

# Surface Watch

## Generating High-Speed, Full-Wafer Maps of Surface Microroughness

Andy Steinbach, Alexander Belyaev, Becky Pinto, David Chen, Sanda Radovanovic, Gordana Neskovic, Hamlyn Yeh, Albert Wang, Jien Cao, Juergen Reich, Dan Kavaldjiev, Prasanna Dighe, Rahul Bammi, Louis Vintro, David Bloom – KLA-Tencor Corporation

In an environment where nanometer and sub-nanometer surface topography variations have important ramifications for device performance, a new application of light scattering can provide angstrom-sensitivity, full-wafer maps of microroughness variations at speeds of tens of wafers per hour. These maps correlate strongly with atomic force microscope (AFM) measurements at discrete points. Process window characterization for grain size of interconnect films and unprecedented bare substrate microroughness characterization are now possible, as well as excursion monitoring and process control based on surface topography.

Previously, surface scattering was viewed mainly as a noise source for optical wafer inspection, a limiting factor in particle detection sensitivity. At best, wafer manufacturers and their customers used surface scattering measurements called ‘haze’ as a simple, single-value representation of surface quality, to accept or reject wafers. However, with the proper architecture and processing, an enhanced version of haze called ‘microhaze’ can divulge a wealth of information that is valuable for process development, and may even be used for process monitoring.

A new product called SURFmonitor™ has been designed, which leverages the system architecture of KLA-Tencor’s Surfscan SP2™ unpatterned wafer inspection system to deliver surface-scattering data at unprecedented sensitivity. The measurement sensitivity of this system can be applied to detect changes in surface roughness for various surface types. Sub-angstrom changes in root-mean-square (RMS) surface roughness can be detected for smooth front-end-of-line (FEOL) substrates and films. Excursions in grain size of rough interconnect films such as Cu, W, and polysilicon can be monitored using this technology. This article presents experimental microhaze data for a Cu film, confirming the theoretically predicted functional relationship of microroughness and scattering theory with a very high correlation coefficient.

The ability to effectively measure surface roughness variations over the entire wafer surface that were previously undetected, or detected only with long measurement times or over very small sampling areas, overcomes current sensitivity and throughput barriers to topographic process window characterization in development, and topographic process window control in production.

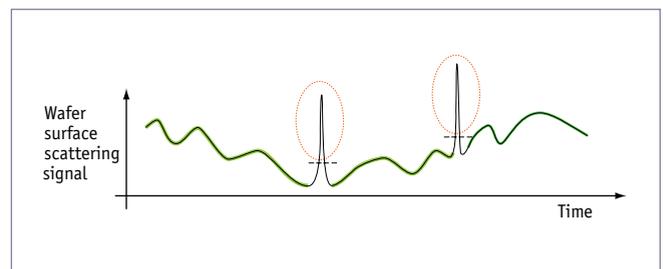


Figure 1: Wafer surface scattering signal as a function of time. Sharp peaks represent localized defects, or LPDs. The background signal represents scattering from the surface on which the defects are found. LPDs can be separated from background scatter, or haze, by applying a threshold.

### Measurement Principles

The Surfscan SP2 scanning surface inspection system works by scanning a laser spot over the surface of a wafer with either normal or oblique incidence, and then collecting the scattered light into a narrow or wide collection channel. From that scattering signal, both light point defects (LPDs) and haze can be extracted. Figure 1 shows a simplified means for distinguishing an LPD from haze, by applying a threshold. The LPD information is used to generate a map of localized defects—the predominant information gathered from a system of this sort.

The haze portion of the signal is often regarded as nuisance when localized defects are the aim of the measurement. As a result, grazing-angle systems with sophisticated algorithms were designed to suppress haze.<sup>1</sup> Soon wafer manufacturers and their customers discovered that haze maps also contain

important information, because haze correlates with surface roughness. However, the value of haze information has been limited by lateral resolution and sensitivity, by the lack of haze standards, and by the visible wavelength employed by most unpatterned surface inspection systems.

To address these limitations and make best use of the information contained in the haze signal, SURFmonitor was developed to provide a haze map of unprecedented resolution, at UV wavelength.

These microhaze maps show surface-roughness, contaminants, residues, film morphology, and even film-thickness variations.

