Controlled material transport and multidimensional patterning at small length scales using electromigration

Santanu Talukder, Praveen Kumar and Rudra Pratap*

Electromigration, mostly known for its damaging effects in microelectronic devices, is basically a material transport phenomenon driven by the electric field and kinetically controlled by diffusion. In this work, we show how controlled electromigration can be used to create scientifically interesting and technologically useful micro-/nano-scale patterns, which are otherwise extremely difficult to fabricate using conventional cleanroom practices, and present a few examples of such patterns. In a solid thin-film structure, electromigration is used to generate pores at preset locations for enhancing the sensitivity of a MEMS sensor. In addition to electromigration in solids, the flow instability associated with the electromigration-induced long-range flow of liquid metals is shown to form numerous structures with high surface area to volume ratio. In very thin solid films on non-conductive substrates, solidification of flow-affected region results in the formation of several features, such as nano-/micro-sized discrete metallic beads, 3D structures consisting of nano-stepped stairs, etc.

Keywords: Electromigration, fabrication and pattern formation, material transport, 3D micro-/nano-structures.

MULTI-DIMENSIONAL (1D, 2D and 3D) micro- and nano-sized structures are of enormous interest to researchers working in the area of micro-/nano-electromechanical systems (MEMS/NEMS). These structures have myriad of interesting applications in several micro- and nano-sized sensors and devices. Figure 1 gives a few such examples and their applications. Designing micro- and nano-sized structures with nano-pores and cracks in a metallic thin film (Figure 1 *a*) can lead to high piezoresistive sensitivity of the metal film[1,2]. Metallic beads of sub-micrometre diameter (Figure 1 *b*) are useful for catalytic growth of nano-wires[3] and also in the field of plasmonics[4,5]. Another useful example of 3D structures (Figure 1 *c*) is the high surface to volume ratio patterns such as porous foams consisting of 3D micro-pillars and fibre network structures. These are used for surface modification, lubrication and different sensing applications[6]. Another interesting microstructure is 3D staircase pattern (Figure 1 *d*), which is widely used in Fabry–Perot etalon arrays, photonic band-gap crystals, blazed grating applications, etc.[7–9]. However, fabricating these structures using conventional wet-bench and photolithography or e-beam lithography techniques is difficult and also time and energy consuming. So, significant efforts have been made to develop modified or alternative lithography techniques to fabricate some of the aforementioned structures and devices[7–10]. Although these modified processes have been successfully developed to fabricate a few of the structures

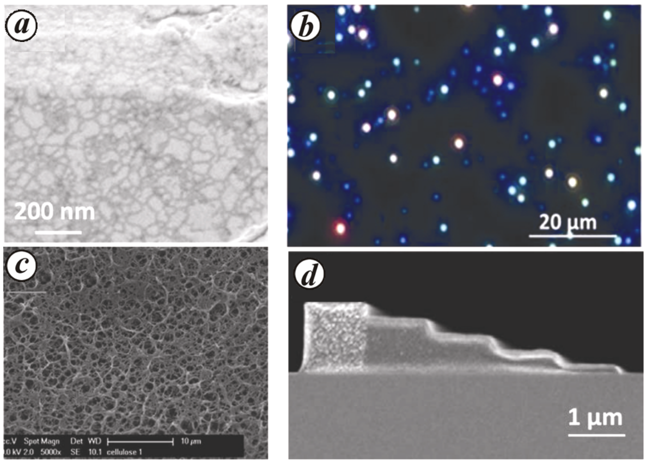

Figure 1. ***a***, The microstructure of a gold metal film having cracks and pores[2] for application in sensors with high piezoresistive sensitivity. ***b***, Metallic bead patterns[4] used in catalytic growth of nano-wires, nano-tubes and also in the field of plasmonics. ***c***, 3D fibre network structure[6], which can be used in lubrication technology and also in sensing applications where structures with high surface area to volume ratio are required. ***d***, 3D staircase patterns[8] used in Fabry–Perot etalon arrays, photonic band-gap crystals, blazed grating applications, etc.

