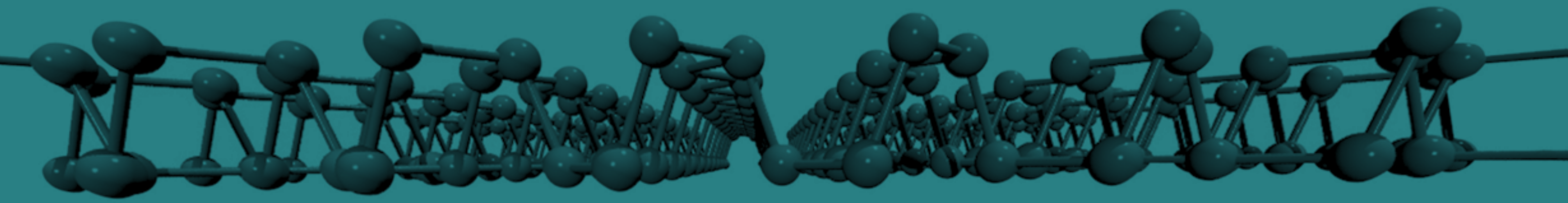

# Less energy loss

International group produces a graphene and phosphorene transistor in the laboratory with one-atom-thick layers

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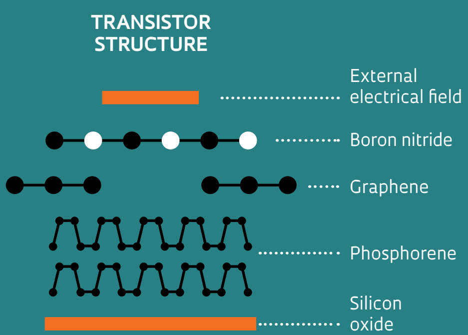



Calculations by three researchers at the University of São Paulo (USP) have shown that by combining two of the most interesting materials that were recently discovered in physics, graphene and phosphorene, one can build a transistor that dissipates minimal energy. Measuring only a few nanometers (millionths of a millimeter) in size, the device works because of a special method of combining the two materials, which preserves the characteristics of each one. José Padilha, Adalberto Fazzio and Antônio José Roque da Silva showed that, contrary to what occurs in current silicon transistors, the electrons in an electrical current lose almost no energy when they pass from a graphene sheet to a phosphorene sheet and vice versa.

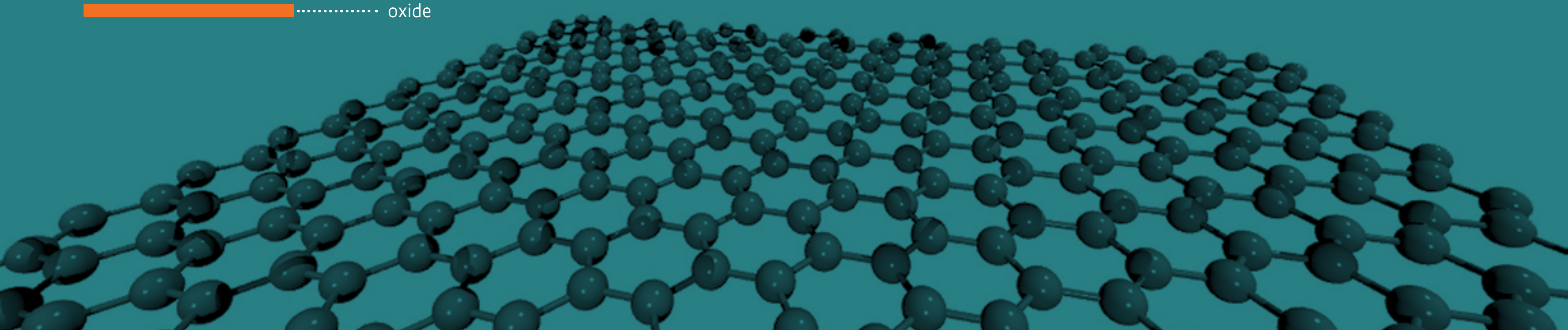
The prediction, published in the February 2015 issue of *Physical Review Letters*, was confirmed in the laboratory by a team at the National University of Singapore (NUS) with the participation of Brazilian researcher Antônio Castro Neto, director of the 2D Advanced Materials Center and the Graphene Research Center at NUS.

