

Electroluminescent Devices Using a Polymer of Regulated Conjugation Length and a Polymer Blend

Taehyoung Zyung and Sang-Don Jung

CONTENTS

- I. INTRODUCTION
- II. DEVICE FABRICATION AND CHARACTERIZATION
- III. LIGHT EMITTING DEVICES USING THE POLYMER WITH REGULATED CONJUGATION LENGTHS
- IV. LIGHT EMITTING DEVICES USING THE POLYMER BLENDS
- V. CONCLUSION

ACKNOWLEDGMENT

REFERENCES

ABSTRACT

A blue light emitting device has been successfully fabricated using a polymer with regulated conjugation length containing trimethylsilyl substituted phenylenevinylene units. Electroluminescence from the device has an emission maximum at 470 nm. The device shows typical diode characteristics with operating voltage of 20 V and the light becomes visible at a current density of less than 0.5 mA/cm². The electroluminescence spectrum is virtually identical with the photoluminescence spectrum, indicating that the radiation mechanisms are the same for both. A light emitting device using the blend of a large band gap polymer and a small band gap polymer was also fabricated. Light emission from the small band gap polymer shows much improved quantum efficiency, but there is no light emission from the large band gap polymer. Quantum efficiency of the blend increases up to about two orders of magnitude greater than that of the small band gap polymer with increasing proportion of the large band gap polymer. The improvement in quantum efficiency is interpreted in terms of exciton transfer and the hole blocking behaviour of the large band gap polymer. Finally, we have fabricated a patterned flexible light emitting device using the high quantum efficiency polymer blend system.

I. INTRODUCTION

Since electroluminescence (EL) from thin film of organic molecules was first demonstrated [1], interest in light emitting devices (LEDs) utilizing π -conjugated organic molecules and polymers was fueled research into EL devices based on polymer thin layers, which are one of the most promising next-generation flat panel display and light emitting diodes. Many π -conjugated polymers have π - π^* energy gap responsible for EL, which can be altered through controlled changes in the molecular structure and hence the color tuning is easily controllable [2], [3]. This color tuning is one of the important advantages of organic over inorganic LEDs especially for the generation of blue light. Processibility is another advantage for application to large-area LEDs, where the device can be fabricated by casting the luminescent polymer layer from solution [4].

Inorganic semiconductors such as GaN and ZnSe have been used for blue light generation, but are not effective for large-area application. The feasibility of large area applications using processible organic polymers spurred research into the use of π -conjugated polymers in blue light generation [5]-[12]. However, the first blue EL polymers showed rather poor processibility and mechanical properties [5], [6], and therefore the search for suitable polymers for blue EL generation has been intensively continued [7]-[12].

For blue light generation, the band gap of semiconducting polymers need to be widened.

An effective way for widening the band gaps of conjugated polymers is to shorten the conjugation length by introducing nonconjugated segments into the backbone [11]-[14]. The introduction of nonconjugated segments not only results in confinement of π -electrons in the conjugated segments but also improves the homogeneity of the film [11], [12]. However, from the view of chemical synthesis, it is hard to obtain the polymer with a short conjugation length of phenylenevinylene units in a soluble form. The introduction of some substituents onto the benzene ring is necessary to improve the solubility [11], [12].

Even though there has been remarkable development in polymer EL device performances, the improvement of quantum efficiency and reliability of the devices is still a challenge. Quantum efficiency of EL can be achieved up to a maximum of one-quarter of that of PL according to the spin statistics [15], but the highest recorded external quantum efficiency for a single layer polymer device is at most 1% [16]. Therefore, the quantum efficiency and the reliability of the polymer EL devices need to be improved for practical uses. New materials and device structures have been actively pursued to improve them.

Better quantum efficiency requires more balanced injection of the opposite carriers into the emissive layer. There are several effective ways to achieve it, such as introducing hole and/or electron transport layers between the luminescent layer and the electrodes [17], [18], or reducing the band offset between the lowest

unoccupied molecular orbital (LUMO) level of the emission layer and the Fermi level of the cathode. Reduction of the band offset can be obtained by using a cathode with low work function [4] or by using an emissive polymer with high electron affinity [16]. Combination of the above two methods produced a device with an internal quantum efficiency about 4% [16].

Blending of luminescent polymers is another useful method for color tuning and improving quantum efficiency. Polymer blends of a luminescent polymer and a matrix polymer with good hole transporting property such as poly(9-vinylcarbazole) or poly(methyl methacrylate) show enhancement of quantum efficiency [9], [19]-[21]. The efficient confinement of the singlet exciton which is responsible for EL in polymer blend is expected to improve the quantum efficiency. EL devices made of a polymer blend composing four luminescent polymers displayed multicolor emission with the emission color depending upon the applied voltage [22]. Single color with much improved quantum efficiency has also been obtained from blends of two luminescent polymers [23], [24].