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mentioned earlier, a single low-cost technique still does not exist that can be used for fabricating many types of small-scale structures. This forms one of the basic goals of the present work, where we demonstrate electromigration-driven controlled material transport to be one such versatile method having potential to create structures with preset patterns.

Electromigration in solid metals is known for a long time as a major reliability issue affecting the service life of thin interconnects in microelectronic devices[11,12]. It is basically a diffusion-controlled phenomenon where material movement is driven by the applied electric field. Assuming ballistic transport mechanism of electron flow in metals, a metal ion, formed due to the ejection of electrons from the conduction band, is subjected to repetitive collisions against the accelerating electrons flowing from the cathode to the anode under the influence of an externally applied electric field. Accordingly, in such a scenario, the metal ions are exposed to the following two forces: (i) electron wind force, which arises due to the momentum transfer from the fast-moving electrons to the metal ions during collision, and (ii) direct force, which arises due to the Columbic interaction between the applied external electric field and the ions. These two forces act in opposite directions: the electron wind force pushes the ions from the cathode to the anode, whereas the direct force moves the ions from the anode to the cathode. The direction of the net material transport is, thus, decided by the greater of the two forces. In case of solid metals, the electron wind force dominates the direct force. So, the metal atoms move from the cathode to the anode, forming voids near the cathode, and hillocks or whiskers near the anode. However, the case of liquid metals is not as straightforward. Depending on the liquid metal, the direct force may sometimes become larger than the electron wind force, such as for liquid Ga, In, Al, etc., resulting in material transport from the anode to the cathode[13–15]. However, a few other liquid metals, such as Pb, flow from the cathode to the anode[14]. Since diffusivity of a metal is several orders of magnitude larger in the liquid state compared to that in the solid state, electromigration-driven material transport is significantly faster in the liquid state.

Although electromigration is a material transport phenomenon, it has found few applications in fabrication[16] and formation of specific micro-/nano-structures[10]. Furthermore, electromigration has not yet been extensively exploited as a tool for effecting long- or short-range material transport. Solid-state electromigration, being a slow process, can be used for short-range controlled transport of metal atoms for microstructural engineering. On the other hand, the liquid state electromigration, being a fast process, can be used for fabricating large as well as small multidimensional structures. Furthermore, since liquid state electromigration also consists of the solidification process, it provides an additional tool for manipulating microstructure, including surface features, of a formed structure through control of cooling rate. In this work, we exploit the widely varying transport capabilities of solid as well as liquid state electromigration to fabricate several micro- and nano-sized structures. In this process, we demonstrate that electromigration, which is a phenomenon known primarily for its destructive capability, can also be used to develop plausible low-cost, one-step pattering technique suitable for fabricating structures and microstructures of myriad surface features at small length scales.

Experimental procedure

Figure 2 shows a micrograph of a MEMS-based strain sensor. This device was designed, as will be shown later, to demonstrate the effectiveness of solid-state electromigration in creating a percolation network which, thereby, can enhance the sensitivity of the sensor. To fabricate the basic template of this sensor, first, a 200 nm thick SiO_2 layer was grown over a 450 μm thick Si ⟨100⟩ wafer by wet oxidation. Next, 20 nm of Cr film was deposited for better adhesion between the SiO_2 layer and Au film, and then 200 nm thick Au film was sputter-deposited in the pattern shown in Figure 2. A notch (inset, Figure 2) was introduced at the centre of the device to localize current density and thus the electromigration-induced modification of the microstructure in that region. After making electrical contacts with the pads, electric current was passed using a source measurement unit along with a feedback control algorithm. The resistance of the device increased due to electromigration-induced microstructural

