

# Synthesis, Electroluminescence, and Photovoltaic Cells of New Vinylene-Copolymers with 4-(Anthracene-10-yl)-2,6-Diphenylpyridine Segments

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**ABSTRACT:** Three new soluble vinylene-copolymers **F**, **C**, and **P** that contain 4-(anthracene-10-yl)-2,6-diphenylpyridine as common segment and fluorene, carbazole, or phenylene, respectively, as alternating segment were prepared by Heck coupling. The glass transition temperature was high for **F** and **C** (110 and 117°C), whereas was lower than 25°C for **P**. The polymers were stable up to ~ 300°C. They emitted blue–green light with maximum located at wavelength of 456–550 nm, which was of the order **F** < **C** < **P**. The photoluminescence quantum efficiency in THF solution was ~ 30% for **F** and **P** and only 5% for **C**. All three copolymers were used as active layers for polymer light emitting diodes (PLEDs) and organic photovoltaic cells. The double PLEDs with configuration of indium-tin oxide

(ITO)/poly(ethylenedioxythiophene (PEDOT) : poly(styrenesulfonate)(PSS)/Copolymer **F**, **C**, or **P**/TPBI(1,3,5-tris(2-*N*-phenylbenzimidazolyl)benzene)/Ca/Al were fabricated. Copolymer **P** emitted green light with maximum brightness of 28 cd/m<sup>2</sup> and a current yield of 0.85 cd/A. Organic photovoltaics with the configuration of ITO/PEDOT : PSS/Copolymer and [6,6]-phenyl-C61-butyric acid methyl ester blend (1 : 1) /Ca/Al were also fabricated. Copolymer **P** showed the highest power conversion efficiency of 0.034%. © 2009 Wiley Periodicals, Inc. *J Appl Polym Sci* 115: 731–739, 2010

**Key words:** vinylene-copolymers; conjugated polymers; Heck coupling; anthracene; pyridine; photophysics; light-emitting diodes; photovoltaic cells

## INTRODUCTION

Opto-electronic devices that make use of organic materials are becoming increasingly desirable for a number of reasons. Many of the materials used to make such devices are relatively inexpensive, so organic opto-electronic devices have the potential for cost advantages over inorganic devices. In addition, the inherent properties of organic materials, such as their flexibility, may make them well suited for particular applications such as fabrication on a flexible substrate. Examples of organic opto-electronic devices include light emitting devices (LEDs), organic transistors/phototransistors, organic photovoltaic cells, and organic photodetectors.<sup>1–5</sup> For LEDs, the organic materials may have performance advantages over conventional (i.e., inorganic) materials. For example, the wavelength at which an organic emissive layer emits light may generally be readily tuned with appropriate dopants. For organic transistors/phototransistors, the substrates upon which they are

constructed may be flexible, providing for broader applications in industry and commerce.

Among these organic materials, fluorene, and/or anthracene-based compounds have been regarded as excellent fluorescent materials because of their ability to achieve high thermal stability as well as high photoluminescence (PL) efficiency.<sup>6</sup> Fluorene and/or anthracene-based compounds, in particular, are often used as emitting materials in electroluminescent (EL) devices.<sup>7–16</sup> On the basis of the previous reports, promising low molecular weight emitter for use in LEDs should have an appropriate HOMO/LUMO band gap as compared with those of the electron- and hole-transporting materials, high PL quantum yield ( $\Phi_f$ ), good film-forming properties, and durability to heat during the vacuum deposition.<sup>17–19</sup> The  $\Phi_f$  is a major interest associated with the improvement of EL device efficiency, since the two properties are generally related.<sup>20</sup> With the aim of increasing PL efficiency, several approaches have been introduced. These include the attachment of strongly fluorescent units,<sup>21</sup> such as anthracene and fluorene to the molecular framework, the extension of  $\pi$ -conjugation,<sup>22,23</sup> and the combination of host-guest functions by energy transfer.<sup>24,25</sup> Recently, a conjugated diarylanthracene bearing two dihexyloxy substituted benzene rings has been used as donor

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material for solar cells.<sup>26</sup> Very recently, phenylenevinylene copolymers have been synthesized in our laboratory and used for photovoltaic cells.<sup>27,28</sup> Furthermore, a star-shaped molecule with triphenylamine as core and benzo[1,2,5]thiadiazol vinylene as arms has been synthesized and used as donor for bulk-heterojunction solar cells.<sup>29</sup> On the other hand, pyridine is a widely used structure for modification of conjugated polymers. Poly(*p*-pyridylvinylene) polymers have been extensively investigated and present the advantages of facile *n*-doping (high electron affinity) and of tuning their electro-optical properties by coordination of different guests to the lone pair of nitrogen atoms.<sup>30–36</sup>

This investigation describes the synthesis and characterization of a new series of vinylene-copolymers that contain the kinked structure of 4-(anthracene-10-yl)-2,6-diphenylpyridine as a common segment and fluorene, carbazole, or phenylene as alternating segment. The latter carried alkyl or alkoxy side groups, which enhanced the solubility of the copolymers. All copolymers were successfully prepared by Heck coupling. The photophysical, EL, and photovoltaic properties of the copolymers were investigated and correlated with their chemical structures.

