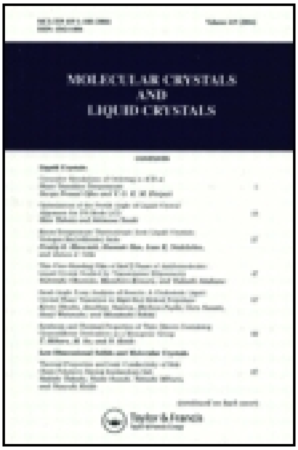

Molecular Crystals and Liquid Crystals Science and Technology. Section A. Molecular Crystals and Liquid Crystals

Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/gmcl19

A Chevron Model of the Electroclinic Effect across the S_A*-S_C* Phase Transition in a SSFLC

Steve M. Beldon [a], Nigel J. Mottram [b] & Steve J. Elston [a]

[a] Department of Engineering Science, University of Oxford, Parks Road, Oxford, OX1 3PJ, UK

[b] Department of Mathematics, University of Strathclyde, 26 Richmond St., Glasgow, G1 1XH, UK

Version of record first published: 27 Oct 2006

To cite this article: Steve M. Beldon, Nigel J. Mottram & Steve J. Elston (2001): A Chevron Model of the Electroclinic Effect across the S_A*-S_C* Phase Transition in a SSFLC, Molecular Crystals and Liquid Crystals Science and Technology. Section A. Molecular Crystals and Liquid Crystals, 365:1, 729-738

To link to this article: http://dx.doi.org/10.1080/10587250108025352

Mol. Cryst. and Liq. Cryst., 2001, Vol. 365, pp. 729-738
Reprints available directly from the publisher
Photocopying permitted by license only

A Chevron Model of the Electroclinic Effect across the S_A*-S_C* Phase Transition in a SSFLC

STEVE M. BELDON[a], NIGEL J. MOTTRAM[b] and STEVE J. ELSTON[a]

[a]*Department of Engineering Science, University of Oxford, Parks Road, Oxford OX1 3PJ, UK and* [b]*Department of Mathematics, University of Strathclyde, 26 Richmond St., Glasgow G1 1XH, UK*

We here present a thorough model of the electroclinic effect across the S_A*-S_C* phase transition, being the first to incorporate the vertical chevron structure. This structure has previously been observed in the S_C* phase of surface-stabilised FLC (SSFLC) devices, and some experimental evidence suggests that it may be present in the electroclinic effect [1–3]. Excellent agreement is achieved when comparing this model with previous experimental results of optical tilt through the A-C* transition for a SSFLC cell with homogeneous alignment.

Keywords: electroclinic effect; chevron structure; SSFLC

1 INTRODUCTION

The electroclinic effect was first discovered as a pre–transitional effect above the smectic A to smectic C phase transition in 1977 by Garoff and Meyer [4]. When an electric field is applied to the smectic A phase a tilt (perpendicular to the applied field) is induced in the molecular axis; the magnitude of the induced tilt being dependent on the magnitude of the field. The fast response time of the electroclinic effect (typically sub–microsecond) as well as it's grey scale capabilities are very useful properties in electro–optic modulator devices [5] and potentially for use in active matrix displays [6].

However, the importance of understanding the electroclinic effect also lies in furthering the understanding of SSFLC displays, which have in recent years emerged as a potential competitor to the now established STN and TFT displays [7, 8].

The chevron layer structure is believed to form in order to retain the Smectic A layer thickness throughout the bulk of the cell on transition into the Smectic C* phase. Much work has been carried out in attempting to describe this structure in bistable switching in SSFLC devices, both experimentally, and also in theoretical modelling. However, to the best of the authors knowledge, no investigation has been carried out on the modelling of such a structure being induced in the electroclinic effect.

We have previously suggested the need for such a model [3], therefore we here present an order parameter chevron model, describing in particular the smectic A–C* phase transition.

2 THE CHEVRON MODEL

2.1 General Description

The free energy density of the smectic A–C* phase transition can be described phenomenologically using a Landau type expansion of the order parameter θ,

$$\begin{aligned} f_{Land} &= \frac{1}{2}a\theta^2 + \frac{1}{4}b\theta^4 \\ &= \frac{1}{2}\alpha(T - T_{ac})\theta^2 + \frac{1}{4}b\theta^4 \end{aligned} \tag{1}$$

where α and b are the Landau coefficients. The Smectic A–C* phase transition occurs at a temperature $T = T_{ac}$.