The relationship between haze and surface roughness is summarized here, and can be examined in more detail by consulting the literature<sup>2-6</sup>. To begin, RMS roughness,  $\sigma$  (or sometimes  $R_q$ ), is most simply described as:

$$\sigma = \lim_{L \rightarrow \infty} \frac{1}{L} \left( \int_{-L/2}^{L/2} [z(x) - \langle z \rangle]^2 dx \right)^{1/2} \quad (1)$$

where  $L$  is the distance over which the measurement is taken,  $z(x)$  is the set of heights of data points collected at distances  $x$ , and  $\langle z \rangle$  is the average height. This definition works very well when comparative measurements are limited to one type of measurement system, such as a profiler or an AFM, and measurement parameters (such as scan size and tip radius) are held constant. However, when the intention is to compare widely different systems—in this case a scanning surface inspection system with an AFM—a more general treatment of surface roughness is warranted.

Every wafer surface comprises a continuum of features, with lengths (or spatial wavelengths) ranging from the distance between atoms to the size of the wafer. Equivalently, each surface can be described by a spectrum of spatial frequencies,  $PSD(f)$ .

In this nomenclature, the RMS roughness for a given measurement system can be obtained by integrating the PSD as follows:

$$\sigma = \left( \int_{f_{min}}^{f_{max}} PSD(f) df \right)^{1/2} \quad (2)$$

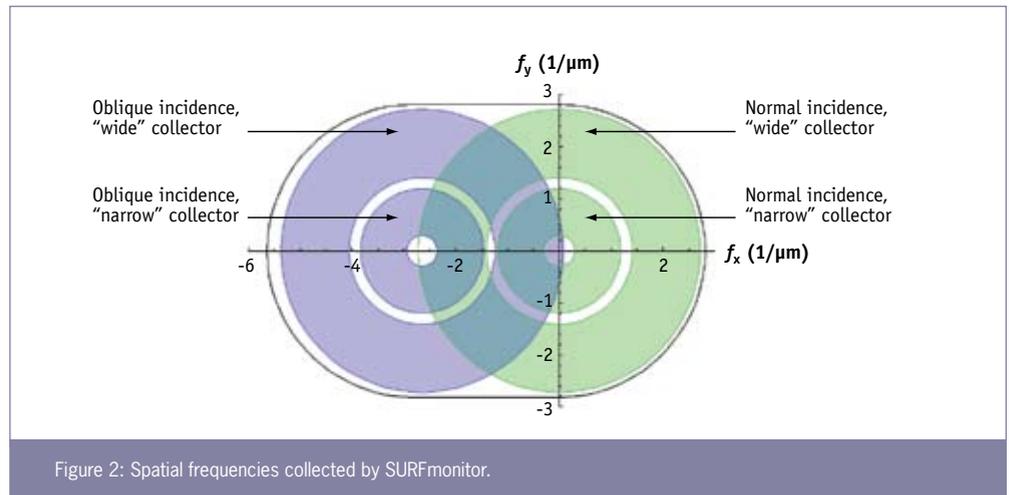


Figure 2: Spatial frequencies collected by SURFmonitor.

where  $f_{min}$  and  $f_{max}$  describe the limits of the instrument used to measure the RMS roughness. (A one-dimensional description is presented for simplicity, but without loss of generality. In reality, one would integrate in two dimensions.)

For a scanning surface inspection system,  $f_{min}$  and  $f_{max}$  can be found by relating the scattering angles to the spatial frequency through the grating equation:

$$f = \frac{\sin(\theta_s) - \sin(\theta_i)}{\lambda} \quad (3)$$

where  $\theta_i$  and  $\theta_s$  represent the angles of incident and scattered light, and  $\lambda$  is the wavelength of the light. In particular, the spatial frequencies encompassed by the SURFmonitor system are shown in figure 2. Note that four collection subsystems are given: *normal-wide*, *normal-narrow*, *oblique-wide*, and *oblique-narrow*. These correspond to different optical configurations of the system. Each has a unique spatial bandwidth.

