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High Speed and High Resolution Two-Dimensional Film Thickness Distribution Measurement System FiDiCa$^{\text{TM}}$ Using Hyperspectral Camera

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Abstract:

High speed and high resolution two-dimensional film thickness distribution measurement system "FiDiCa^{TM}" using a hyperspectral camera can measure more than 4 million points of thickness data within 2 minutes by parallel distributed processing. There are several models of the FiDiCa for thin film, thick film and base materials, respectively. It can be selected depending on the thickness of the measurement object.

1. Introduction

In manufacturing semiconductor devices, in recent years, not only forming of thin films on wafers, as in the conventional technology, but also technologies for forming functional films on minute circuit patterns or thinning the wafers as such are advancing. In those processes, it is necessary to form a uniform film unaffected by the components on the substrate circuit, or to control the thickness uniformly while performing the control necessary in the wafer thinning process1). Since uniformity of functional films and the thickness of wafers is an important requirement that directly affects semiconductor performance, technologies for larger areas and higher resolution are now required, not only in thickness control, but also in thickness measurement. On the other hand, since the time allowed for measurement of the film thickness data of the entire wafer surface has also become shorter, high-speed technologies for acquiring large volumes of film thickness data are also needed.

In the technologies generally used to measure film thickness, light having an intensity across the full measurement wavelength range is irradiated on the area where the target film exists, the spectrum is measured with a light detector using the interference phenomenon of the reflected or transmitted light, and the film thickness is then calculated from the acquired spectrum observed by spectrograph2). Variations in the film thickness on wafers are unavoidable, even with progress in technologies for achieving uniformity. For this reason, it is necessary to acquire data from as many points as possible on the entire wafer surface, but when using a film thickness meter that measures only one point, measurements must be made by moving the meter to various other measurement points.

However, various problems arise when attempting to obtain a high-resolution film thickness distribution of the entire wafer surface, including the lengthy measurement time due to the large area and enormous number of points to be measured.

The hyperspectral camera can simultaneously measure a large volume of spectrum data in a linear region, and the FiDiCa$^{\text{TM}}$ film thickness distribution measurement system is capable of measuring the film thickness over a large area with high resolution and high speed using the hyperspectral camera. The FiDiCa system is capable of measuring the 2-dimensional film thickness distribution using a hyperspectral camera that enables simultaneous measurement of 1 000 to 2 000 points. Moreover, since camera technology is used, the FiDiCa has a high degree of freedom in the selection of the field of view width and spatial resolution, and since it is also possible to select the type of spectrograph used, it also has a high degree of freedom in the type of film to be measured, the thickness range, etc.

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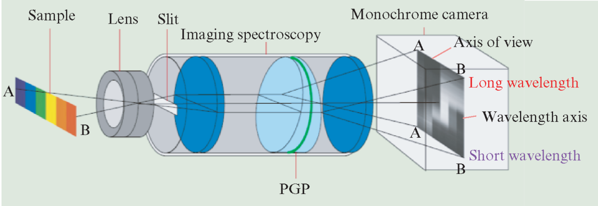

Fig. 1 Conceptual diagram of hyperspectral camera

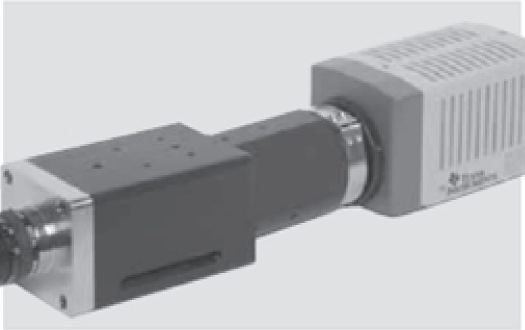

Photo 1 External view of hyperspectral camera

More than 20 years have passed since the FiDiCa was conceived, and 15 years have passed since the first model was launched. During this period, JFE Techno-Research Corporation (JFE-TEC) has accumulated know-how related to measurement and analysis of a large number of measurement objects in a wide range of fields. This article describes the current generation of FiDiCa systems incorporating measurement and analysis technologies based on JFE-TEC's previous experience in measurements up to the present.

