Molecular Foundry Research Highlight

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Nanoscience meets aeronautics: phonon barriers in nanomachines

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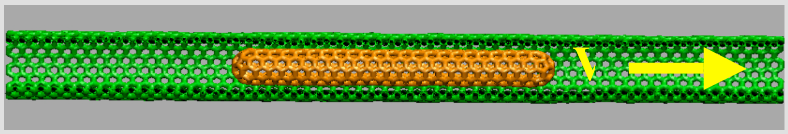
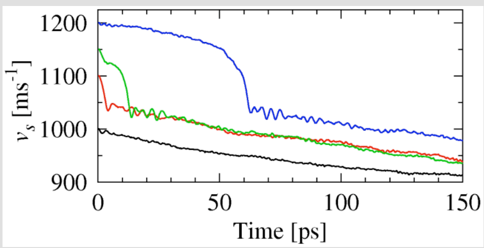
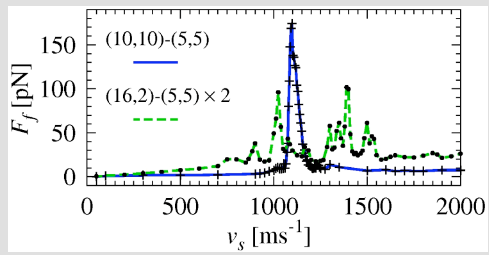
The velocity dependence of friction in carbon nanotube-based mechanical devices

At nanometer lengths scales, the dynamics of mechanical devices can be dramatically altered by a host of new phenomena. Many of these phenomena can be identified and understood using atomistic simulations.







Molecular dynamics simulations of carbon nanotubes sliding relative to one another reveal a dramatic slow-down within narrow velocity ranges. This effect depends strongly on the atomic level structures of the tubes.

The friction force between nanotubes can increase by several orders of magnitude at specific velocities. These nanoscale analogues of the "sound barrier" occur when "wave drag" causes a divergence in the non-linearity in the mutual responses of the nanotubes.

The miniaturization of mechanical devices has evolved to the point that microelectromechanical systems (MEMS) are in widespread use and prototype nanoscale mechanical elements have been constructed. While it appears certain that the size of functional machinery will decrease, very little is known about how the behavior of mechanical devices changes as their sizes get closer to atomic length scales. Much can be learned about this issue from theory and computer simulations, and recent work [1,2] at the Molecular Foundry has demonstrated some striking features of nanomechanical devices.

Many people are familiar with the phrase "sound barrier" that describes the huge increase in air drag that an aircraft experiences, and must overcome, as it approaches the speed of sound. Our work shows that a similar mechanism could result in a dramatic enhancement of friction between the components of nanomachines.
As an airplane moves, it pushes air out of its way causing local changes in pressure that propagate outwards as a wave (or "wake"). At low speeds these "sound waves" travel ahead of the airplane, creating a path for it that allows air to flow around it smoothly and with minimal drag. As the speed of sound is approached, however, smooth air flow becomes impossible because air in the airplane's path has too little warning of its arrival to move out of the way. The result is a massive increase in drag on the airplane.

Atomistic computer simulations of carbon nanotubes [2] have shown that the friction between nanoscale objects that are sliding relative to one another can be dramatically enhanced at velocities the match the velocities with which vibrations ("phonons") excited by the motion are propagating. The complex dynamics in nanomachines that result from these nanoscale analogues of the sound barrier – or "phonon barriers" - is a dramatic example of the new challenges that engineers face as the miniaturization of mechanical devices progresses.

[1] P. Tangney, S. G. Louie, M. L. Cohen, "Dynamic Sliding Friction Between Concentric Carbon Nanotubes," Phys. Rev. Lett. **93**, 065503 (2004).
[2] P. Tangney, M. L. Cohen, S. G. Louie, "Giant Wave-Drag Enhancement of Friction in Sliding Carbon Nanotubes" Phys. Rev. Lett. **97**, 195901 (2006).