In this paper, we report blue EL devices utilizing a PPV derivative poly[1,3-propane dioxy-1,4-phenylene-1,2-ethynylene-(2,5-bis(trimethylsilyl)-1,4-phenylene)-1,2-ethynylene-1,4-phenylene] (hereafter PDSIPV), in which the conjugation length is regulated by incorporating nonconjugated segments into the conjugated backbone. The nonconjugated

alkyl spacer group is designed to be as short as possible in order to keep the good mechanical properties of PPV. Furthermore, the trimethylsilyl groups were introduced onto the benzene ring in order to improve the solubility of the polymers, and hence enhance the processibility for the fabrication of a blue EL device. A trimethylsilyl substituent has almost the same electronic properties as hydrogen but improves the polymer solubility [25]. The EL properties and characteristics of the devices were measured and their results are discussed. Also, we report the improvement of quantum efficiency of EL devices by blending two polymers with different band gaps in various proportions. Poly(2-methoxy, 5-(2'-ethyl-hexoxy)-1,4-phenylene vinylene) (MEH-PPV) was used as a small band gap polymer and blue light emitting PDSIPV as a large band gap polymer. Interestingly, the blend systems show the enhancement of EL quantum efficiency at the wavelength of MEH-PPV without any emission from PDSIPV even when the latter dominates in weight composition. Also the quantum efficiency of MEH-PPV is almost linearly increased with the weight composition ratio of PDSIPV.

II. DEVICE FABRICATION AND CHARACTERIZATION

The chemical structures of the synthesized polymer and the polymer used as the small

band gap polymer in the blend system are shown in Fig. 1(a) and (b), respectively, together with the fabricated device structure. The synthetic schemes of the polymers were reported previously [26].

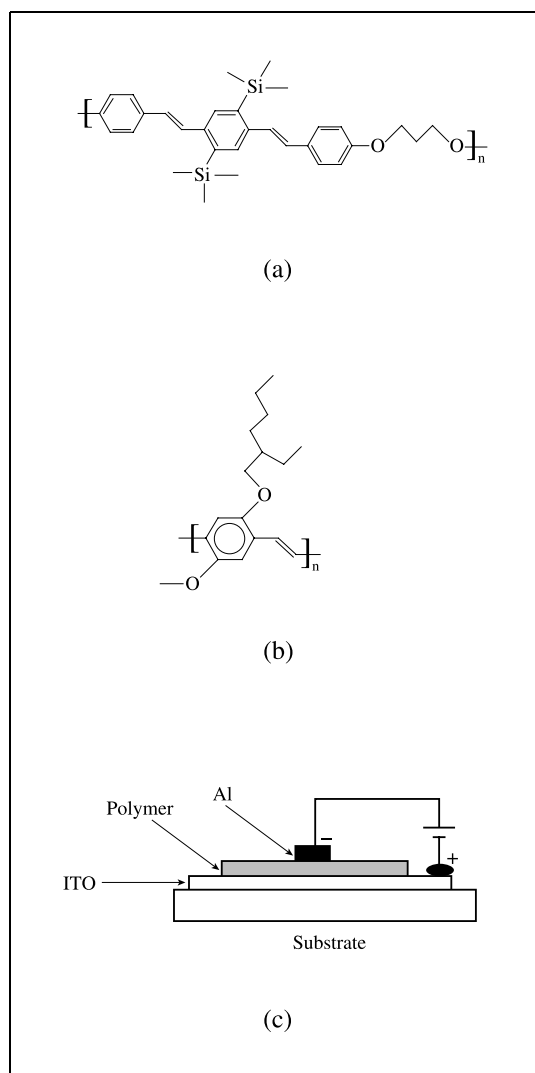


Fig. 1. Chemical structures of the polymers used in this study. (a) PDSIPV, (b) MEH-PPV and (c) the fabricated device structures.

The polymer LEDs are constructed as the following. A polymer film with thickness of about 150 nm was obtained by spin coating the filtered polymer solution onto the substrates with indium tin oxide (ITO) electrode, which were precleaned by successive ultrasonic treatment for an hour in acetone and isopropyl alcohol and followed by drying with nitrogen gas, and then drying in a vacuum oven for several hours. Aluminum was vapor deposited as the cathode at a pressure below 4×10^{-6} Torr, yielding an active size of 5 mm diameter.

The PL spectra were obtained by excitation with ultraviolet light at 351 nm from Ar ion laser (Coherent Innova-305). Luminescence spectra measurements used a monochromator (ISA HR320) with a photomultiplier tube (PMT, Hammamatzu R955) as detector, and were recorded at 1 nm resolution by computer while applying direct current from the current/voltage source (Keithley 238).

Current - voltage (I - V) and light intensity - current (L - I) characteristics were measured using the current/voltage source (Keithley 238) and the optical power meter (Newport 835). The injected current was measured by the voltage supply while applying the bias and recorded by computer. At the same time, the emitted light was collected by a Si photodetector (Newport 818SL) placed in front of the device and recorded by the computer. Since the solid angle of light detection is very small, a great loss in the light detection is unavoidable. All the measurements were performed in air and at room temperature.

