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컬러 카메라 이미징 물리 행렬
엘립소미터를 이용한 영역 분류와
박막 두께 측정에 관한 연구

Region Classification and Thin-film Thickness
Measurement Using Color Camera Imaging Mueller
Matrix Ellipsometry

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Abstract

The ellipsometer, one of the optical measurement systems, are widely used because of the advantages of non-contact, non-destructive and rapid measurement. The spectroscopic method has the superiority of high precision because of high wavelength resolution, but the system can not measure narrow areas and has ambiguity in the measurement area and a limit for measuring only a single area. Imaging systems using 2D CCD are a technique to increase spatial resolution to pixel levels. Traditional monochromatic imaging methods have uncertainty in measurement because of the lack of wavelength data, and multi-wavelength imaging methods have long measurement time due to wavelength changes. In this study, a color camera imaging Mueller matrix ellipsometer is proposed to solve the problem. Further, imaging methods have a problem that takes a long time to analyze the entire pixel of an image, and a clustering method is proposed to solve the analysis time problem.

The measured data with the color camera is the result of a superposition of different wavelengths due to the Bayer filter. Therefore, a new Mueller matrix equation is proposed considering the transmittance of the filter that can be applied to a broadband wavelength filter. Thickness measurements were implemented using the proposed method and verified by comparing with the measured results with validated hardware.

Through the clustering method used in the study, the image was classified into regions having similar Mueller matrices, and the average thicknesses of each class were measured. By examining the standard deviation within each cluster, we have verified that the
mean of the Mueller matrix of the class can represent the class

**Keyword**: Imaging ellipsometry, Imaging Mueller matrix ellipsometry, color camera, broadband filter, Thin-film thickness measurement, Region classification, Clustering

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Chapter 1. Introduction

1.1. Research background

Semiconductor and display manufacturing technology is steadily developed, and the pattern size of a product is steadily decreasing. Process stability and yield management are essential to produce high-quality products. One significant challenge in realizing such nanofabrication is the development of rapid, low-cost, non-destructive metrology. Scanning electron microscopy (SEM) or transmission electron microscopy (TEM) can provide high precision data but are time-consuming, expensive, difficult to operate and difficult to achieve in-line measurements. On the other hand, the ellipsometer is an optical measurement method, which has attractive advantages such as low cost, high throughput, and minimal sample damage[1].

Reflectometry is a method of measuring the thickness using the reflectivity that is the intensity ratio of the incident light on the specimen and the reflected light. The method is widely used for relatively simple formulas and few measurement procedures to measure a thickness of thin-film, there is a limit to the impossibility of measuring the refractive index of a material. In the case of the traditional ellipsometer, the ellipsometric coefficients $\Delta$ and $\Psi$ are measured by measuring the reflectance and phase changes of each polarized light incident on the sample. This technique is an optical metrology technique that characterizes optical constants such as the thickness of a thin film and the refractive index of bulk material. However, the method cannot measure an optical property of
anisotropic materials such as diffraction grating and quartz and the depolarization effect of the matter. Therefore, Mueller Matrix ellipsometer (MME) has been studied.

Among the measurement systems of ellipsometry and reflectometry, the spectroscopic analysis method has the advantage of accurately measuring data with a plurality of wavelength data. However, due to the size of the spectroscopic measurement unit, it is impossible to measure a narrow region, it is difficult to locate the measurement position accurately, and the measurement area is large, which causes ambiguity in the measurement region. Since it is a point measurement, it is disadvantageous in measuring a large number of points or a large area. Research on imaging method using 2D CCD has been studied to solve this problem. The imaging measurement method is advantageous in that it has a high spatial resolution by reducing the measurement area because it is possible to perform a pixel-by-pixel analysis. In the case of the imaging method, when the information of all the pixels is analyzed, the computational time is too long, and only the data of the specific pixel is analyzed.

1.2. Research trends

1.2.1. Mueller matrix ellipsometry

Mueller matrix ellipsometry (MME) was introduced to monitor the critical dimensions (CD) of grating structures in semiconductor fabrication and thin-film thickness measurement of materials in display fabrication. This technique, also known as optical critical dimension measurement (OCD), has attractive advantages over
SEM, AFM, and TEM such as low cost, high throughput, and minimal sample damage.

