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Title: Interfacial Viscosity Measurements of
Adsorbed Monolayers on Metal Surfaces

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Summary of Accomplishments

At the outset of this project, we had just developed a technique, employing a quartz crystal microbalance, for measuring the sliding friction coefficient of a molecularly thin film adsorbed on a metal surface. Funding of the project allowed us to carry out a range of measurements documenting the friction coefficient under various circumstances.

The measurements were the first of any kind to quantitatively probe how much force is required on average to slide an atom across an interface, and were in the mainstream of the emerging field of nanotribology (a word coined by our group, which has now made it to the cover of scientific journals). They hold the world record for the shortest time scale on which friction experiments have been carried out, allowing them to be exactly modelled by molecular dynamics simulations (Mark Robbins at John Hopkins University).

As the research progressed, a number of theoretical models were suggested to explain the physical origin of the observed friction levels. In one case, the friction is electronic, or quantum mechanical in nature. In another scenario, the energy is dissipated through phonons, or lattice vibrations in the participating solids. We are now carrying out a second generation of experiments to specifically test the competing theories.

In the course of this research, it became apparent that a number of practical applications might arise from our ability to slide atoms on a surface. We constructed a quartz microbalance which could operate in conjunction with a scanning tunneling microbalance, and are now monitoring particles with the STM as they are shaken by the action of the microbalance. This apparatus is also successful in the study of tip-substrate adhesion levels in the presence of varying thicknesses of adsorbed lubricant layers.

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Significant Presentations

INVITED PRESENTATIONS AT MEETINGS

- (1) "Probing 2-D Phase Transitions and Surface Melting through Measurements of Interfacial Viscosity", NATO advanced study institute on "Phase Transitions in Surface Films", Erice, Italy (1990)
- (2) "Interfacial Slippage and Sliding Friction of Physisorbed Monolayers", "Surface Physics in Materials Science", El Paso, Texas (1990)
- (3) "Quartz Crystal Microbalance Studies of Atomic-Scale Friction", General meeting of the American Physical Society, Symposium on Nanotribology Cincinnati, Ohio (March, 1991)
- (4) "Statics and Dynamics of Wetting Films Adsorbed on Self-Affine Surfaces", Fall 1991 Meeting of the Materials Research Society, Boston, MA
- (5) "Quartz Crystal Microbalance Studies of Atomic-Scale Friction", Divisional meeting of the American Vacuum Society, Columbus, Ohio (June, 1992)
- (6) "Electronic versus Phonon induced Friction", Molecular Basis of Friction Symposium, Spring meeting of the American Chemical Society, Denver, CO (March, 1993)

INVITED PRESENTATIONS (SEMINAR or COLLOQUIUM)

- (1) University of California, Santa Barbara; April 1990
- (2) University of Virginia, Charlottesville, VA; Sept. 1990
- (3) Harvard University, Cambridge, MA; Oct. 1990
- (4) Naval Research Laboratory, Washington D.C.; Feb. 1991
- (5) Brandeis University, Waltham, MA; Oct. 1991
- (6) University of South Florida, Tampa, FL; Jan. 1992
- (7) I.F.F., Julich, Germany, Feb. 1992
- (8) University of Marseille II, Marseille, France, June 1992

Significant Publications

- (1) "Slippage of Simple Liquid Films adsorbed on Silver and Gold Substrates", J. Krim, E.T. Watts and J. Digel, *J. Vac. Sci. Tech. A*, **8** (4), 3417 (1990) *We reported here our measurements of interfacial friction for a number of adsorbate substrate systems, which represent a range of adsorption categories: H_2O/Ag , C_2H_6/Ag , N_2/Au , and Xe/Au .*
- (2) "Probing Films Phase Transitions through Measurements of Sliding Friction", J. Krim, in "Phase Transitions in Surface Films 2", H. Taub, ed. (B267, NATO ASI Series, Plenum, New York, 1991) pp 169-182 *This book chapter described in detail how to carry out a quartz microbalance measurement of the sliding friction coefficient of an adsorbed film.*
- (3) "Nanotribology of a Kr Monolayer: A Quartz Crystal Microbalance Study of Atomic-Scale Friction", J. Krim, D. Solina and R. Chiarello, *Phys. Rev. Lett.*, **66**, 181 (1991) *This letter relates friction coefficients of adsorbed layers to the morphology (as determined by scanning tunneling microscopy) of a substrate. Velocity and phase dependencies are also reported.*
- (4) "Sliding Friction Measurements of Physisorbed Monolayers: A Comparison of Solid and Liquid Films", J. Krim and R. Chiarello, *J. Vac. Sci. Tech. B*, **9**, 1343 (1991) *This article discusses the difference between solid and liquid film friction coefficients.*
- (5) "Sliding Friction Measurements of Molecularly Thin Films", J. Krim and R. Chiarello, *J. Vac. Sci. Tech. A*, **9**, 2566 (1991) *This paper uses Xe/Au measurements to discuss how an interfacial friction coefficient evolves with total film coverage.*
- (6) "Spreading Diffusion and its Relation to Sliding Friction in Molecularly Thin Adsorbed Films", A. Widom and J. Krim, *Phys. Rev. B* (submitted) *This theoretical paper describes how quartz crystal microbalance measurements of film sliding can also be used to obtain the spreading diffusion coefficient of the film.*

(7) "Determination of an Atomic-Scale Frictional Force Law through Quartz Crystal Microbalance Measurements", J. B. Sokoloff, J. Krim and A. Widom, Phys. Rev. Lett. (submitted) *This letter described how a quartz microbalance measurement can be utilized in order to determine the force law governing the interfacial friction.*

(8) "Applications of Atomic-Scale Friction Measurements with a Combined Quartz Microbalance and Scanning Tunneling Microscope", J. Krim and C. Daly, ACS Symposium on Atomic-Scale Friction (submitted) *This chapter describes in detail how a quartz microbalance can be set up to operate in conjunction with a scanning tunneling microbalance.*