Polarization-Conversion Guided Mode (PCGM) technique for exploring thin anisotropic surface layers

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Abstract: A Polarization-Conversion Guided Mode (PCGM) technique has been developed to quantify optical anisotropy as low as 10^{-5} for a surface layer only 10 nm thick. The optical geometry consists of an index-fluid matched prism-coupler and an air-gap waveguide comprising the thin sample on a glass plate as the incident surface with a gold reflector forming the other surface of the guide. This allows non-destructive characterization of the optical anisotropy of surface layers. The polarization conversion signal is extraordinarily sensitive. Thus the influence of the polarization purity of the incoming beam, very small twists and/or tilts between the normal to the prism bottom surface and the sample plane, have all been analyzed in detail to allow extraction of the sought for information about the thin layer. Rubbed polyimide thin films and incline-evaporated SiOx layers, both used for liquid crystal alignment, have been examined by this PCGM technique to demonstrate its power.

OCIS codes: (230.7370) Waveguides; (240.0310) Thin films; (260.5430) Polarization; (260.1180), Anisotropic media.

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The physical properties of very thin layers are very important from both a fundamental research perspective and also as regards devices. Further there is progressively more interest in exploring thin layers from biological systems. There are a wide range of different techniques used to study thin films on surfaces and, because they are generally non-destructive, optical techniques are often used. In several of these optical techniques the exploration of the optical anisotropy of very thin layers is used as a powerful characterisation tool. This is because the optical anisotropy is often related to the symmetry of electronic surface states, surface topography or the alignment situation of molecules.

Recently Reflection Anisotropy Spectroscopy (RAS) has been developed and widely used for these types of study [1-3]. RAS has been developed within the requirements of UHV (Ultra-High Vacuum) studies and extended to the examination of surface optical anisotropy. It is in essence a polarization-conversion reflection ellipsometry technique generally using normal incidence. The RAS technique has had substantial success in studying the surface structure and chemistry of semiconductor surfaces showing for instance that the absorption processes causing the anisotropic signal takes place in the uppermost few atomic layers of the substrate [4]. Other work exploring the rubbed polyimide layers used to align liquid crystals has also been reported [5, 6]. In these articles the authors have investigated the relationship between the surface topography and dielectric properties of mechanically rubbing polymer thin films and the RAS data has shown the possibility of being a new control tool in liquid crystal device fabrication. In the original RAS studies used for exploring electronic surface states with normal incidence light a wavelength scanning technique is used. This means that dispersion effects from every optical element have to be incorporated into the theoretical analysis and data processing. However, if only information about the surface topography and molecular anisotropy is required, as for example with a rubbed polyimide liquid crystal aligning layer then the polarization-conversion signal (for example p to s) at a single wavelength but angle scanned using some suitable guided mode geometry [7] will provide sufficient information much more easily. Furthermore scanning the incident angle (in-plane momentum) provides extra information on the detailed distribution of optical anisotropy within the thin surface layer.

In this study, a Polarization-Conversion Guided Mode (PCGM) technique has been developed to explore very small optical anisotropy within thin surface layers. The optical geometry is composed of a prism coupler index-fluid-matched to the top glass plate of the sample cell, see Fig. 1. The sample cell itself comprises the top glass plate on which the thin layer to be examined is deposited and an opaque metal reflector (Au) coated on a bottom glass plate which is spaced by mylar spacers to form an air-gap half-leaky guided wave structure of order 20 microns thick. A monochromatic He-Ne laser beam (633 nm) and normal rotating table $\theta/2\theta$ set-up [7] are then used to record p to s conversion signals as a function of incident angle. Because the prism coupler ($n = 1.517$ at 633 nm) is connected by index-matching fluid to the sample cell, the sample twist angle against the incident plane at the prism bottom surface, Φ, can be easily varied, and the optical anisotropy of the thin surface layer fully characterized.

