Transient and Modulation Spectroscopies for the Characterization of Liquid Crystal and Organic Light-Emitting Diodes Displays

Hiroyoshi Naito[1,2]

h.naito@omu.ac.jp
[1]Department of Applied Chemistry, Osaka Metropolitan University
[2]Department of Physics and Electronics, Osaka Prefecture University
(Affiliation at the time of the Slottow-Owaki Prize)
Keywords: liquid crystal, organic light-emitting diodes, organic field-effect transistors, organic photodetectors

ABSTRACT

Transient and modulation spectroscopies for the characterization of liquid crystal and organic light-emitting diodes displays that we have developed are reviewed. The information obtained from the spectroscopies is useful for the understanding of the device operation mechanisms and for the design of display devices.

1 Introduction

The Slottow-Owaki Prize of the Society of Information Display is awarded for outstanding contributions to the education and training of students, and/or professionals, in the field of electronic displays. According to literature [1], The Slottow-Owaki Prize was awarded I received for his contributions to the education of graduate and undergraduate students and research professionals in display material characterization and display device physics to me [1].

The facet of my scientific achievements in both liquid crystal displays (LCDs) and organic light-emitting diodes (OLEDs) display for which the award was given is briefly described in this presentation.

2 Liquid crystal displays

2.1 Transient current spectroscopy

Transient charging currents in nematic liquid crystals (NLCs) induced by a step voltage application have been studied. A peak in the current transient is observed in the nematic phase. It is shown that occurrence of the peak is due to the alignment of the director of the LC molecules in the direction of applied electric field [2]. It is also shown that impurity ions affect the current transients. Drift mobility of impurity ions in NLCs can be determined from transient current induced by polarity reversal square voltage wave, as in case of the transient current measurements in dielectric liquid [3]. Transient dynamic scattering from NLCs with positive dielectric anisotropy was found during the transit of impurity ions [4].

A simple theory for measuring the rotational viscosity has been proposed from the analysis of transient current, induced by step-voltage excitation, in NLCs with positive dielectric anisotropy [5]. The applicability of the theory to NLCs with negative dielectric anisotropy has been examined. It is found that the transient current shape of NLCs with negative dielectric anisotropy is different from that of NLCs with positive dielectric anisotropy, and hence, the theory cannot directly be applied to the analysis of the transient current of NLCs with negative dielectric anisotropy. It is shown that the transient current in NLC cells with negative dielectric anisotropy (vertical aligned NLC) is well explained in terms of the Ericksen-Leslie theory under a free-slip boundary condition for fluid flow in the NLC cells [6, 7]. The effective rotational viscosity and a method for measuring all Leslie viscosity coefficients have been proposed. Leslie viscosity coefficients governing the response of director reorientation in NLC with negative dielectric anisotropy are shown. The flow effects play a key role in eliciting a faster electrooptic response in vertically aligned NLC displays.

2.2 impedance spectroscopy

The transport properties of impurity ions in NLCs have been studied from low-frequency dielectric properties measured by means of impedance spectroscopy (IS) [8]. It was found that the dielectric behavior of the NLC cells without polyimide alignment layers is due to the electrode polarization. The drift mobility and the concentration of the impurity ions are determined from the dielectric behavior. The NLC cells with polyimide alignment layers exhibit interface polarization between the polyimide alignment layers and the NLC slab. The ion concentration is estimated from the frequency at the dielectric loss peak of the interface polarization. The ion concentration can then be measured in NLC cells with and without polyimide alignment layers, which makes it possible to study whether or not impurity ions are dissolved from the polyimide layers. Important information is also gained from the temporal variations of the dielectric properties of the NLC cells with and without polyimide alignment layers after the cell preparation.

The dielectric relaxation caused by the adsorption of impurity ions in NLC onto the electrode surfaces of NLC cells can be studied from the dielectric properties of NLC cells in the ultralow frequency regime [9]. It is shown that the dielectric relaxation is caused by the Helmholtz double layer formed by the adsorption of impurity ions, and hence the thickness of the double layer is comparable to the radius of impurity ions in NLC (~0.5 nm). The dielectric relaxation obeys the empirical Cole - Cole circular arc law, indicating that dielectric relaxation times are distributed. The distribution of dielectric relaxation times can be explained in terms of distributed thicknesses of the Helmholtz double layer (namely, distributed radii of impurity ions).

