Available online at www.sciencedirect.com
ScienceDirect
Thin Solid Films 516 (2007) 107–113
www.elsevier.com/locate/tsf

Production scale deposition of multilayer film structures for birefringent optical components

Markus K. Tilsch *, Karen Hendrix, Kim Tan, David Shemo, Rick Bradley, Ralf Erz, Joerg Buth

JDSU, 2789 Northpoint Parkway, 95407 Santa Rosa, CA, United States

---

Abstract

Many modern optical systems require polarization control of light in addition to spectral control. Light modulation applications include displays, optical data storage, digital imaging, metrology, instrumentation, optical communications and others. Within the information display sector, liquid crystal displays with polarization control components are prevalent. These components are often close to an image plane and thus have stringent defect requirements. Use of these components to control contrast and modulation drives the requirement of uniformity and part-to-part consistency. In a birefringent material the interaction of light with matter depends on the polarization state and orientation of the material. Bulk materials like quartz possess crystalline structures and hence exhibit molecular birefringence. Liquid crystal materials, stretched foils, and obliquely deposited columnar films are examples of engineered materials that have a microstructure or molecular orientation that creates birefringence. But even a stack of thin isotropic layers has birefringent properties when illuminated at non-normal incidence angle. We discuss two deposition technologies which JDSU has scaled into volume production. The first is based on liquid crystal polymers and the second on vacuum multilayer thin-film deposition. Production scale deposition requires high throughput, high uniformity, batch-to-batch reproducibility, and low defect capability. Both processes are standardized on 200 mm wafers, which allows for modular manufacturing within the same work cell and clean room. The two technologies are used together to create specifically tailored birefringent optics. Independent control of in-plane and out-of-plane retardance is enabled. Excellent layer thickness control, knowledge of the optical properties, and suitable metrology enable JDSU to adjust processes to address various customer needs in a rapid manner.

Keywords: Birefringence; Production; Deposition; Retardance

---

1. Introduction

Light can be described as a transverse electromagnetic wave. Besides its intensity and wavelength, the state of light is characterized by the polarization [1]. In many applications, specifically for light modulation, polarization control is required. In a birefringent material the interaction of light with matter depends on the polarization state and orientation of the material. For example, a quarter-waveplate (QWP) retarder at the operating wavelength, with its slow and fast axes aligned at ±45° vs. the incoming linear polarization converts the input into a circularly polarized output. The retarder can be created by bulk materials, like quartz, which possess non-centrosymmetric crystalline structures and hence exhibit molecular birefringence. On the other hand, liquid crystal mixtures, organic stretched foils and obliquely deposited columnar films [2–4] are other engineered anisotropic thin films having a microstructure or molecular orientation that yields birefringence. Even without the birefringence in the constituent materials, a stack of thin isotropic layers yields birefringent properties when illuminated at non-normal incidence angle due to the interaction differences in the geometric S- and P-polarizations [5,6].

To manufacture birefringent components on a production scale, several aspects need to be considered:

- The polarization market is very diverse. A high level of customization is required. This suggests developing a technology portfolio that can be mixed and matched to satisfy the customers' needs.

---

* Corresponding author.
E-mail address: Markus.Tilsch@jdsu.com (M.K. Tilsch).

0040-6090/$ - see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.tsf.2007.06.103

- Complex components may go through many processing steps. The yields at every processing step must be high and well understood.
- The durability and environmental stability of the birefringent components needs to be adequate.
- Some polarization components are used close to a plane conjugate to an image plane in an instrument. The defect requirements may be very stringent.

JDSU has developed an ISO class 5 clean room work-cell with two coating technologies and all the support equipment necessary to manufacture birefringent coatings on a production scale. To take advantage of the efficiencies developed by the semiconductor industry for wafer level processing, the decision was made to standardize all processes for 200 mm diameter glass wafers. JDSU's newly developed coating platform Ucp-1 [7] processes 200 mm diameter wafers and is capable of precisely coating very thin layers, as required for many polarization applications. Additionally, JDSU has focused on the development of a Hybrid Liquid Crystal (HyLC) spin-coated birefringent film technology for processing 200 mm wafers.

