Synopsis

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Title of the thesis: Study and control of electromigration driven material transport for applications in nanofabrication and patterning

Electromigration in conducting film is a major reliability issue associated with microelectronics circuits. In case of solid metals, the net electromigration force, as shown in **Fig. 1,** pushes atoms from the cathode to the anode, resulting in formation of void(s) near cathode and material pile-up in the vicinity of the anode. This creates an open circuit at the cathode and hillocks or whiskers at the anode that may cause short-circuit. On the other hand, in the case of liquid electromigration, a material first melts due to Joule heating and then the liquefied material starts to flow in a directional fashion as long as the electric current flows through it. Direction of flow or material transport in the case of liquid electromigration depends on the material: for liquid Au, Al, Ga, Sn, In, etc., the flow occurs from the anode to the cathode (i.e., in the direction of electric field), whereas in the case of liquid Pb, etc., the liquefied material flows opposite to the applied electric field, i.e., in the direction of electron flow. Unlike the slow mass transfer under the conventional solid-state electromigration resulting in “void-protrusion” formation after an extended period of time, the mass transfer due to the liquid electromigration is extremely rapid. Therefore, liquid electromigration also poses severe reliability concern in the microelectronic systems comprising very thin films carrying currents of large current densities and require critical examination.

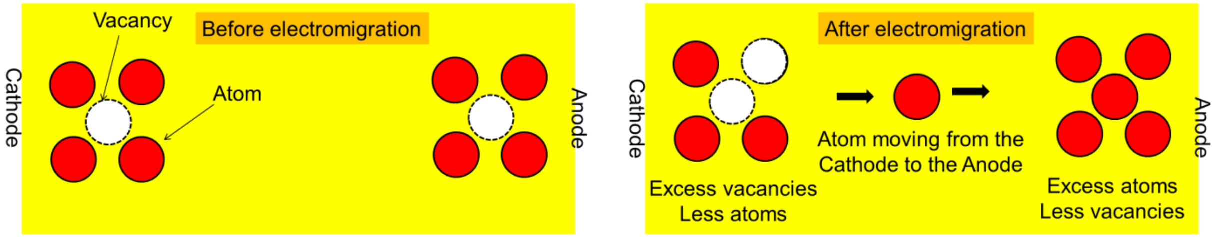

Figure 1: Schematic illustration of the electromigration driven atomic transport process.

In addition to understanding and controlling the destructive nature of electromigration, a few studies have also explored constructive usage of this phenomenon. Electromigration, being a mass transport phenomenon, has particularly been exploited in developing new fabrication and patterning technologies. This thesis focuses on two different aspects of electromigration, namely, (i) study of liquid electromigration to understand the effects of different process parameters on the mass transport, so that these process parameters can be optimized for improving the overall reliability of the MEMS/ NEMS devices, and (ii) precisely control electromigration induced mass transport for fabricating multi-dimensional structures at small length scale. Accordingly, in this work, we performed electromigration study on three different systems: (i) solid electromigration in Au thin film interconnects, (ii) liquid Ga flow on conducting metallic tracks and (iii) liquid electromigration driven material flow in thin infinite films of Cr and Al deposited on SiO_2-Si substrate, and then applied the discoveries to develop a few lithography and patterning technologies.

In solid electromigration experiments using Au metal lines, electromigration driven mass transport is manipulated using a feedback based control system. As shown in **Fig. 2(a),** controlled electromigration is used to tune the void size and its distribution in the Au film thereby increasing its resistance and piezoresistive sensitivity. Controlling electromigration is a very challenging task because of its unpredictable nature, especially close to the final failure or onset of terminal electromigration. We identify a new parameter, incremental resistance (ΔR), which is used as the pre-indicator and main monitoring parameter for electromigration. Using this technique we have been able to increase the resistance of Au thin films by a factor of four. We present an algorithm for the closed-loop control, use it successfully to increase the resistance of gold lines by a desired amount (as shown in **Fig. 2(b)**), 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.

