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Nanoscale Control of Electro-migration for Resistance Tuning of Metal Lines

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Abstract

Electromigration in metal films is a well known phenomenon in the microelectronics field and is usually regarded as a serious problem for interconnect reliability. Here, we exploit electromigration in a constructive way to devise a process for enhancing metal piezoresistivity. A recent study [Mohanasundaram *et al.*, 2012] has shown that electromigration can be used for nanoscale manipulation of local morphology in thin metallic lines to drastically improve their piezoresistivity. This development has significant impact on strain gauge technology, especially for MEMS and NEMS devices. The key to this development, however, is a reliable control over the electromigration process. In this study, we have used electromigration to get a stable increased resistance for gold nano lines without breaking the line. We have used feedback controlled electromigration where the incremental resistance has been used as the main control parameter. Using this technique we have been able to increase the resistance of gold nanowires four fold. We present an algorithm for the closed loop control, use it successfully to increase the resistance of gold lines by four times, and show that this technique can be used to carry out rapid, stable and controlled electromigration. The intended application is significant enhancement of piezoresistive sensitivity of metal lines in MEMS and NEMS devices.

1. Introduction

Electromigration (EM) has been intensively studied over the last few decades [Scorzoni *et al.*, 1991, Pierce and Brusius, 1997] because of the problems it creates for the semiconductor industry. It is a major concern for the reliability of interconnects used in microelectronic circuits [Lloyd, 1997]. Researchers have studied EM to understand the phenomenon in depth so that different methods can be developed (such as using alloys) to slow down EM and to get more robust interconnects [Ames *et al.*, 1970]. The main focus of EM research has been to get rid of this destructive and unwanted phenomenon. Interestingly, in the last decade, researchers have found some positive use of EM. EM has been shown to be useful for nanogap formation or electrode fabrication with nanometre separation [Zheng Ming Wu *et al.,* 2007, Hadeed and Durkana, 2007, Trouwborst *et al.*, 2006]. It has been used successfully in some applications such as microstructure formation [Lu *et al.*, 2011], memresistive switching [Johnson *et al.*, 2010] and molecular circuits [Grose *et al.*, 2008].

In almost all the above cases, researchers have used feedback controlled EM. In the present work, we also use a feedback control and use an algorithm to have precise control over the EM process in order to attain the desired resistance from a metallic line without creating a break in the line.

Piezoresistive strain gauges are heavily used in micro and nano electromechanical systems (MEMS and NEMS) [Bargatin *et al*., 2005]. Metals are unpopular in these systems because their piezoresistive coefficient is one to two orders of magnitude lower in comparison to common semiconductor-based piezoresistors [Barlian *et al*., 2009]. In a recent report, Mohanasundaram *et al.* [2012] have shown that using EM one can get highly increased sensitivity or a very high gauge factor from metallic strain gauges. The enormous enhancement in strain sensitivity is due to a rapid increase in ΔR/R with increasing R of the metal line due to EM. The piezoresistive sensitivity ΔR/R increases as R^3 in the initial phase of EM and as log(R) later on [Mohanasundaram *et al.*, 2012]. The increase in R is unfortunately also accompanied by an increase in noise. In addition, the rapidly increasing R goes out of bound in a very short time when the metal line breaks due to EM and forms a tunnel junction. The key to tunability of the strain sensitivity is, therefore, a precise control of the resistance during EM. The algorithm described and tested in the present work differs from the one described in Mohanasundaram *et al.* [May, 2012] in that it uses the voltage ramping rate effectively to considerably reduce the time taken for a target value of R. In other words, the current algorithm allows rapid EM to reach the target R in a couple of hours as opposed to tens of hours that the other algorithm uses. The key difference is that our algorithm uses the incremental resistance ΔR, as opposed to R as the monitoring parameter. In this work, we use gold nanowires with a notch a (bow-tie kind of structure) in the middle of the wire. Initially, we perform uncontrolled accelerated EM by ramping up the current to find a proper control parameter. We use this parameter (described later) in our feedback control to obtain the desired resistance with the EM process. We also carry out data analysis to show the effect of noise on the EM process.

