X-ray Microbeam Characterization of Cu wires

Recent progress in large-scale integrated circuit (LSI) technology has been remarkably fast. Rapid progress made in the storage capacity of dynamic random access memories (DRAMs). Improvement in the performance of microprocessors (MPUs) is widely recognized. The International Technology Roadmap of Semiconductors [1], which forecasts future trends in the worldwide development of fabrication technology for semiconductor devices, indicates that the minimum feature size of an MPU will be 25 nm and the chip frequency will reach around 7 GHz by 2007, as shown in Table I.

Year of production	'03	'05	'07	'16
DRAM half pitch (nm)	100	80	65	22
MPU gate length (nm)	45	32	25	9
Chip frequency (GHz)	3.09	5.17	6.74	28.7

Table I. *Roadmap about main issues in semiconductor device technology (ITRS 2001).*

As explained in the Roadmap, various new materials and techniques are being introduced into the fabrication processes. Copper interconnect technology [2], first introduced by IBM, is the best example. To achieve a higher performance and more reliable MPUs, copper was introduced as a new material instead of the conventional Al alloy. Copper has lower electric resistivity and a longer lifetime than Al. Copper, however, is very difficult to pattern using conventional subtracting methods like plasma etching. An alternative patterning method used now is the "damascene" method. Here, Cu is deposited in trenches that form nanometer-sized electric circuits.

Such dramatic changes in both materials and patterning methods require tremendous research efforts to understand the interconnect technology. To produce high-performance devices, we must physically understand the reasons of certain failure phenomena, such as interconnect breakdown, occur. For example, Cu atoms in the fine lines migrate due to a strong "wind" of electrons, and this generates voids and hillocks in the metal lines (Fig. 1(a)). This is called electromigration (EM). A second example concerns the mechanical

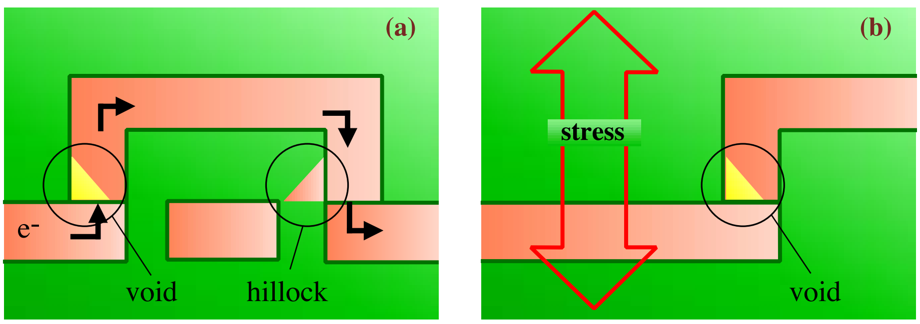

*Fig. 1. Interconnect failure mechanism. **(a)** Electromigration (EM). Strong electron "wind" blows Cu atoms. **(b)** Stress migration (SM). Stress gradient causes migration of Cu atoms.*

environment where stress distribution in interconnects causes voids to form. This is called stress migration (SM) (Fig. 1(b)). These atomic migrations are serious problems for the reliability of MPUs. Crystallographic grains and grain boundaries of Cu metal lines greatly affect the migrations. Consequently, the status of grains must be studied microscopically.

Measurement techniques used in the study of interconnects are scanning electron microscope (SEM), transmission electron microscope (TEM), and X-ray diffraction (XRD) measurements. SEM and TEM have excellent spatial resolutions, but, unfortunately, they cannot see the metal lines buried in dielectric materials in actual chips. Conventional XRD measurement provides precise data about strain in thin films, but its spatial resolution is around several tens of microns, even in the most sophisticated apparatus. To observe the the microscopic and the crystallographic status of fine metal lines without any destructive sample preparations, a new measurement technique is required.

