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STUDIES OF DOMAINS, WALLS AND DISCLINATIONS IN THE SMECTIC C PHASE

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Abstract. — Domains of opposite tilt are generated and studied in smectic C samples with boundary conditions in principle giving a Schlieren type, although more regularly ordered, texture. A number of features characteristic of the C phase as a vector medium and differing from the analogous nematic case are pointed out and investigated experimentally: a closed wall is equivalent to a family of point singularities and transforms to such a structure on annealing. This is a particularly illustrating example of the disclinations being created pair-wise, obeying a kind of conservation law for disclination strength, analogous to charge conservation.

1. Introduction. — We have noticed that a straight and regular dislocation pattern, as can be created by boundaries forming a wedge, [1, 2] seems to have a strong aligning effect on the smectic C phase. It induces tilt preferably around one rotational axis, perpendicular to both the layer normal and the smectic layer makes the twist the only deformation that can take place without locally violating the condition of constant density on crossing the line L-L in figure 1. Right- and lefthanded tilting around the preferred axis now gives a two-fold degeneracy of the C configuration, leading to the formation of domains. We thus expect the appearance of two kinds of energetically equivalent tilt regions, corresponding to +c and -c orientation, and walls between such regions. Because the walls represent curvature strain in the director field the energy of the system will be lower if one kind of orientation predominates over the other with only small wall regions in between. Experimentally, in thin wedge samples, we find the orientation to be nearly homogeneous, with one of the tilts ±c realized almost everywhere. In this case we will call regions with the dominating tilt direction domains, and minority regions, with opposite tilt anti-domains. Small anti-domains enclosed by domains have to be surrounded by closed walls. The walls are π-walls or inversion walls, where the projection of the director on the smectic plane is turned through 180 degrees, or, differently expressed, +c changes continuously to -c, on crossing the wall. There is a connection, valid for vector systems like smectic C, the A phase of He-3 and magnetic spin systems (but not e.g. for the nematic phase), between such walls and point
singularity configurations, and the walls can be expected to anneal by transforming into a family of singularities. In this paper we discuss these equivalencies and report on experimental observations of such transformations.

The compound used is n-undecyl-p-azoxy-o-methylcinnamate (AMC-11) with a characteristic second order phase transition A to C at 79 degrees Celsius.

The spontaneous symmetry breaking at $T_a$ is, in fact, the basis for a controlled generation of the point singularities, as will be evident from the following discussion.

2. Domains and walls. — Smectic C domains are shown in the micrograph of figure 2. The wedge opens toward the lower part of the figure. A regular pattern of edge dislocations (each corresponding to a single smectic layer) is seen, with the compressional side below and the dilatational side above every line. The line contrast is due to a gradient in tilt and changes from black to white when the gradient changes sign. For a general discussion of the visibility conditions, contrast mechanism and other details concerning the appearance of the dislocation lines the reader is referred to references [1]-[3]. We will only use the results here as the basis for our further discussion. Crossing successive lines in the direction of the arrow corresponds to the following changes in molecular orientation: below the black line molecules tilt to the left. This tilt diminishes — a clockwise rotation — when crossing the line, and slowly increases again on the other side, and so on, repetitively, until the border line to the anti-domain is crossed. In this region molecules tilt to the right. The border dislocation has a markedly heavier contrast corresponding to about twice as large a gradient, still in clock-wise direction. The next dislocation appears white because vanishing of the tilt now means an anti-clock-wise rotation, and so on.

This kind of wall between domains is a pure twist or Bloch wall. We learn from this and similar observations that in many cases walls have a tendency to go along dislocations making elongated domains and giving Bloch-wall character to the major part of the wall. If the wall does not coincide with a dislocation, however, it will instead be of a Néel type because then only gradients in tilt direction occur, the magnitude of the tilt being fixed. Especially, very small closed domains often have walls of predominantly Néel type.

3. Point singularities. — At temperatures slightly below $T_{Ac}$, where the A-to-C phase transition takes place, the tilt angle is small and so is the energy contained in walls between domains. With decreasing temperature the curvature strain increases and, at least in large domains containing small misaligned regions, the former can be expected to grow at the cost of the latter, thereby diminishing the total wall energy. Now it is easily seen that in a smectic C a closed wall is topologically equivalent to two, four... $2n$ point singularities of equal strength and opposite sign in the vector field $\mathbf{c}(r)$. This would not be true.

![Fig. 2. — Domains in the smectic C phase. Only two tilt directions are present. The two different shades of gray corresponds to domains of opposite tilt. The horizontal lines are dislocations appearing with black contrast in domains and white contrast in anti-domains.](image1)

![Fig. 3. — Small misaligned domain (i.e. of opposite tilt) enclosed by a predominantly Néel wall in an otherwise homogeneously aligned smectic C phase. A (less probable) non-singular structure ($N = 0$) is possible in a right-hand or a left-hand version: the points can be smeared out along the walls by mirroring e.g. the left-hand side deformation in the vertical symmetry line, and changing the concavity to upward instead of downward in the left Néel wall deformation.](image2)
for the same molecular configuration in a nematic medium where the wall can be replaced by a perfectly continuous structure in the field \( \mathbf{n}(r) \). The simplest equivalent structure is a disclination dipole shown in figure 3. The drawing is made for a Neel-type configuration. However, nothing would change in the argument, if the vertical sides were changed into Bloch walls. Figure 4 shows a structure consisting of four singular points. The disclination strength \( s \) is a topological quantum number, perfectly analogous to those recently introduced in general field theories. We here only need to consider \( s \) equal to \( \pm 1 \). The nematic value \( \pm 1/2 \) cannot occur because the smectic is not invariant under the transformation \( \mathbf{e} \rightarrow -\mathbf{e} \), and higher \( s \)-values require too high energy and would be split up in \( s = \pm 1 \) points. The equivalence between fields like those in figures 3 and 4 means that they have the same over-all topology, i.e. the misaligned region only deforms the outer field without changing any local orientational relationships.

