Supporting Information

Demonstration of Hole Transport and Voltage Equilibration in Self-Assembled Pi-Conjugated Peptide Nanostructures Using Field-Effect Transistor Architectures

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PEPTIDE SYNTHESIS

General Considerations. The chemicals used for 9-fluorenylmethoxycarbonyl (Fmoc)-based solid phase peptide synthesis (*N*-methylpyrrolidone (NMP), *O*-(benzotriazol-1-yl)-*N,N,N',N'*-tetramethyluronium hexafluorophosphate (HBTU), benzotriazol-1-yl-oxytripyrrolidinophosphonium hexafluorophosphate (PyBOP), *N*,*N*-diisopropylethylamine (DIPEA), Wang resin, and Fmoc-protected amino acids) were obtained from Oakwood Products, Inc. or Advanced ChemTech. Tetrahydrofuran (THF) was obtained from an Innovative Technologies PureSolv solvent purification system and stored over 4Å molecular sieves (Sigma-Aldrich). *N*,*N*-dimethylformamide (DMF) was obtained from either Sigma-Aldrich or EMD Millipore Chemicals. DIPEA, THF and DMF were degassed by sparging with nitrogen (N_2) gas for one hour prior to use. Tetrakis(triphenylphosphine)palladium ($Pd(PPh_3)_4$) was obtained from Strem Chemicals. The Biotech-grade cellulose ester dialysis tubings (MWCO 500-1000), with flat widths of either 16-mm or 31-mm were obtained from Spectrum Labs. All other reagents and starting materials were obtained from Sigma-Aldrich and were used as received. 5-bromothiophene-2-carboxylic acid and 5,5'-bis-tributylstannyl-[2,2']-bithiophene were prepared using literature procedures.[1] The ^{1}H-NMR spectra were obtained using a Bruker Avance 400 MHz (unless otherwise stated) and the data was processed using Bruker Topsin 1.3. Chemical shifts are reported in parts per million relative to residual protio solvent [d_6-DMSO δ: 2.50, D_2O δ: 4.79 (^{1}H NMR)]. The tabulated values for NMR peaks may not reflect the theoretical number of protons expected due to some aggregation previously observed for these materials under basic to neutral conditions.[2]

General Solid Phase Peptide Synthesis (SPPS). All peptides were synthesized using the standard Fmoc solid-phase technique with Wang resin pre-loaded with the terminal amino acid (Wang-Asp= 0.6 mmol/g). To the resin in a peptide chamber, Fmoc-deprotection was accomplished by adding a (1:4) piperidine/DMF solution twice (successive 5- and 10-minute treatment) and then washing with NMP, methanol and dichloromethane (DCM). For the amino acid couplings, 3.0 eq. of the Fmoc-protected amino acid (1.0 eq of the Fmoc-deprotected peptide bound to the resin) underwent external activation

with 2.9 eq. of HBTU and 10 eq. DIPEA. The activated amino acid mixture was mixed for one minute prior to addition in the peptide chamber. The reaction mixture was allowed to mix for 60-120 minutes, after which was rinsed with NMP, methanol and DCM. The completion of all couplings was monitored using a Kaiser test on a few dry resin beads, repeating same amino acid coupling as needed. The general procedure for amino acid coupling was repeated until the desired peptide sequence was obtained.

General *N*-acylation procedure for peptides. Following a procedure reported in the literature,[1] a solution containing 2.1 eq. of 5-bromothiophene-2-carboxylic acid that was activated by HBTU (2.0 eq.) with DIPEA (10 eq.) was mixed for 180 minutes with the resin containing the completed peptide sequence. The resin was rinsed with NMP, methanol and DCM. The resin was treated again with 1.1 eq. of 5-bromothiophene-2-carboxylic acid that was activated by HBTU (1.0 eq.) with DIPEA (10 eq.) for 60 minutes. After rinsing the resin with the standard wash cycle (NMP-methanol-DCM), completion was assessed using a Kaiser test on a few dry resin beads. Treatment with 1.1 eq. of the activated 5-bromothiophene-2-carboxylic acid was repeated as needed.

General on-resin Stille coupling procedure. Following a procedure reported in the literature,[1] the *N*-acylated peptide made by following the general procedures described above were transferred to a Schlenk flask topped with a reflux condenser. The dried resin with $Pd(PPh_3)_4$ (4.0 mol % relative to the amino acid loading in the resin) was kept in the Schlenk flask under a nitrogen (N_2) atmosphere (~10-20 mTorr). In a separate vessel, a ~15 mM solution of 5,5'-bis-tributylstannyl-[2,2']-bithiophene was prepared in DMF. This was then added to the reaction flask via syringe. The reaction mixture was heated up to 80^{o}C while agitating by constantly bubbling nitrogen (N_2) gas in the solution. The said conditions were maintained for 16 hours, and then the reaction mixture was allowed to cool to room temperature. The resin was washed with DMF (3×) in a peptide chamber, followed by the standard wash cycle. The synthesized π-conjugated peptides were then subjected to cleavage procedure.

General cleavage procedure for peptides. The cleavage cocktail was prepared with 9.5 mL of trifluoroacetic acid, 250 μL Milli-Q water, and 250 μL of triisopropylsilane. The resin was treated with 10 mL of cleavage cocktail in a peptide chamber for 3 hours. The filtrate was drained and the resin was

washed with DCM (3×). The filtrate was concentrated under reduced pressure. The crude peptide was precipitated out of the filtrate by adding 90 mL of cold Et_2O, allowing the suspension to sit for 5 minutes at 4°C. The pellet formed was isolated by centrifugation, followed by decanting the solvent and drying the solid formed. The pellet was redissolved in Milli-Q water with a few drops of ammonium hydroxide (to completely dissolve the solid) and was subjected to lyophilization. All peptides (both crude and purified) were stored as lyophilized solids at 4°C.

DGG-4T Peptide (HO-DGG-4T-GGD-OH). Prepared according to literature procedure;[3] characterization matched that of literature.

DAA-4T Peptide (HO-DAA-4T-AAD-OH). Prepared according to literature procedure;[3] characterization matched that of literature.

DVV-4T Peptide (HO-DVV-4T-VVD-OH). Prepared according to literature procedure;[3] characterization matched that of literature.

DII-4T Peptide (HO-DII-4T-IID-OH). Prepared according to literature procedure;[3] characterization matched that of literature.

