Effect of Electrooptical Memory in Suspensions of Carbon Nanotubes in Liquid Crystals

L. A. Dolgov^a, N. I. Lebovka^b, and O.V. Yaroshchuk^a

^a Institute of Physics, National Academy of Sciences of Ukraine, pr. Nauki 46, Kiev, 03028 Ukraine ^b Institute of Biocolloid Chemistry, National Academy of Sciences of Ukraine, pr. Vernadskogo 42, Kiev, 252680 Ukraine Received August 30, 2008

Abstract—Electrooptical response and microstructure of dispersions of multiwall carbon nanotubes in *N*-(4-ethoxybenzilidene)-4-*n*-butyl aniline nematic liquid crystal (LC) are studied. Irreversible response on the applied electric field (electrooptical memory) was revealed in oriented layers of such suspensions. The essence of this effect consists in the fact that, after the switch-on and subsequent switch-off of the field, the optical transmittance of suspension layer placed between two crossed polarizers substantially increases compared to the initial value which is typical for homeotropic orientation of LC. The efficiency of electrooptical memory nonmonotonically depends on the concentration of nanotubes in suspension, $c_{\rm CNT}$, reaching its maximum at $c_{\rm CNT} = 0.02-0.05$ wt %. It is shown that the memory of suspensions is caused by the incomplete relaxation of LC molecules from planar to initial homeotropic state after the electric field switch-off. The model is proposed and substantiated, according to which the planar state of LC is stabilized by the network of nanotubes formed upon the disintegration of aggregates under the action of electrohydrodynamic flows. The disclosed memory effect is rather common; it is brought about in the suspensions of carbon nanotubes based on other LCs in which electrohydrodynamic instabilities are developed.

DOI: 10.1134/S1061933X09050044

1. INTRODUCTION

The addition of nanoparticles to organic substances makes it possible to fundamentally expand the range of mechanical, dielectric, magnetic, and optical characteristics of these materials [1, 2]. Recently, increasing attention is focused on the study of composites based on anisotropic dispersion media, first of all, on liquid crystals. As far back as 1970s, de Gennes et al proposed to add ferromagnetic particles to LC to enhance its magnetic susceptibility [3]. Later, LC suspensions of magnetic [4, 5], dielectric [6, 7], metal [8], and ferroelectric [9] nanoparticles have been studied. Small amounts of these particles substantially modify their viscoelastic, dielectric, optical, electro-, and magnetooptical properties.

For a number of reasons, carbon nanotubes (CNTs) occupy a special place among the LC fillers. CNTs are characterized by very large length-to-diameter ratio (reaching 10³ and larger); because of this, such objects can be ideally incorporated into the LC matrix copying its orientation. In addition, because they possess clearly pronounced anisotropy of physical properties, CNTs can greatly influence the anisotropy of the properties of LC matrix in which they are dispersed.

Nematic LC turned out to be the ideal matrix for the preparation of highly dispersed orientative-ordered ensemble of nanotubes [10] with possible control of their orientation using external fields [10, 11]. The formation of strongly anisotropic CNT aggregates in nem-

atic LC, as well as their drift in electric field seems to be very interesting [12, 13]. On the other hand, it was possible to use ordered CNT layers for the orientation of LC [14, 15]. In addition, the incorporation of nanotubes into the bulk of liquid crystal makes it possible to lower the controlling voltage and response times of LC displays and to relieve surface polarization effects and back flows that deteriorate the operation of such displays [16, 17]. Thus, the study of electrooptical effects of CNT suspensions in LCs and peculiarities of structurization and interfacial interaction in such systems causes great theoretical and applied interest.

The goal of this work is to study the interrelation and mutual influence of the structure and electrooptical response of CNT suspensions in LCs. We used nematic N-(4-ethoxybenzilidene)-4-n-butyl aniline (EBBA) as a base anisotropic dispersion medium for studying this problem. This LC possesses negative dielectric anisotropy of dispersion media, the fact that, together with the presence of sufficient number of ions, is the necessary condition for the formation of intensive electrohydrodynamic (EHD) flows [18]. We demonstrate now that highly efficient EHD flows, which develop in the CNT doped EBBA, can substantially modify the electrooptical response and dielectric properties of such systems. In particular, they play an important role in the implementation of the electrooptical memory effect revealed in a given medium.

