Energy Focus

Automotive industry drives search for tunable thermal “switch” materials

In today’s fragile economy and environment, energy lost as heat is cause for concern across any industry that relies on fossil fuel combustion. But novel materials can help to harness and repurpose waste heat. The automotive industry has a vested interest in developing technologies for advanced thermal management. Today, some 60% of the heat energy produced in a combustion engine is wasted. Now they are on the road to a material that could “switch” its ability to transmit heat in response to ambient conditions.

“Originally, we wanted to develop a technology to control heat transport within a vehicle. Now, we’ve developed a material that has both low and high thermal conductivity,” says Gaohua Zhu, senior scientist at the Toyota Research Institute of North America’s Materials Research Department. Along with colleagues including David Cahill at the University of Illinois at Urbana-Champaign and Jun Liu at North Carolina State University, he has demonstrated the ability to tune thermal conductivity in a two-dimensional (2D) layered material by selectively inserting and extracting foreign ions. They reported their research in a recent issue of *Nature Communications* (doi:10.1038/ncomms13211).

Two-dimensional layered materials comprise crystalline sheets of single-atom thickness, held together in stacks by strong intra-layer bonds. They have garnered interest due to unique electronic and chemical properties that differ from their bulk counterparts, which make them prime candidates for use in flexible electronic devices and nanoelectronics. Molybdenum disulfide (MoS_2), in particular, offers promise as a 2D material for energy storage, and has been used as a cathode material in batteries.

The Zhu/Cahill team became interested in how the thermal properties of MoS_2 could be manipulated for energy storage. They believed that by incorporating lithium ions into the layered structures, it would be possible to expand the gap between the layers and therefore change the material’s thermal conductivity.

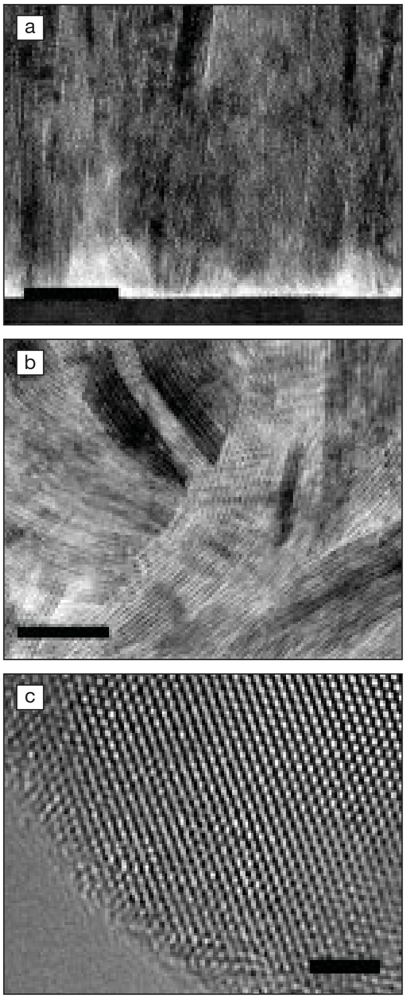
They were indeed able to modify thermal conductivity by inserting, or “intercalating,” lithium ions into the MoS_2 crystal lattice. However, surprisingly, that was not because the lithium ions altered the distance between layers. Rather, the added ions created disorder in the crystal lattice, affecting thermal properties. They also found that this disorder could be systematically varied.

Intercalating ions into a 2D lattice is easily achieved through basic chemical oxidation–reduction reactions. However, Zhu chose to do so electrochemically, by applying a current between thin-film MoS_2 and a piece of lithium foil, “similar to a battery. We wanted to thoroughly understand the mechanism that characterizes thermal transport.” Until now, nobody had studied how the stacking disorder of the layered structure created by ion intercalation could affect the thermal conductivity of MoS_2.

The results of this study demonstrate that thermal conductivity in both the in-plane and cross-plane directions decreases as more lithium ions make their way in between the MoS_2 layers, until the largest degree of disorder is reached. Contrary to the expectation that the ratio of in-plane to cross-plane thermal conductivity decreases with higher levels of disorder, Zhu and colleagues found that this so-called thermal anisotropy ratio could be as much as doubled as the lattice becomes more disordered.

“The work provides important insights into how lithium intercalation [ion insertion] can change thermal transport in 2D layered materials,” says Deyu Li of Vanderbilt University, who was not involved in this work. “Given the importance of lithium intercalation in various electrochemical energy-storage applications, such understanding could help to improve thermal management of important engineering devices.”

The ability to create anisotropy makes possible a material through which heat travels unidirectionally, thus behaving as an insulator in one direction and a conductor in the other direction. Ultimately, the goal is a material that changes its thermal conductivity automatically in response to the temperature of its surroundings.



(a) Cross-sectional transmission electron microscope (TEM) image of MoS_2 thin film (scale bar = 20 nm); (b) plan-view TEM image of MoS_2 thin film (scale bar = 10 nm); and (c) bulk MoS_2 crystal (scale bar = 2 nm). Credit: Zhu et al.

“That’s challenging and counterintuitive,” Zhu says. Normally, a material at high temperature would have lower thermal conductivity. “We want a ‘thermal switch’ material which shows low thermal conductivity at low temperature, but high thermal conductivity at high temperature: that’s useful for fast warming of the vehicle engine or battery at the cold start.”

Controlling heat transport through material design is one important step toward advanced thermal management in the automotive industry and beyond.

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