MME is a powerful technology that can accurately determine the dielectric function, optical properties and geometry of anisotropic materials and complex systems. The Mueller matrix provides the most general and complete description of an optical property of the sample regardless of its reflection or transmission. In the case of calculating the theoretical grating by using RCWA, it is also possible to measure the grating of the complex shape of the multilayer film [2].

1.2.2. Imaging reflectometry

Reflectometry has been used as a powerful tool to monitor thin film thickness in display thin film deposition processes. As the display pattern becomes complicated due to the miniaturization of
the process, difficulties of analysis in a narrow region and simultaneous measurement of multiple spots have appeared. For this purpose, a method of imaging using a CCD camera was studied.

Data of various wavelengths was required to produce a similar performance to the existing spectral analysis system, and there was a study of a method of measuring the reflectance by acquiring an image for each wavelength by changing monochromatic light filters such as a Figure 1.1(a) [3]. There has been studied a method using a color camera to solve the problem of increased measurement time due to the process of changing the filters such as the Figure 1.1(b) [4, 5].

However, there is a problem in that the reflectometer is sensitive to the noise of the sensor because the reflectance is measured using the ratio of the intensity of reflected light from the measurement sample to the intensity of reflected light from the reference sample.

1.2.3. Imaging ellipsometry

Previously studied imaging ellipsometry has the advantage of having much higher spatial resolution than spectroscopic ellipsometry, and it can be used to distinguish abnormal cells in biology by measuring all the Mueller matrices in the region[6]. A monochromatic imaging method, primarily used in biology, has the problem that the same Mueller matrix is measured in thin films of various thicknesses, such as the Figure 1.2, resulting in measurement uncertainty.
In the case of multi-wavelength imaging ellipsometry, the measurement needs a long time because the wavelength is changed several times using a unique light source such as a xenon lamp or several filters in front of the light source [7, 8]. Among the methods to solve this problem, a study using a CCD equipped with three color interference filters has been proposed [9]. However, this method does not measure the Mueller matrix but measures only the ellipsometric coefficients $\Delta$ and $\Psi$, so there is a limitation that anisotropic materials, diffraction gratings, and unpolarized effects cannot be measured.

![Graph showing L2 error of 495nm SiO2 thin film vs. thickness (nm)](image)

**Figure 1.2: Uncertainty in monochromatic ellipsometer**

### 1.3. Research topic

In this study, we developed an imaging Mueller matrix ellipsometer using a color CCD with a Bayer filter. The measured signal was analyzed to measure the Mueller matrix corresponding to the RGB value of each pixel of the sample and the optical characteristics of the sample by the Mueller matrix decomposition.
The quadrant specimens deposited on Si with four thicknesses of SiO2 were measured, and their measurement performance was verified by comparing them with the conventional spectroscopic ellipsometer. After classifying the image region using the measured Mueller matrix and clustering method, the distribution of the thickness of the thin film in each group was confirmed, confirming the reliability that the cluster can represent the region.
Chapter 2. Introduction

2.1. Optical theory

2.1.1. The law of refraction and reflection

When the light enters the boundary of medium with a different refractive index, the incident angle and the reflection angle are the same.

\[ \theta_i = \theta_r \]  \hspace{1cm} (2.1)

In the case of refraction, the complex refractive index of the incident angle, refraction angle, and medium satisfies Snell's law.

\[ \tilde{N}_1(\lambda) \sin \theta_1 = \tilde{N}_2(\lambda) \sin \theta_2 \]  \hspace{1cm} (2.2)

Here, N1 and N2 are optical properties of each medium, which is called a complex refractive index and is a function of wavelength.
The complex index of refraction consists of the refractive index of the real part and the extinction ratio of the imaginary part.

\[ \tilde{N} = n - ik \]  \hspace{1cm} (2.3)

