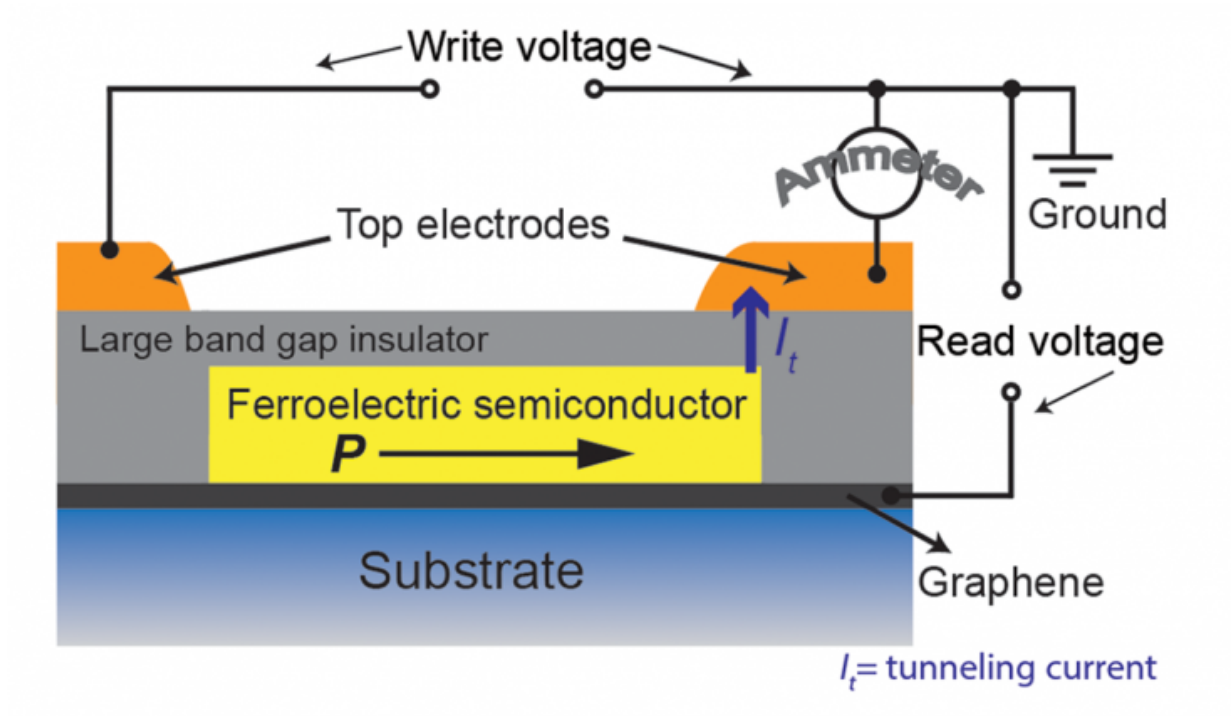
Researchers demonstrate room-temperature ferroelectric states in ultra-thin films of tin and tellurium

July 15 2016, by Denis Paiste



Researchers at MIT and Tsinghua University have demonstrated room temperature ferroelectric states in ultra-thin films of tin and tellurium and have filed a provisional patent for a new kind of random access memory that they call ferroelectric tunneling random access memory. Experiments showed that memory could be written through a top gate voltage, which “flips” the in-plane polarization of the ferroelectric film, and read by a voltage tunneling through an edge without erasing the memory state. Credit: Junwei Liu

Just as magnetic materials have opposing North and South poles, ferroelectric materials have opposing positive charges and negative charges that exhibit measurable differences in electric potential. Researchers at MIT and colleagues in China recently demonstrated this ferroelectric behavior along the edges of atomically thin tin-tellurium film at room temperature.

Measurements showed the energy gap, or bandgap, of this ultra-thin (2-D) film to be about eight times higher than the bandgap in bulk (3-D) tin-tellurium, with an on/off ratio as high as 3,000, they report July 15 in the journal *Science*. Their findings hold promise for making random access memory (RAM) devices from this special semiconductor material, which is known as a topological crystalline insulator.

"This discovery is very exciting because usually when you decrease the thickness from the 3-D to 2-D, the phase transition temperature always decreases and therefore could destroy the ferroelectricity. But in this case, the [ferroelectric] phase transition temperature increased. It's quite unusual," explains MIT postdoc Junwei Liu, a first author of the paper. "As far as we know, this might be the first time to observe this very unusual property." MIT assistant professor of physics Liang Fu is one of the paper's senior authors.

Three years' work

These results follow three years of work based on a prediction by Fu, former student Timothy Hsieh PhD '15, postdoc Liu (who was then a graduate student at Tsinghua University), and collaborators, that ferroelectric structural distortion in tin-tellurium and similar topological crystalline insulators, would open a tunable bandgap on the surface. Hsieh is now a postdoc at University of California at Santa Barbara. Researchers in the U.S. and Europe, including Vidya Madhavan and Ilija Zeljkovic at Boston College, confirmed this prediction experimentally in

bulk materials. "The importance of ferroelectricity in topological crystalline insulators led us to study thin films of tin telluride," Fu says.

