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| **ESRF** | **Experiment title:**<br>In situ measurement of strain profile in Al-Cu interconnect lines during electromigration | **Experiment number**:<br>ME-334 |
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## Report:

Mechanical stress related failure of metal interconnect lines in integrated circuits is an important reliability problem. The electromigration (EM) process - movement of conductor atoms due to high density electrical currents - influences the stress in metal lines. EM causes stress changes by accumulating atoms in certain regions, and depleting them in others. This process creates stress gradients, which cause atomic flow opposing the electromigration. These two effects can balance each other under certain conditions effectively stoping the EM damage. This effect has been experimentally observed [1] and analytically modelled [2]. However there has been only a few measurement of this stress gradient due to the difficulties of stress measurement with such high (1-10 µm) spatial resolution [3-5]. In this experiment we developed and applied a novel approach that brings together x-ray topography and imaging with advanced x-ray optics. In this way we made real time measurements of stress variations along a line during the EM process.

The x-ray topographic technique is based on measurement of the strain induced in the single cyrstalline Silicon substrate by the stress in the overlying thin Aluminum wire. While proven to be immensely useful in practice, conventional x-ray topography imposes certain limitations on the experiment. These are mainly the limited working distance due to the close proximity of the detector and the sample; diffraction blur in the image due to the finite distance between the sample and the detector and finally the one-to-one geometry which demands same resolution on the detector as the feature size to be resolved. Our Imaging X-ray Topography technique schematically shown in Figure 1 overcomes these difficulties by introducing an x-ray lens into the diffracted beam path. The lens images the intensity distribution from the diffracting volumes and therefore removes bluring introduced by finite diffraction angles. In addition, this geometry allows magnification of the image and so overcomes the limitation due to the detector resolution.

We prepared the samples at the Paul Scherrer Institut. Al thin film lines were patterned on Si (100) wafers using standard microfabrication techniques. The stack consisted of $SiO_2/Ti/Al/Si_3N_4$ (100/15/500/500nm) layers. EM experiments are normally conducted in the 175-300$^{o}$C temperature range. This presented a challenge in our *in situ* x-ray topography experiment which required the sample to remain fixed within a few microradians during the length of the experiment to maintain a stable Bragg reflection from the Si substrate. Bulky heater stages may cause too much drift to satisfy this condition. Therefore we used a new approach by patterning integrated tungsten heaters on the chip itself. This allowed heating the sample with excellent temperature control and mechanical stability , using only minimal power. An environmental chamber was placed over the sample to minimize temperature fluctuations due to air convection.

The sample was aligned for the Si(400) Bragg reflection from the substrate at 8 keV photon energy. A Fresnel Zone Plate (FZP) was placed in the reflected beam, which formed a four-times magnified image of the sample in the detector plane. Apertures were placed at appropriate places along the beam path to block the zeroth order undiffracted light from reaching the detector. A high-density electrical current is passed through the sample line, which is held at an elevated temperature. The strain due to the electromigration process influences the underlying substrate lattice. These distortions were imaged over time to follow the

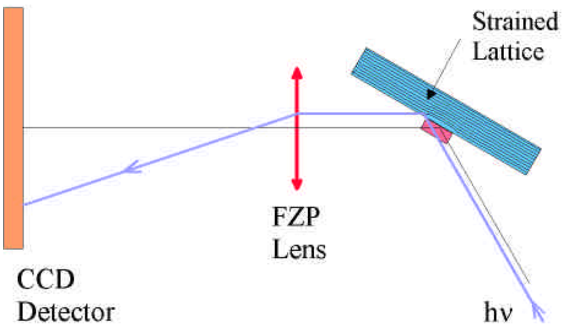

**Fig. 1:** Si (400) Bragg reflected x-rays from the sample are imaged onto a detector surface by an FZP lens.

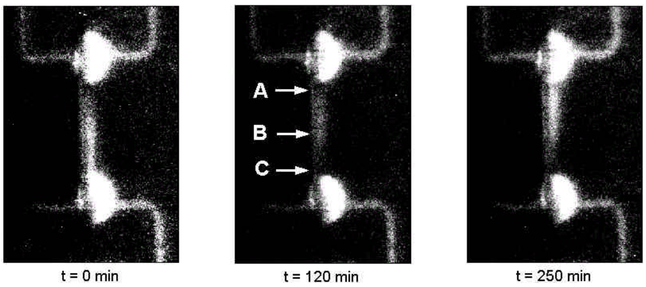

**Fig. 2:** Evolution of stress in an Al interconnect line due to electromigration. The stressed area moves upwards towards the anode end. The two bright round areas are due to the strong stress created by tungsten contacts at the two ends of the line.

