Graphene isn't the only Lego in the materials-science toy box

June 15 2016, by Peter Byrley, University Of California, Riverside

Materials science has lots of options for building. Credit: dolske/flickr, CC BY-SA

You may have heard of graphene, a sheet of pure carbon, one atom thick, that's all the rage in materials-science circles, and getting plenty of media hype as well. Reports have trumpeted graphene as an ultra-thin, super-strong, super-conductive, super-flexible material. You could be excused for thinking it might even save all of humanity from certain doom.

Not exactly. In the current world of nano-electronics, there is a lot more going on than just graphene. One of the materials I work with, molybdenum disulphide (MoS_2), is a one-layer material with interesting properties beyond those of graphene. MoS_2 can absorb five times as much visible light as graphene, making it useful in light detectors and solar cells. In addition, even newer materials like borophene (a one-layer material made of boron atoms projected to be mechanically stronger than graphene) are being proposed and synthesized every day.

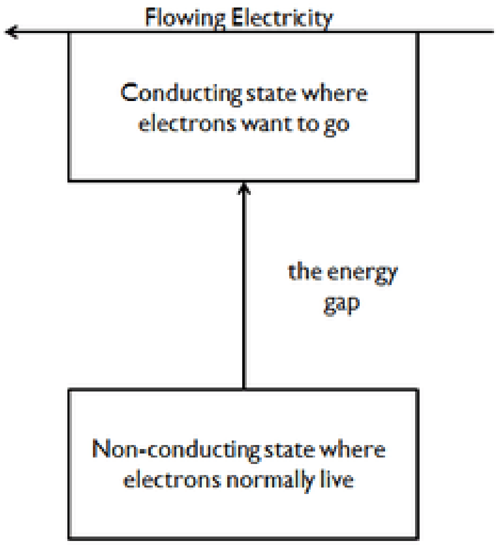
These and other materials yet to be discovered will be used like Lego pieces to build the electronics of the future. By stacking multiple materials in different ways, we can take advantage of different properties in each of them. The new electronics built with these combined structures will be faster, smaller, more environmentally resistant and cheaper than what we have now.

Looking for an energy gap

There is a key reason that graphene will not be the versatile cure-all material that the hype might suggest. You can't just stack graphene repeatedly to get what you want. The electronic property preventing this is the lack of what is called an "energy gap." (The more technical term is "band gap.")

Metals will conduct electricity through them regardless of the environment. However, any other material that is not a metal needs a little boost of energy from the outside to get electrons to move through the band gap and into the conducting state. How much of a boost the material needs is called the energy gap. The energy gap is one of the factors that determines how much total energy needs to be put into your entire electrical device, from either heat or applied electrical voltage, to get it to conduct electricity. You essentially have to put in enough starting energy if you want your device to work.

Some materials have a gap so large that almost no amount of energy can get electrons flowing through them. These materials are called insulators (think glass). Other materials have either an extremely small gap or no gap at all. These materials are called metals (think copper). This is why we use copper (a metal with instant conductivity) for wiring, while we use plastics (an insulator that blocks electricity) as the protective outer coating.



What the energy gap looks like. Credit: Peter Byrley

Everything else, with gaps in between these two extremes, is called a semiconductor (think silicon). Semiconductors, at the theoretical temperature of absolute zero, behave as insulators because they have no heat energy to get their electrons into the conducting state. At room temperature, however, heat from the surrounding environment provides just enough energy to get some electrons (hence the term, "semi"-conducting) over the small band gap and into the conducting state ready to conduct electricity.