A method for studying adsorption and desorption processes of impurity ions in NLC cells from ac conductivity is proposed [10, 11]. The experimental results are interpreted in terms of a rate-equation approach and the time constants for the adsorption and desorption processes of the ions are determined. Using the method, the desorption processes of adsorbed impurity ions on various alignment layers in NLC cells have been examined. The adsorption of the ions is induced by the application of dc voltage to NLC cells. It is found in all alignment layers that the adsorbed ions decay exponentially after the cessation of the dc voltage application, and that the time constants of the decay exhibit thermally activated behavior. It is shown that the desorption process is governed by the surface energy of the alignment layers.

3 Organic light-emitting diodes displays

3.1 Impedance spectroscopy

3.1.1 Organic light-emitting diodes

The electron and hole drift mobilities of organic semiconductor layers, localized tail state distributions, and bimolecular recombination constants in OLEDs with polymer light-emitting layers under operation are determined simultaneously using IS [12 - 16]. Electron and hole transit time effects are observed in the capacitance-frequency characteristics of the OLEDs and their drift mobilities are determined over wide temperature and electric field ranges. The drift mobilities exhibit thermally activated behavior and the localized tail state distributions from the conduction band and valence band mobility edges are then determined from analysis of the electric field dependences of the activation energies. The bimolecular recombination constants are determined from the inductive response of the impedance-frequency characteristics. The IS technique is also applicable to degradation analysis of the OLEDs; changes in the mobility balance, the localized tail state distributions, and the bimolecular recombination constant caused by aging are all shown.

3.1.2 Organic field-effect transistors

Complex modulus spectra of organic field-effect transistors (OFETs) with electrode overlap regions were investigated both experimentally and theoretically [17]. Complex modulus spectra in OFETs were measured by means of IS. An equivalent-circuit of OFETs with the overlap between gate and source/drain electrodes was proposed to interpret the experimentally-obtained complex modulus spectra. The complex modulus spectra calculated from the equivalent circuit were successfully fitted to the experimentally-obtained spectra of P3HT FETs. It is shown that the dielectric properties of the gate insulator, the field-effect mobility of the organic semiconductor, and the contact resistance are obtained by means of the fitting of the theoretically-obtained modulus spectra to the experimentally-obtained spectra.

The field-effect mobility determined from the fitting is not dependent on the contact resistance, meaning that the same values of the field-effect mobility are obtained in OFETs with different channel lengths. In addition, the cut-off frequency can also be determined from the values of equivalent circuit components obtained from the fitting.

3.2 Modulated photocurrent and photovoltage spectroscopies

3.2.1 Organic photodetectors

The touch-panel operation was successfully demonstrated active-matrix LCDs with embedded optical sensor arrays. The development of OPDs is therefore a fundamental issue for flexible displays with touch-panel operation. In principle, IS can be applied to the characterization electronic transport properties of OPDs but IS cannot be applied to the characterization of the electronic transport properties of OPDs with inverted structures because of high electron injection barriers from metal-oxide cathode. The use of the metal-oxide cathode makes the device stability of OPDs much more stable.

Modulated photocurrent (MPC) spectroscopy, originally proposed for the determination of localized-state distributions in disordered semiconductors, was employed to study the electronic transport properties of OPDs [18]. MPC has been successfully applied to the electronic characterization of OPDs under operation; electron and hole drift mobilities were determined simultaneously. Bimolecular recombination constants can also be determined using modulated photovoltage spectroscopy in OPDs. As in OLEDs, the electronic transport properties have been successfully studied by means of MPC and MPV spectroscopies.

4 Conclusions

Brief results of transient and modulation spectroscopies for LCD and OLED displays and OPDs were described. We have studied the transport properties and the adsorption and desorption processes of impurity ions in NLC, and the viscosity coefficients of

NLC. We have also studied the electronic properties of OLEDs, OFETs and OPDs. These results are useful for the understanding of operation mechanisms in LCDs, OLEDs, OFETs and OPDs and for the design of these displays.

Acknowledgments

The studies described here were the results of the collaboration with researchers in display industries and with graduate students. Some of the graduate students gained phD degree and are or were active in display industries or display related industries. I thank the researchers and the graduate students for their valuable contribution. Although details cannot be shown here because of the limitation of space, I also thank the industries, private foundations, JST, MEXT, and JSPS for their financial support.

