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► **To cite this version:**

Laura Thiebaud, Sophie Legeai, Jaafar Ghanbaja, Nicolas Stein. Synthesis of Te-Bi core-shell nanowires by two-step electrodeposition in ionic liquids. *Electrochemistry Communications*, 2018, 86, pp.30 - 33. 10.1016/j.elecom.2017.11.010 . hal-01840644

HAL Id: hal-01840644

<https://hal.univ-lorraine.fr/hal-01840644v1>

Submitted on 4 Oct 2021

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Synthesis of Te-Bi core-shell nanowires by two-step electrodeposition in ionic liquids

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Abstract

Te-Bi core-shell nanowires were synthesized by electrochemical deposition in ionic liquids without using a template. The nanowires were synthesized in two steps: self-standing single crystal Te nanowires with a diameter of 76.2 ± 28.4 nm and a length of a few microns were electrodeposited first, taking advantage of the templating properties of the mixture of ionic liquids EOPipTFSI:EOPipBr 95:5 mole%. The Bi shell was then deposited on the Te core in EOPipTFSI. The influence of various experimental parameters on Bi shell deposition was studied. Thanks to the higher viscosity of the electrolyte compared to an aqueous medium, a lower growth rate is observed, leading to a thin layer of bismuth. In addition, High Resolution Transmission Electronic Microscopy shows that under optimal conditions the Te nanowires are entirely covered by a homogeneous, compact and polycrystalline Bi shell and that the core/shell interface is smooth.

Keywords:

Core-shell nanowires, Ionic liquid, Electrodeposition, Bismuth, Tellurium

1. Introduction

Tellurium exhibits outstanding thermoelectric properties and has a high Seebeck coefficient ($500 \mu\text{V}\cdot\text{K}^{-1}$ [1]). However its thermal conductivity is high ($\approx 3 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ [2]), leading to low thermoelectric efficiency. Nanostructuring, especially the formation of nanowires, is an effective way for decreasing the lattice thermal conductivity by increasing the diffusive phonon scattering [3]. Te nanowires are easily synthesized due to the anisotropic crystalline structure of Te, which seems to favor one-dimensional growth. However, its electrical conductivity is quite low, between 2 and $3.8 \text{ S}\cdot\text{cm}^{-1}$ depending on crystal orientation [4], which limits its potential as a candidate for thermoelectric systems. To overcome this problem, advanced nanostructures, such as core-shell nanowires with a Te core capped by an electrical conducting shell eg of bismuth ($\sigma_{\text{Bi}} = 6.25 \cdot 10^3 \text{ S}\cdot\text{cm}^{-1}$ [5]) are proposed as one possible way of improving the electronic properties of the 1D material. Indeed, compared to conventional nanowires, core-shell nanostructures permit combination of the electronic properties of the materials involved and also further decrease the lattice thermal conductivity by interface phonon scattering [6]. Thus, the synthesis of core-shell structures based on Te nanowires capped by a Bi shell should lead to an interesting thermoelectric material with a very low lattice thermal conductivity, a high Seebeck coefficient and high electrical conductivity.

Te-Bi nanowires have already been synthesized by Zhang et al. using a two-step phase solution method [6]. However, in this case the Bi shell does not completely cover the surface of the nanowires and presents a rough surface with saw-like edges. In contrast, electrodeposition is a coating process which produces a homogeneous covering layer. Bi electrodeposition is usually performed in aqueous media [7-10]. However, Bi^{III} precursor dissolution requires an acidic medium which could corrode the Te nanowires. An alternative is to use an ionic liquid electrolyte. As the viscosity of ionic liquids is very high (typically $> 50 \text{ mPa}\cdot\text{s}$ at 25°C), the resulting deposition rate is also slower than in aqueous media and hence more favourable to the production of thin, homogeneous layers on complex structures such as nanowire arrays [11].