EGG-4T Peptide (HO-EGG-4T-GGE-OH). Solid-supported Wang-EGG-NH_2 peptide *N*-acylated with 5-bromothiophene-2-carboxylic acid was prepared (0.5 mmol). The peptide was coupled with 5,5'-bis-tributylstannyl-[2,2']-bithiophene (0.25 mmol, 0.186 g) in the presence of $Pd(PPh_3)_4$ (0.02 mmol, 0.023 g) using the general on-resin Stille coupling procedure for 14 hours. Resin was then subjected to the general cleavage procedure. Crude peptide obtained was observed as an orange powder (0.077 g, 34%). MS (ESI-) *m/z* 925.3 ($M-2H^+ + Na^+$) (calc. 925.1), *m/z* 903.3 ($M-H^+$) (calc. 903.1), *m/z* 451.3 ($M-2H^+$) (calc. 451.1). ^1H NMR (600 MHz, D_2O) δ, ppm: 8.37 (d, 1H, *J*= 3.6 Hz), 7.53 (s, 1H), 7.21 (s, 1H), 7.14

(d, 2H, *J*= 15.6 Hz), 4.11-4.08 (m, 1H), 4.05 (d, 1H, *J*= 3.0 Hz), 3.93 (d, 1H, *J*= 3.0 Hz), 2.20-2.17 (m, 1H), 2.05-2.00 (m, 1H), 1.89-1.84 (m, 1H).

EAA-4T Peptide (HO-EAA-4T-AAE-OH). The synthesis for **EAA-4T** peptide was adapted from ref. [4], with the exception that the resin was not washed with DMF, isopropanol, water, THF, acetonitrile, ether and hexanes prior to cleavage. Crude peptide obtained was observed as an orange powder; characterization matched that of literature.

EVV-4T Peptide (HO-EVV-4T-VVE-OH). Solid-supported Wang-EVV-NH_2 peptide *N*-acylated with 5-bromothiophene-2-carboxylic acid was prepared (0.5 mmol). The peptide was coupled with 5,5'-bis-tributylstannyl-[2,2']-bithiophene (0.25 mmol, 0.186 g) in the presence of $Pd(PPh_3)_4$ (0.02 mmol, 0.023 g) using the general on-resin Stille coupling procedure for 15 hours. Resin was then subjected to the general cleavage procedure. Crude peptide obtained was observed as an orange powder (0.102 g, 38%). MS (ESI-) *m/z* 1109.5 ($M-2H^+ + K^+$) (calc. 1109.3), *m/z* 1071.7 ($M-H^+$) (calc. 1071.3), *m/z* 535.5 ($M-2H^+$) (calc. 535.2). ^{1}H NMR (600 MHz, D_2O) δ, ppm: 8.37 (dd, 1H, *J*= 1.2 Hz), 7.59 (d, 1H, *J*= 3.6 Hz), 7.25 (s, 1H), 7.19 (m, 2H), 4.20 (dd, 2H, *J*= 8.4 Hz, 2.7 Hz), 4.13 (dd, 2H, *J*= 7.8 Hz, 2.7 Hz), 4.09-4.07 (m, 2H), 2.12 (t, 6H, *J*= 8.1 Hz), 2.07-2.03 (m, 5H), 1.96-1.94 (m, 3H), 1.84-1.80 (m, 3H), 0.95 (d, 8H, *J*= 3.0 Hz), 2.12 (t, 24H, *J*= 6.6 Hz).

EII-4T Peptide (HO-EII-4T-IIE-OH). Solid-supported Wang-EII-NH_2 peptide N-acylated with 5-bromothiophene-2-carboxylic acid was prepared (0.5 mmol). The peptide was coupled with 5,5'-bis-tributylstannyl-[2,2']-bithiophene (0.25 mmol, 0.186 g) in the presence of $Pd(PPh_3)_4$ (0.02 mmol, 0.023 g) using the general on-resin Stille coupling procedure for 16 hours. Resin was then subjected to the general cleavage procedure. Crude peptide obtained was observed as yellow/orange powder (0.055 g, 19%). MS (ESI-) *m/z* 1149.6 ($M-2H^+ + Na^+$) (calc. 1150.4), *m/z* 1127.7 ($M-H^+$) (calc. 1127.4), *m/z* 5-=63.5 ($M-2H^+$) (calc. 563.2). ^{1}H NMR (400 MHz, d_6-DMSO) δ, ppm: 8.48 (d, 1H, *J*= 8.8 Hz), 8.00 (d, 1H, *J*=

8.8 Hz), 7.96 (d, 1H, *J*= 7.2 Hz), 7.92 (d, 1H, *J*= 4.0 Hz), 7.42 (d, 1H, *J*= 4.0 Hz), 7.38 (dd, 2H, *J*= 4 Hz, 2.6 Hz), 4.35 (t, 1H, *J*= 9.00 Hz), 4.20-4.14 (m, 2H), 2.28-2.23 (m, 2H), 1.91-1.74 (m, 4H), 1.49-1.44 (m, 2H), 1.23-1.04 (m, 2H), 0.87-0.78 (m, 12H).

DVV-C10 Peptide (HO-DVV-$(CH_2)_{10}$-VVD-OH). 0.0288 g (0.125 mmol) of dodecanedioic acid and 0.0650 g (0.125 mmol) of PyBOP was dissolved in 10-mL of 2:1 NMP:DCM solution, after which 0.522 mL of DIPEA was gradually added then mixed for one minute. This solution was added to the solid-supported Wang-DVV-NH_2 (0.25 mmol) in a peptide chamber and mixed for 12 h. Resin was rinsed using the standard wash cycle. The general cleavage procedure was followed, only that the cleavage cocktail was diluted in a 1:1 ratio DCM and was mixed with the resin for 2 h. Crude peptide was obtained as a white powder (0.0565 g, 53%). MS (ESI-) *m/z* 893.5 ($M-2H^+ + K^+$) (calc. 893.6), *m/z* 427.2 ($M-2H^+$) (calc. 427.3). ^{1}H NMR (400 MHz, d_6-DMSO) δ, ppm: 7.83 (m, 2H), 7.72 (br), 7.71 (br), 4.24-4.12 (ddd, 4H, *J*= 32. 4 Hz, 8.8 Hz, 7.2 Hz), 2.17-2.10 (m, 2H), 2.03-1.97 (m, 2H), 1.47 (t, 2H, *J*= 9.2 Hz), 1.22 (s, 6H), 0.85-0.81 (m, 12H).