2. MATERIALS AND METHODS

As a main dispersion medium, we used liquid crystal EBBA (Reakhim, Russia) purified by multiple recrystallization. EBBA exhibits nematic properties within 36–77.5°C temperature range; at 40°C, its dielectric anisotropy was $\Delta \varepsilon = -0.13$. As other objects, we used two nematic mixtures with negative dielectric anisotropy: MLC6608 ($\Delta \varepsilon = -4.2$) and MLC6609 ($\Delta \varepsilon = -3.7$), which were in the LC state at room temperature, as well as nematic 4-*n*-pentyl-4'-cianobiphenyl (5CB) with positive dielectric anisotropy ($\Delta \varepsilon =$ 11.7). These LCs were supplied by Merck (Germany) and used as received.

Multiwall CNTs (Spetsmash, Ukraine) were prepared by the vacuum vapor deposition in the presence of catalyst [19]. Outer diameter (12–20 nm) and length of nanotubes (about 5 μ m) were evaluated with electron microscopy. Specific surface area of CNT was 190 m²/g; the conductivity of pressed powder along the deformation axis (at a pressure of 15 TPa) was 10 S/cm. Suspensions were prepared by mixing CNT and LC followed by ultrasonic dispersion for 5 min. LC suspensions with CNT content of 0.004, 0.02, 0.05, 0.1, and 0.5 wt %, as well as pure LC were studied.

LC layers were orientated on glass substrates with transparent conducting coating and the layer of orientating agent. For LC with negative dielectric anisotropy (EBBA, MLC6608, and MLC6609), the layers of homeotropic orienting polyimide AL2021 (JSR, Japan) were used as such agents. The polyimide layer was rubbed with velvet cloth in one direction to ensure uniform planar LC orientation at electric field switch-in. 5CB liquid crystal ($\Delta \varepsilon > 0$) was oriented in plane of the cell (planar) with polyimide SE150 (Nissan Chemicals, Japan) to reorient this LC to the homeotropic state at electric field switch-in. From thus prepared substrates, we made antiparallel (antiparrallel orientation of rubbing directions) optical cells 16-µm thick; studied suspensions or pure LC were filled into these cells by capillary forces.

The presence of CNTs in studied LCs does not noticeably affect the temperature ranges of mesophase existence. Samples based on EBBA were studied at 45°C, which is sufficiently far from both the crystallization temperature and transition temperature into isotropic state. The temperature was maintained at an accuracy of 0.1°C using the computer-aided system of thermal stabilization. Samples based on other LCs were studied at room temperature.

Electrooptical measurements were conducted using original setup designed in our laboratory [20]. Samples were placed between two crossed polarizers so that the direction of substrate rubbing was equal to 45° relative to polarizer axes. The light intensity (laser, $\lambda = 628$ nm) was measured at the output of this optical scheme depending on the applied sinusoidal voltage with frequency f = 2 kHz. Light transmittance of the sample was calculated as the ratio between the intensity of light transmitted through the sample (I_{out}) and incident light (I_{in}) : $T = (I_{out}/I_{in}) \times 100\%$.

Magnetooptical response of suspension was investigated by measuring homeotropic oriented cells in crossed polarizers upon the switch-on of magnetic field. Testing beam of laser radiation was directed perpendicular to the cell and the induction vector of magnetic field was perpendicular to the LC director. Maximal value of the intensity of magnetic field was 5 kGs.

The structure and orientation of samples were controlled by observing samples in crossed polarizers both with naked eye and under the optical polarization microscope.

To measure conductivity, the layer of dispersion was placed between two horizontal platinum electrodes with a diameter of 12 mm and electrode spacing of 0.5 mm. Alternating voltage ranging from 0.1 to 1.2 V (these values were lower than the threshold of LC reorientation) was applied to this cell. The frequency of applied field was 1 kHz. It was additionally checked to avoid the fall of this frequency on the range of the dielectric relaxation of the samples. Fairly high frequency allowed escaping polarization effects on electrodes and field-induced asymmetric redistribution of nanotubes between electrodes [21, 22]. The conductivity σ of samples was measured by the registration of inductance, capacitance, and resistance with a LCRmeter-819 instrument (Instek, Germany). Measurements were performed at 45°C. The average value of measured parameter was calculated from at least 5 readings.