## EXPERIMENTAL

### Characterization methods

IR spectra were recorded on a Perkin-Elmer 16PC FT-IR spectrometer with KBr pellets. <sup>1</sup>H-NMR (400 MHz) spectra were obtained using a Bruker spectrometer. Chemical shifts ( $\delta$  values) are given in parts per million with tetramethylsilane as an internal standard. UV-vis spectra were recorded on a Beckman DU-640 spectrometer with spectrograde THF. The PL spectra were obtained with a Perkin Elmer LS45 luminescence spectrometer. The PL spectra were recorded with the corresponding excitation maximum as the excitation wavelength. TGA was performed on a DuPont 990 thermal analyzer system. Ground samples of about 10 mg each were examined by TGA, and the weight loss comparisons were made between comparable specimens.

Dynamic TGA measurements were made at a heating rate of 20°C/min in atmospheres of N<sub>2</sub> at a flow rate of 60 cm<sup>3</sup>/min. Thermomechanical analysis (TMA) was recorded on a DuPont 943 TMA using a loaded penetration probe at a scan rate of 20°C/min in N<sub>2</sub> with a flow rate of 60 cm<sup>3</sup>/min. The TMA experiments were conducted at least in duplicate to ensure the accuracy of the results. The TMA specimens were pellets of 10 mm diameter and ~ 1 mm thickness prepared by pressing powder of sample for 3 min under 8 kp/cm<sup>2</sup> at ambient temperature. The  $T_g$  is assigned by the first inflection point in the

TMA curve, and it was obtained from the onset temperature of this transition during the second heating. Elemental analyses were carried out with a Carlo Erba model EA1108 analyzer.

To measure the PL quantum yields ( $\Phi_f$ ) degassed solutions of the copolymers in THF were prepared. The concentration was adjusted so that the absorbance of the solution would be lower than 0.1. The excitation was performed at the corresponding excitation maximum and a solution in 1M H<sub>2</sub>SO<sub>4</sub> of quinine sulfate, which has  $\Phi_f$  of 0.546 was used as a standard.

### Reagents and solvents

DMF was dried by distillation over CaH<sub>2</sub>. Triethylamine was purified by distillation over KOH. All other reagents and solvents were commercially purchased and were used as supplied.

### Preparation of starting materials

#### 4-(Anthracene-10-yl)-2,6-bis(4-bromophenyl)pyridine (**1**)

A mixture of 9-anthracaldehyde (1.00 g, 4.85 mmol), 4-bromoacetophenone (1.93 g, 9.70 mmol), CH<sub>3</sub>COONH<sub>4</sub> (27 g), and glacial acetic acid (30 mL) was refluxed for 20 h under N<sub>2</sub>. After cooling at room temperature the precipitate was filtered, washed with acetic acid 50%, then with water, and dried to afford compound **1** as an orange solid. It was recrystallized from ethanol (0.80 g, 29%, mp 135–137°C).

FT-IR (KBr, cm<sup>-1</sup>): 1658, 1594, 1394, 1352, 1264, 1210, 1174, 1068, 1004, 882, 842, 816, 732.

<sup>1</sup>H-NMR (CDCl<sub>3</sub>, ppm): 8.49 (s, 1H, aromatic at position 6 of anthracene); 8.34–8.31 (m, 4H, aromatic *meta* to bromine); 8.13–8.04 (m, 4H, aromatic at positions 1, 4, 6, 9 of anthracene); 7.69 (m, 2H, aromatic *meta* to nitrogen); 7.53–7.41 (m, 8H, other aromatic).

Anal. Calcd. for C<sub>31</sub>H<sub>19</sub>Br<sub>2</sub>N: C, 65.86; H, 3.39; N, 2.48. Found: C, 64.97; H, 3.46; N, 2.50.

