据的工作内存的必要属性。这种内存存储方法被称为自旋轨道扭矩磁阻随机存取存储器，或 SOT-MRAM，具有比当前方法更快、更高效地存储数据的潜力，当前方法使用电荷存储数据，并需要持续的电源输入来维持数据。

“我们为未来的能源高效存储元件提供了一个基本的构建块，”Wang 教授说道。“这是非常基础的[科研]，但这是一个突破。”

电子自旋的应用

SOT-MRAM 依赖于电子的一种本质属性，称为自旋。为了理解自旋，可以将电子想象成平衡在职业运动员手指末端的旋转篮球。由于电子是带电粒子，旋转会使电子成为一个微小的磁体，沿其轴线极化（在这种情况下，从平衡篮球的手指延伸的线）。如果电子改变自旋方向，则磁体的南北极会交换。研究人员可以使用该磁性的上或下方向，即磁偶极矩，来表示组成计算机数据位[比特]和字节的 1 和 0。

在 SOT-MRAM 中，通过一种材料（SOT 层）流过的电流产生特定的自旋方向。这些电子的运动，结合它们的自旋方向，创建了一种扭矩，可以切换相邻磁性材料中的电子的自旋方向和相关磁偶极矩。通过正确的材料，存储磁性数据就像在 SOT 层中切换电流方向一样简单。

但是找到正确的 SOT 材料并不容易。由于硬件的设计方式，当电子自旋方向沿 z 方向朝上或朝下定向时，可以更密集地存储数据。（如果想象一个盘子上的三明治，x-和 y-方向沿着面包边缘，z-方向是插入中间的牙签。）不幸的是，如果电流沿 x 方向流动，大多数材料会将电子自旋在 y 方向极化。

“传统材料只能在 y 方向产生自旋 - 这意味着我们需要一个外部磁场来使 z 方向的开关[切换]发生，这需要更多的能量和空间，”王实验室的博士后研究员 Fen Xue 说。“为了降低能量，实现更高密度的存储，我们希望能够在没有外部磁场的情况下实现这种开关[切换]。”

研究人员发现，锰钯三具有所需的性质。该材料能够产生任何方向的自旋，因为其内部结构缺乏会迫使所有电子朝特定方向排列的晶体对称性。使用锰钯三，研究人员能够演示在不需要外部磁场的情况下在 y 方向和 z 方向上磁化的切换。虽然手稿[Nature Materials 上的新论文]中未进行演示，但在没有外部磁场的情况下也可以切换 x 方向的磁化。

“我们具有与其他传统材料相同的输入电流，但现在我们有了三个不同方向的自旋，”在斯坦福大学担任博士后研究员并担任该论文第一作者的 Mahendra DC 说。“根据应用，我们可以控制磁化的任何方向。”

DC 和王赞扬了跨学科、多机构合作的成果[贡献]。王说：“内布拉斯加大学的 Evgeny Tsymbal 实验室领导了预测意想不到的自旋方向和运动的计算工作，而国家标准与技术研究院的 Julie Borchers ~~实验室~~[及其同事]则领导了揭示锰钯三的精细微观结构的测量和建模工作。这确实需要一个团队[共同]的努力。”

制造可能性 [工业化的前景]

除了其对称性破缺的结构外，锰钯三还有几个其他的性质，使其成为 SOT-MRAM 应用的优秀候选材料。例如，它可以通过电子器件需要经历的后退火过程~~生存~~并保持其性质。

DC 说："后退火需要电子器件在 400 摄氏度下持续 30 分钟，这是这些器件中新材料所面临的挑战之一，而锰钯三可以处理[应付]这个问题。" 此外，锰钯三的一层是使用磁控溅射的过程制造的，这是一种在内存存储硬件的其他方面已经使用的技术。

薛说："这种材料不需要新工具或新技术，我们不需要有纹理[织构]的基板或特殊条件来沉积它。"

结果是一种不仅具有新颖性质的材料，可以帮助满足我们不断增长的计算需求，而且可以顺利地融入当前的制造技术。研究人员已经在使用锰钯三制作 SOT-MRAM 的原型，将其集成到实际设备中。

DC 说："我们正在技术的瓶颈中挣扎，所以我们必须找出其他的选择 [现有的技术遇到了瓶颈，所以我们必须找到其他的选项]。"