2. Device Design and Fabrication

The device we use for our study is shown schematically in Fig. 1 along with the cross sectional

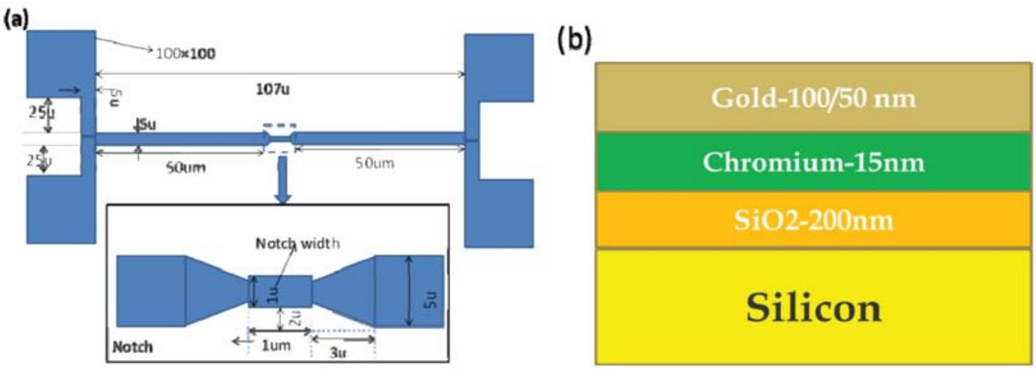

Figure 1. (a) Schematic diagram of the device (top view) (b) layered cross-sectional view with dimensions.

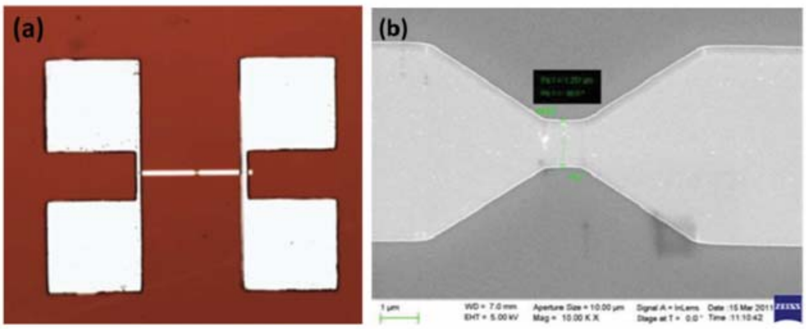

Figure 2. (a) Optical microscope image of the final device (b) SEM image of the notch.

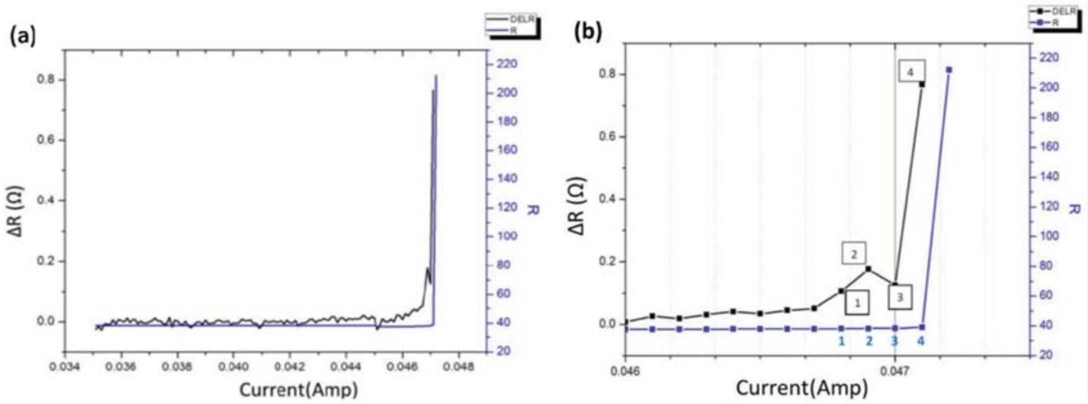

Figure 3. (a) Change of R and ΔR with increasing current (I) by a ramp rate of 100 µA/Sec. Here we can see that though the EM occurred at 47.1 mA significant change in ΔR only started from 46 mA (b) Enlarged view of Fig. 3(a) (after 46 mA). We can see that EM occurred after data point 4 whereas more than a 10 fold change occurred in ΔR from data point 1.

view and thickness dimensions of each layer. For fabrication, we use a <100> silicon wafer, grow 200 nm thick SiO_2 on it, sputter a thin film (15 nm) of Cr over it as an adhesive layer, and finally a 50 nm thick Au film that is patterned into a thin gold wire connected to contact pads (100 nm) as shown in Fig. 2(a). The wire-like gold structure incorporates a notch region in the middle as shown in Fig. 2(b). For different devices, the notch width and length have been varied from 100 nm to 1 µm keeping all other dimensions the same. The notch portion along with the central line is fabricated by e-beam lithography whereas the pads and the side arms are patterned using photolithography.

