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E. G. Wintucky
Lewis Research Center
Cleveland, Ohio

and

R. Mahmood and D. L. Johnson
Kent State University
Kent, Ohio

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# HOMOGENEOUS ALIGNMENT OF NEMATIC LIQUID CRYSTALS BY ION BEAM ETCHED SURFACES

E. G. Wintucky
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

and

R. Mahmood and D. L. Johnson
Physics Department and Liquid Crystal Institute
Kent State University
Kent, Ohio 44242

## ABSTRACT

A wide range of ion beam etch parameters were found capable of producing uniform homogeneous alignment of nematic liquid crystals on $SiO_2$ films. The alignment surfaces were generated by obliquely incident (angles of $5^o$ to $25^o$) argon ions with energies in the range of 0.5 to 2.0 keV, ion current densities of 0.1 to 0.6 $mA/cm^2$ and etch times of 1 to 9 min. A smaller range of ion beam parameters (2.0 keV, 0.2 $mA/cm^2$, $5^o$ to $10^o$ and 1 to 5 min.) were also investigated with $ZrO_2$ films and found suitable for homogeneous alignment. Extinction ratios were very high (>1000), twist angles were small ($\leq 3^o$) and tilt-bias angles very small ($\leq 1^o$). Preliminary SEM results indicate a parallel oriented surface structure on the ion beam etched surfaces which may determine alignment.

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## INTRODUCTION

Ion beam technology could play a potentially important role in the improvement of large area liquid crystal displays by extending their operating environment to higher temperature and humidity. This could lead to a host of new automotive, marine, aeronautical and industrial applications. Surface alignment of the liquid crystal molecules is an essential step in the fabrication of a liquid crystal display. Ion beam etched surfaces and their capability to produce this surface alignment is the subject of this paper.

Two properties important for high quality performance of twisted nematic liquid crystal field-effect displays are a uniform homogeneous alignment of the liquid crystal molecules by the bounding surface and a small angle (tilt-bias angle) between the nematic director and the plane of the bounding surface. Uniform homogeneous alignment is required for high contrast ratios. A tilt-bias angle is needed in general to prevent "reverse tilt" which is characterized by the occurrence of regions of non-uniform contrast when an electric field is applied. A low tilt-bias is desirable for good viewability, especially in multiplexed liquid crystal displays where the number of display elements is large. Low tilt angle results in increased sharpness of threshhold voltages and reduced angular dependence of light transmission (Ref. 1).

One method for producing homogeneous alignment, now used extensively in small area twisted nematic displays, employs the vacuum evaporation of SiO with deposition at an oblique angle (Ref. 2). The result is an alignment surface stable at elevated temperatures, but which has a high tilt-bias angle of 20° or more. A second commonly used method, especially in large area displays, which is capable of producing a small tilt-bias angle on the order of a few degrees, consists of unidirectional rubbing of the bounding surface. A disadvantage of rubbed surfaces is their loss of alignment capability at high temperatures, which makes them incompatible with the glass-frit hermetic sealing process and potentially limits their application in high temperature environments.

At least two precesses have been investigated recently which promise both low tilt angle and stability of alignment capability after exposure to high temperatures (500° C). One process is a double evaporation of SiO with the two layers deposited consecutively at different angles (Ref. 3). The other process uses "shallow angle ion beam etching" to induce homogeneous alignment (Ref. 4).

The results of Ref. 4 demonstrated the ion beam etch technique capable of producing a highly uniform and stable homogeneous alignment of nematic liquid crystals on RF sputter deposited films of $SiO_2$. A tilt-bias angle of 4° was reported. Temperatures of 500° C and washing with solvents did not destroy the alignment capability of the ion beam etched surfaces. A range of ion beam etch conditions were found suitable for producing homogeneous alignment.

The main purpose of the effort reported here was to quantify the dependence of surface alignment properties on various ion beam etch parameters. Test cells were fabricated using ion beam etched films of RF sputter deposited $SiO_2$ and $ZrO_2$ and measurements were made of extinction ratios, tilt-bias angles and twist angles. Disclination loops, which were observed in some samples, are described and factors influencing their occurrence are discussed. Results of a preliminary scanning electron microscope investigation of the ion beam etched surface structure are reported.

## EXPERIMENTAL PROCEDURES

### Preparation of Samples

Film deposition. - The alignment surfaces were prepared from films of $SiO_2$ and $ZrO_2$ RF sputter deposited onto 2.5-cm square glass substrates. An assortment of glasses were used as substrates and included sections of glass microscope slides, Corning 0211 and Corning 7059. The film deposition was performed in a commercial RF sputter apparatus (Perkin-Elmer's Ultek Sputtering Module 6140-6J) operated in the direct sputter deposition mode (no bias voltage on the substrate) at 300 watts forward power in an argon plasma with a pressure of around 20 millitorr.