Few works deal with Bi electrodeposition using ionic liquids. In an imidazolium-based ionic liquid, a Bi thin layer was obtained by underpotential deposition (UPD) on a gold substrate [12,13] by electrochemical reduction of Bi^{III} adsorbed species. On scanning towards more negative potentials, over-potential deposition (OPD) occurs, and the morphology of the Bi deposit varies from a needle-like structure to a monolayer/thin film [13]. Deep eutectic

solvents, consisting in a melt of choline chloride with oxalic acid [14] or malonic acid [15], have also been used to deposit Bi.

This article reports the fabrication of Te-Bi core-shell nanowires by two-step electrochemical deposition in piperidinium-based ionic liquids. The first step involves the template-free electrodeposition of single crystal Te nanowires in a binary mixture of 1-ethyl-1-octyl-piperidinium bis(trifluoromethylsulfonyl)imide and 1-ethyl-1-octyl-piperidinium bromide (EOPipTFSI:EOPipBr, 95:5 mole%). The second step concerns the electrodeposition of a Bi thin film on the Te nanowires, leading to core-shell Te-Bi nanostructures. The electrochemical behaviour of the $\text{Bi}^{\text{III}}/\text{Bi}^0$ system in EOPipTFSI ionic liquid appears quite complex and exhibits several Bi^{III} to Bi^0 reduction signals. The influence of various experimental parameters on Bi shell deposition was studied: these included applied potential, Bi^{III} concentration, density of Te nanowires and applied coulometric charge.

2. Material and methods

The electrochemical experiments were performed in a glove box (MBraun Labstar, $\text{O}_2/\text{H}_2\text{O}$ levels < 1 ppm) using a Biologic potentiostat (VSP300). Platinum-coated glass slides (Applications Couches Minces ACM, 25×10×1 mm, Pt coating thickness 300 nm) were used as working and counter electrodes in the electrodeposition experiments, while a Pt wire was used as a quasi-reference electrode (QRE).

The Te-Bi core-shell nanowires were synthesized using a two-step procedure. First, single crystalline Te nanowires were obtained using TeCl_4 (99 %, Alfa Aesar) at a concentration of either 5 or 20 mM in EOPipTFSI:EOPipBr 95:5 mole%, as reported in a previous work [16]. Te-Bi core-shell nanowires were then obtained by electrodepositing a thin Bi film on the Te nanowires. The EOPipTFSI ionic liquid was used as the electrolyte and BiBr_3 (99 %, Alfa Aesar) as the Bi^{III} precursor. All the ionic liquids used in this work were synthesized and purified according to a previously published procedure [16].

The Te-Bi nanowires were washed several times with acetone and dried before characterization by scanning electron microscopy (SEM, Philips XL30 S FEG, 5 kV) and transmission electron microscopy (TEM, JEM-ARM 200F Cold Field Emission Gun, 200 kV, point resolution 0.19 nm in TEM mode) fitted with a GIF Quantum ER. The direction of growth of the nanostructures was determined by selected area electron diffraction (SAED).

3. Results and Discussion

3.1. Electrodeposition of Te nanowires in an ionic liquid

Te nanowires were obtained in EOPipTFSI:EOPipBr 95:5 mole% by applying a constant potential corresponding to Te^{IV} reduction. Figure 1 shows SEM images of the deposits obtained for two different Te^{IV} concentrations. The nanowires are self-standing single crystals with a growth axis along the [001] direction. As shown previously [17], the density of the nanowires increases with $[\text{Te}^{\text{IV}}]$. Nanowires synthesized for $[\text{Te}^{\text{IV}}] = 5 \text{ mM}$ (Figure 1a) have a mean length of $1.70 \pm 0.15 \mu\text{m}$ and most of them have a diameter between 50 and 100 nm with an average of $83 \pm 37 \text{ nm}$. When the Te concentration is increased to 20 mM (Figure 1b), the deposit is denser and is composed of nanowires that are $1.0 \pm 0.1 \mu\text{m}$ in length and have quite similar diameters, mostly around $140 \pm 20 \text{ nm}$.

