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High Speed, Large Scan Area, Distortion Free Operation of a Single-Chip Scanning Probe Microscope

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Despite the exquisite resolution that may be obtained with AFMs, the industrial nanometrology enterprise has been reluctant to include them in their suite of inspection tools. The single-chip AFM [1] was introduced to overcome several shortcomings of conventional AFMs by replacing bulky piezoelectric scanners with 3 degree-of-freedom electrothermal (ET) MEMS actuators and by replacing laser detection with thermal-piezoresistive resonant sensing. These single-chip instruments are well-suited to high-speed operation and may also be implemented as arrays, as they include all of the components that are required for an AFM to obtain an image on a single chip.

We report a 50-fold increase in the scan speed and a 2x improvement in the distortion-free scan range of a single-chip atomic force microscope (sc-AFM) instrument. The thermal time constants of 3-DOF actuators have been reduced by a factor of ~10 to increase the bandwidth of quasi-static AFM modes, while also increasing efficiency in dynamic modes. These devices have produced the first sc-AFM images of a 22nm SRAM bank (on an Intel Ivy Bridge CPU).

Perhaps the most significant drawback of conventional AFMs, when compared to other scanning microscopes such as confocal or scanning electron microscopes, is that it takes 1-100 minutes to obtain a high-quality AFM image. The first paper on high-speed AFM was published 25 years ago [2]. Several highly customized scanners were then developed to demonstrate video-rate AFM [3,4]. These instruments place severe constraints on the sample volume because the reported scanners cannot accommodate large masses (i.e. wafers). The present work obviates any sample movement because the tip is scanned in 3DOF by MEMS actuators, thus raising the lowest natural frequency of the instrument.

The geometry of the reported instrument is shown in Fig.1a. Lateral actuators are arranged to enable isothermal scanning [5] to suppresses thermal coupling to piezoresistive sensors. A stiffer flexural suspension yields a first lateral mode that is ~2x higher than the cantilever's natural frequency (Fig.1b); the opposite is true for AFMs reported to date, which suffer from deleterious resonances at high scan speeds. Optimal placement of heaters within actuators reduces their thermal time constants by an order of magnitude to enable fast scanning (Fig.1c,d). A lever arrangement provides sufficient geometric advantage to obtain 15µm x 15µm scans. A range of >60µm may be obtained as a line profile.

The surface of a DVD was imaged by a sc-AFM to demonstrate its scan range (Fig.2a). The present device also obtains images of a 22nm SRAM cell, clearly revealing contact-level structure in the 6-transistor bit cell (Fig.2b). SiC atomic lattice steps with 1.5nm height have also been captured (Fig.2c). Vertical actuators with short thermal time constants have enabled the acquisition of tip-sample interaction dynamics at high data rates for the first time with a sc-AFM (Fig.3). Once the tip and sample are engaged, compressive stress in the cantilever may be measured to reveal topography. Upon retraction, the abrupt transition from attractive tip-sample interaction forces to free-oscillation is captured. This information may be used to reconstruct images of the topography, adhesion, and dissipation in the sample simultaneously in a single pass.

To date, high-speed AFM research has employed contact mode, which causes rapid tip wear. The sc-AFM may be operated at higher speeds than conventional instruments in intermittent contact mode. In

Fig.4, line scans of a 100nm calibration grating are obtained with progressively higher scan rates to demonstrate that a 50x improvement in scan speed has been achieved, and that a 200x improvement may be achieved through a combination of compensating the dynamics of the MEMS and increasing the piezoresistor amplifier bandwidth.

