

Application Note #1539

Mechanical Characterization of Ultra Low-k Dielectric Films

Dielectric materials are of critical importance in the function of microelectronic devices because they electrically isolate conductive components from one another in microcircuits. Capacitance between conductors can limit a circuit's maximum operating frequency, and the capacitance increases in inverse proportion to the separation distance between the conductors. Therefore, to minimize the size of a microelectronic device and maximize its operating frequency, the device's components must be separated by a material with a dielectric constant as low as possible. A class of materials known as ultra low-k (ULK) dielectrics are employed for this purpose. Every significant semiconductor node change requires the successful integration of a new generation of higher porosity, lower k materials. However, there is a significant trade-off between mechanical properties and electrical properties for low-k materials. The incorporation of nanometer-scale pores to decrease k typically results in decreased strength, stiffness, and adhesion of the deposited films. Therefore, monitoring mechanical properties of ULK films in a semiconductor production process is critical to ensuring that the device will survive and yield a consistent, reliable finished product. This application note discusses how mechanical reliability monitoring of ULK films is becoming increasingly important to rapidly identify process variation and sustain high device yields; and how nanoindentation and nanoscratch testing provide an ideal means to measure the hardness (strength), modulus (stiffness), and critical scratch force (adhesion) of these critical films.

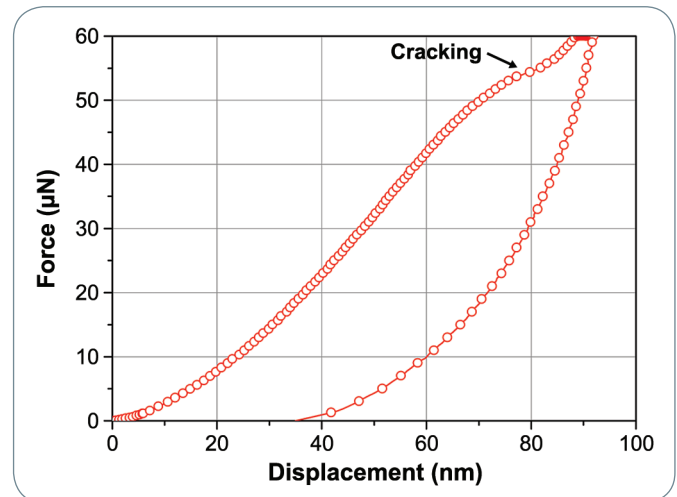


Figure 1. Representative force-displacement curve from an indent on a ULK film.

Nanoindentation Testing

Nanoindentation testing of ULK films is accomplished by forcing a diamond pyramidal probe into the film to a specified force, holding the force for several seconds, and then withdrawing the probe. Force and displacement are measured continuously throughout the test, providing the basis by which the material's hardness and modulus can be calculated.¹ Figure 1 shows an example of a force-displacement curve collected from a test on a ULK film with 200 nm thickness. A cube-corner geometry was employed due to acute geometry, which allowed it to penetrate through a thin, relatively dense skin layer on

the surface of the ULK film, probing the properties of the film's interior. If the indent is too deep, however, the measurement is affected by the properties of the silicon substrate. The best measurement of the film's properties is achieved when the indent depth is just beyond that required to penetrate through the surface layer.²

Nanoindentation, due to its small scale, allows for highly localized characterization of a material's mechanical properties. In addition, when nanoindentation tests are performed in arrays, it can also be used to create maps of mechanical properties of larger surface areas. Bruker's Nanomechanical Metrology Tool (NMT) series of instruments are designed specifically for nanomechanical testing in process control applications. The translation stage of the ATI 8800 (Figure 2) handles silicon wafers up to 300 mm diameter, and provides sufficient range to reach any area on the wafer.



Figure 2. Bruker's ATI 8800, fully automated nanomechanical metrology tool for 24/7 wafer process monitoring.