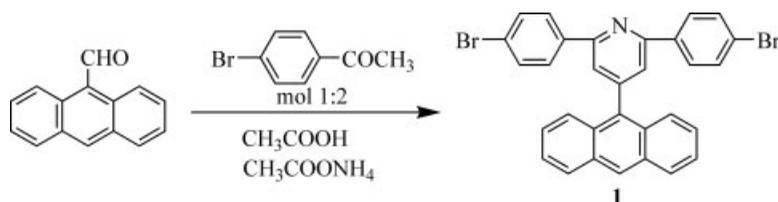
#### 9,9-Dihexyl-2,7-divinylfluorene (**2**)

This compound was prepared by Stille coupling reaction<sup>37</sup> of 9,9-dihexyl-2,7-dibromofluorene with tributylvinyltin in the presence of PdCl<sub>2</sub>(PPh<sub>3</sub>)<sub>2</sub> as catalyst and a few crystals of 2,6-di-*tert*-butylphenol as polymerization inhibitor utilizing toluene as reaction medium. The synthesis and characterization of **2** has been described in our previous publication.<sup>38</sup>

#### 9-Hexyl-3,6-divinylcarbazole (**3**)

This compound was similarly prepared by Stille coupling reaction<sup>37</sup> of 9-hexyl-3,6-dibromocarbazole





**Scheme 1** Synthesis of the key-dibromide **1**.

7.54–7.50 (m, 14H, aromatic “e”); 7.30–7.18 (m, 4H, olefinic “f”); 4.31 (m, 2H, aliphatic “d”); 1.89 (m, 2H, aliphatic “c”); 1.40–1.25 (m, 6H, aliphatic “b”); 0.87 (t,  $J = 0.016$  Hz, 3H, aliphatic “a”).

Anal. Calcd. for  $(C_{53}H_{42}N_2)_n$ : C, 90.05; H, 5.99; N, 3.96. Found: C, 89.34; H, 6.12; N, 4.07.

Copolymer **P** was similarly prepared in 60% yield from the reaction of **1** with **4**.

FT-IR (KBr,  $cm^{-1}$ ): 3046, 2920, 2850, 1656, 1594, 1460, 1416, 1384, 1260, 1200, 1012, 966, 844, 730.

$^1H$ -NMR ( $CDCl_3$ , ppm) [Fig. 1(c)]: 8.49 (s, 1H, aromatic “k”); 8.39–8.25 (m, 4H, aromatic “i”); 8.15–8.05 (m, 4H, aromatic “h”); 7.85–7.51 (m, 10H, aromatic “g”); 7.43–7.30 (m, 4H, olefinic “f”); 7.17 (m, 2H, aromatic “e”); 4.07 (m, 4H, aliphatic “d”); 1.87 (m, 4H, aliphatic “c”); 1.25 (m, 36H, aliphatic “b”); 0.84 (t,  $J = 0.016$  Hz, 6H, aliphatic “a”).

Anal. Calcd. for  $(C_{65}H_{75}NO_2)_n$ : C, 86.52; H, 8.38; N, 1.55. Found: C, 85.70; H, 8.31; N, 1.61.

### Device fabrication

Double- or triple-layer devices were fabricated as sandwich structures between calcium (Ca) cathodes and indium-tin oxide (ITO) anodes. ITO-coated glass substrates were cleaned sequentially in ultrasonic baths of detergent, 2-propanol/deionized water (1 : 1 volume) mixture, toluene, de-ionized water, and acetone. A 50 nm-thick hole injection layer of poly(ethylenedioxythiophene) doped with poly(styrene-sulfonate) (PEDOT : PSS) was spin-coated on top of ITO from a 0.7 wt % dispersion in water and dried at 150°C for 1 h in a vacuum. For polymer light emitting diodes (PLED) devices, thin films of synthesized copolymers were spin-coated from toluene solutions onto the PEDOT layer and dried at 50°C overnight in a vacuum. The thickness of the active layer was ca. 60 nm. 1,3,5-tris(2-*N*-phenylbenzimidazolyl)benzene (TPBI) was then deposited onto the copolymer layer by thermal evaporation.

For organic solar cells, [6,6]-phenyl-C61-butyric acid methyl ester (PCBM) was blended with the synthesized copolymer (1 : 1 in wt/wt ratio), dissolved in chlorobenzene, and cast into thin film by spin-coating. In this case TPBI was left out. Finally, 35 nm Ca and 100 nm Al electrodes were made through a shadow mask onto the copolymer films by thermal evaporation using an AUTO 306 vacuum

coater (BOC Edwards, Wilmington, MA). Evaporations were carried out typically at base pressures lower than  $2 \times 10^{-6}$  Torr. The active area of each EL device was 4 mm<sup>2</sup>. The PLED characterization was carried out by a Keithley 2400 source-measure unit. The brightness was further measured using a Photo Research PR650 spectrophotometer.