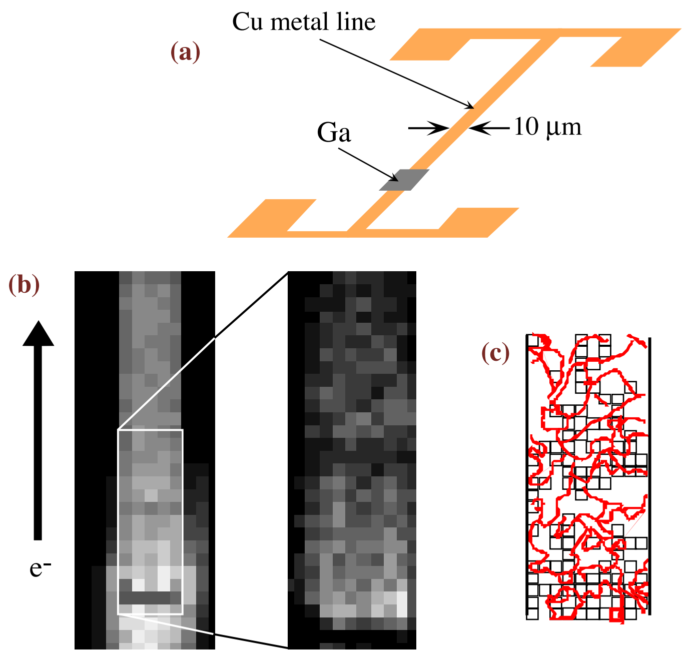

*Fig. 2. Experiment for observing Cu atom migration paths. **(a)** Initial distribution of Ga atoms. **(b)** Gallium distribution after current loading. **(c)** Coincidences between grain boundaries and the Ga distribution.*

An X-ray microbeam is a promising tool for such a purpose. The X-ray microbeam can penetrate thick dielectric materials, and scanning with the microbeam provides a microscopic image of the metal lines buried in the dielectric layer. Moreover, by using the X-ray microbeam, an X-ray micro-diffraction measurement [3] can be taken to measure the strains of the grains in the fine metal lines. We are currently studying physical mechanisms of interconnect failure using X-ray microbeams of 1 µm, which are available in the SUNBEAM beamline **BL16XU**.

Figure 2 shows the preparation and results of the experiment we conducted to observe Cu atom migration paths. Because there was no distinction between migrating Cu atoms and atoms in Cu grains, direct microscopic observation of Cu migration paths has not been done previously. This experiment was the first attempt at observing Cu migration paths by means of tracer atoms. We distributed Ga atoms locally before current loading and observed the redistribution of the atoms due to EM. Figure 2(b) gives the results of Ga X-ray fluorescence (XRF) mapping, obtained by X-ray microbeam scanning, and shows Ga atom distribution after the current was turned off. Figure 2(c) shows both the points of high Ga concentration and the grain boundaries to illustrate the coincidences between grain boundaries and the Ga distribution. This method thus reveals the diffusion paths of Cu, and should be useful when developing the fabrication processes for high-resistance interconnects against EM failure.

Figure 3 shows the microscopic X-ray diffraction experiment. The inset photograph shows diffracted X-ray spots from a 0.3-µm Cu damascene line

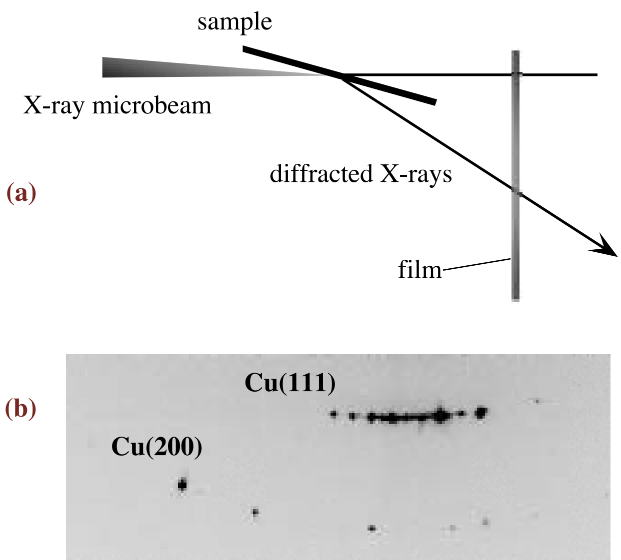

*Fig. 3. X-ray diffraction experiment using X-ray microbeam. (**a**) Experimental setup. (**b**) Diffraction spots from 0.3 µm Cu interconnect.*

irradiated with an X-ray microbeam. The diffraction angles on individual grains at the local area can be estimated from the positions of these spots. Detailed analysis of these spots provides information on the strain state of the individual grains in the metal line. As the stress gradient of the grains is a driving force of SM, these microscopic crystallographic measurements should become important tool for understanding the mechanism of stress migration.

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