On the other hand, a surface profiler or an AFM has a lower frequency limit equal to the inverse length of the scan,

$$f_{min} = \frac{1}{L} \quad (4)$$

and an upper frequency limit given by the Nyquist criterion as

$$f_{max} = \frac{1}{2d} \quad (5)$$

where  $d$  is the sampling distance or the minimum resolution of the system, whichever is larger. (This work involves taking relatively large AFM scans, so  $d$  is the sampling distance.)

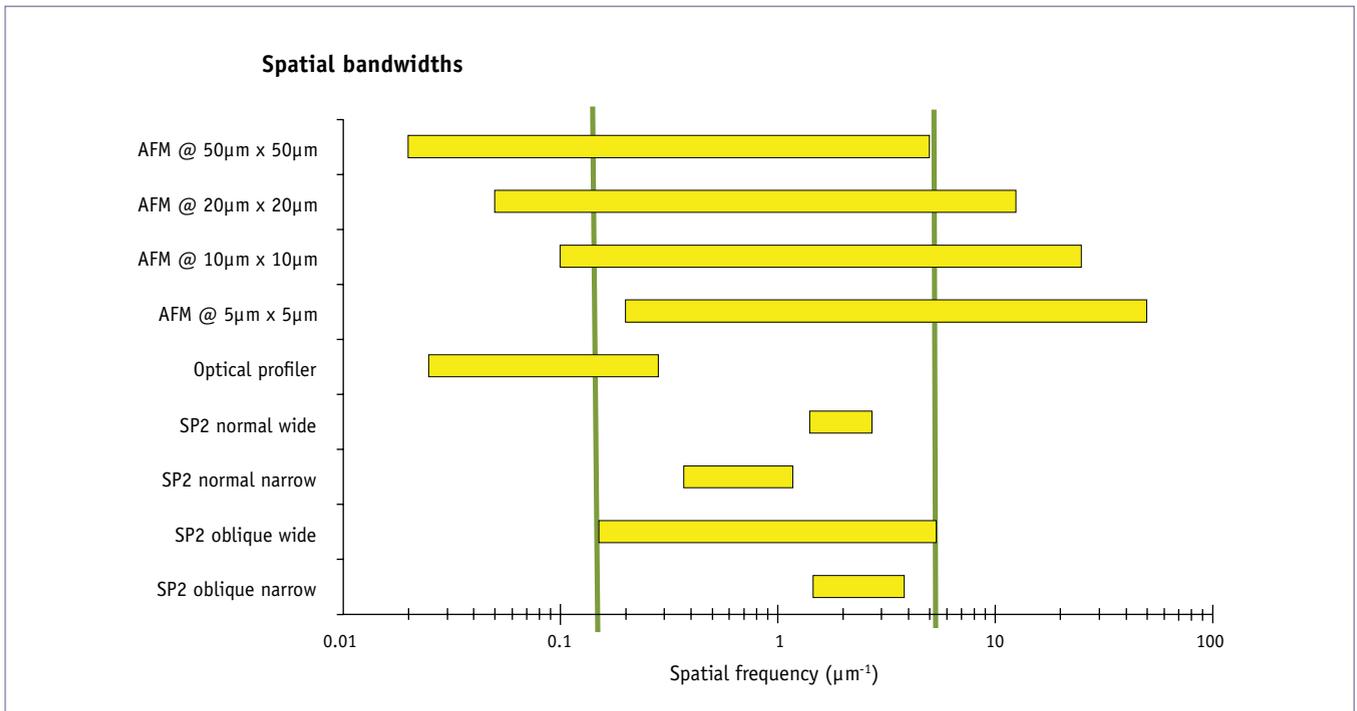


Figure 3: Comparison of the spatial frequencies encompassed by the SURFmonitor and the AFM, showing significant overlap, especially with the SURFmonitor oblique-wide channel.

Thus the spatial bandwidth of the AFM measurement will depend upon the scan size and the number of data points sampled per scan line.

Comparing the spatial frequencies encompassed by the SURFmonitor and the AFM (a Park Scientific Instruments M5™), figure 3 shows significant overlap, especially with the oblique-wide channel of the SURFmonitor. However, RMS roughness measurements by the two systems will correlate best when the data of both instruments are filtered to comprise the same spatial bandwidth—that is, when the integration limits of Equation 2 are equal. The green vertical lines in the figure indicate a possible band-pass filter, to compare the oblique-wide channel of the SURFmonitor with a 10mm or 20mm scan of the AFM.