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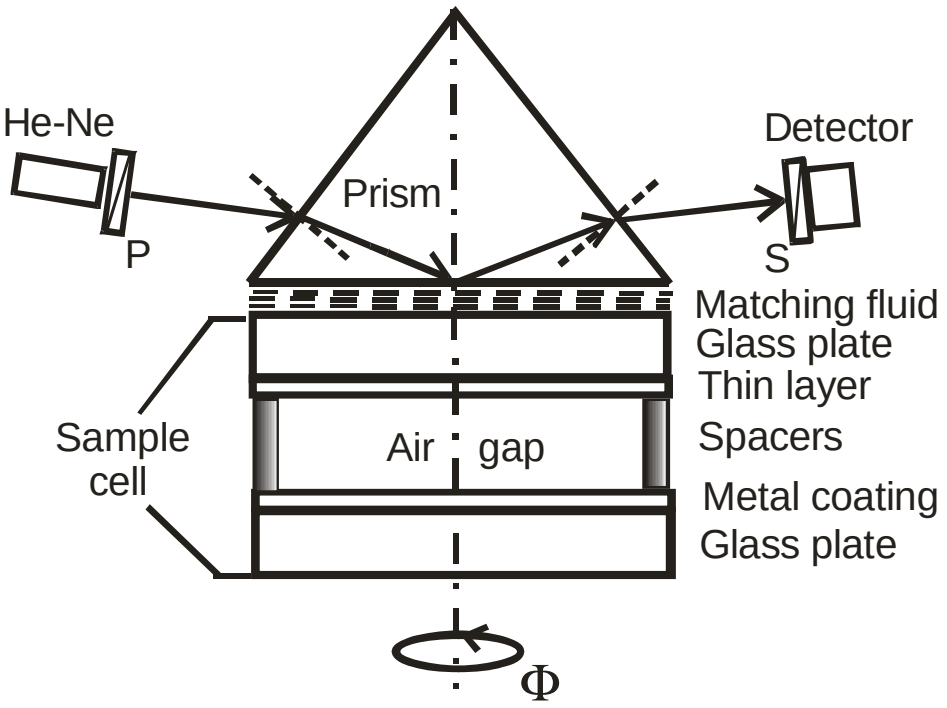

Fig. 1. The sample geometry of the PCGM technique.

Because the layer to be detected may be quite thin (~10 to 20 nm) and the optical anisotropy may be of the order of $\Delta n = 0.1$ [8, 9] or less, then the p to s conversion reflectivity may be only $\sim 10^{-4} - 10^{-5}$. This requires that the resolution of the PCGM technique be at least 10^{-5}, so polarization-conversion signals arising from sources other than the thin sample have to be eliminated or characterized in some way to allow extraction of a clean signal created by the thin layers. There are three primary sources of background polarization conversion signal. These are each addressed in the following.

It is obvious that the polarization state of the incoming beam is a defining factor. Fortunately it is straightforward with high quality crystal polarizers to achieve a crossed polarizer contrast of 10^{+6}. This then means that deviations between the polarization axis of the linearly polarized incoming beam and the eigen p-polarization of the prism interface is important, because the crossed (~ s-polarizer) before the detector (see Fig. 1) is set to cross with the polarization state of the expected incoming beam. This should be the eigen p-polarized state of the prism. If the incident plane is not set correctly so that the incident beam is not p-polarised exactly then some pseudo-polarization conversion signal will appear. Analyses shows that a deviation of 0.1^{o} will introduce a signal of order 10^{-5}, thus it is important to ensure the error in the angle setting of the incident polarization is less than 0.1^{o}. This can be achieved by using the bare prism as a test sample and finely rotating the incoming polarizer to reduce the p to s conversion reflectivity below 10^{-5} as shown in Fig. 4.

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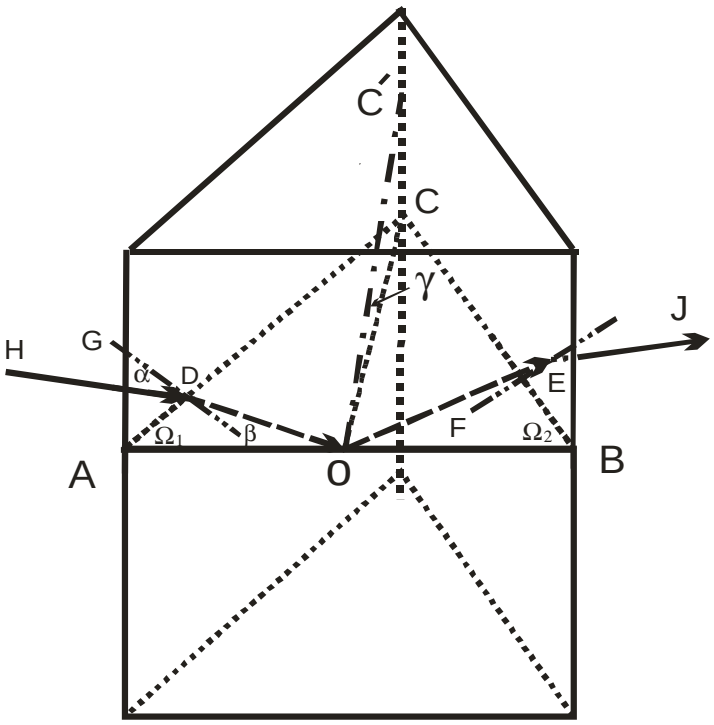

Fig. 2. Diagram for analyzing the extra pseudo-p to s conversion due to sample tilt.

