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LES1200

Thin Film Metrology Sensor

LEYBOLD INFICON

Two Technology Place
East Syracuse, NY 13057-9714
USA

phone: (315) 434-1100
fax: (315) 437-3803

1505 Commonwealth Avenue
Boston, MA 02135
USA

phone: (617) 787-2100
fax: (617) 787-1477

e-mail: les@inficon.com
web site: www.les.com

LES1200 Thin Film Metrology Sensor

Highlights

- Reduces the number of test wafers - every product wafer is examined
- Provides data on product wafers for Statistical Process Control
- Monitors the wafer, the process, and the tool
- Applicable to Production, R&D, and Tool Development

- Works on thin film etching and deposition processes
- Works on polysilicon, oxide, nitride, resist, TiN, Al, etc.
- Works on trench etching

- Measures uniformity over entire wafer
- Determines spatially and temporally resolved etching or deposition rate
- Determines endpoint for both etching and deposition
- Determines endpoint for transparent and non-transparent films
- Determines optical emission endpoint

- Mounts easily on a variety of processing equipment
- Operates in situ and in real time
- Images full wafer for better process visualization

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The LES1200 Thin Film Metrology Sensor monitors thin film etching or deposition rate, rate uniformity, endpoint, endpoint uniformity, and plasma optical emission over the entire wafer surface. These measurements are performed on every product wafer, providing both Real Time Endpoint and Run-by-Run data for process monitoring and control.

The LES1200

The LES1200 Thin Film Metrology Sensor is one of the new, smart sensors designed for real time monitoring of the wafer state. The LES1200 addresses a critical problem in semiconductor manufacturing by in situ monitoring of etching or deposition rate, rate uniformity, and endpoint on every product wafer. The LES1200 is applicable to a large number of processes, including plasma etching and plasma assisted chemical vapor deposition. Based on these measurements, not only is the manufacturing process better controlled, but each product wafer becomes a monitor for the next wafer. Furthermore, direct uniformity measurements lead to faster process development and more rapid process transfer from development to production.

The LES1200 increases equipment effectiveness and decreases the cost of chip production in several ways:

Detects endpoint for processes where endpoint is currently not available, such as planarization etch, trench etch, and deposition. Also provides endpoint for processes where optical emission endpoint is used.

Measures rate and uniformity on every product wafer, so that fewer monitor wafers are required in manufacturing, and fewer wafers are destroyed before problems are detected.

Expedites process transfer from development to production. By using the LES1200 on both development and manufacturing tools, knowledge gained during process development is directly implemented, and process transfer and qualification time is shortened.

Enables rapid scaling up to larger diameter wafers and smaller feature sizes. Process uniformity is more difficult to maintain over larger areas, therefore direct measurement of uniformity greatly simplifies both reactor and process scale-up.

Shortens the time required, and decreases the number of wafers expended, in developing new processes. Determination of the variation in rate and uniformity of the process as a function of power, pressure, gas flow rate, gas composition, and substrate temperature is performed in hours rather than days.

The LES1200 also provides a significant benefit to equipment manufacturers:

Decreases the time and cost to develop new equipment and new processes. The number of wafers expended during development is also substantially reduced.

Enables developing a uniform process for equipment sales demonstrations in hours rather than days.

Helps to differentiate your equipment from the competition.

The strength of the LES1200 is threefold: visualization, signal abundance, and diversity of signal processing algorithms. First, the ability to visualize wafer processing is extremely useful in detecting and solving process and tool problems. Second, the ability to simultaneously obtain signal from over 180,000 independent points on the wafer, when information from 50 points is sufficient, makes it possible to choose the best data, eliminate weak signal, and makes the LES1200 very robust in production applications. Third, the ability to process the data with a variety of algorithms provides a wealth of information about the process. Users can select from 15 analysis algorithms to satisfy their needs.

All of the capabilities above are packaged in the LESWare software. LESWare is designed not only to capitalize on the strengths of the Windows NT operating system, but also to allow simultaneous operation of up to four independent sensor heads located on different processing chambers. LESWare also provides advanced communication between the sensors and the processing tool for real time endpoint and between the sensor and the fab for Statistical Process Control. LESWare also includes an SQL database for tracking results.

Pay Back

The table below gives some examples of the potential return on investment for an LES1200 throughout the equipment and process life cycle. Pay back can be extremely rapid, especially in production applications.

Application	Savings per LES1200	Type of Saving	Payback
Process Development			
Man Hours	100 hours/process	development time	3-6 months
Wafers (materials)	50 wafers/process	development cost	6-12 months
Manufacturing			
Wafer Waste	50-100 wafers/year	lost product	2 months
Monitor Wafers	10-20/week	production cost	2 months
Down Time	1 week/year	lost capacity	1 down time
Throughput	1 wafer/day	increased capacity	1 week
Ramp-up Time	1-5 days/product	increased capacity	1 week
Equipment Development	5-10 days	development time	2 months
Equipment Qualification	1 day	increased output	1 week

Proprietary Technology

The Massachusetts Institute of Technology owns the rights to a patent on the LES1200 technology. Leybold Inficon holds an exclusive, worldwide license to this technology.

System Operation

The LES1200 consists of a computer, proprietary LESWare software, one PCI controller board, and up to four independent CCD sensor modules. Typically, each sensor module is mounted on a separate processing chamber. Each sensor records images of a wafer during processing, with each pixel of the CCD acting as an independent detector. The full images provide visual information about the wafer and process performance, while the signal from 180,000 detectors provides quantitative determination of endpoint, etching or deposition rate and uniformity. The simultaneous use of thousands of independent detectors greatly enhances accuracy and reliability through the use of powerful statistical methods.

Figure 1 shows the installation of the LES1200 sensor. The sensor head is mounted directly onto a semiconductor etching or deposition tool wherever there is a clear view of the wafer. If the wafer can be seen during processing, then the LES1200 will work. Because the LES1200

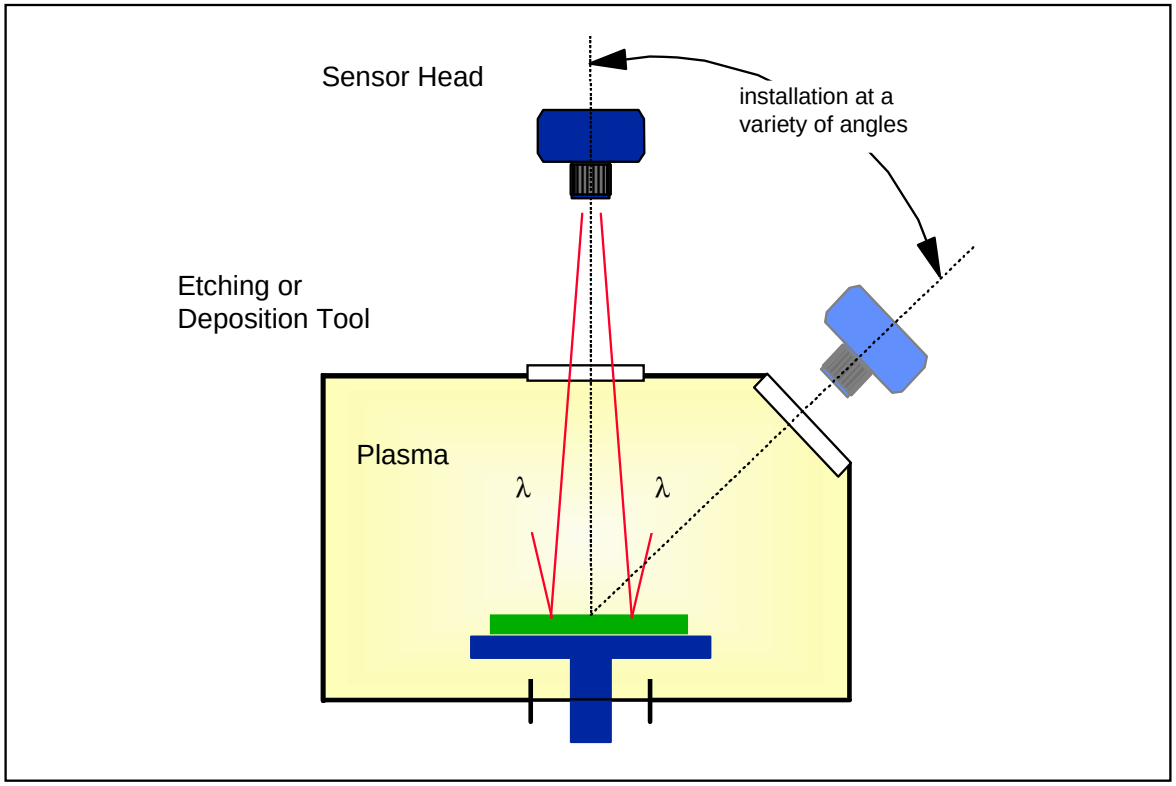


Figure 1. LES1200 Thin Film Metrology Sensor - sensor installation.

records complete images of the wafer, alignment and positioning difficulties inherent to single-point interferometers are avoided. In cases of limited mounting space or in hostile environments, the sensor can be mounted remotely via an imaging multi-fiber optic.