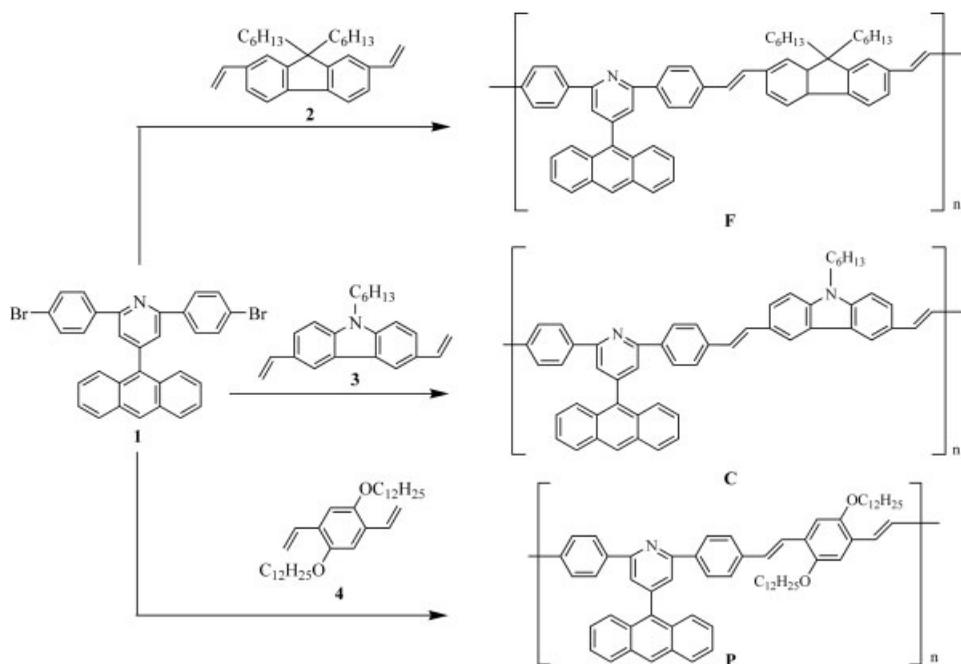
## RESULTS AND DISCUSSION

### Synthesis and characterization

Three new vinylene-copolymers **F**, **C**, and **P** were synthesized by Heck coupling<sup>41</sup> utilizing the key-dibromide **1** as starting material. This dibromide was successfully prepared from the reaction of 9-anthracaldehyde with 4-bromoacetophenone in the presence of glacial acetic acid and large excess of ammonium acetate (Scheme 1). It was characterized by FT-IT and  $^1H$ -NMR spectroscopy (see experimental section).

Copolymers **F**, **C**, and **P** were synthesized by reacting dibromide **1** with divinyls **2**, **3**, and **4**, respectively, in a molar ratio 1 : 1 according to Scheme 2. These reactions took place in DMF and  $Pd(OAc)_2$  and  $Et_3N$  were used as catalyst and acid scavenger, respectively. The copolymers were purified by dissolving in THF and precipitating into methanol. The preparation yields were 56–62%. The number average molecular weights ( $M_n$ ) of the copolymers were 7200–11,500 with a polydispersity of 1.6–2.1 (Table I). All copolymers were soluble in common organic solvents such as THF, chloroform, and toluene due to the alkyl or alkoxy side groups.

The FT-IR and  $^1H$ -NMR spectra of the copolymers were consistent with their chemical structures. Specifically, the copolymers showed common absorption bands which for the **F** appeared at 3026, 1654, 1596, 1540, 1460, 732 (aromatic and pyridine); 2922, 2850 (C–H stretching of aliphatic chains) and 960  $cm^{-1}$  (trans olefinic bond). Besides these absorptions, **P** displayed absorptions at 1200 and 1012  $cm^{-1}$  associated ether bond. Figure 1 presents the  $^1H$ -NMR spectra of the copolymers along with the assignments of peaks. Again, these spectra showed common resonances which for **F** [Fig. 1(a)] appeared at 8.49, 8.39–8.26, 8.19–8.05, 7.62–7.41 ppm assigned to the aromatic protons of the 4-(anthracene-10-yl)-2,6-



Scheme 2 Synthesis of copolymers F, C, and P.

bis(4-bromophenyl)pyridine segment labeled “k,” “i,” “h,” and “g,” respectively. The olefinic protons resonated at 7.43–7.16 ppm, and they were overlapped with the chloroform peak. Moreover, the aliphatic protons gave multiplets at the region of 4.31–0.76 ppm. Finally, all  $^1\text{H-NMR}$  spectra showed small signals between 5 and 6 ppm from the protons  $\text{CH}_2=\text{CH}-$  of the vinyl end groups.