The resulting $SiO_2$ films were clear and colorless, whereas the $ZrO_2$ films showed some coloration because of an index of refraction somewhat higher than that of the glass substrate. $SiO_2$ film thicknesses ranged from 250 nm to 750 nm with most films between 300 nm and 400 nm. $ZrO_2$ film thicknesses ranged from 300 nm to 560 nm with most films between 300 nm and 400 nm. Film thicknesses were measured with a mechanical stylus profilometer (Tencor Alpha-Step).

Ion beam etching. - The alignment surfaces were produced by an obliquely incident argon ion beam from a two-grid, multipole industrial-type ion source (Ion Tech, Inc., Ft. Collins, Col.), the significant features of which are shown in Fig. 1. The ion beam system was capable of generating an 8-cm diameter monoenergetic argon ion beam with a maximum beam voltage (ion energy) of 2000 V (limit of power supplies). Measurements of the ion current density in the range of 0.1 to 1.0 $mA/cm^2$ showed a variation of less than 10 percent across the central 6 cm of the beam. An electron emitting filament was used for ion beam neutralization. Principles of ion source operation and other details are given in Refs. 4 and 5. Vacuum chamber pressures during ion beam etching were typically in the low to mid $10^{-5}$ torr range.

The substrates were placed in the center of the ion beam and etched in pairs at a distance of either 10 or 20 cm downstream from the plane of the grids, these distances being those at which the ion current density was calibrated. Fig. 1 shows the shallow angle orientation between the direction of the ion beam and the surface to be etched.

Four ion beam parameters were varied in order to determine their effects on liquid crystal alignment. The conditions varied were angle of incidence ($5^o$ to $30^o$ between direction of ion beam and plane of substrate), duration of exposure to ion beam (1 to 9 min.), ion energy (0.5 to 2.0 keV) and ion current density (0.1 to 0.6 $mA/cm^2$).

## FABRICATION OF TEST CELLS

The test cells were assembled from pairs of simultaneously etched surfaces with the ion beam etch directions on opposing surfaces oriented antiparallel. The directions of alignment were consequently parallel.

The first group of cells were fabricated with a 95-micron thick, double-faced polyester tape as spacer. These cells had $SiO_2$ surfaces and were filled with the cyano-biphenyl nematic E-7 (BHD, Ltd.).

The remainder of the test cells were assembled using a commercial process for large area displays and filled with a proprietary mixture of esters (LXD, Inc., Cleveland, OH). A polymeric material was used to seal the cells. The liquid crystal thicknesses were approximately 6-7, 30 and 50 microns for the $SiO_2$ cells and 30 microns for the $ZrO_2$ cells.

## MEASUREMENT OF ALIGNMENT PROPERTIES

Twist angles, extinction ratios and tilt-bias angles were measured using a He-Ne laser ($\lambda$= 632.8 nm, 1.8 mW) as a light source. The test cells were placed between crossed polarizers with the laser beam normal to the alignment surfaces. Transmitted light intensities were measured with a photodiode. The experimental arrangement is shown schematically in Fig. 2.

To measure the twist angles, the test cells were placed between crossed polarizers with the assumed direction of alignment parallel to the direction of polarization of incident light (solid arrows in Fig. 2). The edge of the test cell was used a a reference. If the director were aligned perfectly parallel to the edge of the cell on both sides of the liquid crystal, this configuration would result in a relative minimum in transmitted light intensity (maximum extinction) with perfectly crossed polarizers. However, minimum intensity did not occur with perfectly crossed polarizers because of a small twist in the director through the cell resulting from unequal alignment at opposite points on each surface. To obtain minimum intensity, both sample and analyzer were alternately rotated slightly back and forth until an absolute minimum was found. The twist angle was then determined to an accuracy of 0.5 degrees from the final analyzer setting.

Extinction ratios were usually measured at the same points on the test cells as the twist angles. Horizontal rotation (Fig. 2) of the test cells produced four relative minima, which alternated with four relative maxima at $45^o$ intervals. Each relative maximum was further maximized by rotation of the sample about the vertical axis (Fig. 2). This procedure produced a maximum independent of the thickness of the liquid crystal. The extinction ratio was then taken as the average of the four ratios obtained by taking the ratio of each maximum to the adjacent minimum. The maximum extinction ratio for the apparatus only (laser light source, polarizer, analyzer and photodide) was carefully measured and found to be nearly $10^4$.

The extinction ratio measured in the manner described above differs from the "contrast ratio" which is commonly used by the liquid crystal display industry as a measure of electro-optical response. There "contrast ratio" is the ratio of transmitted intensity with voltage "off" to that with voltage "on".

Tilt-bias angles were determined by an optical crystal rotation method in which it was assumed that the tilt angle of the director, and hence the optic axis, was uniformly oriented within the liquid crystal layer. Such a configuration is possible with antiparallel alignment of the liquid crystal molecules on opposite surfaces of the cell. Measurement of tilt-bias angles at the boundaries is then a matter of measuring the orientation of the optic axis relative to the plane of the bounding surface (Ref. 6).

