# Electromigration: A Unique Tool for Microstructure Engineering in Metal Films

S. M. Mohanasundaram, Rudra Pratap, and Arindam Ghosh

***Abstract*—Electromigration has long been studied in the context of interconnect reliability in integrated circuits. It has also been used to create metal electrodes with nanogaps for molecular electronics. Here we report a new application of electromigration as a tool for locally engineering the microstructure of thin metal films. By controlling the level of disorder in the system, electromigration enables us to modify the electrical and electromechanical properties of the film. We have developed and implemented a feedback control algorithm for high precision control of the electromigration process. We have demonstrated the usefulness of the technique by using it to enhance the strain sensitivity of a metal based piezoresistive transducer. This enhancement can be attributed to the change in microstructure of the film which in turn changes the electronic transport mechanism.**

***Index Terms*—Electromigration, microstructure, feedback control, piezoresistance.**

## I. INTRODUCTION

Mass transport due to momentum exchange between conducting electrons and diffusing atoms or ions is called electromigration. This phenomenon is typically observed in metal films where the metal atoms migrate under the influence of a large electric current. In the past few decades, the physics of electromigration has been extensively studied because of its importance to the semiconductor industry, mainly as a failure mechanism of the interconnects in integrated circuits [1]. These studies have led to better choice of materials for these interconnects that can withstand higher current densities for longer time periods.

More recently electromigration has been used as a fabrication technique to make metal electrodes for molecular electronics. The fabrication is achieved by passing a large electrical current through a lithographically defined metal wire. The current flow causes the electromigration of metal atoms and the eventual breakage of the wire. This is a reproducible method to create metallic electrodes with nanometer-sized gap [2]. These electromigration induced break junctions are used as electrical contacts for individual molecules [3] and nanocrystals.

Electromigration in solid metals can occur through different mechanisms, such as lattice diffusion, grain boundary diffusion, surface or interface diffusion, etc. The dominant mechanism depends on various factors including the specific material under consideration, microstructure before electromigration, thermal conductivity of the surrounding medium, and the flexibility of the substrate. Electromigration-induced microstructure evolution has been studied and observed to occur through mechanisms different from standard annealing or joule heating [4]. Nevertheless joule heating plays an important role in determining the local temperature and hence the diffusivity of defects which facilitate electromigration.

## II. EXPERIMENTAL STUDY

### A. Device Details

We have performed electromigration experiments on a microelectromechanical system (MEMS). The MEMS device comprises a bimorph actuator and a piezoresistive sensor, connected by a mechanical coupler. Figure 1(a) is a schematic diagram showing different components of the device and figure 1(b) shows the scanning electron microscope (SEM) image of a typical physically realized device. Both the actuator and the sensor are bilayer cantilevers with silicon dioxide as the structural layer and gold as the conducting layer. First, the silicon dioxide beams are fabricated using electron beam lithography and bulk micromachining of silicon. Then gold films of thickness 50 – 70 nm are evaporated on to the silicon dioxide structures.

A notch is incorporated on one (left) leg of the sensor cantilever for dual purposes: first, to promote electromigration by enhancing the local current density and temperature, and second, to provide stress concentration when the cantilever is bent. This design ensures that the maximum stress is reached exactly where the electromigration damage occurs. The continuity of the gold film on the coupler beam is deliberately broken to electrically isolate the actuator cantilever from the sensor cantilever.

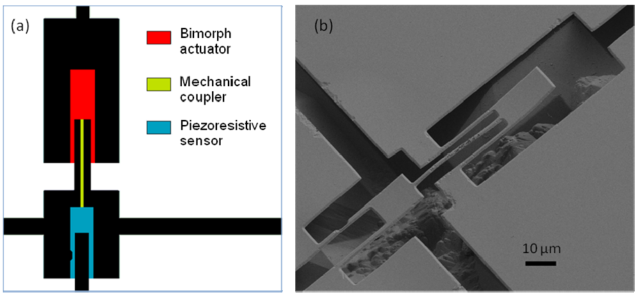

Fig. 1. (a) Schematic showing components of the device (b) Scanning electron micrograph of a fabricated device.

### B. Microstructure Engineering

Our experiments show that electromigration can be used to locally engineer the microstructure – grain size, grain boundaries and void density of thin metal films. Figure 2

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S. M. Mohanasundaram and A. Ghosh is with Department of Physics, Indian Institute of Science, Bangalore 560012, India (email: contactmohan@gmail.com).

