**MICROCANTILEVERS
FOR
ATOMIC FORCE MICROSCOPE
DATA STORAGE**

MICROSYSTEMS

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MICROCANTILEVERS FOR ATOMIC FORCE MICROSCOPE DATA STORAGE

by

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Editor's Preface

This is the second volume in the new Microsystems Series from Kluwer Academic Publishers. Our Editorial Board has the goal of bringing to the Microsystems community, through rapid and timely publication, an outstanding library of reference works, monographs, textbooks, and selected Ph.D. dissertations.

The Microsystems field has an enormously broad scope, combining aspects of conventional microelectronics with non-electronic functionality in such diverse arenas as mechanical sensors, actuators, displays, vacuum microelectronics, chemical sensors and analysis systems, optical components, microfluidic components and systems, mass data storage, printing, switches and relays, even apparatus for research in cell biology and medicine. As our Series grows, it will include works from all these areas.

The first volume in this series (B. Romanowicz) dealt with Computer-Aided Design and modeling of Microsystem components. This second volume addresses the future of mass data-storage technologies. While progress in the speed and density of magnetic storage media continues to make larger mass memories available at successively lower costs, the question remains: What is next? In harnessing the techniques of scanning probe microscopy, specifically atomic force microscopy (AFM) in this case, Dr. Benjamin Chui has demonstrated, in his recent doctoral thesis at Stanford University (supervised by Prof. Thomas Kenny), that with suitable design, a single AFM tip can be used to write data thermally and also to read that data through

piezoresistive sensing of the cantilever deflection. By pushing the state of the art, and then documenting in this volume the design, modeling, fabrication, and testing of prototype devices, Dr. Chui has both opened up a new technological area, and provided a case study that will serve both students and professionals in the Microsystems field.

Publication of outstanding books requires effort from many individuals—the author first and foremost, but also reviewers and publishers. On behalf of myself and our Editorial Board, our thanks to all concerned.

Stephen D. Senturia
Cambridge, MA

Foreword

The density, speed and cost of mass data storage systems have improved steadily in recent years. In order to continue this trend, alternate technologies for data storage need to be evaluated and incorporated as appropriate. IBM is a world leader in data storage technology, and has also been a leading source of advanced technology. An excellent example of this technological leadership is the invention of the Scanning Tunneling Microscope at IBM Zurich.

This Ph.D. thesis describes a research collaboration between Mamin and Rugar's group at IBM Almaden and our group at Stanford University, in which a new mass data storage technology was evaluated. This technology is based on the use of heated cantilevers to form submicron indentations on a polycarbonate surface, and piezo-resistive cantilevers to read those indentations.

There is a strong interdisciplinary component to this work. AFM and related tip-based interactions are generally in the domain of Applied Physics. The writing technology described here is dominated by heat transfer considerations. The dual-axis force sensor represents an effort in mechanical design and testing. The Ph.D. was awarded in Electrical Engineering, but this work is typical of the interdisciplinary nature of the MicroElectroMechanical Systems (MEMS) field.

The research described in this thesis was strongly enhanced by a close collaboration with Mamin and Rugar's IBM Almaden group; this collaboration provided access to

testing facilities, contact with an appropriate industrial partner, and regular interactions with talented researchers. Collaborations with groups at Stanford University also provided support for microfabrication (Quate and Kovacs), assistance with measurements and analysis (Goodson), and many opportunities to exchange ideas and results.

Finally, Dr. Chui is the first Ph.D. student to complete his thesis under my supervision, and his work will always be memorable to me in that regard. Through this work, he has set a standard that subsequent students will struggle to duplicate, and he has helped build a reputation for our group that benefits us all.

Thomas W. Kenny
Stanford, CA

Abstract

Atomic force microscope (AFM) thermomechanical data storage involves the recording of digital information as submicron data pits on a rotating substrate at very high densities up to 30 Gbit/in². In a typical implementation, the sharp tip of a micro-machined AFM cantilever is kept in continuous contact with a spinning polycarbonate disk by a weak loading force. For writing, the cantilever tip is heated above the glass transition temperature of polycarbonate to melt data pits onto the substrate. For reading, the cantilever deflection is measured as the tip rides over the pits. This work describes recent developments in AFM thermomechanical data storage, with a focus on the integration of heating and deflection-sensing elements onto the cantilevers.

Single-crystal silicon cantilevers 1 μm thick have been demonstrated for use in AFM thermomechanical data storage. Cantilevers with integrated piezoresistive sensors were fabricated with measured sensitivities $\Delta R/R$ up to 7.5×10^{-7} per $\text{\AA}$, in close agreement with theoretical predictions. Separate cantilevers with integrated resistive heaters were fabricated using the same basic process. Electrical and thermal measurements on these heating devices produced results consistent with ANSYS simulations. Geometric variants of the cantilever were also tested in order to study the dependence of the thermal time constant on device parameters. Depending on the design, time constants as low as 1 μs were achieved. A thermodynamic model was developed based on the cantilever's geometry and material properties, and the model was shown to predict device behavior accurately. A comprehensive understanding of cantilever

functionality enabled us to optimize the cantilever for high-speed thermomechanical recording.