Graphene's energy gap

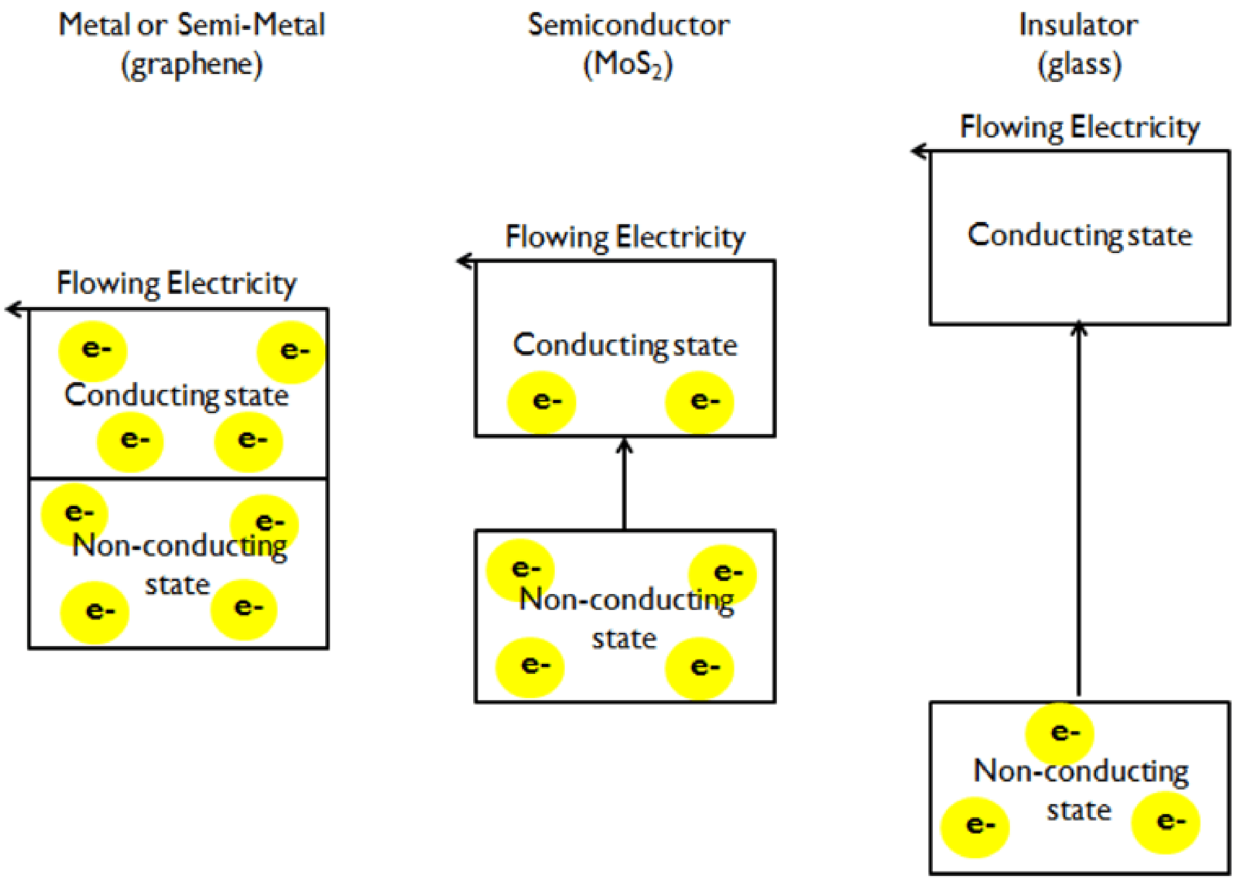
Graphene is in fact a semi-metal. It has no energy gap, which means it will always conduct electricity – you can't turn off its conductivity.

This is a problem because electronic devices use electrical current to communicate. At their most fundamental level, computers communicate by sending 1's and 0's – on and off signals. If a computer's components were made from graphene, the system would always be on, everywhere. It would be unable to perform tasks because its lack of energy gap prevents graphene from ever becoming a zero; the computer would keep reading 1's all the time. Semiconductors, by contrast, have an energy gap that is small enough to let some electrons conduct electricity but is large enough to have a clear distinction between on and off states.

Finding the right materials

Not all hope is lost, however. Researchers are looking at three main ways to tackle this:

Using new materials similar to graphene that actually have a sufficient energy gap and finding ways to further improve their conductivity.Altering graphene itself to create this energy gap.Combining graphene with other materials to optimize their combined properties.



Comparing the band gap in metals (left), semiconductors (center) and insulators (right). Credit: Peter Byrley

There are many one-layer materials currently being looked at that actually have a sufficient energy gap. One such material, MoS_2, has been studied in recent years as a potential replacement for traditional silicon and also as a light detector and gas sensor.

The only drawback with these other materials is that so far, we have not found one that matches the excellent though always-on conductivity of graphene. The other materials can be turned off, but when on, they are not as good as graphene. MoS_2 itself is estimated to have 1/15th to 1/10th the conductivity of graphene in small devices. Researchers, including me, are now looking at ways to alter these materials to increase their conductivity.

Using graphene as an ingredient

Strangely, an energy gap in graphene can actually be induced through modifications like bending it, turning it into a nanoribbon, inserting foreign chemicals into it or using two layers of graphene. But each of these modifications can reduce the graphene's conductivity or limit how it can be used.

To avoid specialized setups, we could just combine graphene with other materials. By doing this, we are also combining the properties of the materials in order to reap the best benefits. We could, for example, invent new electronic components that have a material allowing them to be shut off or on (like MoS_2) but have graphene's great conductivity when turned on. New solar cells will work on this concept.

A combined structure could, for example, be a solar panel made for harsh environments: We could layer a thin, transparent protective material over the top of a very efficient solar-collecting material, which in turn could be on top of a material that is excellent at conducting electricity to a nearby battery. Other middle layers could include materials that are good at selectively detecting gases such as methane or carbon dioxide.

Researchers are now racing to figure out what the best combination is for different applications. Whoever finds the best combination will eventually win numerous rights to patents for improved electronic products.

The truth is, though, we don't know what our future electronics will look like. New Lego pieces are being invented all the time; the ways we stack or rearrange them are changing constantly, too. All that's certain is that the insides of electronic devices will look drastically different in the future than they do today.

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