The relationship between haze,  $H$ , and RMS roughness,  $\sigma$ , is given by

$$H = \left( \frac{4\pi \cos(\theta_i)}{\lambda} \right)^2 \cdot R_0 \sigma^2 \quad (6)$$

where  $R_0$  represents the specular reflectance of the surface, and is a function of  $\lambda$ ,  $\theta_i$ , and polarization of the incident light. Haze, then, varies as the square of the RMS roughness.

For a given surface inspection system ( $\lambda$ ,  $\theta_i$ ,  $\theta_s$  and polarization

held constant), the haze measurement should correlate well with the RMS roughness given by an AFM, as long as the two data sets are corrected by the appropriate band-pass filter, to equalize their spatial frequency ranges.

### Surface Microroughness Measurements

Several simplifications have been made in the preceding discussion. First, we have assumed that the collection of scattered light by the system optics is 100% efficient. In truth a roll-off near the band-pass edges will occur, but this will not have a large effect on the results. Second, we have assumed that surface height variations are small with respect to the wavelength of light—the definition of microroughness, and a condition that is likely well satisfied by any bare or blanket-film wafers we might consider, given that the SURFmonitor uses a wavelength of 355nm. Third, we have assumed that haze arises solely from microroughness effects. A counter example would apply if the system measures material transparent to UV radiation, such as most dielectric films. If the beam penetrates the top surface and reflects from underlying defects or interfaces, the haze measurement will include contributions from sub-surface scattering or thin-film interference effects, not just from microroughness. This kind of haze can also be exploited for process control, and our experiments with using this system to monitor film-thickness variations and detect residual material will be explored in future publications.

To ensure best success in correlating microroughness with microhaze, for our first experiment we chose a wafer that would be as immune to complicating effects as possible: a clean Cu film. At 355nm, the penetration depth of copper is less than 15nm, so haze ought to be a function of only the Cu film topography. In addition, this wafer shows an unusually large variation in grain size across its surface.

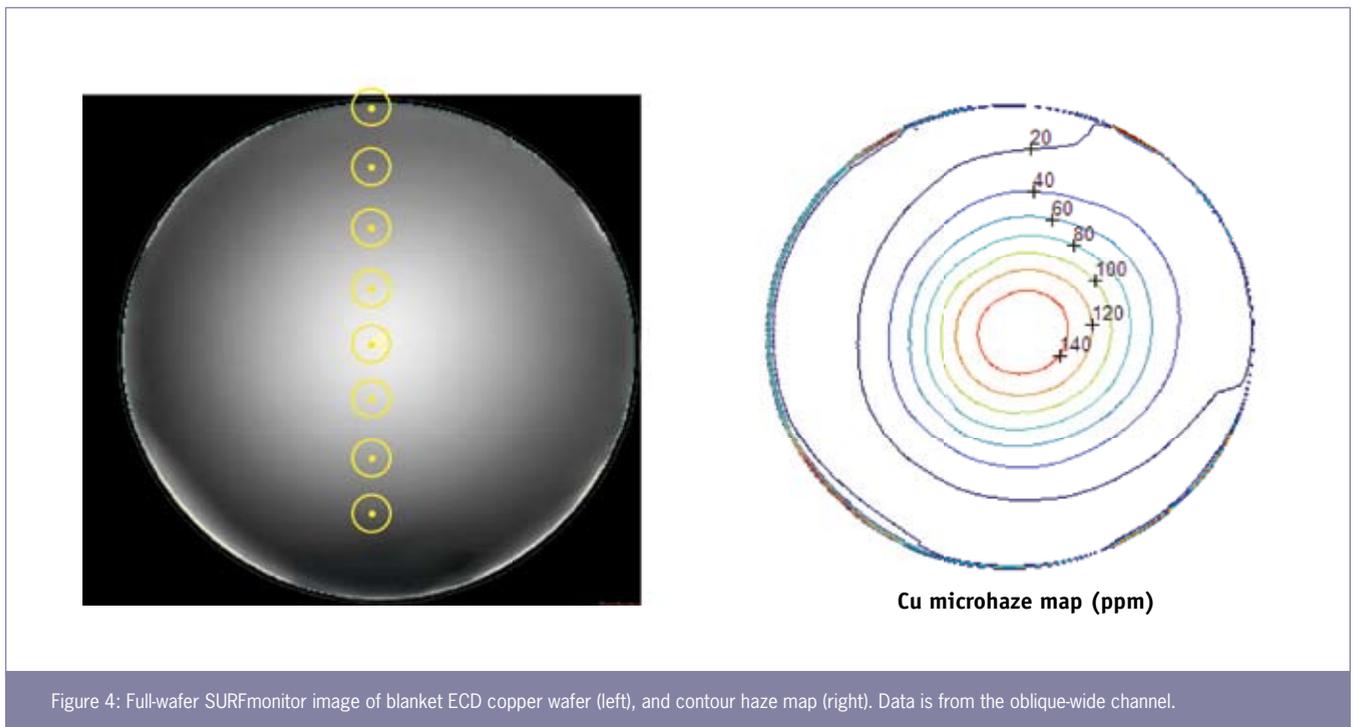
We then calculated ‘frequency-matched’ RMS roughness values from these PSDs, i.e. corrected to match SURFmonitor spatial bandwidths (using equation 2, with frequency values from figure 2). Figure 6 compares the resulting microroughness values derived from the AFM data, with the haze values measured by the normal-wide channel of the SURFmonitor. Note that no fitting parameters are used. The red ‘theory’ points are microhaze values predicted from equation 6, based

