Graphene Spreads the Heat

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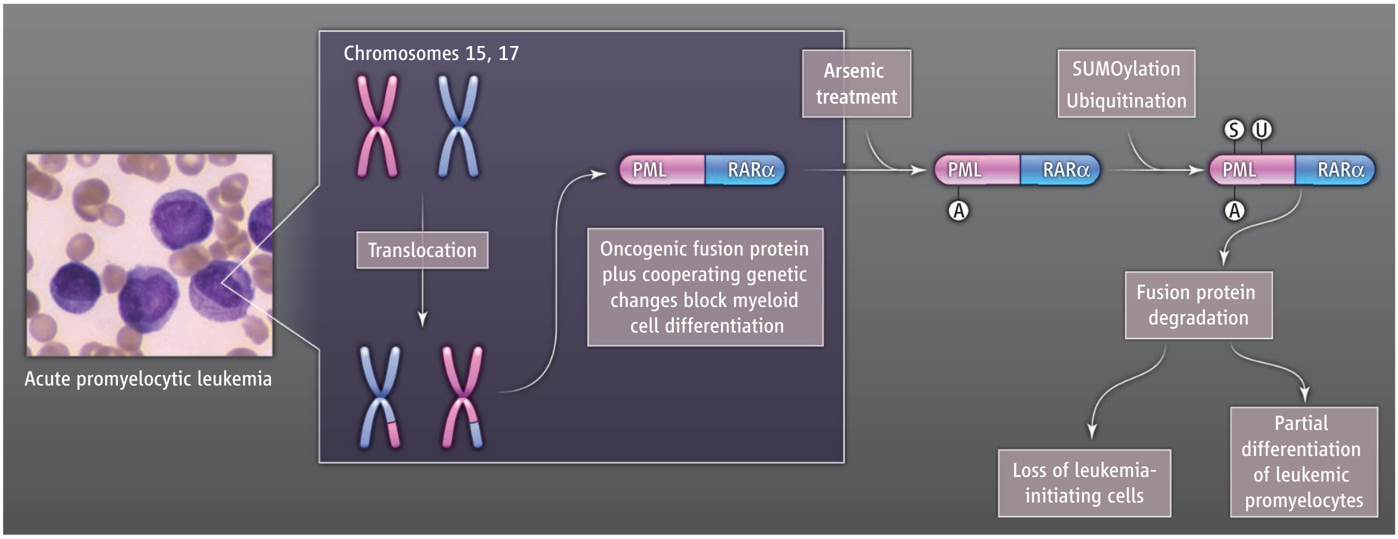

Arsenic therapy. Acute promyelocytic leukemia arises from a translocation that produces the fusion protein PML-RARα. Arsenic binds to PML-RARα, stimulating its SUMOylation, ubiquitination, and degradation. This allows partial differentiation of leukemic promyelocytes and eliminates leukemia-initiating cells.

stimulates the recruitment of the SUMOylation and ubiquitination complexes to PML proteins, remain to be elucidated.

Of note, Zhang *et al*. demonstrate that mutations of cysteine to alanine within either of two zinc fingers of the RING domain in PML decreased arsenic binding, and consequently, abrogated the ability of arsenic to induce degradation of PML. These data indicate that binding to more than one site within PML cooperatively contributes to arsenic's therapeutic effect. It will be of interest to assess whether point mutations can prevent arsenic-induced degradation without disrupting the function of normal PML or the oncogenic effects of PML-RARα.

Understanding the molecular mechanisms underlying promyelocytic leukemia is of great interest, but it remains to be seen whether the findings of Zhang *et al*. will have broader clinical importance. Arsenic-induced degradation of PML might be useful for treating other human malignancies. Recent data suggest that PML degradation might eliminate the cells from which chronic leukemias relapse after therapy (*13*), and implicate the importance of PML for the oncogenic effects of mutant p53 protein, a change seen in many human cancers (*14*). Despite disappointing clinical results with arsenic to date, perhaps proper case selection and combination therapy with arsenic will lead to improved outcomes for treating not only promyelocytic leukemia but other human malignancies as well. If so, an ancient medicine, revived through careful clinical and biological studies in modern times, will have an even greater impact on human health.