2. Hyperspectral Camera

The hyperspectral camera combines an imaging spectrograph, which has a transmission-type optical system materialized by a PGP (prism/grating/prism) element with a structure consisting of a holographic diffraction grating between two prisms, and a monochrome area camera and lens, and is capable of simultaneously measuring the spectral data of multiple continuous points (i.e., a linear region)$^{3)}$. **Figure 1** shows a conceptual diagram of a hyperspectral camera.

This device converts light to 2-dimensional information by linearizing received light by a slit at the focal point of the lens and dispersing that light into separate wavelengths in the direction perpendicular to the slit as it passes through the PGP. This 2-dimensional information is then captured by the monochrome camera located after the spectrograph and transmitted to the computer as image data. Through this process, the spectral data is treated as intensity signals of the camera. **Photo 1** shows the external appearance of a hyperspectral camera.

The most characteristic method of using a hyperspectral camera is to acquire continuous 2-dimensional spectral information by moving the position of the target sample or the hyperspectral camera relative to the linear region in the direction perpendicular to the linear region, and continuously capturing hyperspectral data.

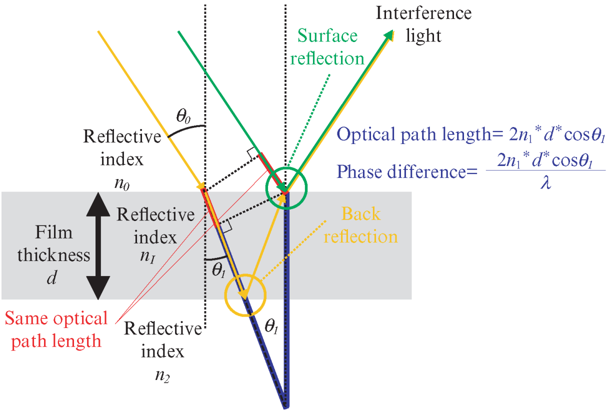

Fig. 2 Principle of optical interference

3. Film Thickness Measurement Applying Optical Interference

When light strikes a thin film, interference between the light reflected by the front surface of the thin film and light reflected by the back surface can be observed. The brightness of the interfering light is determined by the optical path lengths of the light reflected by the front and back surfaces, that is, the difference of the optical path length x the refractive index and the wavelength. The intensity of the interfering light is maximum or minimum when the optical path length is an integer multiple of 1/2 of the wavelength. Whether the intensity is the maximum or minimum is determined by the magnitude of the refractive index of the media before and after the reflecting interface. **Figure 2** shows the principle of optical interference.

Film thickness measurement devices using optical interference focus on this phenomenon. By moving the spectrograph or the measuring object point by point on the thin film and measuring the spectra of the interfering light at designated points on a wafer, and the film thickness is calculated from the changes in the light intensity at various wavelengths$^{4)}$. The period of the changes in light intensity is related to the film thickness, becoming shorter as the film thickness increases and longer as the film thickness decreases. For example, **Fig. 3** and **Fig. 4** show the graphs of a typical spectrum of a 3 µm thick film and a 30 µm film, respectively.

Since the interference spectrum changes in this

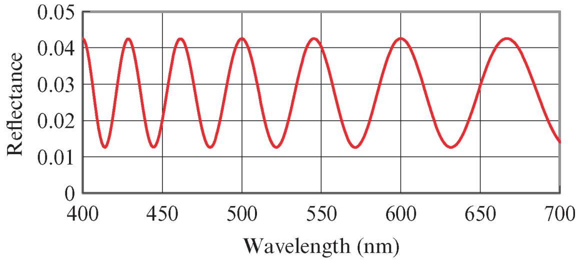

Fig. 3 Typical spectrum for 3 μm thick film

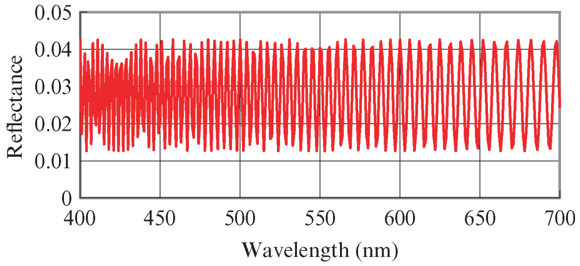

Fig. 4 Typical spectrum for 30 μm thick film

manner depending on the film thickness, it is possible to calculate the film thickness by measuring the interference spectrum.