Plasma optical emission, if available, is used as the light source. This both simplifies the system components, and allows direct detection of optical emission endpoint. If plasma light

is not available, an external light source can be used. A narrow bandpass filter is used to select the measurement wavelength. The user can choose the wavelength best suited to current process conditions (wavelength dependence of plasma optical emission, film thickness and index of refraction, etc.). In general, a shorter wavelength gives better rate resolution, but cannot be used in certain situations, e.g., amorphous silicon absorbs at 435 nm but is transparent at 750 nm.

Figure 2 shows the signals from three different pixels. Each pixel images a small, distinct region; an image is included to indicate the position of these pixels. Two of the pixels are on the wafer and display a periodic signal due to the change in thickness of the thin film. The pixel off the wafer shows the optical emission signal, which rises at endpoint. Analysis of the

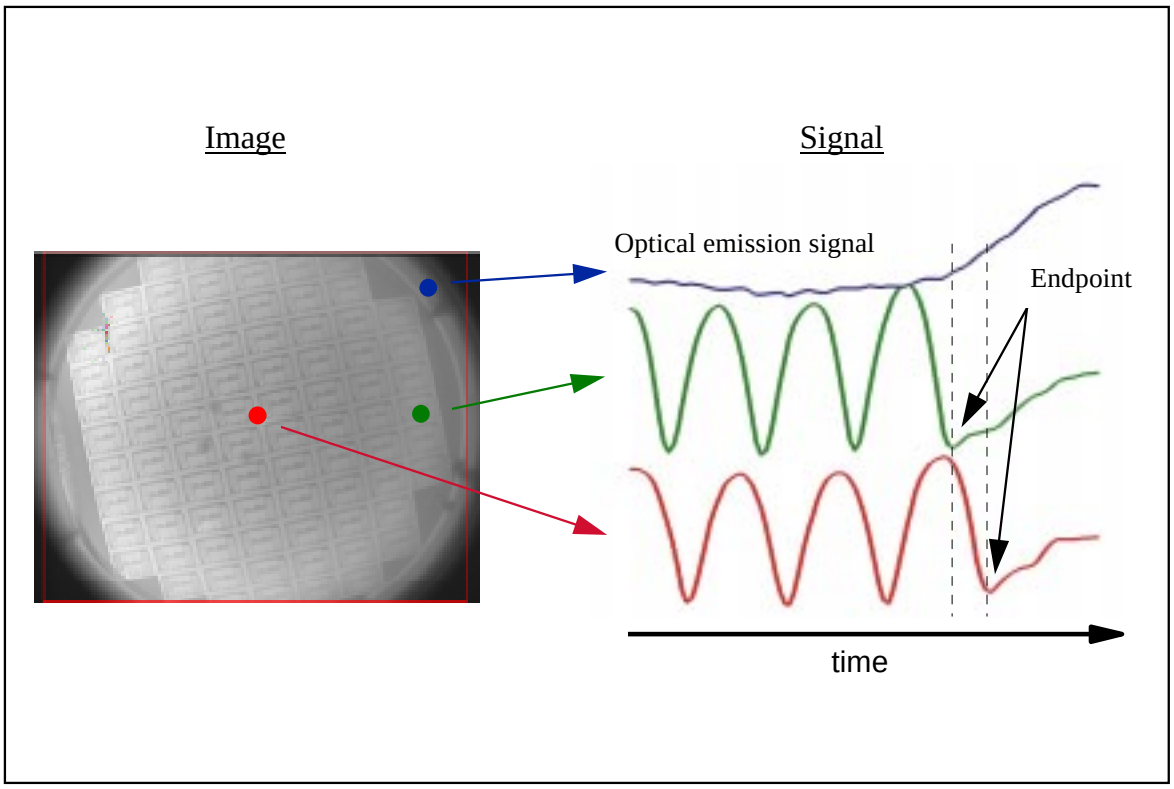


Figure 2. Signal from three positions: two on the wafer and one off the wafer. This signal is from a polysilicon etching process.

periodic signal determines rate and/or endpoint, while analysis of the optical emission signal is used to independently detect endpoint in those etching processes in which all of the film is removed.

Applications

The LES1200 is the only currently available sensor that can determine endpoint, rate and uniformity in situ and in real time.

In real time, the LES1200 detects etching endpoint and sends an "endpoint detected" signal to the process equipment controller. In addition to detecting traditional optical emission endpoint, the LES1200 is capable of detecting endpoint based on reflectivity change and predicting time-to-endpoint based on the real time etching or deposition rate. The capability of detecting/predicting both endpoint and endpoint uniformity makes the LES1200 ideal for real time process control.

Within seconds of process termination, the LES1200 calculates endpoint uniformity, rate and rate uniformity. Traditional film thickness uniformity measurements are accomplished by removing the wafer from the processing tool and making the measurement with a separate instrument, which takes considerable time and requires the use of monitor wafers. The LES1200 provides immediate feedback on every product wafer, allowing both early detection of process faults and more precise Statistical Process Control (SPC). These capabilities enable the LES1200 to be directly integrated into the processing equipment and fab control system.

The LES1200 has been used on devices with feature sizes down to 0.1 μm, aspect ratios up to 50:1, and percent open area as low as 5%. Films more than 2 μm thick have been monitored. Substrate sizes up to 320 mm have been used and the extension to larger substrates is simple. Endpoint, etching or deposition rate, and uniformity have been monitored for a variety of transparent thin films, including: polysilicon, amorphous silicon, silicon dioxide, nitride, and photoresist. For non-transparent materials, such as aluminum, tungsten silicide, chrome, and tantalum, rate cannot be measured directly, but spatially resolved etching endpoint and thus endpoint uniformity have been determined.

Physics

Optical Emission

Power added to a gas at low pressure results in excitation of gaseous species. Each gaseous species produces light at specific wavelengths, which is proportional to the species concentration. By monitoring the light intensity, information about the concentration of the chemical species in the plasma can be obtained. When endpoint is reached, the