2. Experimental

2.1. Liquid crystal polymer deposition

JDSU's HyLC is comprised of a photoaligned polymer alignment layer and a liquid crystal polymer birefringent layer. The alignment layer is a linearly-polymerizable photopolymer (LPP) material, which, when exposed to linearly polarized ultraviolet (UV) radiation, results in cross-linking in a direction parallel with that of the polarization direction. The oriented LPP layer then serves as an alignment layer for a subsequently coated liquid crystal polymer (LCP) precursor layer. The LCP precursor is an acrylate monomer containing mesogenic moieties, which, when oriented, give rise to an in-plane uniaxial-positive optical birefringence. To make permanent the orientation, the LCP precursor is polymerized via a UV curing process, thereby converting it to a solid state film. A HyLC layer is stable and durable with respect to light-flux and environmental exposure (at $\lambda > 400$ nm and in typical commercial application environments). The HyLC retarder film coated on a substrate may be the final product, or it may be laminated to other substrates or optical components. HyLC films may also be used as a substrate for deposition of other films.

The optical retardance of a HyLC film is a linear function of the LCP's physical thickness, which is easily controllable in various liquid coating processes. Single LCP layers may range in thicknesses from <100 nm up to several microns with retardances from just a few nm (i.e. trim retarders) up to several hundreds of nm for QWPs, half-waveplates (HWP), etc. By combining multiple LPP/LCP stacks, achromatic waveplate designs and very high retardance values can be obtained.

There are several unique benefits offered by JDSU's HyLC technology over other types of birefringent optical materials used to produce A-plate retarders. Since HyLC films are formed by a coating process, it allows easy fabrication of true zero-order retarders with high uniformity over a large area. In the case of inorganic single crystal retarders, often non-zero-order retarders are fabricated due to difficulties associated with grinding and polishing extremely thin plates. Usually, crystal retarders are limited to sizes in which single crystals can be feasibly produced (generally <100 mm diameter). In contrast, depending on the coating method and equipment available, HyLC films can be coated on large format substrates. In comparison with stretched polymer foil retarders, HyLC offers greater reliability under conditions of high light-flux and temperature. For example, polarization control elements in projection display systems may typically operate at a temperature of ~ 60 °C with a light-flux level of over 20 MLux. The greater stability of HyLC is due to its high degree of cross-linking and high glass-transition temperature. Also, unlike foils and extremely thin crystal waveplates which generally require one or more laminations, HyLC waveplates may be prepared without lamination since the HyLC films are coated directly onto an optical substrate. Additional coatings may be deposited directly onto the HyLC.

2.2. Vacuum multilayer thin-film deposition

Ucp-1 is a high throughput, fast cycle time, high precision and low defect level vacuum coating platform. Six 200 mm diameter wafers are processed in each batch. Ucp-1 is comprised of a process chamber and a load lock chamber, separated by a gate valve. One side of the load lock chamber mounts to an ISO class 5 clean room. The load lock concept has several advantages over a chamber that is vented for every part exchange. The load lock maximizes machine uptime because the machine coats parts in the process chamber while new parts are prepared for the next run. Once a batch of parts is finished the six coated parts are automatically exchanged for six uncoated parts. A new coating batch can be started without delay. The process chamber stays constantly at temperature and under vacuum improving stability and reducing defects. When a conventional chamber is vented and cooled to unload parts the coating buildup on the walls may flake off and contaminate the parts and chamber. Also a variable amount of moisture gets absorbed at the walls of the coating chamber which can lead to variation in the coating conditions for the next run. Both problems, flaking and moisture variation are greatly reduced though the load lock.

The coating process used in Ucp-1 is magnetron sputtering. The six parts are mounted on a planetary rotary drive system. Tight chamber tolerances and an optimized source to substrate geometry lead to high coating material utilization and good process stability even for very thin layers. Two or more dielectric materials are produced in the same chamber. The time to switch from the deposition of one material to another is minimized by employing an advanced control system and fast mechanical actuation. The short overhead time is of particular importance for the deposition of a high number of very thin layers, as required for producing form-birefringent coating designs.

