Reliability Failure in Microelectronic Interconnects by Electric Current Induced Chemical Reaction

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Abstract. The electric field-induced chemical reaction in Cr thin film by a micro/ nano-probe has been recently reported with detailed characterization. Although the phenomenon is employed for micro-nano fabrication, this can act as a reliability failure, where Cr is used as an adhesion layer or main interconnects in microelectronic circuits. Here, we present an investigation on the role of electric current density for such failure using a specifically designed sample. A 100 µm width and 100 nm thin Cr film is deposited perpendicular to the Pt film of similar dimensions. The anode probe (20 µm diameter) is positioned onto the Pt film, whereas the cathode probe onto the Cr film. It is observed that the chemical reaction, for an applied voltage, initiates at the edge of the Pt film and not at the cathode probe. The localized chemical reaction causes to damage the interconnection line. The analysis based on the COMSOL multiphysics simulation illustrates that the chemical reaction evolves at the high current density locations. The study also builds a fundamental understanding of the mechanism of evolution of patterning by electric field-induced chemical reactions.

Keywords. Reliability failure, Electric field-induced chemical reaction, Electromigration, Micro-nano fabrication

1. Introduction
Reliability failure due to high current density in metallic interconnections has acted as a villain in microelectronics [1]. Miniaturization of electronic devices necessitates the utilization of thin metallic films (nanometre thickness) as interconnects. Therefore, even a tiny current flowing through the circuit results in a high current density (~10⁴ A/cm²) [1]. Such a high current density leads to electromigration, where mass migrates from cathode to anode or vice-versa and the interconnection is permanently damaged [2]. The study of solid and liquid electromigration has been conducted by various researchers. Huntington presented the theoretical model of electromigration responsible for mass flow under an applied electric field [2]. K.N Tu has reported the measurement of electromigration force in Au, Ag, Cu, Al, and Pb [1]. Yang et al. have demonstrated the interconnection failure due to electromigration in Pd, Sc and Y strips [3]. They reported the current density of the order of 1 MA/cm² responsible for electromigration. Kumar et al. reported electromigration in liquid metal, wherein Cu lines are coated with a long-range continuous flow of Bi liquid [4]. We introduced a theory of liquid electromigration that explains the dichotomy (flow direction dependent on metal parameters) in the flow behaviour of liquid metals [5]. Although electromigration is a damaging phenomenon, it can be utilized in positive aspects, for example, coating, nano-patterning, and electrical nano-contacts formation [6]. More detail
on electromigration in various aspects can be found in the literatures [7–9]. Here, we report a different mechanism (other than electromigration) of reliability failure. Before going to the actual scenario, we would like to revisit the phenomenon of patterning by scanning probe tip based on electric field-induced chemical reaction [10]. Herein, a scanning probe microscope, e.g., atomic force microscope (AFM), is utilized for direct writing in metallic/ non-metallic films [11]. Figure 1 shows a ring pattern formation in a 100 nm thin Cr film by tungsten electrode probes [12]. In order to pattern the structure, first, the anode is positioned on Cr film. A potential difference of 10-20 V is applied across the probes. Now, the cathode probe is slowly touched to the Cr film in order to create the pattern. The moment, cathode tip touches the film, the high electric field at the tip-apex causes to initiate a chemical reaction at the cathode location, and chromium trioxide (CrO₃) is formed as a chemical product [10]. If the cathode probe is scanned on a given path (for example, straight lines), line or curved patterns of various dimensions can be generated [13].

![Figure 1](image.png)

Figure 1. A ring pattern formation in Cr film by electric field-induced chemical reaction with a scanning probe tip. The chemical reaction is initiated at the cathode tip.