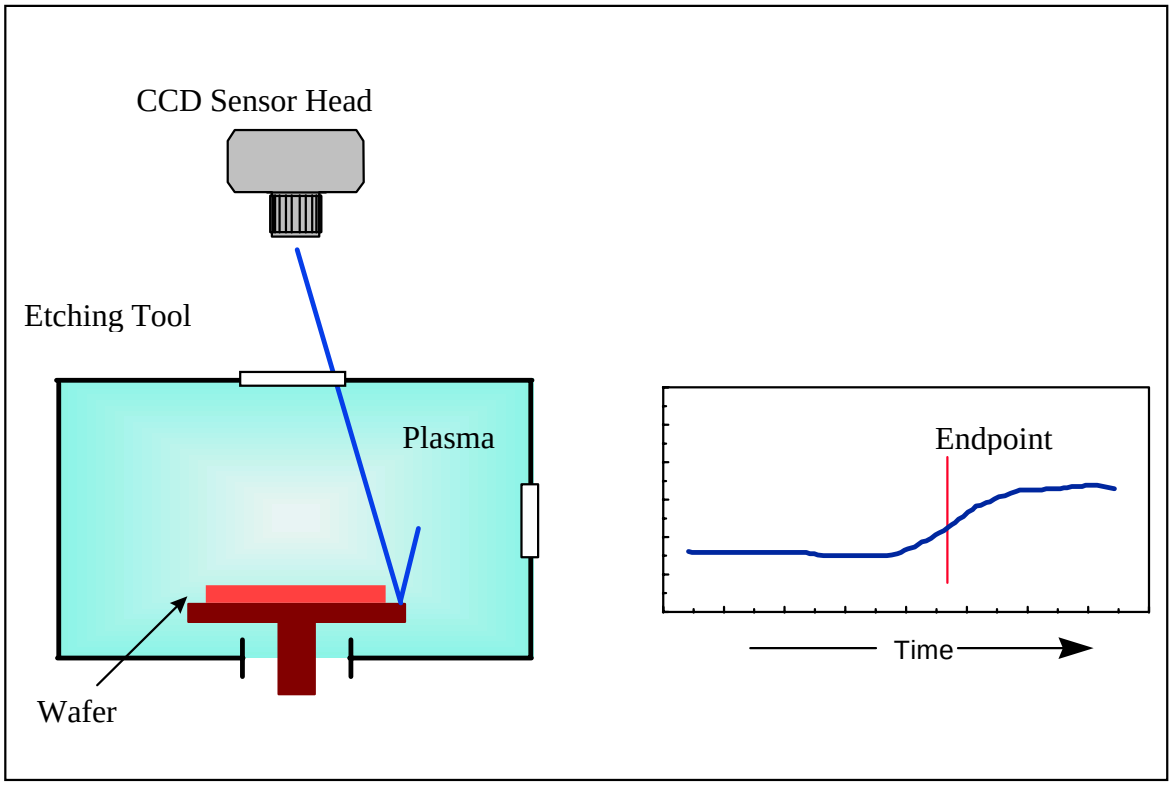


Figure 3. Optical emission.

concentration of both the reactant and product species changes, resulting in a change in light intensity. For example, at the end of a polysilicon etching process, the consumption of reactants decreases, Cl concentration increases, and emission from Cl increases. Figure 3 illustrates the physics of optical emission endpoint detection. The major drawback is that endpoint uniformity cannot be directly or accurately determined, since only average changes in plasma optical emission are observable. The simplicity of this method, however, lends itself to real time endpoint detection.

Interferometry - Transparent Thin Films

Light impinging on a thin film reflects from both the top of the film and from the bottom of the film. The light reflected from the bottom travels farther. The difference in path length results in a difference in phase between the two reflected light beams. The two beams

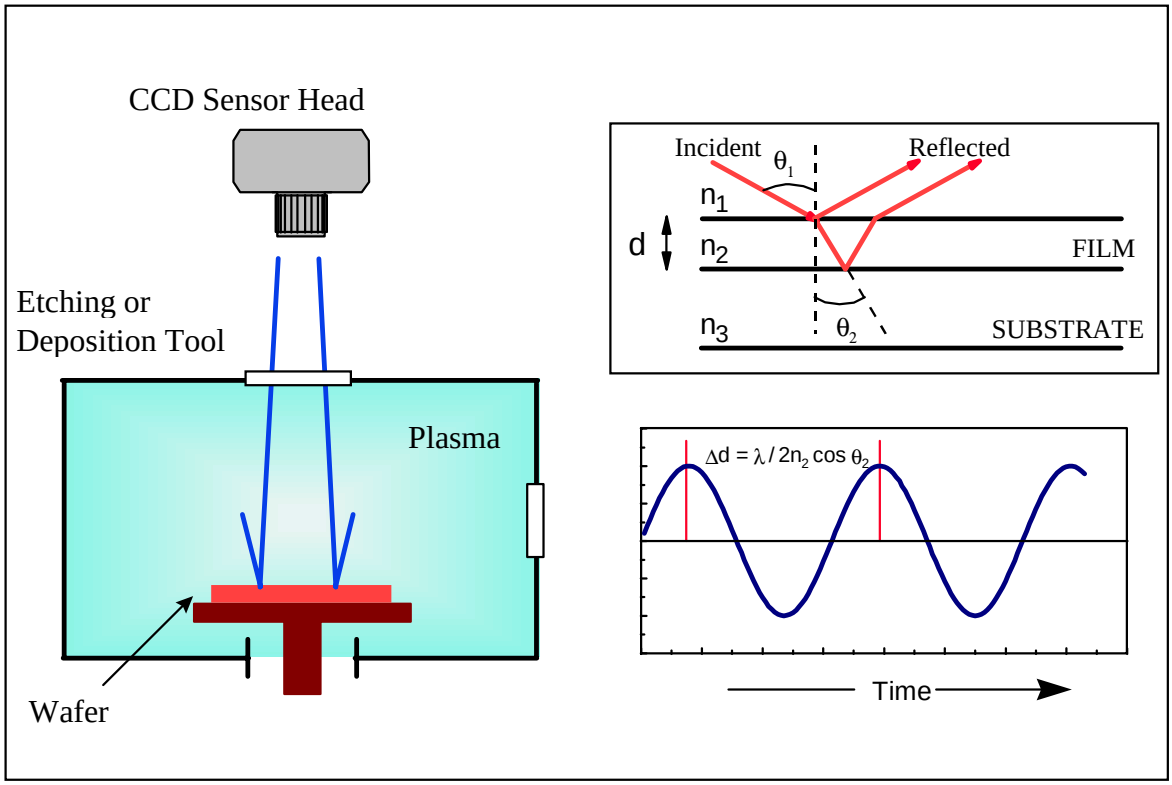


Figure 4. Interferometry of transparent thin films.

combine and interfere, with the resulting light intensity a periodic function of the film thickness. Figure 4 illustrates the basic principles of thin film interferometry.

During an etching or deposition process, as the film thickness changes, a periodic signal is observed. The frequency of the signal is proportional to the etching or deposition rate:

$$\text{rate} = \frac{\lambda}{2\, n_2 \cos\theta_2}\,\frac{1}{T}$$

where λ is the observation wavelength, n_2 is the index of refraction of the film, θ_2 is the angle of refraction within the film, and T is the period of the interferometric signal. The LES1200 analysis engine uses a Fast Fourier Transform (FFT), coupled with advanced model fitting, to convert from the time domain to the frequency domain. The rate is calculated using the above equation with $1/T = f$, where the frequency, f, corresponds to a peak in the FFT. A frequency window is used to designate which peak in the FFT determines the rate. The use of models improves the accuracy of the rate determination in data with low signal to noise ratio. Models are also used in endpoint prediction and detection algorithms.

For transparent thin films, endpoint can be either detected or predicted. The detection method relies on the fact that the periodic modulation of reflected light intensity ceases at endpoint. Endpoint is determined by detecting the deviation of the observed signal from an interferometric model. Endpoint uniformity is directly calculated by comparing endpoint times for different regions on the wafer.

The endpoint prediction method relies on the measured rate and the desired thickness change to predict the endpoint time. The LES1200 performs a rate calculation in real time, before the expected endpoint time. The predicted endpoint time is equal to the thickness change divided by the rate. Endpoint prediction is the only available endpoint method for deposition processes. It is also necessary in etching processes where the film is not completely etched away. Endpoint uniformity is directly calculated by comparing endpoint times for different regions on the wafer.

Interferometry - Trench

The physics of interference during trench etching is similar to the physics described above. Since there is no thin film, the interference is between the light reflected from the top of the substrate and the light reflected from the bottom of the trench. Furthermore, since the interference is between two distinct incoming light beams, a coherent light source, such as a

