Using ellipsometry methods for depth analyzing the optical disc data layer relief structures

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Abstract. We studied the relief depth of the data layer formed in a glass disk by ion beam etching process with using classical ellipsometry at the constant wavelength 632.8 nm for different angles of incidence. It was found that for 0° and 90° azimuth angles, a pair of ellipsometric parameters Ψ and ∆ is sufficient to characterize the changes in light reflection for various structure depths. The depth of optical disc data layer relief structures was estimated via experimental dependences of ellipsometric parameters. The estimated data layer depths were found to be in good agreement with independent tunnelling electron microscopy measurements.

Keywords: data layer, optical disc, relief depth, ellipsometry, scatterometry, effective medium theory, effective refractive indices.

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shift light to calculate the ellipsometric parameters: phase difference between effective indices of refraction for homogeneous birefringent materials. In this case, there exists a model in which the gratings of dielectric material act as homogeneous anisotropic layers. The disc relief structure profile (a) and its view as effective medium sandwiched between two homogeneous dielectrics. The design constant \( \beta \) describes how much smaller the ratio \( \Lambda/\lambda \) is relatively to the ratio \( 1/(n_i + n_s) \).

\[
\beta = \frac{\lambda}{\Lambda(n_i + n_s)},
\]

where \( n_i = 1 \) is the refractive index of air, and \( n_s = 1.5 \) is the refractive index of glass, while \( e_i = n_i^2 \) and \( e_s = n_s^2 \).

The effective dielectric function for the zeroth order is given by [6, 7]:

\[
\varepsilon_{\text{eff}}^0 = \varepsilon_{\text{eff}}(0) \times \left[ 1 + \frac{\pi^2}{36} f^2 (1 - f)^2 (n_s - n_i)^2 \frac{\varepsilon_{\text{eff}}(0)}{e_i e_s} \right],
\]

where the filling factor \( f \) is given by

\[
f = \frac{b}{\Lambda}.
\]

The interaction of light with grating is accurately described by the rigorous coupled-wave analysis (RCWA) developed by Moharam and Gaylord [2-5]. According to this model, nanostructured surface of the disc relief structure profile (a) and its view as effective medium sandwiched between two homogeneous dielectrics. The disc relief structure profile (a) and its view as effective medium sandwiched between two homogeneous dielectrics. The disc relief structure profile (a) and its view as effective medium sandwiched between two homogeneous dielectrics.

\[
\varepsilon_{\text{eff}}^p = \varepsilon_{\text{eff}}^p(0) \times \left[ 1 + \frac{\pi^2}{36} f^2 (1 - f)^2 (n_s - n_i)^2 \frac{\varepsilon_{\text{eff}}(0)}{e_i e_s} \right],
\]

\[
\varepsilon_{\text{eff}}^s = \varepsilon_{\text{eff}}^s(0) \left[ 1 + \frac{\pi^2}{36} f^2 (1 - f)^2 (n_s - n_i)^2 \frac{\varepsilon_{\text{eff}}(0)}{e_i e_s} \right],
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The effective dielectric function for the zeroth order is given by [6, 7]:

\[
\varepsilon_{\text{eff}}^p(0) = f \varepsilon_s + (1 - f) \varepsilon_i.
\]

Using these parameters and formulas (1)-(6), we can calculate \( n_{\text{eff}}^p \), which is represented at Fig. 2b for two polarizations of reflected light:

\[
n_{\text{eff}}^p = \left( \varepsilon_{\text{eff}}^p \right)^{1/2},
\]

\[
n_{\text{eff}}^s = \left( \varepsilon_{\text{eff}}^s \right)^{1/2}.
\]

The design constant \( \beta \) describes how much smaller the ratio \( \Lambda/\lambda \) is relatively to the ratio \( 1/(n_i + n_s) \).

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\[
n_{\text{eff}}^s = \left( \varepsilon_{\text{eff}}^s \right)^{1/2}.
\]
\[ n_i \sin \theta = n_s \sin \theta_1, \]

where \( n_i = 1, n_s = 1.5. \)

We can write the equations for the total Fresnel reflection coefficients [9]:

\[
    r_p = \frac{r_{0p}^2 + r_{1p}^2 \exp(-i2\delta_p)}{1 + r_{0p}^2 r_{1p}^2 \exp(-i2\delta_p)}, \tag{12}
\]

\[
    r_s = \frac{r_{0s}^2 + r_{1s}^2 \exp(-i2\delta_s)}{1 + r_{0s}^2 r_{1s}^2 \exp(-i2\delta_s)}, \tag{13}
\]

where

\[
    \delta_p = 2\pi \left( \frac{d}{\lambda} \right) n_{\text{eff}}^p \cos \theta_1, \tag{14}
\]

\[
    \delta_s = 2\pi \left( \frac{d}{\lambda} \right) n_{\text{eff}}^s \cos \theta_1, \tag{15}
\]

where \( d \) is the grating thickness (Fig. 2).