The interaction of the electric field with the spontaneous polarisation is given by the free energy

$$\begin{aligned} f_{electric} &= -\underline{P} \cdot \underline{E} \\ &= P_0[\underline{k} \wedge \underline{n}] \cdot \underline{E} \end{aligned} \tag{2}$$

where $P_0 > 0$ is the induced polarisation magnitude per radian of tilt and $\underline{E}$ the applied field vector. The vectors $\underline{n}$ and $\underline{k}$ are defined using the coordinate system give in figure 1, where $\underline{k}$ is the layer normal, and $\underline{n}$ is the director,

$$\underline{n} = \begin{pmatrix} \cos\delta\cos\theta + \sin\delta\sin\phi\sin\theta \\ \cos\phi\sin\theta \\ \sin\delta\cos\theta - \cos\delta\sin\phi\sin\theta \end{pmatrix} \tag{3}$$

where δ is the layer tilt, ϕ is the azimuthal angle, and θ is the smectic cone angle (see figure 1).

We can also describe the elasticity using:

$$f_{elas} = \frac{K}{2}\left[(\underline{\nabla} \cdot \underline{n})^2 + (\underline{\nabla} \wedge \underline{n})^2\right] \tag{4}$$

where K is the elastic constant given a one constant approximation, incorporating splay, twist and bend deformations.

The full one–dimensional (i.e. assuming variation in $\underline{n}$ only in the z direction) free energy density, which is simply a sum of the above three contributions, is given by the equation:

$$\begin{aligned} f = &\frac{1}{2}a(T - T_{ac})\theta^2 + \frac{1}{4}b\theta^4 + \frac{K}{2}\Big\{(\delta')^2\left(\cos^2\theta + \sin^2\phi\sin^2\theta\right) \\ &+ (\theta')^2 + (\phi')^2\sin^2\theta - 2\delta'\theta'\sin\phi - \delta'\phi'\cos\phi\sin 2\theta\Big\} \\ &- P_0E_z\sin\theta\cos\phi\cos\delta \end{aligned} \tag{5}$$

where θ', ϕ', and δ' are the first differentials of θ, ϕ, and δ in the z direction.

It is commonly assumed that the layer tilt δ is proportional to the cone angle θ, i.e. $\delta = \mu\theta$ where μ is some constant. In the further analysis of this model, we shall also make this assumption.

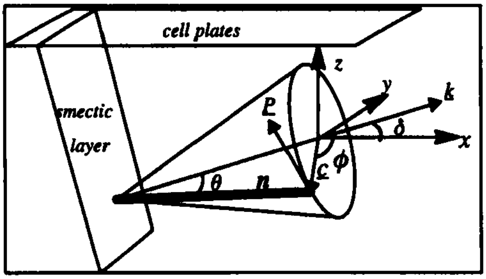

FIGURE 1: The coordinate system defined within a surface–stabilised FLC cell. The chevron layer structure is assumed to be symmetric about the centre of the cell.

2.2 Bulk Tilted Layers

We are able to consider the effect of tilting the layers on the bulk electroclinic effect by neglecting the surfaces and the chevron. We can achieve this by ignoring the elasticity, resulting in a greatly simplified free energy.

$$f = \frac{1}{2}a(T - T_{ac})\theta^2 + \frac{1}{4}b\theta^4 - P_0 E_z \sin\theta \cos\phi \cos\delta \qquad (6)$$

If we minimise this free energy with respect to ϕ we find that the director will always lie on the side of the smectic cone, i.e. $\phi = 0$. If we then minimise the free energy with respect to θ, we find that the tilt angle assymptotes to θ_∞ at large applied field E_z given by the equation:

$$\mu \tan(\theta_\infty) = \cot(\mu\theta_\infty) \qquad (7)$$

Typically, it is assumed that $\mu = 0.85$, in which case, the solution of equation (7) is $\theta \simeq 51°$. Electroclinically induced tilt angles of 22° have been reported, but it would seem unrealistic that the saturation tilt of 51° would ever be reached. The induced cone angle as a function of electric field is shown in figure 2 for bookshelf layers and also tilted layers. The reason for the saturation tilt which exists for tilted layers and not for bookshelf layers, is that though θ tends to increase as E_z increases, when it does increase, the layer tilts and causes the polarisation vector to move away from the vertical (i.e. aligned with the field), so in the end a compromise is reached. In the bookshelf structure, the polarisation vector will always remain parallel to the field and therefore the cone angle should in principle increase indefinitely.