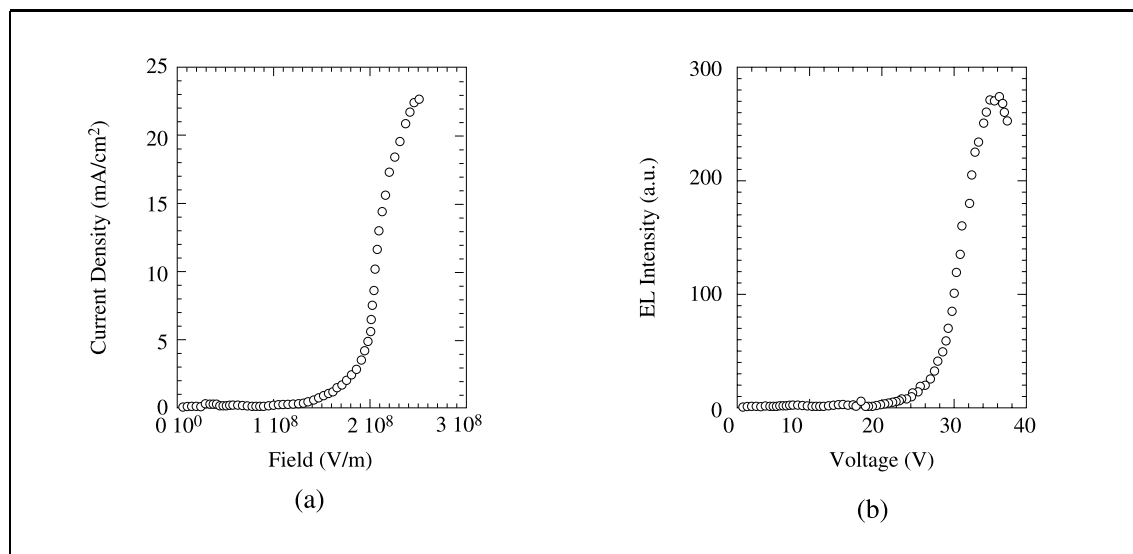


Fig. 2. (a) Current vs. electric field characteristics, (b) light intensity vs. applied voltages of the polymer light emitting devices using PDSIPV.

III. LIGHT EMITTING DEVICES USING THE POLYMER WITH REGULATED CONJUGATION LENGTHS

The polymer (PDSIPV) was soluble in organic solvents such as chloroform, dichloromethane, tetrahydrofuran, etc. Good-quality polymer thin films were obtained by spin coating the filtered polymer solutions without any further thermal processes.

The forward bias current was obtained when the transparent electrode was positively biased and the metal electrode was grounded [26]. Fig. 2 shows the current density vs. electric field characteristics and the voltage dependence of EL measured from a metal/polymer/metal device. The forward

current increased with increasing forward bias voltage and the reverse bias current remained small; the rectification ratios were approximately 10^3 . The emitted light became detectable at almost the same bias as those obtained from the I - V characteristics measurements. The light emitting device showed a high threshold voltage of about 20 V. The current densities at which the emission light became visible were less than 0.5 mA/cm^2 .

The dependence of the emission intensity on the injected current is shown in Fig. 3 in terms of the quantum efficiency without any corrections for the solid angle and the reflections due to differences in refractive indices. The intensity increased sharply with increasing injected current at low current regime, and then more slowly, tending to saturate with in-

creasing current. The shortening of the conjugation length results in a larger band gap so that the barrier height for the carrier injection may be higher. Small increases in the barrier height can produce higher threshold voltages and less major carrier injection into the polymer. Therefore, the higher the barriers for the carrier injection from the electrode into the polymers [27], the lower the quantum efficiency. It is hard to know accurately the external quantum efficiency, defined as number of photons generated per number of electrons injected, of the device since the collection of emission light is not perfect. However, we can estimate from the L-I characteristic curves that the quantum efficiencies are at least in the order of the $10^{-4} - 10^{-5}$ photons per electron.

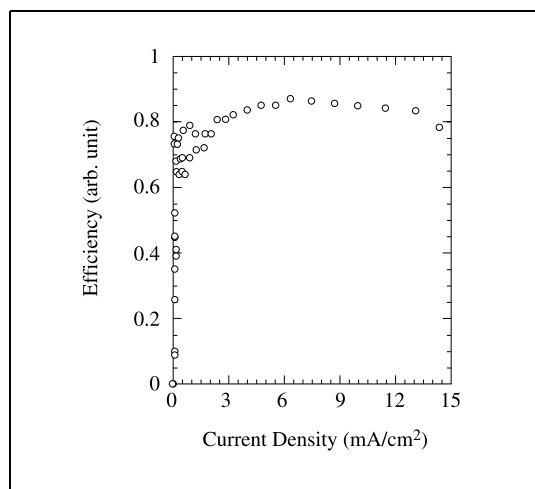


Fig. 3. Current density vs. efficiency curve for PDSIPV device.