R. Pratap is with Centre for Nano Science and Engineering, Indian Institute of Science, Bangalore 560012, India.

illustrates the substantial change in microstructure that can be caused by electromigration. The average grain-size of as-deposited gold film is around 30 nm (figure 2(a)), while the average grain-size after electromigration is around 200 nm (figure 2b). Note that this grain growth is not a result of controlled electromigration (which is discussed later) but is created during actuator-sensor isolation. To isolate the actuator and sensor, a large current is passed through the film on the coupler beam. The current is continuously increased beyond the critical current density (~ $10^{11}$ A/m$^2$), resulting in rapid electromigration. As a result, the gold film becomes discontinuous near the centre of the beam where the maximum temperature is reached. But slightly away from the discontinuity (figure 2(b)) the grain sizes have increased by almost an order of magnitude. This kind of grain growth can also be accomplished by annealing the film.

Of course, grain growth is not the sole purpose of electromigration induced microstructure modification. The rate of electromigration is a function of both current density and temperature, [5] each of which can be controlled. For a given current, at any point on the structure, the current density is only determined by the width of the structure, while the temperature reached will depend on the thermal resistance from that point to the silicon substrate. The suspended structure also provides good thermal isolation for the region of the film to be electromigrated (the notch) from the silicon substrate. Note that silicon is a very good conductor of heat and would otherwise lower the temperature of the metal film. Moreover, the experiments are done in vacuum to minimize heat loss through air. Thus thermal isolation significantly lowers the critical current density by enhancing the temperature for a given current. The device shown in figure 1(b) is designed after taking all these factors into consideration.

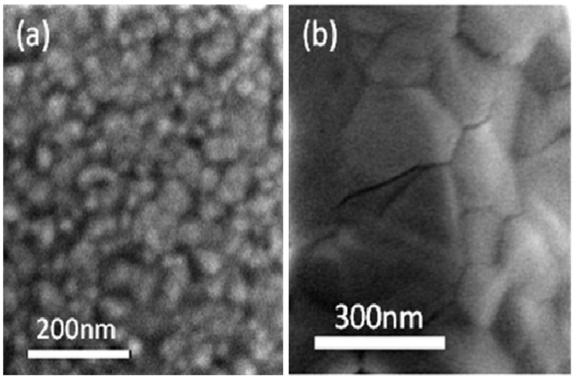

Fig. 2. SEM image of gold film showing (a) microstructure as-deposited (b) microstructure after electromigration.

Thus our experimental design leaves the current as the only parameter to be controlled during electromigration. To control the current in the best possible manner, we have developed a closed-loop feedback control system that adaptively controls the current through the piezoresistive sensor while continuously monitoring the resistance. This system can thus control the level of disorder introduced in the system. This can lead to substantial change in specific physical properties of interest such as electrical resistance and the strain sensitivity of the piezoresistive sensor.

### C. *Feedback Control Algorithm*

The algorithm is designed to carefully control the rate of electromigration and, in turn, to precisely tune the resistance of the piezoresistor. The program, implemented in LabVIEW, has a response time less than 1 second. The current through the piezoresistor consists of a large dc component for electromigration and a much smaller ac component for resistance measurement. The program starts with an initial dc current set by the user at a value a little lower than the critical current. The critical current is the current at which electromigration happens at a considerable rate and is strongly dependent on the dimensions of the notch and the current state of damage in the film. A flowchart for the algorithm is given in figure 3.

The program continuously monitors the resistance while the dc drive current is on. Whenever the resistance changes by more than x% (typically 0.1%) the dc current is stopped. Then the program checks if there is a permanent change in the sensor resistance. If the unheated resistance is found to have increased from the previous value, then the dc current is decreased and if unheated resistance is found to be lower than the previous value, then the dc current is increased. This is done so as to always stay close to or below the critical current density. If the sensor resistance is found to have permanently changed by more than y% (typically 2-5%) then the electromigration process is terminated.

