

Synthesis of the first enantiomerically pure and chiral, disubstituted 3,4-ethylenedioxythiophenes (EDOTs) and corresponding stereo- and regioregular PEDOTs

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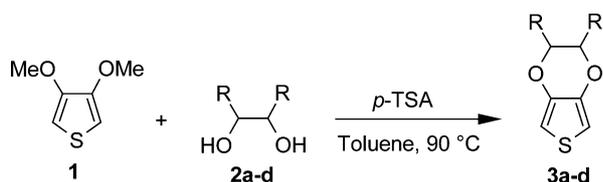
Novel disubstituted EDOT monomers were synthesized in good yields from 3,4-dimethoxythiophene and (chiral) glycols by transesterification. The stereochemistry of the monomers affects the electronic properties of the corresponding chiral PEDOT derivatives.

Poly(3,4-ethylenedioxythiophene) (PEDOT) is among the most widely applied conducting polymers due to its unique combination of high stability, conductivity and transparency in the oxidized form and serves for antistatic coatings, capacitors, and organic devices.¹ In contrast to poly(3-alkylthiophenes) in which the consequences of stereoregularity, chirality, supramolecular ordering and conformations on the electronic properties have been investigated,² only very little information on these important issues exists for PEDOTs.

In this respect, we are exploring novel EDOT derivatives and very recently could demonstrate that the Mitsunobu reaction is an efficient alternative for the synthesis of mono- and disubstituted EDOTs and 3,4-propylenedioxythiophenes (ProDOTs).³ Moreover, with this method the first chiral monoalkylated EDOTs as a basis for corresponding stereoregular polymers were prepared.^{3a} All our efforts to additionally control the regioregularity in these polymers by selective head-to-tail coupling have failed so far.

We successfully developed a valid concept to synthesize PEDOTs which are both regio- and stereoregular. Our approach was the synthesis of EDOTs having two substituents at the ethylene bridge so that two chiral centres are created and regioregularity in the corresponding polymers is automatically given. The additional stereocontrol is achieved by polymerization of enantiomerically pure monomers.

In the case of disubstituted EDOTs, the Mitsunobu reaction led only to moderate yields³ and no reaction was observed when *trans*-configured glycols were used. Despite its efficiency for the synthesis of dialkylated ProDOTs,^{1,4} no studies concerning the use of transesterification for the synthesis of disubstituted EDOTs have been reported. We therefore investigated the acid-catalysed transesterification reaction as an alternative route for their synthesis. The general synthetic applicability is demonstrated by the reaction of 3,4-dimethoxythiophene **1** with glycol derivatives **2a–d** in the presence of catalytic *p*-toluenesulfonic acid (Table 1).



Novel EDOTs **3b–d** were obtained in good to excellent yields (entries 2–10, 47–82%), (*meso*)-2,3-butanediol **2a** gave EDOT **3a** in somewhat lower yield (entry 1, 20%). Interestingly, besides the

introduction of various alkyl groups to the EDOT core (entries 1–4), annulation of cyclohexane (entries 5–9) and heterocyclic rings (entry 10) has directly been achieved. The latter derivative, 1,2-dithiane-functionalized EDOT **3d**, should adsorb and self-assemble on noble metal surfaces leading to strongly adhering PEDOT films.

The stereochemistry of the starting 1,2-diols has minor effects on the efficient formation of the resulting EDOTs in which the configurations are fully retained (entries 2–4: 73–82%; entries 5–9: 52–68%). The synthesis of the (*R,R*)-enantiomer of the dihexyl

Table 1 Transesterification reaction of 3,4-dimethoxythiophene **1** and (chiral) diols **2** to (enantiomerically pure) disubstituted EDOTs **3**