## A full-wafer microroughness map allows engineers to monitor a process for grain-size excursions and thus ultimately ensure consistent device performance.

Figure 4 shows the full-wafer SURFmonitor image of the Cu film wafer, a data set that can be collected at a throughput of tens of wafers per hour, including overhead for wafer handling. Circled points on the image indicate locations where eight AFM scans were taken. Figure 5a presents three representative AFM scans, showing significant variation in RMS roughness arising from grain size differences. We calculated PSDs from these scans and the others indicated on the wafer map in figure 4. The PSDs are given in figure 5b, with spatial bandwidths of the SURFmonitor optics overlaid.

on the frequency-limited AFM data. The green ‘experiment’ points are actual SURFmonitor microhaze measurements at locations where AFM measurements were taken. Note that both the theoretical and experimental data agree well with a common best-fit line—which has a slope of 1.98, very close to the predicted value of 2.

In figure 6 the experimental data show some scatter, which we hypothesize can be attributed primarily to AFM measurement error, such as tip convolution effects<sup>7</sup>. We can conclude



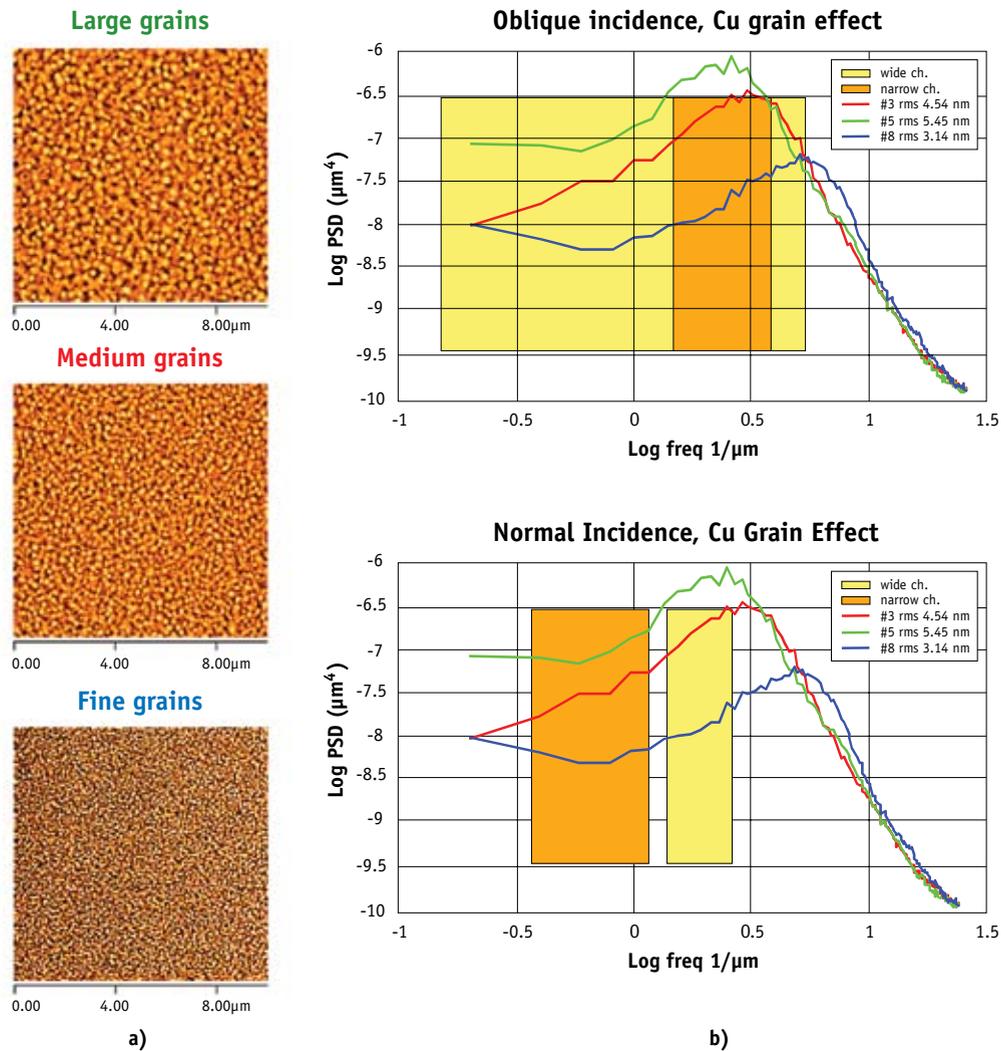


Figure 5: Representative AFM scans (a) of copper wafer from figure 4. PSDs of the AFM scans (b), overlaid with the spatial frequency bands of the various Surfscan SP2 optical configurations.

that, for conducting films, a very strong correlation exists between SURFmonitor microhaze measurements and frequency-matched AFM measurements of RMS roughness.

The correlation between the frequency-matched RMS roughness and the measured haze value can be used to construct a microroughness map of the wafer (figure 7). The translation from microhaze to microroughness is accomplished by applying the microhaze-to-roughness correlation as indicated in the figure. The red symbols in the correlation plot are 'theory' microhaze generated from equation 6, using the AFM data points indicated in figure 4. This data set is analogous to the red symbols in figure 6.

For metal films of interest, such as copper, aluminum and tungsten, microroughness is dominated by grain size. Figure 5b shows that the SURFmonitor collection frequencies overlay ideally with the broad peak in the PSD that indicates grain size distribution. Thus the SURFmonitor haze map may be uniquely suited to serving as a grain size measurement proxy. Grain size can affect the resistance of the interconnects, and ultimately, the speed of the IC device. Furthermore, grain size has been associated with integrated circuit reliability in metal films, and thus may also provide information useful for predicting the probability of circuit failures. Using the SURFmonitor as a means of generating a full-wafer microroughness map, process engineers may be able to map out a