Fig. 4 shows the room temperature EL spectrum of a thin polymer film in a device

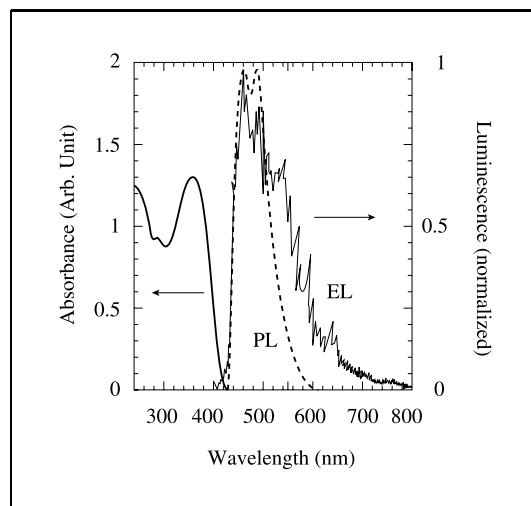


Fig. 4. Absorption (thick solid line), EL (thin solid line) and PL (dashed line) spectra for PDSIPV.

configuration together with the absorption and PL spectra. The EL light from the polymer shows a Stokes shift from the absorption peak. Stokes shift of the emission maximum from the absorption maximum indicates that the optical transitions for luminescence occur between the bands inside the $\pi-\pi^*$ energy gap. In the framework of the one-dimensional semiconductor band model [28], the PL arises from the radiative recombination of the charged polarons, whose energy levels are located within the band gap. The onset of the $\pi-\pi^*$ transition of the polymer in absorption spectrum is about 420 nm and this is blue shifted from that of PPV by 80 nm. The shorter conjugation length causes the blue shift. Both PL and EL spectra show a maximum at 470 nm and the EL spectrum is virtually identical with the PL spec-

trum indicating that the same excitations are involved in both cases. In the case of PL, the photoexcitation of the electron from the highest occupied molecular orbital (HOMO) to the LUMO is known to generate a singlet exciton-polaron, which in turn decays radiatively with emission of light [15]. The same species are formed in the case of EL, that is, the singlet excitons are formed in the polymer films by recombining the positive and negative polarons generated from the injected holes and electrons into the HOMO and the LUMO, respectively. The radiative decay from these singlet excitons is responsible for the EL [15].

IV. LIGHT EMITTING DEVICES USING THE POLYMER BLENDS

Recently, LEDs using polymer blends became a hot topic because the polymer blend might show only the best features of the component polymers or work as a kind of new material with new properties distinct from the properties of the component polymers. If two luminescent polymers are blended and there is a phase separation, each polymer may function individually as a small size diode and hence multicolored light may be generated [22]. For our blend system, atomic force microscope (AFM) as seen in Fig. 5 and scanning electron microscope (SEM) images showed no indication of phase separation or layer formation due

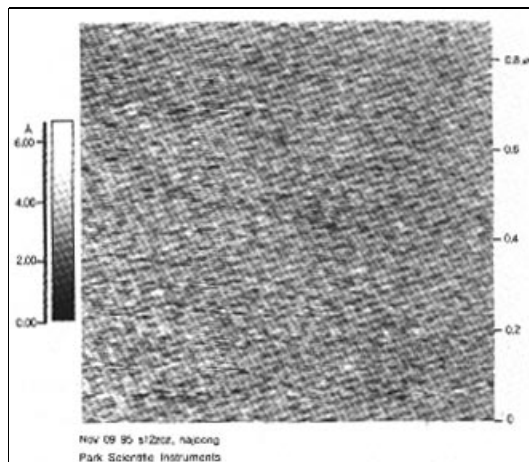


Fig. 5. Atomic force microscopic image of the blend system. Surface roughness is indicated by grey-scale. White spots correspond to the peak points of harsh surface.

to the immiscibility of two polymers, therefore the blend system in this study is considered to be homogeneous.

Table 1. The relative external quantum efficiencies of various blend systems.

sample#	Weight Ratio MEH-PPV:PDSIPV	Relative Quantum Efficiency
1 (MEH-PPV)	1 : 0	1
2 (M9B1)	9 : 1	10
3 (M1B15)	1 : 15	45
4 (M1B30)	1 : 30	150
5 (PDSIPV)	0 : 1	50
M1PVK9*	1 : 9(PVK)	1.6
M8PVK2*	8 : 2(PVK)	2.0
M1PMMA9*	1 : 9(PMMA)	7.5
M1PS9*	1 : 9(PS)	39

* Blend systems in nonluminescent polymers, PVK, PMMA, PS without PDSIPV.