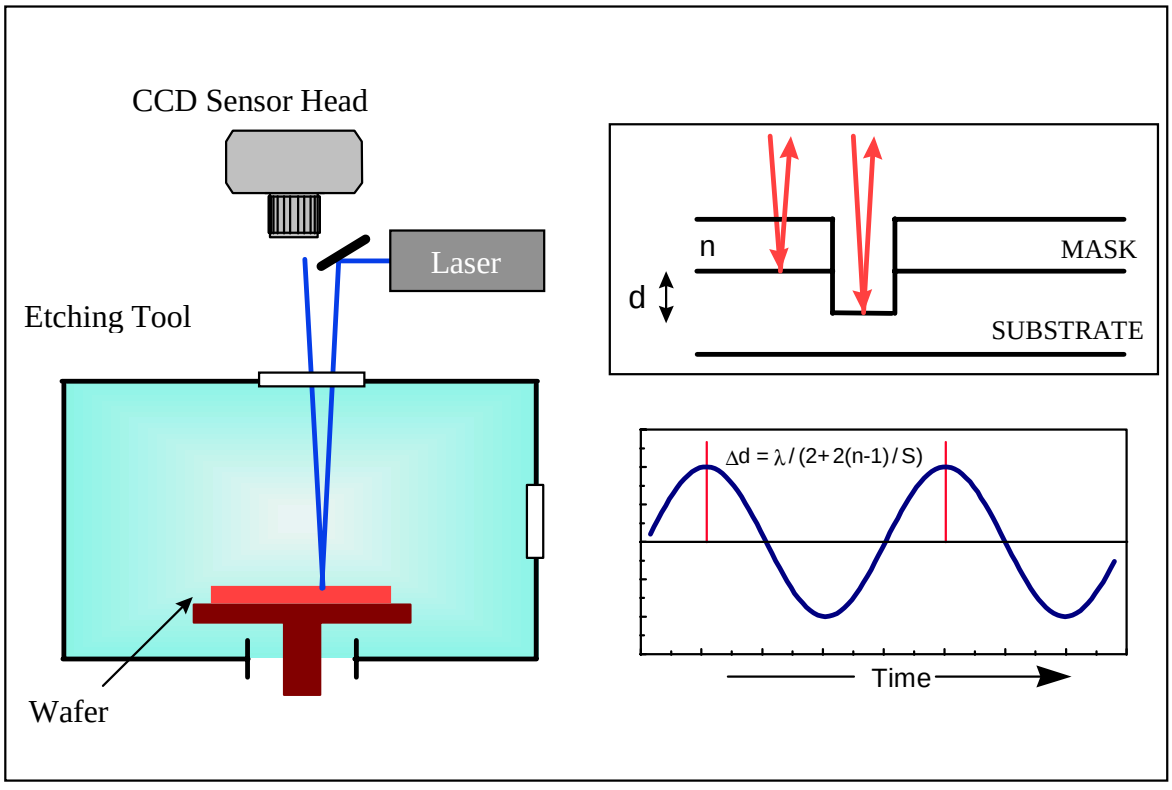


Figure 5. Interferometry of a trench. This illustration applies to a transparent mask.

laser, must be used. Figure 5 illustrates the basic principles of trench interferometry. In trench etching, endpoint is determined by the depth of the trench calculated from the measured etching rate and etching time.

Reflectometry - Non-Transparent Films

Light impinging on a non-transparent film reflects only from the top so there is no thin film interference. However, the reflectivity of a non-transparent film (that is being etched) is different from the reflectivity of the underlying material. Thus the intensity of reflected light changes at endpoint. This method is typically applied to endpoint detection in metal etching.

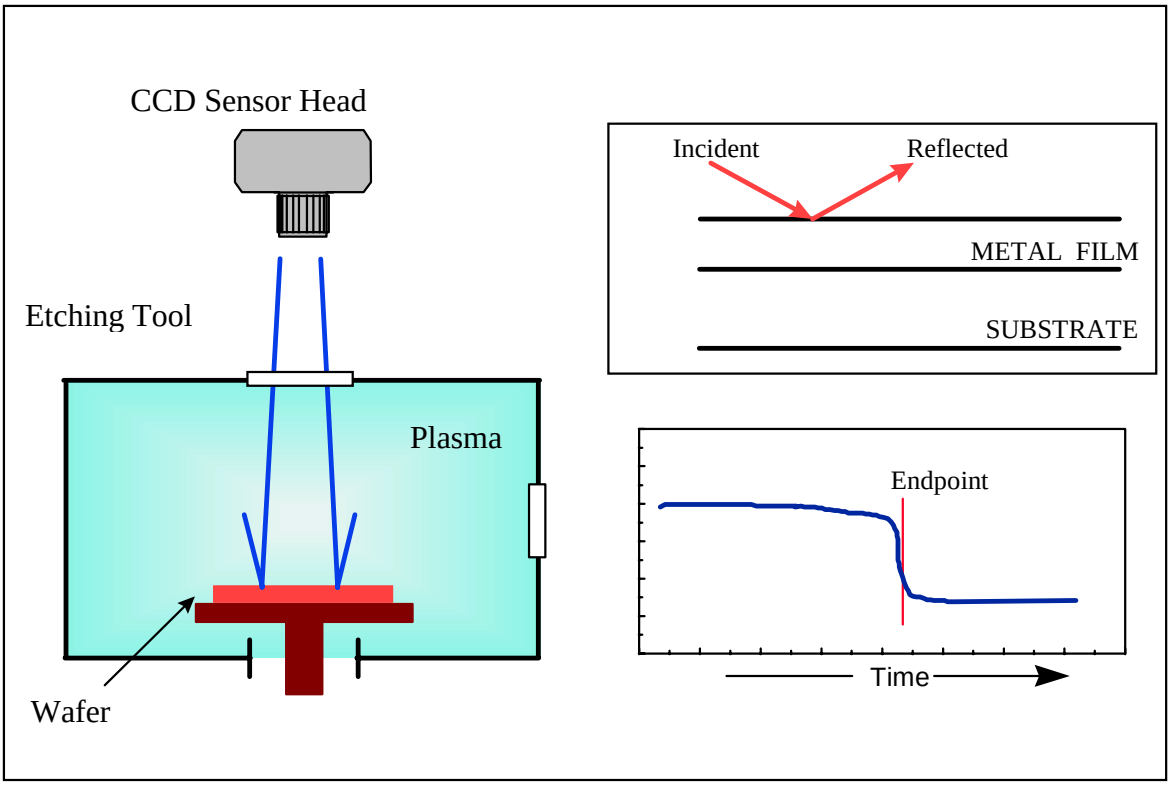


Figure 6. Reflectometry.

Figure 6 illustrates the basic principles of reflectometry. Endpoint uniformity is directly calculated by comparing endpoint times for different regions on the wafer.

Comparison to ex situ metrology

Unpatterned polysilicon wafers were used to compare etching rate and uniformity measurements made by the in situ LES1200 and the ex situ Prometrix SM200. Figure 7 shows that the two rate measurements follow identical trends and agree to 1-2 %, which is within the accuracy of the two tools. These data were collected on five different days

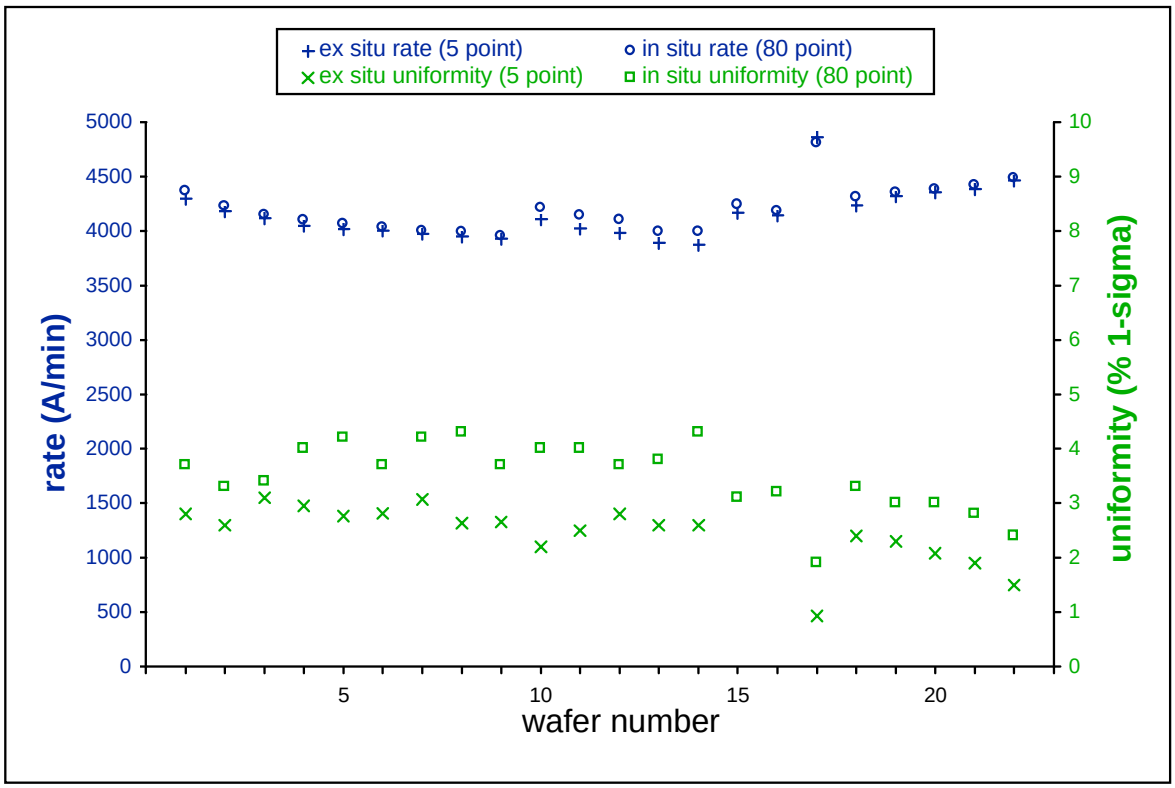


Figure 7. Comparison of etching rate and uniformity measurements made by the in situ LES1200 and the ex situ Prometrix SM200.

scattered over a one month period. The SM200 monitored only 5 points on the wafer, one at the center and four 1 cm from the edge. The LES1200 monitored 80 points distributed over the wafer surface. The main rate variation in this process is center to edge, as determined by both the LES1200 and the SM200. The center of the wafer etches significantly faster than the edge. The SM200 reported a lower rate and lower uniformity, because the 5 points used by the SM200 under-weight the center relative to the edge. (Note: For wafer numbers 15 and 16, the Prometrix SM200 did not report uniformity information.)