evolution of the process. The 500µm diameter FZP had zones as fine as 80 nm wide etched into a Ge film providing ample spatial resolution [6]. The large lens size and narrow outerzone width were essential in obtaining a high magnification factor within the physical constraints of the experimental hutch as well as a large field of view. Typical image acquisition times were 30-300 seconds.

The contrast in the images depended strongly on the angle of incidence on the sample with respect to the Si (400) diffraction curve. We chose a setting that was slightly off the maximum to optimize the stress contrast. Figure 2 shows three images of a 50 µm long 2 µm wide line obtained at three distinct stages of the electromigration process. The first image was acquired after electron flow in the top to bottom direction has already created a strain concentration in the lower half of the line. Following two images show the same sample after the current flow direction was reversed. After the reversal the strained area moved gradually upwards as seen in the second and third images respectively. Figure 3 shows profile of intensity along the line as a function of time clearly showing the gradual reversal of the stress gradient.

To the best of our knowledge this is the first time changes of stress in interconnect structures due to EM were imaged in real time with a full field imaging system. A previous study with a scanning micro-beam system required long (4hr) data acqusition times to obtain full field images [4]. Our result confirms the theory that predicts the formation of a stress gradient that effectively stops EM damage in an interconnect.

Perhaps as important as the specific results is the fact that we have developed a tool with which we can make systematic studies of the electromigration process in real time. Detailed studies of the phenomenon should reveal influences of many factors such as current density, temperature, line width and length, microstructure, and material composition. With the development of imaging topography technique one can now think of x-ray topography experiments at much lower energies than before since the blurring effect of diffraction is removed by the imaging lens.

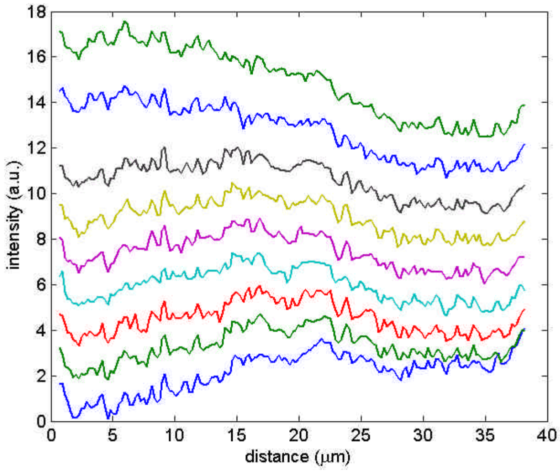

**Fig. 3:** Profile of Si(400) diffracted x-ray intensity along the line at different times during the EM test. The curves are calculated from images acquired at 25minute intervals in the order from the bottom to the top.

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[1] I. A. Blech, J. Appl. Phys. **47**, 1203 (1976).

[2] M. A. Korhonen, P. Borgesen, K. N. Tu, and C. Li, J. Appl. Phys. **73**, 3790 (1993).

[3] H. H. Solak, Y. Vladimirsky, F. Cerrina, B. Lai, W. Yun, Z. Cai, P. Ilinski, D. Legnini, W. Rodrigues, J. Appl. Phys., **86**, 884 (1999).

[4] P.-C. Wang, I. C. Noyan, S.K. Kaldor, J. L. Jordan-Sweet, E. G. Liniger, and C.-K. Hu, Appl. Phys. Lett. **76**, 3726 (2000).

[5] A. A. McDowell, R. S. Celstre, N. Tamura, R. Spolenak, B. Valek, W. L. Brown, J. C. Bravman, H. A. Padmore, B. W. Batterman, and J. R. Patel, Nuc. Inst. & Meth. In Phys. Res. A, **467-468**, 936 (2001).

[6] C. David, B. Kaulich, R. Barett, M. Salome, J. Susini, Appl. Phys. Lett. **77**, 3851 (2000).