[15]An illustration of these processes is given in the numerical analysis of N. J. Zabusky and M. D. Kruskal, Phys. Rev. Lett. 15, 240 (1965).

[16]For negative-dispersion systems, the wave train lags the soliton pulses, which move with velocities $C > C_3$.

[17]C. S. Gardner, J. M. Green, N. D. Kruskal, and R. M. Miura, Phys. Rev. Lett. 19, 1095 (1967); M. Wadati and M. Toda, J. Phys. Soc. Jpn. 32, 1403 (1972).

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Observation of Edge Dislocations in Smectic Liquid Crystals

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(Received 23 June 1978)

Isolated single-layer edge dislocations in smectic liquid crystals are observed by polarization microscopy. The modification of the smectic-A–smectic-C transition temperature by the strain field of the dislocations is used to make them visible. Observations of periodic arrays in thin samples, by various polarization-contrast mechanisms, and the measurement of the Burgers vector confirm the nature of the defects observed.

We report here the first direct observation of elementary edge dislocations in smectic liquid crystals. Theory for the structure and properties of such defects has been developed,[1] and their presence has been invoked as an explanation of various observations,[2] but they have never before been seen as individual defects in an otherwise nearly perfect sample.[3] We have developed an observational technique that takes advantage of the large susceptibility associated with a second-order phase change. Near the critical temperature, T_c, for the smectic-A–smectic-C phase change, the strains associated with a single dislocation modify the structure of the sample in a way that is made visible by using polarized-light microscopy. We describe first the principle underlying the experiment, second, the basic observations and the evidence that we are seeing dislocations, and third, the determination of the Burgers vector of the dislocations.

The smectic-A phase is a one-dimensional crystal in which the rodlike molecules are oriented normal to the molecular layers [Fig. 1(a), left-hand sides]. In the smectic-C phase the long molecular axis is tilted by a polar angle θ with respect to the layer normal [Fig. 1(a), right-hand sides]. This tilting is accompanied by a decrease of layer thickness, which in a simple rigid-rod model should vary as $\cos\theta$. A compressive stress normal to the layers favors the C phase and raises the transition temperature, while a dilative stress lowers it, an effect already studied.[4]

To utilize this effect to make dislocations visible, we prepare thin single-crystal samples between slightly nonparallel glass slides [Fig. 1(a)]. The smectic layers are anchored parallel to the glass surfaces by treatment with a surfactant, typically hexadecyl trimethyl ammonium bromide.[5] Some distribution of edge dislocations must exist, and for a small enough wedge angle ($\lesssim 10^{-3}$ rad) elementary edge dislocations should be separated enough for optical resolution. Upon crossing a dislocation, the abrupt change, Δm, in the number of smectic layers, m, contained in the sample thickness produces an abrupt change, $\Delta\epsilon$, in the component of strain normal to the layers: $\Delta\epsilon = \Delta m/m$. Since the glass is about 1000 times more rigid elastically than the liquid crystal, this strain must be accomodated in the liquid crystal [Fig. 1(b)]. This nonuniform strain produces a spatial modulation of T_c, so that the dislocations become visible as phase boundaries [Fig. 1(c)].

To see this more precisely, we write the free

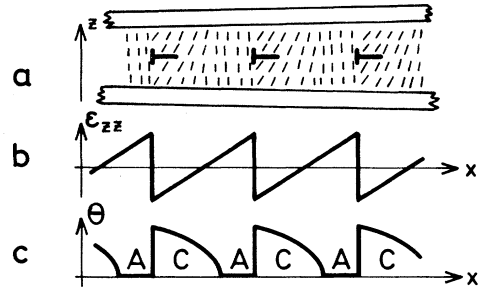

FIG. 1. (a) Schematic cross section of a sample containing a dislocation array, with plots of (b) strain vs position and (c) accompanying variation of tilt angle vs position.

energy density F in terms of θ and the strain ϵ, following Ref. 4:

$$F = F_0 + \tfrac{1}{2}a[(T - T_c)/T_c]\theta^2 + \tfrac{1}{4}B\theta^4 + \tfrac{1}{2}C(\epsilon + \tfrac{1}{2}\theta^2)^2 + \ldots .$$

