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

TIME OF FLIGHT STUDY ON CARRIER GENERATION AND TRANSPORT IN DISCOTIC LIQUID CRYSTAL

Ryo Azumai [a], Masanori Ozaki [a], Hiroaki Nakayama [a], Takeshi Fujisawa [a], Werner F. Schmidt [b] & Katsumi Yoshino [a]

[a] Department of Electronic Engineering, Graduate School of Engineering, Osaka University, 2-1 Yamada-Oka, Suita, Osaka, 565-0871, Japan

[b] Department of Physics, Freie Universitat Berlin, Dahlemer Weg, 172A, 14167, Berlin, Germany

Version of record first published: 24 Sep 2006

Mol. Cryst. and Liq. Cryst., 2001, Vol. 366, pp. 359-367
Reprints available directly from the publisher
Photocopying permitted by license only

Time of Flight Study on Carrier Generation and Transport in Discotic Liquid Crystal

RYO AZUMAI[a], MASANORI OZAKI[a], HIROAKI NAKAYAMA[a], TAKESHI FUJISAWA[a], WERNER F. SCHMIDT[b] and KATSUMI YOSHINO[a]

[a]*Department of Electronic Engineering, Graduate School of Engineering, Osaka University, 2–1 Yamada-Oka, Suita, Osaka 565–0871, Japan and* [b]*Department of Physics, Freie Universitat Berlin, Dahlemer Weg, 172A, 14167 Berlin, Germany*

Carrier generation and transport properties in discotic liquid crystal have been studied by means of a time-of-flight method. The anisotropy of the carrier mobility and dark conductivity has also been estimated using two types of electrode configurations, that is, a sandwich and inter-digited electrodes. The carrier mobility in the direction perpendicular to the columnar structure in the discotic phase has been estimated to be a less than that parallel to the columnar axis. The corresponding anisotropy in the dark conductivity is also confirmed in the discotic phase.

Keywords: discotic liquid crystal; time-of-flight; mobility; conductivity

INTRODUCTION

Although, in organic liquids, the existence of free electrons with large mobility depending on the molecular structure has been confirmed[1] [2], only ionic carrier mobility has been reported in ordinary liquid crystals, which is related to the viscosity of the fluid by Walden's rule[3] [4]. However, recently, observations of hole mobility have been reported in discotic liquid crystals in which disc-shaped aromatic units stack in one direction and form a columnar structure[5] [6]. They are a very important finding for the understanding of the carrier transport process in fluids, because reports on direct observation of holes in dielectric liquids are extremely few.

On the other hand, the study on the anisotropy of the carrier transport is very useful for understanding the carrier generation and transport processes. However, reports on observation of carrier transport perpendicular to columnar direction in the discotic liquid crystal does not exist. Therefore, more detailed study on carrier generation, transportation and migration process in the discotic liquid crystal is necessary.

In this paper, we report on the anisotropy of the carrier mobility and the electric conductivity in the discotic liquid crystal, 2,3,6,7,10,11-hexahexyloxytriphenylene (HHOTP), as a function of temperature, changing the cooling rate and cell configuration.

EXPERIMENTAL

Figure 1 shows molecular structure of HHOTP used in this study. HHOTP was synthesized by the method reported and purified by a column chromatography with silica gel and chloroform/benzene mixture (1/4) as eluent, and then recrystallized from acetone[7]. In the temperature range between 53 °C

and 96°C, the discotic phase of HHOTP, which coincides with the reference [8], was confirmed.

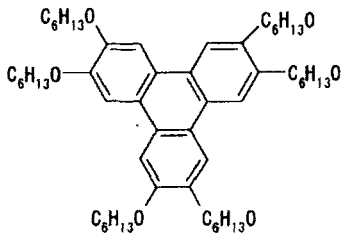

FIGURE 1. Molecular structure of the discotic liquid crystal HHOTP used in this study.

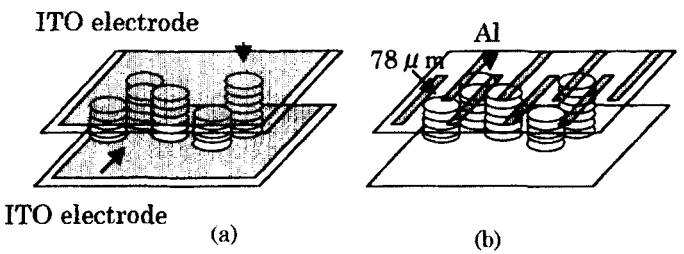

FIGURE 2. Schematic explanation of the relationship between electrode configulation and molecular alignment in the columnar structure.