Examples

Following are three examples of the LES1200 in operation. These examples are intended to provide an introduction to the capabilities of the LES1200, rather than an exhaustive list of its functions.

Example 1

This example demonstrates a typical application of the LES1200 in the determination of full wafer etching rate and uniformity. Images of the etching wafer were recorded in real time at a wavelength of 750 nm. A single image of a 100 mm diameter patterned wafer is shown in

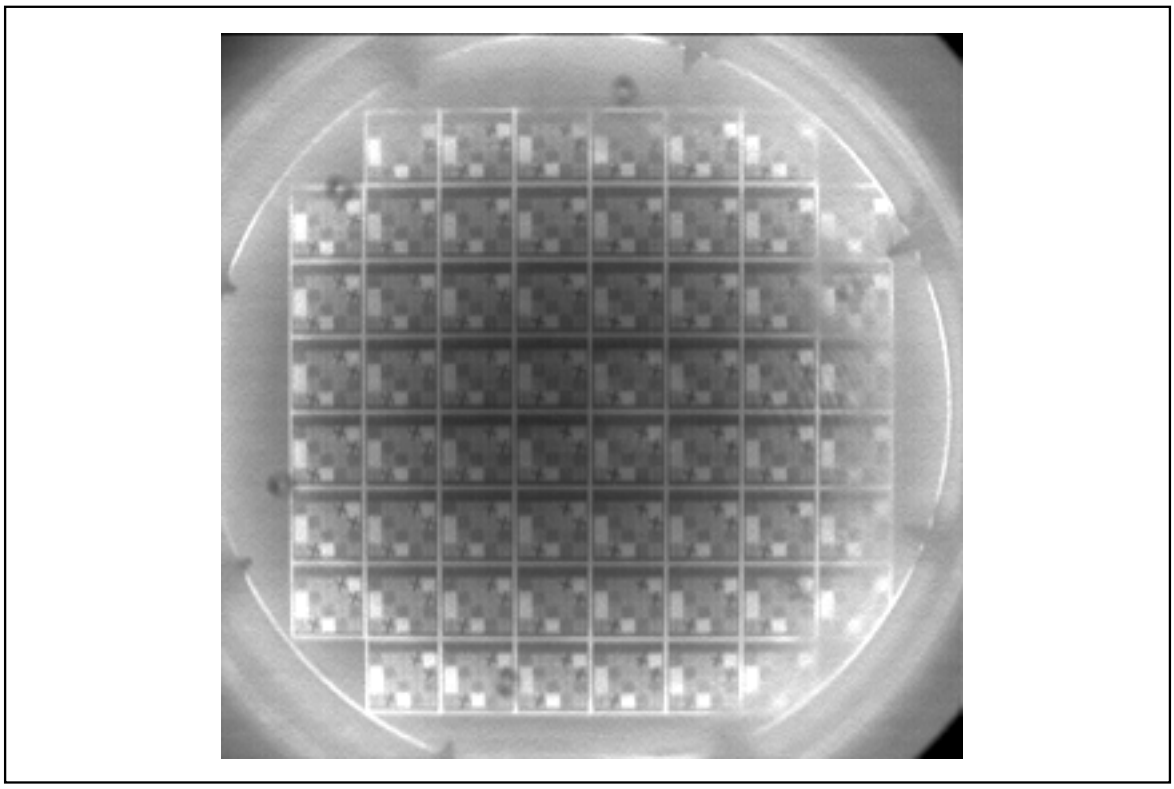


Figure 8. Full wafer image.

Figure 8. (This image is shown in gray scale; the LES1200 can also display images in false color for visual enhancement.) This wafer contains a repeated series of 10 mm square die, each containing a variety of pattern types and densities.

The signal from three pixels is shown in Figure 9. Two of the pixels shown in Figure 9 image patterned polysilicon regions: one at the center of the wafer and one at the edge. The third pixel is chosen to image part of the wafer clamp. The signals from the two polysilicon regions show typical interferometric modulation, while the signal from the clamp shows no

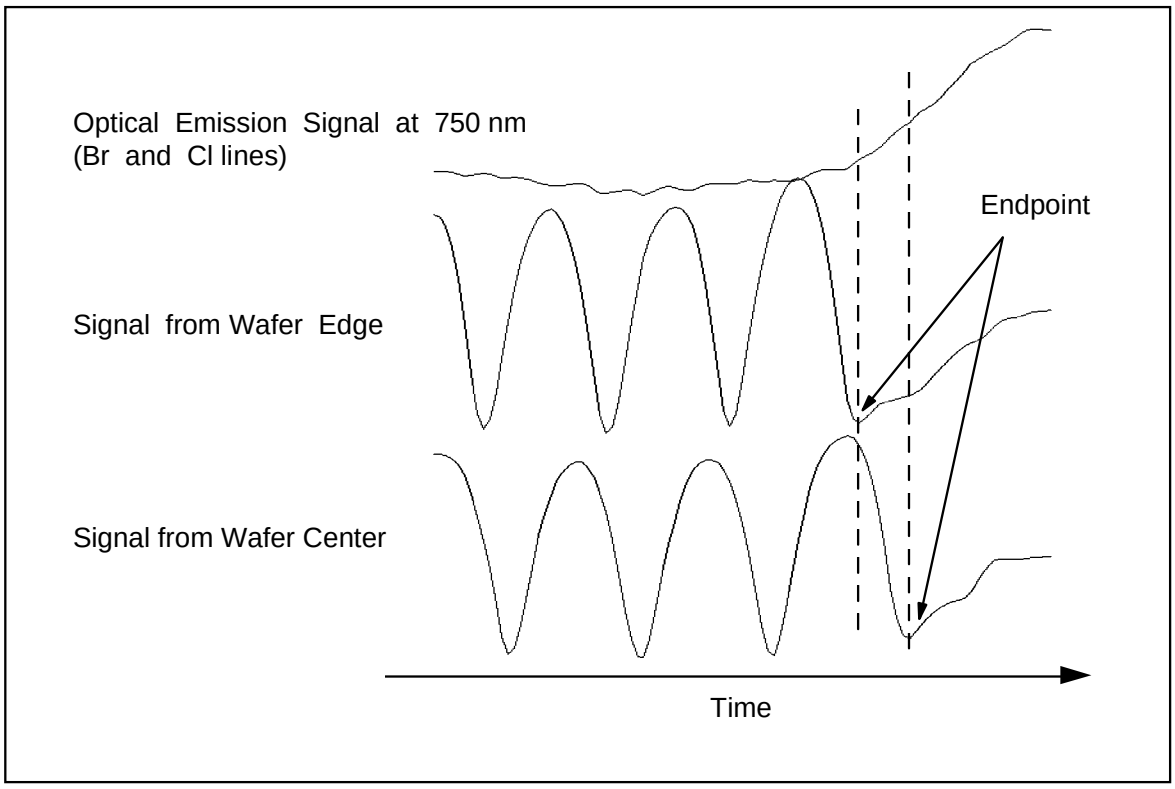


Figure 9. Interferometry signal versus time, with endpoint.