When the light is incident obliquely, the electric field component oscillating in a direction parallel to the incident surface is defined as a P wave, and the vertical component is defined as S wave. The amplitude and phase change of the reflected and refracted light of each wave at the interface of the medium are obtained by Fresnel Coefficient

\[ r_{12}^p(\text{lambda}) = \frac{\tilde{N}_2 \cos \theta_1 - \tilde{N}_1 \cos \theta_2}{\tilde{N}_2 \cos \theta_1 + \tilde{N}_1 \cos \theta_2} = |t_{12}^p| e^{i\delta_{12}} \]  \hspace{1cm} (2.4)

\[ r_{12}^s(\text{lambda}) = \frac{\tilde{N}_1 \cos \theta_1 - \tilde{N}_2 \cos \theta_2}{\tilde{N}_1 \cos \theta_1 + \tilde{N}_2 \cos \theta_2} = |t_{12}^s| e^{i\delta_{12}} \]  \hspace{1cm} (2.5)

\[ t_{12}^p(\text{lambda}) = \frac{2\tilde{N}_1 \cos \theta_1}{N_2 \cos \theta_1 + N_1 \cos \theta_2} = |t_{12}^p| e^{i\delta_{12}} \]  \hspace{1cm} (2.6)

\[ t_{12}^s(\text{lambda}) = \frac{2\tilde{N}_1 \cos \theta_1}{N_1 \cos \theta_1 + N_2 \cos \theta_2} = |t_{12}^s| e^{i\delta_{12}} \]  \hspace{1cm} (2.7)

### 2.1.2. Multiple reflections in thin-film

In the case of a sample on which a thin film is deposited on a substrate, reflected light in the thin-film produce interference. When light is reflected between thin films, the phase and intensity changes follow the Eq (2.4) \((2.7)\) in the previous section. The phase change due to the refractive index of the medium when passing through the thin film is as follows.
\[ \beta = kdN_2 \cos \theta_2 \] (2.8)

\( k = 2\pi/\lambda \) is wavenumber and \( d \) is a thickness of the thin film.

The reflection coefficient is obtained by adding the infinite series along the path of the light shown in the Figure 2.2.

\[ R = \frac{r_{12} + r_{23}e^{-i2\beta}}{1 + r_{21}r_{23}e^{-i2\beta}} \] (2.9)

The reflectivity for each P, S polarization state is obtained as follows.

\[ R^p = \frac{r_{12}^p + r_{23}^p e^{-i2\beta}}{1 + r_{21}^p r_{23}^p e^{-i2\beta}} = |R^p|e^{i\delta_p} \] (2.10)

\[ R^s = \frac{r_{12}^s + r_{23}^s e^{-i2\beta}}{1 + r_{21}^s r_{23}^s e^{-i2\beta}} = |R^s|e^{i\delta_s} \] (2.11)

2.2. Jones and Mueller matrix

The 2x2 Jones matrix is a matrix expression for manipulating the Jones vector describing the polarization of light. The optical properties of optical parts and samples are expressed as Jones matrix as follows.
\[
J = \begin{pmatrix}
    r_{pp} & r_{ps} \\
    r_{ps} & r_{ss}
\end{pmatrix}
\] (2.12)

\(r_{ij}\) represents the degree of reflection of \(j\) polarized light after \(i\) polarized light is incident. \(r_{ps}\), and \(r_{sp}\) have values of 0 for isotropic materials. The theoretical reflections \(R^p\) and \(R^s\) obtained from chapter 2.1.2 correspond to \(r_{pp}\) and \(r_{ss}\), respectively, and the theoretical Jones matrix can be obtained.