3. RESULTS AND DISCUSSION

3.1. Response of Suspension on Electric Field and Electrooptical Memory Effect

Under the action of external electric field, homeotropic oriented LC samples with negative dielectric anisotropy are reoriented from the initial homeotropic to planar state. This affects the value of optical transmittance of samples placed between crossed polarizers. Typical dependences of transmittance on applied voltage U for EBBA–CNT samples are shown in Fig. 1. In these experiments, the voltage smoothly increased to 60 V, then decreased to 0 V. The observed T(U) dependence has oscillating character, which is related to the fact that, upon the LC reorientation under external field, the rise of phase incursion becomes much larger than $\pi/2$. The saturation of T(U) curve is observed at fairly stronger fields, when the reorientation can be extended not only on the bulk but also on the subsurface region of liquid crystal formed near the substrate. For pure LC, as well as for samples with a low content of CNTs $(c_{\rm CNT} < 0.01 \text{ wt } \%)$, the reverse response with low hysteresis (Fig. 1a), which as a rule, is associated with the formation of adsorption ionic layers [16].

The pattern of T(U) curve changes with an increase in the nanoparticle concentration. Above all, transmittance oscillations are less pronounced for the curve cor-



Fig. 1. Dependences of light transmittance T on voltage U for CNT suspensions in EBBA at CNT concentrations: (a) 0, (b) 0.05, and (c) 0.1 wt %. Arrows indicate the increase and drop of voltage.

COLLOID JOURNAL Vol. 71 No. 5 2009



Fig. 2. Dependences of memory parameter M and conductivity σ of EBBA–CNT suspensions on the CNT concentration.

responding to decreasing voltage. In addition, upon the field switch-off, transmittance $T_{\rm m}$ of sample is much higher than initial T_0 value prior to the field switch-on (Figs. 1b and 1c). Thus, the electrooptical memory effect is manifested, which will be characterized by the parameter

$$M = \frac{T_{\rm m} - T_0}{T_{\rm max} - T_0} \times 100\%,$$
 (1)

where T_{max} is the maximal value of light transmittance (see Fig. 1a).

The dependence of memory parameter M on the CNT concentration in suspension, c_{CNT} , is nonmonotonic: the M value first abruptly rises with increasing c_{CNT} , reaches its maximal value at $c_{\text{CNT}} = 0.02-0.05$ wt %, and then gradually decreases (Fig. 2). The reason for this abrupt rise is discussed below, while the decay is apparently connected with a decrease in the effective voltage applied to the suspension layer due to a marked increase in the conductivity of the sample at higher CNT concentrations.

The efficiency of memory effect depends on the value of applied voltage and time of its action τ (Fig. 3). The time of formation of state with memory increases with a decrease in the voltage. The τ values changes from approximately 60 s at 50 V to 270 s at 20 V. At voltages lower than 10 V, the electrooptical memory effect is not observed, i.e., the response of system on the applied voltage is completely reversible.

Figure 4 presents the photographs of cells placed between crossed polarizers and filled with pure LC (photos 1a, 1b, and 1c) and CNT suspension in LC ($c_{\text{CNT}} = 0.05 \text{ wt \%}$), (photos 2a, 2b, and 2c) prior to filed switch-on (Figs. 4a and 4 b), in 60-volt field (photos 1b and 2b), and after field switch-off (photos 1c and 2c).



Fig. 3. Dependences of memory parameter *M* on the time of action of electric field (f = 2 kHz) with voltage (*I*) 10, (2) 20, and (3) 50 V on EBBA–CNT suspension ($c_{\text{CNT}} = 0.02 \text{ wt \%}$).

For pure LC, we observe uniform switching from initial (homeotropic) state to planar state upon the electric field switch-on and return to the initial state after the field switch-off (LC with low CNT content ($c_{\text{CNT}} < 0.01 \text{ wt \%}$) behaves itself similarly). In the case of suspension, planar orienting nonuniform state appears, which partially relaxes to initial homeotropic state upon the field switch-off that leads to high residual cell transmittance; i.e., the electrooptical memory effect is exhibited.

Note that the memory can be completely or partially erased by applying to sample mechanical stress, low-frequency voltage (f = 10-50 Hz, U > 30 V) or by the transition of a system to crystalline or isotropic states with subsequent return to the mesophase.

