Synthesis and characterization of nanostructured DNA-templated polyimidazole nanowire

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Abstract
In this research work, nanostructured DNA-templated polyimidazole nanowires synthesized using simple and low-cost fabrication method that employed DNA as a template on which to carry out the polymerisation was reported. Their chemical properties were probed using different spectroscopic techniques (Ultra-Violet Visible (UV-vis) spectroscopy, X-ray Photoelectron Spectroscopy (XPS) and Fourier Transform Infrared (FTIR) spectroscopy). Atomic force (AFM) and electron microscopy (SEM and TEM) were used to characterize the nanowire dimensions. The techniques proved the formation of a supramolecular hybrid polymer containing DNA and imidazole polymers. The electrical property was measured using probe station. Morphological results exhibit different morphologies with agglomerate nanostructures for the diluted film, while dense rope like network of nanostructures were observed for undiluted templated polymers with diameter of 2-13 nm. Activation energy (Ea) including the uncertainty on it for the Plm/DNA bulk nanowires calculated was 10.6 ± 0.5 x 10^{-3} J mol^{-1} equivalents to 0.110 ± 0.005 eV which is not surprising because the process is thermally assisted tunneling between localized sites.

Keywords: Nanowire, polymer, template, DNA, Characterization

1. Introduction
Conductive polymers and their derivatives have continuously been used as active layers in nanoelectronics devices. Composites of conjugated polymers are getting increasingly utilized in organic electronics devices, thanks to the electronic and optical properties of the polymers, which are like those of semiconductors. However, the mechanical properties and processability of polymers makes them more attractive than crystalline inorganic semiconductors for future applications: their light weight, flexibility and inexpensive preparation procedures are drawing the attention of many researchers [1-2].
They have lots of advantages over their metal oxides counterparts that operate at higher temperatures [3]. They are easy to synthesize by different electrochemical and chemical methods and copolymerisation/structural derivations can refine their molecular chain structure. The formation of charge carriers upon oxidizing or reducing their conjugated backbone is responsible for their inherent conductivity [4].

One dimension (1D) nanomaterials have high surface to volume ratios resulting in higher sensitivity, straight conduction pathways, fast electron transport and adjustability of their surface modification [5-6].

Electrochemical and electronic devices are easier to manufacture and miniaturize than optical ones because they can use microelectronic fabrication techniques [7-9]. This motivated the present research that synthesized polyimidazole DNA-templated (Plm/DNA) nanowires through low cost chemical method and their chemical, morphological and electrical characterizations.

2. Experimental section

2.1 Materials

All chemicals were purchased from Sigma-Aldrich Company Ltd. Lambda DNA (λ- DNA, Cat no. N3011S) was purchased from New England Biolabs (UK) Ltd. n-Si (100) wafers were purchased from Compart Technology Ltd. Platinum microband electrodes were supplied by Windsor Scientific Ltd (Pt-MB4000) and Copper grids (HC300Cu) for TEM were purchased from EM Resolutions Ltd. UK. Deionised water was obtained from a NaNOpure Diamond Life Science ultrapure water system equipped with a DIamond RO Reverse Osmosis System.

2.2 Substrates Cleaning

The n-Si (100) wafers was cut into ~1 x 1 cm² pieces using a diamond scribe and immersed in acetone for 50 min. The chips were then rinsed with copious deionised water and dried in a gentle stream of N2 gas before further drying in an oven for 5 - 10 minutes. Final cleaning with FEMTO low pressure plasma system, using oxygen plasma oxidation (90W, 15 sccm, 15 min) at 40% power was carried out.

2.3 Chemical Synthesis of Plm/DNA Nanowires

DNA-templated Polyimidazole nanowires were chemically synthesized using FeCl₃ as an oxidant. Typically, 5 μL of freshly prepared imidazole (C₃H₄N₂) (solution (3 mM) was added to 20 μL of λ-DNA (500 ng μL⁻¹) in the presence of 5 μL of MgCl₂ (0.5 mM), then 5 μL of FeCl₃ (1 mM) was added drop-wise into this solution. The solution was thoroughly mixed and allowed to react for at least 2 h at room temperature prior to analysis [10].
2.4 Samples Preparation for Fourier Transform Infrared Spectroscopy (FTIR)

For all FTIR measurements in this work about 5μL of the prepared Plm/DNA nanowires films were drop-cast on clean Si (100) substrate and left to dry for 1h prior to measurements. FTIR spectra were acquired using a Shimadzu FTIR (IRAffinity-1S). Spectra were recorded in the range 400–4000 cm⁻¹, with 128 scans at 4 cm⁻¹ resolution and a clean Si (100) substrate was used as a background.