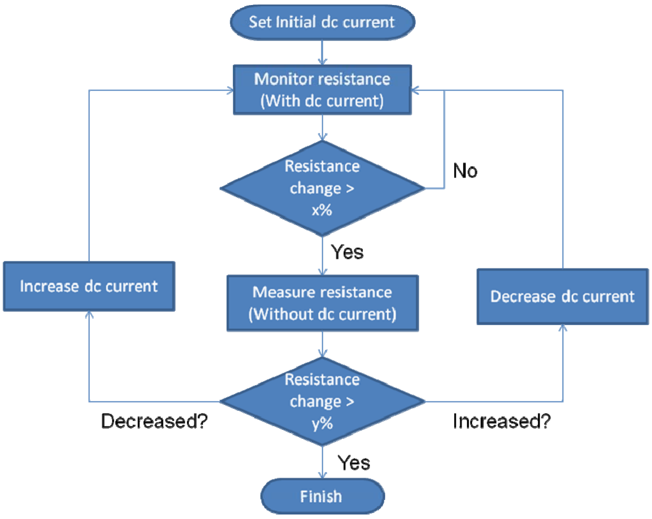

Fig. 3. Flowchart of the algorithm for control of electromigration.

### D. *Frequency Response Measurement*

At different values of piezoresistive sensor resistance ($R$), the electromigration is stopped and strain sensitivity of the piezoresistive sensor is measured. The strain sensitivity can be determined from the piezoresistively detected frequency response. Heterodyne principle is used to measure these frequency responses. In this method, the cantilever is vibrated at a frequency $f_A$ while biasing the piezoresistive sensor at a slightly different frequency $f_A+\Delta f$ with $\Delta f << f_A$. The piezoresistor acts as a frequency mixer [6] and generates a signal at $\Delta f$. This $\Delta f$ component is detected using the lock-in amplifier (SR830) with phase acquired using an external mixer. The rms amplitude of this $\Delta f$ component scaled by half of the rms bias voltage directly gives the relative change in resistance ($\Delta R/R$) due to strain.

## III. RESULTS AND DISCUSSION

Figure 4a shows piezoresistively detected frequency response at various stages of electromigration represented by the sensor resistance, *R*. The frequency responses are measured with much lower sensor current - at least 10 times lower than the current used for electromigration. In order to compare frequency responses at different stages of electromigration, the current through the bimorph actuator is kept constant throughout. The sensor resistance *R* increases because electromigration increases the level of disorder, in particular the void density in the film. As R increases due to electromigration, the strain sensitivity also increases as seen from the larger amplitudes of the resonance curves.

Comparing figures 4(b) & 4(c), we can observe a large change in the microstructure caused by electromigration. This change in microstructure is responsible for the enhancement in strain sensitivity. Due to electromigration and the growth of voids, atomic-scale gaps develop at the grain boundaries. So the conduction mechanism changes from metallic transport towards tunnelling. But since there can be several current paths in parallel, the film becomes a percolation network of tunnel junctions.

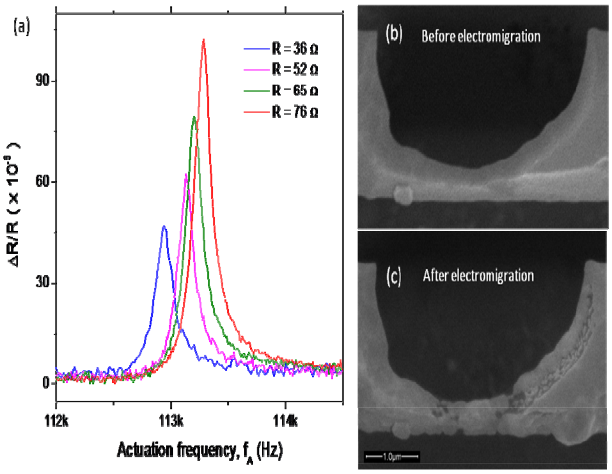

Fig. 4. (a) Piezoresistively detected frequency response at various stages of electromigration. Gold film at the notch (b) as-deposited (c) after electromigration.

## IV. CONCLUSION

In this work, we have proposed and shown that electromigration can be used as a tool for engineering the microstructure of metal films. We have demonstrated a substantial change in grain size and void density that can be effected by electromigration. We have developed and implemented an adaptive feedback control algorithm to precisely control the amount of disorder introduced by the electromigration. We have shown the usefulness of this technique by improving the strain sensitivity of the metal based piezoresistive sensor.

## ACKNOWLEDGEMENTS

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