Reference

1. L. A. Wilson, “2022 SID Honors & Awards”, J. Soc. Information Display, Vol. 30, No. 2, pp. 6-14 (2022).
2. H. Naito, K. Yoshida, M. Okuda, and A. Sugimura, “Transient charging current in nematic liquid crystals”, J. Appl. Phys. Vol. 73, No. 3, pp. 1119-1125, (1993).
3. K. Ochi, M. Todorokihara, H. Naito, N. Manabe and M. Inoue, " Determination of drift mobilities of impurity ions in nematic liquid crystal cells from transient current induced by polarity reversal voltage pulses", Proceedings of Japanese Liquid Crystal Society Annual meeting, pp. 237-238, (2000).
4. K. Ochi, M. Todorokihara and H. Naito, "Transient diffraction due to ionic conduction in nematic liquid crystal cells," Proceedings of 1999 IEEE 13th International Conference on Dielectric Liquids (ICDL'99), pp. 575-578, (1999).
5. M. Imai, H. Naito, M. Okuda and A. Sugimura, “Method for Determination of Rotational Viscosity in Nematic Liquid Crystals”, Jpn. J. Appl. Phys. Vol. 33, No. 1B, pp. L119 – L121 (1994).
6. Y. Iwata, H. Naito, M. Inoue, H. Ichinose, M. Klasen-Memmer, and K. Tarumi, “Transient Current of Nematic Liquid Crystals with Negative Dielectric Anisotropy Induced by Step-Voltage Excitation”, Jpn. J. Appl. Phys. Vol. 43, No. 12B, pp. L1588 – L1591 (2004).
7. H. Naito, Y. Iwata, M. Inoue, H. Ichinose, M. Klasen-Memmer, and K. Tarumi, “Transient response of vertical-alignment nematic liquid crystal cells: flow effect and transient current”, J. Jpn. Liq. Crist. Soc. Vol. 14, No. 1, pp. 22 – 31.
8. S. Murakami and H. Naito, “Electrode and Interface Polarizations in Nematic Liquid Crystal Cells”, Jpn. J. Appl. Phys. Vol. 36, No. 4R, pp. 2222 – 2225 (1997).
9. S. Murakami, H. Iga, and H. Naito, “Dielectric properties of nematic liquid crystals in the ultralow frequency regime”, J. Appl. Phys. Vol. 80, No. 11, pp. 6396 – 6400.
10. Y. Yasuda, H Naito, M Okuda, A Sugimura, “Observation of adsorption and desorption processes of impurity ions in nematic liquid crystal cells”, Mol. Cryst. Liq. Cryst. Vol. 263, No. 1, pp. 559 – 565.
11. H. Naito, Y. Yasuda and A. Sugimura, “Desorption processes of adsorbed impurity ions on alignment layers in nematic liquid crystal cells”, Mol. Cryst. Liq. Cryst. Vol. 301, No. 1, pp. 85 – 90.
12. T. Okachi, T. Nagase, T. Kobayashi, and H. Naito, “Determination of charge-carrier mobility in organic light-emitting diodes by impedance spectroscopy in presence of localized states”, Jpn. J. Appl. Phys. Vol. 47, No. 12, pp. 8965 – 8972 (2008).
13. T. Okachi, T. Nagase, T. Kobayashi, and H. Naito, “Determination of localized-state distributions in organic light-emitting diodes by impedance spectroscopy”, Appl. Phys. Lett. Vol. 94, No. 4, pp. 043301-1 – 043301-3 (2009).
14. K. Takagi, T. Nagase, T. Kobayashi, and H. Naito, “Determination of deep trapping lifetime in organic semiconductors using impedance spectroscopy”, Appl. Phys. Lett. Vol. 108, No. 5, pp. 053305-1 – 043301-5 (2016).
15. M. Takada, T. Mayumi, T. Nagase, T. Kobayashi, and H. Naito, “Determination of bimolecular recombination constants in organic double-injection devices using impedance spectroscopy”, Appl. Phys. Lett. Vol. 114, No. 12, pp. 123301-1 – 123301-5 (2019).
16. M. Takada, T. Nagase, T. Kobayashi, and H. Naito, “Full characterization of electronic transport properties in working polymer light-emitting diodes via impedance spectroscopy”, J. Appl. Phys. Vol. 125, No. 11, pp. 115501-1 – 115501-9 (2019).
17. Y. Suenaga, M. Higashinakaya, T. Nagase, T. Kobayashi and H. Naito, “Interpretation of the modulus spectra of organic field-effect transistors with electrode overlap and peripheral regions: determination of the electronic properties of the gate insulator and organic semiconductor”, Jpn. J. Appl. Phys. Vol. 59, No. 9, pp. 094002-1 – 094002-7 (2020).
18. H. Nojima, T. Kobayashi, T. Nagase and H. Naito, “Modulated Photocurrent Spectroscopy for Determination of Electron and Hole Mobilities in Working Organic Solar Cells”, Sci. Rep. Vol. 9, pp. 20346-1 – 20346-8 (2019).