Thermal characteristics of the copolymers were studied by TGA and TMA (Fig. 2, Table I). No weight loss was observed up to about 300°C for all copolymers. F and C displayed similar TGA and TMA traces with almost identical decomposition temperature ( $T_d$ ) at  $\sim 393^\circ\text{C}$  and char yield ( $Y_c$ ) of  $\sim 63\%$ . These copolymers had glass transition temperature ( $T_g$ ) of 110 and  $117^\circ\text{C}$ , respectively. The  $T_g$  was obtained from the onset temperature of the baseline shift recorded during the second heating of

the TMA thermogram (insert of Fig. 2) when a penetration probe was used. Copolymer P showed a slightly lower thermal stability ( $T_d = 370^\circ\text{C}$ ,  $Y_c = 58\%$ ) and much lower  $T_g$  ( $<25^\circ\text{C}$ ), which could not be exactly determined by the TMA method. The two dodecyloxy side groups and the less compact phenylene unit of the P reduced its thermal stability and rigidity.

### Photophysical properties

Figures 3 and 4 present the normalized UV-vis absorption spectra and PL emission spectra of copolymers in both dilute ( $10^{-5}$  M) THF solution and thin films. The latter were prepared from THF

TABLE I  
Molecular Weights and Thermal Characteristics of Copolymers

Copolymer	$M_n^a$	$M_w/M_n^a$	$T_d^b$ ( $^\circ\text{C}$ )	$Y_c^c$ (%)	$T_g^d$ ( $^\circ\text{C}$ )
F	7200	1.6	393	63	110
C	11,500	2.1	392	64	117
P	8400	1.8	370	58	<sup>e</sup>

<sup>a</sup> Molecular weights determined by GPC using polystyrene standards.

<sup>b</sup> Decomposition temperature corresponding to 5% weight loss in  $\text{N}_2$  determined by TGA.

<sup>c</sup> Char yield at  $800^\circ\text{C}$  in  $\text{N}_2$ , determined by TGA.

<sup>d</sup> Glass transition temperature determined by TMA.

<sup>e</sup> The  $T_g$  was lower than  $25^\circ\text{C}$ .

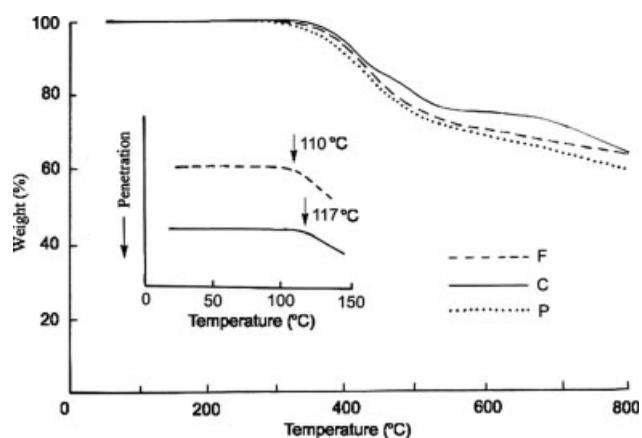


Figure 2 TGA thermograms of copolymers in  $\text{N}_2$ . The insert shows the TMA traces of copolymers. Conditions:  $\text{N}_2$  flow,  $60\text{ cm}^3/\text{min}$ ; heating rate,  $20^\circ\text{C}/\text{min}$ .

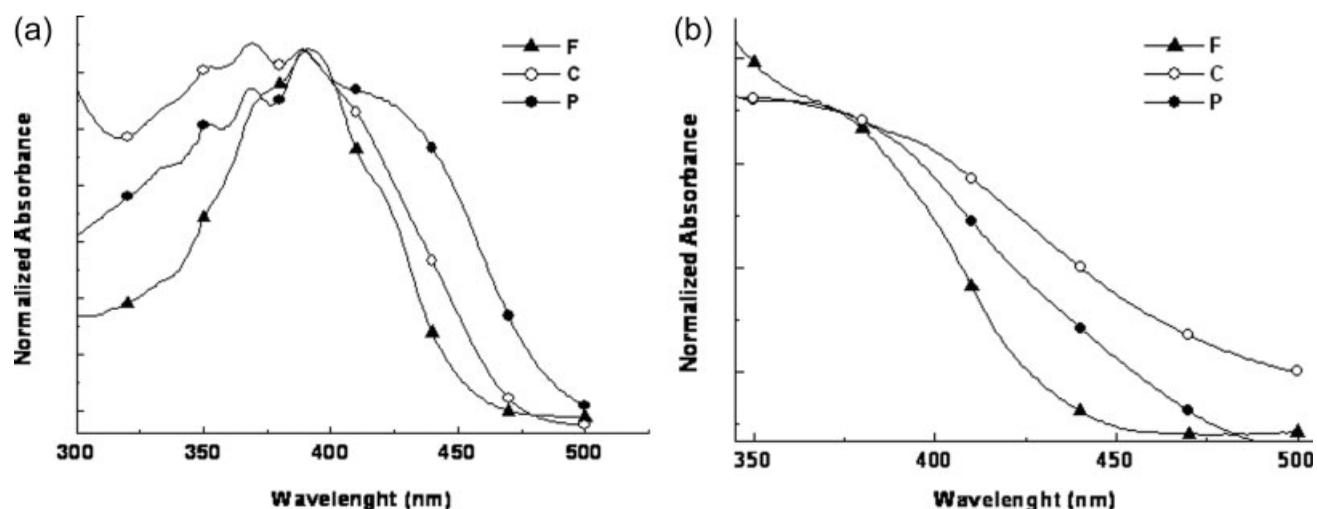


Figure 3 Normalized UV-vis absorption spectra of copolymers in  $10^{-5}$  M THF solution (a) and thin film (b).

solution on quartz substrate by spin casting. All photophysical characteristics are summarized in Table II.

