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# POLYMORPHISM OF MACROCYCLIC OLIGOTHIOPHENE 8-MERS

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Dedicated to Professor Kiyoshi Tomioka on the occasion of his 70th birthday

Abstract – Macrocyclic oligothiophene 8-mer *E,E*-**8T6A** composed of eight thienylene, six ethynylene, and two vinylene units exhibits unique polymorphism. In the solid state, *E,E*-**8T6A** formed nanostructured polymorphs such as single crystals, fibers, long and short rods, and square tubes depending on the solvent used for crystallization. In contrast, *E*-**8T7A** with one vinylene unit and **8T8A** without vinylene unit afforded single crystals, microcrystalline, and short rods in the solid state. Morphological difference between *E,E*-**8T6A** and *E*-**8T7A**/**8T8A** is due to the flexibility of the macroring of *E,E*-**8T6A** with two vinylene units, and the shape-persistent but rather flexible *E,E*-**8T6A** forms various polymorphs in the solid state.

Polymorphism is an important concept in chemistry,[1] medicine,[2] molecular biology,[3] and materials science.[4] In organic chemistry, polymorphism of molecules is mainly due to various semi-equivalent metastable structures in the solid state. Recently, we reported polymorphism of giant macrocycles composed of thienylene, ethynylene, and vinylene building blocks.[5] Macrocycles *E,E*-**8T6A**, *E*-**8T7A**, and **8T8A** are regarded as an infinite π-conjugated system with a large inner cavity (Figure 1), and their physical properties are strongly affected by their structures in solution and the solid state.[6,7] Since macrocyclic thiophenes have both moderate molecular rigidity and mobility,[2] the nanophase separation between interior and exterior sites in large macrocycles results in the formation of attractive polymorphs based on one-dimensional (1D), two-dimensional (2D), and three-dimensional (3D) supramolecular

nanostructures.[8] In this paper, we report on polymorphism of shape-persistent macrocyclic oligothiophenes caused by a small conformational flexibility of macrorings.

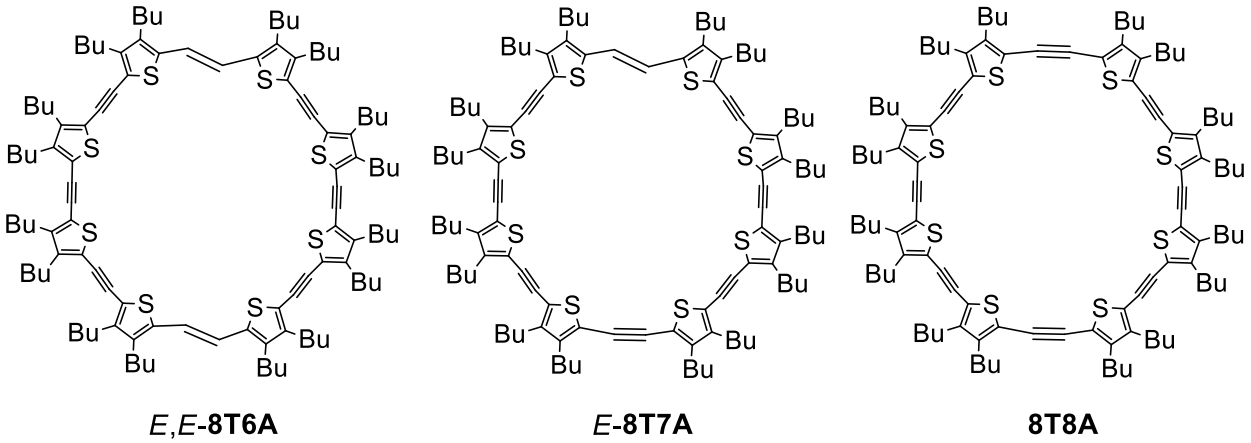
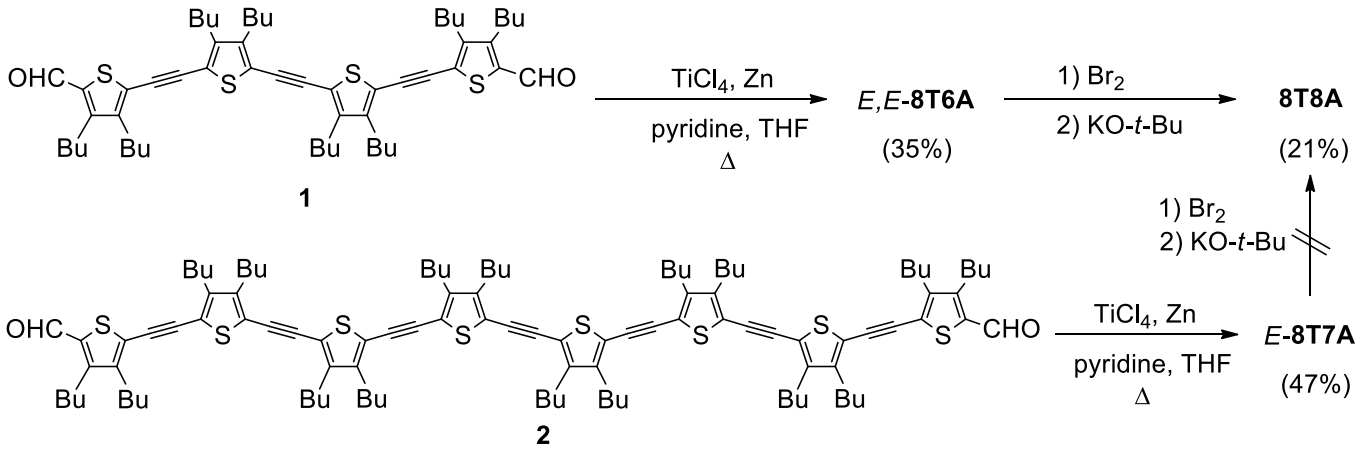