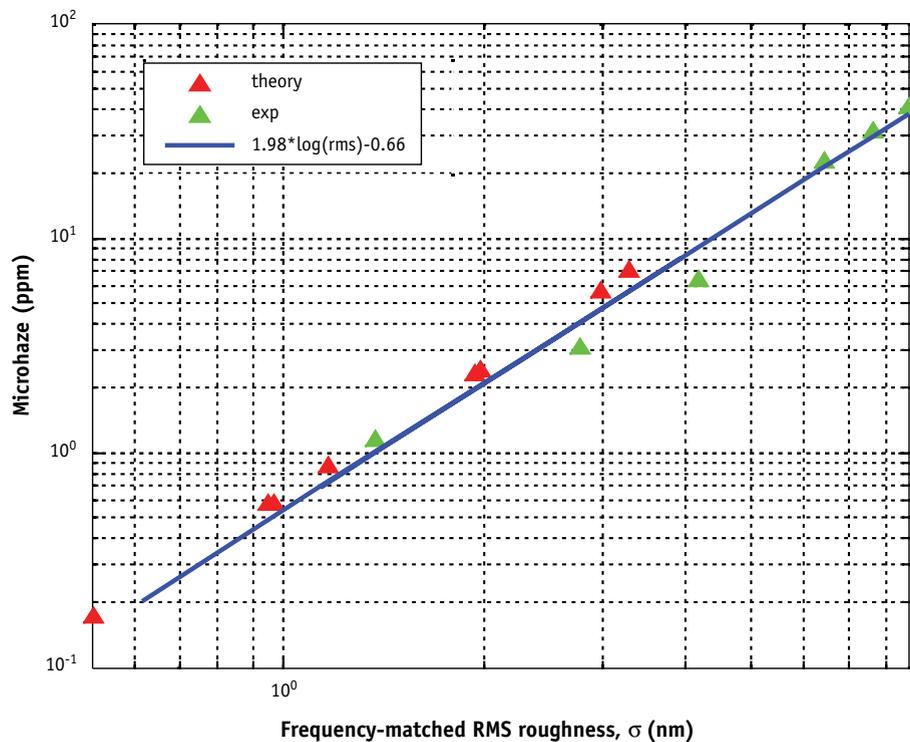


Figure 6: Log-log comparison of frequency-matched microroughness values (theory), derived from the AFM data, with the haze values (experimental) measured by the normal-wide channel of the SURFmonitor. See text for details.

process window for interconnect microroughness. Furthermore, the ability to generate these full-wafer maps at a speed of tens of wafers per hour enables process monitoring for grain-size excursions.

by the RTA step cause changes in surface roughness that show up in the value of the microhaze. Another application under study is the detection of pinholes in thin transparent films. In this case, clustered pinholes are in effect creating

## SURFmonitor has immediate applications in process development, with the added potential to serve as a high-speed, low-cost process monitor.

### Future Work

We are currently investigating the relationship between SURFmonitor haze and microroughness for other films, FEOL materials, as well as substrates. For polysilicon, where microroughness affects electron-hole mobility in CMOS devices and capacitance in DRAM trenches, we have measured a similarly strong correlation between frequency-matched AFM microroughness and SURFmonitor haze. For nickel silicide, the changes in film morphology induced

a surface roughness whose PSD is in the SURFmonitor detectable frequency range, if the density of pinholes is high enough.

The extension of this concept to monitoring the roughness of wafer substrate surfaces is more difficult, mainly because the surfaces are so much smoother, and the noise in the AFM measurements confounds the correlation to haze<sup>8,9</sup>. We are currently collaborating with a major manufacturer

