

## Change an Atom; Change a Material

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With just the change of an atom, [Jian Liu](http://www.phys.utk.edu/faculty/faculty-liu.html) (<http://www.phys.utk.edu/faculty/faculty-liu.html>) and his colleagues have found it's possible to change a material's properties. As modern technology demands components that fit into smaller spaces, research like theirs plays a valuable role in making that possible. The results, published in the *Proceedings of the National Academy of Sciences*, reveal a novel magnetic state that could pave the way for new devices.

### Spin Doctors

Understanding this discovery starts with the electrons: particularly how they spin. Liu, Assistant Professor of Physics, explained that spin, like charge, is a fundamental property of an electron.

"The difference is that spin has directionality as a vector," he said. "We have to use an *electric* field to control charge and a *magnetic* field to orient spin."

The exception is when an electron is on the move.

"Einstein's relativity tells us that the spin of an electron 'sees' its own charge motion – the electron orbit," he said. "Or, conversely, the charge 'knows' the spin direction as soon as it moves. The orbital provides a channel for the two properties to interact and affect each other. This is very much like we always add some spinning to a ball to control its trajectory, such as a football, baseball, and basketball." This phenomenon is called spin-orbit coupling (SOC) and plays a key role in the *PNAS* paper. Spintronics is a growing field of interest with the goal of using electron spin for devices. This requires controlling the magnetism.

"One of the key challenges is to exploit spin-orbit coupling such that we do not have to have a magnetic field, which causes lots of energy to generate," Liu said.

Several studies in this vein have featured different transition metal oxides (TMOs), but there have been limits to their potential. Some materials, for example, are ferromagnetic but have weak spin-orbit coupling, while others have stronger SOC but the spin-spin interaction isn't strong enough to host magnetism. Liu, along with Lipeng Zhang and Haixuan Xu of [UT's Materials Science and Engineering Department](http://www.engr.utk.edu/mse/) (<http://www.engr.utk.edu/mse/>), worked with colleagues from UC-Berkeley and Lawrence Berkeley and Argonne National Laboratories to get the best of both worlds.

### The "Super-Sandwich"

To achieve the best magnetic state, researchers combined two materials. One was ferromagnetic and comprised lanthanum, strontium, manganese, and oxygen (LSMO). The second was paramagnetic and was made from strontium, iridium, and oxygen (SIO). They grew layers of the materials on top of one another in a specific pattern.

"Normally, to create or grow a three-dimensional crystal, we just keep piling up these layers," Liu explained. "Here what we did is, when we grew LSMO, we stopped the piling process after every three layers, laid down one layer of SIO, and resumed the piling for LSMO. What happened in the end is that we had a LSMO crystal with intercalated SIO layers. One can think of it as sliding in thin layers of ham into a long breadstick with equal spacing, and turning it into a super-sandwich."

A critical step was tuning the layer dimensions. Building the sandwich (or superlattice, in scientific terms) as they did scaled down the SIO layer to 0.4 nanometer, containing only one iridium atomic plane. This confinement allowed for manipulation of the magnetism, owing to a novel spin-orbit

coupling state that developed in the SiO layers and oriented the magnetization of LSMO to a different direction. Those results wouldn't have been possible without precise control—at the atomic level—of the SiO thickness.

As Liu explained, tuning the layer size “causes something that would not happen in each individual material. The bread and the ham would never taste the same as the sandwich.”

## Atomic Scale Engineering

The benefits of controlling magnetism at the atomic scale continue to grow with the demand for more sophisticated devices.

“As modern technology develops, we want to make everything small and fit more processors, more memories, and more circuits into a small space,” Liu said. “There is nothing better than being able to design your material property and device function with just a change of an atom, which is exactly what we achieve. We replace one atomic plane of manganese with iridium, and the magnetization points to a different direction.”

The possibilities of engineering at this scale could also open doors for all-oxide spintronics. Liu explained that modern magnetic devices rely on metals and alloys, but they can be unstable in an oxidizing environment, which isn't a problem for oxides. Moreover, oxides have functionalities that metals lack, such as high-temperature superconductivity and ferroelectricity.

“An all oxide platform allows integrating these materials for multifunctional devices,” he said.

The research, published in the paper “Atomic-scale control of magnetic anisotropy via novel spin-orbit coupling effect in  $\text{La}_{2/3}\text{Sr}_{1/3}\text{MnO}_3/\text{SrIrO}_3$  superlattices,” was the first the authors know of that experimentally studies this type of superlattice and the effects of dimensional confinement. The work also showed that non-magnetic materials can be used to engineer magnetic materials if they're matched with the right partner in the appropriate geometry. Liu said it's possible other combinations of this type might have the same effect. While the possibility of finding materials for spintronic devices is exciting, the physics itself is equally interesting for scientists like Liu. In this case, they found the unexpected control over magnetism originates from the quantum entanglement of two different spin-orbits.

“(This) means that the electron can exist in two different orbits simultaneously and its spin can point to opposite direction at the same time,” Liu said. “I can't imagine how to throw the same football along two trajectories with different spinning motions at the same time. Quantum mechanics is just fascinating.”

See the paper at: <http://www.pnas.org/content/early/2016/05/18/1524689113.full>  
(<http://www.pnas.org/content/early/2016/05/18/1524689113.full>)