CHARACTERIZATION DATA

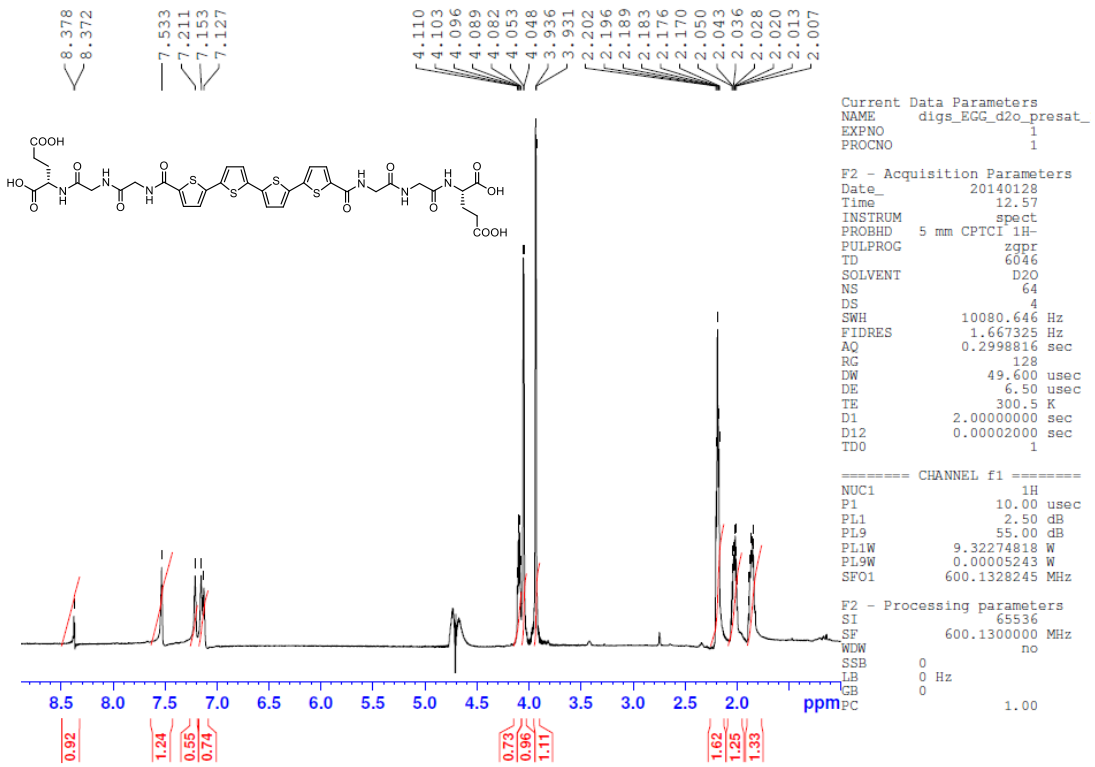

Figure S1. ^{1}H (600 MHz, D_2O) NMR spectrum of **EGG-4T** peptide.

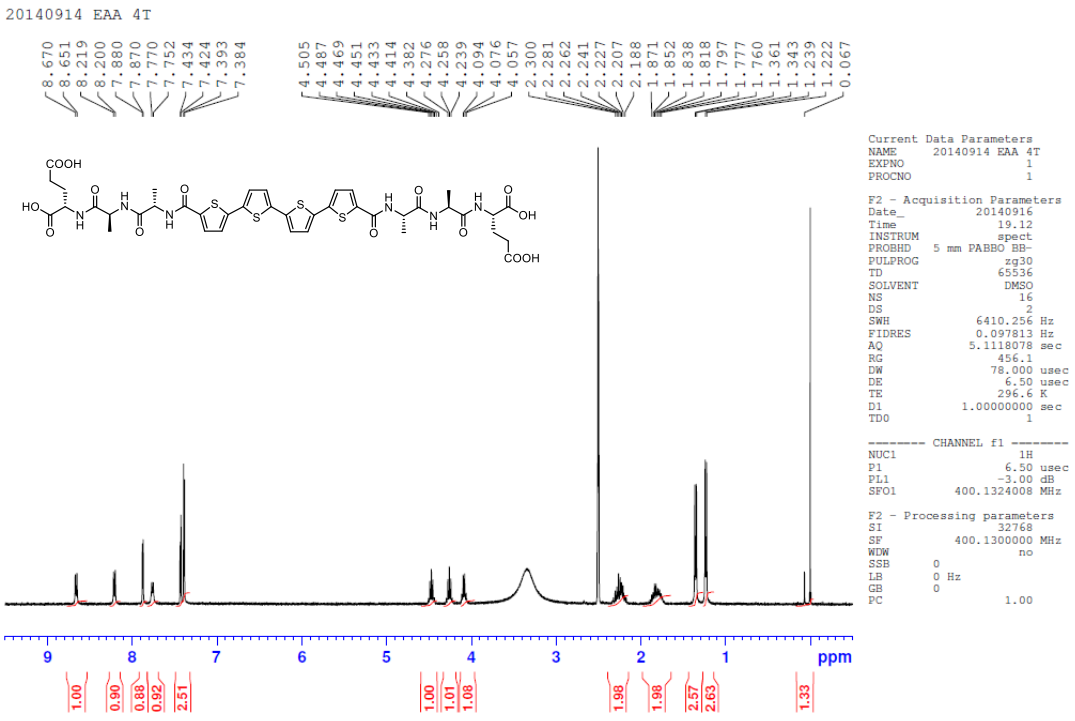

Figure S2. ^{1}H (400 MHz, d_6-DMSO) NMR spectrum of **EAA-4T** peptide.

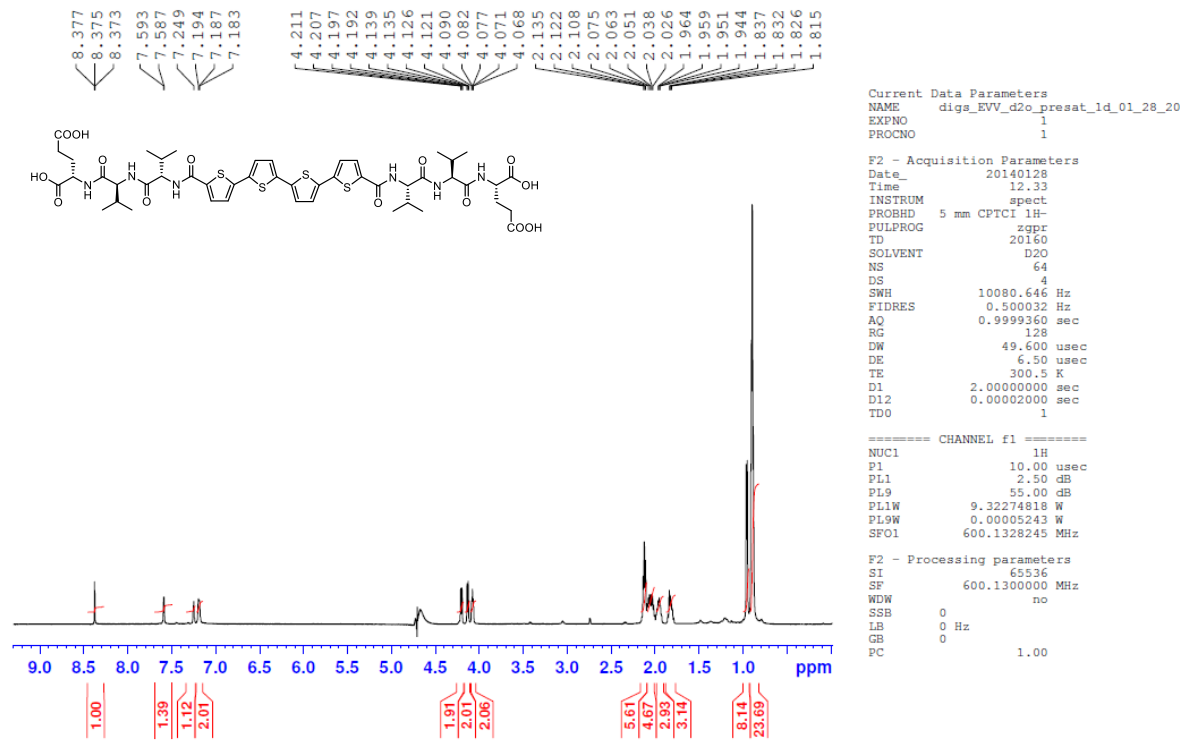

Figure S3. ^{1}H (600 MHz, D_2O) NMR spectrum of **EVV-4T** peptide.