The absorption spectra of the copolymers in solution [Fig. 3(a)] showed more than one peaks with absolute maximum ( $\lambda_{a,max}$ ) at 390 nm corresponding to the  $\pi$ - $\pi^*$  transition of the polymer backbone. They are wide and cover a large part of the ultraviolet and visible region approximately from 300 to 500 nm owing to the presence of the anthracene segment. This feature bodes well for the photovoltaic properties of the copolymers since they depend critically on their absorption. The absorption onset located at 450, 468, and 477 nm for the copolymers F, C, and P, respectively, from which the respective optical band gaps ( $E_g$ 's) in solution were determined to be 2.76, 2.65, and 2.60 eV (Table II). The absorp-

tion spectra of copolymer thin films [Fig. 3(b)] were very broad and therefore their  $\lambda_{a,max}$  and  $E_g$ 's could not be precisely determined. These values of  $E_g$ 's are in agreement with those (2.61–2.66 eV) of related poly(phenylenevinylene) derivatives containing *m*-terphenyl or 2,6-diphenylpyridine kinked units along the main chain.<sup>36</sup>

All copolymers emitted blue-green light by photoexcitation at the corresponding maximum excitation wavelength. The emission maximum ( $\lambda_{f,max}$ ) followed the trend  $F < C < P$  and was at the region of 456–498 nm for solutions and 469–550 nm for thin films (Fig. 4, Table II). Thus, the color of the emitted light could be tuned by changing the chemical structure of the second moiety of the copolymers, namely by introducing fluorene, carbazole, or phenylene units. P showed the most red-shifted  $\lambda_{f,max}$  among

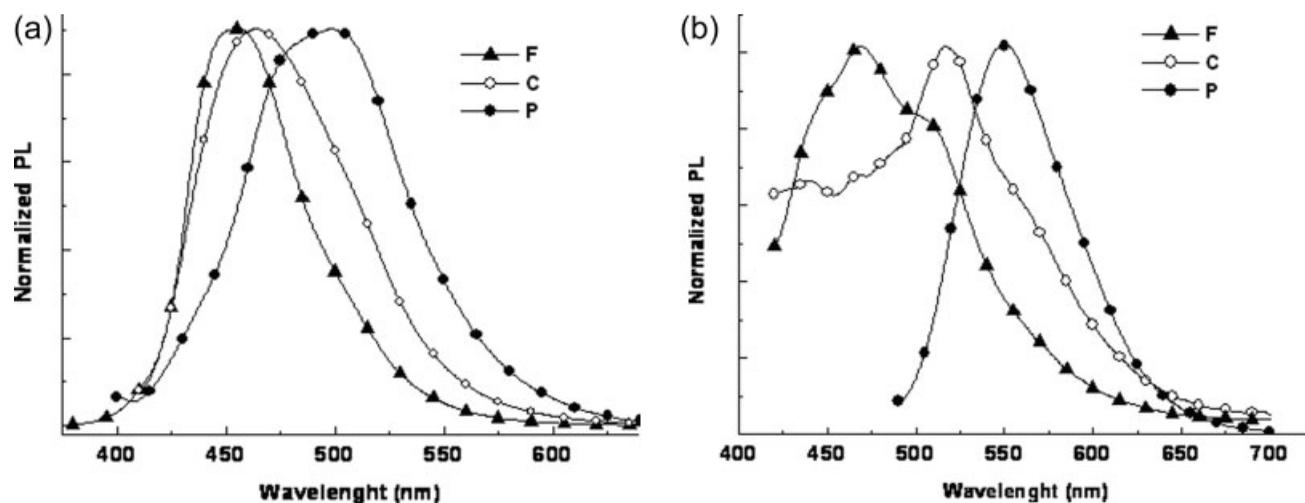


Figure 4 Normalized PL emission spectra of copolymers in  $10^{-5}$  M THF solution (a) and thin film (b). The PL emission spectra were recorded using as excitation wavelength the corresponding excitation maximum.

