Supporting Online Material for

Electronic Control of Friction in Silicon pn Junctions
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Electronic control of friction in silicon pn junctions

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Experimental methods

The array of p-type stripes, located at 30 µm intervals, was fabricated by B implantation at 190 keV into an n-type Si(100) substrate with a low dopant concentration of 1.6 x 10^{14} cm^{-3}. The nominal depth of the implanted stripes was 0.7 µm with a B concentration 1x10^{18} cm^{-3}. The surface was prepared by wet chemical oxidation using the Shiraki procedure (1, 2). Scanning tunneling microscopy (STM) studies revealed that the oxide layer was 0.4 to 0.5 nm thick (1). The lateral distribution of carrier density and potential across the p-n junction has been studied with STM and conductance mapping (3, 4).

The friction experiments were performed with an RHK Technology STM/AFM system in a chamber with base pressure in the 10^{-10} torr range (5). We used cantilevers with nominal spring constants of 2.5 N/m coated with approximately 50 nm of TiN, which is hard and conducting (6). Details regarding calibration of the lever and tip characterization are described elsewhere (5). The normal force was kept constant during imaging while current and friction force were simultaneously recorded. The sample was mounted with a common electrical contact to both p and n regions.

Friction and current images of biased pn junctions

Figure 1 shows (A) topographic, (B) current, and (C) friction images 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 (~50 µA) and low in the n region (~5 µA). Friction was significantly higher in the p region than in the n region, as shown in Fig. 1C and D.

Figure 1 also shows images of the (E) topography, (F) current, and (G) friction at the opposite sample bias of –4 V. In this case the n region is forward biased while the p region is in inversion. The current in the n region was higher (~10 µA) than in the p region (~6 µA), as shown in the line profile in Fig. 1H. The depletion layer between the p and n regions is also visible and shows an even lower current (~0.2 µA). Interestingly, no significant variation of friction force was observed between the n and p regions at negative bias. The observed conductivity ratio between the n and p regions, a factor of 2 for negative sample bias and a
factor of 10 for positive bias, is due to the large difference in dopant density, four orders of magnitude smaller in the n than in the p region.

References

6. NT-MDT Co., Zelenograd Research Institute of Physical Problems, Moscow, Russia.

Figure 1. (A) 3.5 x 5.0 µm topography, (B) current, and (C) friction images of a silicon pn junction at +4 V bias. Bright corresponds to high values, dark to low. The p region is forward biased (strong accumulation), and the n region reverse biased. The applied load was 8 nN and the scanning speed was 5 µm/second. (D) Line profiles of current and friction across the pn junction. (E) 3.5 x 5.0 µm topographic, (F) current, and (G) friction images of the silicon pn junction at –4 V bias. The p region is reverse biased and n region forward biased. (H) Line profiles of current and friction across the pn junction.