The ATI 8800 can be used to perform a number of tests in a pre-determined area of a wafer to check for inter-wafer process variability or for mapping mechanical properties over a selected area. In this case, a series of 1,884 nanoindentation tests were performed to determine the homogeneity of a ULK film's mechanical properties over the entire surface of a 300 mm wafer (Figure 3). The mechanical property maps created by performing the array of tests revealed that hardness and modulus varied by ~10 to 15% across the surface of the ULK film.

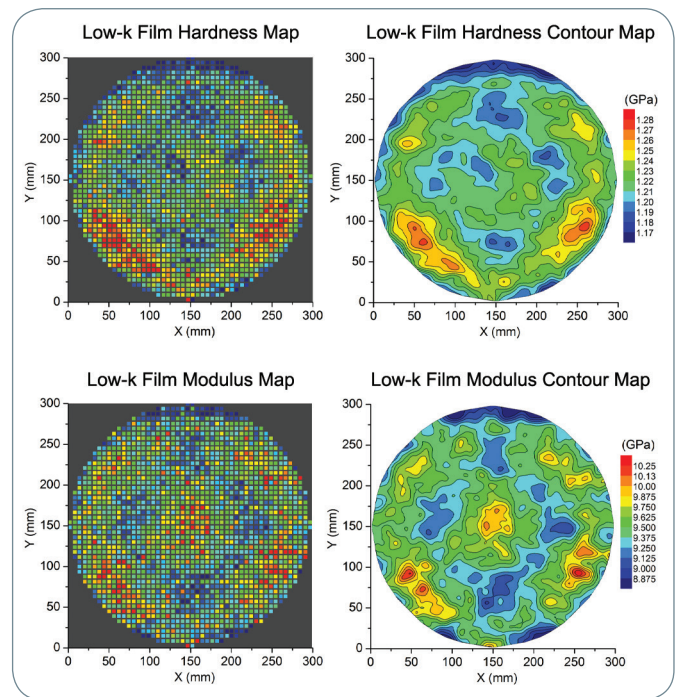


Figure 3. Results from 1,884 nanoindentation tests on a 200 nm ULK film, showing a property variability of 10 to 15% due to non-uniform processing conditions.

Nanoscratch Testing

Nanoscratch tests were performed to measure the ULK film's adhesion to the underlying substrate. Each scratch test was performed by moving the probe laterally (in the plane of the wafer) a distance of 10 μm while concurrently ramping the normal force from 1 to 1500 μN . The probe used for the tests was a diamond 90° conospherical probe with a 1 μm radius of curvature. As the normal force increases in a scratch test, the probe sinks deeper into the material, increasing the lateral force and placing increasing stress on the film/substrate interface. At a certain applied stress, the film delaminates from the substrate, and the delamination event is evidenced in the data as a sudden decrease in lateral force combined with an increase in normal displacement. The normal force at delamination is recorded as the critical normal force and is used as a measure of the interfacial delamination load or interfacial failure load of the film (see Figure 4). The instrument's in-situ SPM imaging capability was used to capture a topographical image of scratches at different points in the test to confirm that the initial critical event corresponds to film delamination while the much larger event that follows is due to film spallation. It is therefore important that the instrument used to perform such tests be able to accurately detect the relatively subtle onset of delamination as opposed to the much more obvious film spalling event.