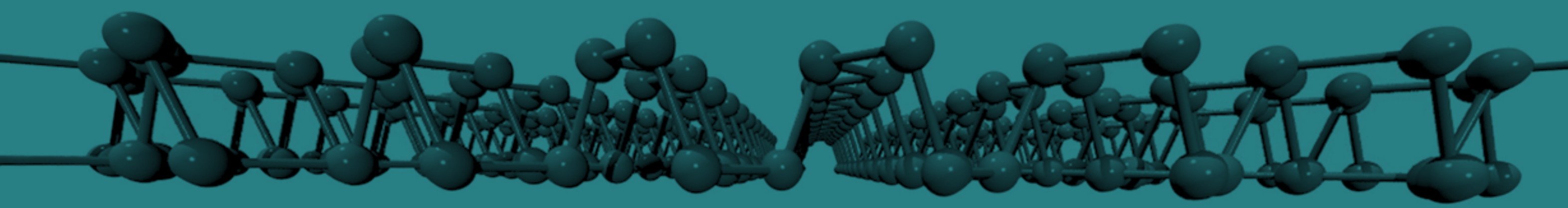
Transistors, which are the basis of today's computers, act as power switches that are able to turn light bulbs on and off. The "on" and "off" states represent the zeros and ones in binary code, which is the language of computers. More recent microprocessors contain 1 to 2 billion transistors made of silicon-based materials, each of which measures 45 nanometers in length. These transistors are connected to one another and to other electronic components of the microprocessor via metal wires (gold or copper).

When the electrons pass from the wires to the transistors and vice versa, the electrons in the electrical current lose part of their energy in the form of heat because of the contact resistance between the metal and the semiconductor. Currently, this heat does not affect the microprocessor operation. However, if the miniaturization trend of these components continues as it has in recent decades, the situation can become complicated. "There may come a point where the heat dissipated will burn the device or prevent its operation," explains Padilha. When Padilha was a post-doctoral researcher at USP and was supervised by Fazzio and Silva, he performed the calculations that demonstrated the possibility of building transistors from graphene and phosphorene. Now, Padilha is a professor at the Federal University of Paraná, Jandaia do Sul Advanced Campus.

In recent years, researchers from various centers have come to believe that the solution to the contact problem involves graphene. Discovered in 2004, this material comprises of carbon atoms that are placed in a hexagonal pattern, forming a sheet with a thickness of one atom. Electrons pass through graphene thousands of times faster than through silicon with a minimal loss of energy.

"The only problem is that graphene is not a semiconducting material like silicon," explains Padilha. Transistors are made of semiconducting materials





because they enable the control of the electron passage and the creation of zeros and ones in a computer. Semiconductors only transport electrons with energy above a certain limit. In a transistor, this limit acts as a barrier that can be raised or lowered using an electric field. This adjustable barrier, which either lets the electrons pass through or blocks them, is used to encode binary information. "If graphene acted this way, it would be the perfect material," says Padilha.

This limitation has led researchers worldwide to search for other materials made of a single atomic layer. Several materials were discovered, but the most interesting material is currently the one most recently identified: phosphorene. Consisting of a single atomic layer (monolayer) of phosphorus, phosphorene does not let electrons move as fast as graphene does, but they still move faster than in silicon. The advantage of phosphorene is its semiconducting property. In December 2013, Silva began discussing with Padilha and Fazzio the idea of investigating what the ideal contact would be between a phosphorene transistor and an electric circuit. "Phosphorene loses its semiconducting properties if soldered to copper or gold wires in a conventional circuit," explains Padilha. "Additionally, the contact with the atoms in the metallic wires would lead to dissipation of the electrons' energy in the form of heat."

Padilha, Fazzio and Silva proposed to solve the problem by replacing the metal-wire contact with a graphene layer superimposed on a phosphorene layer. Although the contact between the wires and phosphorene are through chemical bonds among atoms, the phosphorene and graphene layers are connected via a low-intensity attractive force called the van der Waals interaction. Despite being weak, this electromagnetic force allows graphene and phosphorene atoms to share their electrons without the interference of the electronic properties of one material with those of the other.