To measure the tilt-bias angle, the test cell was placed between crossed polarizers with incident light polarized at an angle of $45^o$ (broken arrows in Fig. 2) with respect to the assumed direction of alignment, which was perpendicular to both the laser beam and the vertical axis. Transmitted intensity was then maximized by slight back and forth rotations of the sample and the analyzer about the beam direction.

Incident light breaks up into ordinary and extraordinary waves which propagate at different velocities through the birefringent liquid crystal, producing a relative phase shift. Rotation of the sample through 360° about the vertical axis (Fig. 2) then produced an interference fringe pattern similar to that shown in Fig. 3, which is a typical plot of transmitted light intensity versus angle of rotation, $\theta$. Angles of $\theta = 0^\circ$ and $180^\circ$ correspond to the laser beam normal to the surface. A zero tilt angle results in a fringe pattern symmetric about $\theta = 180^\circ$, whereas a nonzero tilt angle results in a displacement of the point of symmetry, as shown in Fig. 3. The tilt-bias angle can be calculated directly from the displacement angle. For small angular displacements, $\Delta\theta_{max}$, the expression for the tilt angle (see Eq. 3 of Ref. 6) is well approximated by $\Delta\theta max/(n_0 + n_E)$. $n_o$ and $n_E$ are the indices of refraction of the ordinary and extraordinary rays, respectively. For a nematic liquid crystal, typical values are $n_o = 1.55$ and $n_E = 1.75$. The tilt angle is then given by $0.3\Delta\theta_{max}$.

## RESULTS AND DISCUSSION

Quality of alignment. - A wide range of ion beam etch conditions were found capable of inducing good quality homogeneous alignment of nematic liquid crystals on RF sputter deposited films of $SiO_2$ and $ZrO_2$. The quality of the alignment was determined by visual examination under a polarizing microscope at a magnification of 320 X. Alignment was judged to be of good quality if characterized by (1) a smooth and uniform appearance across the field of view of the microscope, and (2) good contrast when the sample was rotated. Surface defects, such as disclination loops, are not included in this evaluation and are discussed later.

Table I summarizes the ion beam etch conditions at which good quality homogeneous alignment was observed for $SiO_2$ and $ZrO_2$. Various combinations of ion acceleration voltage (500 to 2000 V), ion current density (0.1 to 0.6 MA/cm$^2$), etch angle (5° to 25°) and etch time (1 to 9 min.) were found suitable for $SiO_2$. Although etch angles of 30° or more did not generally produce good alignment, it is evident that a wide range of ion beam sputtering condition results in good quality alignment. Not all conditions were tested nor were the limits of most parameters determined. A much smaller number of etch conditions were examined with the $ZrO_2$ coatings. However it is probable that a much larger range of conditions would also yield good quality alignment with $ZrO_2$ as with $SiO_2$.

### Twist Angles

Twist angles were measured on 52 test cells, the distribution for which is shown in Fig. 4. Most values (37 of 52) were small, 3° or less, while the largest observed value was 6°. The twist angles were measured at the centers of the test cells and represent the differences in alignment at opposite points on each surface. The causes of the twist arc primarily: (1) misalignment of the substrates in the ion beam during etching, and (2) splay in the alignment across the surface resulting from divergence of the ion beam (Ref. 4).

The twist angles could be reduced by more accurate alignment of the substrates in the ion beam. As shown in Fig. 4 the samples on which twist angles were measured are divided into three groups. Group I samples (25) were etched 10 cm downstream from the ion source at 0.2 $mA/cm^2$. More than half of the twist angles in this group (15 of 25) ranged from $4^o$ to $6^o$. Subsequently, greater care was taken to more accurately align the edges of the substrates parallel to the ion beam axis. The result was smaller twist angles as shown for Groups II and III. Group II samples (13) were etched 10 cm downstream at 0.2 $mA/cm^2$. All twist angles except one were $3^o$ or less. Group III samples (16) were etched 20 cm downstream at 0.1 $mA/cm^2$. All twist angles in this group were $2^o$ or less.

Splay in the alignment, caused by divergence of the ion beam, was also investigated. Fig. 5 shows twist angle measurements made on three test cells at the center and at points approximately 5 mm from the center along two lines, one parallel and the other perpendicular to the assumed ion beam direction. The three samples were ion beam etched at voltages of 500, 1000, and 2000 V, with all other etch conditions the same ($15^o$, 3 min., 0.1 $mA/cm^2$). On each sample the twist angles along the direction of the ion beam showed essentially no variation. Whereas, the value of the twist angle reflects both misalignment of the substrate in the ion beam and splay in the alignment due to ion beam divergence, the differences between values of twist angles at points along the line normal to the assumed ion beam direction (parallel to a sample edge) are a measure of splay effects only. The splay effects were found to be small. Differences in twist angles measured at points approximately 1 cm apart were $1^o$, $1.5^o$ and $2^o$ for the samples etched at 500, 1000 and 2000 V, respectively. This result indicates that splay decreased with decreasing ion beam voltage, which is contrary to Ref. 4 where decreasing ion acceleration voltage was reported to increase the splay. The difference may be ion source dependent. Accounting for it would require knowledge of the dependence of ion beam divergence on ion acceleration voltage, which was not measured for the ion source used in this investigation.