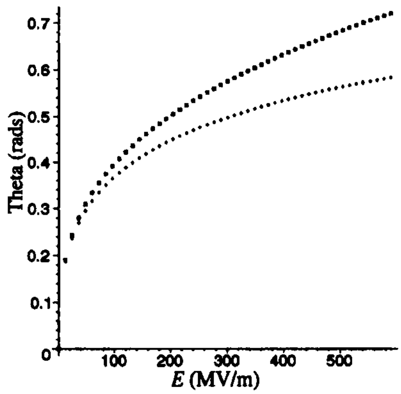

FIGURE 2: Plots of $\theta(E)$ at $T-T_{ac}$ = 0.1K for bookshelf (□) and tilted (+) layers.

2.3 Surface-Stabilised LC Cell

We now consider a homogeneously aligned liquid crystal device, parallel rubbed with pre-tilt β, assuming infinite anchoring at the surfaces. In defining the boundary conditions, we stipulate that the director at the chevron interface must lie in the plane of the cell surfaces, it therefore must satisfy the condition

$$\sin\phi = \frac{\tan\delta}{\tan\theta} \tag{8}$$

There must also be zero torque at the chevron interface, which results in the boundary condition $\theta' = 0$. The assumption of infinite anchoring defines our boundary conditions at the surfaces, as the director must remain fixed along the rubbing direction at the pre-tilt angle. If there is no pre-tilt present then C1 and C2 states are degenerate, however if some pre-tilt is present, then for small θ the C1 state is