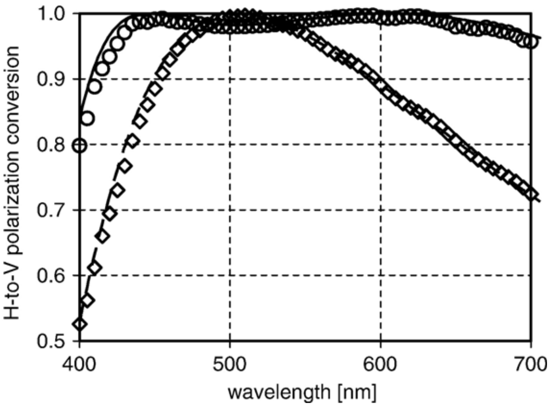

Fig. 1. Polarization conversion efficiency of HWP (diamonds: measurement, dashed line: theoretical) vs. AHWP (circles: measurement, solid line: theoretical) HyLC coatings.

Typical physical coating rates for Ucp-1 are 1 nm/s. A design with a total thickness of 2 μm consisting of 100 layers, is typically coated in less than an hour. Ucp-1 is fully automated and integrated with JDSU's other state of the art design, control, and evaluation systems.

2.3. Pre- and post-processing

In addition to the Ucp-1 and HyLC process equipment, there are many other important processes required for manufacturing products with birefringent optical properties. A key aspect was the standardization of the substrate form factor on 200 mm diameter wafers. To guarantee the customer specifications without incurring significant costs, a wafer level approach was used to develop an extensive line of metrology equipment for the characterization of birefringent, spectral, environmental, and defect properties. The wafers are cleaned prior to film deposition with an automated spin cleaner. After coating deposition, retardance metrology is typically performed to characterize the birefringent properties of the wafer. For some products a wafer is laminated to a second wafer. Wafers or laminates are mapped for surface defects using an automated wafer inspection system. The final steps in the manufacturing flows involve dicing of the wafer as well as cleaning, inspection and packaging of the dies. Dicing often must be done at very precise angles relative to the orientation of the HyLC on the wafer. This ensures that the resulting die orientations are within certain mechanical tolerances of fixturing employed in the end-application.

3. Results

3.1. HyLC coating results

An application for the HyLC technology is the fabrication of an HWP retarder. An HWP rotates plane-polarized light. In the application example of light conversion, horizontally linearly polarized light (H) needs to be converted to vertically linearly polarized light (V). An HWP with its fast axis oriented 45° relative to the incoming H polarization direction will convert the light to the orthogonal V state. The conversion efficiency measures the fraction of the output light in the converted polarization state. A conversion efficiency of 1.0 is produced when the retardance value at a particular wavelength is one-half of the wavelength. A single layer HyLC retarder can meet the HWP condition at the design wavelength, but exhibits a higher or lower retardance value than a halfwave when the illumination wavelength deviates from the design wavelength. The deviation becomes larger the further the wavelength is away from the design wavelength. Thus, at the design wavelength the conversion efficiency is 1, while at shorter and longer wavelengths the polarization conversion efficiency drops off.

For applications requiring high polarization conversion over a large spectral range rather than at a single wavelength, achromatic HWP's (AHWP) can be designed and fabricated through the use of two or more HyLC retarder layers in series, with each having a specific azimuthal orientation direction. A similar product, an achromatic QWP is needed in Compact-Disc (CD) and Digital Versatile-Disc (DVD) optical pick-up units (OPU) for converting linear polarizations to circular polarizations in different segments of the OPU.

To demonstrate the HyLC capability a non-achromatic HWP and an AHWP were designed and prepared on 200 mm diameter substrates using HyLC coatings. The HWP retarder was made with a single HyLC layer of approximately 2 μm thickness, targeting the HWP condition to be at $\lambda = 505$ nm. The nominal AHWP design was optimized to produce a high H-to-V polarization conversion efficiency of ≥95%, over the wavelength range from 430 to 680 nm.

The measured polarization conversion spectra of the HWP and AHWP samples are shown in Fig. 1 along with the corresponding theoretical models. The performance of the samples is in excellent agreement with the models. Slight deviation of the measured AHWP from its nominal design model is attributed to certain fabrication tolerances vs. the nominal design. Over the wavelength band of interest, the AHWP sample was found to have an average polarization conversion efficiency of ~ 98.7% and a minimum efficiency of ~ 97.1%. By comparison, the HWP sample's average and minimum conversion efficiencies in the wavelength band were 90.3% and 75.7%, respectively. However, the HWP did provide near perfect conversion at the design wavelength of 505 nm.