3.2. Conductivity of Composites

The dependence of conductivity σ on the concentration of nanotubes is shown in Fig. 2. Two regions can be specified on monotonically increasing $\sigma(c_{\text{CNT}})$ curve. At the initial stage, conductivity sharply increases with c_{CNT} , but its growth essentially slows down when the concentration approaches the 0.03– 0.05 wt %. This behavior is explained by the achievement of the threshold of electric percolation when CNTs form bound network structure piercing the LC layer from one electrode to another. Because CNT is characterized by high conductivity in the direction of its axis, the formed network becomes the main channel of current flow. In this case, highly efficient charge transfer typical for CNT is achieved within the scale of one CNT, whereas the charge transfer from one nanotube to another is supposedly realized by the hopping mechanism [22, 23].

3.3. Macro- and Microstructure of Composites

It is known that the structure of CNT suspensions in LC depends on the procedure of suspension preparation, characteristics of CNTs, the functionalization of their surfaces, the CNT concentration in suspension, viscoelastic and orientational characteristics of LC, as well as on the presence of external fields [11, 12, 16, 17, 23].

Carbon nanotubes are characterized by high affinity for aggregation, whose efficiency depends on factors listed above. Large aggregates are well seen in polarization microscope (Fig. 5). Sizes of aggregates grow with the CNT concentration reaching tens and even hundreds of microns. At low content of nanotubes ($c_{\rm CNT} <$ 0.02 wt %), single aggregates are observed, which are bound with one another to form the developed network structure with an increase in the CNT concentration. Naturally, only the largest aggregates are observed under polarization microscope. Simultaneously, there exists highly dispersed CNT phase with typical size comparable with the resolution of optical microscope.

The evolution of the structure of CNT-EBBA suspensions under the action of high-frequency electric field (f = 2 kHz) depends to a greater extent on the CNT concentration. In pure EBBA liquid crystal, as well as in EBBA with the minor concentration of nanotubes $(c_{\rm CNT} < 0.002 \text{ wt }\%)$, originally homeotropic orientation (Fig. 6a) is transformed into planar form (Fig. 6b) at a voltage on the order of 10 V. Further increase in voltage gives rise to the appearance of classical EHD instabilities in these samples. First, at $U \approx 80$ V, laminar flows appear in LC, which are manifested as Kapustin-Williams domains [18] (Fig. 6c). Domain picture becomes more complicated with an increase in voltage; at 110– 120 V, this picture is changed for the boiling of liquid crystal testifying to the development of turbulent flows (Fig. 6d). When the electric field is switched-on, the system returns to its initial state (Fig. 6e).

In samples with high CNT concentration (0.02-0.05 wt %), the development of EHD instabilities is different. First, at $U \approx 10$ V, the transition from homeotropic to planar orientations occurs (Figs. 7a and 7b). However, no later than at this voltage, turbulent EHD flows are yielded near the CNT aggregates. Domains of EHD perturbations expand (Fig. 7c), merge, and cover the whole sample volume at U > 40 V. In this case, Kapustin-Williams domains can be observed in some of sample parts, although the regular structure of this type is not formed. It can be seen from Fig. 7 that the EHD-stimulated boiling of liquid crystal leads to the disintegration of aggregates and efficient dispersion of CNTs. After the field switch-off, LC in these samples still retains its unoriented planar state, thus demonstrating the schlieren structure under polarization micro-



Fig. 4. Photomicrographs of cells placed between crossed polarizers and filled with (column 1) pure EBBA liquid crystal and (column 2) EBBA–CNT suspension ($c_{\text{CNT}} = 0.02$ wt %): (a) prior to the field switch-on, (b) in the field (U = 60 V, f = 2 kHz), and (c) after the field switch-off. Voltage was applied to rectangular regions in the sample middle for 1 min.

scope (Fig. 7d). The presence of such texture provides for residual transmittance $T_{\rm m}$ or the memory effect.

In samples with still higher concentration of nanotubes ($c_{\text{CNT}} > 0.1$ wt %), EHD instabilities are also observed, although they do not cause substantial disintegrating effect on LC aggregates. The reason for this effect is discussed below. In these media, along with the low efficiency of EHD dispersion, the much weaker conservation of planar orientation is observed after the field switch-off; the schlieren texture appears only in a few small domains, while homeotropic orientation is detected in the remaining parts of cell.