**Figure 1.** Chemical formulae of macrocyclic oligothiophene 8-mers *E*,*E*-**8T6A**, *E*-**8T7A**, and **8T8A**

As reported previously, the synthesis of *E*,*E*-**8T6A** was performed by using a McMurry coupling of the dialdehyde **1** with low-valent titanium reagent (Scheme 1).[6] *E*,*E*-**8T6A** was obtained in 35% yield as a main product, together with higher cyclic oligomers.[6] The synthesis of *E*-**8T7A** was also carried out by a similar McMurry coupling of the dialdehyde **2** to produce *E*-**8T7A** in 47% yield with corresponding higher oligomers.[7] *E*,*E*-**8T6A** was converted into **8T8A** by using 'bromination-dehydrobromination' procedure in total 21% yield, whereas a similar bromination-dehydrobromination reactions of *E*-**8T7A** resulted in a complex mixture, in which no **8T8A** was included. All macrocyclic oligothiophene 8-mers are stable in the solid state in air at room temperature in spite of the fairly low oxidation potentials (*E*,*E*-**8T6A** : 0.22 V, *E*-**8T7A**: 0.31 V, and **8T8A**: 0.36 V vs $Fc/Fc^{+}$).




**Scheme 1.** Synthesis of *E*,*E*-**8T6A**, *E*-**8T7A**, and **8T8A**

Macrocyclic oligothiophene *E,E*-**8T6A** forms various nanostructures polymorphs depending on solvents used for crystallization (Figure 2). From hot benzene, single crystals of *E,E*-**8T6A** were obtained, whereas a wide variety of fibrous polymorphs precipitated from solution. Thus, fibers, rods, square tubes, and short rods were produced from benzene/hexane, $CHCl_3$, benzene/diisopropyl ether (IPE), and toluene, respectively. None of these polymorphs contains any solvent determined by $^1H$ NMR measurements, but the morphological difference depends on the solvent used.