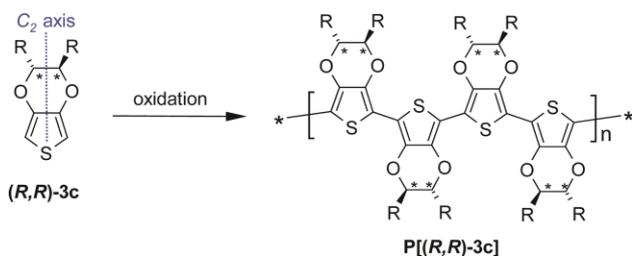
Entry	Diol	Product	Yield (%) ^a	
1		(<i>meso</i>)- 2a ^b	(<i>meso</i>)- 3a	20
2		(<i>trans</i>)- 2b ^c	(<i>trans</i>)- 3b	79
3		(<i>R,R</i>)- 2b ^{c,d}	(<i>R,R</i>)- 3b	73
4		(<i>meso</i>)- 2b ^c	(<i>meso</i>)- 3b	82
5		(<i>trans/cis</i>)- 2c ^b	(<i>trans/cis</i>)- 3c	63
6		(<i>trans</i>)- 2c ^b	(<i>trans</i>)- 3c	65
7		(<i>R,R</i>)- 2c ^b	(<i>R,R</i>)- 3c	68
8		(<i>S,S</i>)- 2c ^b	(<i>S,S</i>)- 3c	66
9		(<i>cis</i>)- 2c ^c	(<i>cis</i>)- 3c	52
10		(<i>trans</i>)- 2d ^b	(<i>trans</i>)- 3d	47

^a Isolated yields. ^b Commercially available diol. (*meso*)-2,3-Butanediol (*meso*)-**2a**, (*R,R*)-1,2-cyclohexanediol (*R,R*)-**2c** (*ee* > 99%) and (*S,S*)-1,2-cyclohexanediol (*S,S*)-**2c** (*ee* > 99%) were purchased from Fluka, (*trans/cis*)-1,2-cyclohexanediol (*trans/cis*)-**2c** and (*trans*)-1,2-cyclohexanediol (*trans*)-**2c** from Acros, (*trans*)-1,2-dithiane-4,5-diol (*trans*)-**2d** from Aldrich. ^c Diols (*trans*)-7,8-tetradecanediol (*trans*)-**2b** and (*R,R*)-7,8-tetradecanediol (*R,R*)-**2b** were prepared in 83% and 87% yield, respectively, according to ref. 5, (*meso*)-7,8-tetradecanediol (*meso*)-**2b** according to ref. 6 in 72% yield. (*cis*)-1,2-Cyclohexanediol (*cis*)-**2c** was prepared in 44% yield according to ref. 7. ^d The enantiomeric excess of (*R,R*)-**2b** (*ee* > 94%) was determined by HRGC separation of the bis-MTPA esters.⁸

derivative (**R,R**)-**3b** was carried out by transesterification of 3,4-dimethoxythiophene **1** and the enantiomerically pure (7*R*,8*R*)-tetradecanediol (**R,R**)-**2b** (entry 3: 73%) which was synthesized in high enantiomeric excess (*ee* > 94%) by asymmetric dihydroxylation⁵ of *trans*-tetradec-7-ene. The optically active cyclohexa-1,2-diyl derivatives (**R,R**)-**3c** (entry 7: 68%, [α]_D²⁰ +101°) and (**S,S**)-**3c** (entry 8: 66%, [α]_D²⁰ -101°) were obtained by analogous reaction of **1** with diols (**R,R**)-**2c** and (**S,S**)-**2c**, respectively, exhibiting exactly the opposite rotational angles under polarized light.†

EDOT monomers typically are polymerized either by chemical or electrochemical oxidation.^{1b} By potentiodynamic electrooxidation we could polymerize all novel disubstituted EDOT derivatives **3a–d** to the corresponding PEDOTs. As an example, we here describe the electrochemical properties of a series of cyclohexa-1,2-diyl-substituted PEDOTs **P3c** prepared from monomers **3c** (entries 6–9) which are compared to the parent PEDOT created under identical conditions. In Fig. 1, typical cyclic voltammograms (CV) of the polymer-modified electrodes are shown.‡

The *I/E*-curves exhibit the typical shape of conducting polymers including broad redox waves and plateaus. By comparison of the peak potentials which are indicative of the conjugation length of the polymers and the overall electroactivity which corresponds to the charging and the thickness of the films the following major trends are derived: **P[(*cis*)-3c]** has the same oxidation potential ($E_p^a = -0.33$ V) as **PEDOT**, but about double the peak current and much higher electroactivity which we attribute to the increased polymerization tendency of the EDOT (*cis*)-**3c** compared to the other monomers. The other derivatives, **P[(*R,R*)-3c]** ($E_p^a = -0.53$ V), **P[(*S,S*)-3c]** ($E_p^a = -0.56$ V) and **P[(*trans*)-3c]** ($E_p^a = -0.56$ V), which consist of a mixture of *R,R*- and *S,S*-configured monomer units, are charged and transformed to the conducting form at distinctly lower potentials, indicating higher mean conjugation lengths than the former two examples. We rationalize this result by the *C*₂ symmetry of the monomers (**R,R**)-**3c** and (**S,S**)-**3c**, which irrespective of the way of coupling during the polymerization result in a fully stereoregular arrangement of the chiral centres leading to improved interchain interactions and self-organization. Furthermore, enantiomerically pure PEDOTs **P[(*R,R*)-3c]** and **P[(*S,S*)-3c]** are optically active. In contrast, the *C*_s symmetry of EDOT (*cis*)-**3c** only gives rise to a statistical distribution of the stereocenters on the conjugated polymer chains.