COLLOID JOURNAL Vol. 71 No. 5 2009



Fig. 5. Photomicrographs of the structure of EBBA–CNT suspensions with different contents of CNT: (a) 0.05, (b) 0.1, and (c) 0.5 wt %. State prior to field switch-on.

Note that the nature of the observed effect of EHD dispersion of nanotubes in LC media substantially differs from the nature of earlier studied disintegration of aggregates due to the polarization of CNTs and the effect of dielectrophoretic forces [12, 13]. The effect of dispersion described above is stronger and is observed exclusively in suspensions with pronounced EHD processes.

3.4. Effect of EHD Dispersion and Mechanism of Electrooptical Memory

Experimental data obtained testify to the existence of direct relation between the electrooptical memory effect and the stabilization of random planar orientation observed in CNT suspensions after the external electric field switch-off.

One of the reasons for such stabilization can be the spatial drift of carbon nanotubes toward electrodes and their adsorption on orienting layers under the action of external electric field. Adsorbed layers of CNT can screen the homeotropic action of orientating agent. Because of this, after the removal of orientating field, the effect of orientating agent can be weaken or vanish, and the LC cell will not be returned to originally homeotropic state. However, this mechanism is quite improbable due to several reasons. First, the adsorption of CNT on substrates should lead to the partial cleaning of LC layer from ions and, hence, to a decrease in the conductivity of samples. At the same time, we recorded substantial (nearly by the order of magnitude) increase in the conductivity of EBBA-CNT system after the field switch-on. Second, this fact contradicts the following experiment. Carbon nanotubes were deliberately deposited onto homeotropic orientating layer by the centrifugation of their suspension in toluene. It turned out that CNTs deposited onto the surface do not significantly affect the homeotropic orientation of LC even in the regions of their maximal accumulation.

Another more probable reason for the appearance of the memory state is the formation of a connected, threedimensional CNT network in LC, which is similar to the situation observed in LC filled with other types of nanoparticles. It is known that this network can stabilize LC oriented states and, as a result, lead to the memory effect. This memory mechanism was studied in the greatest detail for suspensions of Aerosil [6, 24, 25]. Aerosil nanoparticles interact with one another via surface silanol (Si-OH) groups to form hydrogen bonds. In this case, the developed network composed of Aerosil particles is formed in the dispersing LC matrix. Aerosil aggregates became involved into the reorientation of LC in the electric field. Over the course of this process, weak hydrogen bonds between aggregates are ruptured and the Aerosil network is disintegrated. Instead of this network, new network is formed in the LC oriented state to stabilize new LC orientational state. Similar mechanism can be implemented also in liquid-crystal suspensions of carbon nanotubes.

The percolation behavior of conductivity is evidence of the formation of bound network in CNT–EBBA suspensions (Fig. 5). Comparing the runs of $M(c_{\text{CNT}})$ and $\sigma(c_{\text{CNT}})$ curves, we can see that the electrooptical memory effect is manifested at CNT concentrations that exceeds the percolation threshold (> 0.05 wt %).

The formation of large, bound aggregates can also be observed at photomicrographs (Fig. 6). The dynamics of CNT structurization in the LC matrix upon the electric field switch-on can be rather complicated; however, unlike Aerosil, it is not reduced to the simple rupture of bonds between the fragments of such network during the LC reorientation. At a voltage of 10 V, the



Fig. 6. Photomicrographs demonstrating changes in the structure of strongly diluted CNT suspensions in EBBA ($c_{\text{CNT}} = 0.001$ wt %) under the action of electric field (f = 2 kHz): (a) prior to the field switch-on, in the fields (b) U = 10 V, t = 1 s, (c) U = 80 V, t = 5 s, (d) U = 110 V, t = 5 s, and (e) after the field switch-off. t is the time of action. Cells are placed in crossed polarizers so that the direction of rubbing is 45° with polarizer axes.