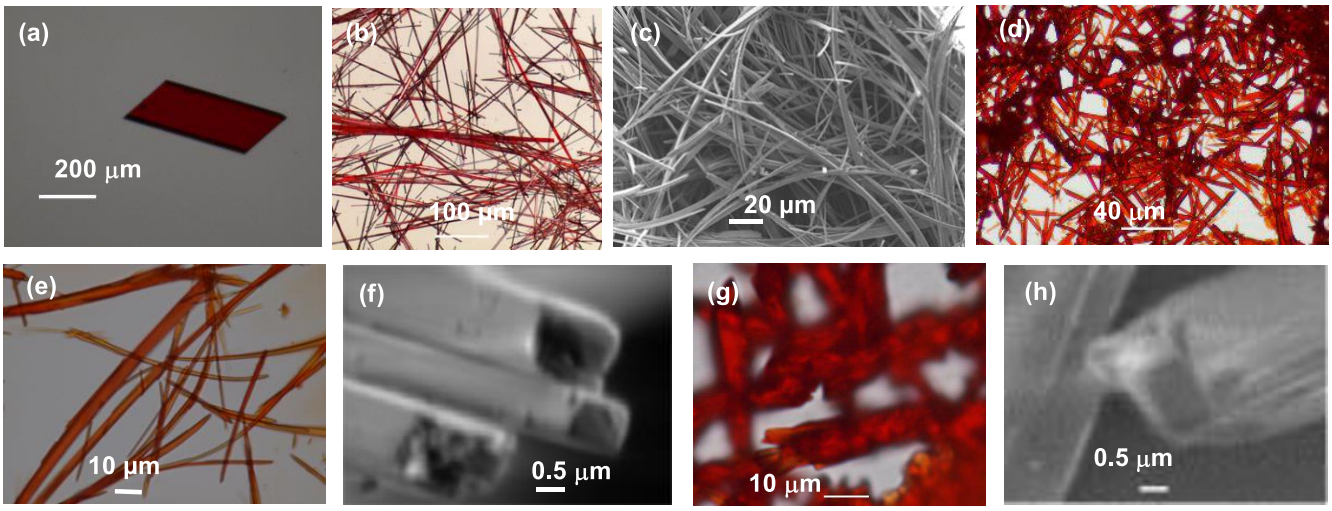



**Figure 2.** Optical and scanning electron microscopy (SEM) images of nanostructured polymorphs of *E,E*-**8T6A**. Optical images of single crystal from hot benzene (a), fibers from benzene/hexane (b), rods from $CHCl_3$ (d), square tubes from benzene/IPE (e), and short rods from toluene (g). SEM images of fibers from benzene/hexane (c), square tubes from benzene/IPE (f), and short rods from toluene (h).

As shown in Figure 3a, single crystal of *E,E*-**8T6A** exhibits a typical power pattern of the X-ray diffraction (XRD) profile obtained from the X-ray structural analysis. In contrast, the XRD profile of fibers of *E,E*-**8T6A** shows simple reflections at $2\theta = 3.88°$, 7.76°, and 11.64° corresponding to a lamellar structure (Figure 3b). Since the molecular diameter of *E,E*-**8T6A** is estimated to be 28 Å, the fibers of *E,E*-**8T6A** have a 1D supramolecular structure stacked in the direction of the fiber. Although the XRD profiles of rods and short rods of *E,E*-**8T6A** exhibit a high crystallinity (Figure 3c),[ref] reflecting a 3D structure in the crystals, square tubes of *E,E*-**8T6A** have a 1D lamellar structure (Figure 3d). The XRD profile of square tubes of *E,E*-**8T6A** shows simple reflections at $2\theta = 3.77°$, 7.54°, and 11.31° as a 1D structure, and the molecules in the square tubes stack in the direction of the fiber. It is noteworthy that the SEM image of square tubes of *E,E*-**8T6A** indicate an aging of the tube structure under ambient conditions to gradually afford tapes. However, fibers, rods, and short rods of *E,E*-**8T6A** are stable and remain unchanged under ambient conditions.