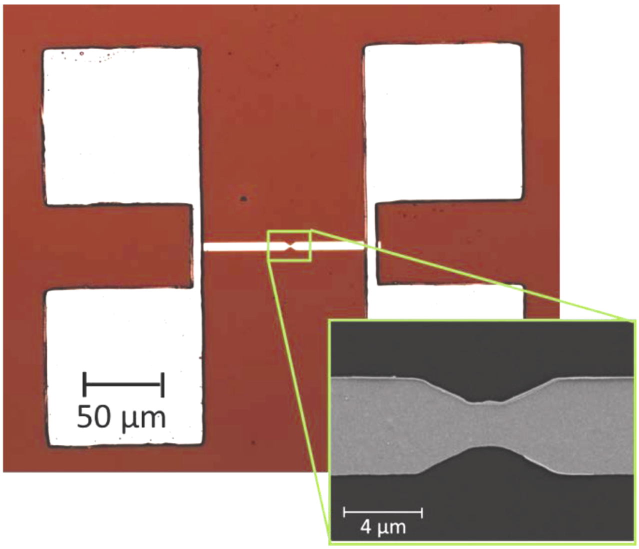

Figure 2. An optical micrograph of a MEMS sensor. (Inset) Magnified view of the notched region, where the desired percolation network is set to be formed. The structure is made up of Au, whereas the interlayer between the SiO_2 substrate and the Au film is made of Cr.

evolution in the notched region and this change in the resistance was used as the feedback parameter to control the electric current and hence the electromigration. The test was programmed to stop after achieving the desired resistance. Additional details of the experimental procedure can be found in ref. 1.

For fabricating numerous small structures along a predefined path, a solid metal (Ga) bead was placed over a long strip of a thin metal (Au or Pt) line and then an electric current of high density (>10^6 A/cm^2) was passed through the metal line (Figure 3). The metal lines in this study were straight: 30 mm long, 500 µm wide and 200 nm thick. However, the same experiments could also be conducted on tortuous as well as very narrow lines. As the electric current passed through the metal line[14], the Joule heating melted the metallic bead, which then started to flow from the anode to the cathode (Figure 3). Upon solidification, the structure of the flowed metal was observed under a scanning electron microscope (SEM). Different combinations of substrate–metal, substrate surface roughness, electric current and scheme of choosing the direction of current flow were employed to generate various structures discussed in the next section.

Figure 4 schematically shows the experimental set-up employed to produce structures containing nanometre-sized steps and micrometre-sized solid metallic beads. Several blanket Cr films of different thicknesses were sputter-coated on SiO_2 layer. Using the set-up shown in Figure 4, an electric current was passed through the film for a predefined duration. The material near the probes melted because of the Joule heating, perhaps aided by the formation of some low melting temperature compound of Cr. However, the liquefied metal or metal compound flowed only from the cathode in a radially symmetric fashion towards the anode; this type of flow formed ring patterns[14,17]. For generating the stair pattern, current was passed in an intermittent fashion, i.e. the current was passed for 2 sec followed by an off-period of 2 sec. On the other hand, the metallic beads were formed at the periphery of the flow-affected region developed during either a constant or an intermittent current loading. The microstructure and patterns formed were observed under SEM.

