Chameleon Magnets
Igor Zutic, *et al.*
Science **332**, 1040 (2011);
DOI: 10.1126/science.1205775

point to another, and gate operation with threshold behavior—constitute most of the components needed to enable arbitrary binary logic. So what is preventing the wiring up of an atomic-scale calculator? Aside from practical issues such as room-temperature operation, a conceptual challenge is the implementation of energy gain: Does the binary signal decay in longer chains? Can the output of the logic gate drive one or more successive gates? It is likely that in order to achieve this goal, energy must be put into the system at certain stages. Borrowing ideas from nanodot logic, one possibility might be to elevate the spins into metastable states at a clock frequency (*3*, *4*). If a successful technology could be built from such spins, it promises low energy consumption.

So when will we reach the end of Moore's law? It is clear that the ultimate size limit is the scale of atoms, and this work takes a decisive step toward a real demonstration of spin-based computation at this limit. Given that there is currently about a factor of 1000 difference in areal density between silicon chip technology and the demonstration by Khajetoorians *et al.*, there is still sufficient time to tackle the intriguing questions opened up by this work.

References

1. A. A. Khajetoorians, J. Wiebe, B. Chilian, R. Wiesendanger, *Science* **332**, 1062 (2011); 10.1126/science.1201725.
2. D. A. Allwood *et al.*, *Science* **309**, 1688 (2005).
3. A. Imre *et al.*, *Science* **311**, 205 (2006).
4. L. Gross *et al.*, *Nanotechnology* **21**, 325301 (2010).
5. A. J. Heinrich *et al.*, *Science* **298**, 1381 (2002); 10.1126/science.1076768.
6. D. M. Eigler, E. K. Schweizer, *Nature* **344**, 524 (1990).

10.1126/science.1206086

PHYSICS

Chameleon Magnets

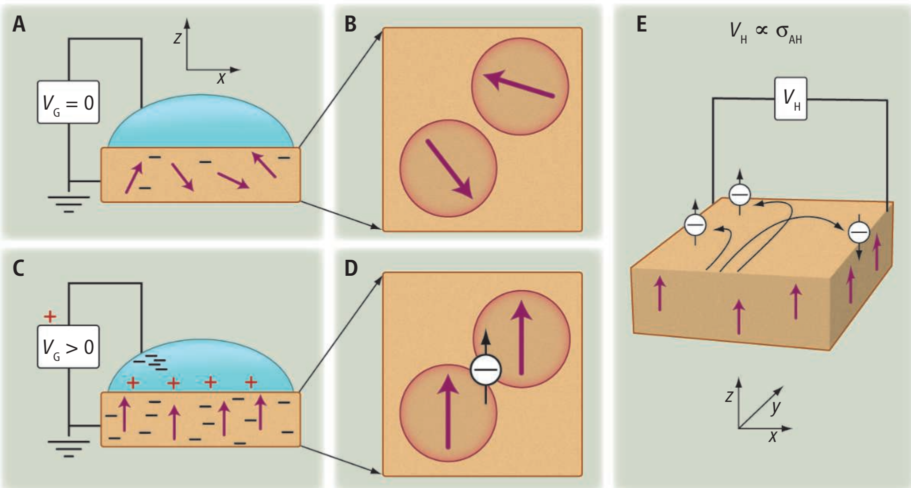
An external voltage can switch ferromagnetism on and off in a material at room temperature, which may add new functionality to electronics.

Igor Žutić and John Cerně

The spin of an electron can serve as a magnetic messenger. Permanent magnetism, or ferromagnetism, comes from the spontaneous alignment of the electron spins and their associated magnetic moments in metals such as iron and cobalt, which results in their or magnetization. Ferromagnetism plays an important role in information storage, not only to keep refrigerator magnets in place (and notes held by them) but to store data in computer hard drives (*1*, *2*). A more common effect is paramagnetism—a material becomes magnetic only when an external magnetic field causes its spins to align. Silicon is paramagnetic, but its semiconductor properties, not its magnetism, make silicon useful in logic circuits. On page 1065 of this issue, Yamada *et al.* (*3*) report a breakthrough that brings together these two different worlds of ferromagnetic metals and paramagnetic semiconductors and may better integrate logic and memory. By adding cobalt impurities to nonmetallic and nonmagnetic titanium dioxide, they created an intriguing material $(Ti,Co)O_2$, which, like a chameleon, can reversibly transform from a paramagnet to a ferromagnet at room temperature.