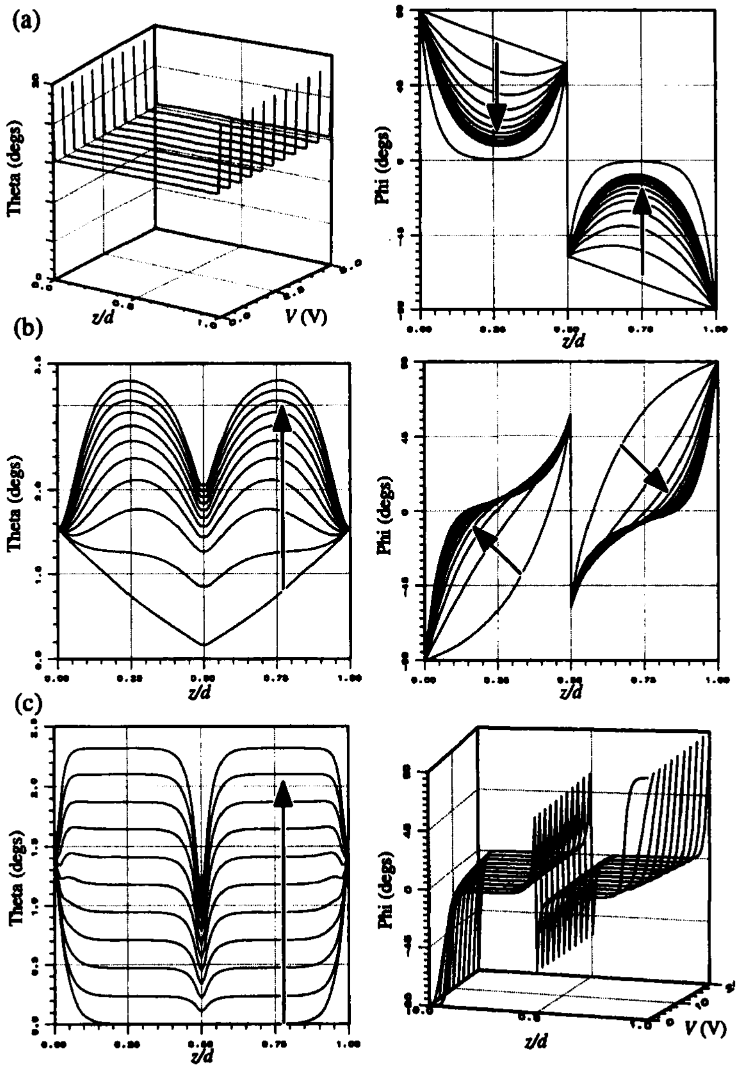

FIGURE 3: Profiles as a function of voltage for (a) $T < T_{ac}$ ($V = 0 \rightarrow 5$V in steps of 0.5V, & also 20V plot in $\phi(z)$), (b) $T = T_{ac}$ ($V = 0 \rightarrow 1$V in steps of 0.1V), and (c) $T > T_{ac}$ ($V = 0 \rightarrow 20$V in steps of 2V). Note: Arrow signifies direction of increasing V.

more likely to occur as C2 results in large distortions at the surfaces. In the C1 case, the cone angle is defined by $\theta = \beta - \delta$ and the director lies at the top of the distorted cone at $\phi = -90°$. In the C2 case, the cone angle is defined by $\theta = \beta + \delta$ and the director lies at the bottom of the distorted cone at $\phi = +90°$.

Solutions for $\theta(z)$ and $\phi(z)$, obtained by solving the Euler–Lagrange equations in θ and ϕ using the relaxation method, are shown in figure 3, for (a) $T < T_{ac}$, (b) $T = T_{ac}$, and (c) $T > T_{ac}$. The three regimes give very different behaviour and illustrates the competition between two interactions, that between the elasticity and the field, and that between the order parameter θ and the field.

In the smectic C* phase we see a large variation in the azimuthal angle ϕ and a small variation in θ, implying the dominance of the interaction between the elasticity and the field. This agrees well with existing smectic C* models [9] which assume a constant order parameter θ and only vary ϕ.

In the smectic A phase, $\phi(z)$ remains relatively unchanged as a function of voltage, with the director is at the side of the cone in the bulk of the cell. The order parameter θ however varies approximately linearly with voltage, though again the shape of the profile remains relatively unchanged. Therefore it is now the interaction between the order parameter θ and the field which is predominant. This behaviour is in agreement with the simple electroclinic model [4], assuming only variations in θ.

Close to the A–C* phase transition, the results show a large variation in both θ and ϕ, which implies that both the interaction between the order parameter θ and the field, and the interaction between the elasticity and the field are important. Therefore in describing the behaviour close to the A–C* phase transition, the assumption that either θ or ϕ is constant can not be made, and in this regime the complete model we have presented is particularly important.

2.4 Experimental Results

So far we have only been concerned with the theoretical modelling of the electroclinic effect. We now consider the effects of the above behaviour on the polarisation of light incident on a surface–stabilised LC cell and compare these effects with experimental results in the three regimes already considered.

The experimental results in figure 4 show the effective rotation of linearly polarised monochromatic light, normally incident upon a homogeneous parallel rubbed polyimide cell of 1.5μm thickness filled with SCE8. Comparison is made with predictions based on a simple bookshelf structure model of the EC effect, and with the model presented above which allows the distortion of smectic layers (into a chev-