A novel dual-axis piezoresistive cantilever has also been developed for tracking in AFM data storage. The cantilever was fabricated using a new technique for making high-aspect-ratio sidewall-implanted microstructures. The device allows simultaneous, independent detection of vertical and lateral forces. The vertical force sensor of the cantilever can be used for data readback and loading force control, while the lateral force sensor can be used for data groove edge detection and tracking. The dual-axis cantilever consists of a flat, triangular probe with a sharp tip, connected to the support by four parallel high-aspect-ratio ribs. Piezoresistors are fabricated on the horizontal surface of the triangular probe and the vertical sidewalls of the ribs for orthogonal deflection sensing. A special oblique ion implant at approximately 45° to the normal is used to form the piezoresistors. Groove tracking on a spinning disk has been demonstrated using a custom two-channel servo controller for load regulation and tracking. Lateral force microscopy measurements as well as microscale friction measurements have also been performed using the dual-axis cantilever.

Acknowledgments

It has been a very enjoyable and rewarding three-and-a-half years for me. It seemed like only yesterday that I started my Ph.D. program at Stanford, and before I know it, here I am finishing up my thesis. I guess I'll have to first thank El Niño for keeping me indoors during all these rainy days, so that I had no choice but to start writing....

First I'd like to acknowledge various funding sources for this work, including an International Business Machines Corporation Graduate Cooperative Fellowship, the Defense Advanced Research Projects Agency (contract no. DABT63-95-C-0019), a Terman Fellowship, and the NSF CAREER Program (no. ECS-9502046).

This work was a collaboration between Stanford University and IBM Almaden Research Center, and I believe I have benefited tremendously from the synergy that stemmed from this type of academic-industrial collaboration. I have numerous people to thank, both at Stanford and at IBM.

My studies at Stanford would not have been successful without the guidance and attention of my thesis advisor, Prof. Tom Kenny. He was always accessible whenever I had questions to ask or simply wanted to chat, and his refreshing humor was always welcome, as my fellow group members can attest to. Tom gave me a lot of freedom to pursue my project the way I wanted to, yet at the same time managed to keep tabs on my progress and give the right advice at the right time. Tom also kindly accommodated my outrageous requests for conference travel more times than once—I think I

owe him a “Ben’s world tour” T-shirt for the ten cities, six countries and three continents that I visited during my research-related trips.

Of equally valuable support to my Ph.D. work was Dr. John Mamin, my mentor at IBM Almaden Research Center. He used a significant portion of his time to help me get up to speed on the test apparatus at IBM labs, and taught me various aspects of AFM theory and operation. He kindly allowed me to include some of his AFM writing and readback results in my thesis. He was always available to answer any questions I had despite my sometimes unannounced visits to his office; I certainly feel very fortunate to have had John for my mentor.

I would also like to thank the rest of the exploratory storage group at IBM—namely Dr. Dan Rugar, Dr. Bruce Terris and Dr. Bob Ried—for their support and assistance. Dan was manager of the group and helped me formulate the overall strategy for my project. Bruce helped with major technical aspects of my assignment, particularly with the tracking experiment setup and the polymer test-disk fabrication. Bob and I had many useful discussions about cantilever design and fabrication. Dr. Long-sheng Fan was also an important contributor to the project. Acknowledgments are also due to Dr. Koichi Wago, Dr. Nino Yannoni and Dr. Doug Thompson at IBM. I am also grateful to numerous researchers at IBM Zurich Research Laboratory—including Dr. Gerd Binnig, Dr. Peter Vettiger, and Dr. Juergen Brugger—for sharing their valuable technical expertise with me, and for hosting me during a very enjoyable site visit in Switzerland.

This project would not have occurred without Dr. Storrs Hoen. He was the person who introduced the Kenny group to IBM Almaden, catalyzing collaborative research between the two parties, eventually leading to my IBM fellowship in connection with the AFM data storage project. I am very much indebted to Storrs indeed for his continued support.

I would like to thank the rest of my academic committee at Stanford University. Prof. Greg Kovacs, my associate advisor, with his expertise and vigor, has been giving me inspiration for my MEMS research since my M.S. years. I owe you a beer, Greg. Prof. Ken Goodson provided me with valuable advice on thermal subjects, and Prof. Cal Quate helped me benefit significantly from his group’s expertise in atomic force microscopy. Prof. Robert Dutton, committee chairman, also devoted significant time and effort to matters in connection with my oral examination and thesis review.

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B. W. Chui
Stanford, CA

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