In Jones matrix, it is simple to express the change of the intensity and phase difference of P and S polarization state, but there is a limitation that it cannot express partially polarized light and non-polarized light. The Mueller matrix, a matrix of 4x4, can express all polarization states including incoherent and partially polarized radiation. To convert the Jones matrix to the Mueller matrix, use the following equation.

\[
M = A(J \otimes J^*)A^{-1}
\] (2.13)

\[
A = \begin{pmatrix}
1 & 0 & 0 & 1 \\
1 & 0 & 0 & -1 \\
0 & 1 & 1 & 0 \\
0 & -i & i & 0
\end{pmatrix}
\] (2.14)

2.3. Mueller matrix ellipsometry

2.3.1. Ellipsometry configuration

The conventional ellipsometer mainly utilizes a Polarizer–Sample–Analyzer (PSA) structure consisting of only polarizers. The PSA structure cannot get the entire Mueller matrix like the Figure 2.3 but only cover the 3x3 matrix. Therefore, we use
ellipsometry with a polarizer–compensator–sample–compensator–
analyzer (PCSCA) structure to obtain all of the 4x4 Mueller matrix.

Figure 2.3: Ellipsometer type and measurable Mueller matrix
2.3.2. MME part

The Mueller matrix ellipsometry is divided into a polarization state generator (PSG) section that creates and radiate various types of polarized light into the sample, and a polarization state analyzer (PSA) section that analyzes the polarization state of reflected light from the sample. The PSG and PSA are composed of polarizers and compensators, and each component is selected according to the wavelength band or use of the light source to be used.

The compensator is used to create and analyze various polarization states by changing the phase of the P and S waves. Among them, dual-rotating retarder (DRR), liquid crystal retarder (LCR), or photoelastic modulator (PEM) are widely used[10]. Each type has advantages and disadvantages, among which DRR system has advantages for available in a wide range of wavelengths and low complexity in hardware alignment and correction. Therefore, in this study, DRR Mueller matrix ellipsometer (DRR-MME) is used.
In the case of DRR-MME, two compensators is rotated and measured at a specific angular rate. As the compensators rotate, the measured data is transformed to the frequency axis through the Fourier transform, and the elements of the Mueller matrix of the sample can be obtained by using the Fourier coefficients.

**2.3.3. Decomposition**

Analysis of the Mueller matrix is difficult due to the nonuniformity of the measurement area, the depolarizing effect by multiple scattering effect in medium, the imperfections of optical components such as optical filters, waveplates and polarizers, numerical apertures of lenses, and noise of detector. Therefore, a decomposition of the Mueller matrix is needed to separate the data into simple elements to obtain meaningful data.

Many authors have discussed the decomposition of the Mueller matrix. Any Mueller matrix can be expressed as the sum of four nondepolarizing Mueller matrices. In addition, the Mueller matrix can be expressed as a product of three matrices: diattenuator, retarder, and depolarizer matrix [11].

In the measurement of the smooth surface such as thin film measurement, the depolarization matrix component of the sample can be considered to be the cause of errors due to other devices. Therefore, when the Mueller matrix is obtained by removing the depolarization matrix, the similar result to the theoretical value can be obtained as shown in the Figure 2.5 [12]. In the measurement of biological tissues and cells, methods of detecting abnormal tissue
through the degree of scattering effect in the cell is used. In this case, the depolarization index or depolarization matrix is measured and analyzed[6].

![Image](image.png)

**Figure 2.5: Muller matrix (4,3) element of SiO2 1.5 um thin film**

2.4. Clustering

2.4.1. Mueller matrix ellipsometry

The data used in this study is high dimensional data containing Mueller matrix information in RGB space for each image pixel. When clustering is performed using high-dimensional data, there is a problem that the clustering performance decrease and the computation time increase. Therefore, it is necessary to perform the clustering after preprocessing the data using the principal component analysis (PCA).

PCA is a technique for converting high-dimensional data into low-dimensional data. The method finds a new coordinate axis that maximizes the dispersion of the data.
If there are $n, d$ dimensional data such as Eq (2.15), the covariance matrix of this data set is as follows.

$$
\Sigma = \frac{X^T X}{n} \quad (2.16)
$$

When the eigenvalues of the covariance matrix are $\lambda_1, \lambda_2, \ldots, \lambda_n$ in ascending order of magnitude, to reduce the dimension without loss of data, the following condition must be satisfied when the data of dimension $d$ is reduced to dimension $m$.

$$
\frac{\sum_{j=1}^{m} \lambda_j}{\sum_{j=1}^{d} \lambda_j} > 0.9 \quad (2.17)
$$

