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Thermal fatigue as a possible failure mechanism in copper interconnects

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Abstract

Microelectronic devices experience thermal cycles with amplitudes as large as 100 K during normal use. Differences in the thermal expansion coefficients of the different materials comprising the device lead to strain changes during thermal cycling. We demonstrate here that cyclic thermal strains lead to surface damage formation and failure in copper lines during the application of an alternating electrical current. The presence of soft coatings like photoresist on the Cu lines does nothing to inhibit damage formation in the copper lines. Thus, thermal fatigue of Cu interconnects may be a serious reliability threat to devices containing soft interlevel dielectric materials.
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Keywords: Fatigue; Alternating current; Metal interconnect; Passivation

1. Introduction

With every new generation of integrated circuits, the interconnects are placed under more extreme conditions, including larger mechanical stresses, higher current densities, and higher temperatures. Due to the ever-increasing demands on performance, Al-based interconnects are now being replaced with Cu-based interconnects and silicon-oxide-based dielectric layers are now being replaced by compliant materials with low dielectric constant. These changes alter the mechanical integrity of the devices and may lead to new reliability problems.

We discuss in this paper a possible new threat to the reliability of chip-level interconnects, namely mechanical fatigue due to cyclic thermal strains. Such cyclic thermal strains are induced by time-varying power dissipation in the interconnects or elsewhere in the device. Evidence that imposed thermal cycles can lead to damage in unpassivated wide Al interconnects was presented in a study performed 30 years ago [1] as well as more recently in narrower Al and Cu interconnects [2–5]. Here, we present observations on both passivated and unpassivated Cu interconnects and show that extensive damage and electrical failures can occur under typical device operation conditions both with and without the presence of a soft coating. It is argued that hard coatings inhibit the formation of this damage and that microelectronic devices made with soft interlevel dielectrics may be much more susceptible to failure from fatigue than devices with rigid dielectric layers.

2. Experimental details

10 nm thick Ta/200 nm thick Cu lines with 8 μm width on $Si/SiN_x/SiO_2$ wafer were fabricated using conventional micro-fabrication methods, including e-beam lithography, Cu sputter deposition, and lift-off [3,4]. Then the samples were annealed for 15 h at 400 °C in vacuum ($< 10^{-6}$ mbar), to allow for grain growth. In order to investigate the effect of passivation layers on the formation of surface damage, a 0.6 μm thick photoresist layer was spun on some of the structures and baked at 210 °C for 60 min.

The grain size and microstructure of the annealed Cu structures were characterized by scanning electron microscopy (SEM) with backscattered electron imaging and focused ion beam microscopy. The mean Cu grain sizes were determined using the linear intercept method as 1.3 ± 0.5 μm and extensive twinning was observed in all samples. Crystallographic texture of the Cu films was investigated using $\theta - 2\theta$ X-ray diffraction

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and electron backscatter diffraction. The structures showed strong <111> and weak <100> out-of-plane texture components, with randomly oriented in-plane orientations.

Thermal fatigue testing of the structures was conducted in situ in a scanning electron microscope. The basic idea behind the method, described in detail elsewhere [3,4], is that alternating electrical currents are used to generate cyclic temperatures and thermal strains in the Cu lines. The Joule heating resulted in temperature increases in the Cu line and the underlying Si which were monitored during testing using time-resolved 4-point resistance measurements [4]. The samples were attached to a probe stage using silver paint and electrical contacts were made to the bonding pads with 4 probe needles. Sinusoidal voltages with frequencies of 100 Hz and 10 kHz were applied to the structures (DC offsets of several mV) resulting in rms current densities from 10 to 40 MA/cm^2. The Joule heating resulted in temperature changes in the Cu line which were monitored during testing using time-resolved 4-point resistance measurements. For example, an rms current density of 22 MA/cm^2 at 10 kHz generates temperature cycles with a range (ΔT) of roughly 130 °C at a frequency of 20 kHz. The total strain range is approximately given by thermal strain $\Delta\varepsilon = (\alpha_{Cu} - \alpha_{Si})\Delta T$, where $(\alpha_{Cu} - \alpha_{Si})$ is the difference between the Cu and Si thermal expansion coefficients [4].