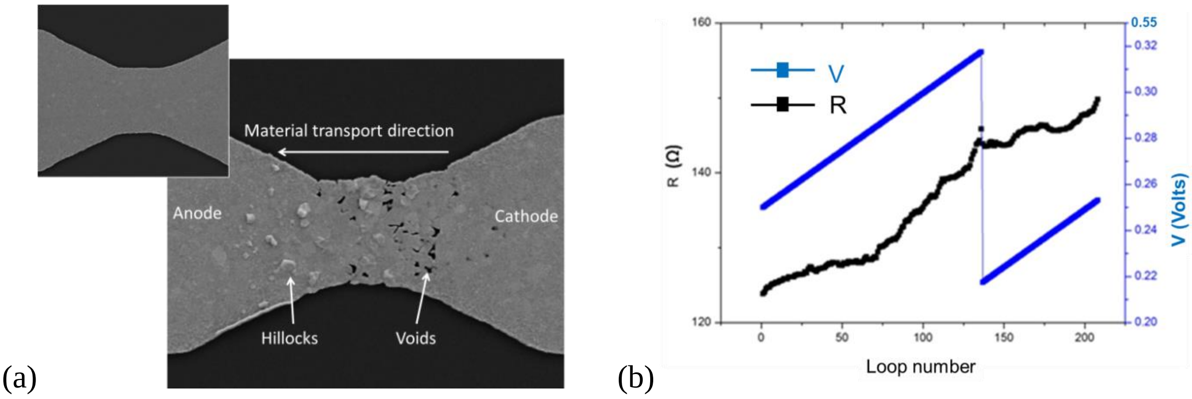

Figure 2: (a) SEM image of the microstructure of the notch area of the device after electromigration. Inset shows the low magnified image of the pristine device. (b) Variations in driving voltage, *V* (blue) and electrical resistance, *R* (black) are shown against the loop number for a device. We reached a resistance value of 150 Ω from 120 Ω.

Liquid electromigration studies on metallic tracks fabricated on a solid, insulating substrate show that application of electric current of high current densities (>10^8 A/m^2) results in liquid metal flow over the path from the anode to the cathode. We demonstrate it by flowing liquid Ga on “1-D path” of Au or Pt lines deposited on Si substrate (see **Fig. 3**). Velocity of the liquid material flow increases linearly with the current and exponentially with the temperature.

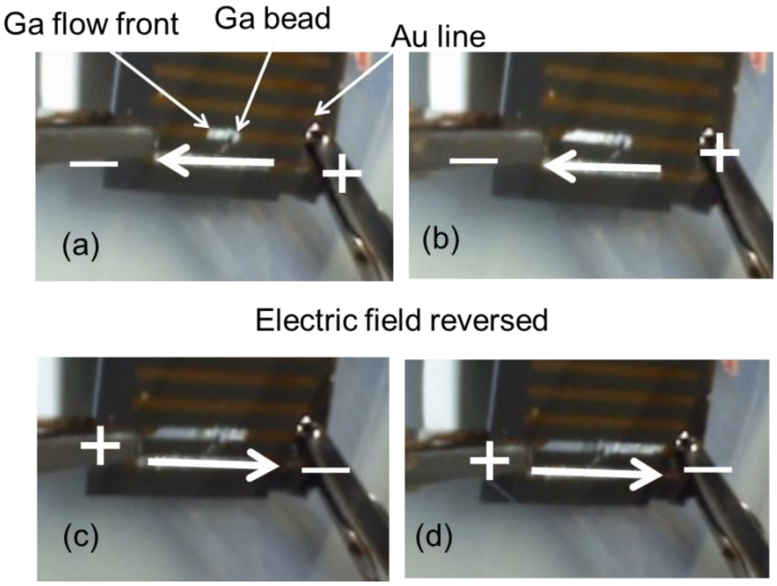

Figure 3: Time-lapse snapshots of Ga flow on Au track: In (a) and (b) right electrode is positive and the left one is negative. In (c) and (d), the electric field is reversed resulting in reversal in the direction of Ga flow. Horizontal thick arrows in each image show the flow direction.