The dimension is reduced by using the smallest value among $m$ satisfying the condition, and the method is as follows.

$$
X_{\text{new}} = XV \quad (2.18)
$$

$$
V = \begin{pmatrix} v_1 & v_2 & v_3 & \cdots & v_m \end{pmatrix} \in \mathbb{R}^{d \times m} \quad (2.19)
$$

$v_1, v_2, \ldots, v_m$ are the eigenvector of the covariance matrix.
2.4.2. K-means clustering

K-means clustering is an algorithm for grouping data into \( k \) clusters.

\[
S_i^t = \{ x_p : |x_p - \mu_i^{(t)}|^2 \leq |x_p - \mu_j^{(t)}|^2 \forall j, 1 \leq j \leq k \} \tag{2.20}
\]

\[
\mu_i^{(t+1)} = \frac{1}{|S_i^t|} \sum_{x_j \in S_i^t} x_j \tag{2.21}
\]

The most popular method calculates the distance between randomly positioned cluster centers \( k \) and total data (Eq (2.20)) and group the data into the nearest cluster, and the cluster centers move to the average of the clusters (Eq (2.21)). If the average position does not change while repeating, the clustering procedure is completed.

In this method, the cluster results can be changed according to the initial positions of the cluster center randomly given, and undesired outcomes are obtained if the total number of clusters is unknown.
Chapter 3. Data Acquisition Method

3.1. Beam drifting correction

In a dual rotating compensator ellipsometer, a waveplate is used as a compensator. As shown in the Figure `fig:beam_drifting`, the beam drift occurs when the waveplate is placed not perpendicular to the optical path. When the waveplate rotates, the measured image fluctuates within 10 pixels. By using the template matching algorithm method, it is necessary to correct the fluctuated image so that the same position can be correctly analyzed.

![Figure 3.1: Beam drifting effect](image)

3.2. Mueller matrix calculation

The dual rotating compensator Mueller matrix ellipsometry proposed by Azzam[13] can measure all sixteen Mueller matrix elements by rotating two compensator with a specific angular velocity ratio. Various combinations of angular velocity ratios have been studied, and robust results can be obtained when measuring
the angular velocity ratio of 5:3 or 1:5, which can minimize the condition number \[14\]. In this study, the angular velocity ratio of 5:3 was used. The measured signal can be represented by the following equation through the Fourier transform of a detected signal while rotating the retarder.

\[
I(t) = I_0(1 + \sum_{n=1}^{16} (\alpha_{2n}\cos(2nC) + \beta_{2n}\sin(2nC)))
\]

(3.1)

\(C\) is the angle of a compensator rotating at the base angular frequency such that \(C = \omega t\). \(I_0\) is dc Fourier coefficient and \(\alpha_{2n}, \beta_{2n}\) are the 32 normalized ac Fourier coefficients. The detail method of finding each element of the Mueller matrix through Fourier coefficients is described in Ref. [15].

### 3.3. Calibration

In dual rotating compensator Mueller matrix ellipsometer system, two polarizers and two waveplates is used as components of PCSCA ellipsometric structure. The installed polarizer and waveplate have misalignment errors, and the waveplate additionally contains a retardation error as a systematic error. Smaller orientation and retardation errors of less than 1 degree require more than 10\% error in some elements of the measured Mueller matrix signal, requiring calibration before measurement [16].
\[ \theta_{2n} = \tan^{-1}\left(\frac{\gamma_{2n}}{\alpha_{2n}}\right) \]  
(3.2)

\[ P_{mis} = 0.25(2(\theta_4 + \theta_{16}) - (\theta_8 + \theta_{32})) \]  
(3.3)

\[ C1_{mis} = 0.25((\theta_4 + \theta_{16}) - (\theta_8 + \theta_{32})) \]  
(3.4)

\[ C2_{mis} = 0.25(-(\theta_4 - \theta_{16}) + (\theta_8 - \theta_{32})) \]  
(3.5)

\[ A_{mis} = 0.25(-2(\theta_4 - \theta_{16}) + (\theta_8 - \theta_{32})) \]  
(3.6)