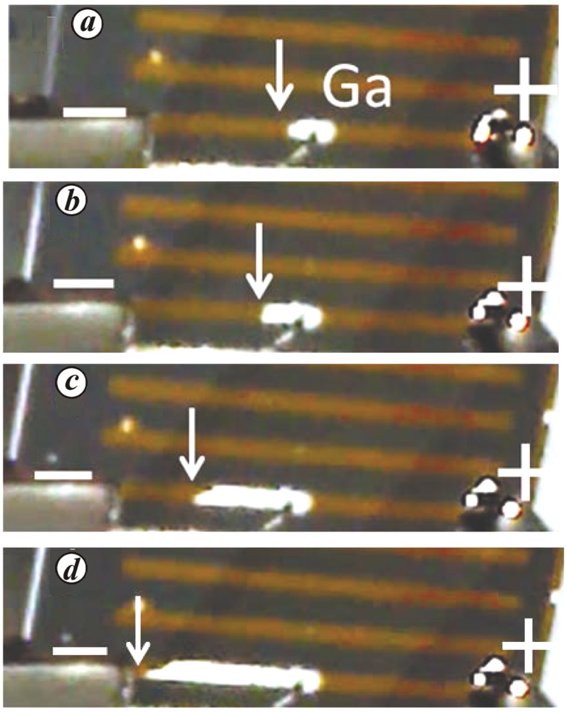

Figure 3. Time-lapse optical images showing flow of liquid Ga over fabricated Au lines captured at (***a***) 110, (***b***) 240, (***c***) 340 and (***d***) 430 sec respectively, after the flow commenced. Arrow in each photograph shows the flow front.

Results and discussion

Patterning for improving sensing capabilities

Figure 5 shows the variation in resistance and applied voltage over the time period during which electric current was passed through the sensor component. The resistance feedback-based control algorithm[1] ensured that the electric current was never too high to cause open circuit. Hence, the voltage was reduced in steps to control the generation and growth of the electromigration-induced voids in the notched region. The material transport and hence the damage in the conductor was precisely controlled through optimization of the notch geometry and the aforementioned algorithm.

Figure 6 shows the microstructure of the notched region following electromigration. As expected, voids and hillocks are concentrated near the cathode and the anode regions respectively. Due to the presence of voids, not only did the resistance of the line increase but also a percolation network consisting of several tunnel junctions was seen to develop along the path of the current making it extremely sensitive to strain, whereby any small deflection

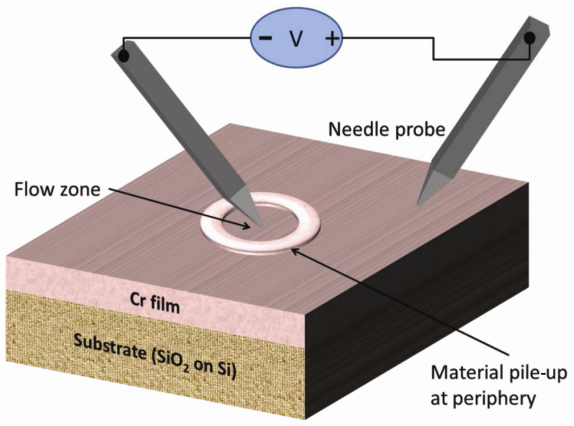

Figure 4. Schematic showing the experimental set-up for passing electric current through an infinitely large thin film.

in the notch area could produce large change in the electrical resistance of the device[2]. It should be noted that the tunnel resistance further increases as the separation between the junctions increases as the line vibrates. Due to formation of the electromigration-induced voids in the pattern shown in Figure 6, which is extremely difficult to fabricate using conventional cleanroom practices, these electromigrated gold lines show much higher piezoresistive sensitivity than the conventional metallic strain gauges[2].

Patterning for increasing surface to volume ratio

Figures 3 and 7 show the effect of electric current on the liquid metal flow on a thin metallic line. As shown in Figure 3, a long-range flow of liquid Ga, from the anode to the cathode, can be observed upon application of an electric current, resulting in a maskless conformal coating of the substrate metallic path[13]. Evidently, the direct force is greater than the electron wind force in liquid Ga. A closer inspection of the solidified coating shown in Figure 7 reveals the formation of a variety of surface and structural features. Figure 7 *a* shows the formation of a pile-up of material, resembling networks of canyons and fjords, at the flow front (i.e. in the direction of the electric field), whereas Figure 7 *b* shows formation of vein or wrinkled, skin-like structures over the surface of almost the entire coating. As mentioned earlier, the unidirectional flow of a liquid metal under an electric field is prone to flow instabilities, which explains the formation of the solid structures at the flow front (Figure 7 *a*). The vein or wrinkled skin-like structures (Figure 7 *b*) were formed by first passing the current in a set direction followed by turning-off the current, allowing the liquid material to solidify and finally, by passing an electric current again through the solidified material but in the opposite direction. These patterned structures, which are difficult to fabricate using standard cleanroom practices, have very high surface to volume ratio. For example, the surface to volume ratio of 11 canyons or fjords shown in Figure 7 *a* is 78.1 μm^{-1}, whereas it will be only 1.81 μm^{-1} for a non-splitting flow pattern. Hence, these are suitable for sensing applications where large surface area is often required to improve the interaction between the sensor and the stimulus. In addition, these microstructures can be useful for surface modification and also in lubrication technologies[6]. The structural and surface features produced can be tailored by controlling current, voltage, substrate roughness, environment, etc.