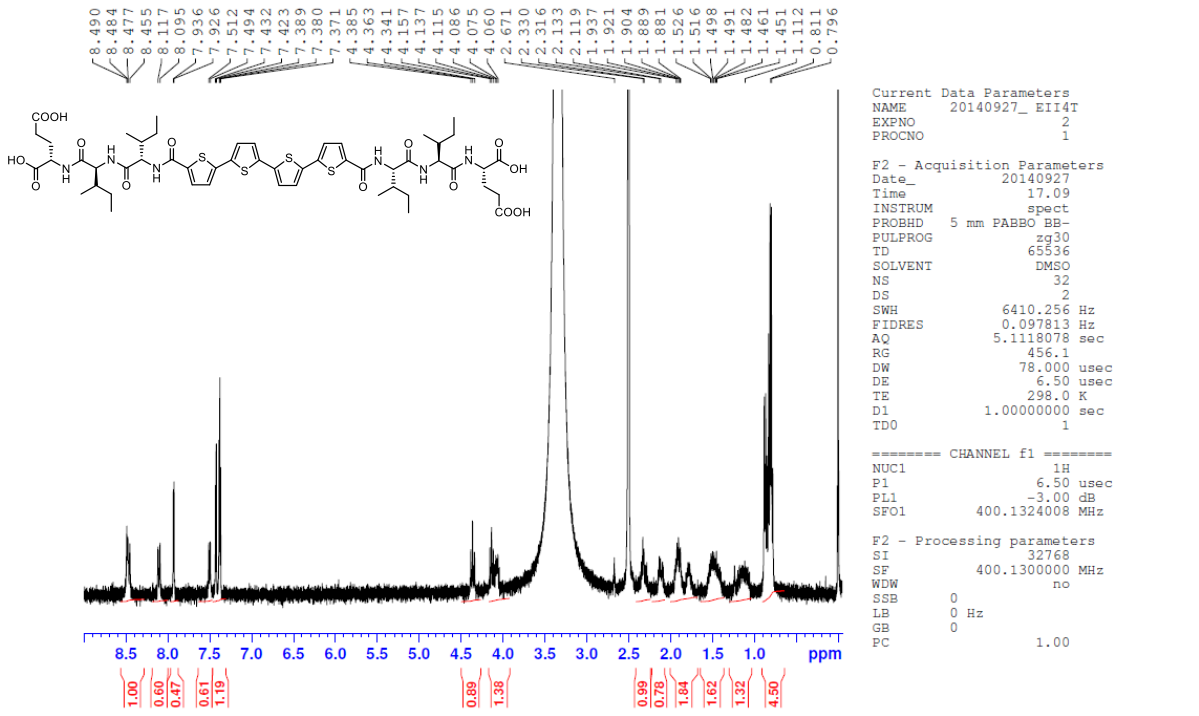

Figure S4. ^{1}H (400 MHz, d_6-DMSO) NMR spectrum of **EII-4T** peptide.

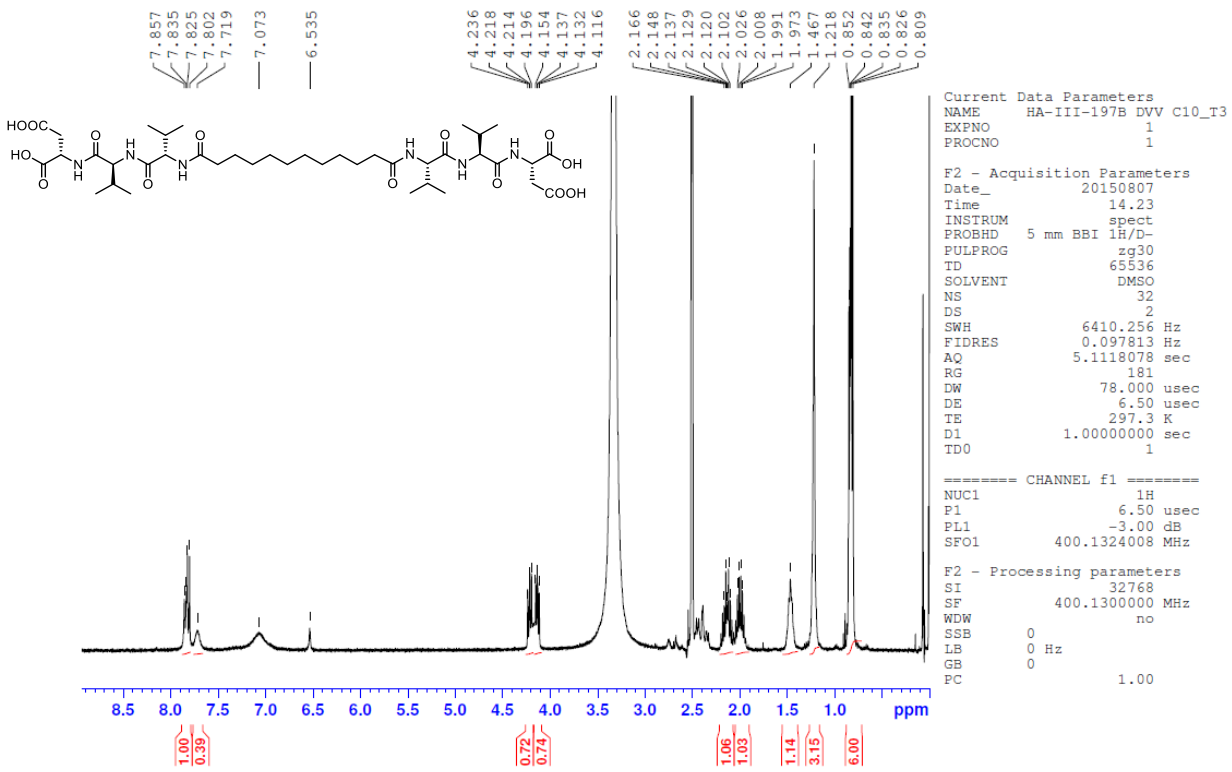

Figure S5. ^{1}H (400 MHz, d$_6$-DMSO) NMR spectrum of **DVV-C10** peptide.

