Anchoring Strength onto Simple Surface Edge Dislocations in an Induced Smectic-*O* Film

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Surface freezing is able to produce thick smectic-*O* films at the free surface of isotropic droplets of 1-(methyl)-heptyl-terephthalidene-bis-amino cinnamate, which are naturally free from solid contacts. This particular situation allows us to realize a microbalance for determining the anchoring conditions of the director onto the surface edge dislocations. The director of the film is thus found to be anchored at normal angle to the simple edge dislocations with an anchoring constant per unit length of dislocation independent of the film thickness: $k_a \sim 5\times10^{-14}$ N. This value corresponds to a maximum anchoring energy $\sim \frac{1}{25} k_B T$ per molecule of the dislocation line.

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Surface freezing generally occurs in liquid crystals and produces a smectic film at the free surface of isotropic droplets [1]. This film is induced by the surface field, with the layers parallel to the surface, at a temperature higher than the normal temperature of existence of the bulk smectic phase. Though in most liquid crystals, the film grows a few smectic layers only, in 1-(methyl)-heptyl-terephthalidene-bis-amino cinnamate (MHTAC) it can get very thick depending on the chosen temperature [2]. Moreover, in this compound, the film is in the smectic-*O* (Sm-*O*) phase, with tilted and positionally disordered molecules inside the layers as in the smectic-*C* phase, but in alternate directions from one layer to the other. The tilt angle is $\psi \approx 50°$, and the layer thickness is $e = 3.0$ nm [3]. The general structure of the Sm-*O* phase is thus of the *herringbone* type. An interesting consequence of this particular structure is the antiferroelectric properties with alternate in-plane polarization that the optically pure MHTAC demonstrates [2]. Let us note here that a similar structure has almost simultaneously been claimed for the smectic-C_A phase of 4-(1-methylheptyloxycarbonylphenyl) 4′-octyloxybiphenyl-4-carboxylate, but on the basis of rather indirect arguments [4].

Because the molecules are tilted in the Sm-*O* film, the electric polarization which naturally exists at the interface with air is tilted also. Its projection **P** onto the film is oriented, for symmetry reasons, along the direction of the projections of the molecules onto the film [5], i.e., along the director of the film **n**. On applying an electric field **E** tangentially to the film, we thus exert a torque on the film which orients it uniformly except in the places where disclination walls [2] or objects like dust or dislocation lines make perturbations. Edge-dislocation lines are currently observed at the Sm-*O*–isotropic phase interface of the induced film. They are steps in the film where one or several supplementary smectic layers, depending on their Burgers vector, begin and thicken the film or conversely thin it down [Fig. 1(a)]. Their more visible effect at the surface of the film is to anchor the director **n** in a preferred direction and to produce orientational perturbations in the film. Mechanically, the induced films are free from solid contacts, like suspended films [6]. They therefore are very interesting 2D systems for observing and measuring tiny mechanical effects such as those produced by the anchoring conditions of the director **n** onto the surface edge-dislocation lines. In this paper, we report for the first time on the measurement of the preferred anchoring direction and of the strength of the anchoring onto surface edge dislocations with Burgers vector equal to unity in an induced Sm-*O* film. We use in this way the induced Sm-*O* film itself as a microbalance to oppose a known electric torque to the anchoring one and to weight it.

We consider a straight edge-dislocation line with unit

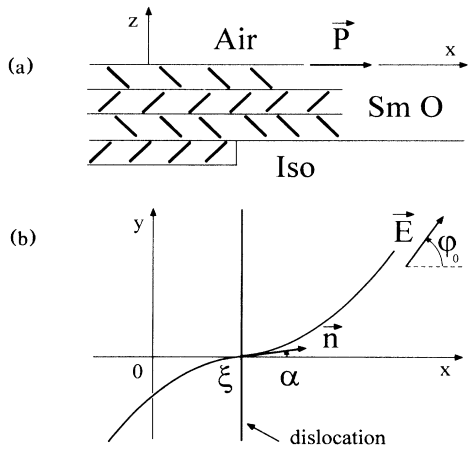

FIG. 1. (a) Vertical cut of the Sm-*O* film, perpendicularly to a surface edge-dislocation line with unit Burgers vector. The smectic layers are perpendicular to the z axis; the dislocation line is parallel to the y axis. To simplify the drawing, the nematic layer between the Sm-*O* film and the isotropic (Iso) droplet is not shown here; the vertical component of the electric polarization at the interface with air is also not represented. (b) Schematic top view of the same Sm-*O* film. A distortion of the director, represented by the curve, results from the competition between the anchoring to the dislocation line and the applied electric torque.