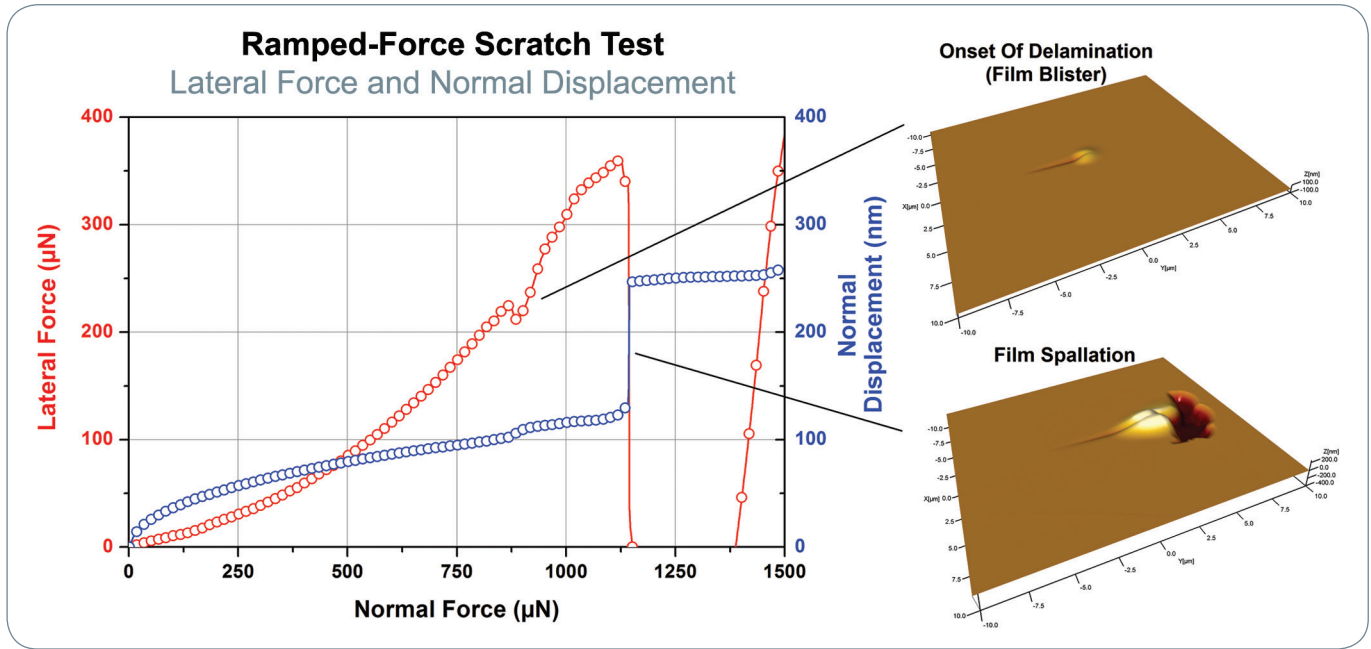


Figure 4. Representative data from a nanoscratch test showing how the critical load was determined.

A set of 1,884 nanoscratch tests was performed on the wafer to map the ULK film's interfacial adhesion over the surface. As Figure 5 shows, significant variation in film adhesion from one side of the wafer to the other was revealed, and over most of the wafer, the adhesion was clearly lower within ~20 mm of the wafer edge.

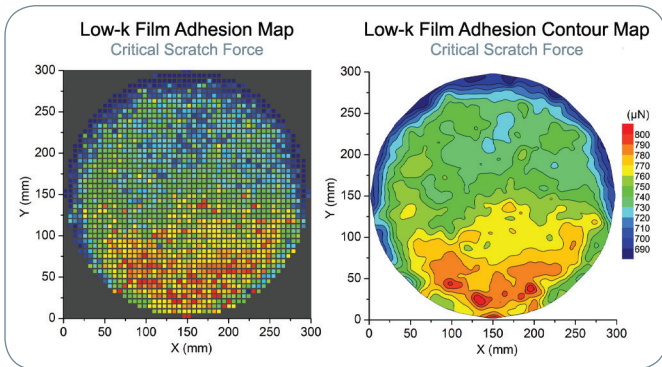


Figure 5. Results of 1,884 scratch tests on a 200 nm ULK film, showing adhesion variability due to non-uniform processing conditions.

Conclusions

As the above discussion shows, today's top nanomechanical metrology systems are uniquely capable of helping semiconductor manufacturers accurately balance the mechanical, adhesion, and electrical properties of ULK dielectrics. As nodes continually advance, instruments such as Bruker's ATI 8800 can ensure device reliability and non-interrupted production yield.

References

1. W.C. Oliver and G.M. Pharr, *J. Mater. Res.*, 7, 1564 (1992).
2. R. Nay et al., *Microelectronic Engineering*, 75, 103-110 (2004).

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Contact Bruker for additional information about the NMT series and ATI 8800.