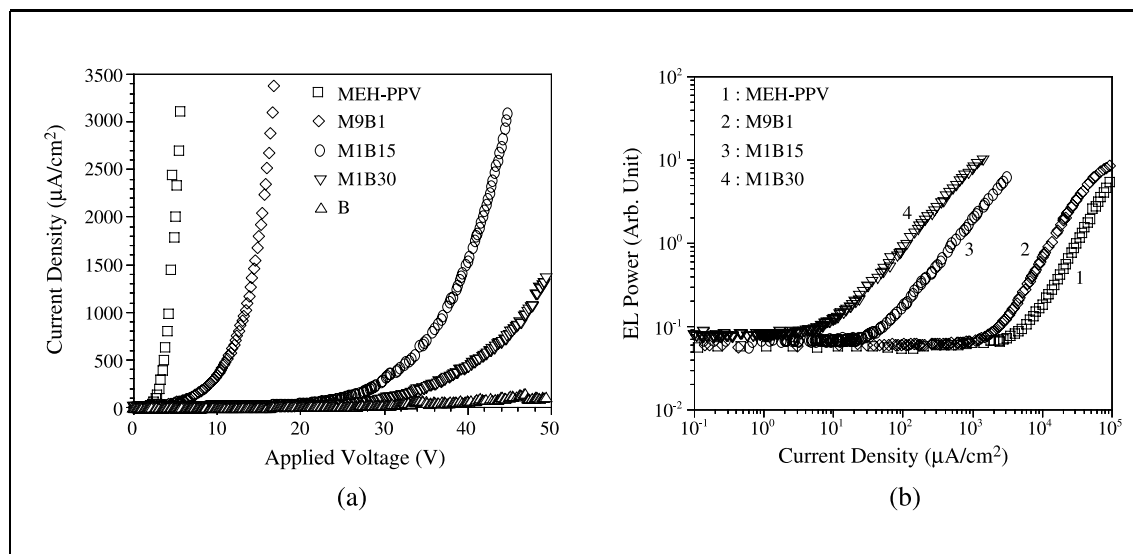


Fig. 6. (a) Current vs. applied voltage curve, (b) the log-log plot of light intensity vs. current density characteristic curves for various blend systems.

Current - voltage (I - V) and log-log plot of light intensity - current (L - I) characteristic curves of the blend systems are shown in Fig. 6. As the proportion of PDSIPV increases, the I - V characteristic behavior shows a shift from the MEH-PPV-like to the PDSIPV-like. The relative external quantum efficiencies obtained from L - I characteristics of several EL devices with various composition ratio of two polymers are shown in Table 1. The quantum efficiency increases with the composition ratio of PDSIPV reaching up to two order of magnitude larger than that of MEH-PPV. The device quantum efficiency is known to depend inversely on the energy barriers of minor carrier injection [27]. Since the I - V characteristics of EL devices are determined by the major carriers [27], the band offsets in our systems are related to the major carrier injection or the hole

injection.

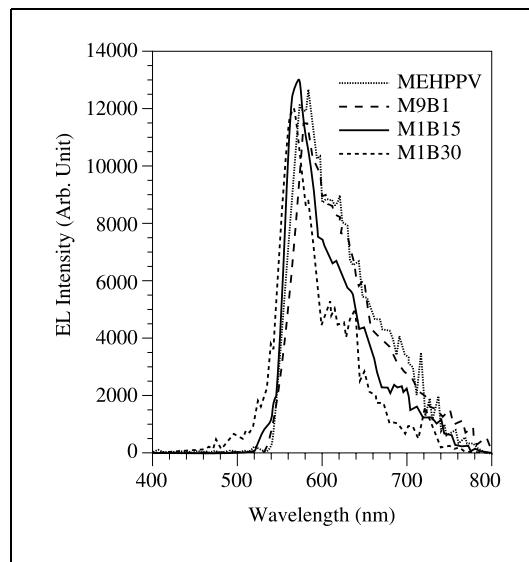


Fig. 7. EL spectra of the blend systems with various compositions.