Liquid electromigration experiments on infinitely extended thin films deposited on SiO_2-Si substrate shows that Joule heating results in visible melting of the material, and then in case of Cr thin film, the electromigration induces flow of the melt from the cathode in a radially symmetric fashion (see **Fig. 4(a)**). Such a material flow results in formation of a distinct micro-scale ring around the cathode probe whereas no noticeable mass transport or pattern formation occurs near the anode. Diameter of the electromigration ring increases as the square root of the applied voltage and monotonically with the thickness, as shown in **Fig. 4(b)**. The developed insight has been used to minimize the electromigration damage in the Cr interlayer (or adhesive layer) between Au and SiO_2 in a MEMS/NEMS sensor by optimizing the thickness of the Cr film. Thus, more reliable MEMS/ NEMS sensors could be fabricated using controlled electromigration.

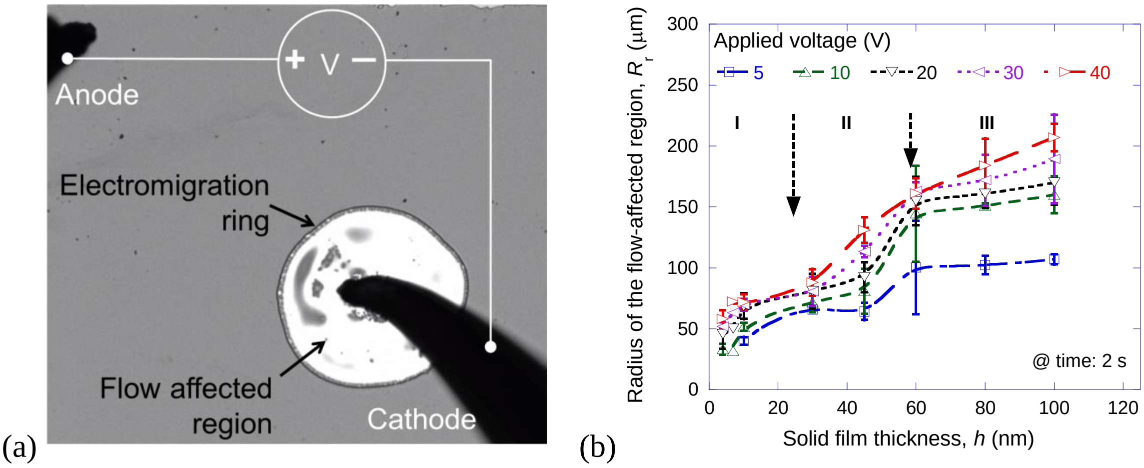

Figure 4: (a) This optical micrograph showing a typical electromigration ring around a static electrode in a 20 nm thick Cr film deposited on SiO_2-Si substrate. (b) Variation of the instantaneous ring radius with the solid film thickness. Regions I, II and III are the three segments of the sigmoidal variation where the increase in the radius of the flow-affected region is gradual, rapid and slow, respectively.

Using the electromigration induced material flow of thin Cr film deposited on a substrate, we have invented a new, low cost lithography technique, named as, *electrolithography*. In this technique, thin Cr film is used as a masking layer and a polymer layer beneath it as a pattern transfer layer. The desired pattern is drawn in the metal layer by etching the metal with a conducting scanning probe assisted by liquid electromigration. The drawn patterns are then transferred to other materials by subsequent polymer etching and deposition of new material. As shown in **Fig. 5,** using this simple technique, we have achieved pattern resolutions of 9 nm on the polymer and 40 nm on transferring the pattern to another material. Electrolithography does not use any high-cost and high-power consuming UV source, e-beam source or UHV systems. All processes employed in electrolithography are carried out at room temperature and atmospheric pressure.