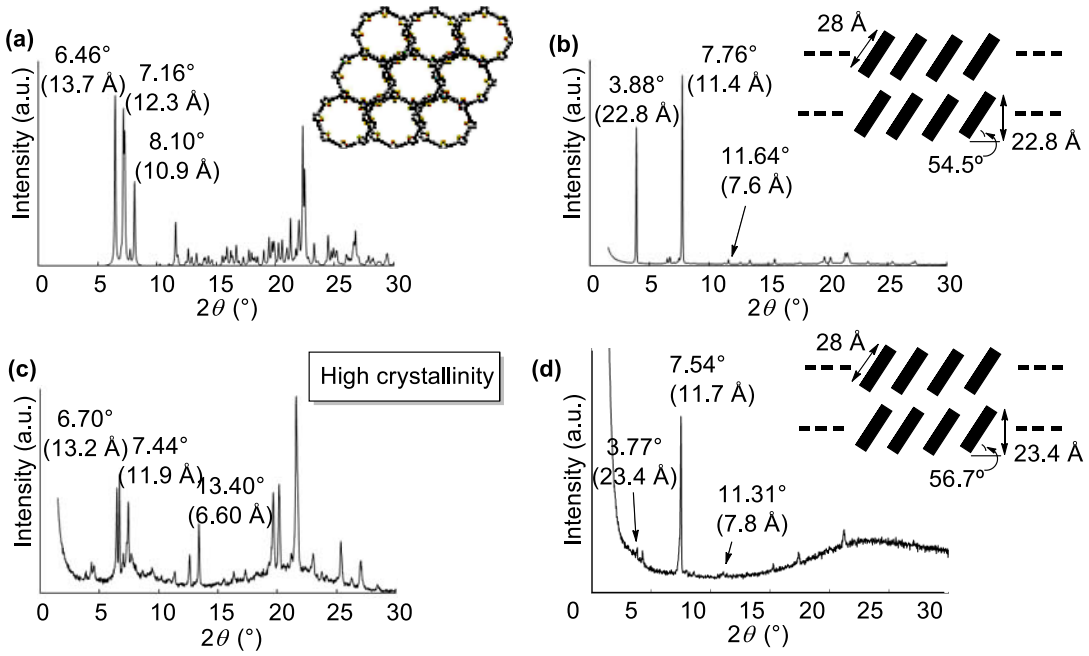



**Figure 3.** XRD patterns for the single crystal (a), fibers (b), rods (c), and square tubes (d) of *E,E*-**8T6A**

In contrast to the formation of various nanostructured polymorphs of *E,E*-**8T6A**, *E*-**8T7A** affords single crystals from hot benzene and microcrystalline from toluene (Figure 4a). As shown in Figure 4b, microcrystalline of *E*-**8T7A** exhibits low crystallinity different from the XRD profile of single crystals, and the reflections at $2\theta$ = 21.61° and 24.12° can be assigned as a roughly π–π stacked structure. Similarly, **8T8A** produces single crystals from hot benzene, short rods from benzene (Figure 4c), and amorphous film from $CS_2$. The XRD profile of short rods of **8T8A** shows rather high 3D crystallinity; however, this profile is different from the XRD profile of single crystals. The difference in the XRD profile between *E,E*-**8T6A** and *E*-**8T7A**/**8T8A** can be explained by the flexibility of macroring, and the shape-persistent but rather flexible *E,E*-**8T6A** forms various polymorphs in the solid state. However, *E*-**8T7A** and **8T8A** have a conformationally rigid macroring, and hence, they afford only limited polymorphs.

