Part I

Note: All work listed here has been performed on a cost sharing basis between IBM and ONR

A. Papers Submitted to Refereed Journals (and not yet published)

B. Papers Published in Refereed Journals


C. Books (and sections thereof) submitted for Publication.

D. Books (and sections thereof) Published.


E. Technical Reports Published and Papers Published in Non-Refereed Journals

The papers listed above are also IBM Research Reports.

F. Patents Filed.

G. Patents Granted.

H. Invited Presentations at Topical or Scientific/Technical Society Conferences


"Direct Observation of Friction at the Atomic Scale," AVS National Meeting, Atlanta, October 6, 1988.


"Tribology at the Atomic Scale" Sandia National Labs, February 9, 1990.


I. Contributed Presentations at Topical or Scientific/Technical Society Conferences


J. Honors/Awards/Prizes

Gary McClelland was named an American Physical Society Fellow in October, 1990.

K. Number of Graduate Students Receiving Full or Partial Support on ONR Contract

zero

L. Number of Postdoctoral Fellow Receiving Full or Partial Support on ONR Contract

two
Part II

A. Principal Investigator

Gary M. McClelland

B. Cognizant ONR Scientific Officer

Dr. Richard Brandt

C. Current telephone number

408-927-2406, if emergency 415-494-3730

D. Brief Description of project

We are using atomic force microscopy (AFM) to characterize the tribological properties of materials on an atomic scale. For these experiments we employ an ultrahigh vacuum instrument which measures the lateral and normal forces and current through a tip in contact with a surface which can be positioned with sub-Angstrom resolution. Friction of a sharp tip on a surface is investigated by profiling the surface, sliding the tip across the surface while measuring the normal and parallel forces and contact resistance, and profiling the surface after sliding.

E. Significant results

Under this project the construction of the first ultrahigh vacuum atomic force microscope (AFM) was completed. This same instrument was the first AFM to employ capacitance for measuring the deflection of the force-sensing cantilever and was also the first AFM to measure forces simultaneously both parallel and perpendicular to the sample surface, a practice now adopted by many other groups. Electronics for fast, sensitive and drift-free capacitance measurement were developed, and the noise sources for the capacitance technique were analyzed in detail.

The bidirectional vacuum AFM was used to study the tribology of an iridium tip on Au(111) in UHV. When it was published, this was the highest resolution tribology study ever performed on metals. Elastic indentation experiments only 10 Å deep into the surface can be interpreted in terms of Angstrom-scale surface roughness. Friction loops 50 Å wide observed at ≈ 10^{-7} N were free of any stick-slip structure associated with a difference between static and dynamic friction or with any features on the surface. Sliding the surface back and forth across the tip while advancing it toward and away from the tip, we found that the friction changed much more rapidly with increasing load (effective friction coefficient = 1.0) than with decreasing load (effective friction coefficient = .4). This difference appeared, even though any plastic deformation during contact was no more than 1 Å, indicating that extremely subtle changes in the tip-surface interface must effect the frictional force. In the friction loops, a curvature is observed just before full sliding, an effect attributed to partial stick/partial slip of the tip.

A CVD method was developed for forming single crystal diamond force microscope tips. By examining the tips by SEM at very low electron dose and thermally flashing in UHV, tips of known orientation and surface chemistry were
prepared. There are the best-characterized tips to have been used in AFM experi-
ments.

Using the diamond tips, we investigated diamond-diamond friction in UHV. The measured attractive tip-surface interaction agreed with predicted dispersion interactions. On the (111) surface, the frictional force shows features arising from the (1×1) reconstructed hydrogen-terminated crystal surface. The lateral force appears to be the sum of a position-dependent conservative part and a position-independent dissipative part, which changes sign with the direction of motion. The differential friction coefficient is nearly zero, suggesting the interface may be in the regime of “zero friction” predicted for incommensurate weakly interacting solids.

As a method to characterize tips, we became interested in field ion and field emission microscopy. This led to the development of the femtosecond field emission camera (FFEC), a device for observing the dynamics of individual atoms and molecules on the subpicosecond time scale. In this instrument an electron beam field-emitted from an extremely sharp metal tip is focused and swept across a detector screen. The motion of a single adsorbed atom on the tip causes a fluctuation in the field emission which is recorded on the screen. During the ONR contract, only the construction of this instrument was completed. Subsequent work has recorded with 1 ps resolution the hopping of single Cs atoms between sites on a tungsten tip and the vibration of single adsorbed copper phthalocyanine molecules with respect to the tip.