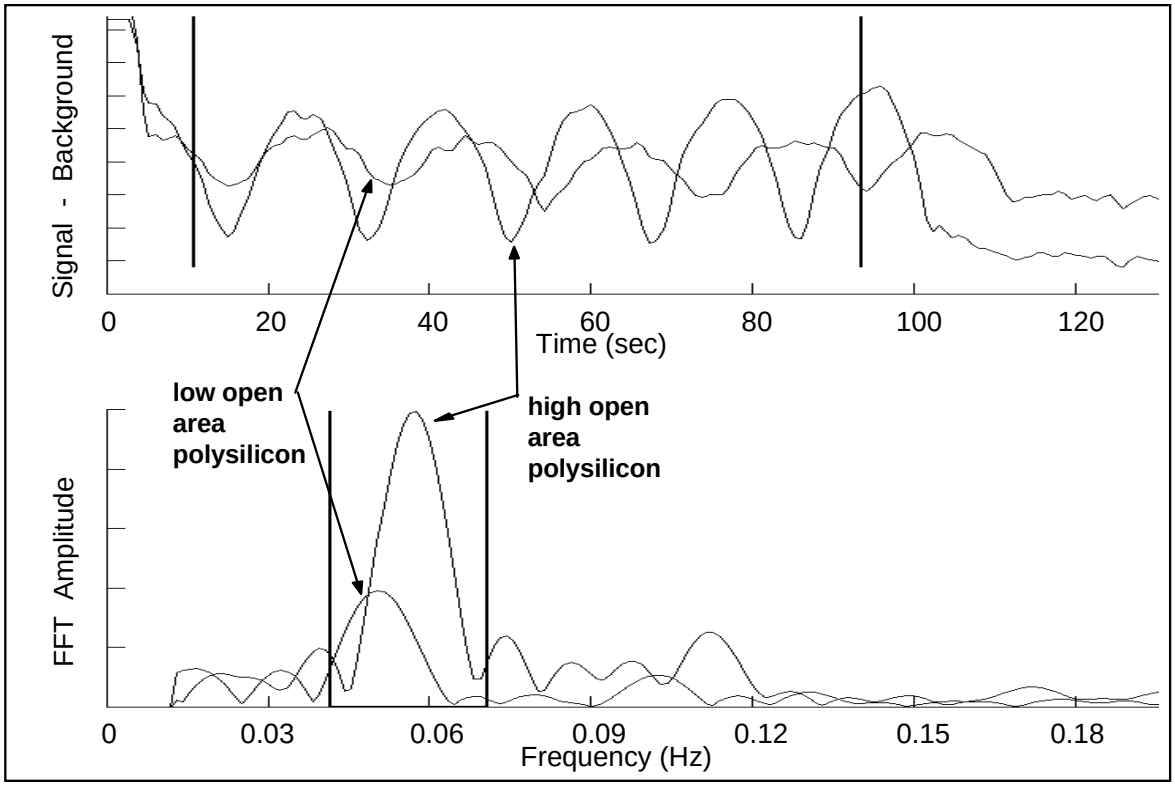


Figure 10. Time and frequency domain data - low and high open area polysilicon regions.

modulation and represents optical emission from the plasma. Endpoint for the two etching regions is clearly visible. As expected, endpoint also corresponds to a change in optical emission intensity at 750 nm (Br and Cl emission). In this case, emission increased due to decreased consumption of reactants. Figure 9 also shows that the center of the wafer etched more slowly than the edge, as indicated by the longer time required for the region in the center of the wafer to reach endpoint.

Figure 10 shows the time domain signal and its FFT used in the calculation of etching rate. The upper plot displays the signal as a function of time for two regions. The optical emission background has been scaled and subtracted from the time domain data to suppress intensity variations of the plasma optical emission. As previously discussed, accurate rate determinations are made using an FFT of the time domain data. Fast Fourier Transforms of the time domain signals are shown in the lower plot in Figure 10. In this frequency domain plot, it is easy to see that the rate for the two regions differs by approximately 20%. The vertical bars in Figure 10 represent the limits used in data analysis.

Figure 11 shows the etching rate for 54 different used-selected regions on the wafer. The regions are selected as 4 diagonal cuts across the wafer. The arrows at the top of the figure show the progression along each cut: from one edge, through the center, to the opposite edge. Figure 11 clearly shows that the etching rate is lowest at the center of the wafer. User-defined regions allow direct comparison of process uniformity from wafer to wafer by automatically using the same position on every wafer. This not only enables a robust run-by-run control scheme, but also permits statistical process analysis.

Figure 12 shows the etching rate uniformity surface plot determined by the LES1200 from the recorded images. The plot is based on analysis of 4000 positions on the wafer. Two trends are evident. First, the etching rate at the center of the wafer is lower than at the edge. Second, variations within each 10 mm square die are visible as a regular array of peaks and valleys in the etching rate surface plot. The deepest of these valleys (at the top of each die) correspond to the photoresist mask, which did not etch appreciably in this high-selectivity process.

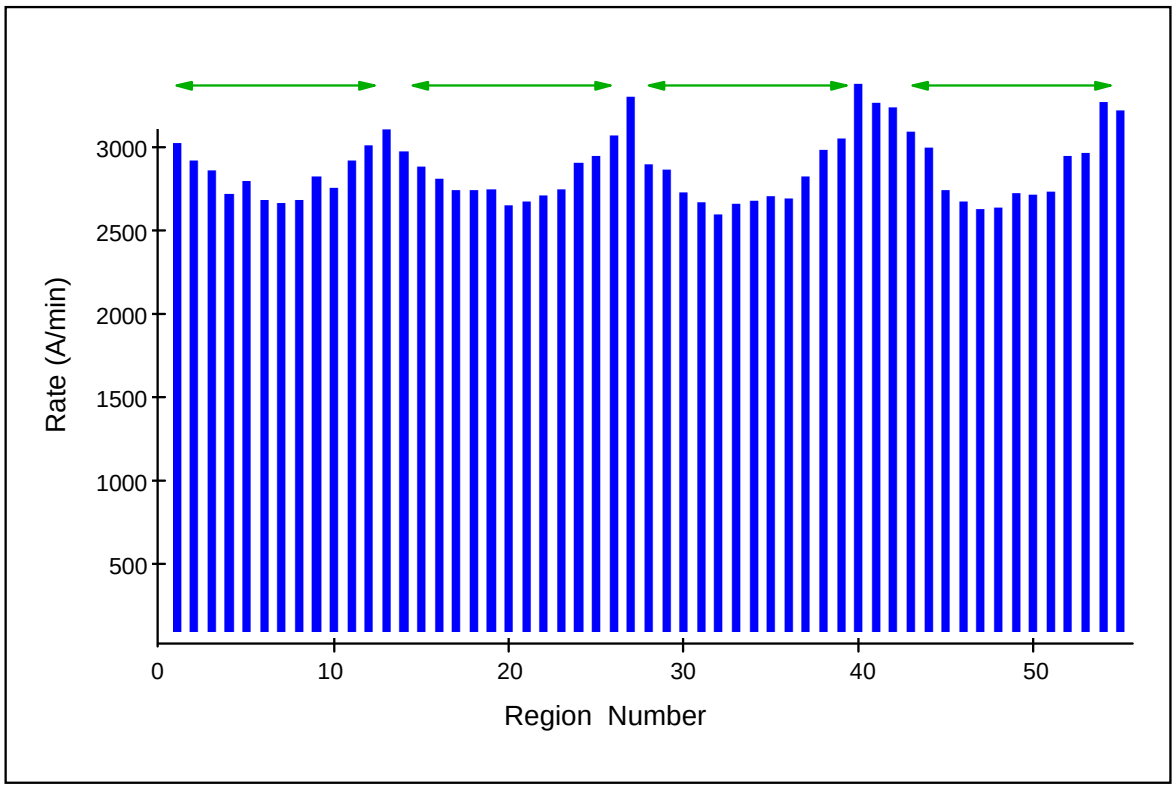


Figure 11. Etching rate for user-selected regions. Average = 2770Å/min, uniformity = 4.1% 1-σ.