![Fig. 4. Misaligned region with four point singularities. Each one of them would appear with four extinction brushes under crossed polarizers.](image)

From what has been said it follows that a closed wall when shrinking will not disappear directly but rather transform into a disclination family of an even number of singular points satisfying the condition \( \Sigma q_i = 0 \), corresponding to no net turn of the \( \mathbf{e} \)-vector when going around an enclosing Burgers circuit far away out from the singularities. It may be adequate in this connection to point out the fact, first noticed by Ericksen [4] (cf. also Chandrasekhar [5]) that the deformation energy of a finite number of singularities is finite when the sum over their \( s \)-values vanishes, but is otherwise infinite. This is the physical reason behind the fact that the disclinations appear in pairs, obeying a conservation law regarding their strength. An experimental observation of this is shown in figure 5. Starting in \( (a) \) at a temperature slightly below the A-to-C transition the disclination families appear in \( (b) \) taken after a temperature decrease of three degrees. The smectic tilt direction is quite homogeneous: only very small anti-domains can be seen in \( (a) \) (recognizable on the change from white to black in dislocation contrast). Furthermore, the correspondance between these misaligned regions and the disclination groups is evident. To stress this point an exposure \( (c) \) has been made of the same situation as in \( (b) \) but with a filtering technique (cf. [1] and [3]) preferably illuminating only the tilt differing from the majority orientation. Obeying the rule given above the three dominant disclination groups are seen to contain two, four and eight point singularities.

Our available experimental material shows that, in order to observe how closed walls transform into disclinations, the misaligned regions have to be very small; larger anti-domains tend to be stationary down to the crystallization temperature. The reason for this is not difficult to understand: in absence of any external field no domain is energetically preferred, thus the only driving force for wall motion is the elastic deformation in the wall itself. This is illustrated in figure 6, showing how a closed wall transforms into a pair of disclinations by the mutual attraction of the dipole charges inherent in the wall configuration. As this mutual attraction is inversely proportional to the distance between disclinations it will be expected to be efficient only at small distances, where it cannot furthermore be cancelled by contributions from other, more distant, singularities.

Larger domains can be thought of as built up by a repeated process of charge separation (pair creation), corresponding to the backward direction of what is indicated in figure 6. The disclinations line up along the wall (being actually part of it) and tend to stabilize each other by being alternatively of plus and minus sign (Fig. 4). An example of this is the large domain of figure 7 with \( N = 16 \). In this picture, as well as in that of figure 5b, close inspection shows that alternating points tend to have black and white contrast, respectively, of their core region. Considering the different geometry of the \( +1 \) and \( -1 \) core regions, this difference might be expected: the \( +1 \) core has rotational symmetry and the tilt must go to zero in the middle, giving a black core region (extinction). The \( -1 \) core has a saddle-splay (two-fold) symmetry allowing some effective tilt. However, the core radius ought to be of the order of \( (K/|B_1|)^{1/2} \) which should be far to small to be observed. On the other hand, \( B_1 \rightarrow 0 \) at the A-C transition, making the core radius diverge. It is possible, therefore, that we are actually observing the cores, but as the points in the pictures roughly correspond to the resolution limit of the microscope, the question of agreement between alternating black and white contrast and alternating plus and minus sign of the singular points has to be further investigated.
FIG. 5. — Disclinations originating from small misaligned regions in a smectic C aligned phase. In (a) the temperature is $T_{AC}$ corresponding to the phase transition A-C. The other micrographs picture the same region at lower temperatures, i.e. in the C phase. Micrographs (b) and (c) are taken at $T = T_{AC} - 2$, (d) at $T = T_{CK}$. A Schlieren pattern appears as regions with an even number of point-like singularities. In (a) regions are distinguished with $N = 2$, 4 and 8. The regular array of edge dislocations is simultaneously visible. Polarizers crossed at 45 degrees to the dislocation lines. In (d) the sample is crystallizing during the exposure. The crystallization front is coming in from the left in the picture. The dislocations are no longer visible across the picture. Between (d) and (e) the sample has been taken up to the isotropic phase and then slowly cooled down. In (e), again prior to crystallization, a $N = 4$ region is seen coalescing into a dipole ($N = 2$) at right, together with a $N = 0$ wall to the lower left. A true $N = 0$ inversion wall is possible if it has a certain handedness. The skew symmetric configuration can be obtained from figure 3 by mirroring the deformation of the left half of the figure (replacing concavity with convexity) and adding the two halves together. Anchoring seems to influence the localization of anti-domains, as can be judged from comparing (b) and (e). Average distance between dislocations about 5 µm.

An observation likewise to be pursued, may be mentioned at this stage, e.g. in connection with figure 7. When studying situations like this one we observe that the disclinations tend to nucleate at the crossings between wall and dislocation. Once created at these preferred loci the disclinations seem to be rather stationary, whereas dislocations move when the temperature is changed. Thus, in figure 7 the dislocations have moved upward after a small decrease in temperature since the disclinations appeared, and the initial correspondence between singular points and crossings, evident near $T_{AC}$, has vanished.

FIG. 6. — Illustration of the annealing of misaligned regions and the forces causing walls to shrink and move. The two singularities of opposite sign attract each other similar to charges in a two-dimensional space.
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Fig. 7. — Domain with $N = 16$ four degrees below the A-C transition crossed polarizers.

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