The measured spatial uniformity of the AHWP's polarization conversion efficiency is shown in Table 1. The area mean and standard deviation (SD) of the polarization conversion are listed for the wavelengths 430 (shortest wavelength of the specified spectrum), 550, and 680 nm (the highest wavelength of the specified spectrum).

Table 1
Measured spatial mean and standard deviation of polarization conversion efficiency over 200 mm diameter AHWP sample

Wavelength (nm)	Mean H- to-V conversion (%)	SD H-to-V conversion (%)
430	97.7	0.6
550	99.4	0.1
680	97.3	0.3

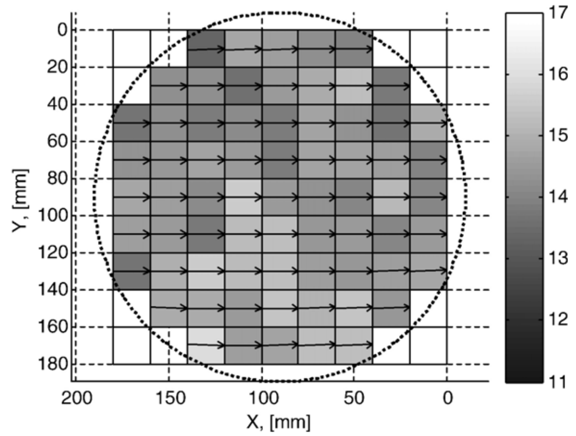

Fig. 2. Retardance magnitude and orientation map of small magnitude retarder (HyLC coating), measured at 633 nm on 20 mm spatial grid across 200 mm. Average magnitude is 14.7 nm, 3σ retardance uniformity 11.7%, and 3σ orientation uniformity 1.7°.

The HWP retarder from the previous example has a retardance on the order of 250 nm at its design wavelength. The next example demonstrates HyLC capabilities for much smaller retardance values. A retardance on the order of 10 nm is required for liquid crystal on silicon (LCoS) micro-display contrast enhancement applications. Such low magnitude retarders are referred to as “trim-retarders”.

An example of a HyLC trim-retarder coating with nominally ~ 14 nm in-plane retardance on a 200 mm glass substrate is given in Fig. 2. The 14 nm retardance in this example is somewhat arbitrary. By the selection of the appropriate spin-coating process conditions, the magnitude of retardance value may be easily tailored to specific LCoS panel compensation requirements. The figure shows the uniformity with which the HyLC can be coated at low retardance levels. It is important to note, however, that at such low retardance levels the observed variation may have other sources in addition to the HyLC process itself. Stress effects, present in the glass substrate material can have a significant influence on the measured retardance. Careful selection of substrate materials and substrate quality is important. The method to hold the parts during the measurement should impose low force on the parts. The capability of the metrology needs to be well-known and adequate for this application.

JDSU is mass-producing a trim retarder, commercialized under the name Birefringent Contrast Enhancer (BCE). Fig. 3A shows measured A-plate (in-plane) retardance data for about 200 consecutive lots after the HyLC production step. The retardance is normalized to the targeted value to protect the exact customer specification. The data include one data point of machine malfunction, which is easily identifiable. This value is omitted in the following process statistics. The average normalized retardance is 0.999, while the standard deviation is 0.022. Fig. 3B shows the same data organized in a histogram, which is overlaid with the corresponding normal distribution. This statistical information is used to estimate the machine capability and process yields as will be shown in the discussion section.

3.2. Vacuum coating (Ucp-1) results

JDSU’s capability to design and coat form-birefringent structures was published previously [8]. A form-birefringent antireflection coating (FBAR) was designed for a target C-plate retardance of −120 nm at 630 nm and good antireflection performance from 590 to 700 nm. To measure the process capability, the design was coated 24 times in Ucp-1. Fig. 4 overlays the theoretical retardance with the measurements from the 24 coating runs. The retardance of each part was measured from −30° to 30° angle of incidence (AOI) in 1° increments. To determine the C-plate retardance the data was fitted to the model:

$$\Gamma_c \approx \frac{1.5^2 \Gamma(\theta)}{\sin^2\theta}$$

where θ is the AOI in air and $\Gamma(\theta)$ is the measured retardance at that angle. The measured average retardance is close to the theory. The average was −113 nm with a standard deviation of 6.8 nm. The averaged average reflectance from 590 to 700 nm was 0.01%, with a standard deviation of 0.003%.