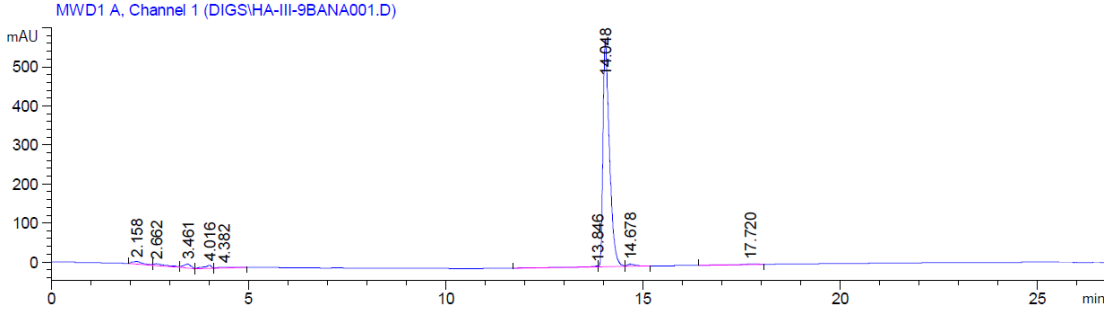

Figure S6. Analytical HPLC trace of **EGG-4T** peptide, monitoring at 400 nm.

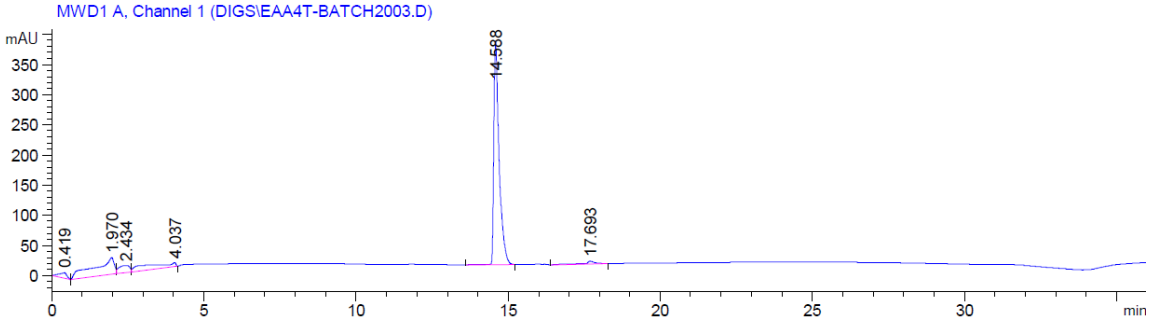

Figure S7. Analytical HPLC trace of **EAA-4T** peptide, monitoring at 400 nm.

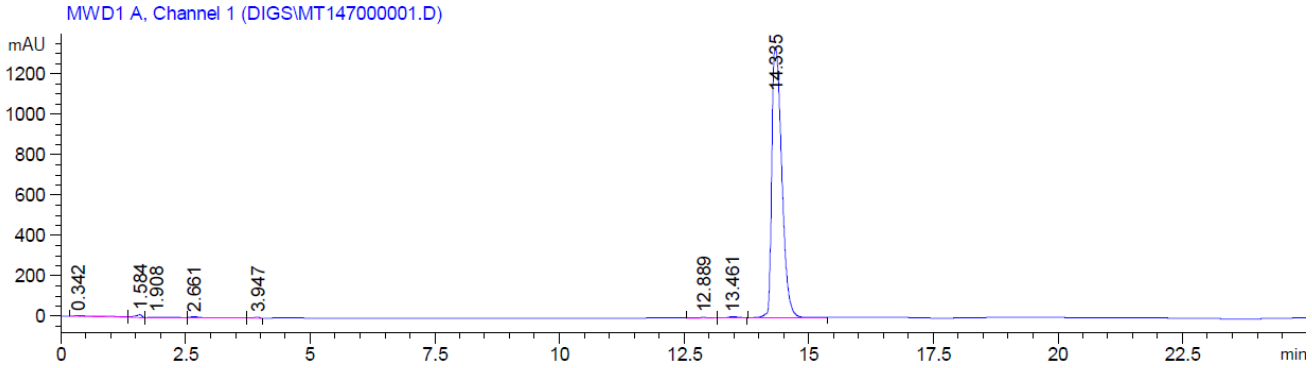

Figure S8. Analytical HPLC trace of **EVV-4T** peptide, monitoring at 400 nm.

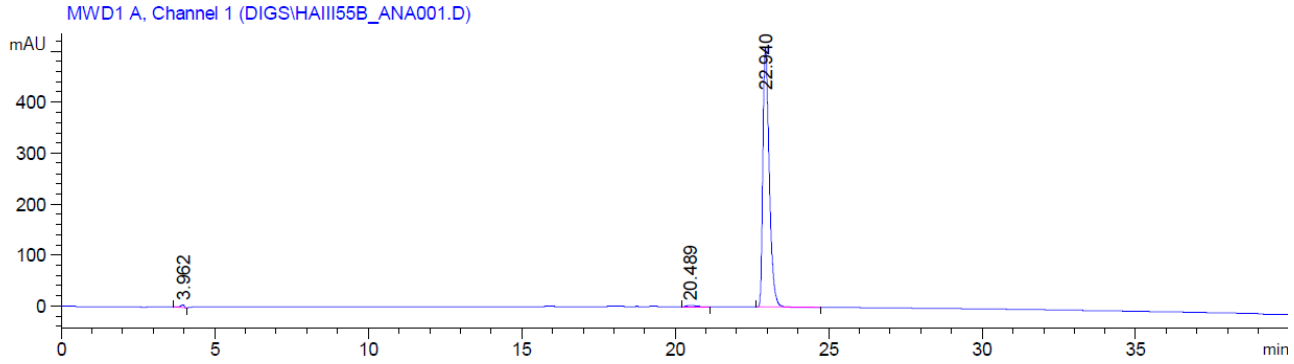

Figure S9. Analytical HPLC trace of **EII-4T** peptide, monitoring at 400 nm.