The first three terms are the Landau series in terms of the order parameter θ, and the last term is the strain energy, corrected to lowest order for the θ dependence of the layer thickness. Minimizing F with respect to θ, we find

$$\theta = \begin{cases} [(a/B')(T_0 - T)/T_c]^{1/2}, & T < T_0, \\ 0, & T > T_0, \end{cases}$$

$$T_0 = T_c(1 - C\epsilon/a), \quad B' = B + C/2.$$

The transition temperature T_0 changes linearly with strain. Since C and a are both of the order of 10^6 J/m^2 and $T_c \sim 350$ K, a single-layer dislocation in a 1000-layer-thick sample, for which $\Delta\epsilon = 10^{-3}$, should be visible as a phase boundary in a temperature range $\Delta T \sim 0.35$ K around T_c. At lower temperature it should still be visible as an abrupt change in θ. The maximum optical contrast, or largest $\Delta\theta$, occurs at $T = T_c(1 - C|\Delta\epsilon|/2a)$, when the regions of A phase between dislocations are just disappearing [Fig. 1(c)].

Figure 2 shows typical micrographs of samples a few microns thick, using different contrast mechanisms. Figure 2(a) is made using crossed polarizers and ordinary illumination, that is, a cone of light focused on the sample by the microscope condenser, the axis of this cone being normal to the sample. The smectic-A phase is dark, and the smectic-C phase appears more birefringent and brighter. In this case the contrast is weak, varying as θ^2 in the C phase.

For Fig. 2(b), the condenser aperture diaphragm is supplemented by an added metal foil, allowing only oblique incidence of light from one quadrant of the aperture. The direction of incidence lies in the plane containing the molecular tilt direction. This produces contrast which is linear in θ. The smectic-A phase looks slightly birefringent, and therefore gray. In the C phase, if the molecules tilt toward the direction of incidence, the birefringence is reduced; such regions are darker. The opposite tilt increases the birefringence and the brightness. In this photograph most of the C regions are black, with only a few bright domains of opposite tilt. For some reason, in these samples, near T_c the tilt direction lay in a single plane, for large areas, and so only two tilt directions were observed, rather than the complete cone of orientations possible in the C phase.

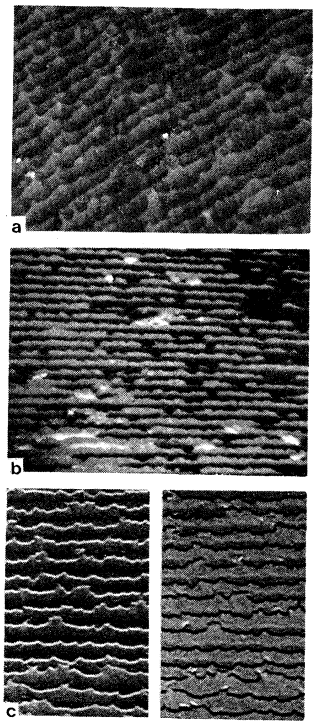

FIG. 2. Photomicrographs of dislocation arrays. (a) Normal illumination and crossed polarizers; (b) oblique illumination and crossed polarizers; (c) normal illumination and $\pm 3°$ uncrossed polarizers. Each figure is about 100 μm square.

Finally, Fig. 2(c) shows gradient-sensitive contrast achieved with illumination as in 2(a) and slightly uncrossed polarizers. Light traversing the sample obliquely, and at a finite angle to the plane defined by the tilt direction, has its polarization rotated by spatial gradients of θ. Thus, a dislocation, where the gradient of θ is the largest, produces a bright or dark line, depending on the tilt direction and the direction of uncrossing of the polarizers.

The observations are all consistent with the interpretation of these striped patterns as arrays of dislocations. The orientation and spacing of the lines relative to the gradient of sample thickness are correct. The appearance and growth of the C phase as the temperature is lowered occurs as the model predicts. Smectic-C regions first appear to one side of each dislocation. As the temperature is lowered, the smectic-A–smectic-C transition line moves from each dislocation toward its neighbor. In Fig. 2(b), for example, the dislocations are very irregular because of pin-

ning of their motion, while the transition lines are very straight, attesting to the smoothness of the glass. The distinction between these two kinds of lines is very clear with gradient contrast, since the dislocations stand out in high contrast, while the transition lines are only weakly visible.