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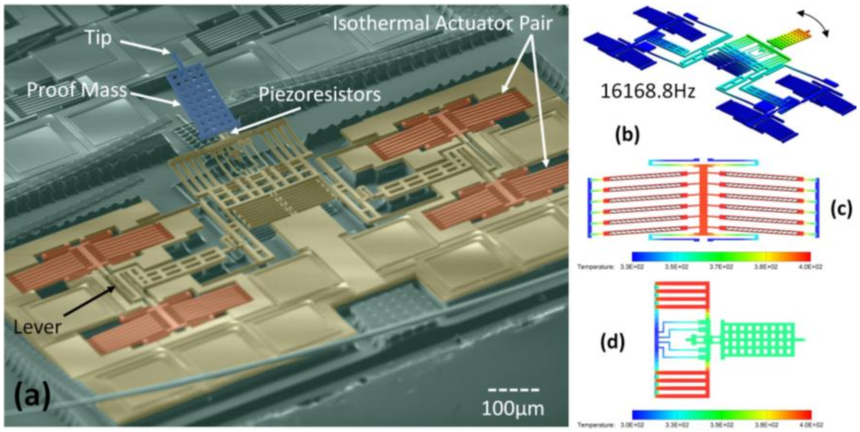

Figure 1. (a) False color SEM image of a single-chip AFM with several components highlighted. (b)The first lateral resonance of the flexural suspension occurs at ~16kHz, while the cantilever's vertical resonance is at ~8kHz. (c,d) Polysilicon heaters are arranged to efficiently heat the active material in lateral and vertical actuators.

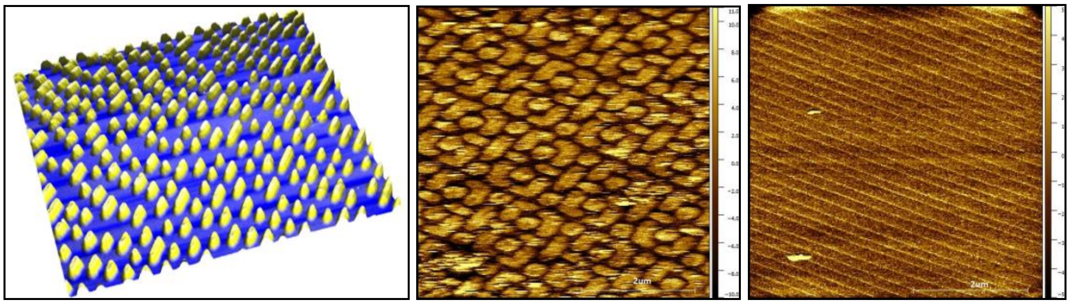

Figure 2. (a) left, 17x17μm scan of the topography of a DVD. (b) center: 6-transistor bit cells in an SRAM fabricated at the 22nm technology node. (c) right: 1.5nm atomic lattice steps on a silicon carbide calibration standard.

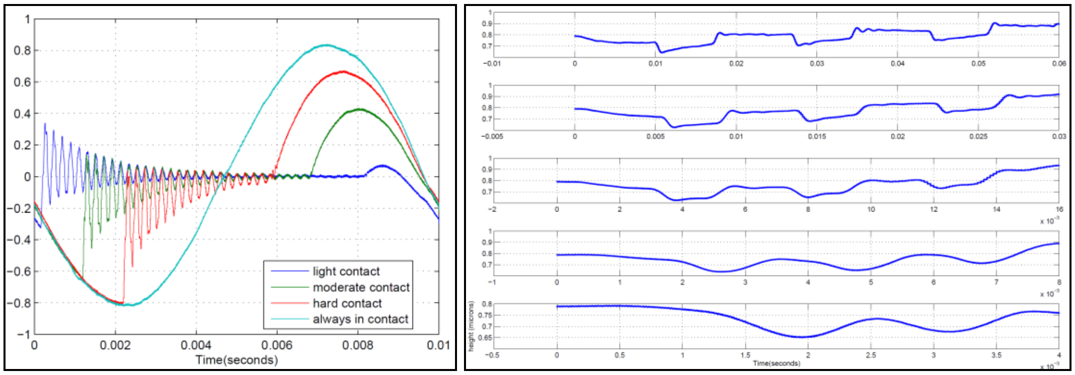

Figure 3. (a) left: data captured with tip oscillating at 100Hz at various tip-sample separations. Repulsive forces are positive. After the tip snaps out of contact, ringing at the natural frequency of the cantilever is observed. (b) right: 10μm line scans of a 100nm calibration standard in 60ms, 30ms, 15ms, 8ms,