A C-plate only product of this type is mass-produced by JDSU. Parts are manufactured for the red, green, and blue channels of a projection television set. The difference between

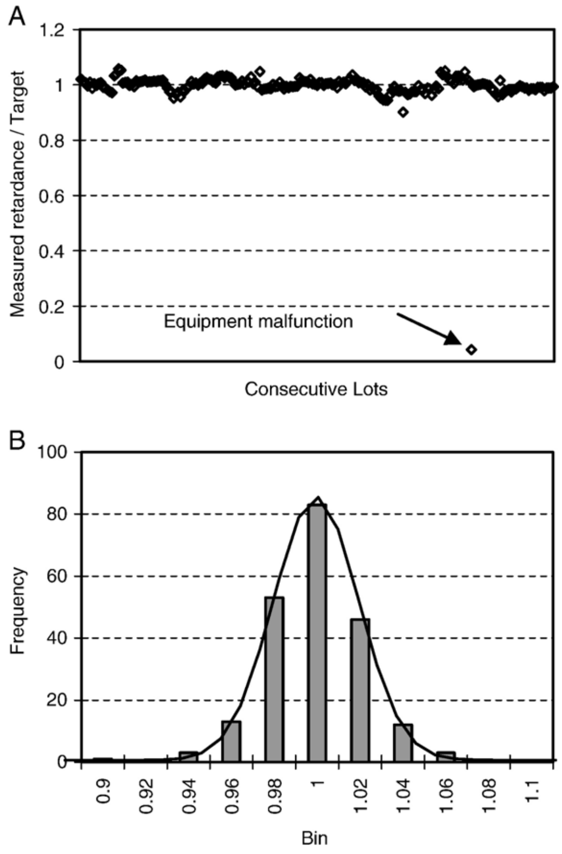

Fig. 3. A. Measured A-plate retardance for 200 consecutive HyLC production lots. Retardance is normalized to target. B. Histogram of data from Fig. 3A, overlaid with normal distribution.

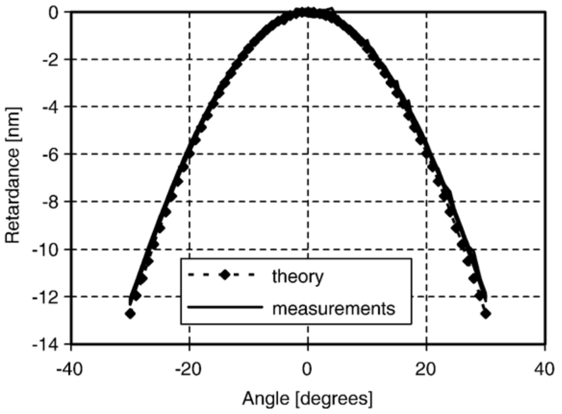

Fig. 4. Theoretical (dotted line, diamonds) and measured (solid lines) retardance at 630 nm of 24 FBAR runs from Ucp-1. Measurements are taken in 1° angle increments.

the three products is the wavelength range for the antireflection performance. Retardance targets are very similar. For quality control the retardance and spectral performance of each produced wafer is characterized. A retardance measurement at multiple angles of incidence is time and cost prohibitive. Thus, the retardance is only measured at a fixed AOI of 10°. Fig. 5 shows the C-plate retardance performance of 22 wafers from a production sequence. The retardance is normalized to the target retardance. The retardance level is roughly 300 nm. The sequence spans 12 consecutive runs and includes data from two randomly picked wafers of the six wafers that are produced in each batch. Only one wafer was measured in runs 4 and 5. The average is 0.995, i.e. the average C-plate retardance is 0.5% under the target. The standard deviation is 0.0114.