4. Film Thickness Distribution Measurement System: FiDiCa™

4.1 Image Data Captured by the Hyperspectral Camera

The FiDiCa film thickness distribution measurement system is a technology that uses a hyperspectral camera in place of the point measurement-type spectrograph used in film thickness measurements in conventional devices, and is capable of capturing spectral data, that is, film thickness data equivalent to the pixel number of the spatial axis of the camera. **Figure 5** shows an example of a hyperspectral image of a thin film.

The horizontal direction in Fig. 5 is the spatial axis, and the vertical direction is the wavelength axis. The intensity (brightness) on an arbitrary line in the vertical direction shows the relative intensity of the reflected light generated by interference at each position. Looking at the horizontal direction, vertical variations in the position of the fringe indicating intensity can be observed. Since qualitative agreement of these vertical changes in the fringe with changes in the film thickness is a characteristic phenomenon, the film thickness distribution of the photographed linear region can be understood, even by simple observation of this image.

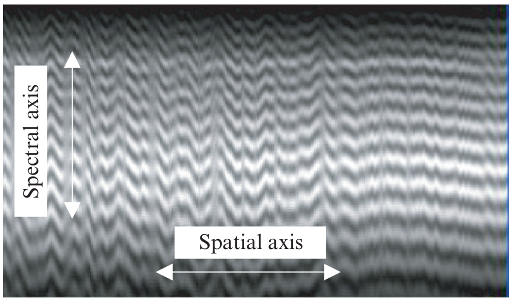

Fig. 5 Typical image of film using hyperspectral camera

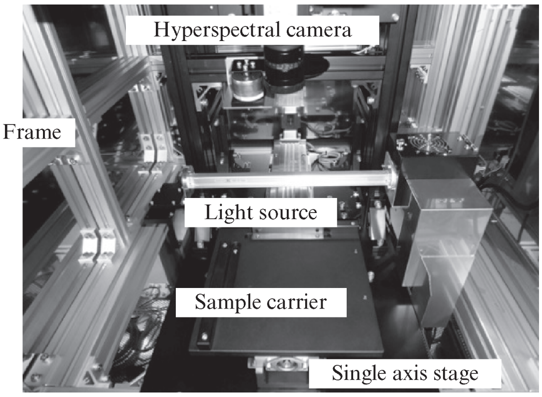

Photo 2 Internal structure of FiDiCa™

4.2 Hardware Configuration of FiDiCa™

In the FiDiCa, data for a 2-dimensional region are acquired by relative movement of the hyperspectral camera and measurement object in the direction perpendicular to the linear region being measured. When a film or other object is to be measured by continuously moving the measurement object, the data for the 2-dimensional region can be acquired simply by setting the hyperspectral camera and lighting device. However, when measuring semiconductor wafers, the measurement of the specified 2-dimensional region can be carried out by moving a sampling table on which the measurement object is set, corresponding to the size of the object.

Photo 2 shows the internal structure of the FiDiCa. The hyperspectral camera is installed in the upper part, and linear irradiation light source and the movable stage on which the sampling table is set are in the lower part. The slit of the hyperspectral camera and the light source are arranged in parallel, and the wafer moves in the direction perpendicular to that direction. Photo 2 is an example of a FiDiCa system which is capable of measuring wafers with a maximum size of up to 8 inches.

The object wafer is set on a sample table installed on a uniaxial stage. FiDiCa systems include a stand-

Photo 3 External view of standalone type (left) and robot transport type (right) of FiDiCa$^{\text{TM}}$

alone type (**Photo 3**, left) used for the development in the laboratory and similar applications, in which the wafer is placed on the sample table by hand, and an in-line automatic measurement system (Photo 3, right) equipped with a robot transport function, which automatically extracts wafers from a cassette, correctly positions and sets the wafer on the sample stand, and carries out measurements continuously.

