

# Modeling, Design, and Verification for the Analog Front-End of a MEMS-Based Parallel Scanning-Probe Storage Device

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**Abstract**—We present an integrated analog front-end (AFE) for the read-channel of a parallel scanning-probe storage device. The read/write element is based on an array of microfabricated silicon cantilevers equipped with heating elements to form nanometer-sized indentations in a polymer surface using integral atomic-force microscope (AFM) tips. An accurate cantilever model based on the combination of a thermal/electrical lumped-element model and a behavioral model of the electrostatic/mechanical part are introduced. The behavioral model of the electrostatic/mechanical part is automatically generated from a full finite-element model (FEM). The model is completely implemented in Verilog-A and was used to co-develop the integrated analog front-end circuitry together with the read/write cantilever. The cantilever model and the analog front-end were simulated together and the results were experimentally verified. The approach chosen is well suited for system-level simulation and verification/extraction in a design environment based on standard EDA tools.

**Index Terms**—Analog integrated circuits, integrated circuit modeling, MEMS interface circuits, model-order reduction, multidomain modeling, nanotechnology, sensor interface circuits.

## I. INTRODUCTION

ULTRAHIGH storage densities of 1 Tb/in<sup>2</sup> or higher can be achieved by using local-probe techniques to write, read back, and erase data in very thin polymer films. The thermomechanical scanning-probe-based data-storage concept, internally dubbed “millipede” [1], [2], combines ultrahigh density, small form factor, and high data rates. High data rates are achieved by parallel operation of large 2-D arrays with thousands of micro/nanomechanical cantilevers/tips that can be batch-fabricated by silicon surface-micromachining techniques. Fig. 1 illustrates the “millipede” concept.

The high precision required to navigate the storage medium over the probe tips is achieved by MEMS-based  $x/y$  actuators that position the large arrays of probe tips for parallel write/read/



Fig. 1. The “millipede” concept.

erase operations. Thermomechanical writing is achieved by applying a local force through the cantilever/tip to the polymer layer and simultaneously softening the polymer layer by local heating. To read the written information, the same cantilever is used to scan the surface. The change in the thermal flow between a second heating element and the medium surface leads to a change in the electrical resistance of the heating element (see Fig. 2) [3].

The parallel operation of hundreds of cantilevers makes the CMOS integration of the analog front-end (AFE) imperative. To this end, a 3-D assembling technology has been developed to transfer the cantilevers onto the CMOS read-out circuitry [4]. The small relative resistance change ( $\Delta R/R < 10^{-5}$  for a typical indentation) renders the design of the AFE’s read-channel a challenging task. This paper describes the design of the critical input stage of the read-channel based on co-simulation of the AFE circuitry and a multi-domain cantilever model. The resulting read-channel is the centerpiece of a 32-channel AFE chip [5]. Section II of the paper focuses on the model of the cantilever and Section III presents its experimental verification. Section IV gives the details on the model-based design and optimization of the critical first stage in the read-channel. Experimental results obtained with the complete 32-channel chip that was wirebonded to a cantilever array are also shown. Section V summarizes the paper.

## II. VERILOG-A CANTILEVER MODEL

The AFE for the thermomechanical storage device is in essence a transducer interface circuit. As described above, information is stored in the mechanical topography of a thin polymer film. The micromechanical cantilever acts as a transducer to convert topographical variations into electrical energy during the read process, and vice versa during the write process.

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