## Extinction Ratio

The Extinction Ratio (ER) was measured near the centers of 56 different test cells. For most cells (75 percent), the ER was very high ( 1000). The high ERs agree with the good quality alignment observed with the polarizing microscope. Twelve samples, most of which also had large numbers of disclination loops, had ERs between 200 and 1000. When viewed under the polarizing microscope, however, the alignment quality of these 12 samples was comparable to that of cells with ER > 1000. Only two samples had an ER less than 100, both of whose alignment quality was observed to be not quite as good as those with higher ER (>200). One sample had many point defects and the other a very large number of disclination loops.

Table II is a distribution of the 56 measured ERs and covers a large range of values. The arithmetic mean values for the $SiO_2$, $ZrO_2$ and total distribution were 2790, 1480 and 2620, respectively. Because of large variations, no systematic dependence of ER on ion beam etch conditions could be inferred. Large variations in ER (although all ER > 1000) were also observed at different points on the same test cell. Such large variations were not unexpected. The ER obtained using the laser beam are a measure of alignment uniformity over only a small region approximately 0.5 mm in diameter. Therefore they are very sensitive to local defects such as dust particles, disclinations and other imperfections. An ER more useful for correlation with overall alignment quality would be one obtained using white light and sampling a larger surface area. None the less, the fact that most ERs were very large (>1000) and were measured at essentially randomly selected points indicates that very high contrasts are obtainable with ion beam etched surfaces.

## Tilt-Bias Angles

The tilt-bias angles as measured by the optical rotation method were found to be very small with most values less than $1^{o}$. Table III presents a distribution of mean values of tilt angle for thirteen $SiO_2$ and seven $ZrO_2$ samples, at a total of 30 positions. The mean value of the distribution was $0.78^{o}$. The tilt angles were taken as $0.3\ \Delta\theta_{max}$, where $\Delta\theta_{max}$ was defined earlier as the angular displacement of the central maximum in the transmitted intensity-angle of rotation fringe pattern (Fig. 3). Standard deviations ranged from less than $0.1^{o}$ up to $0.7^{o}$. Because the tilt angles were very small, the standard deviations occasionally exceeded the value of the tilt angle, particularly for the more ragged fringe patterns. As in the case of the extinction ratio, using the laser beam as a light source measures the tilt angle over a small region and can result in large variations in the measured values. Because of the large scatter in the data, it was not possible to establish a correlation between tilt bias angles and ion beam etch parameters. The most that can be concluded from these measurements is that ion beam etched surfaces result in very small tilt-bias angles, generally less than $1^{o}$. Table III is a summary of the arithmetic mean values of the tilt-bias angle measurements according to type of coating and liquid crystal. The mean values for the E-7 and ester liquid crystals for all samples were both $0.78^{o}$. The mean value of all the measurements on $SiO_2$ was $0.55^{o}$ with mean values of $0.78^{o}$ and $0.32^{o}$ for the E-7 and ester liquid crystals, respectively. The mean value for the $ZrO_2$ samples was slightly higher at $1.04^{o}$. In comparison, Ref. 4 reported a tilt-bias angle of $4^{o}$, which was measured by a magneto-capacitive technique.

## Disclination Lines

Surface disclination lines of random shapes, sizes, densities and locations were observed in a number of test cells with ion beam etched $SiO_2$ and $ZrO_2$. Densities ranged from 1 to $2/cm^2$ up to $600/cm^2$ with the $ZrO_2$ surfaces having a much lower incidence of occurrence than the $SiO_2$ surfaces. Also, approximately an order of magnitude fewer disclinations were observed in $SiO_2$ cells where the liquid crystal was 30 μm thick than in cells of 50 μm. Figure 6 shows a representative area of a 50-μm thick $SiO_2$ cell. Early observations suggested a correlation between the occurrence of disclinations and liquid crystal thickness. However, a subsequent study of cells with liquid crystal layers 6-7, 30 and 50 μm thick failed to support this. It was determined that the disclinations were associated with surface defects that occurred only when glass substrates with significant alkali content had been used, viz., the microscope slide sections and the Corning 0211 glass. The largest numbers of disclinations were observed with the microscope slide sections, which were a soft soda-lime glass. No disclination loops were observed with the Corning 7059, which is a low alkali, barium alumina borosilicate glass. These facts suggest, but do not prove, a correlation between the occurrence of disclinations and sodium content. Further studies would be required to determine whether indeed such a correlation exists. There was no correlation between occurrence of disclinations and either $SiO_2$ coating thickness or ion beam etch conditions.

The defects were unlike the "assembly marks" reported in Ref. 4, which were metastable alignment states whose cause was attributed to the direction of flow of the liquid crystal during cell assembly. Assembly marks of this type were not observed in our test cells. Heating the liquid crystal from the nematic phase to the isotropic phase and then recooling to below the clearing point ($\sim 56^o$ C) did not generally remove the defects, although thermal cycling was observed to occasionally alter the type of disclination at a given surface defect. A close examination of Fig. 6 shows that some of the lines are at the top surface of the liquid crystal layer and others at the bottom surface. The three loops in the upper right of Fig. 6 are in focus, whereas the others are not. Analysis under the polarizing microscope indicated only two focal planes for the defects, separated by approximately the liquid crystal thickness.