The temperature range in which the dislocations are visible varies as expected with sample thickness. For samples a few microns thick it is a few tenths of a degree. Approaching a point of contact between the glass surfaces, when the thickness is just a few smectic layers and $\Delta\epsilon$ is 10 to 20%, the lines are visible from 10° above T_c to 20° below T_c.

Since we observe a periodic array of identical dislocations, their Burgers vector is the product of the angle between the glass plates and the distance between a pair of dislocations. To measure the angle accurately, an interferometric method was used. Samples were prepared between semitransparent gold coatings on glass slides. The resulting Fabry-Perot interferometer produced sharp fringes when illuminated with a He-Ne laser. With the use of a simultaneous laser and white light illumination, the fringes and dislocations were visible simultaneously and the number N of dislocations between fringes could be counted. The Burgers vector is then $b = \lambda_{vac}/2nN$. For the compound *p*-azoxy-(*n*-undecyl-α-methyl cinnamate) which is the material shown in Fig. 2, the index of refraction[6] n is 1.482 and N is 48 ± 1. For $\lambda_{vac} = 632.8$ nm, then $b = 44.5 \pm 1$ Å. This agrees with x-ray measurements of the smectic layer thickness at Göteborg and at Orsay,[7] and confirms our belief that these are elementary edge dislocations.

We have made similar observations on *p*-heptyloxybenzylidene-*p'*-heptylaniline, terephthal-*bis*-butylaniline, and *p*-decyloxybenzylidence-*p'* amino-(β-methylbutyl cinnamate). Whenever well-aligned single crystals can be prepared the same qualitative behavior is observed. Further Burgers vector measurements remain to be done.

We conclude that we have made for the first time unambiguous direct observations of elementary edge dislocations in smectic liquid crystals. Although we cannot determine from these observations whether the dislocations are at the surfaces or in the bulk of the sample, two points are in favor of their being in the bulk. First, "image" forces, due to a smooth solid surface, repel dislocations, and so theoretically they should be in the bulk. Second, their rather free movement suggests that at least they are not pinned strongly to the sample surfaces. Experiments are in progress to observe the generation and movement of these defects in response to applied stress. This may lead to a determination of their energy and mobility.

The authors thank Professor M. Nilsson of Chalmers University for synthesizing the cinnamate compound, and to Dr. Liébert, Dr. Strzelecki, and Dr. Keller of Orsay, France, for samples of all four materials studied. We thank Professor S. Abrahamson of Göteborg University for the use of his x-ray equipment and Mr. B. Hellguist for performing the x-ray measurement. We thank Y. Galerne of Orsay for his unpublished index-of-refraction data on the cinnamate compound, and J. Doucet of Orsay for x-ray data. Finally, we gratefully acknowledge research grants from the Carl Trygger Foundation, and the Swedish National Science Research Council, and one of us (R.B.M.) thanks NORDITA for a research scholorship.

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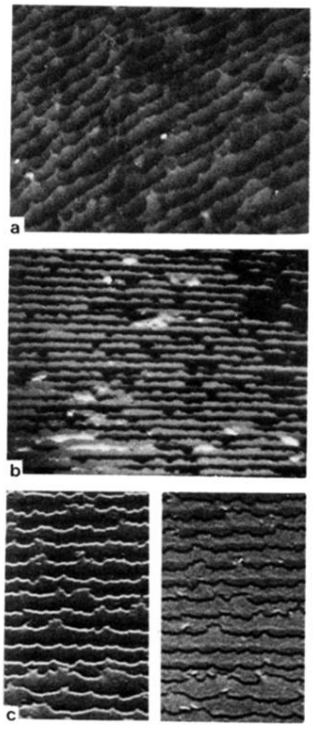
[7]J. Doucet (Orsay), private communication.



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