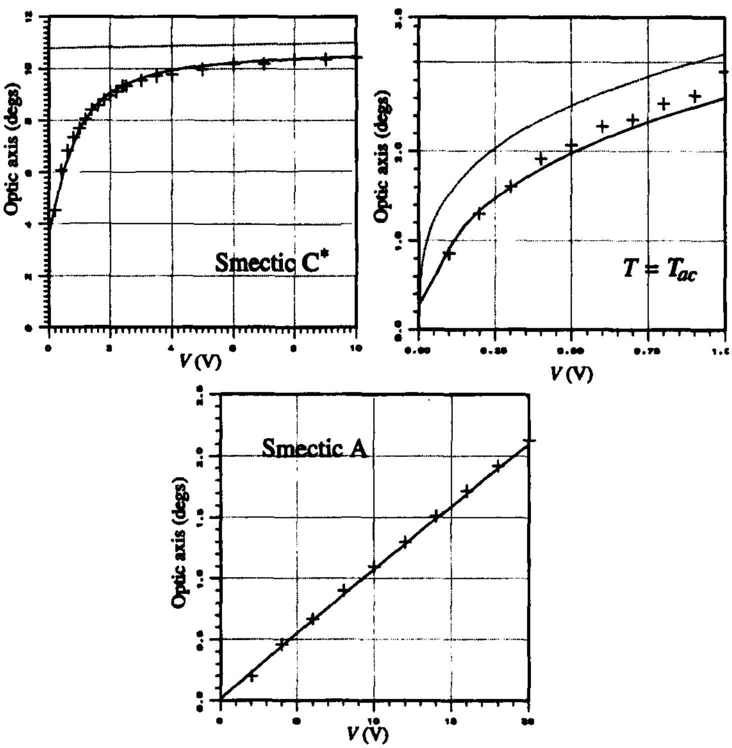

FIGURE 4: Comparison between experimental data (+), and the bookshelf (dotted) and chevron (solid) models.

ron type structure). The optic effects of the above model are calculated using Berremann routines [10].

Excellent agreement between the chevron model and the experimental results is seen for all three regimes with an elastic constant which is reasonable for SCE8 [11]. The bookshelf model gives good agreement well above the phase transition, but diverges from the experimental results near the A–C* phase transition.

3 CONCLUSIONS

The first 'order parameter' model of an electric field induced chevron has been developed. Though it ignores the DeVries' like azimuthal ordering in ϕ [12] and molecular conformation, the present model provides excellent agreement with previous experimental results of optical tilt through the A–C* transition for a SSFLC cell with homogeneous alignment.

The results also show how the interactions of elasticity and tilt angle θ with the applied field compete, with both being significant at the phase transition, and one dominating the other either side of the transition.

Future work will aim to incorporate the effect of changing ordering in the azimuthal angle ϕ and also the influence of molecular conformation change. It is interesting to note the importance of such effects in the context of recent results showing enhanced EC effects in materials which show minimal changes in smectic layer thickness across the A–C* phase transition [13]. It is also hoped to probe the layer structure dynamically/synchronously using X–rays, to confirm the presence of an induced chevron in the electroclinic effect.

Acknowledgements

The authors wish to acknowledge the financial support of the EPSRC, and also Sharp Laboratories of Europe Ltd. (SLE), Oxford, for providing a CASE award and the test devices used in this work. We would also like to acknowledge useful discussions with M.J. Towler and P.A. Gass.

References

[1] M. Johno, A.D.L. Chandani, Y. Takanashi, Y. Ouchi, H. Takezoe & A. Fukuda, *Ferroelectrics*, **114**, 123 (1991).
[2] H. Okada, M. Shabata & H. Onnagawa, *Jpn. J. Appl. Phys.*, **35**, 5426 (1996).
[3] S.M. Beldon & S.J. Elston, *Liquid Crystals*, **26**, 143 (1999).
[4] S. Garoff & R.B. Meyer, *Phys. Rev. Lett.*, **38**, 848 (1977).
[5] G. Andersson, I. Dahl, L. Komitov, S.T. Lagerwall, K. Skarp & B. Stebler, *J. Appl. Phys.*, **66**, 4983 (1989).
[6] A. Hermanns, C.M. Wilson, J.Y. Patel, J.W. Naciri, J.R. Lindle & B.R. Ratna, *Appl. Phys. Lett.*, **73**, 3644 (1998).
[7] M. Koden et al., *Proc. SID IDW '97*, 269 (1997).
[8] M.J. Bradshaw et al., *Proc. SID IDRC '97*, L16 (1997).
[9] M. Nakagawa, *Displays*, **11**, 67 (1990).
[10] D.W. Berremann, *J. Opt. Soc. Am.*, **62**, 502 (1972).
[11] C.V. Brown & J.C. Jones, *J. Appl. Phys.*, **86**, 3333 (1999).
[12] A. de Vries, *Mol. Cryst. Liq. Cryst.*, **41**, 27 (1977).
[13] M.S. Spector et al., *Phys. Rev. E*, **61**, 1579 (2000).