effective reorientation of LC molecules occurs in electric field (Figs. 1 and 7b); however, the memory effect is still not observed at this voltage. This effect appears at higher voltages, when EHD flows are developed and the disintegration of large aggregates takes place. The latter effect, which is called the effect of EHD dispersion, makes an important (and apparently decisive) contribution to the restructurization of CNT network stabilizing the LC planar state. New network consists of smaller CNT aggregates and, seemingly, is more developed and bound than the initial network. The enhancement of connectivity is supported by the observed increase (more than order of magnitude) in the conductivity of samples after switching to the regime of EHD instability and consequent formation of the memory state.

with magnetic field. It was demonstrated that, under the action of magnetic field with induction H = 5 kGs, the volume part of LC is efficiently reoriented into the planar state. At the same time, the T(H) curve demonstrates the reversibility. We believe that the absence of the memory effect upon the magnetic reorientation of LC is associated with the absence of convection flows launching the memory state is built-up upon the devel-

An important role of EHD instability in the development of the memory effect is supported by experiments

Thus, the memory state is built-up upon the development of convection flows destroying the old strongly aggregated CNT structure rather than during the simple reorientation of LC. The effect of the EHD-induced restructurization of colloidal system leads to the formation of network with large number of bonds consisting of small CNT aggregates. In turn, this network can sta-



Fig. 7. Photomicrographs demonstrating changes in the structure of EBBA–CNT suspensions ($c_{CNT} = 0.05$ wt %) under the action of electric field (f = 2 kHz): (a) prior to the field switch-on, in the fields (b) U = 10 V, t = 5 s, (c) U = 10 V, t = 300 s, (d) U = 40 V, t = 3 s, and (e) after the field switch-off. t is the time of action. Cells are placed in crossed polarizers so that the direction of rubbing is 45° with polarizer axes.

bilize a planar LC state formed in the electric field that explains the appearance of the electrooptical memory effect in studied anisotropic suspensions.

It is quite possible that the EHD dispersion of CNTs is necessary for the observation of memory effect only in the case of nanotubes with a nonfunctionalized surface. In some other cases, e.g., in the case of CNTs with hydrophobized surface, their highly dispersed bound structure will be formed even in the absence of additional influence of EHD flows. However, this structure can be insufficiently strong to counteract the anchoring forces and so to stabilize the LC planar state. The study of LC suspension of nanotubes with modified surface will be the next stage of this work.

In conclusion, let us consider how general the memory effect is for LCs containing carbon nanotubes. To elucidate this situation, we conducted experiments with the induction of memory in MLC6608 and MLC6609 nematic mixtures with negative dielectric anisotropy and 5CB nematic with $\Delta \varepsilon > 0$. In the case of MLC6608 and MLC6609, at $c_{\text{CNT}} > 0.05$ wt %, as in the case of EBBA liquid crystal, the effective memory is observed. It is interesting to note that the EHD instability is not developed in samples free of nanotubes. This is related to the low concentration of ions in liquid crystals applied in current LC displays. EHD instabilities appears upon the addition of nanotubes; however, in contrast to EBBA, they appear locally, predominantly near the large CNT aggregates that facilitates the disintegration of aggregates and launching the memory mechanism described above. In the case of 5CB liquid crystal, no memory effect is observed both in the absence and in the presence (0.01–0.50 wt %) of CNTs. These facts confirm the important role of EHD instabilities in the implementation of effect. On the other hand, these facts testify to the higher probability of the development of this effect in LC–CNT suspensions with efficient EHD flows.

4. CONCLUSIONS

Electrooptical response of anisotropic suspensions of multilayer non-functionalized carbon nanotubes in EBBA nematic liquid crystal ($\Delta \varepsilon < 0$) is studied upon the reorientation of the latter from the initial homeotropic to the planar state. The addition of nanotubes to liquid crystal leads to the appearance of irreversible response on the applied electric field (the electrooptical memory effect). This effect is expressed as a substantial increase in the light transmittance in crossed polarizers by the samples after the switching-on and off of the electric field. The observed residual transmittance is associated with the incomplete switching of LC component of suspension from planar schlieren texture appearing in the electric field to the initial homeotropic state.

The stabilization of the schlieren texture of liquid crystal can be achieved due to the formation of bound network of small CNT aggregates. Significant factor of CNT dispersion and, hence, of the formation of such network are EHD flows that are developed in a system upon the field switch-on. It was shown that the revealed memory effect is also exhibited for the CNT suspensions in other nematics with $\Delta \varepsilon < 0$, thus testifying to its rather wide occurrence.