TABLE II  
Photophysical Properties of Copolymers

Copolymer	$\lambda_{a,max}^a$ in THF solution (nm)	$\lambda_{f,max}^b$ in THF solution (nm)	$\Phi_f^c$ in THF solution	$E_g^d$ (eV)	$\lambda_{a,max}^a$ in thin film (nm)	$\lambda_{f,max}^b$ in thin film (nm)
F	390	456	0.31	2.76	<sup>e</sup>	469 (507)
C	390	464	0.05	2.65	<sup>e</sup>	517
P	390 (423)	498	0.30	2.60	<sup>e</sup>	550

<sup>a</sup>  $\lambda_{a,max}$ : The absorption maxima from the UV-vis spectra in  $10^{-5}$  M THF solution or in thin film.

<sup>b</sup>  $\lambda_{f,max}$ : The PL emission maxima in  $10^{-5}$  M THF solution or in thin film.

<sup>c</sup>  $\Phi_f$ : PL quantum yield.

<sup>d</sup>  $E_g$ : The optical band gap calculated from the onset of solution absorption spectrum.

<sup>e</sup> The absorption maxima in thin film could not be determined due to the broadening of the spectra.

The PL emission spectra were recorded using as excitation wavelength the corresponding excitation maximum. Value in parenthesis exhibits a shoulder in the absorption or emission spectra.

the copolymers due to the presence of the electron-donating dodecyloxy side groups. Generally, the existence of the kinked structure of 4-(anthracene-10-yl)-2,6-bis(4-bromophenyl)pyridine in the copolymers disrupted the  $\pi$ -conjugation along their backbone. This feature has been well established in the literature with other related pyridine derivatives.<sup>36</sup>

The emission efficiency of the copolymers in solution was evaluated by determination<sup>42</sup> of their quantum yield ( $\Phi_f$ ) values relative to quinine sulfate (Table II). F and P showed almost same  $\Phi_f$  value of  $\sim 0.30$ , whereas C was significantly less photoluminescent with  $\Phi_f$  of 0.05. The existence of the carbazole unit in C, which has been believed to be low emission efficiency chromophore,<sup>43</sup> was responsible for this behavior. A  $\Phi_f$  value of 0.40–0.61 has been reported for related poly(phenylenevinylene) derivatives with *m*-terphenyl or 2,6-diphenylpyridine kinked units along the main chain, which have been prepared in our laboratory.<sup>36</sup> Upon comparing the  $\Phi_f$  values of these related poly(phenylenevinylene)s with those of the present copolymers, it seems that

the introduction of the anthracene instead of phenyl segment reduced the emission efficiency.

### PLED and photovoltaic performance

To investigate opto-electrical properties and application of synthesized copolymers, triple-layer light-emitting diodes with the configuration of ITO/PEDOT : PSS/copolymer/TPBI/Ca/Al were fabricated and characterized. TPBI was used as hole-blocking layer to further improve the device performance. Figure 5 shows the current density-voltage and luminescence-voltage characteristics of PLED devices using copolymers F, C, and P as the active layer. The device using F as active layer showed a maximum luminescence of 33  $\text{cd/m}^2$  at 16 V, with the maximum current density of 334  $\text{mA/cm}^2$ . Using C as the active layer, the maximum luminescence of the device reached 33  $\text{cd/m}^2$  at 11 V, with the maximum current density of 960  $\text{mA/cm}^2$ . For P, the maximum luminescence and current density obtained at 15 V were measured