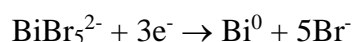
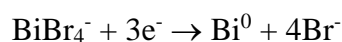
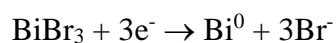
Figure 1: SEM images of Te nanowires obtained in EOPipTFSI:EOPipBr 95:5 mole% for $[\text{Te}^{\text{IV}}] =$ (a) 5 mM and (b) 20 mM. The corresponding histograms show the distribution of diameters of the nanowires.

In order to deposit Bi on the Te nanowires, the cathodic behaviour of Bi^{III} in EOPipTFSI ionic liquid was studied on Pt-coated glass slides with and without Te nanowires. Linear sweep voltammograms obtained on Pt and Te working electrodes are shown in Figure 2.

Figure 2: Linear sweep voltammograms showing the electrochemical cathodic behaviour of Bi^{III} in EOPipTFSI on Pt-coated glass slides with and without Te nanowires (synthesized using $\text{Te}^{\text{IV}} = 5\text{mM}$). $[\text{Bi}^{\text{III}}] = 5 \text{ mM}$, $T = 100^\circ\text{C}$, $5 \text{ mV}\cdot\text{s}^{-1}$.

Whatever the substrate, three reduction peaks are observed, at -0.49 V (C_1), -0.70 V (C_2) and -0.99 V (C_3) vs Pt, which appear before the reduction of Te^0 to Te^{II} at -1.5 V [18]. These signals all correspond to Bi^0 deposition, as confirmed by XRD analysis (not shown here). The electrochemical behaviour of Bi^{III} is the same as that observed by Fu et al. in tetrafluoroborate medium [12] but is totally different to what was observed by Szymczak et al. in EOPipTFSI:EOPipBr 95:5 mole% [19] and in DESs [14,15]. Indeed, only one reduction peak is observed in these halide-rich media. As in the case of Te [17], In [20] and Ta [21] electrochemical systems, the low amount of halides in the TFSI-based ionic liquid leads to complex cathodic behaviour. As previously suggested in the literature [17,20], this could be due to the reduction of successive BiBr_x^{3-x} complexes to Bi^0 during the potential scan. The low mass transport rate during the formation of the Bi^0 deposit, due to the high viscosity of the ionic liquid ($\eta = 15 \text{ mPa}\cdot\text{s}$ at 100°C [19]), could favour an increase in the concentration of halide ions in the vicinity of the electrode and thus modify the $[\text{Br}^-]/[\text{Bi}^{3+}]$ concentration ratios at the electrode/electrolyte interface. Successive BiBr_x^{3-x} complexes could then be formed,

leading to multiple cathodic signals corresponding to their successive reduction. The C_1 peak would thus correspond to the reduction of BiBr_3 into Bi^0 regardless of halide content and the later signals to the higher halide complex reductions outlined below:



3.2. Electrodeposition of Bi on Te nanowires

Bismuth was electrodeposited on Te nanowires under different experimental conditions, using a coulometric charge of 50 mC/cm^2 . The influence of the deposition potential was studied by applying different values, namely the C_1 , C_2 and C_3 peak potentials. The corresponding SEM images are given in Figures 3a, 3b and 3c, respectively. The influence of Bi^{III} concentration can be seen in Figures 3a ($[\text{Bi}^{\text{III}}] = 5 \text{ mM}$) and 3e ($[\text{Bi}^{\text{III}}] = 10 \text{ mM}$), which show SEM images of deposits obtained at C_1 peak potential. On comparing the SEM images, it seems that the highest current densities, corresponding to high overpotential values (C_2 – Figure 3b, and C_3 – Figure 3c), and the highest Bi^{III} concentration (10 mM – Figure 3e) lead to preferential deposition on top of the Te nanowires. By contrast, for the lowest overpotential, C_1 , and the lowest Bi^{III} concentration (Figure 3a), the deposit is rough but homogeneous and is composed of sheets surrounding the Te nanowires, as confirmed by TEM. It thus appears that, at higher growth rates, bismuth preferentially deposits on top of the nanowires, probably because of the highly anisotropic crystalline structure of tellurium [22].