ACKNOWLEDGMENTS

This work was supported by the project of the National Academy of Sciences of Ukraine, no. 10-07-N, "Optical, Electrical, and Structural Features of Carbon Nanotube–Liquid Crystal Nanosized Heterogeneous Systems." We are grateful to A.V. Melezhik for supplying samples of nanotubes.

REFERENCES

- 1. Chae, H.G, Liu, J, and Kumar, S, in *Carbon Nanotubes*. *Properties and Applications*, Connell, M.J., Ed., New York: Taylor and Francis, 2006, p. 213.
- 2. Dubois, P. and Alexandre, M., *Adv. Eng. Mater.*, 2006, vol. 8, p. 147.

- 3. Brochard, F. and De Gennes, P.G., *J. Phys.* (Paris), 1970, vol. 31, p. 691.
- 4. Chen, S.-H. and Amer, N.M., *Phys. Rev. Lett.*, 1983, vol. 51, p. 2298.
- Buluy, O., Ouskova, E., Reznikov, Yu., et al., J. Magn. Magn. Mater., 2002, vol. 252, p. 159.
- 6. Glushchenko, A. and Yaroshchuk, O., *Mol. Cryst. Liq. Cryst.*, 1999, vol. 330, p. 415.
- Boxtel, M., Janssen, R., Bastiaansen, C., and Broer, D., J. Appl. Phys., 2001, vol. 89, p. 838.
- 8. Shiraishi, Y., Toshima, N., Maeda, K., et al., *Appl. Phys. Lett.*, 2002, vol. 81, p. 2845.
- 9. Li, F., Buchnev, O., Cheon, C.I., et al., *Phys. Rev. Lett.*, 2006, vol. 97, p. 147801.
- Lynch, M.D. and Patrick, D.L., *Nano Lett.*, 2002, vol. 2, p. 1197.
- Dierking, I., Scalia, G., Moralez, P., and LeClere, D., *Adv. Mater.* (Weinheim, Fed. Repub. Ger.), 2004, vol. 16, p. 865.
- 12. Jeong, S.J., Park, K.A., Jeong, S.H., et al., *Nano Lett.*, 2007, vol. 7, p. 2178.
- Srivastava, A.K., Jeong, S.J., Lee, M.-H., et al., J. Appl. Phys., 2007, vol. 102, p. 043503.
- 14. Russel, M., Oh, S., LaRue, I., et al., *Thin Solid Films*, 2006, vol. 509, p. 53.
- 15. Vasil'ev, P.Ya. and Kamanina, N.V., *Pis'ma Zh. Tekh. Fiz.*, 2007, vol. 33, p. 8.
- 16. Lee, W., Wang, C.-Yu., and Shih, Yu.-C., Appl. Phys. Lett., 2004, vol. 85, p. 513.
- 17. Baik, I.-S., Jeon, S.Y., Lee, S.H., et al., *Appl. Phys. Lett.*, 2005, vol. 87, p. 263110.
- Blinov, L.M., *Elektro- i magnitooptika zhidkikh kristallov* (Electro- and Magnetooptics of Liquid Crystals), Moscow: Nauka, 1978.
- 19. Melezhyk, A., Sementsov, Yu., and Yanchenko, V., *Appl. Chem*, 2005, vol. 78, p. 938.
- Kovalchuk, O., Zakrevska, S., Yaroshchuk, O., and Maschke, U., *Mol. Cryst. Liq. Cryst. Sci. Technol.*, A, 2001, vol. 368, p. 129.
- 21. Liu, L., Yang, Y., and Zhang, Y., *Physica E* (Amsterdam), 2004, vol. 24, p. 343.
- Kovalchuk, A., Dolgov, L., and Yaroshchuk, O., Semicond. Phys. Quantum Electron. Optoelectron., 2008, vol. 11, p. 337.
- 23. Lisetski, L., Lebovka, N., Sidletskiy, O.Ts., et al., *Funct. Mater.*, 2007, vol. 14, p. 233.
- 24. Kreuzer, M., Tschudi, T., and Eidenschink, R., Mol. Cryst. Liq. Cryst., 1992, vol. 223, p. 219.
- 25. Glushchenko, A., Kresse, H., Reshetnyak, V., et al., *Liq. Cryst.*, 1997, vol. 23, p. 241.