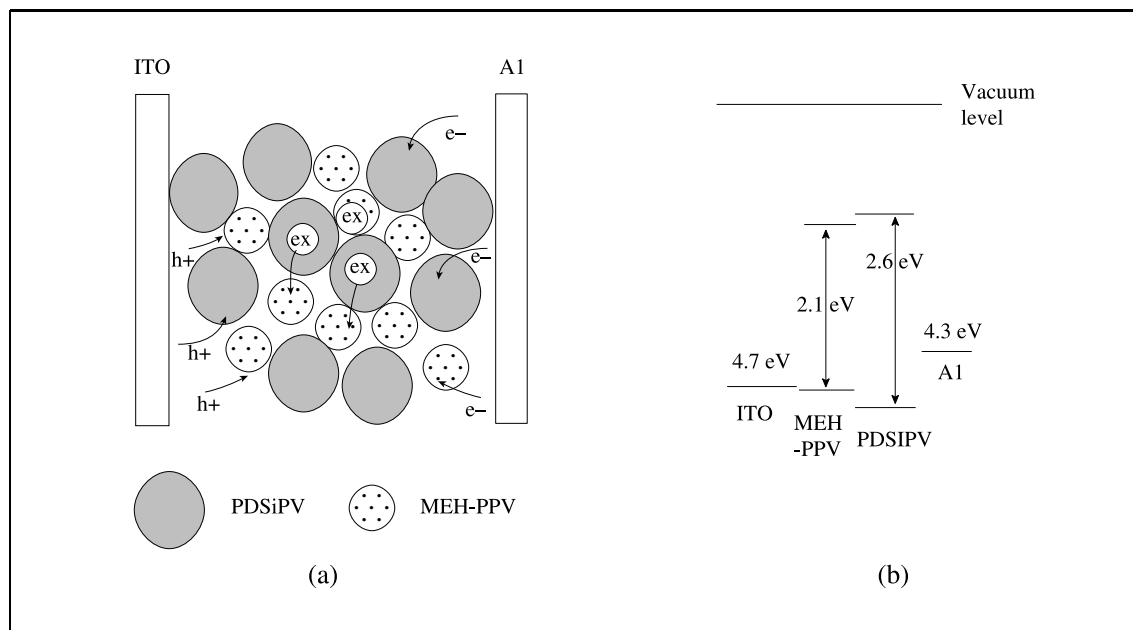


Fig. 8. (a) Schematic model diagram for the carriers behavior in the blend system. “ex” stands for singlet exciton. (b) energy levels of the polymers and the electrodes obtained by the Fowler-Nordheim plot and the absorption spectra.

EL spectra of the various blend compositions obtained at room temperature are shown in Fig. 7 [29]. Even when PDSiPV which emits with an emission maximum of 470 nm is in the higher proportion, only emission from MEH-PPV is observed. On the other hand, the absorption spectra show two absorption peaks located at 350 nm and 540 nm corresponding to PDSiPV and MEH-PPV, respectively. When we compare the peak positions in the EL spectra of the blend system with that of pure MEH-PPV, there is little shift in the peak position indicating no chain conformation or aggregation of MEH-PPV in PDSiPV, consistent with AFM and SEM results. EL intensities of MEH-PPV increased with the proportion of PDSiPV. This indicates that PDSiPV functions

as a polymer matrix enhancing the quantum efficiency without its own emission.

Based on the trends of the external quantum efficiencies, the device characteristics and luminescent spectra described above, the luminescence behavior in the blend system is interpreted as follows. The electrons and holes are injected into blend systems from cathode and anode, respectively, and move toward opposite electrodes. The carriers are trapped in MEH-PPV due to efficient hole blocking by PDSiPV, since the band offset of PDSiPV for hole injection is larger than that of MEH-PPV which can be confirmed by Fowler-Nordheim plot. This hole blocking enhances the electron injection due to stronger space-charge field and results in the improvement of the quantum ef-

iciency. This carrier trapping in MEH-PPV causes the recombination of the carriers to be more probable and lengthens the lifetime of the excitons formed which are responsible for EL. Any such excitons formed in PDSIPV are to be transferred into the MEH-PPV, since there is only a peak corresponding to emission from MEH-PPV in both the EL and PL spectra. The schematic diagram for this interpretation is shown in Fig. 8. Band offsets and band gaps were determined by Fowler-Nordheim plot and absorption spectra respectively, and the band offset of PDSIPV is greater than that of MEH-PPV by about 0.3 eV. Since I - V characteristics are dominated by major carrier (here hole) injection process [27], the band offset corresponds mainly to the difference between HOMO of the polymer and Fermi level of ITO. As the concentration of PDSIPV increases, this hole blocking and trapping of carriers becomes more efficient and more excitons formed in PDSIPV are transferred to MEH-PPV. This was confirmed by the results of time-resolved PL experiments [30], which show longer radiative lifetime for the blend system with larger composition of PDSIPV.

The dilution effect in the blend system is also effective for confining the singlet-excitons in MEH-PPV because the dilution effect reduces interactions between the MEH-PPV chains, resulting in the additive enhancement of the quantum efficiency. The increase of quantum efficiency due to dilution effect can be obtained from the blend systems composed of the luminescent polymer with non-



Fig. 9. Illumination from the flexible patterned EL device with bending. The illuminating pattern shows distortion.

luminescent polymers (see Table 1).

By using the blend system with the enhanced quantum efficiency, a flexible EL device is fabricated. A flexible LED was first reported by Heeger *et al.* using three different polymers, that is, a polymer substrate coated by anodic polyaniline and the emissive polymer [31]. In our case, the ITO electrode on the plastic substrate is patterned, the polymer blends are spin coated and finally Al electrode is vacuum deposited. Fig. 9 shows the emission from the patterned flexible EL device fabricated using the polymer blend. The device was forced to bend so that the illuminating pattern shows distortion. Consequently, the pattern in the bent device looked smaller than that of the device without bending.

V. CONCLUSION

Blue electroluminescent devices have been fabricated using a PPV derivative with a well-defined conjugation length backbone. The trimethylsilyl substituents are attached on the central benzene ring in the conjugated segment. The trimethylsilyl substituted polymer with trimethylsilyl substituents has good solubility and shows bright blue EL. The EL spectra are similar to the PL spectra indicating the origins of the light emission in both cases are the same. The devices show typical diode characteristics with high threshold voltage but low current density. A small increase in the barrier height and non-Ohmic contact between the polymer and the electrode for the injection of major carriers may result in the high threshold voltage. The efficiencies are still low, but may be improved by packaging the device under an oxygen-free environment and using a low work function metal electrode as a cathode.

The device characteristics of blend system with various proportions of two different band gap polymers have been studied. Only EL from MEH-PPV was observed with negligible luminescence from PDSIPV. A quantum efficiency about two order of magnitude larger than that of pure MEH-PPV was obtained for the polymer blend system. The observation of high quantum efficiency was interpreted as being due to the hole blocking and exciton transfer behavior of the matrix polymer, PDSIPV.