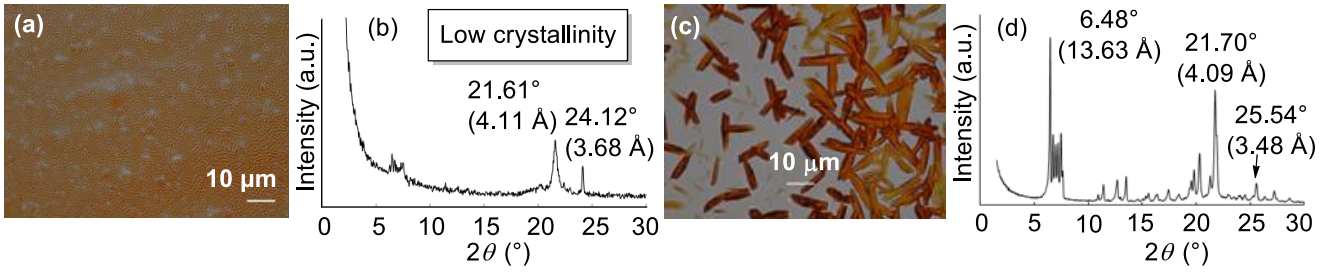



**Figure 4.** Optical images and XRD profiles of *E*-**8T7A** and **8T8A**. Optical image (a) and XRD profile (b) microcrystalline of *E*-**8T7A**. Optical image (c) and XRD profile (d) of short rods of *E*-**8T6A**.

In summary, polymorphism of macrocyclic oligothiophene 8-mers *E,E*-**8T6A**, *E*-**8T7A**, and **8T8A** is dependent on the nanophase separation between interior and exterior sites in large mobile macrocycles. The shape-persistency and flexibility of macrocycles cause many semi-equivalent metastable structures in the solid state to afford polymorphs, and slightly more flexible *E,E*-**8T6A** compared to *E*-**8T7A**, and **8T8A** produces a variety of polymorphs having attractive structures. Our findings about polymorphism of macrocyclic oligothiophenes open a new guiding principle to design new polymorphs of shape-persistent macrocycles.

## EXPERIMENTAL

**Synthesis of *E,E*-8T6A, *E*-8T7A, and 8T8A.** *E,E*-**8T6A**, *E*-**8T7A**, and **8T8A** were prepared according to our reported procedures. *E,E*-**8T6A**, *E*-**8T7A**, and **8T8A** are soluble in benzene, toluene, $CH_2Cl_2$, $CHCl_3$, THF, and carbon disulfide; however, these compounds are slightly soluble in hexane, $Et_2O$, diisopropyl ether (IPE), and EtOAc.

**Single crystals of *E,E*-8T6A, *E*-8T7A, and 8T8A (Figures 2a and 3a).** Single crystals of *E,E*-**8T6A**, *E*-**8T7A**, and **8T8A** were obtained by recrystallization from hot benzene under ambient conditions, and their structures were determined by using X-ray analysis.

**Fibers of *E,E*-8T6A from benzene/hexane (Figures 2b,c and 3b).** In the dark *E,E*-**8T6A** (10 mg) was dissolved in benzene (0.2 mL) and hexane (0.5 mL) at 50 °C. The solution was allowed to stand at room temperature to produce fibers of *E,E*-**8T6A**.

**Rods of *E,E*-8T6A from chloroform (Figures 2d and 3c).** In the dark *E,E*-**8T6A** (10 mg) was dissolved in $CHCl_3$ (0.2 mL). The solution was cast on a glass plate to produce rods of *E,E*-**8T6A**.

**Square tubes of *E,E*-8T6A from benzene/diisopropyl ether (IPE) (Figures 2e,f and 3d).** In the dark *E,E*-**8T6A** (10 mg) was dissolved in benzene (0.3 mL) and IPE (0.1 mL) at 50 °C. The solution was allowed to stand at room temperature to produce square tubes of *E,E*-**8T6A**.

**Short rods of *E,E*-8T6A from toluene (Figures 2g,h).** In the dark *E,E*-**8T6A** (10 mg) was dissolved in toluene (0.5 mL). The solution was cast on a glass plate to produce short rods of *E,E*-**8T6A**.

**Small crystals of *E*-8T7A from toluene (Figures 4a,c).** *E*-**8T7A** (10 mg) was dissolved in toluene (3.5 mL), and the solution was cast on a glass plate to produce small crystals of *E*-**8T7A**.

**Short rods of 8T8A from benzene (Figures 4b,d). 8T8A** (10 mg) was dissolved in benzene (4 mL), and the solution was cast on a glass plate to produce short rods of *E*-**8T7A**.

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