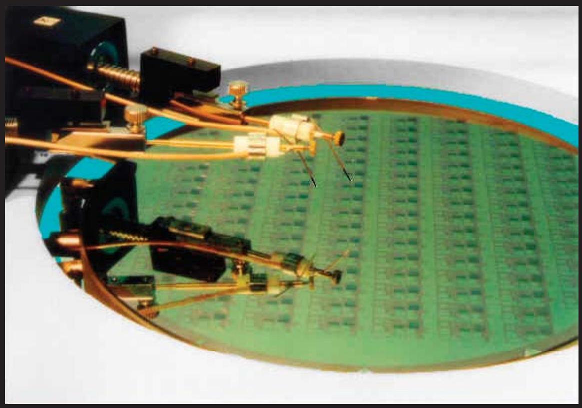
Thin Film Reliability

SEMICONDUCTORS

Objective

Our goal is to develop new ways to evaluate the reliability of thin films and interconnects in their as-manufactured states. Such tests are particularly important for nanoscale structures, where extrapolation of bulk properties is largely inaccurate. To generate fatigue *in situ*, we apply controlled alternating currents which, in turn, generate thermo-mechanical stress. This method can be applied to advanced integrated circuits, discrete devices, optoelectronic components, and sensors.

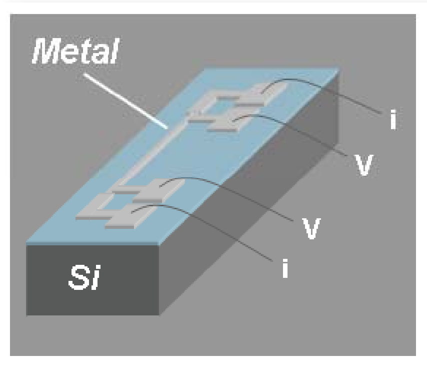


Impact and Customers

- Semiconductor products represent a global market of more than $250 billion per year. As semiconductor devices become ultra miniaturized, reliability testing becomes increasingly challenging as direct access to specific materials is extremely difficult.
- Testing *in situ* is highly desirable as materials experience considerably different stresses when incorporated into a device than when fabricated as an isolated, idealized test specimen. Providing data in as close to real-world conditions as possible will enable product designers to better balance performance and reliability.
- Reliability data for new materials are critical during the design and development phases of device manufacture. In the past year, we have worked with Freescale, Intel, and Novellus on specialized measurements to quantify the effects of process variations on performance, illustrating the importance of novel metrologies during the development process.

Approach

High-performance devices, such as microprocessors and memory chips, are typically composed of structures of specific dimensions and geometries and are made up of various materials, all in close proximity in a three-dimensional system. Material interactions lead to reliability issues such as fracture, delamination, fatigue cracking, and void formation. To measure material response in such complicated systems, we have developed an electrical method to determine the properties of these materials *without the need for special specimens*.



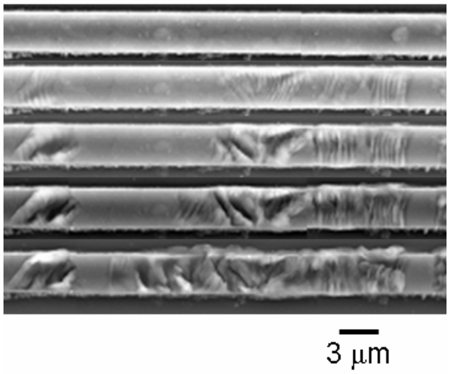
Our test applies controlled joule heating via a 4-point probe system. Conditions are such that electromigration does not take place; rather, heat is generated and dissipated in each power cycle. Cyclic thermal strain is induced, allowing for determinations of fatigue lifetime and estimates of strength. Whereas tests that directly measure force-displacement response are restricted to certain specimen geometries or limited to surfaces, the electrical approach can evaluate extremely narrow lines, including those buried beneath other materials. We have validated our method using aluminum, gold, and state-of-the-art damascene copper lines and vias.