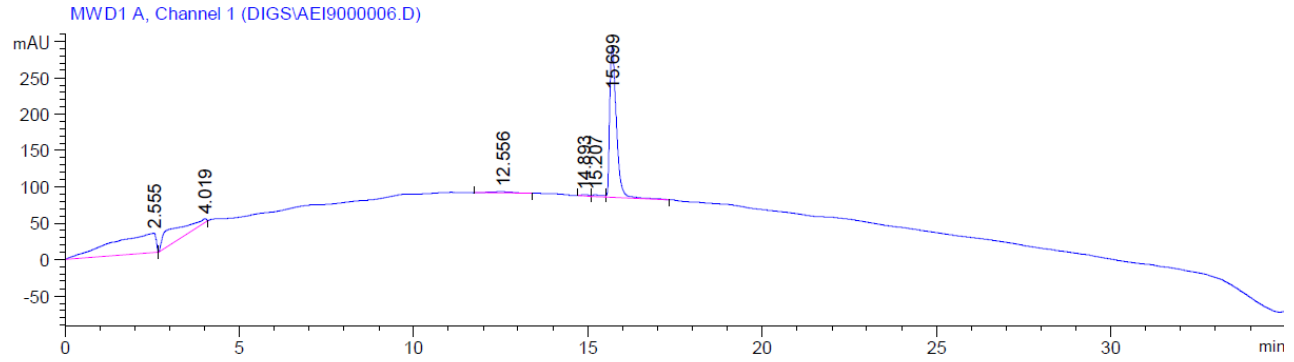

Figure S10. Analytical HPLC trace of **DVV-C10** peptide, monitoring at 220 nm.

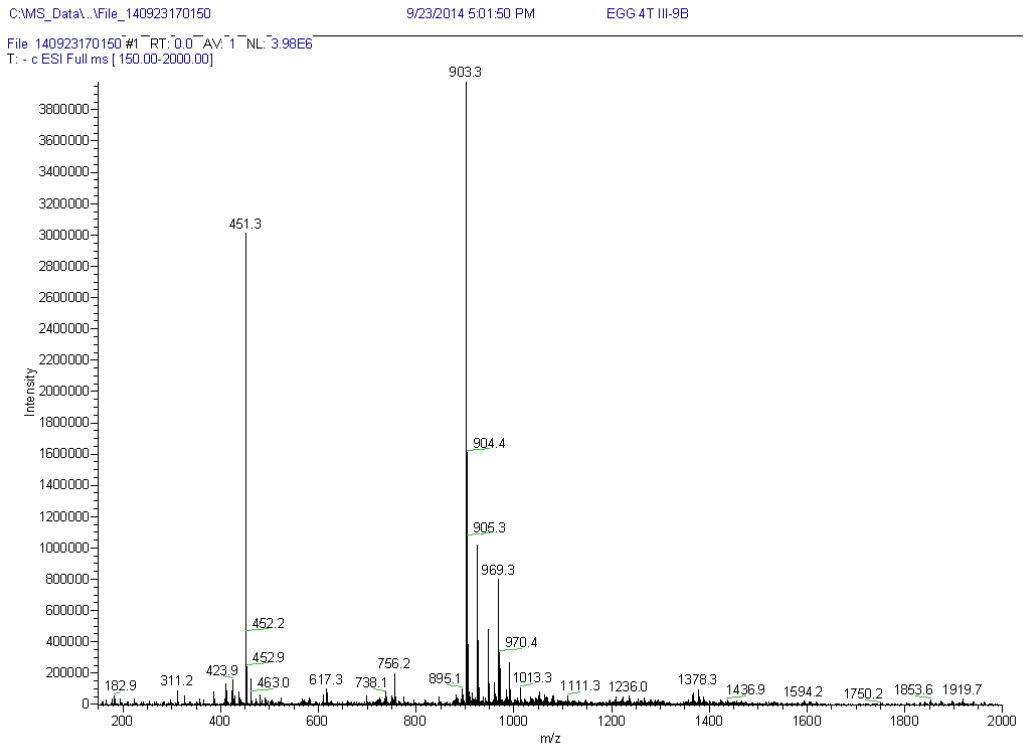

Figure S11. ESI spectrum of **EGG-4T** peptide.

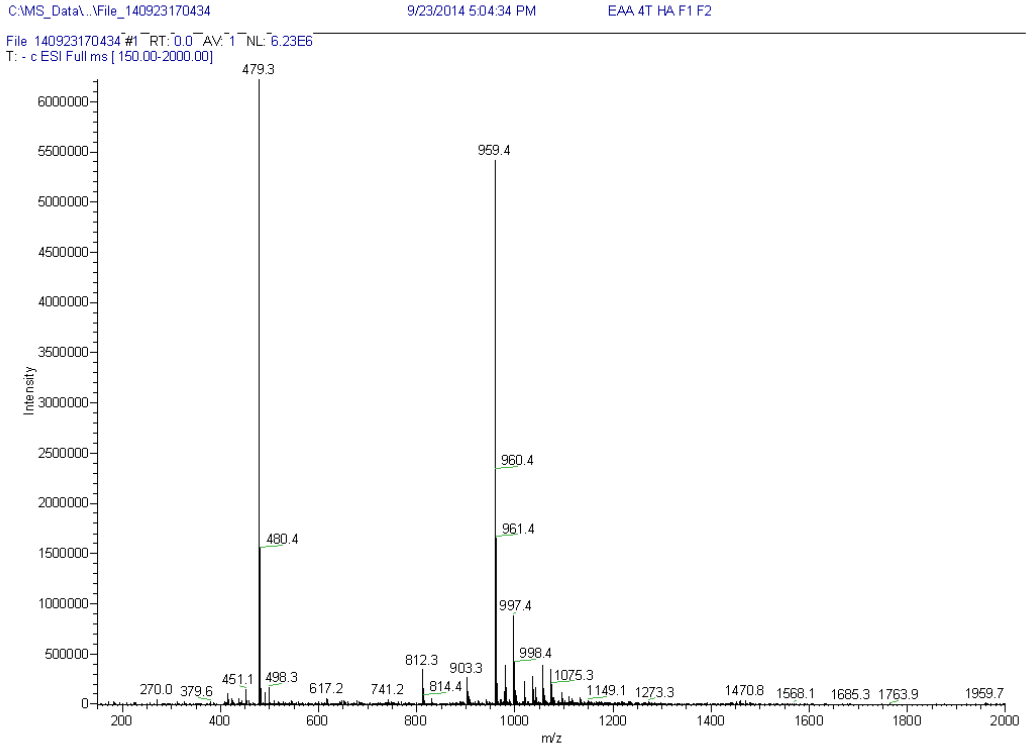

Figure S12. ESI spectrum of **EAA-4T** peptide.