In summary, we have disclosed a novel concept for the synthesis of regio- and stereoregular PEDOTs with superior conjugation. The basis was led by the efficient preparation of disubstituted EDOTs by transesterification of 3,4-dialkoxythiophenes and 1,2-diols. For the first time, enantiomerically pure and chiral derivatives were prepared in good yields. Corresponding PEDOTs exhibit a clear relationship of the degree of stereoregularity and the (opto)electronic properties.

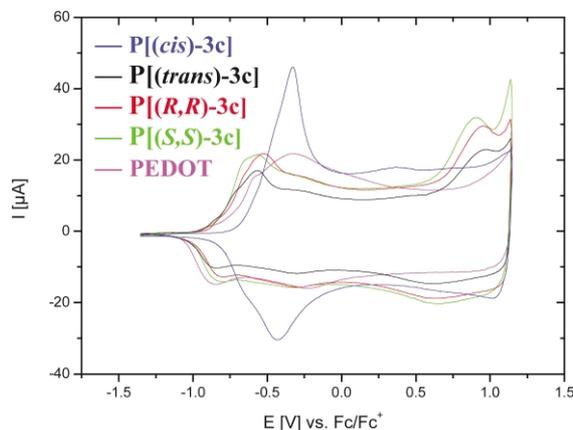


Fig. 1 Cyclic voltammograms of PEDOTs **P3c** of different stereochemistry and **PEDOT** in $\text{CH}_3\text{CN}/\text{TBAHFP}$ (0.1 M) at a scan rate of 100 mV s^{-1} .

Notes and references

† *General procedure for the transesterification reaction of 3,4-dimethoxythiophene 1 and 1,2-diols 2:* To a three-necked flask equipped with an argon purge was added 3,4-dimethoxythiophene **1** (0.65 g, 4.5 mmol), diol **2** (9 mmol), *p*-toluenesulfonic acid monohydrate (0.086 g, 0.45 mmol), and 12 mL of toluene. The solution was heated for 72 h at 90 °C and then cooled to r.t. After removal of the solvent, the crude product was isolated by flash chromatography on SiO_2 (eluent $\text{CH}_2\text{Cl}_2/\text{hexane}$ 2 : 1) and purified by fractionated distillation or sublimation.

Representative data for enantiomerically pure EDOTs: (**R,R**)-**3c**: mp 144–146 °C; ¹H NMR (400 MHz, CDCl_3 , 25 °C): $\delta = 6.28$ (s, 2H), 3.74–3.67 (m, 2H), 2.21–2.17 (m, 2H), 1.83–1.81 (m, 2H), 1.48–1.31 (m, 4H); ¹³C NMR (100 MHz, CDCl_3 , 25 °C): $\delta = 142.39, 99.04, 77.11, 30.12, 23.79$; [α]_D²⁰ +101° (c 1, CHCl_3); Anal. calc. for $\text{C}_{10}\text{H}_{12}\text{O}_2\text{S}$: C 61.20, H 6.16, S 16.34; found: C 61.22, H 6.18, S 16.25%. (**S,S**)-**3c**: identical data, except for [α]_D²⁰ -101° (c 1, CHCl_3) and anal. found: C 61.17, H 6.27, S 16.07%.

‡ Electrochemical cyclic voltammetry experiments were performed using a Pt-disk as working and Pt-wire as counter electrode, a Ag/AgCl reference electrode and acetonitrile/tetrabutylammonium hexafluorophosphate (TBAHFP; 0.1 M) as the electrolyte. All potentials were internally referenced to the ferrocene/ferricenium couple (Fc/Fc^+).

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