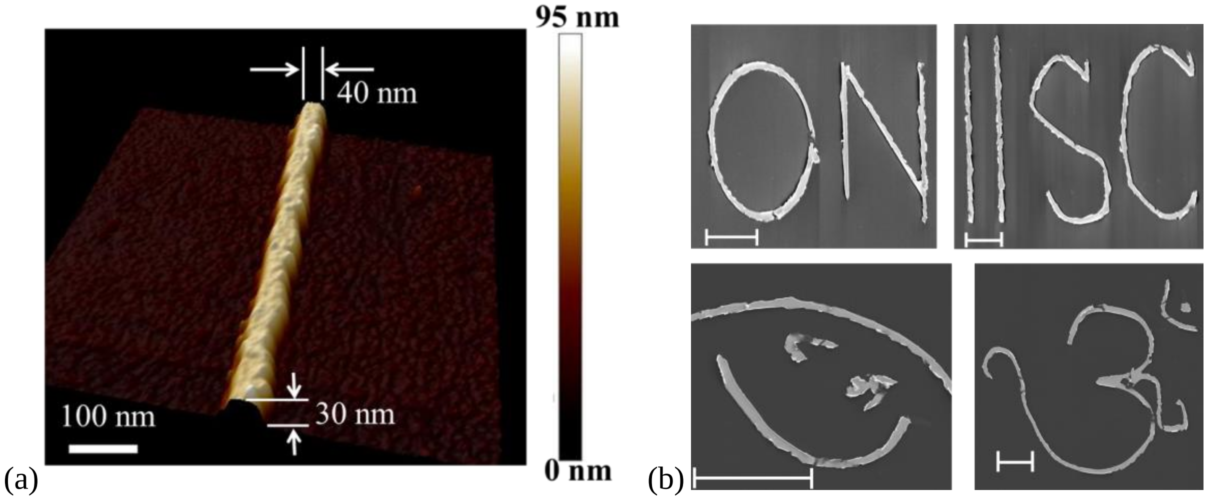

Figure 5: Patterns fabricated using electrolithography (a) 3-D AFM image of the narrowest Ti thin film line with an average width of 40 nm and thickness 30 nm. (b) Tilted SEM images of various types of patterns fabricated in Au on Si substrate. The scale bar shown in each picture is 5 μm. The thickness of all metal lines here is ~75 nm

Both the linear flow of material on conducting metal tracks and radial flow of material in case of infinite thin films have been used for multi-dimensional (1-D, 2-D and 3-D) patterning of different discrete metallic structures, such as nano-stairs (see **Fig. 6(a)**), micro- and nano-sized beads, etc. In particular, the material flow on conducting linear track is used to form periodic structures with surface ripple patterns (see **Fig. 6(b)**), which has numerous applications in optics, sensing and microfluidic devices.

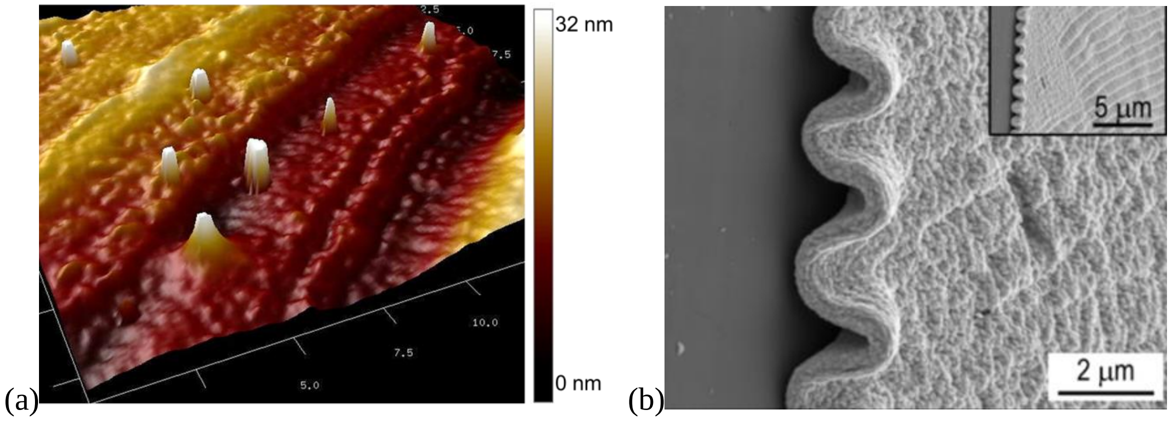

Figure 6: (a) 3-D AFM image showing a section of the staircase region. (b)SEM image showing the tilted view of the edge of a ripple pattern; inset shows the zoomed out view of the edge region.