Electrically controlled material properties are at the heart of modern microelectronics, which rely on devices such as silicon field-effect transistors (FETs). An applied electric field changes the number of current carriers in a semiconductor (an effect called doping) and can switch the current flowing through the FET on and off. This reversible effect differs from chemical doping (adding impurities), where the number of charge carriers is permanently changed. The FET approach allows an electric field to dope the same sample reversibly and even transform it from insulating to metallic (*4*, *5*). Yamada *et al.* start with chemical doping. They replace approximately 10% of Ti^{4+} ions in TiO_2 with Co^{2+} ions, which introduces three aligned spins for each Co^{2+}. The Co^{2+} ions and their spins (depicted by thick arrows in the figure) are localized, and their random orientations do not align in any particular way from Co^{2+} ion to Co^{2+} ion, a characteristic of a paramagnet (see the figure, panels A and B).

With applied positive voltage (depicted in the figure, panel C), extra electrons and their associated spins are added to $(Ti,Co)O_2$. These electrons are mobile and convey information about electron spin alignment between different Co^{2+} ions. The Co^{2+} ions adopt a ferromagnetic alignment and also transfer this spin alignment to the mobile electrons (see the figure, panel D).



Tunable ferromagnetism. Cobalt-doped titanium dioxide, $(Ti,Co)O_2$, is paramagnetic. Yamada *et al.* show that applying a voltage to this material in an electrolytic cell causes it to become a ferromagnet. (**A** and **B**) With no applied gate voltage V_G between the electrolytic top contact and the $(Ti,Co)O_2$, the carrier density (electrons, e^-) is low, and the Co^{2+} spins (violet arrows) interact weakly and are not aligned. (**C** and **D**) For V_G at 3.8 V, the carrier density increases by nearly a factor of 10 and the electrons act as magnetic messengers, aligning the Co^{2+} spins. (**E**) Magnetization can be detected because it creates an imbalance in the electron spin populations. For an electron current flowing in the *y* direction, the spin-up electrons will tend to scatter to the left (–*x* direction) and the spin-down electrons to the right (+*x* direction). With more spin-up electrons, there will be a net accumulation of electrons on the left side of the sample, which in turn can be measured as an anomalous Hall voltage V_H or Hall conductivity σ_{AH}. Reversing V_G to zero transforms the ferromagnet back into a paramagnet.

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Similar chameleon magnets were initially demonstrated by Ohno *et al*. (*6*), but they operated at cryogenic temperatures (about 25 K) and required very large applied voltages (±125 V). What allowed Yamada *et al*. to produce magnetic order at room temperature (300 K) and require only a few volts to turn the ferromagnetism on and off was a clever twist on the standard FET principle (*3*, *5*, *7*). Very large electric fields can irreparably damage materials—they act like a lightning strike. The maximum carrier density that can be reversibly induced in a material occurs at a field strength known as the breakdown electric field. Yamada *et al*. incorporated an electrochemical cell into a FET and effectively increased both the breakdown field and the maximum carrier density that can be added to a semiconductor by a factor of 10. The more carriers, the more their spin can promote a robust ferromagnetic alignment that can persist at higher temperatures.

With ferromagnetic alignment in place, the challenge remains to detect it. For example, tiny magnetic nanoclusters may form and give a spurious magnetization (*1*, *8*) that is not tunable with an electric field and lacks chameleon features. The authors measured the anomalous Hall effect (AHE), first reported in 1880 (*9*), which yields a voltage (V_{AH}), or equivalently conductivity (σ_{AH}), in the direction transverse to the charge flowing through the material. With imbalance in the electron spin populations, the AHE arises from the coupling of spin and orbital properties of the carriers, which produces asymmetry of the scattering: Carriers of opposite spins ("up" or "down") are deflected in opposite directions, transverse to the charge current (see the figure, panel E). By carefully comparing AHE for samples with carrier density altered by chemical or electric field doping, the authors provide strong support for the idea that the magnetization comes from mobile magnetic messengers (*10*).

What are the next steps, and can we expect further surprises? Unlike in chameleon magnets, ferromagnetism in semiconductors can have different origins and can be independent of electric fields (*11*). To simplify quests for other chameleon magnets, complementary measurement techniques could overcome challenges associated with constant-current measurements, in which genuine material properties can become obscured if the current flows nonuniformly along an atypical path. One possible approach is to perform higher-frequency (infrared) AHE measurements (*12*), which could reduce these difficulties and directly probe how the carriers in the host semiconductor are altered with the addition of magnetic ions.