The HHOTP sample was introduced in a sandwich cell, which was composed of two parallel quartz plates one has a pair of sandwich electrodes of ITO(In-Sn Oxide), and the other has an inter-digit Al electrode on one of surfaces with separation of 6-12 μ m by using the polyethyleneterephthalate (PET) sheets used as spacers. Two types of cell configurations were used for the measurement of an anisotropy as shown in Fig.2

The conductivity and mobility parallel and perpendicular to the columnar axis were measured utilizing a conventional sandwich cell (Fig.2 (a)) and interdegit cell (Fig.2 (b)), respectively. In the discotic phase, molecular alignment of HHOTP with columnar structure which perpendicularly oriented to the glass substrates was realized by cooling the temperature of the sample from the isotropic phase slowly and was confirmed by a polarizing microscopic observation.

Carrier mobility was evaluated by a time-of-flight method [9] using a third harmonics generation (355nm) of Q-switched Nd:YAG light of 20ns pulse width as the exciting light source. Figure 3 shows an experimental setup for the time-of-flight measurement. In the care of inter-digit cell, exciting light pulses were irradiated from the electrode side of the cell. The photocurrent signal amplified by a voltage-current amplifier was recorded by a storage oscilloscope (Tektronix, TDS 360. or 2440).

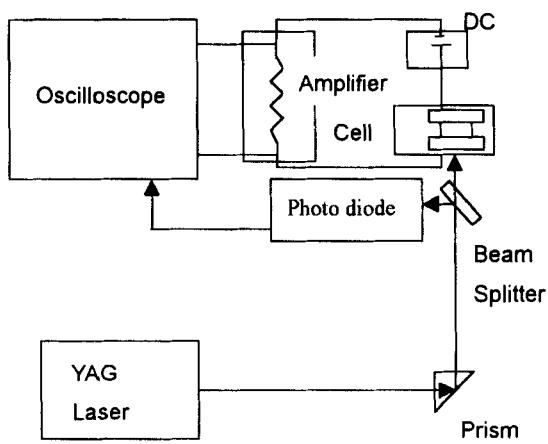

FIGURE 3. The experimental setup of the time-of-flight measurement.

Dark conductivity was evaluated by a conventional circuit for current measurement using a digital electrometer (Keithley 617).

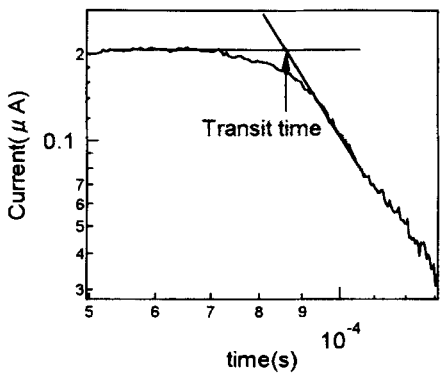

FIGURE 4. Time response of photo-induced current signal for the case of the anode irradiation parallel to the columnar direction.

RESULTS AND DISCUSSION

Figure 4 shows a typical double logarithmic plot of induced current (i) decay (log i vs log t) for a positive polarity in the sandwich electrode cell in the discotic liquid crystal phase (80°C). In this cell geometry, the photocurrent should originate from the carrier migration parallel to the columnar structure.

As is evident from Fig.4, photoinduced current decay profiles are quite common in the time-of flight measurement. The transit time T_r between electrodes in the case of positive carriers is interpreted to be the time when a shoulder appears in the current curve in Fig.4.

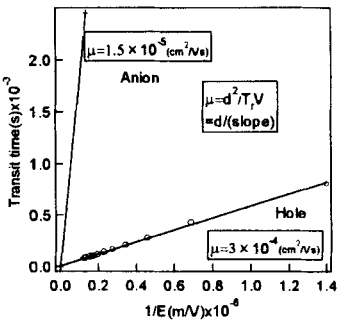

FIGURE 5. Field dependence of the response time for both positive and negative carriers parallel to columnar direction.

Figure 5 indicates field dependence of the transit time. It is clear that the transit time *Tr* is inversely proportional to the applied voltage *V*. The carrier mobility μ can be evaluated by the relation of $\mu = d^2/TrV$, where d is the electrode distance. The evaluated value of the mobility of positive carrier in the discotic phase is about 3×10^{-4} cm^2 /Vs.

In order to evaluate mobility for the carrier migration perpendicular to the columnar axis, the inter-digit electrodes cell was used for the time-of-flight measurement. Figure 6 shows an experimental waveform of transient photocurrent. When the carrier density n_0 emerged by exciting light pulse is constant between electrodes and the carriers are traveling by the applied voltage at the velocity v_d, the total current density $J(t)$, which drifts between electrodes at time t, is given as the integration of the charge carrier density [10]:

$$J(t) = \frac{e_0 n_0 V_d}{d} \int_{V_d t}^{d} dx = J_0 \left[1 - \frac{t}{t_d} \right]$$

where d is the distance between electrodes, J_0 is the initial current density at t=0

and t_d is the transit time of the carrier.

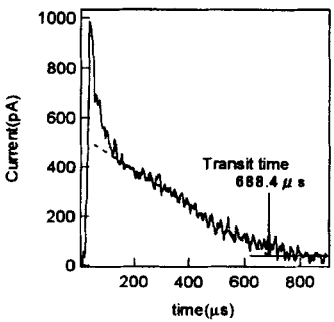

FIGURE 6. Time response of photo-induced current signal perpendicular to the columnar direction for the case of the irradiation to an inter-digit electrode.

