Researchers Find a Way to Use Coal in Advanced Electronic Devices

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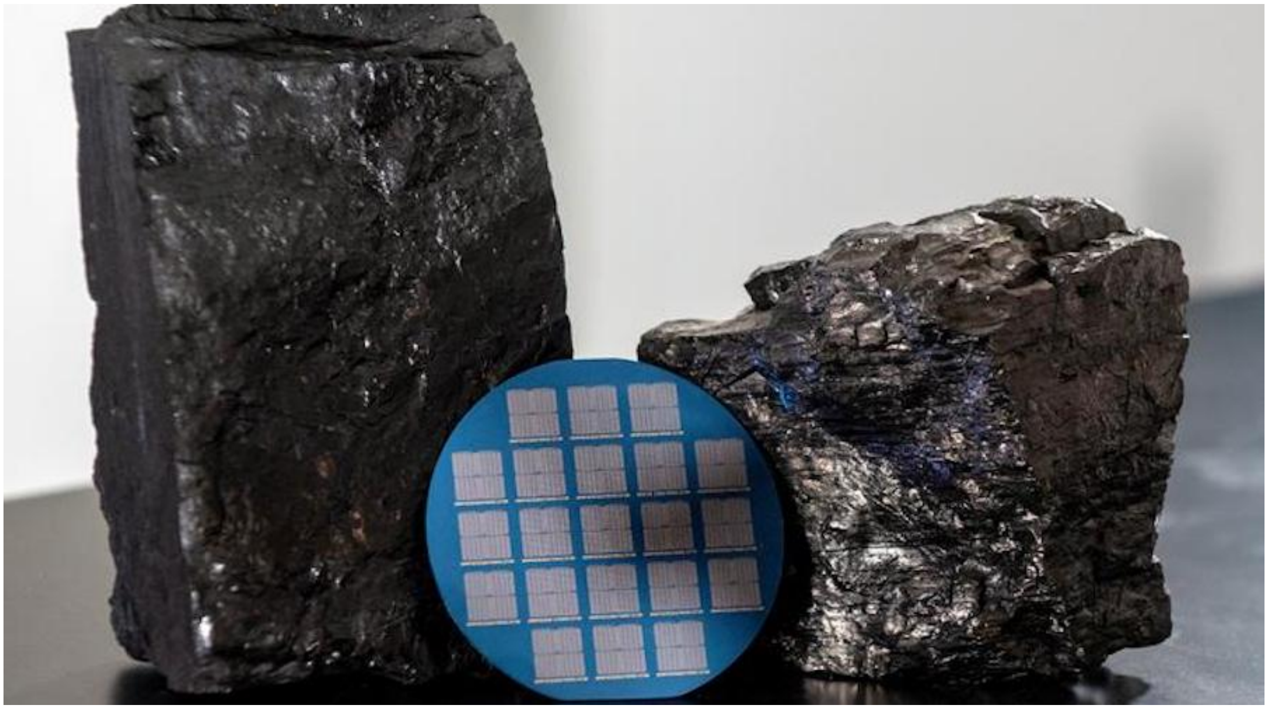

A wafer containing memristors fabricated with high-quality two-dimensional carbon processed from bituminous Blue Gem coal mined in southeastern Kentucky, two samples of which are shown here. (Image by the Grainger College of Engineering at University of Illinois Urbana-Champaign).

Carbon dots created by converting coal char into nanoscale carbon disks can be connected to form atomically thin membranes for applications in both two-dimensional transistors and memristors, technologies that will be critical to constructing more advanced electronics.

In a new paper published in the journal Communications Engineering, researchers with the US National Energy Technology Laboratory (NETL), the University of Illinois Urbana-Champaign, the Oak Ridge National Laboratory and the Taiwan Semiconductor Manufacturing Company show that coal can play a vital role in next-generation electronic devices.“Coal is usually thought of as something bulky and dirty, but the processing techniques we’ve developed can transform it into high-purity materials just a couple of atoms thick,” research co-lead Qing Cao said in a media statement. “Their unique atomic structures and properties are ideal for making some of the smallest possible electronics with performance superior to state-of-the-art.”

Cao explained that in the ongoing search for smaller, faster and more efficient electronics, the final step will be devices made with materials just one or two atoms thick. Devices can't be smaller than this limit, and their small scale often makes them operate much quicker and consume far less energy. While ultrathin semiconductors have been extensively studied, it is also necessary to have atomically thin insulators – materials that block electric currents – to construct working electronic devices like transistors and memristors.

Coal char-derived carbon layers as insulators

Atomically thin layers of carbon with disordered atomic structures can function as an excellent insulator for constructing two-dimensional devices. The researchers in the collaboration have shown that such carbon layers can be formed from carbon dots derived from coal char. To demonstrate their capabilities, the U of I group led by Cao developed two examples of two-dimensional devices.

"It's really quite exciting because this is the first time that coal, something we normally see as low-tech, has been directly linked to the cutting edge of microelectronics," Cao said.

His group used coal-derived carbon layers as the gate dielectric in two-dimensional transistors built on the semimetal graphene or semiconductor molybdenum disulphide to enable more than two times faster device operating speed with lower energy consumption.

Like other atomically thin materials, the coal-derived carbon layers do not possess "dangling bonds," or electrons not associated with a chemical bond. These sites, which are abundant on the surface of conventional three-dimensional insulators, alter their electrical properties by effectively functioning as "traps," slowing down the transport of mobile charges and thus the transistor switching speed.

However, unlike other atomically thin materials, the new coal-derived carbon layers are amorphous, meaning that they do not possess a regular, crystalline structure. They therefore do not have boundaries between different crystalline regions that serve as conduction pathways leading to "leakage," where undesired electrical currents flow through the insulator and cause substantial additional power consumption during device operations.

Suited for AI

Another application Cao's group considered is memristors – electronic components capable of both storing and operating on data to greatly enhance the implementation of AI technology. These devices store and represent data by modulating a conductive filament formed by electrochemical reactions between a pair of electrodes with the insulator sandwiched in between.

The researchers found that the adoption of ultrathin coal-derived carbon layers as the insulator allows the fast formation of such filament with low energy consumption to enable high device operating speed with low power. Moreover, atomic size rings in these coal-derived carbon layers confine the filament to enhance the reproducible device operations for enhanced data storage fidelity and reliability.

The new devices developed by the Cao group provide proof-of-principle for the use of coal-derived carbon layers in two-dimensional devices. What remains is to show that such devices can be manufactured on large scales.

“The semiconductor industry, including our collaborators at Taiwan Semiconductor, is very interested in the capabilities of two-dimensional devices, and we’re trying to fulfill that promise,” Cao said. “Over the next few years, the U of I will continue to collaborate with NETL to develop a fabrication process for coal-based carbon insulators that can be implemented in industrial settings.”