2.5 Samples Preparation for Ultraviolet–Visible Spectroscopy (UV-vis)

For UV-vis measurements, 2 mL of aqueous CT-DNA (162.5 ng μL⁻¹) solution was mixed with 0.5 mL freshly prepared imidazole solution in the presence of 0.5mL MgCl₂ (0.5 mM). Then, 0.5 mL of FeCl₃ (1 mM) was added drop-wise to the solution. The mixture was stirred and allowed to react at room temperature for 1 h. UV-vis absorption spectra were recorded on a CARY 100 BIO spectrophotometer at room temperature. Water was used as the background. The absorbance values reported have been scaled to a standard path length of 1 cm by the instrument software.

2.6 Samples Preparation for X-ray Photoelectron Spectroscopy (XPS)

Samples were prepared for XPS by drop-casting ~20 µL of solution onto a clean Si(100) substrate and then left to dry in air at room temperature in a laminar flow hood. A Theta Probe photoelectron spectrometer was used to collect photoemission spectra. The binding energies obtained in the XPS analysis were calibrated using Carbon (284.8 eV) as a reference. Photoemission spectra were fitted with a combination of mixed singlet components using the CasaXPS software version 2.3.16 from Casa Software Ltd. Backgrounds were subtracted by the Shirley method [11].

2.7 Samples Preparation for Transmission Electron Microscopy (TEM)

Samples (5 μL) were cast dropped on copper grids and placed on a laminar flow hood to dry for 5 h. Transmission electron microscopy experiments in this research were carried out with Philips CM100 TEM (FE1) using Holey carbon films in a mesh of copper grids as substrate and camera images were acquired with AMT CCD (Deben).

2.8 Samples Preparation for Scanning Electron Microscopy (SEM)

Five microlitres (5 μl) of samples were cast dropped on treated n-Si (100) wafers. The deposited samples were dried in a C-Flow vertical unidirectional over night before SEM analysis. The SEM analysis was carried out using JEOL JSM-5610LV Scanning Electron Microscope and some samples were coated with few nanometers of gold film using sputter coater machine.
2.9 Electrical Measurements

Two-terminal conductivity measurements were conducted using Pt microband electrodes deposited on clean silanized Si/SiO₂ chips. A 2 μl drop of an aqueous solution of Pln/DNA nanowires was placed on these electrodes and aligned across the gap between the Au fingers by molecular combing. A Cascade Microtech 110008-M probe station with Agilent B1500A Semiconductor Device Analyzer controlled by B1500A’s EasyEXPERT software was used for the measurements. Prior to electrical testing, the two-terminal device undergoes a heating/cooling cycles from 223 to 423 K by using a heating/cooling chuck, under nitrogen gas supply to drive up any water bound to the Pln/DNA nanowire. All the electrical measurements were carried out under dry nitrogen without illumination in the shielded sample compartment of the probe station.

Current-voltage measurement from 223 to 423 K was performed on the probe station using a thermal chuck system. For each of the electrical tests, the current was measured for applied voltages from -2 to 2 V in steps of 0.2 V.

3. Results and Discussion

3.1 FTIR characterization of Plm/DNA nanowires

Figure 1 display the joined IR spectra of both Plm and imidazole, in Plm nanostructures spectra, the band located at 1640 cm⁻¹ is attributed to N-H bend/–C=Cs– and the one at 1527 cm⁻¹ is due to C-H stretching in ring. The peak at 1327 cm⁻¹ in both Plm and imidazole, are due to C-N stretching in aromatic compounds. In same region, bands at 1527 cm⁻¹ in Plm spectra and the one at 1535 cm⁻¹ in imidazole are both ascribed to C-C stretching in ring just like the bands at 1640 and 1647 cm⁻¹ respectively, are assigned to N-H bending and –C≡C- stretching. In contrast, peaks at 1065 and 1258 cm⁻¹ were observed in imidazole but disappeared in polyimidazole, which may be due to the polymerization of the imidazole monomer [12-14].
According to previous studies [15-17] imidazole molecular structure shows the presence of C-H stretching vibrations in the regions greater than 3000 cm$^{-1}$ which is characteristic region for the ready identification of SP$^2$ C-H stretching vibrations and at this region, the bands are not affected considerably by the nature of the substituents. But an N–H stretching band is observed in the 3500-3200 cm$^{-1}$ region; this position depends upon the degree of hydrogen bonding. They exhibit characteristic band patterns in the 1600-1300 cm$^{-1}$ ring stretching region which pattern is affected by the nature of the substituent. At 800-600 cm$^{-1}$ region the pattern of out-of-plane C–H bending bands are the characteristic of these compounds.