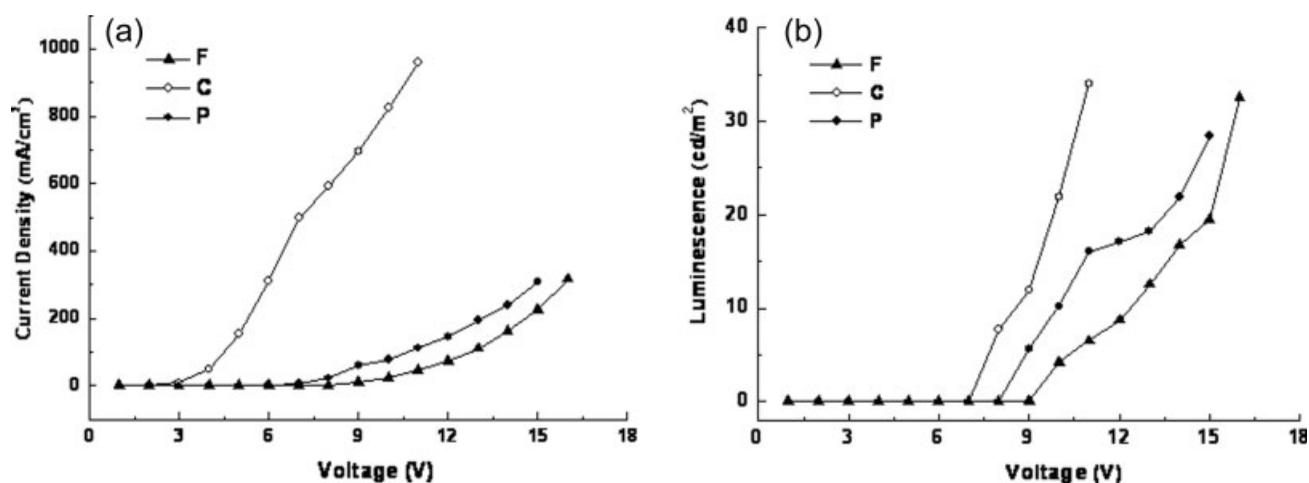


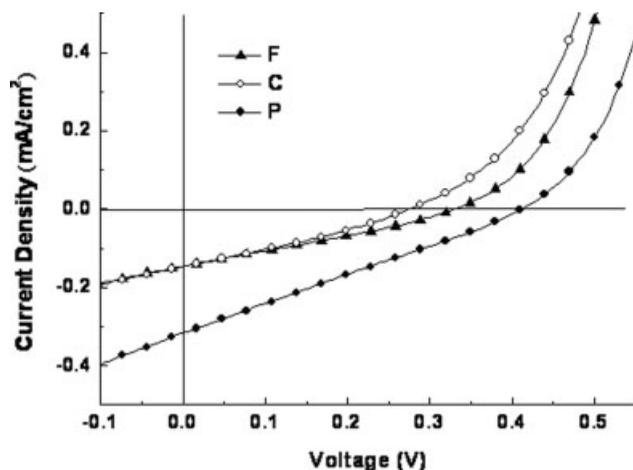
Figure 5 Current density-voltage (a) and luminescence-voltage (b) characteristics of PLED devices using copolymers F, C, and P as the active layer.

to be 28 cd/m<sup>2</sup> and 307 mA/cm<sup>2</sup>, respectively. The luminescent efficiency of three devices was calculated to be 0.97, 0.35, and 0.85 cd/A for copolymers **F**, **C**, and **P**, respectively. **C** showed the lowest luminescent efficiency among three copolymers, being in accordance with the observation of PL quantum yield measurement. The device performance of three synthesized copolymers was poor.

Organic solar cells with the configuration of ITO/PEDOT : PSS/copolymer+PCBM (1 : 1)/Ca/Al were also fabricated to evaluate the photovoltaic properties of the synthesized polymers. PCBM was typically added in organic solar cells as the electron-acceptor. Figure 6 shows the current density-voltage characteristics of three solar cell devices under standard AM 1.5G illumination. The open-circuit voltage (*V*<sub>oc</sub>), short-circuit current (*J*<sub>sc</sub>), fill factor (*FF*), and power conversion efficiency were summarized in Table III. It can be seen that three copolymers own similar *FF* value about 26–30%. Copolymer **P** showed the highest *V*<sub>oc</sub> and *J*<sub>sc</sub> values, which explain the best conversion efficiency among three solar cell devices. These preliminary photovoltaic results were obtained without any solvent screening, film thickness optimization, or postfabrication annealing of the devices.

## CONCLUSIONS

Starting from 4-(anthracene-10-yl)-2,6-bis(4-bromophenyl)pyridine three new vinylene-copolymers **F**, **C**, and **P** that contain fluorene, carbazole, or phenylene, respectively, as alternating segments were successfully prepared by Heck coupling. **F** and **C** showed higher thermal stability and glass transition temperature than **P**. All copolymers emitted blue-green light with emission maximum at 456–550 nm.



**Figure 6** Current density-voltage characteristics of organic solar cells using copolymers **F**, **C**, and **P** blended with PCBM (1 : 1) as the active layer under standard AM 1.5G illumination.

**TABLE III**  
Photovoltaic Properties of Solar Cells

Copolymer	<i>V</i> <sub>oc</sub> <sup>a</sup> (V)	<i>J</i> <sub>sc</sub> <sup>b</sup> (mA/cm <sup>2</sup> )	<i>FF</i> <sup>c</sup> (%)	PCE <sup>d</sup> (%)
<b>F</b>	0.331	0.193	29	0.014
<b>C</b>	0.276	0.192	30	0.012
<b>P</b>	0.415	0.400	26	0.034

<sup>a</sup> *V*<sub>oc</sub>: open-circuit voltage.

<sup>b</sup> *J*<sub>sc</sub>: short-circuit current.

<sup>c</sup> *FF*: fill factor.

<sup>d</sup> PCE: power conversion efficiency.

The data listed above were recorded under standard AM 1.5G illumination.

**P** displayed the most red-shifted emission maximum among the copolymers. The synthesized copolymers showed poor performance in both PLED and photovoltaic cell applications.

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