Observation of Current Crowding near Fabricated Voids in Au Lines

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Abstract

The spatial variation of current density in lines with model void defects fabricated using Focused-ion Beam (FIB) milling has been imaged using Magnetic Force Microscopy (MFM). At current densities of 3-4$\times10^6$ A/cm^2, an asymmetry in the MFM signal is clearly visible at (1$\times$1) μm^2 and (0.5$\times$0.5) μm^2 notches at the edge of a 10μm wide line. Comparison to a simple model calculation suggests that the asymmetry is due to current crowding, with the displaced current 70% localized to within 1μm of the notch.

PACS: 68.37.Rt, 66.30.Qa, 07.79.Pk, 85.40.Ls, 85.40.Qx, 61.72.Qq

Electromigration [1-3] is the directionally biased mass transport of metal atoms under the influence of applied electric fields. This mass transport can result in the formation of defects, such as voids and hillocks, that are a major cause of interconnect failure in integrated circuits. It is believed that the localized current crowding around the voids leads to a positive feedback cycle that further induces void growth and line failure [4, 5]. Evaluation of current crowding has been performed using numerical simulations, based on structural evolution observed using Scanning Electron Microscopy (SEM) [2]. Since voids are generally sub-micron in size, there is presently no adequately-resolved method of direct current density measurement around the void. The only experimental technique with sufficient spatial resolution is Magnetic Force Microscopy (MFM), which measures magnetic field curvature which in turn can be used to deduce current density variation. Here, we report on the observation of anomalous asymmetry in MFM signal that we believe is due to current crowding.

Experiments were performed using a Digital Instruments Multimode, operated in tapping (intermittent non-contact) and standard phase detection mode. The signal detected is the curvature of the magnetic field component perpendicular to the sample plane. The magnetic tips used are commercially available Co/Cr coated Digital Instruments MESP tips and Silicon-MDT MSC12 tips, magnetized along the tip axis, perpendicular to the sample surface.

The samples used for this study were fabricated using a combination of standard photolithography/liftoff and focused-ion beam (FIB) milling techniques. A blank template of the sample design, with the potential-nulling mechanism previously discussed [6, 7], was created on thermally grown SiO_2 by photolithography and liftoff, followed by thermal evaporation of 10nm Cr and 100nm Au. Notches of sizes $1\mu m\times 1\mu m$ and $0.5\mu m\times 0.5\mu m$ were fabricated on the edge of the $10\mu m$ wide metal line by FIB milling [8]. Ion milling was performed with 50 kV Ga^+ ions using a Micrion 2500 FIB machine with a 5 nm beam column. A serpentine beam scanning procedure and relatively low (~30 pA) ion current were chosen to provide a better notch shape.

MFM measurements were made with typical currents in the individual lines of about 33mA, corresponding to current densities on the order of $3\text{-}4\times 10^6 A/cm^2$. To exclude topographical artifacts, the MFM phase measurements were performed in Interleave Linear Lift Mode [7, 9], using lift heights ranging from 200nm to 300nm.

A tapping AFM image and the corresponding MFM phase image for the $1\mu m\times 1\mu m$ notch are shown in Figure 1. Given the vertical tip magnetization, there is MFM contrast only at the line edges where the magnetic field must curve into or out of the sample plane. There is significantly higher contrast at the notch edge than at the line edge on the side opposite the notch. The bold gray line profile in Figure 2, averaged over a $0.5\mu m$ segment (12 out of 512 line scans) along the notch center, shows high asymmetry in the

MFM peak heights. As a reference for comparison, the thin line profile of Figure 2, which shows the signal averaged along a 0.5μm segment away from the notch, has the typical symmetry of a line with uniform current density. This reference profile was used to determine the non-uniform background, which was fixed by requiring that the reference line peaks have identical heights. After background subtraction, the asymmetry in the peak heights at the notch is found to be 1.5. Using the same commercial tips, a similar asymmetry can be seen at notches as small as 0.5μm×0.5μm, as shown in Figure 3. In this case, the ratio of peak heights is about 1.2-1.3.

In the presence of a uniform current density, the MFM signal at the line edges must be symmetrical. This behavior is observed for lines of constant width [6, 10] and in the present lines for measurements away from the notch. Our sample design incorporates a potential-nulling mechanism which eliminates any electrostatic interaction. The phase data is taken at a significant lift height above the sample surface to ensure the absence of any topographical interaction. We have previously shown that our MFM phase measurement excludes non-magnetic interaction [6, 7] and can thus be certain that the asymmetry is a completely magnetic effect. Asymmetry in the MFM peak heights thus indicates a non-uniform current distribution.