Fig. 7 shows two types of narrow line defects, one of which is characterized by a bright disclination line and the other by a darker line. The narrowness of the disclination lines ($<5\,\mu$) indicates the surface pinning energies to be in the strong anchoring regime (Ref. 7).

## Ion Beam Etched Surface Structures

An attempt was made to discover the ion beam etched surface structure responsible for liquid crystal alignment using Scanning Electron Microscopy (SEM). Preliminary results are presented in Fig. 8, which are SEM photographs of ion beam etched surfaces of $SiO_2$ and $ZrO_2$ at magnification of 50 000 X and 41 000 X, respectively. The electron beam was incident at an angle of $40^o$ to the plane of the surface. Both the $SiO_2$ and $ZrO_2$ surfaces were etched at 2000 V, 0.2 mA/cm$^2$ and $10^o$, the only difference being a 5 minute etch time for the $SiO_2$ and 3 min. for the $ZrO_2$. The two surfaces appear similar with the $ZrO_2$ perhaps showing a finer, more dense structure. Both surfaces show a definite parallel oriented structure with lateral dimensions on the order of tens of namometers. The direction of the ion beam was not recorded when the photographs were taken. For comparison, Fig. 9 is a high magnification (170 000 X) transmission electron microscope photograph of an RF sputter deposited $SiO_2$ surface without ion beam etching. The surface appears smooth with a small randomly oriented texture on the order of 5 nm. The $SiO_2$ and $ZrO_2$ samples in Fig. 8 were each one half of a simultaneously etched pair. A drop of liquid crystal was placed between the other two halves (one $SiO_2$ and one $ZrO_2$). Observation with a polarizing microscope verified that the ion beam etched surfaces shown in Fig. 9 indeed produced uniform homogeneous alignment.

## CONCLUDING REMARKS

A wide range of ion beam etch parameters have been demonstrated capable of producing uniform homogeneous alignment of nematic liquid crystals on RF sputter deposited surfaces of $SiO_2$. The results of the present investigation are in general agreement with those of Ref. 4 and extend the ranges of ion beam parameters for which good alignment is obtained, viz., ion acceleration voltages of 500 to 2000 V, ion current densities from 0.1 to 0.6 $mA/cm^2$ and etch angles of $5^o$ to $25^o$. Also, ion beam etching was shown capable of producing uniform homogeneous alignment on RF sputter deposited surfaces of $ZrO_2$. Extinction ratios were very high and corresponded with the good alignment observed under the polarizing microscope. Samples with relatively low extinction ratios (<100) were observed to exhibit lower quality alignment. Tilt-bias angles were found to be very small with most less than $1^o$. No systematic variation of either extinction ratio or tilt-bias angle with ion beam etch parameters was found. Twist angles could be made small ($3^o$ or less) by careful alignment of the substrates in the ion beam during etching. Splay in the alignment due to ion beam divergence was found to be small ($2^o$ or less at a separation of 1 cm) for the multipole ion source, and appeared to decrease with decreasing ion beam voltage.

It was found that $SiO_2$, RF sputter deposited directly onto glass substrates with significant alkaline content, could result in surface defects, which produce disclination lines at the liquid crystal interface. No disclinations were observed in test cells prepared from low alkali glass substrates.

A preliminary SEM examination of ion beam etched $SiO_2$ and $ZrO_2$ surfaces showed the presence of a parallel oriented structure. The relationship of this structure to liquid crystal alignment and its orientation relative to the ion beam direction are being presently investigated.

## ACKNOWLEDGEMENTS

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TALBE I. - ION BEAM ETCH CONDITIONS AT WHICH GOOD HOMOGENEOUS ALIGNMENT WAS OBSERVED

| Type of coating | Ion beam voltage, V | Ion current density, ($mA/cm^2$) | Angle, deg | Etch time, min |
|---|---|---|---|---|
| $SiO_2$ | 500 | 0.1 | 5, 10, 15 | 3 |
| | | 0.2 | 10 | 5 |
| | 1000 | 0.1 | 5, 10, 15, 20, 25 | 3 |
| | | 0.2 | 10 | 1, 3, 5 |
| | | | 5, 15, 20 | 3 |
| | 2000 | 0.1 | 10 | 1, 3, 5, 7 |
| | | | 20 | 3, 5 |
| | | | 5, 15 | 3 |
| | | 0.2 | 5, 10 | 1, 3, 5 |
| | | | 15 | 1, 3 |
| | | | 20 | 3 |
| | | 0.3 | 20 | 5 |
| | | 0.5 | 10 | 3 |
| | | 0.6 | 10 | 3, 5, 7, 9 |
| $ZrO_2$ | 2000 | 0.2 | 5 | 5 |
| | | | 10 | 1, 3, 5 |