ACKNOWLEDGEMENT

The authors would like to thank Prof. H.-K. Shim, Dr. D.-H. Hwang, and Mr. I.-N. Kang at KAIST for synthesis of polymers and Dr. J.-J. Kim and Dr. B.-S. Yoo for their helpful discussion. This work was supported by grants from Ministry of Information and Communication, and Korea Telecom.

REFERENCES

- [1] C. W. Tang, and S. A. VanSlyke, "Organic electroluminescent diodes," *Appl. Phys. Lett.*, vol. 51, pp. 913-915, 1987.
- [2] J. H. Burroughes, D. D. C. Bradley, A. R. Brown, R. N. Marks, K. MacKay, R. H. Friend, P. L. Burn, and A. B. Holmes, "Light-emitting diodes based on conjugated polymers," *Nature*, vol. 347, pp. 539-541, 1990.
- [3] T. Zyung, D.-H. Hwang, H.-K. Shim, J.-J. Kim, and W.-Y. Hwang, "Electroluminescence from poly(p-phenylenevinylene) with monoalkoxy substituent on the aromatic ring," *Synth. Metals*, vol. 71, pp. 2167-2169, 1995.
- [4] D. Braun, and A. J. Heeger, "Visible light emission from semiconducting polymer diodes," *Appl. Phys. Lett.*, vol. 58, pp. 1982-1984, 1991.
- [5] Y. Ohmori, M. Uchida, K. Muro, and Y. Yoshino, "Blue electroluminescent diodes utilizing poly(alkylfluorene)," *Jpn. J. Appl. Phys.*, vol. 30, L1941-L1943, 1991.
- [6] G. Grem, G. Leditzky, B. Ulrich, and G. Leising, "Realization of a blue-light-emitting devices using poly(p-phenylene)," *Adv. Mater.*, vol. 4, pp. 36-37, 1992.
- [7] J. Kido, K. Hongawa, K. Okuyama, and K. Nagai, "Bright blue electroluminescence from poly(N-vinylcarbazole)," *Appl. Phys. Lett.*, vol. 63, pp.

- 2627-2629, 1993.
- [8] C. Hosokawa, N. Kawasaki, S. Sakamoto, and T. Kusumoto, "Bright blue electroluminescence from hole transporting polycarbonate," *Appl. Phys. Lett.*, vol. 61, pp. 2503-2505, 1992.
- [9] C. Zhang, H. von Seggern, K. Pakbaz, B. Kraabel, H.-W. Schmidt, and A. J. Heeger, "Blue electroluminescent diodes utilizing blend of poly(p-phenylphenylene vinylene) in poly(9-vinylcarbazole)," *Synth. Metals*, vol. 62, pp. 35-40, 1994.
- [10] W. Tachelet, S. Jacobs, H. Ndayikengurukiye, H. J. Geise, and J. Gruner, "Blue electroluminescent devices with high quantum efficiency from alkoxy-substituted poly(p-phenylenevinylene)-trimers in a polystyrene matrix," *Appl. Phys. Lett.*, vol. 64, pp. 2364-2366, 1994.
- [11] I. Sokolik, Z. Yang, F. E. Karasz, and D. C. Morton, "Blue-light electroluminescence from p-phenylene vinylene-based copolymers," *J. Appl. Phys.*, vol. 74, pp. 3584-3586, 1993.
- [12] Z. Yang, F. E. Karasz, and H. J. Geise, "Intrinsically soluble copolymers with well-defined alternating substituted p-phenylenevinylene and ethylene oxide blocks," *Macromolecules*, vol. 26, pp. 6570-6575, 1993.
- [13] P. L. Burn, A. B. Holmes, A. Kraft, D. D. C. Bradley, A. R. Brown, R. H. Friend, and R. W. Gymer, "Chemical tuning of electroluminescent copolymers to improve emission efficiencies and allow patterning," *Nature*, vol. 356, pp. 47-49, 1992.
- [14] T. Zyung, D.-H. Hwang, I.-N. Kang, and H.-K. Shim, "Observation of new wavelength electroluminescence from multilayer structure device using poly(p-phenylenevinylene) derivative," *SPIE*, vol. 2528, pp. 89-93, 1995.
- [15] A. B. Holmes, D. D. C. Bradley, A. R. Brown, P. L. Burn, J. H. Burroughes, R. H. Friend, N. C. Greenham, R. W. Gymer, D. A. Halliday, R. W. Jackson, A. Kraft, J. H. F. Martens, K. Pichler, and I. D. W. Samuel, "Photoluminescence and electroluminescence in conjugated polymeric systems," *Synth. Metals*, vol. 55-57, pp. 4031-4040, 1993.
- [16] N. C. Greenham, S. C. Moratti, D. D. C. Bradley, R. H. Friend, and A. B. Holmes, "Efficient light-emitting diodes based on polymers with high electron affinities," *Nature*, vol. 365, pp. 628-630, 1993.
- [17] Y. Ohmori, M. Uchida, C. Morishima, A. Fujii, and K. Yoshino, "Enhancement of emission efficiency in electroluminescent diode utilizing vapor-deposited poly(alkylfluorene)," *Jpn. J. Appl. Phys.*, vol. 32, pp. L1663-1666, 1993.
- [18] S. Aratani, C. Zhang, K. Pakbaz, S. Hoyer, F. Wudl, and A. J. Heeger, "Improved efficiency in polymer light-emitting diodes using air-stable electrodes," *J. Electron. Mater.*, vol. 22, pp. 745-749, 1993.
- [19] H. Nishino, G. Yu, A. J. Heeger, T.-A. Chen, and R. D. Rieke, "Electroluminescence from blend films of poly(3-hexylthiophene) and poly(N-vinylcarbazole)," *Synth. Metals*, vol. 68, pp. 243-247, 1995.
- [20] Z. Hu, Y. Yang, and F. E. Karasz, "Electroluminescence of pure poly(N-vinylcarbazole) and its blend within multiblock copolymer," *J. Appl. Phys.*, vol. 72, pp. 2419-2422, 1993.
- [21] I. D. Parker, Q. Pei, and M. Marrocco, "Efficient blue electroluminescence from a fluorinated polyquinoline," *Appl. Phys. Lett.*, vol. 65, pp. 1272-1274, 1994.
- [22] O. Inganäs, M. Berggren, M. R. Andersson, G. Gustafsson, T. Hjertberg, O. Wennerström, P. Dyreklev, and M. Granström, "Thiophene polymers in light emitting diodes: Making multicolor devices," *Synth. Metals*, vol. 71, pp. 2121-2124, 1995.
- [23] G. Yu, H. Nishino, A. J. Heeger, T.-A. Chen, and R. D. Rieke, "Enhanced electroluminescence from semiconducting polymer blends," *Synth. Metals*, vol. 72, pp. 249-253, 1995.