In order to provide evidence that intimate interaction of polyimidazole and DNA chains in the self-assembled nanowires is indicated by FTIR, comparative transmission spectra of Plm/DNA and controls (free DNA and Plm) is shown in Figure 2, the strong sharp peak at 748 cm$^{-1}$ spotted in the imidazole spectrum is characteristic of the N-H wag mode; it becomes broad and shifts to 732 cm$^{-1}$ in Plm/DNA nanowire. The C-C stretch peaks due to imidazole (1527 cm$^{-1}$) have remained in the Plm/DNA material (1527 cm$^{-1}$) spectrum, indicating that the hybrid polymer contains both the polymeric materials and DNA [15].
Figure 2. FTIR Transmission spectra of Plm/DNA (orange) vs. spectra of free λ-DNA (green) and Plm (blue). 128 scans co-added and averaged 4 cm\(^{-1}\) resolutions. The spectra are offset for clarity.

Finger print region FTIR transmission spectra comparison of DNA and PlmDNA nanowires from same figure above reveals, a secondary amine N-H wag frequency between 700-800 cm\(^{-1}\); C-N stretching between 1100-1200 cm\(^{-1}\) and the C=O stretches of cytosine, guanine and thymine between 1600-1800 cm\(^{-1}\). These data demonstrated that there were slight changes in the hydrogen bonding environment between PlmDNA nanowires and DNA samples. The transmittance peaks that were observed from 900-1000 cm\(^{-1}\) for both DNA and PlmDNA samples can be assigned to bending vibration of water molecules due to moisture absorption by samples [18].

Table 1. Selected finger print bands in DNA and Plm/DNA spectra and their assignments

| Wave number in DNA (cm\(^{-1}\)) | Wave number in Plm/L (cm\(^{-1}\)) | Peak Shift (cm\(^{-1}\)) | Assignment [19-20] |
|---------------------------------|----------------------------------|--------------------------|-------------------|
| 687                             | 664                              | -23                      | C-C bending vibrations |
| 964                             | 910                              | -54                      | C-C deoxyribose stretch |
| 1087                            | 1056                             | -31                      | Symmetric PO\(_2\) stretch |
| 1505                            | NO                               | -                        | In-plane vibration of cytosine and Guanine |
| 1550                            | 1527                             | -23                      | Purine stretching (N7) |
| 1690                            | NO                               | -                        | Thymine (C2 = O stretching) |
| 1219                            | NO                               | -                        | Asymmetric PO\(_2\) stretch |
| 1465                            | NO                               | -                        | In-plane vibration of cytosine |

NO, not observed

A more detailed tabulated analysis of the finger print region of DNA and PlmDNA (Table 1) reveals that C-C bending vibrations were assigned to the peaks at 687 and 664 cm\(^{-1}\) respectively, while C-C
deoxyribose stretch for both DNA and PlmDNA were observed at 964 and 910 cm$^{-1}$ individually. The symmetric PO$_2^-$ stretch; asymmetric PO$_2^-$ stretch; in-plane vibration of cytosine and Guanine; Purine stretching (N7); in-plane vibration of cytosine and Thymine C2 = O stretching (1087, 1505, 1550, 1464, 1219 and 1690 cm$^{-1}$) were found to shifts to lower frequencies or absent in the hybrid material (910, 1056 and 1527 cm$^{-1}$ and absent).

It can be concluded that from the IR transmission spectra results that some changes in the DNA-related bands to different values in Plm/DNA spectra after the synthesis of the nanowires, proves the interaction of the Plm and DNA during the templating and that the prepared nanowires are not mere mixtures of Plm and DNA molecules which is similar to other studies [21].