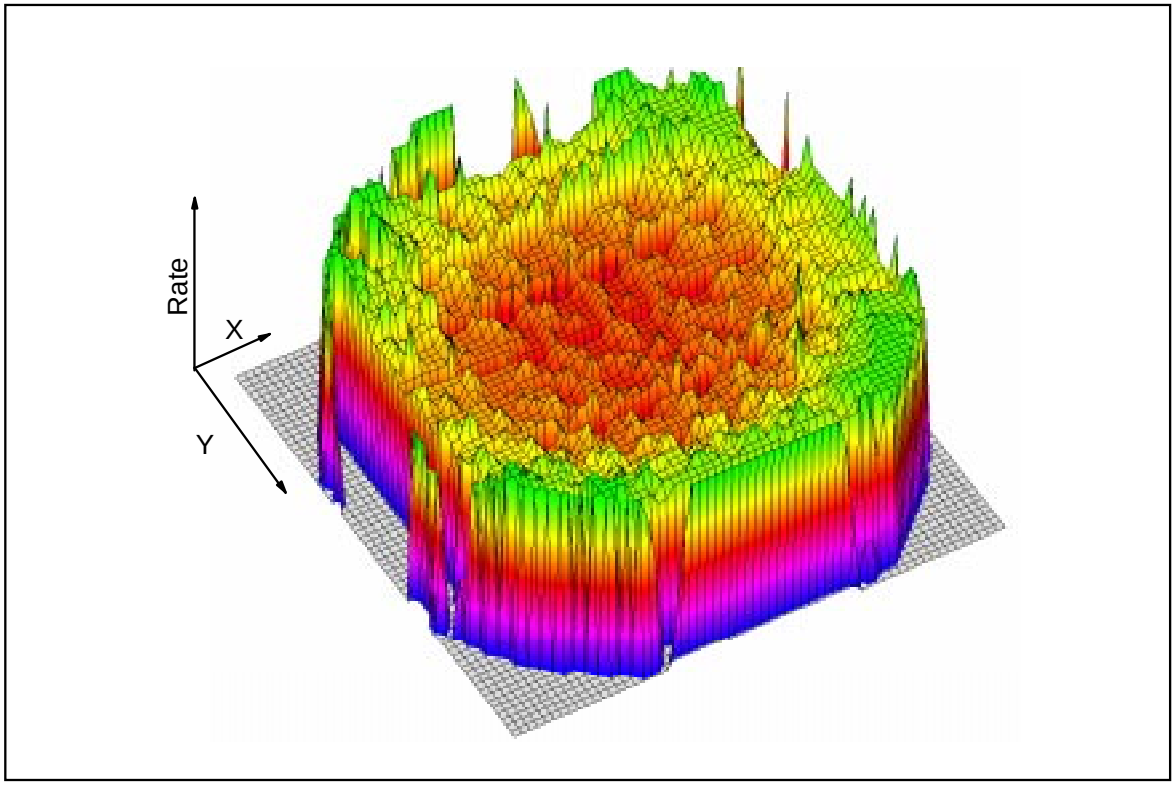


Figure 12. Full wafer etching rate map. Average = 2765Å/min, uniformity = 3.9% 1-σ.

Example 2

This example demonstrates the use of the LES1200 to automatically monitor every product wafer. A recipe was used to record data and calculate etching rate and rate uniformity for each wafer processed. Results for each wafer were determined and displayed before processing of the next wafer was started.

Figure 13 shows the etching rate and uniformity for four consecutive product wafer lots. The lack of large fluctuations in both rate and uniformity indicates that the process is stable. On

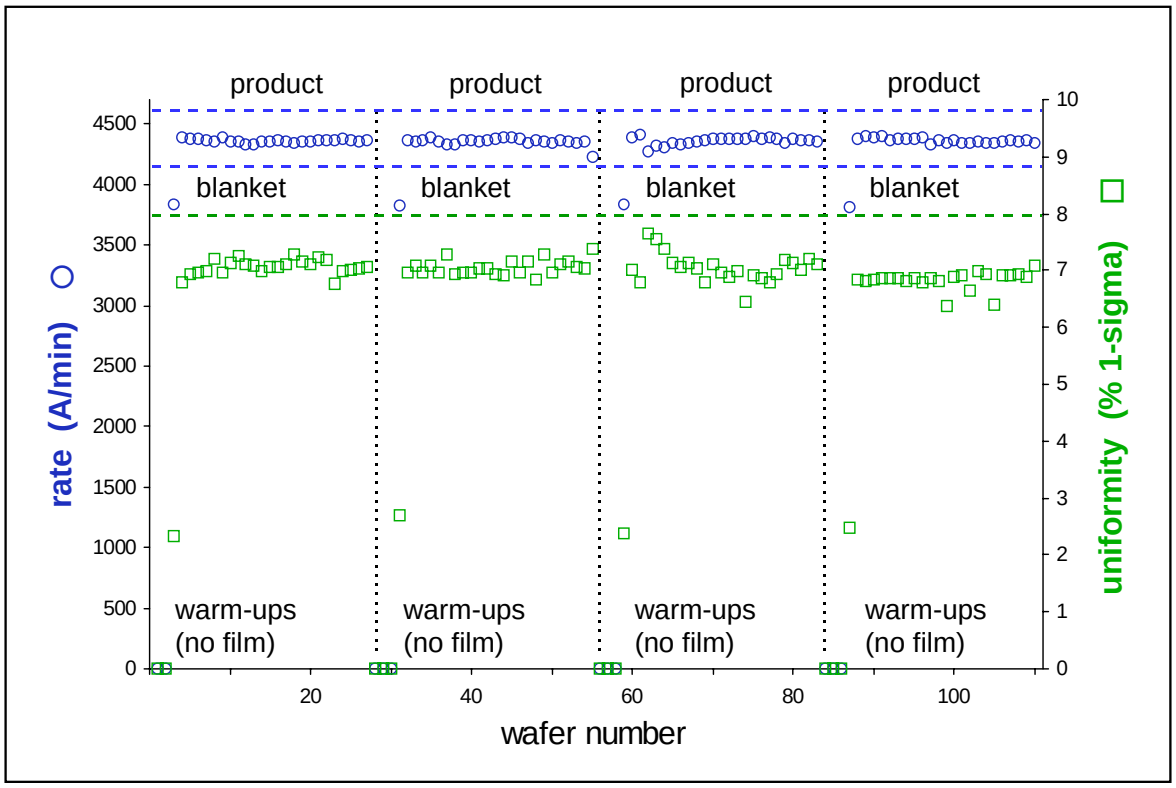


Figure 13. Rate and uniformity for four product wafer lots.

the other hand, the high percent uniformity (7% 1-σ) shows that the process is not very uniform. Furthermore, pattern dependent etching is clearly evident in the data shown in Figure 13. At the beginning of each lot, several bare silicon warm-up wafers and one blanket (not patterned) wafer are run to condition the chamber, then the patterned product wafers are run. Figure 13 shows that the blanket wafers etched about 10% slower and much more uniformly than the product wafers. The difference between blanket wafers and product wafers further demonstrates the need to use real product wafers to monitor the process.

Example 3

This example demonstrates the use of the LES1200 to measure deposition rate and uniformity. Figure 14 presents the rate uniformity surface map for depositing silicon dioxide on a 200 mm diameter wafer. This data was recorded at a wavelength of 480 nm. The deposition rate uniformity map in Figure 14 shows a noticeably decreased rate at the center of the wafer.