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Burgers vector, i.e., a simple dislocation, at the surface of the Sm-O film, oriented parallel to the y axis (Fig. 1). The dislocation at the abscissa ξ separates two sides in the film, the $x>\xi$ side with N smectic layers from the $x<\xi$ one with $N+1$ layers. A uniform electric field $\mathbf{E}$ is applied at the angle φ_0 referred to the x axis. Its coupling to the polarization $\mathbf{P}$ of the film produces an electric torque onto the film which is balanced by the anchoring torques at the dislocation that, for simplicity, we suppose to be equal on both sides of the dislocation. The equilibrium distortion of the film may be calculated as for the disclination walls [2]. We make the one-elastic-constant approximation, and put $K=Ne\mathcal{K}\sin^2\psi$ as the 2D elastic constant of the film, $\mathcal{K}$ being the average Frank elastic constant [6]. For simplicity also, we neglect the relative difference between N and $N+1$, and consider the same elastic constant K for both sides of the film. Moreover, taking into account the small values of our electric fields, we neglect the induced polarizations and the space charges $\nabla\cdot\mathbf{P}$ in this problem [7]. Under these conditions, the density of the free energy of the film is simply [6]

$$f=\frac{1}{2}K\left(\frac{\partial\varphi}{\partial x}\right)^2+PE(1-\cos\varphi)\,,$$

where $\varphi=\alpha-\varphi_0$ is the angle $[\mathbf{E},\mathbf{n}]$ and α is the angle of $\mathbf{n}$ or $\mathbf{P}$, relative to the x axis. This expression is remarkably independent of φ_0, that is, of the electric field direction. Integrating f over a continuously distorted region of the film, i.e., free of dislocation lines or other anchoring objects, and minimizing yields the Euler-Lagrange equation,

$$\frac{d^2\varphi}{dx^2}-A\sin\varphi=0\,,$$

where $A=PE/K$. Following classical calculations [8], we get the torque equation to within the multiplicative elastic constant K,

$$\varphi'=-2\sqrt{A}\sin\frac{\varphi}{2}\,, \tag{1}$$

with the correct integration constant since φ' and φ both tend to zero when x goes to infinity. Integrating again, and taking the origin of the x axis such that $\varphi(x=0)=\pi$, we get the distortion equation

$$\varphi=\pm 4\arctan\exp(\sqrt{A}x)\,, \tag{2}$$

where the $\pm$ sign depends on the sense of rotation of the distortion.

So, the determination of the orientational distortion in the film yields the distribution of the local torques and the orientations of the director everywhere in the film, and in particular, along the dislocation lines. In Fig. 1(b) is represented such a dislocation line with the distorted director field around it. Because the anchoring conditions to the line are considered as identical on both sides, the calculated distortion field is symmetrical and the total torque per unit length of the line is twice the torque exerted by one side of the film,

$$\Gamma=-4K\sqrt{A}\sin\frac{\alpha(\xi)-\varphi_0}{2}\,. \tag{3}$$

In the case of a small anchoring angle $\alpha(\xi)$, a first order approximation may be used. The torque per unit length of the line can then be written as

$$\Gamma=4\sin\frac{\varphi_0}{2}\sqrt{KPE}\,, \tag{4}$$

which is proportional to $\sqrt{E}$. Let us notice that such a $\sqrt{E}$ dependence is natural since the torque experienced by the line is equal to the torque exerted by the electric field on the film, which is roughly proportional to E multiplied by the width of the distorted region, itself being of the order of magnitude of the wall width $w\propto E^{-1/2}$ [2].

The sample and experimental setup are as described in Ref. [2]. A small quantity of racemic MHTAC is deposited on a clean glass plate between two evaporated gold electrodes 2 mm apart from each other. The whole system is precisely thermostated inside an Instec stage, and observed between crossed polarizers with a Laborlux Leica microscope. The surface induced Sm-O film is easily observable under these conditions, because the molecules are tilted and strongly birefringent. The direction of maximum birefringence yields the direction of $\mathbf{n}$ to within $\pm\pi$, and the measurement of the birefringence of the Sm-O film, its thickness [9].