3. Experiment

3.1 Electromigration without feedback control and its effect on incremental resistance

The resistance is generally stable up to just before the terminal EM. The most interesting phenomenon seems to take place just before the terminal EM when we notice a large change (almost 10 fold) in the incremental resistance ΔR (see Fig 3). To track ΔR, we use a sampling frequency of 250 Hz. A rapid and large change in ΔR was recorded in all the devices we tested.

3.2 Algorithm used for feedback control EM

We use pre EM measurements of ΔR as a monitoring parameter and use it effectively to control the march towards EM in order to stop the process at a desired value of resistance before the EM breaks the metal line. We use dual slope deferential control. Our feedback parameter is R and we calculate ΔR from $\Delta R = (R_{n+1} - R_{n-1})/2$. If ΔR is greater than some critical set value ΔR_c (here we have used typically 0.5% of R) then the test exits from the primary section (loop) and goes to the main section. Two different slope values for voltage ramping are used for the two different sections. In

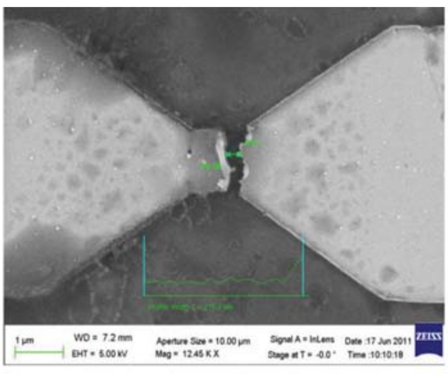

Figure 4. SEM image of the device R2C3 after EM.

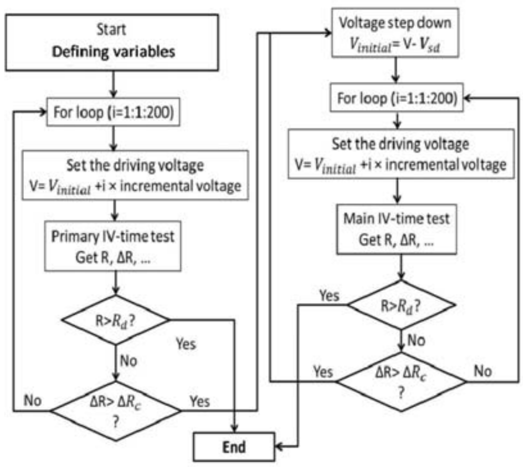

Figure 5. Flow chart of Feedback Controlled EM test

the primary section, we ramp current more rapidly (typically with 5 mV incremental voltage).

Once the EM is indicated, we switch to the second section, i.e., the main section, where we ramp up more cautiously with lower incremental voltage (typically 500 µV). The ΔR_c in the main section is half of its value in the primary section, i.e., 0.25% of R. When we switch from the primary to the main section, or even encounter a ΔR that is greater than ΔR_c, in the main section, we decrease the starting driving voltage by a certain amount V_{sd}, where V_{sd}=(V_{end} of primary loop - V_{start} of main loop). Generally V_{sd}= 100 mV. The control parameter values (ramp rate for the two loops, ΔR_c,V_{sd}) are decided on the basis of the low current resistance measurement of the pristine sample. If the pristine sample is noisy, then we take a higher value of ΔR_c and a lower ramping rate. On the other hand, for a stable sample we use a lower ΔR_c and a higher ramping rate. The time taken to reach the desired resistance R_d is also of concern. Therefore, if the test takes too long then we use a higher ramping rate and low V_{sd} to accelerate the test. Using this algorithm (shown in Fig.5) the test is stopped when R_d is reached.

4. Results and Discussion

Using the feedback algorithm described above, controlled EM (CEM) is successfully carried out for several devices to get the desired resistance. The final resistance, however, is not time invariant in all cases. We find three different kinds of final resistance value which are described below.

i) Fluctuating resistance

For the device R3C2, CEM was done successfully to get R_d=120 Ω starting from 70 Ω but this resistance was not stable. With low current measurements, the resistance was found to fluctuate between 120 Ω to a few kΩs.

ii) Decreasing resistance

For the device R4C2, we reached 150 Ω starting from 70 Ω in three steps 70-110, 110-120 and 120-150 Ω. The increase from the 120 Ω to 150 Ω step is shown in Fig. 6(a), but later, with low current measurements, we found that the resistance decreased with time (see Fig. 6(b)) and finally settled around 95 Ω.

iii) Stable resistance

For the devices R4C4 and R3C6, we obtained the desired resistance R_d and the final resistance was found to be stable. For R3C6 we obtained 250 Ω resistance starting from 60 Ω. For R4C4 we started from 80 Ω and reached 150 Ω in 3 steps (80-100, 100-120 and 120-150 Ω). The final resistance was almost stable around 150 Ω. This small fluctuation is probably due to the noise embedded in the system (device analyzer) which is discussed later.