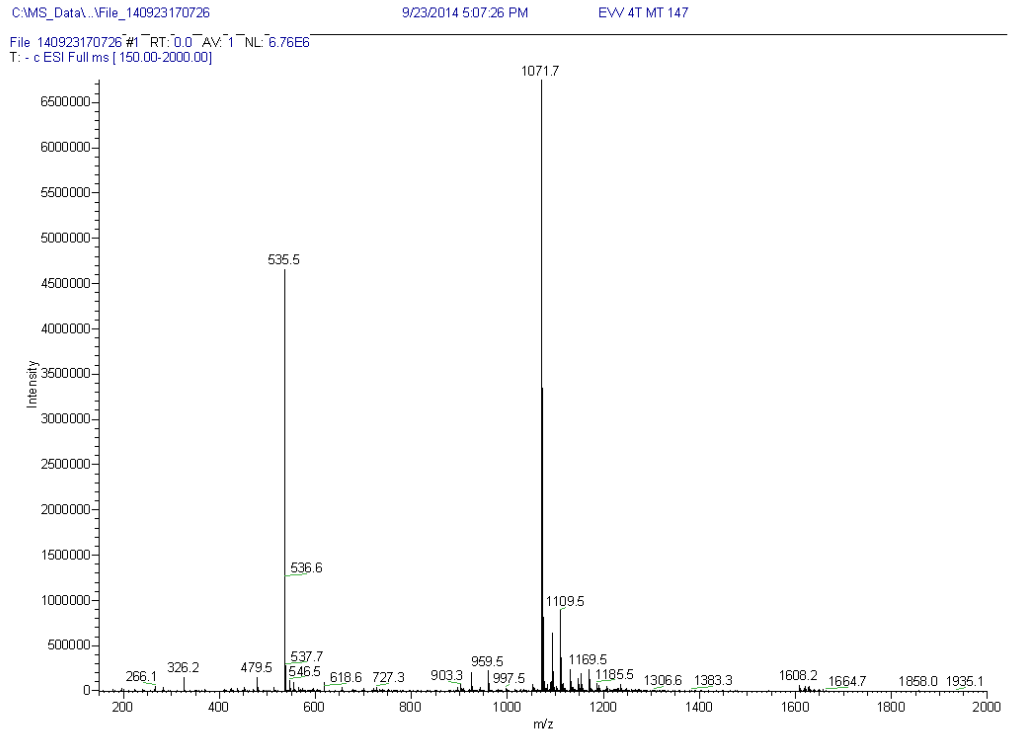

Figure S13. ESI spectrum of **EVV-4T** peptide.

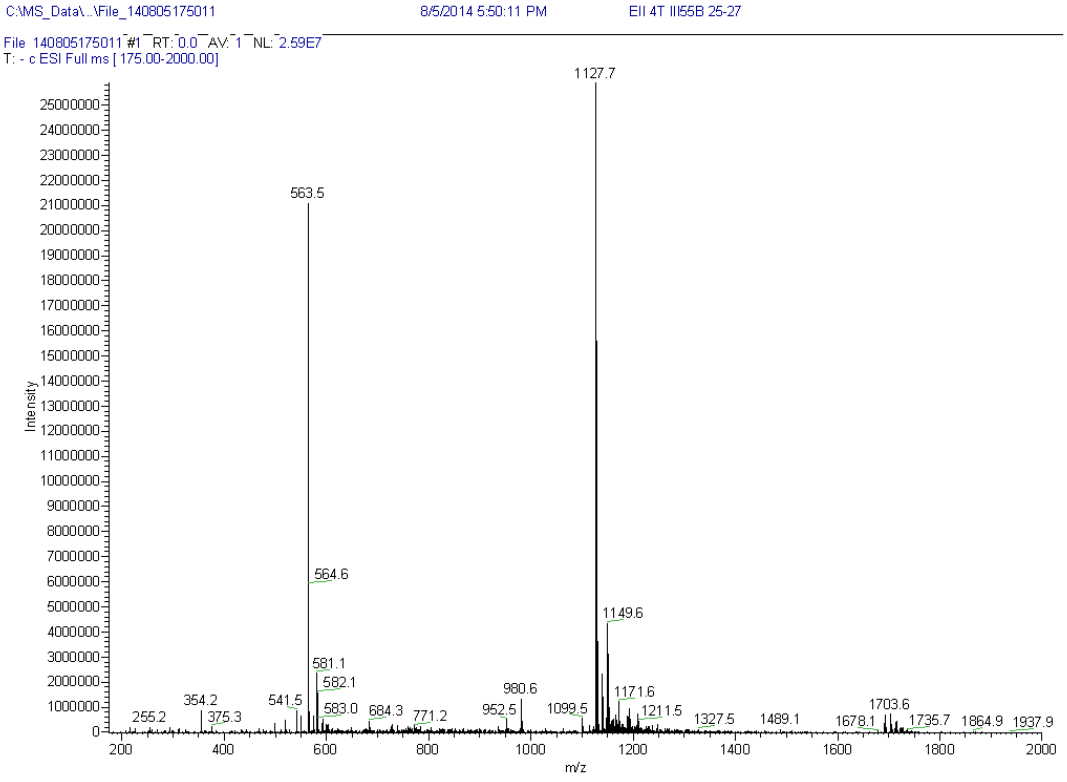

Figure S14. ESI spectrum of **EII-4T** peptide.