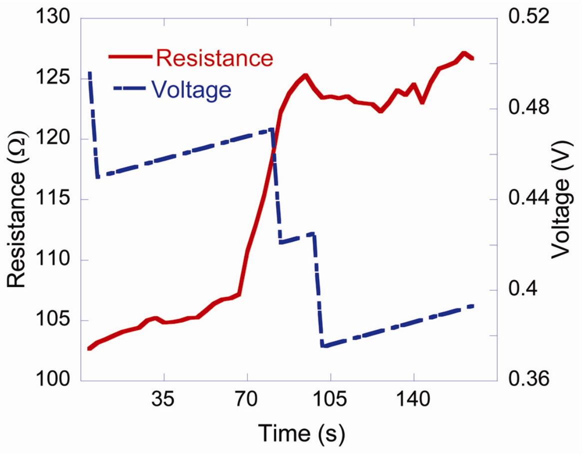

Figure 5. Variation in voltage and resistance with time for a particular device. As the resistance increased, the driving voltage was decreased in preset steps to control the current for electromigration.

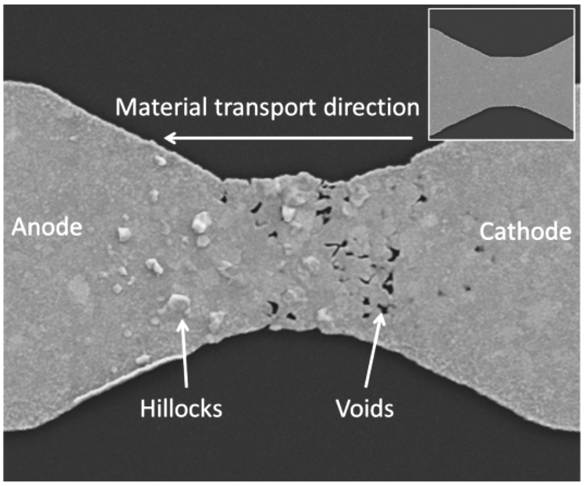

Figure 6. High magnification SEM micrograph of the notch area after electromigration. (Inset) Low magnification image of the pristine device. The voids and hillocks are mainly concentrated near the cathode and anode respectively, which is a signature of classical electromigration in solid metals.

Patterning regular nano-stairs and small beads

As mentioned earlier and shown in Figure 8 (inset), Cr compound melts around the point electrode upon application of electric current and then the liquefied material near the cathode begins to flow towards the anode in a radially symmetric fashion. Liquid Cr compound flows from the central region towards the periphery of the ring and accumulates there forming a material pile-up at the periphery[14]. When the electric current is passed intermittently, the liquefied material solidifies between two successive current loadings. Upon the next current loading, the material near the periphery or pile-up could not readily liquefy because of its higher thermal mass and relatively low current density through it. However, the liquefied material between this piled-up material and the centred electrode can easily flow over the raised region leading to formation of permanent step-marks at these locations (Figure 8)[14]. These staircase patterns, which are again difficult and time-consuming to fabricate using standard cleanroom practices, have, as mentioned earlier