4.3 Data Measured by FiDiCa$^{\text{TM}}$

The data measured by the FiDiCa is called cube data, in which the light intensity at points in 3 dimensions is shown by arranging 2-dimensional images consisting of the X axis (field of view width direction) and λ axis (wavelength direction) on the Y axis, which is the scan direction, by continuously scanning images like those in Fig. 5 using the hardware shown in Photo 2. **Figure 6** is an image obtained by extracting only the 2-dimensional intensity distribution of the X axis-Y axis of a single band (wavelength region) from the cube data measured by a FiDiCa system.

FiDiCa systems can generate images of all bands when measuring several 100 bands. Although similar images can also be captured by a monochrome camera equipped with a bandpass filter, it would be necessary to use several 100 bandpass filters having a peak height at half width similar to the optical wavelength resolution of the hyperspectral camera.

Various types of spectrographs are used in the FiDiCa systems. Spectrographs with optical wavelength resolution of approximately 2 nm are used with thin films. However, since even higher optical wavelength resolution is required in spectrographs used with thick films and in measurements of the base material thickness, it is realistically impossible to capture data with performance similar to a FiDiCa system by using bandpass filters.

The acquired cube data are stored temporarily in the computer memory, and film thickness calculations are performed after scanning.

Fig. 6 Typical image of single band intensity (650 nm)

4.4 Film Thickness Calculations by FiDiCa$^{\text{TM}}$

As the algorithms used when calculating the film thickness, algorithms using the Fourier transform method[5)], the curve fitting method[6)], and a proprietary JFE-TEC method are installed in the FiDiCa. The Fourier transform method enables direct calculation of the film thickness from the measured interference waveform. However, with FFT (Fast Fourier Transform), which is used as a Fourier transform method that can be implemented in computers, the applicable wavelength region is limited, as it is known that adequate film thickness resolution cannot be obtained with thin films because the interference spectrum contains fewer waves with relative intensity variations. For this reason, the curve fitting method is generally used with objects that require high film thickness resolution. However, this method is not suitable for calculations involving a large number of points, as in the case of FiDiCa, due to the high computational load in processing such as calculations by the least squares method, etc.

To overcome these problems, JFE-TEC developed a proprietary technique for calculating the film thickness from the actual spectrum. In this method, the theoretical spectra of various thicknesses, which are calculated theoretically in advance, are stored in the memory as a table. The actual (measured) spectrum is then compared with the theoretical spectra, and the theoretical spectrum with the smallest separation from the actual spectrum is used as the calculated value of the film thickness.

However, simply calculating the theoretical spectra in advance does not significantly shorten the time required for film thickness calculations. Since calculating all individual points under the same conditions is extremely time-consuming, in order to perform film thickness calculations for large numbers of points in a short time, FiDiCa achieves a revolutionary technique

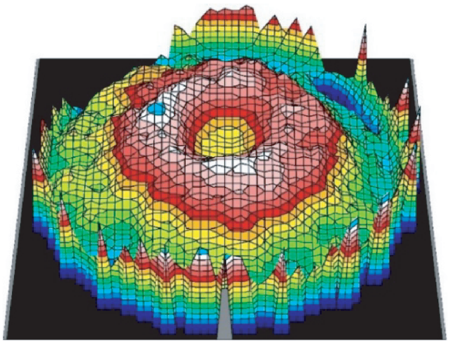

Fig. 7 Result of conventional equipment

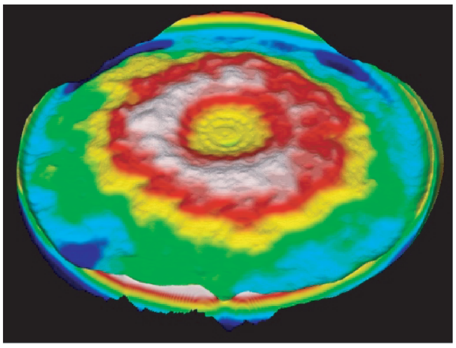

Fig. 8 Result of FiDiCa™

that transforms the demerit of calculating a huge number of points into a merit by adopting a method that speeds up the calculation process, by not only applying distributed parallel processing to increase the number of points that can be calculated simultaneously, but also using information from neighboring points. The development of this ultra-high-speed algorithm has made it possible to perform film thickness calculations involving 10 000 to 100 000 points in 1 second.