Accomplishments

Application of low-frequency alternating current to a film on a substrate results in cyclic thermal straining of the film. We have made significant strides in understanding the materials science associated with this phenomenon in order to confirm its validity as a reliability test. We have also demonstrated its applicability to industrially relevant structures.

Materials Science

Rapid thermal cycling due to a.c. stressing can cause severe damage to patterned films, as seen in the figure, obtained from a cycled non-passivated aluminum line.



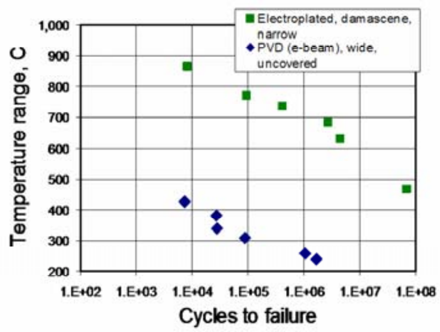
Damage evolution due to thermal cycling

Electron microscopy showed that damage arises from dislocation activity, specifically the development of surface topography by formation of intrusions and extrusions. Continued cycling eventually leads to open circuit failure, as selected regions become so seriously damaged that they can no longer sustain current flow.

This result showed that an electrical method can indeed be used to perform thermal cycling, which is a common product qualification test used by the electronics industry. Advantages of the more localized test include easier isolation of root failure causes, significantly faster testing, and lower energy consumption.

Reliability Tests for Industry

These processes result in overall cyclic lifetime behavior strongly resembling classic S-N curves (stress vs. cycles to failure) in metal fatigue. As cyclic deformation depends heavily on interactions with any neighboring material, such as those in a complex interconnect architecture, we initiated studies on oxide-passivated damascene copper lines supplied by a semiconductor tool supplier. We found that these fully constrained lines also exhibited S-N-like behavior, as shown in the figure, but withstood much higher temperatures and stresses than those shown by non-passivated lines. This result showed that not only is an electrical method for measuring reliability feasible for industrial structures, it can distinguish material quality differences arising from different processing methods.



Fatigue lifetimes for copper

Our work on cyclic behavior also led to a new method for estimating strength of patterned thin films on substrates. We directly compared this new method with a more established method, microtensile testing, to further validate the utility of the electrical approach.

By extrapolating S-N data back to a single load reversal, we estimated the ultimate strength of a film while it remained attached to its substrate. A comparison between this method and microtensile testing resulted in values for ultimate strength that agreed within experimental uncertainty. This result suggested that multiple forms of mechanical reliability can be measured electrically through a single series of tests.

Output and Customer Engagement

Our work on electrical test methods represents a dramatic leap forward in the development of size-appropriate metrologies for assessing reliability of not only thin films and interconnects, but nanomaterials in general. In an effort to disseminate our methods to a diverse set of industrial and academic customers, we conducted two workshops on nanomaterials, published numerous articles detailing our test methods, taught a short course to industry conference attendees, and presented numerous keynote and invited talks on our work.

Learn More

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Publications

Keller RR, Barbosa III N, Geiss RH, Read DT, *An electrical method for measuring fatigue and tensile properties of thin films on substrates*, Key Engineering Materials 345-346: 1115 (2007)

Barbosa III N, Keller RR, Read DT, Geiss RH, Vinci RP, *Comparison of electrical and microtensile evaluation of mechanical properties of an aluminum film*, Metallurgical and Materials Transactions 38A: 2160 (2007)

Keller RR, Geiss RH, Barbosa III N, Slifka AJ, Read DT, *Strain-induced grain growth during rapid thermal cycling of aluminum interconnects*, Metallurgical and Materials Transactions 38A: 2263 (2007)

Mönig R, Keller RR, Volkert CA, *Thermal fatigue testing of thin metal films*, Review of Scientific Instruments 75: 4997 (2004)