\[ ONE = 0.5(\cos(-2A + 4C1_{mis} + 2C2_{mis} - 2P)\alpha_{26} - \sin(-2A + 4C1_{mis} + 2C2_{mis} - 2P)\beta_{26}) \]  
(3.7)

\[ TWO = 0.5(\cos(-2A + 2C1_{mis} + 2C2_{mis} - 2P)\alpha_{16} - \sin(-2A + 2C1_{mis} + 2C2_{mis} - 2P)\beta_{16} - \cos(2A + 2C1_{mis} - 2C2_{mis} - 2P)\alpha_{14} + \sin(2A + 2C1_{mis} - 2C2_{mis} - 2P)\beta_{14}) \]  
(3.8)

\[ THREE = 0.5(-\cos(-2A + 2C1_{mis} + 4C2_{mis} - 2P)\alpha_{22} + \sin(-2A + 2C1_{mis} + 4C2_{mis} - 2P)\beta_{22} + \cos(2A + 2C1_{mis} - 4C2_{mis} - 2P)\alpha_{2} - \sin(2A + 2C1_{mis} - 4C2_{mis} - 2P)\beta_{2}) \]  
(3.9)

\[ FOUR = \cos(2A + 4C1_{mis} - 4C2_{mis} - 2P)\alpha_{8} - \sin(2A + 4C1_{mis} - 4C2_{mis} - 2P)\beta_{8} - \cos(-2A + 4C1_{mis} + 4C2_{mis} - 2P)\alpha_{32} + \sin(-2A + 4C1_{mis} + 4C2_{mis} - 2P)\beta_{32} \]  
(3.10)
The above Eq (3.7) ~ (3.10) can be used to correct the retardance error as shown below.

\[
C_{1\delta} = 2 \tan^{-1}(\sqrt{\frac{-2\text{FOUR} \bullet \text{ONE}}{\text{TWO} \bullet \text{THREE}}})
\]

\[
C_{2\delta} = 2 \tan^{-1}(\sqrt{\frac{-2\text{FOUR} \bullet \text{THREE}}{\text{TWO} \bullet \text{ONE}}})
\]

### 3.4. Mueller matrix decomposition

\[
M = M_{\Delta} M_{R} M_{D}
\]

In which is measured Mueller matrix, \(M_{\Delta}\) is diattenuator Mueller matrix, \(M_{R}\) is retarder Mueller matrix, \(M_{D}\) is depolarizer Mueller matrix. These three matrices represent diattenuation, retardance, and depolarization properties of the measured sample.

Each matrix can be expressed as

\[
M_{R} = \begin{pmatrix}
1 & 0 \\
\vec{D} & m_{R}
\end{pmatrix}
\]

\[
M_{D} = T_{u} \begin{pmatrix}
1 & \vec{p}_{D} \\
\vec{D} & m_{D}
\end{pmatrix}
\]

\[
M_{\Delta} = \begin{pmatrix}
1 & 0 \\
\vec{p}_{\Delta} & m_{\Delta}
\end{pmatrix}
\]

Detailed instructions can be found in Ref. [11].
3.5. Mueller matrix in a RGB color space

Thickness measurement is a process by comparing the theoretical matrix with the measured. Therefore, a theoretical formula is needed to obtain the Mueller matrix in RGB space. The measured data with the color camera is the sum of all the light transmitted through the Bayer filter [5]. Therefore, the following method is used to integrate the values of the bayer filter and the intensity of the input light as a function of wavenumber.

\[ M_{\text{rgb}}^{ij} = \frac{\int_k M(k)_{ij} F(k) I(k) dk}{\int_k F(k) I(k) dk} \]  \hspace{1cm} (3.17)

\( M_{\text{rgb}}^{ij} \) is Mueller matrix in a RGB color space, \( M(k)^{ij} \) is Mueller matrix of wavenumber axis, \( F(k) \) is Transmittance of the Bayer filters mounted on the camera and \( I(k) \) is intensity of the input light.
3.6. Thickness measurement

The thickness of thin film is measured by comparing the measured Mueller matrix with the theoretical Mueller matrix. The Levenberg–Marquardt method is used to solve the following nonlinear least squares problem.

\[ \varepsilon = \sum_C (M^{\text{Theory}}(d, C) - M^{\text{measured}}(C))^2 \] (3.18)

\( \varepsilon \) is sum of squares error between theory and measured Mueller matrix, \( d \) is thickness of the thin film, \( M^{\text{Theory}} \) and \( M^{\text{measured}} \) are the theoretical and measured Mueller matrix and \( C \) is RGB color space.