TABLE II. - DISTRIBUTION OF EXTINCTION RATIOS MEASURED NEAR CENTERS OF 56 SAMPLES. MEAN VALUE IS 2620. MEAN VALUES FOR $SiO_2$ AND $ZrO_2$ ARE 2790 AND 1480, RESPECTIVELY

| Extinction ratio | Number of samples |
|---|---|
| <100 | 2 |
| 200-500 | 2 |
| 500-1000 | 10 |
| 1000-2000 | 13 |
| 2000-3000 | 6 |
| 3000-4000 | 10 |
| 4000-5000 | 4 |
| 5000-6000 | 8 |
| >6000 | 1 |

TABLE III. - DISTRIBUTION OF MEAN VALUES OF TILT-BIAS ANGLES MEASURED ON 13 $SiO_2$ AND 7 $ZrO_2$ SAMPLES. MEAN VALUE FOR TOTAL DISTRIBUTION = 0.78 DEG

| Tilt bias angles, deg | 0.0 - 1.0 | 1.0 - 2.0 | 2.0 - 3.0 |
|---|---|---|---|
| $SiO_2$ (16 positions) | 13 | 3 | 0 |
| $ZrO_2$ (14 positions) | 9 | 2 | 3 |

TABLE IV. - SUMMARY OF MEAN VALUES OF TILT-BIAS ANGLE MEASUREMENTS ACCORDING TO TYPE OF COATING AND LIQUID CRYSTAL

| Type of coating and liquid crystal | Mean values of tilt angle, deg | Number of measurements |
|---|---|---|
| $SiO_2$ - E-7 | 0.78 | 8 |
| - Ester | .32 | 8 |
| - All | .55 | 16 |
| $ZrO_2$ - Ester | 1.04 | 14 |
| All - E-7 | 0.78 | 8 |
| - Ester | .78 | 22 |

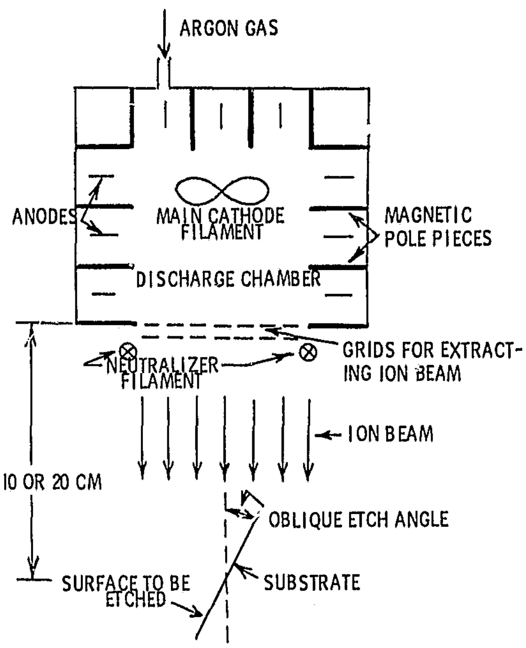



Figure 1. - Basic features of two-grid multipole argon ion source used for ion beam etching

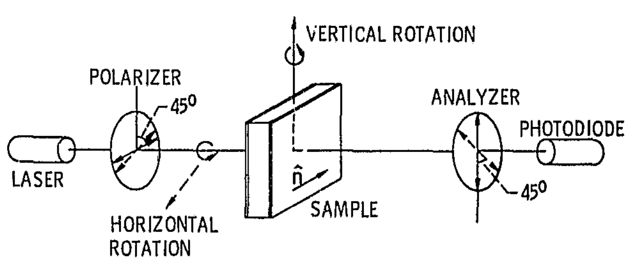



Figure 2. - Schematic of apparatus used for measurement of extinction ratio, twist angle, and tilt-bias angle.

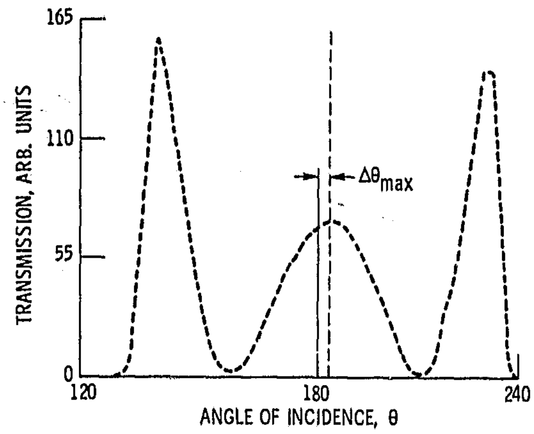



Figure 3. - Fringe pattern for determining tilt-bias angle (~0.3 $\Delta\theta_{max}$).