For the data of Figure 14, the LES1200 sensor viewed the wafer at an angle of 70° off-normal, which is why the wafer appears foreshortened. (In the preceding examples, the

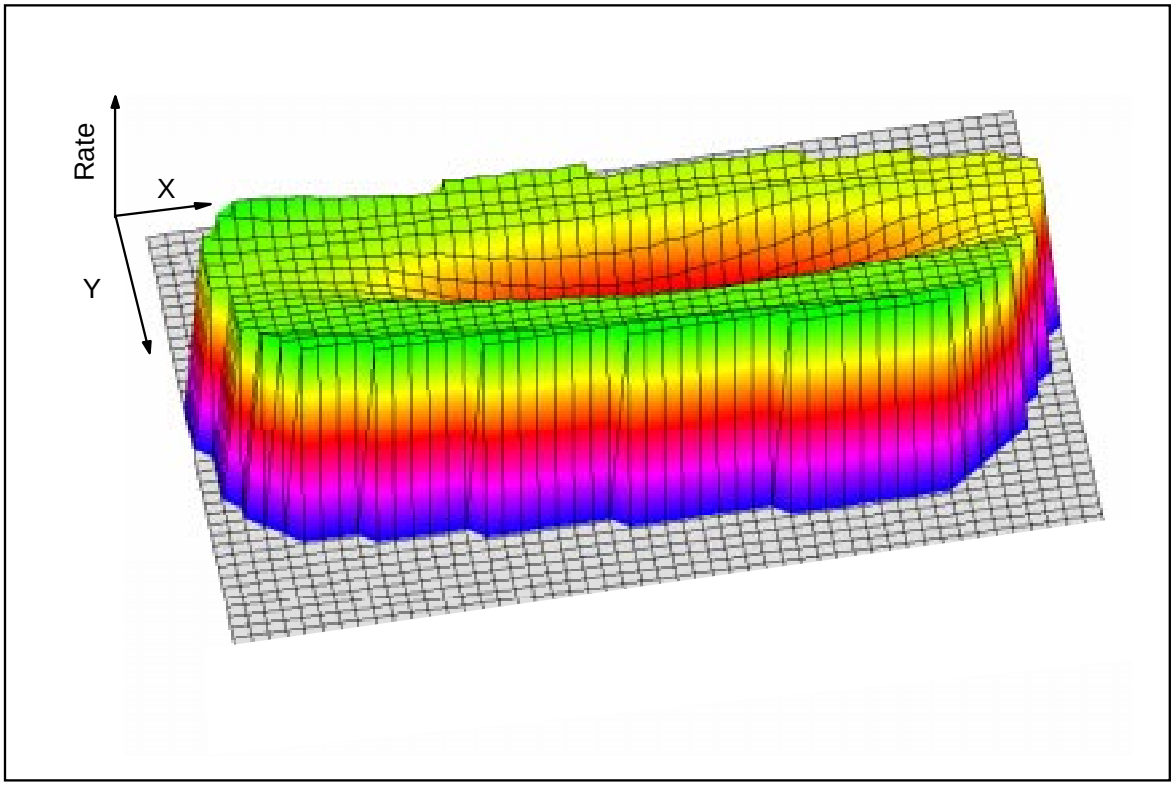


Figure 14. Deposition rate map - 200 mm wafer, imaged 70 degrees off-normal. Average = 6720Å/min, uniformity = 2.1% 1-σ.

wafers were viewed straight down, at 0° off-normal.) Although such an extreme angle degrades spatial resolution, the LES1200 is still able to accurately determine rate uniformity. Off-axis capability is essential for use on processing equipment, where a top-down view of the wafer is often unavailable.

Example 4

This example demonstrates how the LES1200 is used to measure spatially resolved endpoint when etching aluminum, a non-transparent film. In this example the observation wavelength

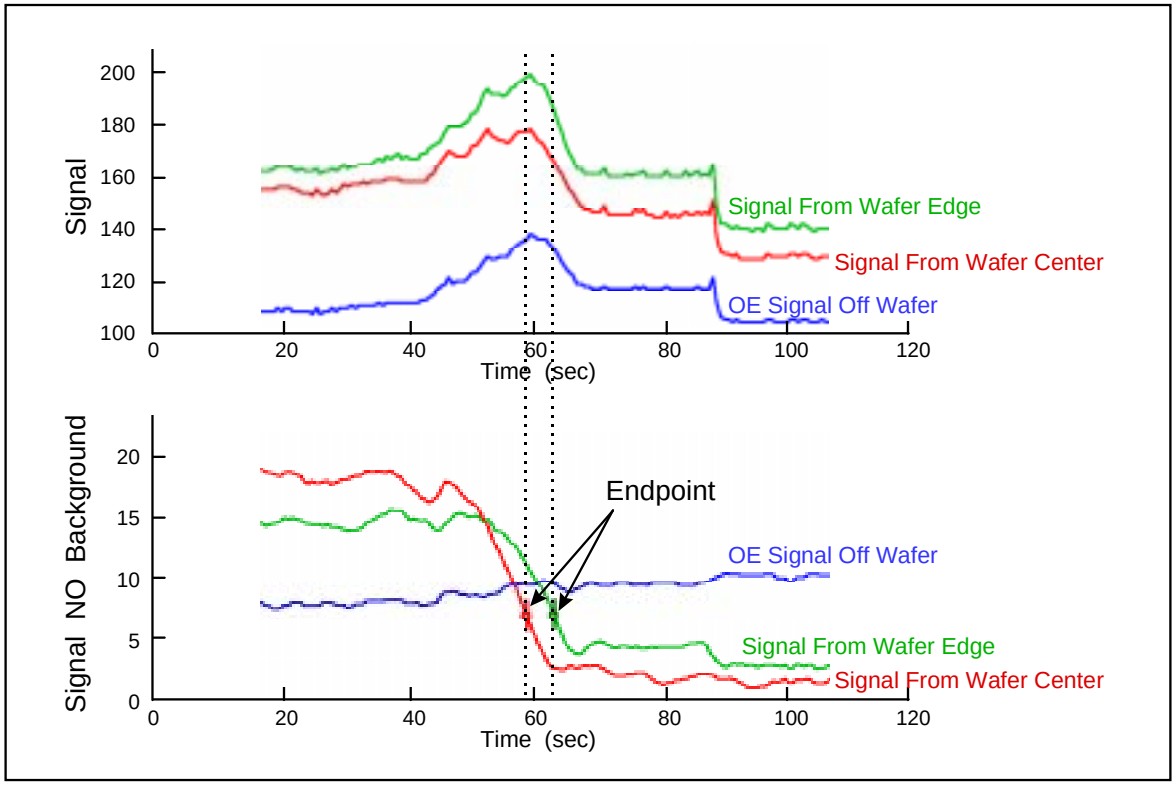


Figure 15. Reflectometry: top - raw signal, bottom - signal divided by optical emission.

was near 610 nm, which corresponds to an atomic chlorine emission line. Figure 15 shows the signal versus time recorded by the LES1200 from three different locations: one at the wafer edge, one at the wafer center, and one off the wafer. The signal off the wafer is the optical emission at 610 nm.

The top part of Figure 15 shows that the optical emission intensity at 610 nm increases considerably at endpoint. This is due to the decrease in atomic chlorine consumption by aluminum that occurs when the aluminum clears. The large increase in optical emission intensity makes it very difficult to detect any changes in reflectivity on the wafer surface that occur when the aluminum clears and the underlying material is uncovered.

The raw signal as a function of time is equal to the reflectivity of the wafer surface multiplied by the light source (the optical emission). Therefore dividing the raw signal by the optical emission yields the true reflectivity. The bottom part of Figure 15 shows the raw signal divided by the optical emission signal. Spatially resolved endpoint is clearly evident. In this example, the center of the wafer reached endpoint before the edge.

LES1200 System Parameters

Specifications (Representative, actual values depend on process, equipment, and film properties.)

Maximum Rate:	130,000 Å/min (polysilicon)	300,000 Å/min (oxide)
Minimum Rate:	~ 20 Å/min	
Rate Accuracy:	1-2%	
Maximum Film Thickness:	15,000 Å (polysilicon)	50,000 Å (oxide)
Minimum Change in Thickness:	700 Å (polysilicon)	1200 Å (oxide)
Maximum Data Acquisition Rate:	25 Hz	
Minimum Open Area:	~ 5% (applies to etching only)	
CCD Spectral Range:	400 - 1100 nm (down to 220 nm with UV modifications)	

Components

LESWare - software for data acquisition, control, and analysis
PCI multi-sensor control board for up to four sensor heads
Remote, pixel-memory-mapped CCD head(s)
Control daughter board(s)
Imaging optics
System installation
Clean room and regular copies of manual
On-line Help
User training

Computer control system for data acquisition and analysis:
- PC compatible Pentium 200 MHz CPU (or faster)
- 128-256 MB memory
- 2-4+ GB SCSI hard drive
- 4 GB SCSI DAT tape backup
- 1280x1024, 256 color graphics: 2 MB memory PCI card and non-interlaced monitor
- PCI and ISA bus
- Windows NT 4.0

Options

Tool communication interface and software
TR1200 Trench Metrology Sensor head
External light source
High magnification lens
Multi-station software license
Extended service contract

Installation Requirements

1. Optical access to the wafer via a viewport at an angle of less than 60^{o} from wafer normal. (Larger angles can usually be accommodated.)
2. Clear view of the region of interest on the wafer during processing.
3. Room for 70x100x70mm sensor and mounting bracket.

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