Due to the nature of the algorithm, the time required for film thickness calculations differs depending on the wavelength range and film thickness range specified for the calculation of film thickness. The calculation speed is fast when the separation from the theoretical spectrum is small, that is, the phenomenon is close to the theoretical condition, and in calculations for objects with little variation in the film thickness, and is slow under the opposite conditions.

4.5 Comparison of FiDiCa™ and Other Equipment

Figure 7 shows a quasi-3D representation of the film thickness distribution obtained by 2-dimensional scanning a certain sample with a point measurement-type film thickness meter. In this measurement, a time of about 1 hour was required to obtain the results for 50 points x 50 points.

In contrast, **Fig. 8** shows the results when the same sample was measured with a FiDiCa system. The time required to obtain the results for 1 024 points x 1 024 points was approximately 100 seconds.

As can be understood from these figures, in addition to the fact that data for about 400 times as many points can be obtained in about 1/30 of the time, the fine pattern created by variations in the film thickness can also be observed.

Thus, while the ability to acquire a large volume of film thickness information in a short time is a strong point of FiDiCa, this technology does not simply obtain information for a large number of points, but also allows the user to “see what could not be seen until now.”

4.6 Problems of Film Thickness Calculations by FiDiCa™

When the FiDiCa calculates the film thickness from the measured interference spectrum, the actual measured thickness is compared with interference spectra obtained by theoretical calculations. However, since these theoretical interference spectra are calculated from theoretical optical interference equations, it is impossible to consider the effects of the film surfaces and interfaces of each layer, internal scattering, impurities in the layers and similar problems. Moreover, in theoretical calculations, it is also necessary to input optical constants for each layer, including the base material, that is, the values of the refractive index and extinction coefficient, which change within the wavelength range of the spectrograph. Although these optical constants can be obtained by measuring the actual object of measurement, in almost all cases, either values found in the literature or only the values at specified wavelength are used, and in actuality, the separation from the actual values in the wavelength range in which theoretical calculations are performed is not negligible. Due to these factors, there is some separation between the actual interference spectrum and the theoretical spectrum in most cases.

Figure 9 is an example of an interference spectrum (red line) obtained by measuring a certain sample and an interference spectrum (blue line) obtained by theoretical calculation. While the maximum and minimum values of the interference spectra are generally in agreement, there is a large separation in reflectance.

Among the causes of separation of the wavelengths with the maximum and minimum values, the main cause is frequently the effect of error in the optical constants of the layer of interest. On the other hand, in many cases, the causes of separation of reflectance are disorder of the shape from the ideal mirror surface, such as the surface roughness of the measurement object, etc., and the effect of error in the ratio of the