As well as the case of the sandwich electrode cell, we can evaluate the mobility by the relation $\mu = d^2/t_d V$, where d is the electrode distance(Fig. 7). The experimental value of the mobility perpendicular to the columnar structure is evaluated about 1.8×10^{-4} cm^2 /Vs(80°C), which is smaller than that parallel to the columnar axis. Although the kind of carriers, i.e. hole or electron, can not be determined by this cell geometry, this value may be hole mobility, because of the similarity in value to that measured parallel to the columnar axis.

The temperature dependence of the dark conductivity parallel and perpendicular to the columnar structure was evaluated using the sandwich and inter-digit electrode configurations, respectively, during cooling from isotropic phase to crystalline phase at a rate of –0.2°C/min. The temperature dependence of the dark conductivity in the isotropic and crystalline phases show similar characteristics, and has the same slope even in a different electrode geometries as shown in Fig. 8. Whereas in the discotic phase the slope of the temperature dependence of the conductivity perpendicular to the columnar axis is larger than

that for parallel one.

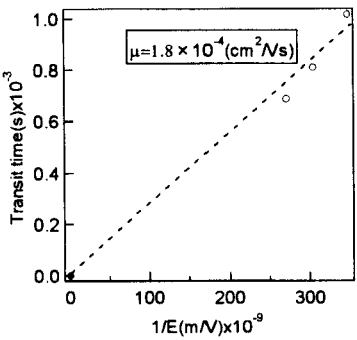

FIGURE 7. Field dependence of the transmit time for carriers migration perpendicular to columnar direction.

Clear phase transitions can be confirmed at the phase changing points. At the transition temperature between discotic and crystalline phases, the change of conductivity perpendicular to the columnar axis is larger compared with that of along the columnar direction.

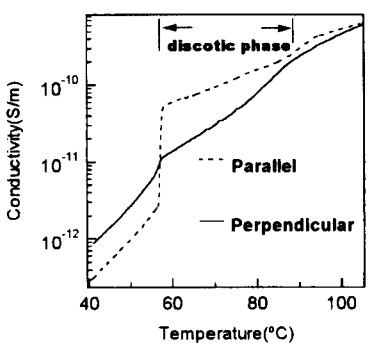

FIGURE 8. Temperature dependence of dark conductivity in the direction parallel and perpendicular to the columnar structure. (cooling rate –0.2°C/min)

It should be noted that activation energy of the dark conductivity shows no difference between that parallel and perpendicular to the columnar axis, in the isotropic and crystalline phases, whereas, in the discotic phase, the perpendicular one is twice as large as the parallel one. This means that carrier transport process in the discotic liquid crystal strongly depends on the order of the formed columnar structure in the discotic phase.

CONCLUSION

The summary of this experimental study is as follows.

(1) In the discotic liquid crystal HHOTP, using a time-of-flight method with an inter-digit electrode cell geometry, the carrier mobility perpendicular to the columnar structure in the discotic phase could be evaluated to be smaller than that of parallel to the columnar structure.

(2) In the discotic phase, the anisotropy of the dark conductivity was confirmed in the columnar structure. At the phase transition from the discotic to crystal phases, the conductivity parallel to the columnar direction decreased more than that perpendicular to the columnar direction. This suggests carrier transport of HHOTP in the discotic phase strongly depends on the order of the formed columnar structure.

References

[1] W.F. Schmidt and A.O. Allen: J. Chem. Phys. **50** (1969) 5037.

[2] R.M. Minday, L.O. Schmidt and H.T. Davis: J. Chem, Phys. **50** (1969) 1473.

[3] K. Yoshino, S. Hisamitsu and Y. Inuishi: J. Phys. Soc. Jpn. **32** (1972) 867.

[4] K. Yoshino, N. Tanaka and Y. Inuishi: Jpn. J. Appl. Phys. **15** (1976) 735.

[5] D. Adam, W. Rokhildt and D. Haarer: Jpn. J. Appl. Phys. **35** (1996) 1826.

[6] D. Adam, F. Closs, T. Frey, D. Funhoff, D. Haarer, H. Rigsdorf, P. Schuhmacher and K. Siemensmeyer: Phys. Rev. Lett. **70** (1993) 457.

[7] L.Y. Chiang, C.R. Safinya, N.A. Clark, K.S. Liang and A.N. Bloch: J. Chem. Soc. Chem. Commun. (1985) 695.

[8] C. Destrade, M.C. Mondon and J. Malthete: J. Phys. (Paris) **40** (1979) C3–17. .

[9] K. Yoshino: IEEE Trans. Electr. Insul. **21** (1986) 999.

[10] W.F. Schmidt: *Liquid State Electronics of Insulating Liquid*. (Boca Raton, (1997) CRC Press).