The antireflection performance for the same product is measured at 12° AOI. Fig. 6 shows the average reflectance over the specification wavelength range for 20 runs where two wafers were picked randomly per run (total of 40 data points). The measured average reflectance is 0.029% with a standard deviation of 0.0055%.

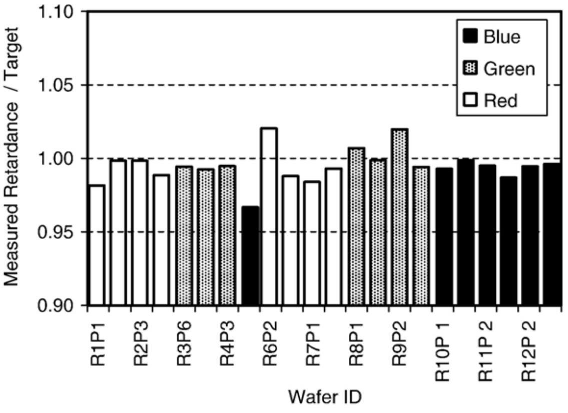

Fig. 5. Measured C-plate retardance for 12 consecutive Ucp-1 production runs. Two of the six produced wafers per run were randomly selected and measured. Only one wafer was measured in runs 4 and 5. Retardance is normalized to target.

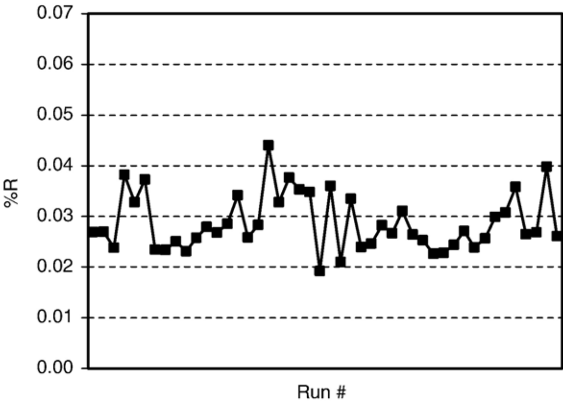

Fig. 6. Measured antireflection performance of 20 Ucp-1 production runs. Two of the six produced wafers per run were randomly selected and measured.

3.3. Combined HyLC and vacuum coating (Ucp-1) results

JDSU is in production with a BCE component that combines the HyLC and Ucp-1 coating technologies. The component is used to correct the retardance aberration of an LCoS panel. The optical parameters of the BCE need to be matched to the specific requirements of the LCoS imager. The LCoS imager with homogeneous, vertically aligned nematic liquid crystals exhibits a small in-plane retardance due to a pre-tilt. The use of positive uniaxial liquid crystals results in a large positive C-plate retardance, approx. $\Delta n \cdot d$ of the liquid crystal birefringence (Δn) and cell gap (d). An A-plate retardance on the order of 10 nm and a C-plate retardance on the order of −250 nm are typical to compensate such an LCoS panel.

For the fabrication of each BCE, two wafers are coated with FBARs in Ucp-1. The HyLC coating is applied to one of the wafers and the two wafers are laminated with an adhesive. The wafer is cut into individual parts with dimensions of 1–2 cm for the final product. The contrast enhancements of a projection system are quite dramatic, as typical data in Table 2 show. A three- to five-fold improvement over the LCoS panel alone is measured. The improvement comes from minimizing the leakage of the off-state (dark-state).

In a LCoS projection system the BCE is subjected to high light-flux and elevated temperature. Maintaining the optical properties in this harsh environment is critical. Light-flux reliability testing results for JDSU's BCEs were previously published [9]. Under the specific test conditions of the test setup with 20 MLux and 60 °C, the BCE trim retarder product is predicted, with 95% confidence, to have a mean time to failure (MTTF) of at least 15,000 h, which comfortably exceeds the service requirement for a rear projection TV. The spectral

Table 2
Typical measured contrast ratios of LCoS panels with and without the addition of a BCE component