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MATERIALS SCIENCE

Graphene Spreads the Heat

Can graphite monolayers outcompete traditional heat-spreading materials in electronic devices?

Ravi Prasher

The reliability and speed of electronic and optoelectronic devices strongly depend on temperature (*1*, *2*). Materials with very high thermal conductivities are required to spread the heat generated locally in such devices (*2*). Bulk copper, which is widely used as heat spreader in computers, has a thermal conductivity of ~400 W m^{-1} K^{-1} at room temperature, but copper thin films, used as electrical interconnects, can have lower thermal conductivity (below 250 W m^{-1} K^{-1}) (*3*). The search is thus on for materials with thermal conductivities higher than that of copper. On page 213 of this issue, Seol *et al*. (*4*) report that single monolayers of graphite (graphene) in contact with silicon dioxide (SiO_2) has a thermal conductivity of ~600 W m^{-1} K^{-1}.

Pure-carbon materials such as diamond, graphite, and carbon nanotubes have very high thermal conductivities, because the strong covalent bonding between carbon atoms results in a large phonon (lattice vibration) contribution to the thermal conductivity. Recently, graphene has attracted much attention due to its unique properties (*5*), such as very high intrinsic charge carrier mobility. Yin *et al*. have reported the fabrication of 100-GHz graphene-based transistors (*6*).

For future applications, it will be crucial to understand heat generation and dissipation from graphene-based devices. Previous measurements (*7*, *8*) on single monolayers of single-wall carbon nanotubes and graphene were performed in suspended form (see the figure, panel A), where the thermal conductivity was very high due to the strong covalent

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bonds between the carbon atoms. Suspended graphene has a thermal conductivity of 5000 $\mathrm{W\,m^{-1}\,K^{-1}}$ at room temperature (*7*)—about 2.5 times as large as that of diamond, which has the highest thermal conductivity among natural materials.

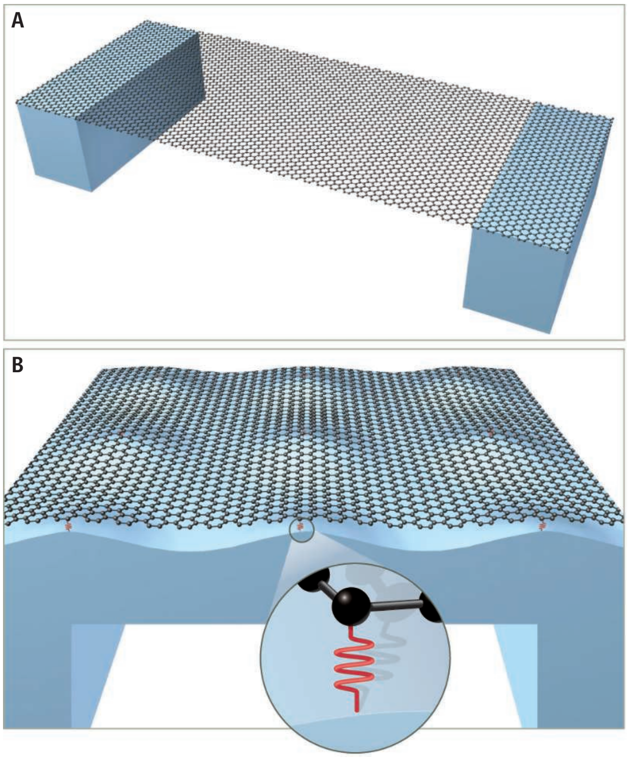
However, in most practical applications—such as composites for thermal interface materials (*9*) or heat spreaders in devices (*10*)—single-layer materials will be bound to a much thicker bulk material, such as SiO_2 or a polymer, typically through weak van der Waals forces. How do these weak contacts affect thermal transport in the monolayers?