The second factor which may be somewhat harder to control is the deviation between the two surface normal directions defining the prism bottom surface and the sample cell surface. This is illustrated in Fig. 2. In this figure the plane ABC, in which the incident beam HD arrives from air, is parallel to the prism's two unpolished end faces and the planes ACC′ and BCC′ lie on the incoming and outgoing faces of the prism, respectively. Because the twist and tilt deviations are likely both to be very small they may be treated separately. Consider the tilt of the sample cell surface normal line OC′ has an angle γ deviating from the prism bottom surface normal line OC as shown in Fig. 2. Then a p-polarized incoming beam with an external incident angle α, passes through the front prism face at point D and becomes a beam with an angle β (= $\sin^{-1}[\sin\alpha/n]$) propagating inside the prism to touch the sample cell surface at point O, where the line GD is normal to the incoming plane ACC′. From now the incident plane for the sample cell is plane ODC′E, this is the first eigen polarization mode translation between the plane ABC and ODC′E. The reflected beam inside the prism after the O point contacts the prism outgoing face at point E. Then we need to make a second eigen polarization mode translation between the plane ODC′E and the plane OEF, where the line EF is normal to the prism outgoing plane BCC′, to calculate the transmission of the eigen polarization mode through the boundary between the prism and air. The outgoing beam EJ passes through the s-polarizer before entering the detector. Then, we need a third eigen polarization mode translation between the plane OEF and the plane ABC, in which the polarization state of the s-polarizer is defined, to obtain the apparent p to-s conversion. Using the geometry shown this has been modeled and for a tilt deviation of about 0.1^o, a signal of order 10^{-5} is created. Because this deviation can be readily set less than 0.05^o then the pseudo-polarization conversion from this source may be reduced to ~ 10^{-6}. For the twist deviation between the two normals of the prism bottom face and the sample top surface in the plane

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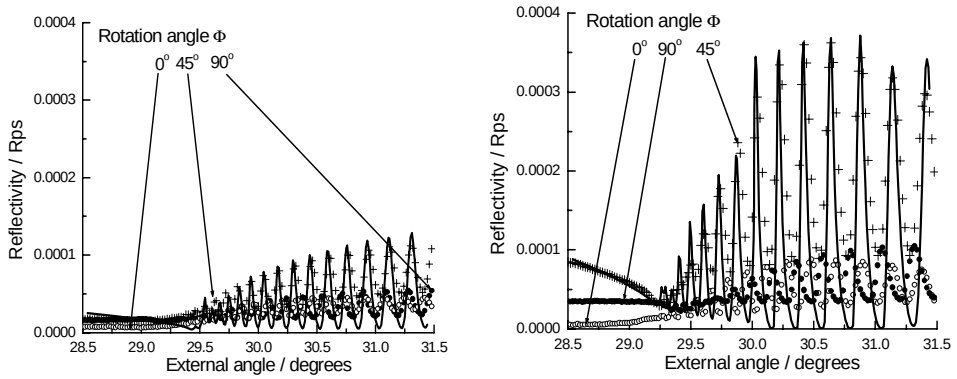
ABC, the situation is simple as there is no extra pseudo-polarization conversion signal created by this twist deviation, one only needs to change the prism bottom angles Ω_1 and Ω_2 (see Fig. 2) to effective prism bottom angles of Ω_1' (= Ω_1 - χ) and Ω_2' (= Ω_2 + χ) for a twist deviation of χ. This then corresponds to a small shift of the incident angle. A program for modeling the pseudo-p to s polarization conversions created by the factors mentioned above has been written. From modeling with this program the introduced PCGM spectrum features arising from the two factors considered above are quite different to and easy to distinguish from the experimental data.

The third factor which was originally seen to produce p to s conversion signals was the pressure applied to the system to hold it together, as this introduced stress birefringence in the glass. This led to a redesign of the experimental geometry such that the sample cell is held in gentle contact with the prism bottom surface by the index-matching fluid leading to no detectable p to s signal arising from stress birfringence The redisign also means that it can be freely rotated around an axis normal to the substrate. The designed holder also allows for fine adjustment of the parallelism between the prism bottom and sample top surfaces to minimise the pseudo-p to s polarization conversions introduced by the deviation of the two surface normals. In practice with care one may repeatably limit the pseudo-p to s polarization conversion to less than of order 10^{-5}.

Two types of thin layers for aligning liquid crystals in LCD devices have been used to demonstrate the power and usefulness of this technique. One is a rubbed polyimide coating and the other is an angle-evaporated SiOx layer.