	Blue	Green	Red
Panel-only	900	1200	1600
Panel+BCE	4000	5300	6700

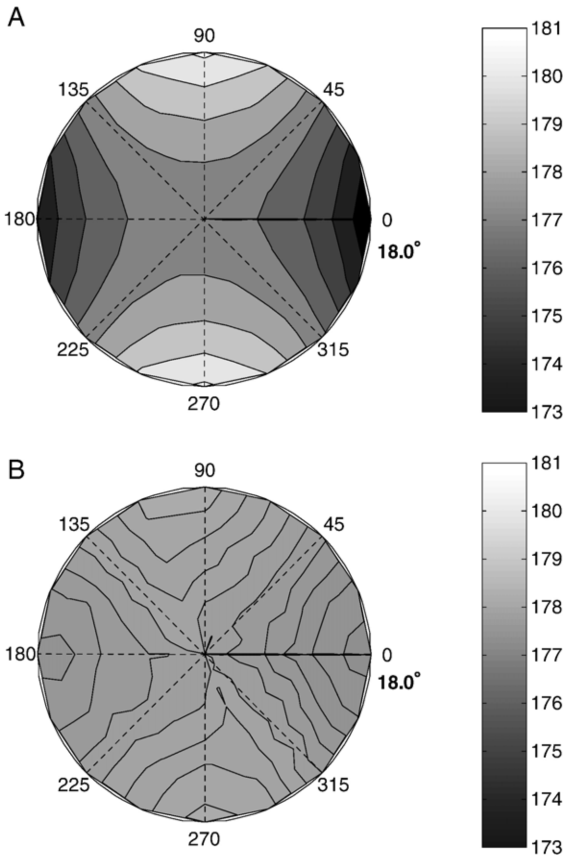

Fig 7. A. Conoscopical measurement (0° to 18° AOI in 22.5° azimuthal orientations) of HyLC only HWP retarder. Retardance ranges from 173.1° to 181.2°. Normal incidence retardance is 177.5°. B. Conoscopical measurement (0° to 18° AOI in 22.5° azimuthal orientations) of HyLC HWP retarder with additional Ucp-1+C-plate coating. Retardance ranges from 177.4° to 178.4°. Normal incidence retardance is 178.0°.

composition in the test station is considered to be aggressive compared to that found in commercial rear projection television. So, as tighter UV cut-off filters are employed, the BCE lifetime would be extended. As a result of its high light-flux reliability, the BCE will facilitate stable, high contrast ratio performance of LCoS rear projection television sets over their expected service lifetime.

The final example shows another combination of HyLC and Ucp-1 coatings. In some ophthalmic metrology systems, a retarder is scanned at multiple polar and azimuthal angles. For a constant phase difference regardless of the AOI, a constant linear retardance profile over all scanning cone angles is desirable. The combination of the HyLC technology with the Ucp-1 dielectric coating technology offers the capability to produce A/C-plate configurations that result in a flattened retardance profile with respect to the AOI.

For demonstration, two HyLC HWPs were made for a wavelength in the near-IR. An additional birefringent dielectric AR coating was coated on one wafer in Ucp-1. The birefringent AR provided an out-of-plane+C-plate retardance component, specifically designed to compensate for the retardance vs. AOI profile of the HyLC A-plate. Fig. 7A shows a measured conoscopic retardance map of the HyLC HWP by itself, while Fig. 7B shows the same type of map for the HyLC/Ucp-1 combined component. Data were acquired in 22.5° azimuthal angle increments and 2° AOI steps from normal up to 18°. The retardance range for the unflattened component is 8.1° of retardance, while that of the compensated component is only 1°. This represents a demonstrated eight-fold improvement.

4. Discussion

Two birefringent coating technologies, HyLC and Ucp-1, were developed to production scale. For some product opportunities only one technology is required, but in many cases the technologies are combined. Both technologies are integrated into an ISO class 5 clean room manufacturing work-cell. The coating technologies process 200 mm diameter wafers. That standardized format allows for modular production. The required support equipment for cleaning, measuring, inspection, singulation, and packaging is developed.

For both coating technologies a variety of results from the manufacturing cell were presented. The retardance was the primary performance parameter in all examples. The results show that JDSU has the ability to model their films and can predict the resulting performance. Multilayer coatings can be designed to meet a variety of customer specifications. In many cases additional optical performance criteria, like the spectral transmission and reflection behavior of the coatings are combined in the design. All equipment is designed to minimize defect generation. Stringent requirements for optical components close to conjugate image planes can be addressed successfully.