3.2 UV-vis characterization of Plm/DNA nanowires

Figures 3 show the UV-vis absorption spectra of free DNA, polyimidazole and Plm/DNA. Imidazole derivatives absorb UV light because of the presence of conjugated pi (π) bonding systems (π-π* transition) and nonbonding electron system (n-π* transition). There are certain energy gaps between π-π* and n-π* orbitals. From the figure, it was observed that structural changes occurred in synthesized imidazole nanowires as compared to controls (Plm and free DNA), which were not sufficiently large to alter UV-visible spectral properties in solution state. Polyimidazole DNA-templated nanowires compared to free DNA exhibited both hypsochromic and bathochromic effect in absorbance maxima (λ$_{max}$) 267 and 290 nm respectively. Whereas, it exhibited only bathochromic shift at the same absorbance maxima (λ$_{max}$) compared to 277 nm for Plm. These π-π* and n-π* electron transitions are as a results of the presence of conjugated chromophores in the compound [22].

The continuous variation of wavelength and intensity of UV-vis bands may result from the copolymerization effect of polyimidazole with DNA. Put differently, the polymer formed by oxidative polymerization of imidazole with DNA is a complex mixture of two substances rather than the mixture of two homopolymers as shown in our UV-vis results [23]. This is similar to FTIR results.
Figure 3: UV-Vis absorption spectra at different stages of the synthesis process: absorption spectra of aqueous 3 mM Plm (green); free DNA (red) and PlmDNA (blue)

3.3 XPS characterization of Plm/DNA nanowires

XPS survey spectra of Plm/DNA samples (Figure 4) exhibit the presence of the elements C, N, O, Cl, and (weakly) P. Clear evidence for the presence of DNA in the sample material was obtained from the P2p signal at 133.2 eV, arising from the phosphorus in the phosphodiester backbone of the DNA. No signature of the presence of iron was observed in the survey spectra which confirm that the FeCl₃ was used only to drive the polymerization without any oxidative damage to DNA (the Cl observed is likely from MgCl₂)

Figure 4: XPS Survey scan chart of Plm/DNA nanowire at pass energy of 20 eV and the step size of 0.3 eV. Some higher resolution spectra were recorded with pass energy of 40 eV and a step size of 0.1 eV.
The N1s and C1s spectra of PIm/DNA samples examined in this study are presented in Figures 5a and b respectively. Three main peaks were observed in the N1s spectrum of PIm/DNA (399.3, 400.3 and 401.7 eV). Previous researchers have observed two components in the N1s spectra of DNA alone - the lower binding energy component at 398.8 eV and another at 400.6 eV. The lower energy peak is ascribed to neutral N atoms. The component at 400.6 eV is observed for peptidic N atoms and is also typical of the N atoms in the pyrimidines of DNA [24-25].

While it is likely that the two lowest energy peaks in the N1s spectra of PIm/DNA contain similar contributions from the DNA, there will also be a contribution to these features from the N atoms of polyimidazole according to the extent of protonation and doping level. This is consistent with previous reports on polyindole [26] and polypyrrole [27] in which it was proposed that the higher binding energy components are due to nitrogen atoms that bear a positive charge and are in chemically or structurally inequivalent environments. The third component at 401.7 eV in our spectra is not present in N1s spectra of DNA and can be assigned to polyimidazole alone. N1s spectra of polypyrrole have similarly been reported to contain a major peak at 400.6 eV and a higher binding energy signal at 402.5 eV; these were attributed to (- NH+) and (= NH +), respectively [28]. Therefore the third component in our PIm/DNA samples, with a binding energy of 401.7 eV, can be assigned to positively charged nitrogen atoms associated with the charge carriers in PIm.

The C1s spectra (Figure 5b) can be resolved into four different components centered at 284.9, 286.6, 288.3, and 289.2 eV. Four components have also been observed in C1s spectra of pure DNA by previous workers, although the peak at 284.4 eV is dominant in pure DNA [29]. The two components at the lowest binding energy were assigned to C-H, C-C, and C-N species from PIm and DNA. The third peak at 287.3 eV is ascribed to carbons in functional groups of the type, C=N or C-N’, mainly from PIm because this feature is more intense relative to the 284.9 and 286.6 eV components in our samples than in pure DNA.
Considering that the fourth peak at 289.0 eV is comparable to that at 284.9 eV in our samples, but is very weak in pure DNA, it was assigned to C=N+ carbons in Plm.

In general, the XPS spectra of Plm/DNA show large contributions from species assigned to Plm, which indicate that the Plm/DNA nanowires can be visualized as a thick coat of Plm on the DNA template instead of small number of Plm chains wrapping around the DNA while chloride ions make up the required counter charge.