Figure 3: SEM images of Te nanowires after Bi deposition in EOPipTFSI. Te nanowires synthesized at $[\text{Te}^{\text{IV}}] = 5 \text{ mM}$, Bi deposition at the peak potentials: (a) C_1 , (b) C_2 and (c) C_3 . The inset of Figure 3(a) represents a TEM image of a single nanowire. $[\text{Bi}^{\text{III}}] = 5 \text{ mM}$, $Q = 50 \text{ mC/cm}^2$, $T = 100^\circ\text{C}$. Te nanowires synthesized at $[\text{Te}^{\text{IV}}] = 20 \text{ mM}$, Bi deposition at C_1 peak potential for $[\text{Bi}^{\text{III}}] =$ (d) 5 mM and (e) 10 mM. $Q = 50 \text{ mC/cm}^2$, $T = 100^\circ\text{C}$.

Finally, the influence of the density of Te nanowires on Bi deposits obtained at C_1 peak potential and for $[\text{Bi}^{\text{III}}] = 5 \text{ mM}$ can be observed by comparing the SEM images in Figures 3a (low density of Te NWs as shown in Figure 1a) and 3d (high density of Te NWs as shown in Figure 1b). It should be noted that when the density of tellurium nanowires is high, the nanostructures are interconnected by the deposited bismuth. So in this case, no individual core-shell nanowires are obtained (Figure 3d). However, by applying low growth rate

conditions and using substrates with a low density of Te nanowires, a smooth bismuth shell is obtained on decreasing the coulometric charge down to 16 mC/cm^2 (Figure 4).

Figure 4: Morphological and structural analyses of Te-Bi core-shell nanowires: (a) SEM image of Te-Bi core-shell nanowires obtained after Bi electrodeposition on Te nanowires (Figure 1a type) at C_1 peak potential in EOPipTFSI (inset shows the corresponding TEM image of a single nanowire); (b) histogram showing the diameter distribution of the core-shell nanowires; (c) Te-Bi interface with the corresponding Fast Fourier Transform of the Te core and the Bi shell; (d) EDX-mapping of Bi (yellow) and Te (green). $[\text{Bi}^{\text{III}}] = 5 \text{ mM}$, $Q = 16 \text{ mC/cm}^2$, $T = 100^\circ\text{C}$.

The Bi deposit is homogeneously deposited around the Te nanowires (Figure 4a). The statistical analysis presented in Figure 4b shows that most of the nanowires have a diameter of between 75 and 125 nm with an average of $125.5 \pm 37.0 \text{ nm}$; this is an increase of 42 nm compared to the initial diameter of the Te nanowires (Figure 1a). This is in accordance with the HRTEM analysis of Figure 4c. Indeed, the cross-sectional view confirms that the Bi deposit is homogeneous along the Te nanowires with a smooth interface and a thickness of around 20 nm (Figure 4, c and d). The Te and Bi crystallographic structures are highlighted in the Fast Fourier Transform images (Figure 4c). It appears that the bismuth shell is present as a polycrystalline phase whereas the Te core is a single crystal with a growth direction along the c-axis.

4. Conclusion

In this work, we have shown that it is possible to synthesize Te-Bi core-shell nanowires by a two-step electrodeposition procedure in ionic liquids. By optimizing the synthesis parameters, a homogeneous polycrystalline Bi layer 20 nm thick was deposited around Te nanowires of diameter $83.2 \pm 36.9 \text{ nm}$. These nanostructures are promising materials for thermoelectric applications.

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