From the graphs in Fig. 7 we can see how the algorithm works. In both cases (a) and (c), we see that the step down of driving voltage occurs at some point of the voltage ramp, i.e., where $\Delta R > \Delta R_{c,}$ which implies that the device is close to the critical breaking point. So, to save the device from breaking,

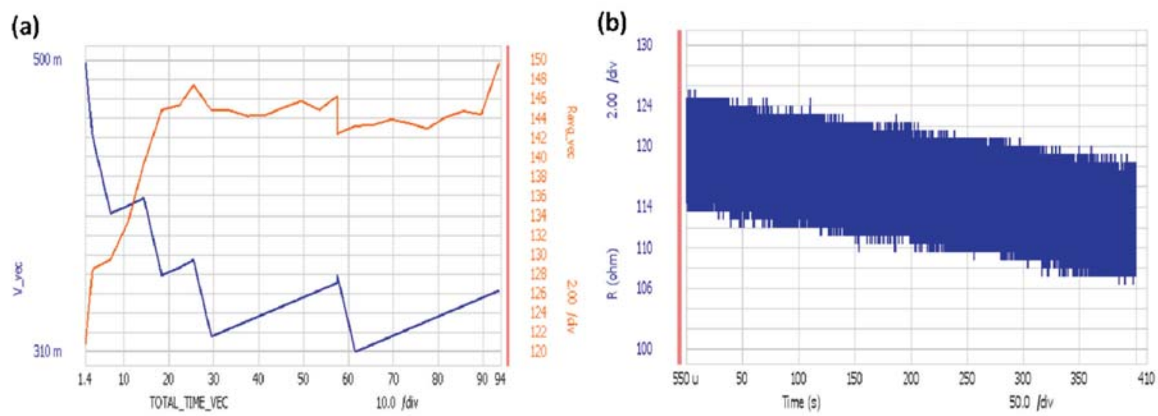

Figure 6. (a) voltage (blue) and resistance (red) values with time during the controlled EM test run. (b) Resistance variation over a long time when the test is off. The resistance is not stable but decreases with time.