A typical edge-dislocation line with unit Burgers vector is shown in Figs. 2(a)–2(c) for increasing electric fields. The polarizers are oriented at $\pi/4$ to the electric field direction, and therefore the black fringes in the figures mark the places where the director is tilted by $\pi/4$ relative to $\mathbf{E}$. On increasing the electric field, the orientational distortion in the vicinity of the line increases and the torque Γ applied to it increases also, making the anchoring angle $\alpha(\xi)$ become larger. Both effects contribute to push the black fringes close to the dislocation line. In Fig. 2(a), taken at the smallest field, the fringes are well separated and allow the dislocation line to be faintly visible right in the middle. This observation is consistent

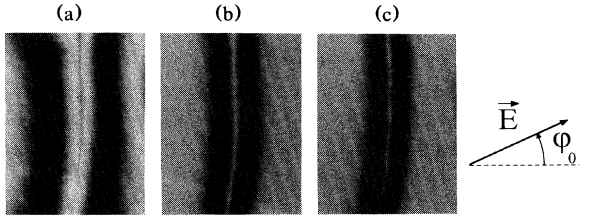

FIG. 2. Edge-dislocation line with Burgers vector equal to unity in a Sm-O film of 72 layers submitted to a uniform electric field. The orientation of $\mathbf{E}$ is the same in the three cases ($\varphi_0=26°$). The polarizers are crossed and oriented at $\pi/4$ relative to $\mathbf{E}$. (a) $E=1\times10^4$ V/m; (b) $E=2\times10^4$ V/m; (c) $E=4\times10^4$ V/m.

with the assumption of symmetrical anchoring. It allows us to determine the distance of the fringe to the dislocation, $x(\pi/4)-\xi$, by measuring the distance between both the fringes, which is easier. $x(\pi/4)$, the abscissa of the fringe at $\varphi=\pi/4$, is obtained from Eq. (2): $x(\pi/4)=A^{-1/2}\ln\tan(\pi/16)$. Being also the distance of the $\pi/4$ fringes of a disclination wall to its center, $x(\pi/4)$ may be experimentally determined from the wall width $w=2\times x(\pi/4)$ of a disclination wall in the same film. We thus obtain a direct and *in situ* determination of A for the studied film, and consequently the abscissa ξ of the dislocation line. From Eq. (2) again, we deduce the distortion angle $\varphi(\xi)$, and the anchoring angle to the dislocation line, $\alpha(\xi)=\varphi(\xi)+\varphi_0$. Figure 3(a) shows typical measurements of the anchoring angle $\alpha(\xi)$, simply denoted α from now on, as a function of the square root of the electric field in an induced Sm-O film of 72 layers. They exhibit a linear behavior within the experimental errors of ± 10 deg, except, however, at the lowest voltage point for which the parasitic elastic energy due to neighboring objects, like dust or other lines, cannot be neglected anymore [7]. So in the weak field limit, the data in Fig. 3(a) extrapolate down to zero within a few degrees. This indicates that the preferred anchoring direction is normal to the dislocation line, in agreement with symmetry. A complementary observation is used to get its full determination, modulo 2π. As previously noticed [2], the dislocation lines appear to be thicker, i.e., to produce larger distortions, when **E** is oriented from a region of the film containing an odd number of smectic layers N to a region with an even N than when oriented in the opposite direction. This observation shows that the preferred anchoring direction of **n** is perpendicular to the dislocation line, oriented from the even N region to the odd N one. Taking into account that the molecular direction in the first layer in contact to air is directly connected to the **P** orientation [2], we may thus deduce the molecular organization in the vicinity of the dislocation line [Fig. 1(a)], and remark in particular that it is determined in a unique manner.