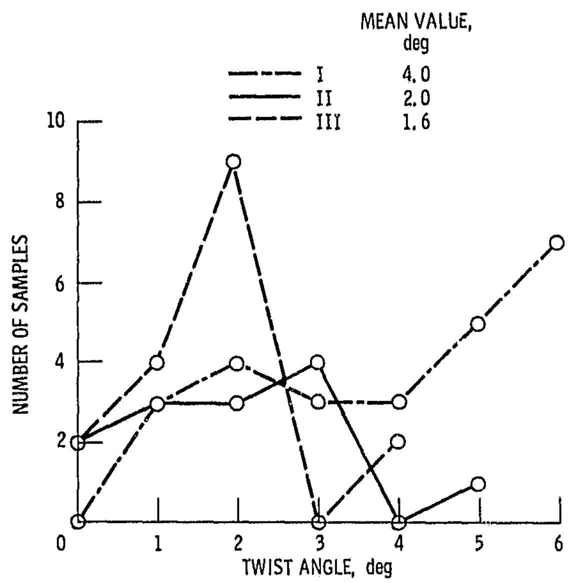



Figure 4. - Distribution of twist angles for 54 samples etched at 10 cm (I and II) and 20 cm (III) downstream from ion source. Mean value is 2.8°.

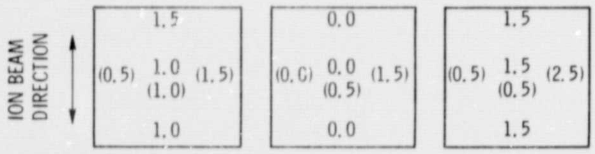



Figure 5. - Twist angles (deg) along lines parallel and perpendicular (values in parentheses) to ion beam direction for etch voltages of 500, 1000, and 2000 V.

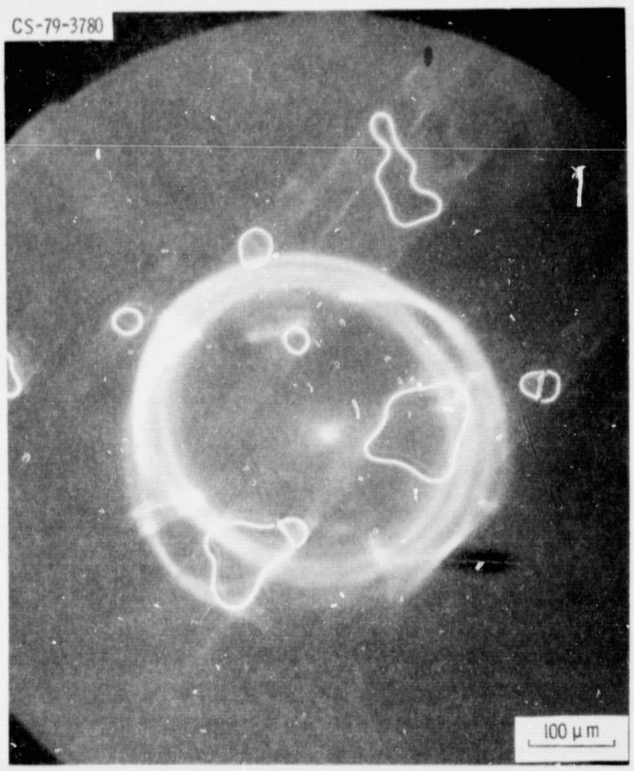



Figure 6. - Representative example of disclination loops in $SiO_2$ test cell. Ring in center and light streaks are of photographic origin.