A number of local minimums are existed as shown in Figure 3.4 when calculating the error by changing the thickness value using the RGB color space. If the thickness of the specimen is roughly known, it is easy to select the initial thickness value. However, if the target thickness is not known, a skimming process is required.
The skimming process usually calculates the minimum in 10 nm increments.

![L2 error of 405 nm SiO2 thinfilm](image)

**Figure 3.4: Error of 405 nm SiO2**

### 3.7. Clustering

The measured data is an image with a resolution of 1024x1280 pixels, and each pixel has 4x4 Mueller matrix information in RGB color space. The matrix is decomposed to have a total of 144 dimensions of data for each pixel. High dimensional data takes a long computational time to perform clustering and clustering does not work suitably. Therefore, the dimension is reduced by using Principal Component Analysis (PCA). The graph obtained by the eigenvalue can be seen to considerably decrease when moving from 3D to 4D as in Figure 3.5.
The dimensional reduction is applied to the three dimensions, and the result of the dimension reduction through the PCA is the same as the Figure 3.6.

Clustering is performed using K-means clustering in the reduced dimension. In this paper, we use the histogram method to solve the random initial position problem of k clusters. After cutting the entire data space into a window size of $h_i$, which is a hyperparameter, count the number of data in the area and use it as the start point of
the cluster from the window area with a large value. When this method is used, it is possible to obtain fast convergence even with a small number of iterations. Also, a weighted average is used as a method to improve the performance of clustering. The values used as weights are the reciprocals of the distance from the cluster mean, and the closer the distance is, the more the representative cluster can be selected by contributing to the average.

In this study, we use a new hyperparameter $\varepsilon$ to remove noise in the image due to sample defects or foreign objects. It is possible to increase the representativeness of the cluster by allowing it to belong to the cluster only if it is closer than $\varepsilon$ and to decide it as noise when it is not. The cluster is thought as noise when the

$$
\mu_i^{(t+1)} = \frac{1}{|S_i^{(t)}|} \sum_{x_j \in S_i^{(t)}} x_j w_j
$$

Figure 3.7: Histogram window
number of data in the cluster is less than a defined amount.

\[ S_i^t = \{ x_p : |x_p - \mu_i^{(t)}|^2 \leq |x_p - \mu_j^{(t)}|^2 \forall j, |x_p - \mu_i^{(t)}|^2 \leq \epsilon, 1 \leq j \leq k \} \]  \quad (3.20)

Figure 3.8: Result of the clustering method
Chapter 4. Result

4.1. Measurement sample

The sample used in this study is a thin film of SiO2 deposited on Si in 100, 200, 500, and 1000 nm thickness, respectively. The thickness values measured by the verified spectroscopic ellipsometer are shown in the table below.

![Quadrant specimen](image_url)

**Figure 4.1: Quadrant specimen**

The sample used in this study is a thin film of SiO2 deposited on Si in 100, 200, 500, and 1000 nm thickness, respectively. The thickness values measured by the verified spectroscopic ellipsometer are shown in the table below.

<table>
<thead>
<tr>
<th>[nm]</th>
<th>T1</th>
<th>T2</th>
<th>T3</th>
<th>T4</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOMINAL</td>
<td>105.7</td>
<td>189.4</td>
<td>488.8</td>
<td>977.2</td>
</tr>
</tbody>
</table>
4.2. Classification and thickness measurement

The left image of Figure 4.2 is the image measured through the camera, and the right is the result of the classification using the clustering technique.