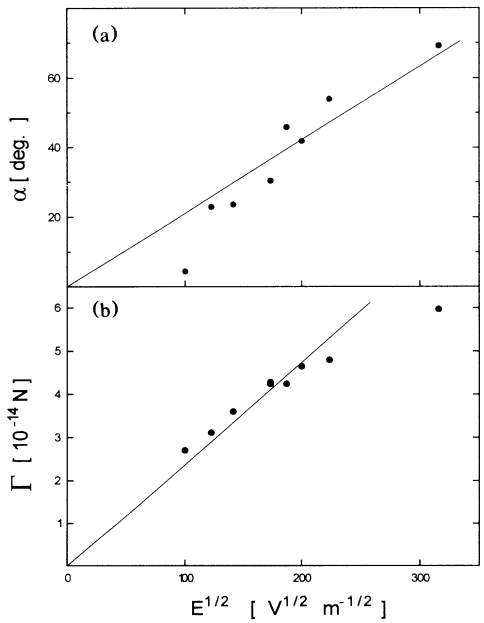

FIG. 3. Anchoring angle and torque at a surface dislocation line as a function of $\sqrt{E}$ in a Sm-O film of 72 layers with $\varphi_0=26°$. (a) Anchoring angle $\alpha=\alpha(\xi)$. (b) Torque Γ exerted per unit length, i.e. per meter, of the line.

We can now evaluate the torque Γ received per unit length of the line from the measured distortion angle $\varphi(\xi)$ using Eq. (1) multiplied by $2K$. The result is plotted in Fig. 3(b). In the weak values region, Γ is found to vary linearly with the square root of the electric field within a few percent relative error. Such a behavior may easily be understood when observing that in this region α is small and that therefore Eq. (4) applies. In the larger fields region, α cannot be neglected anymore in Eq. (3) and Γ begins to deviate noticeably from linearity. Both the linear variations of Γ and α with $\sqrt{E}$ are naturally transmitted to the variations of Γ vs α. We thus have $\Gamma=k_a\alpha$, to a first order approximation. From the above experimental results [Figs. 3(a) and 3(b)], we may estimate k_a, the restoring constant of the anchoring at a simple dislocation line in an induced Sm-O film, to be $\sim 5\times 10^{-14}$ N per unit length of the line, i.e., per meter.

This anchoring constant k_a is small and corresponds to an extrapolation length $b=K/k_a\sim 10$ μm, relatively large compared to the extrapolation lengths of a few molecular lengths usually found with solid substrates [8]. Note that such a large value explains that we have been able to resolve optically the distortions around the dislocations, and subsequently to determine the anchoring conditions.

The weakness of the anchoring at the dislocation lines may also be appreciated from the maximum anchoring energy sustainable per molecule of the line, E_a. The anchoring energy per molecule is $\frac{1}{2}k_aL\alpha^2$, where L is a molecular width. Its maximum E_a is reached for $\alpha=\pi$. We thus estimate $E_a\sim\frac{1}{25}k_BT$ (k_B, Boltzmann constant; $T\sim 430$ K) to be smaller by 1 order of magnitude than the energy involved in the smectic order itself, $\sim k_BT$. This estimate indicates that the smectic order around the dislocation line cannot be significantly perturbed by the deviation of **n** from the preferred anchoring direction, and that the line structure keeps them roughly the same as described in Fig. 1(a), except for a uniform rotation of the molecules around the z axis [5].

Preliminary measurements of the anchoring conditions have been performed for different thicknesses of the Sm-O film. They indicate that the preferred anchoring direction remains independent of the film thickness, perpendicular to the dislocation line, with about the same restoring constant k_a. This result is clearly consistent with the

unique molecular organization found around the core of the dislocations. It is consistent also with an anchoring mechanism governed by short range interactions only.

Improvements of the experiment are now under way with automatic measurements performed on video recordings, taking the anisotropy of the elastic constants into account. It will be particularly useful in the case of thin films where the extrapolation length b (proportional to K, i.e., to the film thickness) becomes small and the fringes difficult to resolve. Such improvements would allow us to extend the study to the anchoring properties of the dislocation lines in the induced Sm-C and Sm-C^* films of other chemical compounds.

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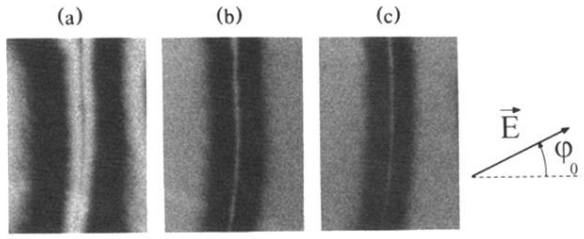

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