王是材料科学与工程教授，电气工程联合教授，斯坦福[Geballe]高级材料研究所实验室成员，斯坦福 Bio-X（http://biox.stanford.edu/）和 Wu Tsai 神经科学研究所（https://neuroinstitute.stanford.edu/）的成员；是 Precourt 能源研究所（https://energy.stanford.edu/）和斯坦福伍兹环境研究所（http://woods.stanford.edu/cgi-bin/index.php）的成员。

本研究的其他斯坦福合著者包括高级研究科学家 Arturas Vailionis、兼职教授 Wilman Tsai、研究顾问 Chong Bi、研究助理 Xiang Li 和研究生 Yong Deng。其他合作者来自内布拉斯加大学、台湾积体电路制造公司、考纳斯工业大学、国家标准与技术研究所、亚利桑那大学、科罗拉多矿业学院、国立阳明交通大学和成蹄[成蹊]大学。

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Stanford News (http://news.stanford.edu/)

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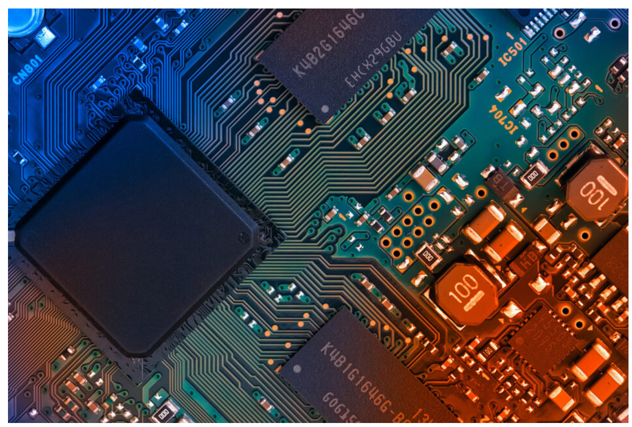
A new material could enable more efficient magnet-based computer memory

Engineers have found a metallic compound that could bring more efficient forms of computer memory closer to commercialization, reducing computing's carbon footprint, enabling faster processing, and allowing AI training to happen on individual devices instead of remote servers.

BY LAURA CASTAÑÓN

Over the last decade, with the introduction of increasingly complex artificial intelligence (AI) technologies, the demand for computing power has risen exponentially. New, energy-efficient hardware designs could help meet this demand while reducing computing's energy use, supporting faster processing, and allowing AI training to take place within the device itself.

"In my opinion, we have already transitioned from the internet era to the AI era," says **Shan Wang (https://profiles.stanford.edu/shan-wang)**, the Leland T. Edwards Professor in the School of Engineering at Stanford University. "We want to enable AI on edge – training locally on your home computer, phone, or smartwatch – for things like heart attack detection or speech recognition. To do that, you need a very fast, non-volatile memory."



(https://news.stanford.edu/wp-content/uploads/2023/05/shutterstock_raigvi.jpg)

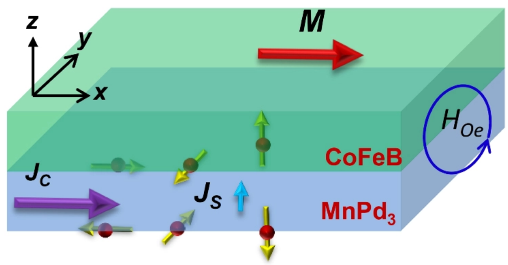
The spin orbit torque magnetoresistive random access memory (SOT-MRAM) has the potential to store data more quickly and efficiently than current methods, which store data using electric charge and require a continuous power input to maintain that data. *(Image credit: Shutterstock/raigvi)*

Wang and his colleagues recently found a material that could bring a new type of memory closer to commercialization. In a new paper **published (https://www.nature.com/articles/s41563-023-01522-3)** in *Nature Materials*, the researchers demonstrated that a thin layer of a metallic compound called manganese palladium three had the necessary properties to facilitate a form of working memory that stores data in electron spin directions. This method of memory storage, known as spin orbit torque magnetoresistive random access memory or SOT-MRAM, has the potential to store data more quickly and efficiently than current methods, which store data using electric charge and require a continuous power input to maintain that data.

"We've provided a basic building block for future energy-efficient storage elements," Wang says. "It's very foundational, but it's a breakthrough."

Harnessing electron spin

SOT-MRAM relies on an intrinsic property of electrons called spin. To understand spin, picture an electron as a rotating basketball balanced on the end of a professional athlete's finger. Because electrons are charged particles, the rotation turns the electron into a tiny magnet, polarized along its axis (in this case, a line that extends from the finger balancing the ball). If the electron switches spin directions, the north-south poles of the magnet switch. Researchers can use the up or down direction of that magnetism – known as the magnetic dipole moment – to represent the ones and zeroes that make up bits and bytes of computer data.



