Electronic Control of Friction in Silicon pn Junctions

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The nature of the fundamental processes that give rise to friction between sliding bodies in close proximity is a long standing question in tribology, both theoretically and experimentally (*1*, *2*). Ultimately energy is dissipated by conversion of kinetic energy of the moving bodies into lattice vibrations (heat). The vibrations of the surface atoms are damped by energy transfer to bulk phonon modes and in metals also by electronic excitations. Although excitation of electron-hole pairs has been invoked as a mechanism of frictional energy dissipation (*1*, *3*–*5*), the importance of this dissipation channel has not been ascertained experimentally in contacts between two solids.

Semiconductors offer the interesting possibility to test the effect of free charge carriers in the energy dissipation balance, because it is possible to reversibly change their density over many orders of magnitude. To test this idea, we used an atomic force microscopy (AFM) with a conductive TiN tip sliding on a silicon sample that was patterned with p and n regions of different doping levels (Fig. 1A). Friction was monitored as a function of carrier accumulation or depletion, which was controlled by the application of a voltage to the tip. Although the p and the n regions have different electronic properties, their chemical nature and structure is the same because of the oxide layer ($\sim$0.4 nm thick) that covers both regions. This layer also prevents Fermi-level pinning, which could obscure dopant-dependent contrast in the conductance (*6*). A remarkable dependence of the friction force on carrier concentration was found on doped silicon substrates. Charge depletion or accumulation resulted in a substantial difference in friction force.

The array of p-type stripes (concentration of 10^{18} cm^{-3}) was fabricated by B implantation at 190 keV into an n-type Si(100) substrate with a low dopant concentration of 1.6×10^{14} cm^{-3}. The normal force was kept constant during imaging while current and friction force were simultaneously recorded (*5*). No wear traces were observed in repeated high-resolution images, and the friction and adhesion measurements were reproducible.

When a voltage is applied between sample and tip, band bending changes the electrical character of the p and the n regions in opposite directions. When a positive voltage is applied to a p-type semiconductor, band bending causes accumulation of majority carriers (holes) near the semiconducting surface. When a negative voltage is applied, carriers are depleted near the surface. At a sample bias of +4 V, the highly doped p region is forward-biased and in strong accumulation, leading to a high carrier concentration near the surface. The n region is reverse-biased, causing depletion or weak inversion. As a result, the current was high in the p region ($\sim$50 μA) and low in the n region ($\sim$5 μA) (*7*). Friction was substantially higher in the p region than in the n region. Interestingly, no notable variation of friction force was observed between n and p regions at negative bias (*7*). Figure 1B shows a plot of the friction force versus load at +4 V sample bias. The line through the friction data is a fit to the Derjaguin-Müller-Toporov (DMT) contact model. Although the agreement with the DMT curve is very good in the n region, the p region shows a substantial "excess" friction. This difference is only observed for positive bias > +2 V. The Fig. 1B inset shows that the change in tip-sample pull-off force with bias increases in proportion to V^2 as expected, with no significant difference between p and n regions.

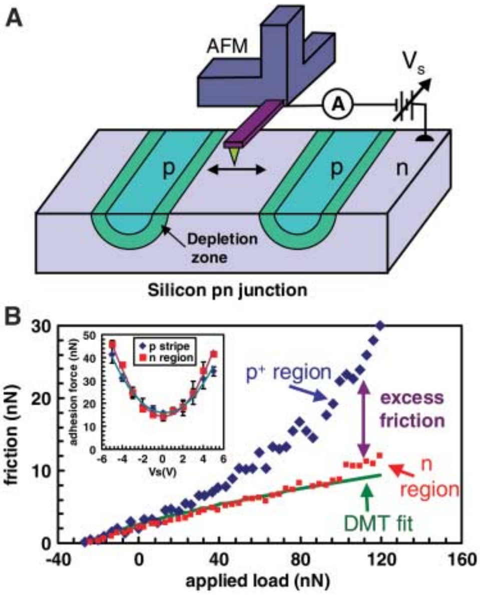

Fig. 1. (**A**) Schematic of AFM measurements on a silicon pn junction device. (**B**) Plot of friction force as a function of applied load at +4V sample bias. The scanning speed was 5 μm/s. (Inset) The pull-off force as a function of sample bias. The error scales represent the standard deviation from five independent measurements.

Although the excess friction in the p region during accumulation increases significantly with contact stress, it is not related to wear. It is not proportional to tip-sample current either, which excludes chemical effects as the potential origin. Previous calculations of electronic friction do not include the effects of localized strain under the AFM tip at $\sim$GPa levels, and this may play a role in excess friction, perhaps by creating electronic surface states that are charged and then discharge upon release of the stress. In the pressure range of GPa, the band gap decreases, which in our geometry should produce an elastically induced quantum dot under the tip (*8*). This should lead to a substantial enhancement of electron-hole recombination, with the energy emitted in the form of phonons. Another possibility worth exploring is the enhancement of dislocation mobility (*9*) due to the increase in charge carrier density. The ability to modulate friction through control of doping levels and electric fields might have interesting technical applications for microelectromechanical (MEMS) devices and in the motion of nano-objects in patterned semiconductor substrates.

References and Notes

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Supporting Online Material

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Materials and Methods
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Fig. S1
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