Tin-tellurium, which is also known as tin telluride, is classified as a IV-VI semiconductor, because tin (Sn) is from Group IV on the periodic table and tellurium (Te) from Group VI-A. At extremely cold temperatures, below about -283 degrees Fahrenheit, bulk tin-tellurium is a ferroelectric material, which means it becomes polarized with positive and negative electric charges splitting into opposing alignments, but it is not practical for room temperature applications.

Liu, whose work involves theoretical calculations, says in 2013 MIT researchers partnered with experimentalists at Tsinghua University in China to explore ferroelectricity in thin films of the tin-tellurium material. Kai Chang of Tsinghua University in China conducted experiments and is a first author of the Science paper. The paper's co-authors also include a dozen colleagues at Tsinghua and Renmin Universities and other research facilities in China, and RIKEN Center for Emergent Matter Science in Japan.

A unit cell is the smallest repeating pattern of atoms in the tin-tellurium molecular structure. Built on a base of graphene and silicon carbide, the tin-tellurium layers in the experiments ranged in size from 1 to 8 unit cells. In an actual device, the tin-tellurium would be capped with insulating material, as seen in the illustration in the slideshow above. The new study shows this ferroelectric state persists up to only about 26 F in the single-unit cell thin film tin-tellurium material, but in 2-, 3- and 4-unit cells, the ferroelectric state was robust to 300 kelvins, or 80 F, the highest temperature the experimental apparatus could measure.

"Room-temperature devices could have a very large commercial application. That's why we are very excited about this work; it's really robust even in room temperature," Liu says.

Tests showed that memory could be written through a top gate voltage, which "flips" the in-plane polarization of the ferroelectric film, and read by a voltage tunneling through an edge without erasing the memory state. Evidence of this behavior in a sample that was a mere 16-nanometers in width means that tin-tellurium memory cells could be densely packed. Nanosensors and electronics are also possible.

Zeros and ones

Advantages of ferroelectric memory include lower-power consumption, fast write operations, and durable storage, Liu says. The MIT-Tsinghua results show the separation of positive and negative charges, or polarization, in their sample was in-plane, or parallel, with the atomically flat sample, creating a potential change on the edges of square-shaped islands of the material. Since this potential difference along edges is measurably different, one with large tunneling current, the other small, it can realize two different states that represent either a zero or a one, and these states can be detected simply by measuring the current.

"Based on this property, we proposed a new kind of random access memory. We call it ferroelectric tunneling random access memory," says Liu, who proposed the initial architecture for this kind of memory, along with Fu and three coauthors at Tsinghua University: Kai Chang, Xi Chen, and Shuai-Hua Ji. MIT has filed for provisional patent protection and is in the process of filing a utility covering the findings regarding in-plane polarization and tunneling current. "It's very simple, and it's really practical, and I think it could be realized in the near future," Liu says.

Previous conventional capacitive ferroelectric random access memory technologies had to destroy a state to read it, Liu says, which meant an extra step of rewriting the information stored in memory after reading it. "In our case, we read the signal without destroying it," Liu says. "This is the intrinsic advantage of our approach. … Therefore it can have much

higher read operation performance."

"In our experiments, we found that ferroelectricity persists for the very small islands, as small as 25 nanometers by 25 nanometers by 0.5 nanometers; even in these very small islands, the ferroelectricity persists. We could achieve much higher storage density because it is really small," he explains.

"The authors and their collaborators use a state-of-the-art combination of molecular beam epitaxy and scanning tunneling microscopy to demonstrate a completely unexpected enhancement of ferroelectricity in ultrathin films of [tin-tellurium]," comments Ilija Zeljkovic, an assistant professor of physics at Boston College, who was not involved in this research. "This discovery can potentially be employed in nanodevices, such as the ferroelectric RAM nanodevice the authors describe [in Figure 4 of the *Science* report]."

Although the 3-D bulk form of tin-tellurium has been studied for decades, the new results in ultrathin 2-D film of the same material exhibit this surprising new phenomenon, Zeljkovic notes. "The study itself is extremely thorough, and the data presented is of the highest quality in spite of the high difficulty of the experiment performed. The study also highlights the recent effort in the condensed matter physics community to search for novel interface phenomena in ultrathin films of existing materials, for example, graphite versus graphene."

Fewer tin vacancies

Mathematical calculations known as density functional theory matched the experimental findings that there are 1/20 to 1/30 as many tin vacancies in the atomically thin tin-tellurium film than in the bulk form of the material. This lack of defects is believed to contribute to formation of the ferroelectric state.

The next step will be to show these results in actual devices. Future challenges include how to easily and inexpensively produce high quality tin-tellurium thin films and how to precisely control the polarization direction.

More information: K. Chang et al. Discovery of robust in-plane ferroelectricity in atomic-thick SnTe, *Science* (2016). DOI: 10.1126/science.aad8609

This story is republished courtesy of MIT News (web.mit.edu/newsoffice/), a popular site that covers news about MIT research, innovation and teaching.

Provided by Massachusetts Institute of Technology