It would also be important to understand how changing the carrier density modifies the maximum temperature for the onset of ferromagnetism. The elegant spin alignment in ferromagnets tends to be fragile at elevated temperatures. Heat ruins the order of nicely aligned spins in the same way that it ruins the order in a snowflake by melting. However, with chameleon magnets, the reverse may be possible. Heating semiconductors creates extra carriers, which could strengthen their role as magnetic messengers and could conceivably overcome the usual role of heat as the main foe of ferromagnetism (*13*, *14*).

Chameleon magnets could also help us make more versatile transistors and bring us closer to the seamless integration of memory and logic by providing smart hardware that can be dynamically reprogrammed for optimal performance of a specific task (*1*, *15*). Large applied magnetic fields can enforce the spin alignment in semiconductor transistors (*16*). With chameleon magnets, such alignment would be tunable and would require no magnetic field and could revolutionize the role ferromagnets play in technology.

References

1. I. Žutić *et al*., *Rev. Mod. Phys*. **76**, 323 (2004).
2. S. Maekawa, Ed., *Concepts in Spin Electronics* (Oxford Univ. Press, Oxford, 2006).
3. Y. Yamada *et al*., *Science* **332**, 1065 (2011).
4. C. H. Ahn *et al*., *Rev. Mod. Phys*. **78**, 1185 (2006).
5. K. Ueno *et al*., *Nat. Mater*. **7**, 855 (2008).
6. H. Ohno *et al*., *Nature* **408**, 944 (2000).
7. M. Endo *et al*., *Appl. Phys. Lett*. **96**, 022515 (2010).
8. S. R. Shinde *et al*., *Phys. Rev. Lett*. **92**, 166601 (2004).
9. M. I. Dyakonov, Ed., *Spin Physics in Semiconductors* (Springer, Berlin, 2008).
10. H. S. Hsu *et al*., *Appl. Phys. Lett*. **96**, 242507 (2010).
11. M. Venkatesan *et al*., *Nature* **430**, 630 (2004).
12. G. Acbas *et al*., *Phys. Rev. Lett*. **103**, 137201 (2009).
13. A. G. Petukhov *et al*., *Phys. Rev. Lett*. **99**, 257202 (2007).
14. M. J. Calderón, S. Das Sarma, *Phys. Rev. B* **75**, 235203 (2007).
15. H. Dery *et al*., http://arxiv.org/abs/1101.1497 (2011).
16. N. Rangaraju *et al*., *Phys. Rev. Lett*. **105**, 117202 (2010).

10.1126/science.1205775

BEHAVIOR

Explaining Human Behavioral Diversity

Ara Norenzayan

A study of 33 nations explores the ecological, historical, and cultural foundations of behavioral differences.

People have been captivated and puzzled by human diversity since ancient times. In today's globalized world, many of the key challenges facing humanity, such as reversing climate change, coordinating economic policies, and averting war, entail unprecedented cooperation between cultural groups on a global scale. Success depends on bridging cultural divides over social norms, habits of thinking, deeply held beliefs, and values deemed sacred. If we ignore, underestimate, or misunderstand behavioral differences, we do so at everyone's peril.

When it comes to understanding these differences, getting the science right is more important than ever. Ironically, one reason that the scientific study of human thought and behavior is so daunting, fascinating, and often controversial is precisely because, more than any other species, so much of human behavior is subject to considerable population variability. To better understand both this variability and humanity's shared characteristics, in recent years researchers in the social, behavioral, cognitive, and biological sciences have been using a variety of methods (including ethnographic and historical studies, experiments, and surveys) to deepen and extend our knowledge of cultural differences. These research programs are producing quantifiable, falsifiable, and replicable results. On page 1100 of this issue, for example, Gelfand *et al*. (*1*) report on an ambitious 33-nation study that compares the degree to which societies regulate social behavior and sanction deviant behavior. It highlights differences between "tight" cultures with strong norms and high sanctioning, and "loose" cultures with weak norms and low sanctioning.

Gelfand *et al*. surveyed 6823 people in the 33 nations, asking them to rate the appropriateness of 12 behaviors (such as eating or crying) in 15 situations (such as being in a

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