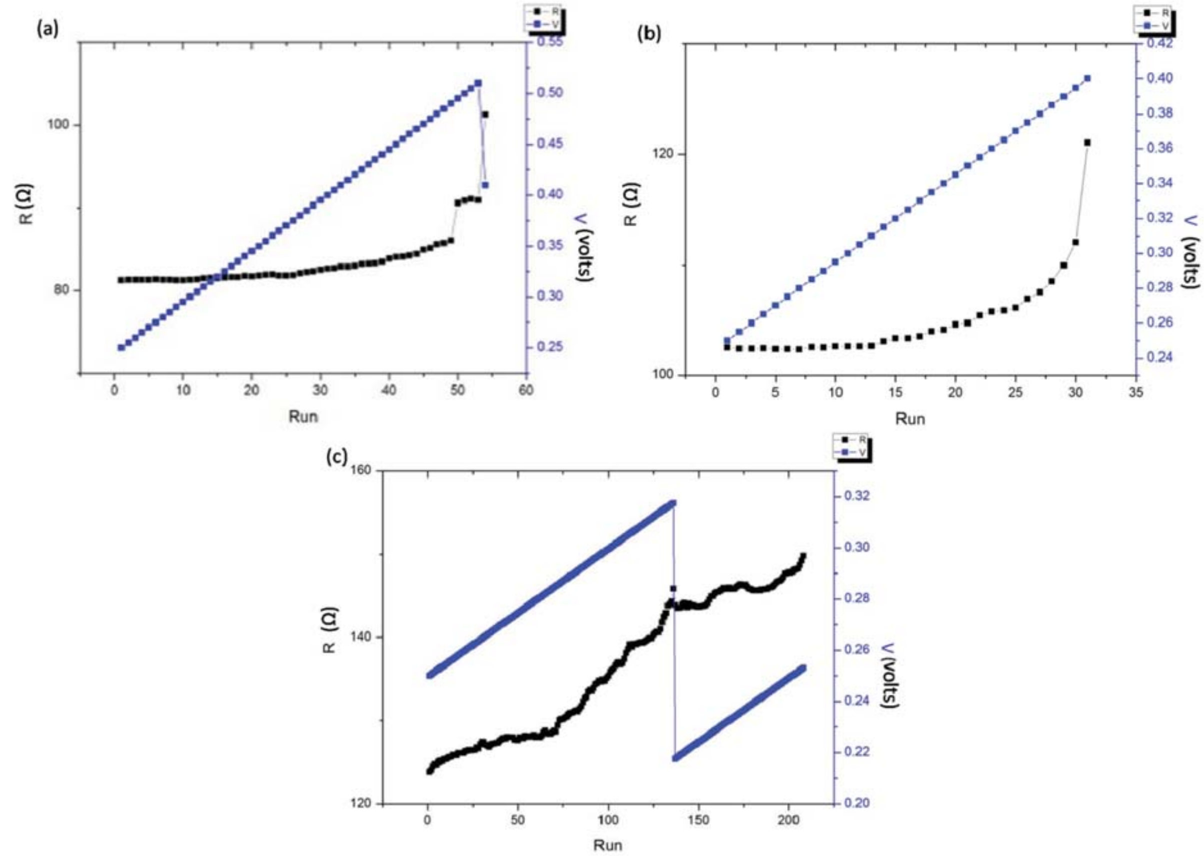

Figure 7. Variations in driving voltage V (blue) and resistance R (black) are shown against the loop number (run); in three steps we reach 150 Ω resistance from 80 Ω (a) 80-100 Ω (b) 100-120 Ω (c) 120-150 Ω

we decrease the voltage by a certain amount V_{sd}. Sometimes, no step down happens in the desired range and we get the resistance aimed at (Fig. 7(b)). On the other hand, many step downs sometimes occur in a small range (Fig. 6(a)), so the driving voltage decreases by a large amount which makes the test very slow.

The three different kinds of results can be explained using concepts from stress dynamics [Zhang *et al.*, 2005, J.He *et al.*, 2004] inside the notch region. The EM force knocks out atoms from the cathode side to create voids in those regions. These atoms accumulate on the anode side and create a compressive stress. This stress gradient pushes the atoms in opposite directions and refills those voids, pushing the resistance to revert to its earlier value. When we run the test very fast, i.e., with high incremental voltage, this creation and annihilation of voids happens dynamically during the test resulting in a fluctuating resistance (case 1). Sometimes, because of the presence of high electron wind force, the back stress gradient is unable to drive the atoms from the anode to the cathode during the test. However, once the electric field is removed, the atoms flow towards the cathode annihilating the voids and thus decreasing the resistance with time (case 2). In the third case, the feedback control test has been done more cautiously with lower incremental voltage and higher step down voltage (V_{sd}). In this case, the compressive stress at the anode side has enough time to relax the stress (by forming local hillocks or beads) during the test and therefore the created voids are stable. By the time the desired resistance (R_d) is reached, there is not enough stress gradient to cause a backflow of atoms thus making the resistance stable.

Considering the high current that passes through the small notch area, one might think that joule heating may be responsible for an increase or decrease in the resistance. In this case, however, we can rule out any significant effect of joule heating because, during the test, we observe the same incremented value of resistance even with a very low current (10 μA to 50 μA) measurement when the driving current is switched off. Considering the fact that at this scale, metallic structures have a very small thermal time constant (of the order of milliseconds) the temperature rise or resistance increase should relax in a fraction of a second when the test is off. But, we see no decrease in resistance for case 3, and a very slow decrease of resistance with time for case 2 (Fig. 6(b)), which, therefore, cannot be due to thermal effects.

We also recorded and analysed the noise in our measurements of R and ΔR during the entire process. As expected [Bora and Roychaudhury, 2006, 2008], we find that the noise increases considerably just before the terminal EM. It may, therefore, be possible to use noise also as a monitoring parameter for the control loop. We have, however, not pursued this route.

5. Conclusions

We have successfully used a feedback control algorithm to control the change in resistance of a gold line during EM and obtained the desired resistance without breaking the device. Incremental resistance (ΔR) is used as the main monitoring parameter for EM. By tuning different monitoring and control parameters (such as critical incremental resistance ΔR_c, critical step down voltage V_{sd}, ramping rate of voltage for the primary and main sections) we have been able to control the speed of the test. The rate of current stressing or the speed of the test affects the void dynamics inside the notch region which, in turn, controls the stability of the final electromigrated resistance. A slower test gives more stable electromigrated resistance.

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