![Figure 4.2: Result of classification](image)

The thickness value on the table 4.2 was obtained by averaging the Mueller matrix of the pixels in each classified region. The measurement results are similar to those of existing equipment. The thickness values measured by the verified spectroscopic ellipsometer are shown in the table below. 3 sigma of the thickness distribution in each cluster is within 2% of the thickness in regions except for T1, which means that the cluster thickness value represents the entire clustering region.

<table>
<thead>
<tr>
<th>[nm]</th>
<th>T1</th>
<th>T2</th>
<th>T3</th>
<th>T4</th>
</tr>
</thead>
<tbody>
<tr>
<td>THICKNESS</td>
<td>103.778</td>
<td>182.808</td>
<td>488.116</td>
<td>985.102</td>
</tr>
<tr>
<td>3STD</td>
<td>2.55</td>
<td>2.58</td>
<td>2.59</td>
<td>8.53</td>
</tr>
</tbody>
</table>
The reason why the standard deviation is high in the T1 area is that the profile of the section is inclined as shown in Figure 4.3. The thickness distribution in the slanted region can be classified when the initial number of clusters is increased. The thickness distribution in the clustered region is as follows the table.

<table>
<thead>
<tr>
<th>Thickness distribution of the slanted regions</th>
</tr>
</thead>
<tbody>
<tr>
<td>[nm]</td>
</tr>
<tr>
<td>------</td>
</tr>
<tr>
<td>THICKNESS</td>
</tr>
<tr>
<td>3STD</td>
</tr>
</tbody>
</table>

When the number of clusters was increased, the standard deviation of each cluster was reduced, which confirmed that more representative classification result could be obtained.
Chapter 5. Conclusion

Through the research using a color camera, we improved the ambiguity and measurement time which is a problem of the existing monochromatic and multiwavelength imaging methods. In the case of the imaging method, the limit of the thickness measurement in the whole image area is improved through the clustering technique.
Bibliography


타원계는 광학 측정 방식으로 반도체, 디스플레이 공정 검사에서 비접촉, 비파괴, 신속 측정이 가능한 장점이 있다. 분광 방식의 경우 높은 과장 해상력을 통해 높은 정밀도를 얻을 수 있다는 장점이 있으나, 단일 영역 측정 한계와 좁은 영역의 측정이 불가능하며 측정 영역 내의 모호성 문제가 있다. 2D CCD를 이용한 이미징 방식의 측정 방법은 공간 해상력을 픽셀 수준까지 높일 수 있어 많은 연구가 진행되었다. 기존의 단파장 이미징 방식은 과장 데이터의 부족으로 측정 모호성이 있으며, 다파장 이미징 방식의 경우 과장은 바꾸는 과정으로 인해 측정 시간이 길다는 한계가 있다. 이에 본 연구에서는 컬러 카메라를 이용한 이미징 투과율 타원계를 이용하여 문제를 해결한다. 추가적으로 이미징 방식의 경우 이미지 영역 전체 픽셀 분석의 경우 많은 시간이 걸려 불가능한 문제가 있다. 이 문제를 제안하는 클러스터링 방식을 사용하여 해결하고자 한다.

연구에 사용되는 컬러 카메라는 베이어 필터로 인해 여러 과장의 투과율이 중첩된 결과가 측정되게 된다. 따라서 광대역 과장 필터에 적용할 수 있는 필터의 투과도를 고려한 새로운 투과율 결과를 제안한다. 제안한 방식을 이용하여 두께 측정을 진행하고, 검증된 하드웨어로 측정된 결과와 비교하여 검증하였다.

연구에 사용된 클러스터링 방법을 통해 이미지 영역을 비슷한 투과율을 갖는 영역끼리 분류하였고, 분류한 영역의 평균 두께를 측정하였다. 각 클러스터 내의 표준편차를 확인하여 평균값이 클러스터를 대표할 수 있음을 확인하였다.

주요어 : 이미징 타원계, 이미징 투과율 투과율 타원계, 컬러 카메라, 광대역 필터, 박막, 두께 측정, 영역 분류, 클러스터링
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