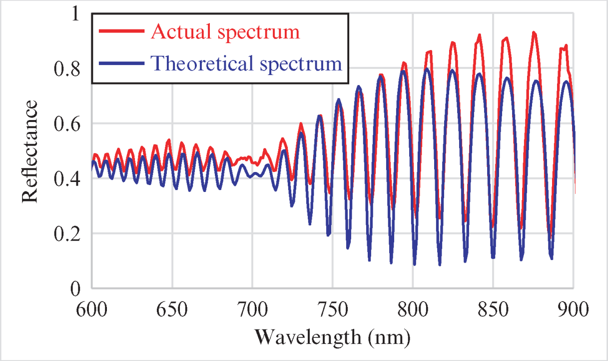

Fig. 9 Actual spectrum and theoretical spectrum

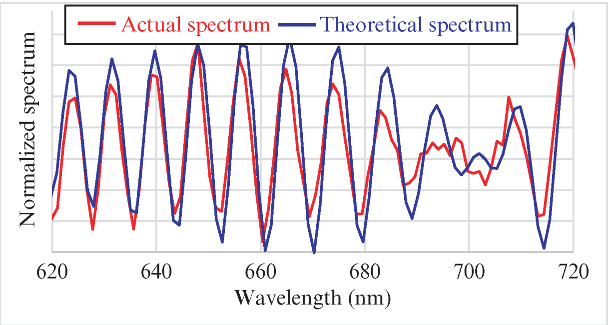

Fig. 10 Normalized spectrum over limited wavelength range

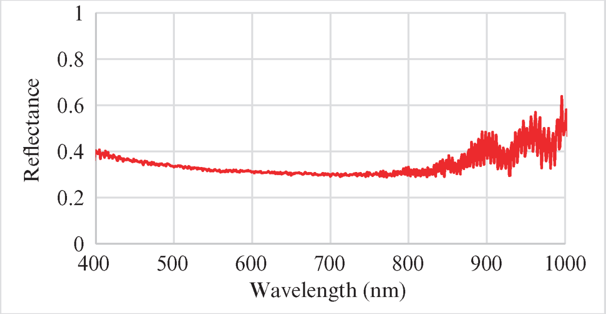

Fig. 11 Actual spectrum of SOI wafer with silicon layer thickness of 20 µm measured using FiDiCa^{TM} for thin film

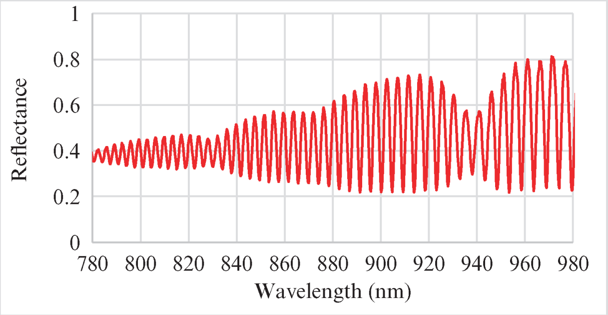

Fig. 12 Actual spectrum of SOI wafer with silicon layer thickness of 20 µm measured using FiDiCa^{TM} for thick film

refractive indices of each layer. Realistically, it is almost impossible to completely eliminate these types of separation. Therefore, in some cases, the film thickness is calculated after reducing the separation between the actual spectrum and the theoretical spectrum by limiting the wavelength range in order to reduce the effect of errors in wavelength dispersion, and normalizing the refractive index in the wavelength range to be calculated by the maximum and minimum values of reflectance to reduce the effect of errors in reflectance.

Figure 10 shows an example of the actual spectrum and the theoretical spectrum when the data in Fig. 9 were normalized over a limited analysis wavelength range.

5. Examples of Measurement by FiDiCa^{TM}

5.1 Measurement of Silicon Layer Thickness of SOI Wafer

SOI (Silicon on Insulator) is a type of wafer in which an insulation film is arranged between the transistors and the silicon layer. Since various properties are controlled by the thickness of the insulation film layer and the silicon layer, it is extremely important to form the thickness of each layer uniformly.

In order to measure thickness by applying optical interference, light must be transmitted through the film being measured, but the most necessary thickness measurement in SOI wafers is considered to be the measurement of the silicon layer. However, due to the low visible light transmissivity of silicon, almost no interference is observed in the visible light region as the silicon layer becomes thicker. **Figure 11** shows the actual measured spectrum of a SOI wafer with a silicon layer thickness of approximately 20 µm in the 400–1 000 nm wavelength range. As can be understood from **Fig. 11**, in measurements of the silicon layer of SOI wafters with a thick silicon layer, it is necessary to use near-infrared light, and not visible light.

Figure 12 shows the spectrum measured in the 780–980 nm wavelength range. This spectrum was measured with a FiDiCa specially designed for measurement of thick films. In addition to using a longer wavelength range than the spectrograph used in the FiDiCa for thin films, its optical wavelength resolution is also higher.