3. Results and discussion

Fig. 1 shows damaged regions at the surfaces of Cu lines after they were subjected to 1.73×10^5 cycles at $\Delta T = 215$ °C and 100 Hz. In situ SEM observation showed that the damaged regions grew in severity, density, and lateral extent during testing. They formed along the length of the Cu lines but were more extensive and severe in the middle of the lines (see inset of Fig. 1), presumably because this region experienced somewhat larger temperature swings [3,4]. Within many of the damaged regions, clearly defined and regularly spaced surface extrusions were found, which are similar to those which develop due to irreversible slip at the surfaces of mechanically fatigued fcc metals [7]. Eventually, failure occurred due to localized resistance increases and a catastrophic electrical open, due to localized melting at the very end of the test.

The observed damage is generated by thermal fatigue, not by electromigration. A pure alternating current signal is not expected to lead to electromigration damage under these conditions, due to the very short atomic diffusion length in each cycle [6]. This has been demonstrated conclusively in an experiment where surface damage formed in a Cu line that had been subjected to temperature cycles without passing a current [3,4].

EBSD analysis revealed that the damage was localized within single grains and was different for the <111> and <100> out-of-plane oriented grains [3–5]. Fig. 2 shows typical damage morphologies of <100> and <111> out-of-plane oriented grains. The left images showed early stages of damage formation and the right images show later stages. For both grain orientations, damage first appeared as surface wrinkles near twin and grain boundaries and then spread to fill the grain. The damaged <100> grains then grew to consume neighboring grains and often reached sizes comparable to the line width (Fig. 2(a)). The grain boundaries were facetted along <110> directions. Compared to the damage morphology in the <100> grains, the <111> grains showed no evidence of growth during testing and the wrinkles had larger amplitudes and spacings and were less regular (Fig. 2(b)).

In order to investigate the effects of the applied strain range and the presence of a soft coating on the formation of surface damage, tests were run on both uncoated and coated (hard-baked photoresist) Cu lines for various applied temperature ranges. After the test, the photoresist was dissolved using acetone and the Cu surfaces were observed by scanning electron microscopy. Fig. 3(a) shows the applied strain range (and temperature range) vs. cycles to failure for both samples. The number of cycles to failure decreases with increasing applied strain, which is typical fatigue behavior. No difference was observed between the uncoated and coated samples. The extent of damage at failure can be described in terms of the

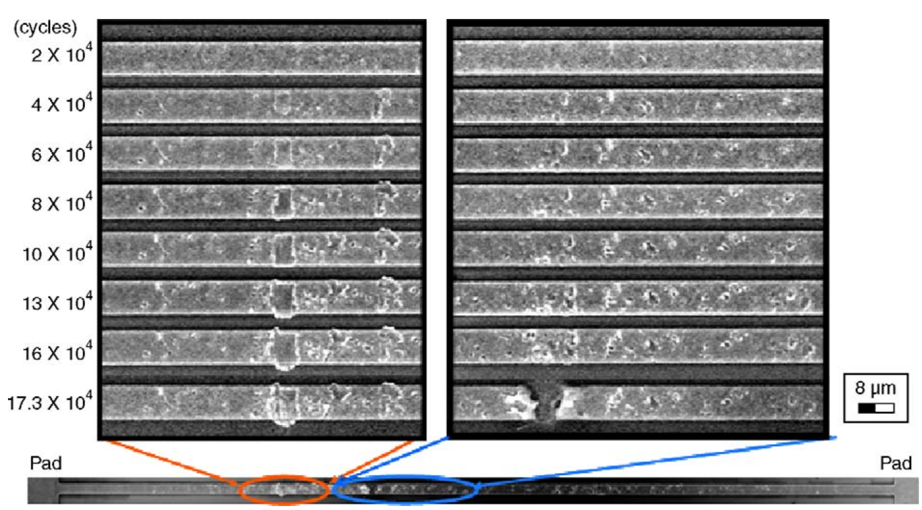

Fig. 1. Scanning electron microscope images of the evolution of damage in a Cu line subjected to 1.73×10^5 cycles at $\Delta T = 215$ °C and 100 Hz. The upper images show regions of severe damage including the failure site. The inset at the bottom shows the entire line.

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