If we have the Fresnel reflection coefficients \( r_p \) and \( r_s \), we can write the main ellipsometry law [8]:

\[
    \frac{r_p}{r_s} = \tan(\Psi) \exp(i\Delta). \tag{16}
\]

We carried out theoretical simulation for a CD-type disc structure to verify the diffraction sensitivity of the ellipsometric technique. Our parameters for calculation were as follows: \( \Lambda = 1500 \text{ nm}, \ b = 1500-600 = 900 \text{ nm}, \ \lambda = 632.8 \text{ nm}, \ n_i = 1, \ n_s = 1.5. \) We performed the theoretical simulations of disc relief structures with the path line either parallel (\( \phi = 0^\circ, \ \Psi_0, \ \Delta_0 \)) or normal (\( \phi = 90^\circ, \ \Psi_90, \ \Delta_90 \)) to the incident plane. Fig. 3 shows the \( \Psi_0, \ \Delta_0 \) variations versus the angle of incidence for various profile depths in glass. Second-order EMT predicts the minimum for the function of \( \Psi \) around Brewster angles. On the other hand, this theory predicts that the function of \( \Delta \) must cross 90 deg. for these angles of incidence. As expected, both ellipsometric parameters \( \Psi_0, \ \Delta_0 \) are very sensitive to the depth \( d \) in the region of the Brewster angle of incidence for pure glass substrate (\( \theta \approx 57^\circ \)). These simulations were performed to characterize the changes in \( d \) of 10 nm. We can note that changes in the diffracted light parameters \( \Psi_0 \) and \( \Delta_0 \) are sufficient to detect 10-nm variations in depth of the disc profile.

3. Experiment

The ellipsometric parameters \( \Psi_0, \ \Delta_0 \) and \( \Psi_90, \ \Delta_90 \) at \( \lambda = 632.8 \text{ nm} \) of 7 disc profile structures were measured. He-Ne laser was used as the source of illumination. The incident beam passed through the polarizer and compensator and illuminated the disc structure. The glass disc was rotated about the vertical axis to provide \( \phi \) variations. The ellipsometric parameters were measured for angles of incidence \( \theta \) ranging from 50 to 65 degrees. This allowed us to determine the ellipsometric functions, as well as the minimum of the restored angle \( \Psi \), which corresponds to the Brewster angle.

Fig. 4 shows the experimental measurements of the functions \( \Psi_0 \) and \( \Delta_0 \) for different values of the depth \( d \). The experimental result shows the polarization effect from subwavelength profile features. Different depths, \( d \), give different angle dependences of \( \Psi_0 \) and \( \Delta_0 \). The region in the vicinity of the Brewster angle \( \theta_0 \approx 57^\circ \) can be used as sensitive signatures of the depth \( d \).

Comparison of the experimental (Fig. 3) and theoretical (Fig. 4) curves gives that angle dependences of the ellipsometric parameters \( \Psi \) and \( \Delta \) for different profile depth disc structures agree rather well with the second-order EMT calculations in predicting the thickness \( d \) for which the minimum of \( \Psi \) is reached and approximate homogeneous layer models provide a reasonable estimate of the thickness of the profile depth.
We performed measurements of disc relief structures with the path line either parallel ($\phi = 0^\circ$, $\Psi_0$, $\Delta_0$) or normal ($\phi = 90^\circ$, $\Psi_90$, $\Delta_90$) to the plane of incidence. It is difficult to estimate the profile depth $d$ directly from the data for $\Psi$ and $\Delta$, because it is difficult to determine values of minimums for functions $\Psi$ and $\Delta$. Then, to estimate the structure depth we have used diagrams ($\Delta_0 - \Delta_90$) versus the angle of incidence $\theta$ for various values of $d$ (Fig. 5).

The dimensions of the disc profile were also measured before the optical measurements by atomic force microscopy. The agreement between these both measurements is reasonably good, although the value of $d$ from optical measurements for small thicknesses is larger than the expected ones (Table).

<table>
<thead>
<tr>
<th>Number of Test</th>
<th>Estimated depth, $d$ (nm)</th>
<th>AFM, $d$ (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test 120</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Test 127</td>
<td>40</td>
<td>38</td>
</tr>
<tr>
<td>Test 130</td>
<td>45</td>
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</tr>
<tr>
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<td>82</td>
</tr>
<tr>
<td>Test 011</td>
<td>90</td>
<td>93</td>
</tr>
</tbody>
</table>

4. Conclusion

We have demonstrated the feasibility of ellipsometric scatterometry for the metrology of the depth by analyzing the optical disc data layer relief structures within the accuracy of 5 nm. For correct reading optical discs by the standard player, the depth of relief structures must be 125±30 nm, then the accuracy of proposed estimations is enough to control disc manufacture. Therewith, because material of substrate may consist of many components, the difference of even neighbour pit depth can reach 5 nm after ion beam etching. The diameter of scanning laser beam is about 3 mm, then almost 2000 data tracks get in the scanned area. It means that the averaged depth is estimated in contrast to analysis of a single pit by atomic-force microscope. Obtained results are extremely useful in the context of optical disc fabrication due to monitoring and controlling the depth of etching into a glass (dielectric) wafer in real time (in situ) by using ellipsometric measurements.
References