To determine whether the observed asymmetry can be explained by current crowding, comparisons of the data have been made with a very simple model calculation. These calculations involve integrating the magnetic field contributions of infinitesimally thin, infinitely long wires over the cross sectional area of conductor segments. To introduce the effect of current crowding, these wire segments were given increasing current densities as they approach the notch. The curvature of the vertical component of the magnetic field was then calculated and convolved with an estimated instrumental phase response [6] to account for tip dimensional effects. For our calculations, five conductor segments were used, four of width 2μm and one of width 1μm. Calculations using current densities with constant or gently-increasing gradients yielded asymmetries about 20% lower than observed. A current density distribution that is much more localized to the notch, as shown in the inset bar graph of Figure 4, yields an asymmetry, shown in the curve of Figure 4, more consistent with what was observed. This particular current distribution puts about 70% of the current displaced by the 1μm notch into the 1μm adjacent segment and yields a calculated asymmetry of 1.5. We thus conclude that the observed asymmetry in the MFM signal is consistent with a highly localized current crowding effect and is qualitatively similar to the numerical analysis of Artz et al [2, 11].

In summary, we have observed anomalous asymmetry in the MFM signal, believed to result from current crowding, around a 1μm×1μm notch in a 10μm-wide current-carrying line. Comparison of a simple model calculation with the data suggests that the current crowding is localized, with 70% of the displaced current within 1μm of the notch edge. Further quantification of the current crowding will require numerical calculations which are in progress. The asymmetry can be seen in notches as small as 0.5μm×0.5μm.

Pushing the limits of measuring spatially variable current densities will involve fabrication of smaller defect structures and development of magnetic tips with higher spatial resolution.

The authors would like to thank Tom Loughran, at the Engineering Clean Room at the University of Maryland, in College Park. This work has been supported by the NSF-Materials Research Science and Engineering Center under grant DMR-00-80008.

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Figure Captions

FIG. 1. 20μm×20μm image of a 10μm line with a 1μm×1μm notch on one side. This line is carrying a 33mA current, corresponding to a 3.3×10^6A/m^2 current density. Left: AFM topography (z-range: 350nm). Right: Corresponding MFM phase measured with 200nm linear lift height (z-range: 1.0 deg).

FIG. 2. The bold gray line shows an MFM scan measured perpendicular to the line and across the notch center, averaged over a 0.5μm segment (12 out of 512 line scans) from the right image in Figure 1. The thin dark line shows an MFM reference scan averaged along a 0.5μm segment away from the notch, from the right image in Figure 1.

FIG. 3. 20μm×20μm image of a 10μm line with a 0.5μm×0.5μm notch on one side. The line is carrying a 35mA current, corresponding to a 3.5×10^6A/m^2 current density. Left: AFM topography (z-range: 400nm). Right: Corresponding MFM phase measured with 300nm linear lift height (z-range: 2.5 deg).

FIG. 4. Bottom inset bar graph: model current density profile along the conductor width, normalized to the base uniform current in a normal, homogenous line. Top curve: calculated MFM signal at the notch center, using the current density distribution shown in the inset. The calculated peak asymmetry is about 1.5.