Having found the solution, Padilha, Fazzio and Silva calculated the behavior of electrons in the transistor. This task is difficult because the electrons do not act as tiny balls that move in the device. Instead, they are a quantum mixture of waves and particles whose behavior is described by mathematical equations that take months to solve using computer superclusters. The published results in *Physical Review Letters* show that the phosphorene and graphene "sandwich" acts as a transistor that loses notably little energy through its contacts and can be "turned on" or "turned off" by an electric field.

Almost simultaneously, a team of physicists led by Barbaros Özyilmaz at NUS built a similar transistor to that envisioned by the Brazilians in a laboratory. The difference is that a layer of hexagonal boron nitride covers the phosphorene layers, which act as a semiconductor, and the two strips of graphene, which are used as the contact between the transistor and the remainder of the circuit of silicon electronic devices. This material protects the other layers from oxygen in the air. The transistor worked perfectly in the tests. "We obtained the best results of all phosphorene devices built," states Antônio Castro Neto. A theoretical physicist and researcher working on the collaboration project "Graphene: photonics and opto-electronics: UPM-NUS" as part of the FAPESP São Paulo Excellence Chair (SPEC) program and based at the MackGraphe Center at Mackenzie Presbyterian University, Castro Neto collaborated on the experimental data analysis, which confirmed the predictions of the USP group.

According to Padilha, the identical calculations can lead to combinations of sheets of graphene and other monolayer semiconductors. "We made a transistor, but we could develop a solar cell whose electrons, excited by sunlight, would transfer from the semiconducting layer to the graphene layer with almost no loss of energy," says Padilha. "Many people are exploring combinations of bidimensional materials, such as these, to produce structures with new properties," concludes Silva. ■


### Project

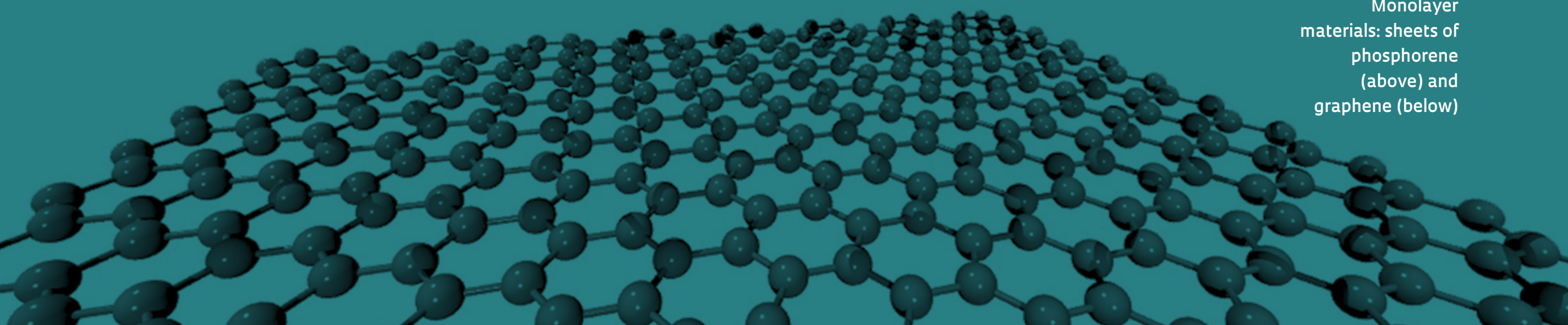
*Electronic, magnetic and transport properties of nanostructures* (No. 2010/16202-3); **Grant mechanism** Thematic Project; **Principal investigator** Adalberto Fazzio (IF-USP); **Investment** R$1,327,201.88 (FAPESP – for the entire project).


### Scientific articles


PADILHA, J. E. *et al.* Heterostructure of phosphorene and graphene: Tuning the schottky barrier and doping by electrostatic gating. **Physical Review Letters**. V. 114. Feb. 12, 2015.

AVSAR, A. *et al.* Air-stable transport in graphene-contacted, fully encapsulated ultrathin black phosphorus-based field-effect transistors. **ACS Nano**. V. 9, No. 4 Mar. 4, 2015.


IMAGES JOSÉ PADILHA / UFPR



Monolayer materials: sheets of phosphorene (above) and graphene (below)