To address this question, Seol *et al*. first attached a graphene layer to an SiO_2 surface through a process known as mechanical exfoliation (*11*) and measured the thermal conductance of the combined structure. They then etched away the graphene layer and measured the thermal conductance of only the SiO_2 layer. The difference between the two values gave them the conductance of the graphene layer, from which the thermal conductivity of the graphene layer was extracted. At room temperature, the thermal conductivity of the supported graphene layer is ~600 $\mathrm{W\,m^{-1}\,K^{-1}}$, an order of magnitude lower than that of suspended graphene. However, this is still higher than the thermal conductivities of bulk or thin-film copper (*3*). When Klemens (*12*) first envisioned this type of experiment, he predicted a decrease in the thermal conductivity of graphene in contact with a substrate, even before single-layer graphene exfoliation was first demonstrated (*11*).

In bulk carbon materials such as diamond, three acoustic phonon modes contribute substantially to the thermal conductivity: one longitudinal (LA) and two transverse (TA) modes. For LA modes, the atomic vibration is in the direction of the wave propagation, whereas for TA modes, it is perpendicular to the wave-propagation direction. For both modes, the phonon frequency is proportional to the wave vector (inverse of wavelength), that is, the phonon dispersion is linear. In large-diameter single-wall carbon nanotubes, there are also three phonon modes, but one of them is a flexural (ZA) mode with a quadratic phonon dispersion. Similarly, in graphene, the third mode is flexural.

Thermal conductivity is given by the product of specific heat, mean phonon scattering time, and the square of phonon group velocity integrated over the whole phonon frequency range. In suspended graphene, the contribution of the ZA mode was thought to be negligible (*13*), because the group velocity of the ZA mode is smaller than the group velocity of the LA and TA modes. Starting with this assumption for suspended graphene and then applying the van der Waals forces for supported graphene, Seol *et al*. could not explain their experimental data on supported graphene both in magnitude and trend.

To explain their data over the entire temperature range, Seol *et al*. performed a revised calculation for suspended graphene. They show that the ZA mode contributes substantially to the thermal conductivity of suspended graphene, for two reasons: First, the specific heat for the ZA mode is higher than that of the LA and TA mode for temperatures up to ~360 K, because the maximum frequency of ZA mode is smaller than that of the LA and TA modes. Second, the mean scattering time of the ZA mode is much larger than that of the LA and TA modes. Because of these two effects, the ZA mode can contribute as much as 77% at 300 K and 86% at 100 K of the calculated thermal conductivity for suspended graphene. In the case of supported graphene, the van der Waals interactions between graphene and the substrate (see the figure, panel B) reduce the contribution of the ZA mode (*4*): At room temperature, the ZA mode contributes only 25% to the thermal conductivity in supported graphene, compared to 77% in suspended graphene.



Lending support. (**A**) Previous thermal conductivity measurements were performed on suspended graphene. (**B**) Seol *et al*. instead studied graphene supported on a substrate. The graphene layer does not conform to the nanoscale roughness of the substrate; rather, it makes contact on the summits of the rough surface, interacting with the substrate through van der Waals forces (red springs).

To explain their results, Seol *et al*. propose that ZA mode phonons leak into the substrate through the van der Waals springs that connect the graphene to the substrate (see the figure, panel B). The force constant of the ZA mode is much larger than that of the LA and TA modes. Larger force constant means tighter coupling with the substrate, leading to more leaking of ZA modes compared to the LA and TA modes. Leaking of phonons into the substrate was also predicted by Klemens (*12*). To explain their data, Seol *et al*. also assume—based on scanning probe microscopy studies (*14*)—that the graphene does not conform completely to the surface (see the figure, panel B).

What makes this study remarkable is that it combines thermal, structural, and mechanical phenomena into one theoretical framework. This is a crucial first step toward explaining the thermal conductivity of supported graphene. However, many questions remain. For example, the large thermal contact resistance of carbon nanotubes has severely limited their use as a high-thermal-conductivity material. Can graphene overcome this limitation due to its flat structure? Future studies should also investigate what will happen to the in-plane thermal conductivity and contact resistance if the graphene completely conforms to the surface or is embedded in a bulk material, or if the interactions with the substrate are stronger, for example, in contact with metals.

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