An Electrical Switch for Magnetism

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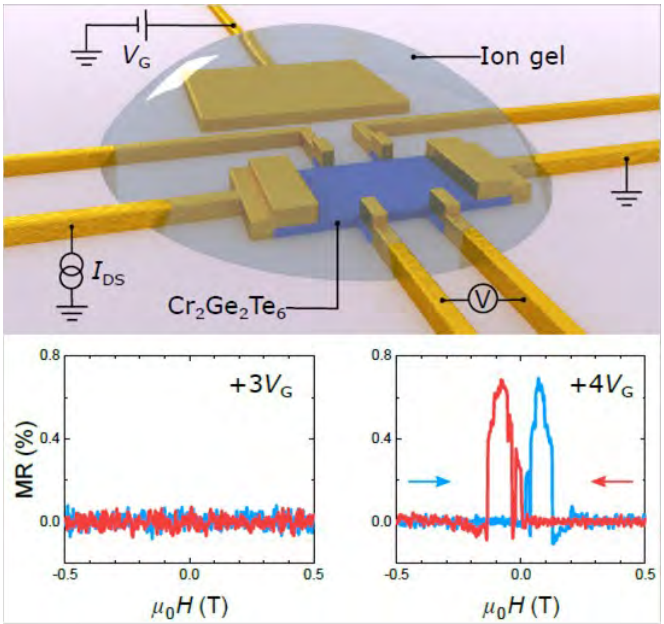
Semiconductors are the heart of information-processing technologies. As components for transistors, semiconductors act as a switch for electrical currents, allowing switching between the binary states of zero and one. Magnetic materials, on the other hand, are an essential component for information storage devices. They exploit the spin degree of freedom of electrons to achieve memory functions. Magnetic semiconductors are a unique class of materials that allow control of both the electrical charge and spin, potentially enabling information processing and memory operations in a single platform. The key challenge is to control the electron spins, or magnetization, using electric fields, in a way similar to how a transistor controls electrical currents. However, magnetism typically has weak dependence on electric fields in magnetic semiconductors, and the effect is often limited to cryogenic temperatures.

Recently, my research group at the Department of Physics and the Department of Chemistry, and the Centre for Advanced 2D Materials at NUS, in collaboration with Prof. Hidekazu KUREBAYASHI from the London Centre for Nanotechnology, University College London, discovered that the magnetism of a magnetic semiconductor, $Cr_2Ge_2Te_6$, shows exceptionally strong response to applied electric fields. With the applied electric fields, the material was found to exhibit ferromagnetism (a state in which electron spins spontaneously align) at temperatures up to 200 K (-73°C). At such temperatures, without the applied electric fields, ferromagnetic order is normally absent in this material.

We applied large electric fields to this material by coating it with a layer of polymer gel containing dissolved ions.



(Top) Schematic of field-effect transistor based on ultra-thin ferromagnetic semiconductor Cr2Ge2Te6. The material is covered with an ion gel to enhance the field effect. (Bottom) Magneto-resistance (MR) with increasing (blue) and decreasing (red) magnetic field sweeps. When the gate voltage (VG) is increased from 3 V (left) to 4 V (right), MR hysteresis emerges, indicating that ferromagnetic order is induced.

When voltage is applied to the polymer gel, a layer of ions forms at the material's surface, inducing strong electric fields and a high density of mobile electrons in the material. In the absence of these mobile electrons (i.e., when the applied voltage is zero), ferromagnetism occurs only below 61 K (-212°C). This critical temperature, below which ferromagnetic order emerges, is known as the Curie temperature. Above this temperature, the spin orientations are randomized (paramagnetic state), making magnetic memory operations impossible. When an electrical potential of a few volts is applied to the polymer gel, we found that the Curie temperature increased by more than 100˚C. Such a dramatic increase in the Curie temperature triggered by electric fields is unusual in a magnetic semiconductor. We concluded that the mobile electrons induced by the ions are responsible for the observed magnetic order at the higher temperature.

The lead author, Dr. Ivan Verzhbitskiy, a research fellow in the team said, "The mobile electrons present in the material help to carry the spin information from one atomic site to another and establish magnetic order, resulting in a higher Curie temperature."

The operation temperature of these devices is still well below room temperature, which makes their implementation into current technologies impractical. However, the team aims to research ways to overcome this limitation.

We believe that this unique phenomenon that we observed is not limited to this particular compound and can be expected in other related materials systems. With careful selection of materials, we believe it will be possible to develop devices that operate at room temperature, which could lead to groundbreaking new technologies.

References

[1] Ivan A. Verzhbitskiy, Hidekazu Kurebayashi, Haixia Cheng, Jun Zhou, Safe Khan, Yuan Ping Feng, and Goki Eda. "Controlling the magnetic anisotropy in $Cr_2Ge_2Te_6$ by electrostatic gating." Nature Electronics 3, no. 8 (2020): 460-465.

[2] https://www.science.nus.edu.sg/blog/2020/08/06/an-electrical-switch-for-magnetism/