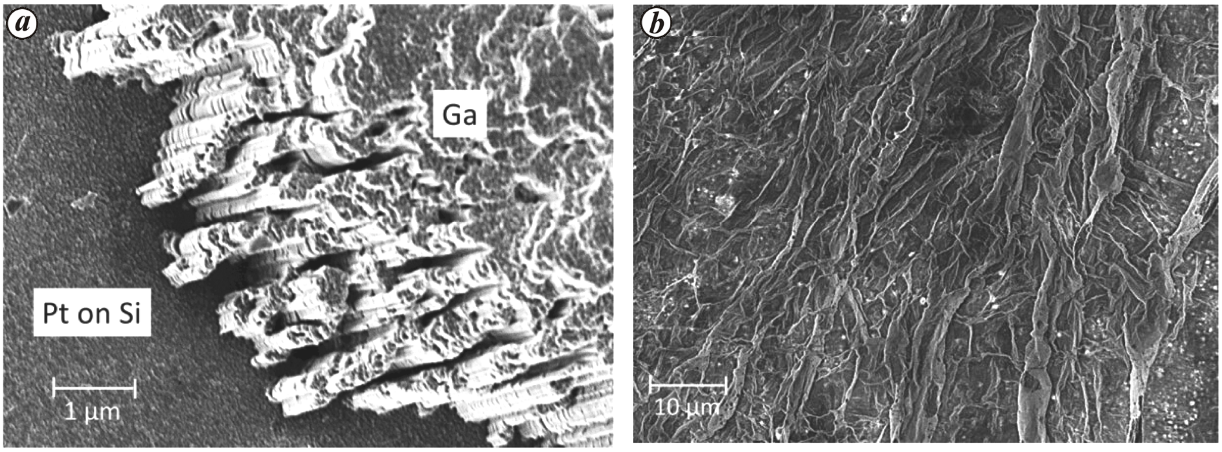

Figure 7. SEM images of the structures formed during Ga flow on Pt metal line: ***a***, 3D pattern, resembling canyons and fjords, formed at the flow front; ***b***, An array of microstructural network, resembling veins or wrinkled skin, formed in solidified Ga upon applying current in the reverse direction relative to the original flow direction of the liquid metal.

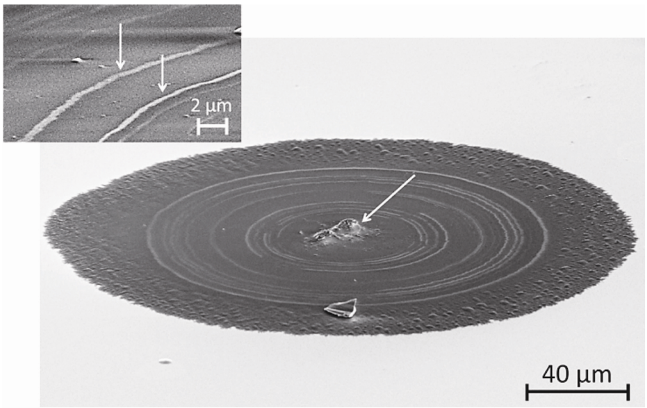

Figure 8. A representative SEM micrograph showing step formation due to intermittent electric loading. (Inset) A high magnification image of the flow-affected region. The arrow in the low magnification image show the position of the cathode, whereas arrows in the magnified view (inset) shows the steps forming stairs.

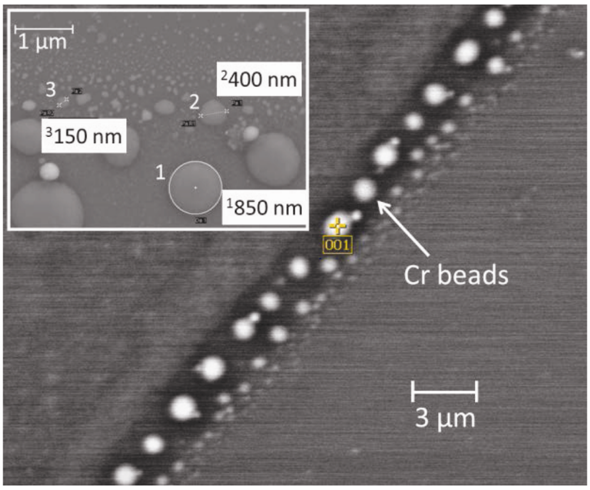

Figure 9. SEM image of a chain of Cr beads formed at the periphery of a ring formed by electromigration as shown schematically in Figure 4. (Inset) Magnified view of a few beads. The numerical values are the diameters of a few beads. The largest beads were of size 1 ± 0.2 µm, whereas the smallest beads were of size 20 ± 10 nm.