3.4 AFM characterization of Plm/DNA nanowires

Figures 6a-d delineate AFM height images of Plm/DNA nanostructures placed on plasma treated Si/SiO₂ wafers surfaces in this study. The images exhibit different morphologies with agglomerate nanostructures for the diluted film, while dense rope like network of nanostructures were observed for undiluted templated polymers.

![AFM height images of Plm/DNA nanostructures](image)

**Figure 6.** (a) Tapping mode AFM height images of Plm/DNA nanostructures aligned on Si/SiO₂ substrate after 24 hours incubation (a) Plm/DNA agglomerate structures (b) Individual spherical shape disperse nanostructures (c) individual wires unfolding from the dense film (d) dense rope like network of undiluted Plm/DNA ropes like nanostructures.

This agglomeration is likely due to either free polymer or the presence of residuals of buffer salts or both. Additional possibility is condensation of DNA strands due to shielding of charges on the phosphate groups of the DNA by the action of metal ions [30-31].
Statistical study carried out on 150 Plm/DNA nanowires shows the distribution of the diameters, with a modal diameter of 3-4 nm (Figure 7). Small number of larger structures can be seen in the chart with diameters greater than 13 nm. Previous studies attributed these larger structures to the wrapping/bundling of the Plm/DNA structures into larger rope-like assemblies formed in the solution and concluded that the formation of polymer on DNA takes place initially through the low density of binding spherical-shaped conducting polymer particles on the duplex DNA templates [32].

3.5 TEM characterization of Plm/DNA nanowires

Figure 8 shows the TEM images of Plm/DNA nanowires absorbed on carbon coated copper grid with different morphologies comprising of (a) dense networks, (b-c) align rope/thread like Plm/DNA nanomaterials and (d) DNA-templated nanomaterials bridging the holes in the substrate. These images further revealed the nanowires to be continuous and uniform in the bounding of polymers to the DNA. The images shows similar morphologies as shown in the AFM images, even though they are not as explicit as AFM since DNA is not easily observed by TEM due to a lack of contrast and usually requires a stain to image the nanostructure or using other innovative techniques.
Figure 8: TEM images of Plm/DNA absorbed on copper grid: (a) nanostructures films/network (b) aligned Plm/DNA film showing the joining/bridging of the nanomaterials (c) thread/rope like image (d) TEM image bridging across hole in a copper grid. Scale bar = 100 nm

3.6 SEM Characterization of Plm/DNA Nanowires

Figure 9: Plm/DNA and water diluted Plm/DNA sputtered with gold, SEM images on Si/SiO$_2$ surface: (a-b) thick films of the Plm/DNA materials (c-d) fern like network structures of diluted Plm/DNA. Scale bar = 5 nm.
Like other polymers, the SEM micrographs for the undiluted Plm/DNA in Figures 9(a-b) revealed a dense film of the DNA template polymer composite which may result from the agglomeration of the material. But the diluted Plm/DNA materials are loosely bond, that the SEM images in Figures 9(c-d) indicate a fern like morphologies for the Plm/DNA [33].

3.7 Electrical characterization of Plm/DNA nanowires

In order to investigate the conduction mechanism and electrical behaviour of the Plm/DNA nanomaterials current voltages measurements were carried out using a four terminal probe. Sweeps at different probe needles point, gives noisy and show negligible current (<1pA) around zero bias indicating high resistivity.

![Current-Voltage plots](image)

*Figure 10. Current-Voltage plots for Pt and free lambda-DNA aligned across Pt electrodes as control*

To check the instrument for comparison and proved that the current measured is from the Plm/DNA, measurements were made on a single platinum microelectrode point and free lambda DNA aligned across the Pt electrodes. The result is displayed in Figure 10; the curves for both the Pt electrode and the lambda DNA which displayed Ohmic behaviour in the pA regime at close to zero bias, but the currents are very low and may include contribution from ion transport.
Additionally to test the claim that the polyimidazole DNA-templated nanowire’s bridges were responsible for the electrical conduction. Current-voltage sweepings in the range of -2 to +2 V at a constant temperature of 20 °C were measured. As shown in Figure 11, the polyimidazole DNA-templated bulk nanomaterials shows a significant current value when compared to Pt and DNA. The current voltage control measurements support the assertion that the Plm/DNA bridges are responsible for the electrical conduction, therefore they have electrical conductivity.