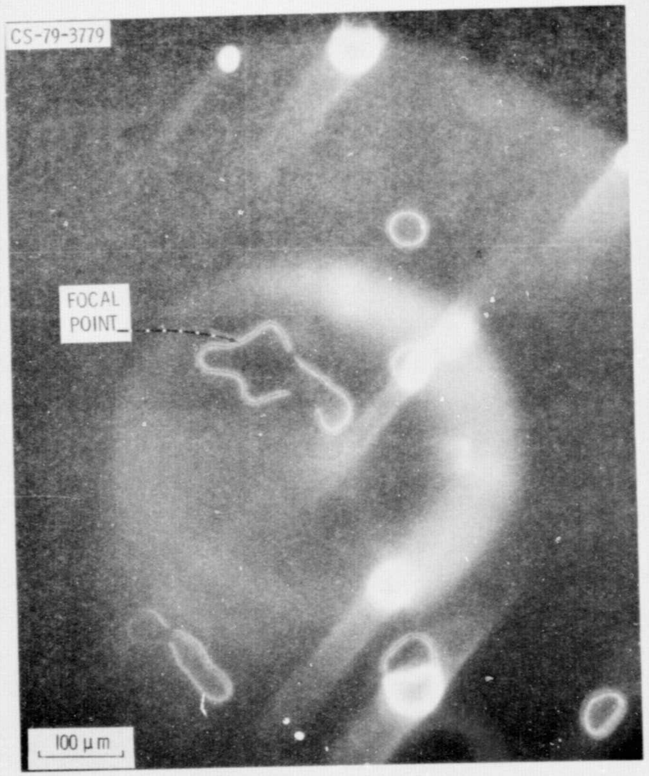
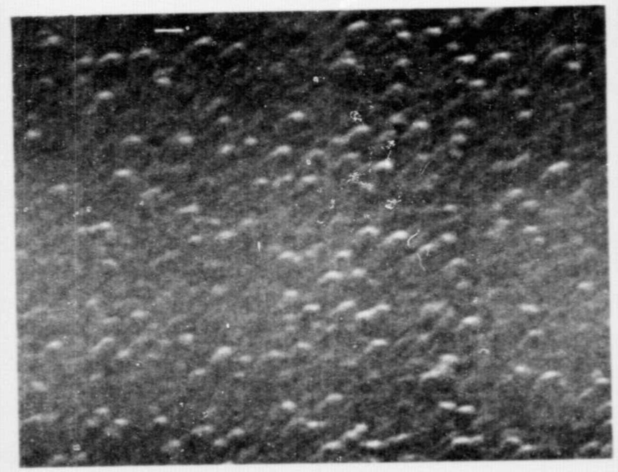
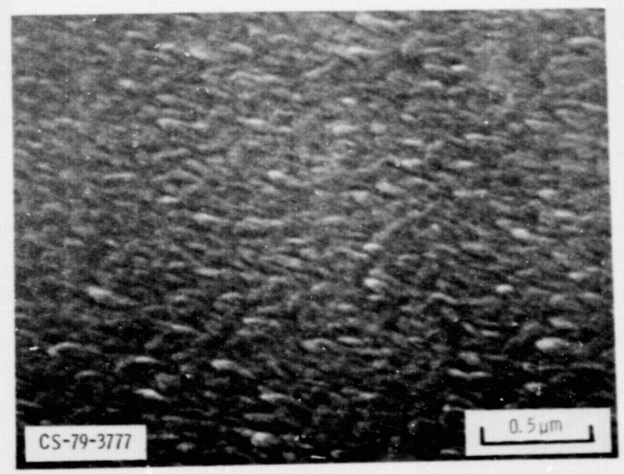



Figure 7. - Two types of disclinations observed in $SiO_2$ test cell. Ring in center and light streaks are of photographic origin.



(a) $SiO_2$ (50 KX).




(b) $ZrO_2$ (41 KX).

Figure 8. - Scanning electron microscope photographs of similarly etched surfaces of (a) $SiO_2$ and (b) $ZrO_2$.

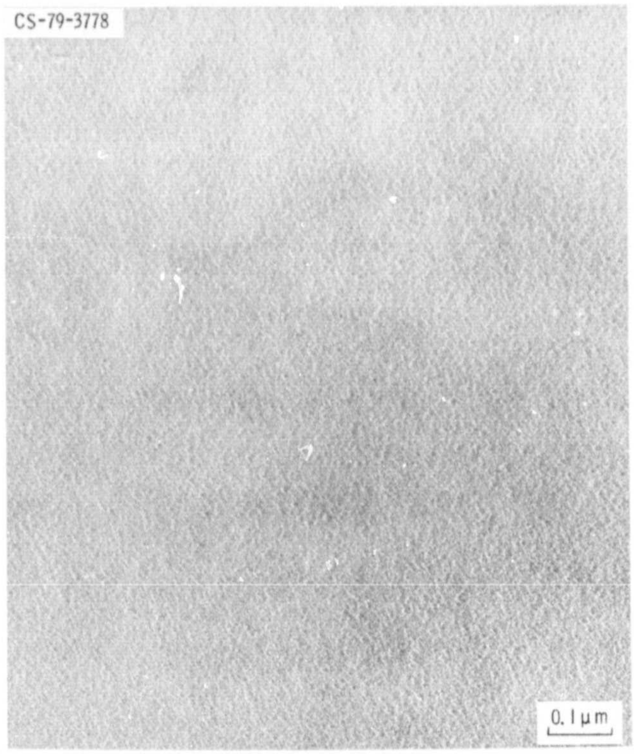



Figure 9. - Transmission electron microscope photograph of rf sputter deposited $SiO_2$ film (170 000 X).

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15. Supplementary Notes

E. G. Wintucky, NASA Lewis Research Center; R. Mahmood and D. L. Johnson, Kent State University, Kent, Ohio 44242.

16. Abstract

A wide range of ion beam etch parameters were found capable of producing uniform homogeneous alignment of nematic liquid crystals on $SiO_2$ films. The alignment surfaces were generated by obliquely incident (angles of $5^o$ to $25^o$) argon ions with energies in the range of 0.5 to 2.0 keV, ion current densities of 0.1 to 0.6 mA/cm$^2$ and etch times of 1 to 9 min. A smaller range of ion beam parameters (2.0 keV, 0.2 mA/cm$^2$, $5^o$ to $10^o$ and 1 to 5 min.) were also investigated with $ZrO_2$ films and found suitable for homogeneous alignment. Extinction ratios were very high ($>1000$), twist angles were small ($\leq 3^o$) and tilt-bias angles very small ($\leq 1^o$). Preliminary SEM results indicate a parallel oriented surface structure on the ion beam etched surfaces which may determine alignment.

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