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Electromigration of Copper in Lithographically-Defined Aluminum Nanowires

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Electromigration is the transport of matter by an electric current. High current densities of over 10^{10} A/m^2 in pure aluminum wires can move material to the point of failure [1]. Alloying aluminum with 4% copper has been found to increase wire lifetimes by nearly two orders of magnitude [1]. We have biased Al/Cu (96%/4%) nanowires at a current density of 2.4×10^{11} A/m^2 in a scanning transmission electron microscope (STEM). Energy dispersive spectroscopy (EDS) reveals significant movement of copper along the wire after biasing at these high current densities.

Polymer-resist patterns of 150 nm width and 1 µm length were exposed with e-beam lithography, and aluminum films containing nominally 4% copper by weight were e-beam evaporated on to electron-transparent silicon nitride windows. Devices were annealed in a reducing atmosphere for 30 minutes at 480 ºC to evenly disperse the copper though the wires. After annealing, the nanowires were milled with a helium-ion beam to remove excess silicon nitride membrane and narrow the wires to a 30 nm width (Fig. 1A). The cross section of our nanowires is a rectangle of 30 nm width and 100 nm height.

These nanowire samples were biased in a JEOL JEM-2100F using a biasing holder. EDS maps of a nanowire were acquired before and after 10 minutes of biasing at a current density of 2.4×10^{11} A/m^2. Biasing moved copper towards the anode, in agreement with previous results [2, 3]. Comparing the line profiles (Figure 1B) distilled from the before and after EDS maps, we see that copper accumulated near a macroscopic defect in the wire (Figure 2A). Away from the accumulation point, the concentration of copper did not change significantly. Imaging with dark-field STEM (Figure 2B, 2C) shows no voids in the adjacent aluminum. This result confirms that, within this alloy, the copper is more mobile than the aluminum for a given current density [4].

We have observed electromigration of copper in nanoscale aluminum-copper alloys under high current densities. Copper accumulation implies a divergence in ion flux. Modeling the ion current density using the Nernst-Einstein equation [3, 5] shows that a temperature gradient leads to a divergence in ion flux. These wires are thermally sunk to room temperature at the contacts, which places the largest temperature gradients away from the center of the wire. Thus this model may explain the location of the copper accumulation point.

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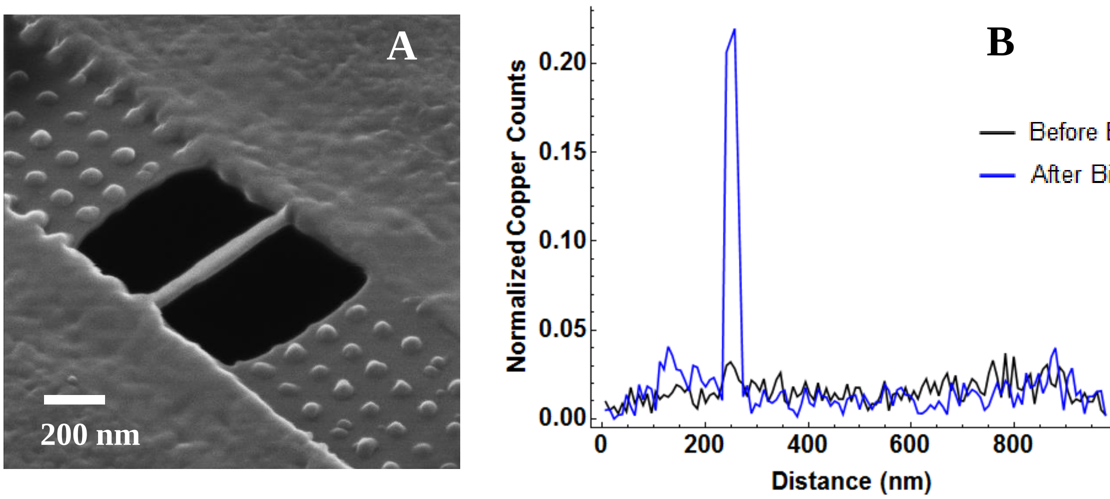

Figure 1. A) Tilted-SEM image of a helium-ion milled wire. The nitride support film and some alloy islands surrounding the Cu/Al alloy wire have been removed by milling. **B)** EDS copper profiles along the wire axis before and after biasing. A large spike in copper counts appears after biasing. Copper counts are normalized to aluminum counts since the aluminum count rate was unchanged.

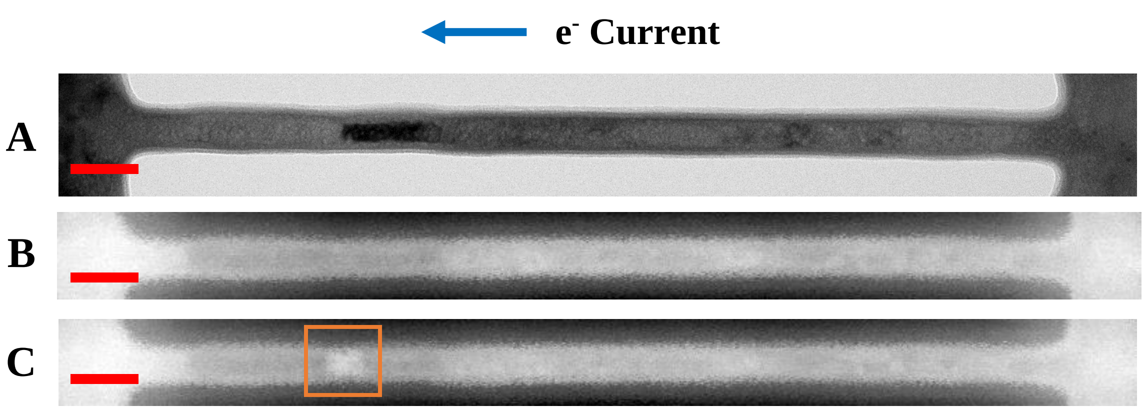

Figure 2. A) BF STEM image of an Al/Cu nanowire before biasing. The macro-scale defect where copper later accumulates is clearly visible. **B)** DF STEM image of the same nanowire before biasing. **C)** DF STEM image of the nanowire after biasing. A mass appeared near the macro-scale defect (indicated by an orange rectangle), and is identified as copper by EDS analysis. Scale bars are 50 nm.

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