First, a bare prism is tested. The results show that the background p to s polarization conversion signal is ~ 10^{-6}. Then the sample cells have been attached and the p to s polarization conversion signals recorded against the external incidence angle, α, with the sample cell rotation angle, Φ, as a variable. As shown in Figs. 1 and 2, Φ is defined as a deviation angle between the incident beam plane ABC and some special direction on the tested thin layer, this is the rubbing direction for the rubbed polyimide sample and the direction normal to the evaporation direction for the angle-evaporated SiOx layer.



(a) (b)

Fig. 3. Experimentally recorded R_{ps} signals (+ 45°, full circles 90° and open circles 0°) against the external incident angle for different sample rotations for two rubbed polyimide layers: (a) once rubbed and (b) twice rubbed. The solid lines are the model fits for 45° sample rotation.

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Figures 3(a) and 3(b) show the experimentally recorded p to s conversion signals against the external incident angles for two different rubbed polyimide thin layers, for different twist angles of the rubbing directions relative to the incident plane. The polyimide is AL 1254 (JSR Corporation, Japan) and is treated according to the normal aligning procedure: that is it is first spin-coated on to the surface of the glass plate and then rubbed after hard baking at high temperature. The sample producing the data of Fig. 3(a) is rubbed once while the sample giving the data of Fig. 3(b) is rubbed twice using the same rubbing conditions. Because the p to s conversion signals are strongest for the rubbing axis aligned at 45^o to the incident plane it appears clear that the rubbed polyimide layers are at least uniaxial with an optic axis along the rubbing direction. Comparing the signals shown in Figs. 3(a) and 3(b) it is also very clear that the p to s conversion signals from the sample (b) rubbed twice are substantially stronger than the signals from sample (a). By modeling the data in Fig. 3 for 45^o rotation angle (solid line in Fig. 3) using a mean optical refractive index of 1.5970 the optical anisotropy ($n_{\parallel}$ - $n_{\perp}$) and thickness of the two samples are found to be 0.05 and 10 nm for sample (a) and 0.075 and 13 nm for sample (b). The presence of weak p to s conversion signals for 0^o and 90^o together with the mode-width being wider than the theoretical prediction (see Fig. 3) indicates that the effective optical axes has some randomness leading to general scatter.

Two TN cells were fabricated using separately the two tested layers combined with a glass plate treated with another rubbed polyimide aligning layer made from an industry product line. Crossed polarization microscopy images for these two cells show uniform textures indicating that both rubbed polyimide layers give good alignment.

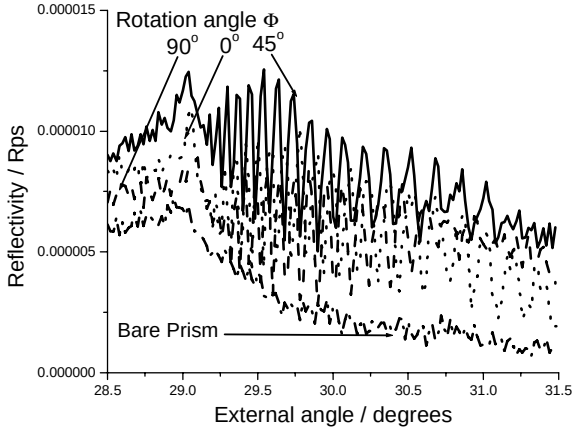

Fig. 4. Experimentally recorded R_{ps} signals against the external incident angle for an angle-evaporated SiOx layer. The data for the bare prism is also shown.

In contrast to the above Fig. 4 shows the data recorded for an angle-evaporated SiOx layer with a thickness of about 20 nm. The sample rotation angle is defined as between the incident plane and the alignment plane which also contains the surface normal and is at right angles to the plane containing the evaporation direction line and the surface normal. According to [10] the SiOx grooves align the liquid crystal director in this alignment plane. From Fig. 4 it is clear and perhaps surprising that the SiOx aligning layer has an almost optically isotropic behavior. The p to s conversion signal is lower than ~ 10^{-5} for any angle of rotation. Using 1.5170 as the mean optical refraction index and 20 nm as the layer thickness modeling leads to an anisotropy ($n_{\parallel}$ - $n_{\perp}$) less than 0.01. Nevertheless the micro-grooving of the SiOx still gives good alignment of the liquid crystal.

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In conclusion, a PCGM (Polarization Conversion Guided Mode) technique has been developed to explore the p to s conversion created from a very thin surface layer. Based on modeling together with careful design of the sample geometry and experimental procedure it is shown that one may distinguish p to s conversion down to ~ 10^{-5}. Two types of thin layers for aligning liquid crystals in displays, a rubbed polyimide coating and an incline-evaporated SiOx layer, have been explored to demonstrate the technique. The rubbed polyimide layer has significant optical anisotropy while the SiOx layer gives no measurable signal and appears isotropic optically.

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