(https://news.stanford.edu/wp-content/uploads/2023/05/MnPd3-material.jpg)

Unconventional z-spin polarization in MnPd3 material. *(Image credit: The Wang Group)*

In SOT-MRAM, a current flowing through one material (the SOT layer) generates specific spin directions. The movement of those electrons, coupled with their spin directions, creates a torque that can switch the spin directions and associated magnetic dipole moments of electrons in an adjacent magnetic material. With the right materials, storing magnetic data is as simple as switching the direction of an electrical current in the SOT layer.

But finding the right SOT materials isn't easy. Because of the way the hardware is designed, data can be stored more densely when electron spin directions are oriented up or down in the z-direction. (If you imagine a sandwich on a plate, the x- and y-directions follow the edges of the bread and the z-direction is the toothpick shoved through the middle.) Unfortunately, most materials polarize electron spins in the y-direction if the current flows in the x-direction.

"Conventional materials only generate spin in the y-direction – that means we would need an external magnetic field to make switching happen in the z-direction, which takes more energy and space," says Fen Xue, a postdoctoral researcher in Wang's lab. "For the purpose of lowering the energy and having a higher density of memory, we want to be able to realize this switching without an external magnetic field."

The researchers found that manganese palladium three has the properties they need. The material is able to generate spins in any orientation because its internal structure lacks the kind of crystal symmetry that would force all of the electrons into a particular orientation. Using manganese palladium three, the researchers were able to demonstrate magnetization switching in both the y- and z-directions without needing an external magnetic field. Although not demonstrated in the manuscript, x-direction magnetization can also be switched in the absence of external magnetic field.

"We have the same input current as other conventional materials, but we have three different directions of spins now," says Mahendra DC, who conducted the work as a postdoctoral researcher at Stanford and is first author on the paper. "Depending on the application, we can control the magnetization in whatever direction we want."

DC and Wang credit the multidisciplinary and multi-institutional collaboration that enabled these advances. “Evgeny Tsymbal’s lab at the University of Nebraska led the calculations to predict the unexpected spin directions and movement and Julie Borchers’s lab at the National Institute of Standards and Technology led the measurements and modeling efforts to reveal the intricate microstructures within manganese palladium three,” says Wang. “It truly takes a village.”

Manufacturing possibilities

In addition to its symmetry-breaking structure, manganese palladium three has several other properties that make it an excellent candidate for SOT-MRAM applications. It can, for example, survive and maintain its properties through the post-annealing process that electronics need to go through.

“Post-annealing requires electronics to be at 400 degrees Celsius for 30 minutes,” DC says. “That’s one of the challenges for new materials in these devices, and manganese palladium three can handle that.”

Also, the layer of manganese palladium three is created using a process called magnetron sputtering, which is a technique that is already used in other aspects of memory-storage hardware.

“There’s no new tools or new techniques needed for this kind of material,” Xue says. “We don’t need a textured substrate or special conditions to deposit it.”

The result is a material that not only has novel properties that could help meet our growing computing requirements, but can fit smoothly into current manufacturing techniques. The researchers are already working on prototypes of SOT-MRAM using manganese palladium three that will integrate into real devices.

“We are hitting a wall with the current technology,” DC says. “So we have to figure out what other options we have.”

Wang is a professor of Materials Science and Engineering, and jointly of Electrical Engineering, a member of Geballe Laboratory of Advanced Materials, **Stanford Bio-X (http://biox.stanford.edu/)**, and the **Wu Tsai Neurosciences Institute (https://neuroinstitute.stanford.edu/)**; and an affiliate of the **Precourt Institute for Energy (https://energy.stanford.edu/)** and the **Stanford Woods Institute for the Environment (http://woods.stanford.edu/cgi-bin/index.php)**.

Additional Stanford co-authors of this research include senior research scientist Arturas Vailionis, adjunct professor Wilman Tsai, research consultant Chong Bi, research associate Xiang Li, and graduate student Yong Deng. Other coauthors are from University of Nebraska, Taiwan Semiconductor Manufacturing Company, Kaunas University of Technology, National Institute of Standards and Technology, University of Arizona, Colorado School of Mines, National Yang Ming Chiao Tung University, Seikei University.

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