The final developed pattern of dimensions up to 40 nm has been demonstrated by this technique [11]. Nano beads in the range of 10-40 nm have been fabricated by atomic force microscope (AFM) [14,15]. In this paper, we report an investigation to understand the role of electric current density on chemical reaction at cathode-probe in a Cr film. A simple question arises that why reaction starts at the cathode only and not elsewhere in the film. The answer lies in the current density. The configuration shown in Figure 1 doesn’t explain clearly the effect of current density. Therefore, an experiment is conducted on a specifically designed sample to understand the contribution of current density. A COMSOL simulation is also performed to verify the experimental observation.

2. Experiment
A typical sample for patterning is prepared by depositing Cr film (10-100 nm) on an insulator substrate (usually Si/ SiO₂). Here, to observe the current density contribution, we fabricated a sample by cross-depositing Cr film on a Pt line. First, a Pt line of 100 µm width and 100 nm thickness is fabricated by standard lift-off process on a Si/SiO₂ substrate. Second, the Cr film of 200 µm width and 100 nm thickness is sputter deposited on and perpendicular to the Pt line (Figure 2).

For the experiment, the anode probe is placed on the Pt line, whereas the cathode is touched on the Cr line. A constant voltage of 10 V is applied across the probes. Surprisingly, the reaction starts at the edge
of Pt-film and not at the cathode point. Figure 2 shows the time-lapse images of the chemical reaction. The video of the phenomenon is recorded by a digital microscope mounted above the sample (see supplemental material).

![Chemical reaction initialization](image)

Figure 2. Reaction initialization check with the cathode probe on a Cr film deposited on and perpendicular to the Pt line. The reaction starts (see at 5 s) at the edge of the Pt line. The Cr over the Pt-region is completely consumed and converted to CrO$_3$ at 18 s.

3. Results and discussion
COMSOL multiphysics is used to perform FEA simulations to get the distribution of the current density. A 3D FEA model having a similar geometry as the sample is constructed. The thickness of the Pt and Cr films are taken to be 1 µm for each for easier meshing. Small circular discs were chosen as the anode and the cathode points on the Pt and Cr film, respectively; the diameters of these discs are 10 µm. Free tetrahedral mesh of sizes in the range of 100-500 nm is used for the meshing. The electrical conductivity of Pt and Cr were taken to be 8.9×10$^6$ S/m and 7.9×10$^6$ S/m, respectively. Electric current module is used for the simulation.

Figure 3 shows the FEA simulation results. The electric current density is the highest at the edge of the Pt film. This is also the point where the chemical reaction is initiated. In other words, the chemical reaction is most probable at the high current density locations. The high current density location serves as a source of the electric field induced chemical reaction in Cr film.

Microelectronic utilizes the Au, Cu, and other metallic films as interconnects where Cr is also used as an adhesion layer. The reliability failure can be caused due to the chemical reaction at a high current density location. Therefore, it is suggested to avoid the use of Cr film for interconnections as it may cause chemical reaction-based reliability failure. Titanium metal could be a better choice instead for adhesion purposes.
Figure 3. FEA simulation showing the (a) distribution of current density in the sample shown in Figure 2. The red arrows indicate the current direction. The current density is high in the region between the anode and cathode. (b) Isometric views of the model, especially focusing on the edge of Pt and Cr interaction region shown in Figure 3(a). The maximum current density is observed at the turning edge of the Cr-Pt configuration. The red arrows show the current flow direction.

4. Summary
The reliability failure in microelectronic circuits caused by an electric field-induced chemical reaction in Cr film (other than electromigration) is introduced in this work. The investigation is done on a Cr film, as an interconnection, deposited perpendicular to the Pt film. An electric current is made to pass from Pt to Cr by applying a potential difference through metallic probes. The chemical reaction in Cr film is observed to be initiated at the high current density location (at the edge Pt film), and it damages the Cr film. The experimental observation is verified by COMSOL simulation, and it is identified that the high current density points act as the source of the chemical reaction. Based on the study presented in this paper, it is recommended to avoid the use of Cr film for adhesion or as a direct interconnection in micro/nano-electronic circuits.

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