5.2 Measurement of SAW Wafter by High-Resolution FiDiCa^{TM}

Since FiDiCa uses a hyperspectral camera, it has the various merits of camera technology. The greatest of those advantages is the ability to freely change the field of view width and spatial resolution by adjusting

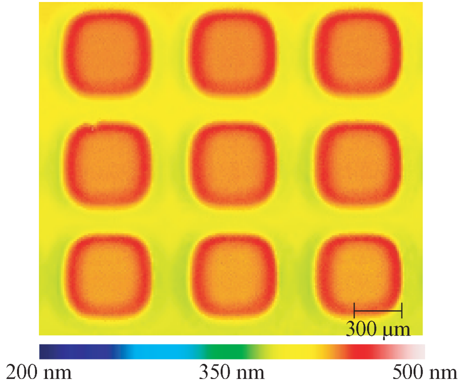

Fig. 13　Result of SAW wafer using high-resolution FiDiCa$^{\text{TM}}$

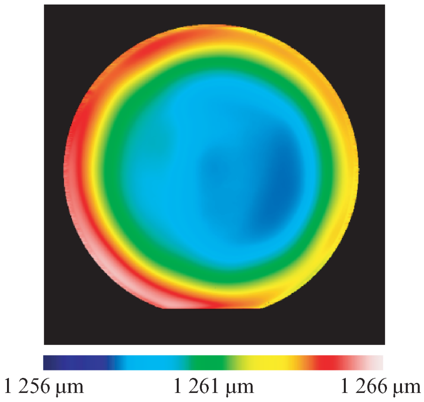

Fig. 14　Result of crystal wafer using FiDiCa$^{\text{TM}}$ for base material

the focal length and image distance of the lens being used. When the measurement object is a film or other object with a wide width, a width of several meters can be measured with one camera using a wide-angle lens to increase the imaging distance. It is also possible to expand the field of view width while maintaining the same high resolution by increasing the number of cameras.

In SAW (Surface Acoustic Wave) devices, the thickness of the thin film formed on the densely arranged circuit directly affects the performance of the device, resulting in emerging needs for film thickness distribution measurement with spatial resolution of 10 µm or less. In response to these needs, a high-resolution FiDiCa was also released. This instrument features a magnifying-type lens in the hyperspectral camera and is equipped with a scanning stage that allows highly precise control of the wafer setting position and angle.

Figure 13 shows the results of a measurement of test base materials simulating the substrates on which the wafers of SAW devices are integrated. Here, a high-resolution FiDiCa with spatial resolution of approximately 6 µm was used. The FiDiCa system with the highest magnification lens has a spatial resolution specification of approximately 1.5 µm, and is used to accurately measure the film thickness in specified narrow regions within complex patterns.

5.3 Measurement of Crystal Thickness by FiDiCa$^{\text{TM}}$ for Base Material Thickness Measurement

FiDiCa systems are available in a range of models, including systems for thin films for measuring thicknesses of 20 nm to 20 µm, for thick films with thicknesses of 1 µm to 200 µm, and for thicker films, namely, wafers as such. The FiDiCa for base material thickness measurement is equipped with a spectrograph with higher wavelength resolution than the FiDiCa for thick films, allowing measurement of silicon thicknesses from 20 µm to 800 µm.

Figure 14 shows an example of a measurement of the thickness distribution of a crystal wafer using the FiDiCa for base material.

6. Conclusion

At present, 17 years have passed since the start of sales of FiDiCa$^{\text{TM}}$ film thickness measurement systems, and a number of different models have been developed in response to various needs. In order to respond to further diversification of user needs, development of multiple new models is also planned in the coming year. The development of film thickness measurement systems also includes the development of spectrographs as such, as well as the development of new algorithms for film thickness analysis, methods of handling measurement objects and measurement of features other than film thickness, spanning a diverse range from standalone laboratory instruments to in-line systems that are expected to operate 24 hours a day, 365 days a year.

The fields of measurement objects are also diverse, and include various objects, ranging from unique “one-off” items to objects with high repeatability.

The merits of acquiring film thickness data for a large number of points by using the hyperspectral camera are not limited simply to increasing the number of measurement points of objects that had be measured with point-type film thickness meters and shortening the measurement time, but also include visualization of highly-precise film thickness distributions that was not possible until now. Starting from that point, we hope to discover completely new operating methods together with our customers.

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