Processing of 200 mm wafers means that many final devices are processed in parallel. The uniformity across the whole wafer was measured and results were presented. For typical commercial requirements the coating uniformity performance of both technologies across 200 mm substrates is very good.

The BCE product is an example where a part undergoes many processing steps. The overall yield is the product of all individual processing yields. For mass manufacturing it is important to know the capabilities of each piece of equipment. This enables yield predictions, allows setting up production sampling plans, and shows where to focus the process improvement work if tighter specifications have to be satisfied. For both deposition technologies, retardance information from production sequences have been presented. In addition, a sequence of reflectance values was shown for Ucp-1. Statistical information for the process centering and variation has been derived. Table 3 shows typical requirements for the discussed categories of A- and C-plate retardance magnitude and antireflection performance of BCE products. The Cpk process

Table 3
Cpk process capability analysis for retardance and reflectance of BCE product

	Attribute	Typical	Specification (%)	Cpk	Est. yield (%)
BCE	Reflection %	N/A	<0.1	2.78	100.00
	In-plane Retardance [nm]	10	±10	2.66	100.00
	Out of plane Retardance [nm]	250	±10	1.50	99.999

capability values are calculated from the statistical process information for the specification limits of the product [10]. For the typical BCE product requirement the three Cpk values are above 1.33 with yield expectations of these process steps exceeding 99.9%. The final product has to satisfy many additional specifications such as retardance orientation, maximum allowed quantity and size of defects, physical part size tolerances, and edge chips, which were not discussed in detail in this paper.

Both deposition technologies offer large flexibility for product customization. In Ucp-1 the coating design is controlled by a recipe. A new recipe can easily be loaded if a different design needs to be coated. The production sequence of a C-plate only retarder (Fig. 5) illustrates how wafers for different colors were coated in almost arbitrary sequence. No test runs were coated between the different products. The thickness of HyLC films can be readily changed allowing rapid customization of the retardance over a broad range from a few nm to several 100 nm. This flexibility is important to address the high level of customization in the markets of birefringent products.

5. Conclusions

JDSU has developed two birefringent coating technologies for production scale manufacturing. HyLC is a birefringent thin-film technology. The HyLC material is applied via spin-coating. Its optical birefringence is derived from a molecularly oriented liquid-crystal polymer. The Ucp-1 vacuum deposition technology allows fabrication of precision optical coatings including form-birefringent thin films. Such coatings exhibit out-of-plane birefringence. Both process technologies have been implemented on 200 mm diameter substrates and are integrated in one clean room work-cell. Additional support equipment is available for cleaning, characterization, singulation, and packaging. Examples for vacuum coating only, HyLC only, and combined products have been discussed. The processes can be mixed and matched to address the customer needs in a rapid fashion. The combined Ucp-1/HyLC production cell is able to turn around orders of a few wafers quickly and also sustains quantities of several thousand parts per day.

References

[1] E. Hecht, Optics, Addison Wesley Longman, Inc., New York, 1998, p. 319.
[2] J.P. Eblen, et al., in: J.D. Rancourt (Ed.), Optical Thin Films IV: New Developments, Proc. SPIE, vol. 2262, 1994, p. 234.
[3] K. Robbie, M.J. Brett, J. Vac. Sci. Technol., A, Vac. Surf. Films 15 (3) (1997) 1460.
[4] I.J. Hodgkinson, Q.H. Wu, Birefringent Thin Films and Polarizing Elements, World Scientific, Singapore, 1997 ch. 7.
[5] M. Born, E. Wolf, Principles of Optics, Pergamon Press Inc., New York, 1993, p. 705.
[6] A. Macleod, Thin-Film Optical Filters, Institute of Physics Publishing, Philadelphia, 2002 ch. 8.
[7] S. Sullivan, M. Tilsch, F. Van Milligen, Photonics Spectra 39 (11) (November 2005) 86.
[8] K. Hendrix, et al., J. Vac. Sci. Technol., A, Vac. Surf. Films 24 (4) (2006) 1546.
[9] D.M. Shemo, et al., SID 2006 Digest, vol. 1038, 2006.
[10] K.R. Bhote, World Class Quality, AMACOM, New York, 1991, p. 27.