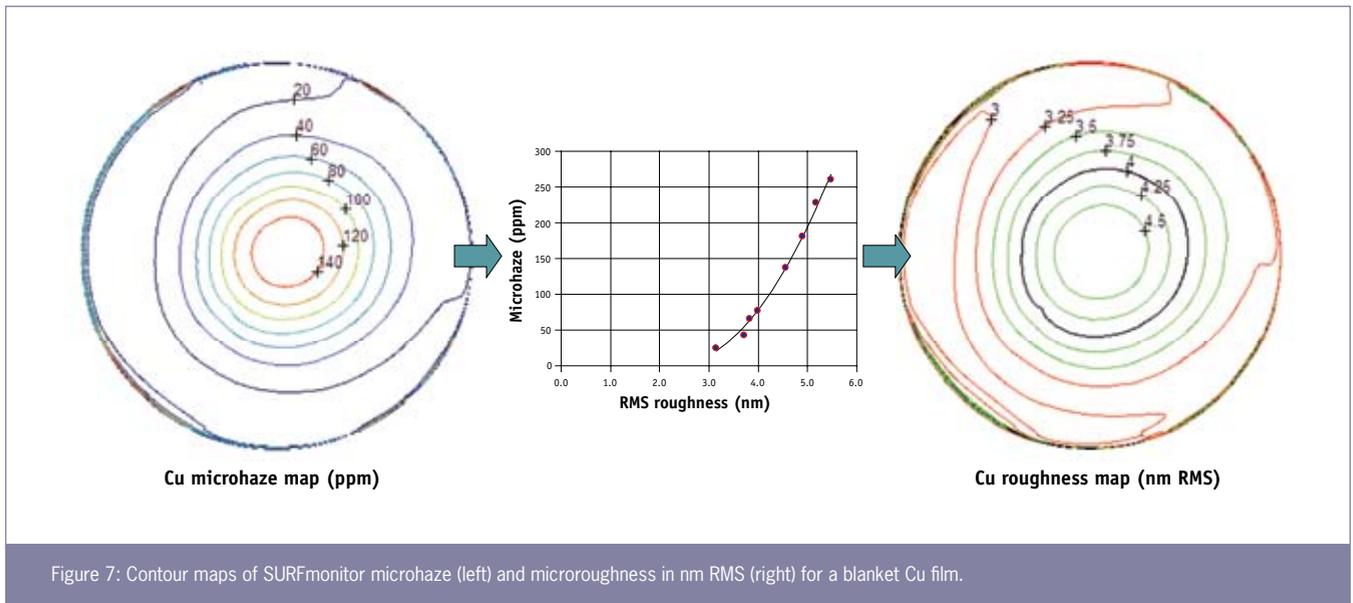


Figure 7: Contour maps of SURFmonitor microhaze (left) and microroughness in nm RMS (right) for a blanket Cu film.

of silicon substrates, to investigate the feasibility of using SURFmonitor as a high-speed, full-wafer proxy for substrate microroughness measurements.

### Summary

A new application of surface scattering uses broad collection optics, UV illumination, and new algorithms to produce full-wafer microhaze maps of angstrom-level sensitivity and unprecedented lateral resolution, at a throughput of tens of wafers per hour. We used the new system to measure a blanket Cu film, and demonstrated strong correlation between AFM microroughness measurements and SURFmonitor haze maps, when frequency matching was applied. Using SURFmonitor as a high-speed means of generating a full-wafer microroughness map, process engineers can quickly map out a process window for interconnect microroughness, and then monitor the process for grain-size excursions. In this way, SURFmonitor helps ensure more consistent device performance.

We are exploring further SURFmonitor microroughness applications, including extensions to blanket polysilicon films, silicides, substrate characterization, and detection of pinholes in thin films. In summary, SURFmonitor is finding immediate applications in process development, and also holds potential for serving as a high-speed, low-cost process monitor.

### Acknowledgments

This article originally appeared in the July 2006 issue of *Nikkei Microdevices*.