Figure 1

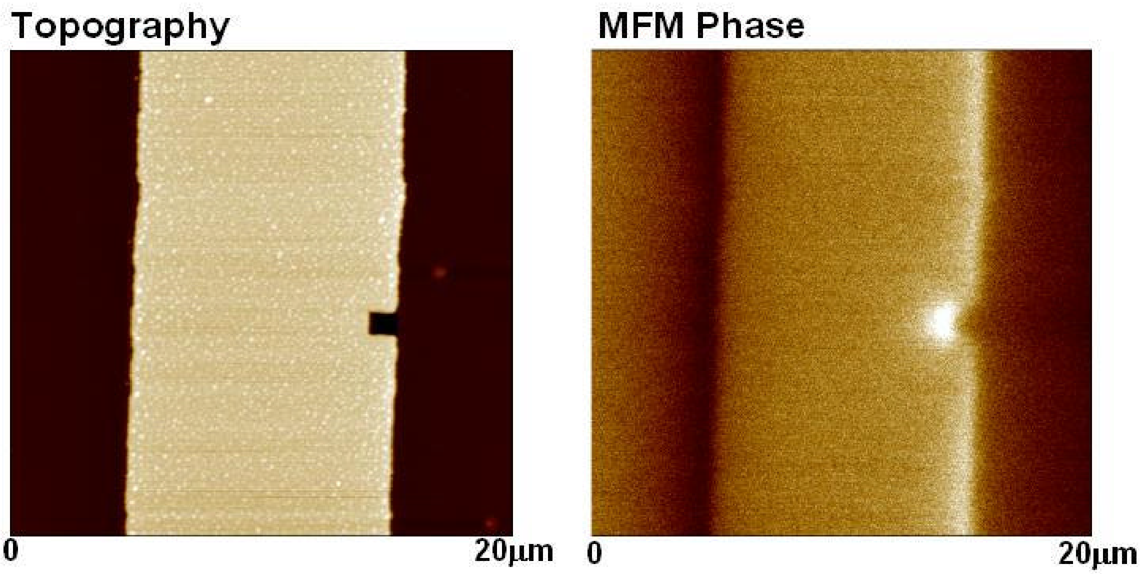

Figure 2

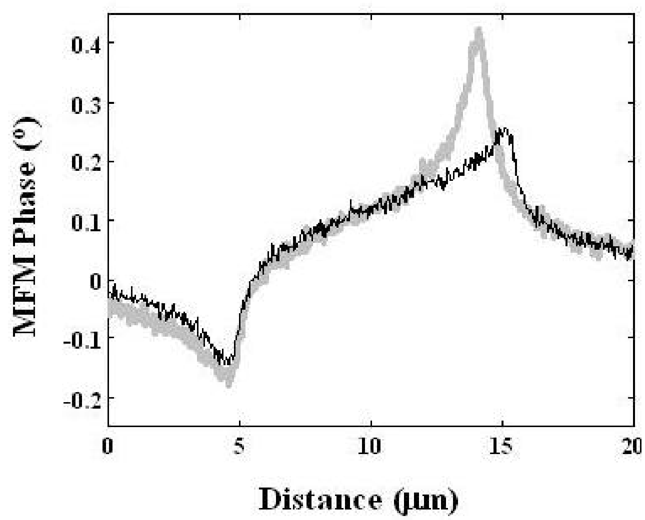

Figure 3

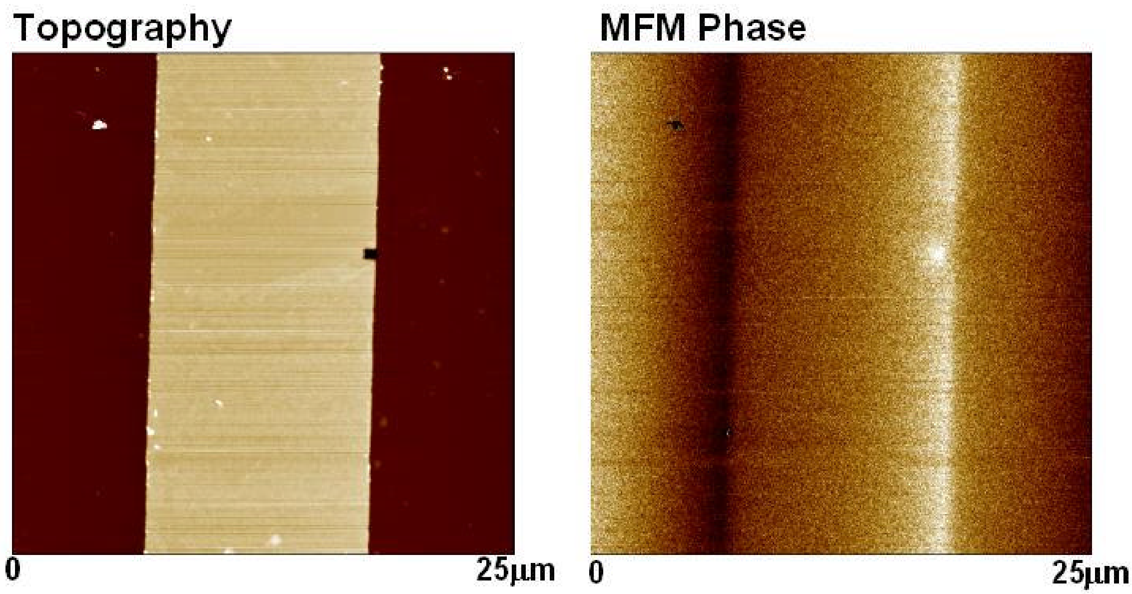

Figure 4