(Figure 1 *d*), interesting optical properties and can be used in different optical applications such as Fabry–Perot etalon arrays[7], photonic band-gap crystals, blazed gratings[9], etc.

As shown in Figure 9, another interesting patterned structure consisting of a chain of small metallic beads formed at the periphery of the above electromigration generated circular flow affected region. These metal beads, formed only at the boundary of the flow-affected region, vary in diameter from 20 ± 10 nm to 1.0 ± 0.2 µm. These beads can be described geometrically as half spheres, which are difficult and time-consuming to prepare using traditional lithography processes. If the beads of a precursor or appropriate catalyst metals are prepared, they can be used for growing corresponding structures, such as nano-tubes or nano-wires[3]. Beads having diameter less than 100 nm can be used for plasmonics applications[4,5].

As shown in Figure 9, bead size varies across the periphery of the flow-affected region, wherein large and small beads are observed at inner and outer sides of the periphery respectively. Furthermore, preliminary experiments have revealed that the voltage (or current density), time of passage of electric current and film thickness play an important role in determining the size and spacing between the beads. Interestingly, there was little sample-to-sample variation related to location, shape and size distribution under the same experimental conditions (i.e. time, voltage, film thickness and ambient condition), indicating deterministic or repeatable nature of these experiments as well as the resulting patterns.

The few examples discussed above covering a wide range of structures and surface features provide only a glimpse of the vast possibility where electromigration-driven material transport can be used to develop single-step, low-cost, fast techniques for fabricating complex, multidimensional structures which are difficult and time-consuming to pattern using conventional techniques.

However, this method is still in its infancy. A series of in-depth experimental studies are required to develop the fundamental understanding of how to precisely control the process parameters such as voltage (or current density), film thickness, substrate and ambient conditions, and current passage algorithm to produce a pattern of the desired shape, size, spacing, orientation and dimensionality (i.e., 1D, 2D or 3D). Along with these experiments, theoretical models incorporating electric field-driven material transport (or electromigration), temperature and phase (or state) change effects on the electromigration-driven material transport, fluid mechanics related instabilities, etc., will help in the development of suitable techniques for creating patterned structures with good control and repeatability.

Furthermore, electromigration-driven controlled material transport can proffer numerous other applications in the area of micro- and nano-fabrication and coating technologies. For example, one-dimensional liquid metal flow on conducting track can be used for developing periodic structures (S. Talukder *et al.*, unpublished) as well as maskless coating of the conducting substrate[13]. On the other hand, 2D material flow can potentially be employed for general purpose lithography for patterning user-defined structures[18].

Conclusion

Electromigration, being a directional transport phenomenon, can be used for moving a group of metallic atoms from one point to another. Solid-state electromigration causes short-range transport. However, electromigration in liquid state can cause long-range flow of materials. This short- and long-range transport of materials can be used for microstructure engineering and multidimensional pattern creation at micro- and nano-scale, such as formation of certain volume fraction of voids at predefined locations, canyons, fjord and vein structures, nano-stairs and regularly spaced metallic beads. The electromigration-driven flow of material can be precisely tuned by controlling different parameters, such as current, voltage, scheme of current flow directions, substrate roughness, film thickness, etc. Overall, the electromigration-driven transport phenomenon presents a single-step, low-cost versatile fabrication technique which can be used for patterning small sized, complex structures in 1D, 2D and 3D.

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