### References

1. Wayne McMillan, "Surfscan SP2: Enabling Cost-Effective Production at the 65nm Node and Beyond," Yield Management Solutions, pp. 14-23, Spring 2004.
2. C. Thomas Larson, "Measuring haze on deposited metals with light-scattering-based inspection systems," MICRO, September, 1996.
3. John C. Stover, Optical Scattering: Measurement and Analysis, SPIE Optical Engineering Press, Bellingham, WA, 1995.
4. J.M.Elson, J.P.Rahn, and J.M.Bennett, Applied Optics 22, 3207, 1983.
5. B. W. Scheer, "Development of a physical haze and microroughness standard," SPIE Vol 2862, pp. 78-95, 1996.
6. Hamlyn Yeh, "SP2 Haze Correlation with NC-AFM (ECD Cu)," internal publication of KLA-Tencor, BKM 262, 2005.
7. For example, J.E. Griffith, D.A. Grigg, M.J. Vasile, P.E. Russell and E.A. Fitzgerald, "Characterization of Scanning Probe Tips for Linewidth Measurement," J. Vac. Sci. Technol. B 9(6), pp. 3586-3589, Nov/Dec 1991.
8. Igor J. Malik, Krishna Vepa, Saeed Pirooz, Adrian C. Martin, and Larry W. Shrive, "Surface Roughness of Si Wafers: Correlating AFM and Haze Measurements," Semiconductor Silicon/1994: Seventh International Symposium on Silicon Materials Science and Technology, ed. H.R. Huff, W. Bergholz, and K. Sumino, The Electrochemical Society, Inc, PV 94-10, Pennington, NJ, p. 1182, 1994.
9. Egon Marx, Igor J. Malik, Yale E. Strasser, Thomas Bristow, Noel Poduje and John C. Stover, "Power spectral densities: A multiple technique study of different Si wafer surfaces," J. Vac. Sci. Technol. B 20(1), pp. 31-41, Jan/Feb 2002.