- [24] M. Yoshida, K. Yoshimoto, T. Akashi, M. Uchida, T. Kawai, Y. Ohmori, T. Noguchi, T. Ohnishi, and K. Yoshino, "Electroluminescence in molecularly doped conducting polymer," *Synth. Metals*, vol. 71, pp. 2111-2112, 1995.
- [25] S. Hoger, J. J. McNamara, S. Schricker, and F. Wudl, "Novel silicone-substituted, soluble poly(p-phenylenevinylene)s: enlargement of the semiconductor bandgap," *Chem. Mater.*, vol. 6, pp.171-173, 1994.
- [26] T. Zyung, D.-H. Hwang, I.-N. Kang, H.-K. Shim, W.-Y. Hwang, and J.-J. Kim, "Novel blue electroluminescent polymers with well-defined conjugation length," *Chem. Mater.*, vol. 7, pp. 1499-1503, 1995.
- [27] I. D. Parker, "Carrier tunneling and device characteristics in polymer light-emitting diodes," *J. Appl. Phys.*, vol. 75, pp. 1656-1666, 1994.
- [28] D. D. C. Bradley and R. H. Friend, "Photoexcitations in poly(phenylenevinylene)," *J. Molec. Electron.*, vol. 5, pp. 19-24, 1989.
- [29] I.-N. Kang, D.-H. Hwang, H.-K. Shim, T. Zyung, and J.-J. Kim, "Highly improved quantum efficiency in blend polymer LEDs," *Macromolecules*, vol. 29, pp. 165-169, 1996.
- [30] J.-I. Lee, I.-N. Kang, D.-H. Hwang, H.-K. Shim, S.C. Jeoung and D. Kim, "Energy transfer in the blend of electroluminescent conjugated polymers," *Chem. Mater.*, in press.
- [31] G. Gustafsson, Y. Cao, G. M. Treacy, F. Klavetter, N. Colaneri, and A. J. Heeger, "Flexible light emitting diode," *Nature*, vol. 357, pp. 477, 1992.

Taehyoung Zyung graduated Seoul National University with B.S. degree in chemical education in 1977 and received Ph.D. degree in physical chemistry from Texas Tech University in 1986. He had worked on polymer chemistry at Korea Institute of Science and Technology from 1978 to 1981 after military service. During 1986 to 1989, he joined the ultrafast phenomena research group at University of Illinois at Urbana-Champaign as a postdoctoral research associate. He returned to Korea in 1989 to join ETRI and had worked on the linear and nonlinear optical properties of semiconductors and polymers. His current research interests include the optoelectronics of the polymers, optical properties of conducting polymers, and molecular engineering.

Sang-Don Jung received the B.S. degree in chemical engineering from Soongjeon University, Seoul, Korea in 1984 and the M.S. and Ph.D. degrees in chemical engineering from Seoul National University in 1986 and 1993, respectively. In 1986, he was with Korea Advanced Institute of Science and Technology. Since 1989, he has been with Research Department of ETRI, where he is currently a Senior Researcher. His research interests include the molecular engineering using ultra thin Langmuir-Blodgett films, gradient-index optics, and polymer electroluminescence devices.