Current-voltage measurements over a range of temperatures were performed to provide useful qualitative and quantitative information regarding I-V behaviour and to elucidate details of conduction mechanism. This method relies on the alignment of the nanowires by spreading molecular combing method across two micro fabricated Pt electrodes on a thermally oxidized Si chip. Variable-temperature I-V studies of the two-terminal device were performed over a temperature range of 223 to 423 K to elucidate details of the conduction mechanism.
In Figure 12, the resulting I-V curves are presented, which shows linearity at low voltages and exhibit a reproducible, linear response at a range of temperatures at low bias and displayed an increase in current output with increase temperature which is consistent with results of similar measurements on DNA-templated conductive polymers nanowires in other studies [34-37].

Many researchers have suggested that another way to view the metal/polymer or nanowire/metal system is to consider the charge transport process in the same framework as that proposed for thin films of redox polymers like ours. They behave very differently to inorganic semiconductors because of high doping level therefore; the ion transport cannot be explained by Nernst Plank equation, which described the flux of ions under the influence of both an ionic concentration gradient and an electric field [38-40].

Analysis of the temperature dependence of conductance in conjugated polymers gives a more in-depth of the conduction mechanism and is typically carried out through fitting conductance (G) values to the following equation:

\[
\ln G = \ln G_0 - \left(\frac{T_0}{T}\right)^\beta
\]  

This expression is used when describing the conductance behaviour of a conjugated polymer system through a variable range hopping (VRH) model. This in turn describes the low temperature conductance behaviour in strongly disordered systems where electronic states are localized. In this approach, the
outcome is dependent upon the dimensionality of the system which is described by the parameter β=1/(1+D), where ‘D’ is the dimensionality of the system.

Figure 13 shows the corresponding Arrhenius plot of the conductance of the Plm/DNA. The plot displayed the temperature dependence of the rate constant and suggests simple electron hopping is the dominant mechanism for electron transport, shown through the exponential behaviour of the conductance upon increasing the temperature.

![Figure 13. Arrhenius plot for the conductance G of Plm/DNA nanowires](image)

The slopes of the Arrhenius plots in Figure 13 was analyzed to determine the activation energies associated with the hopping of charge in these polymer samples using the following equation:

\[ \ln G = \ln G_0 - \frac{E_a}{K_B T} \]  

(2)

The slopes are \(-E_a/k_B\) for \(E_a\) in J mol\(^{-1}\) and \(-eE_a/k_B\) where \(e\) is the charge on a proton, \(K_B\) is the average kinetic energy and \(E_a\) is in eV.

Activation energy \((E_a)\) including the uncertainty on it for the Plm/DNA bulk nanowires calculated was 10.6 ± 0.5 x 10\(^{-3}\) J mol\(^{-1}\) equivalents to 0.110 ± 0.005 eV which is lower than 0.43 ± 0.02 eV reported in similar studies. The band gap of most conductive polymers is of order 3 eV that would predict \(E_a\) equal to 1.5 eV if the process was limited by thermal excitation across the gap. Instead, in our studies \(E_a\) is <1 eV. This is because the process is thermally-assisted tunneling between localized sites [41].
4. Conclusion

In this research work, nanostructured DNA-templated polyimidazole nanowires were synthesized by simple and low-cost fabrication method that applied DNA as a template for the polymerization. From IR results, changes in the DNA-related bands to different values in Plm/DNA spectra after the synthesis of the nanowires, proves the interaction of the Plm and DNA during the templating and that the prepared nanowires are not mere mixtures of Plm and DNA molecules. Similarly, UV-vis results have shown that, the polymer formed by oxidative polymerization of imidazole with DNA is a complex mixture of two substances rather than the mixture of two homopolymers. The XPS spectra of Plm/DNA show large contributions from species assigned to Plm, which indicate that the Plm/DNA nanowires can be visualized as a thick coat of Plm on the DNA template instead of small number of Plm chains wrapping around the DNA while chloride ions make up the required counter charge. Morphological (AFM, SEM and TEM) studies exhibited different morphologies with agglomerate nanostructures for the diluted film, while dense rope like network of nanostructures were observed for undiluted templated polymers with diameter of 2-13 nm.

Activation energy ($E_a$) including the uncertainty on it for the Plm/DNA bulk nanowires calculated was $10.6 \pm 0.5 \times 10^{-3}$ J mol$^{-1}$ equivalents to $0.110 \pm 0.005$ eV which is not surprising because the process is thermally-assisted tunneling between localized sites.

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