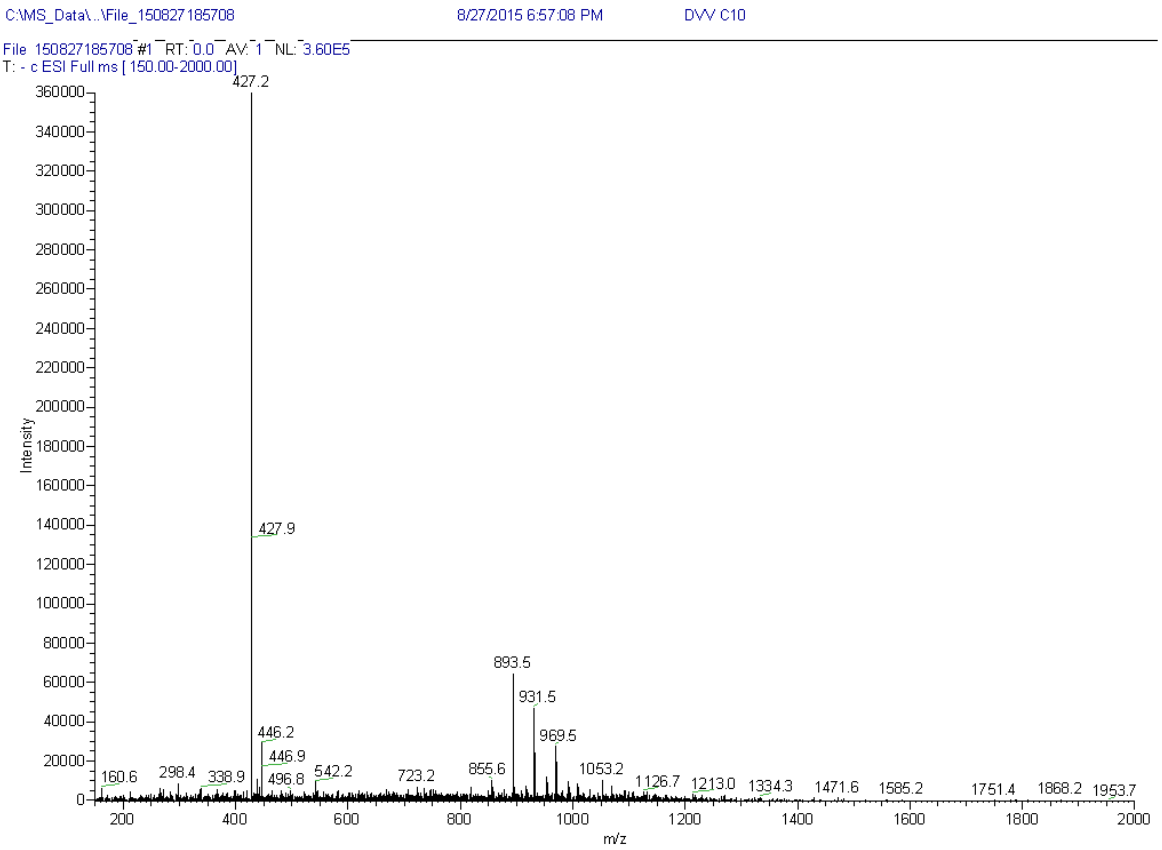

Figure S15. ESI spectrum of **DVV-C10** peptide.

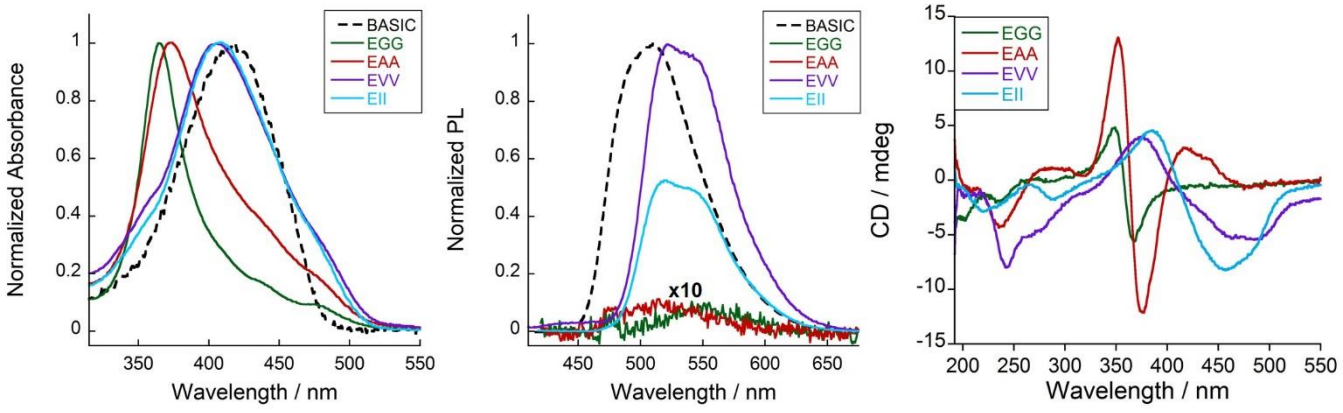

Figure S16. (a) Absorption, (b) emission (λ_{exc}= nm) (~14 µM), and (c) circular dichroism spectra (~6 µM) of 4T-peptides in basic (*ca.* pH 10, ---) and acidic solutions (*ca.* pH 2, —). For the emission spectra, peptides were normalized with respect to EVV and the basic spectrum was arbitrarily set to the same intensity as EVV.

Table S1. Absorption maxima of DXX-[3] and EXX-4T peptides.

Peptide-4T	λ_{max} / nm
DGG	362
DAA	366
DVV	403
DII	408
EGG	361
EAA	374
EVV	406
EII	409

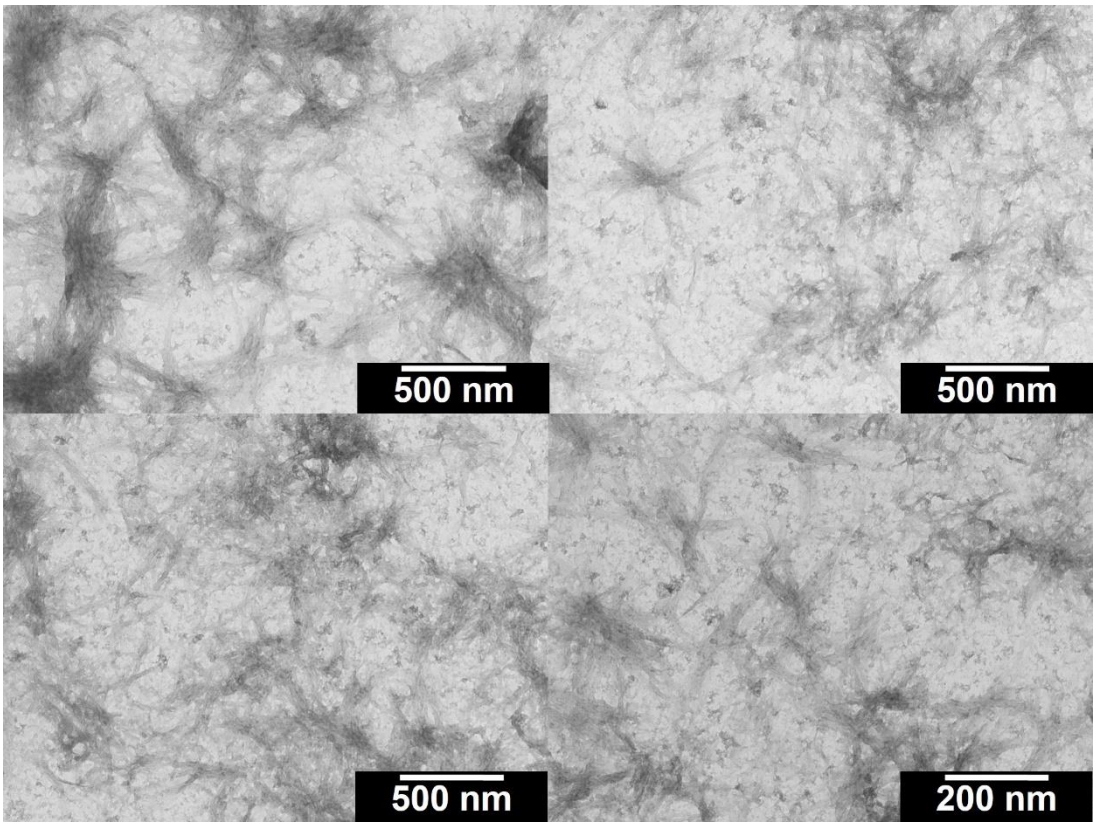

Figure S17. TEM images of 1 wt% DGG-4T peptide gel.

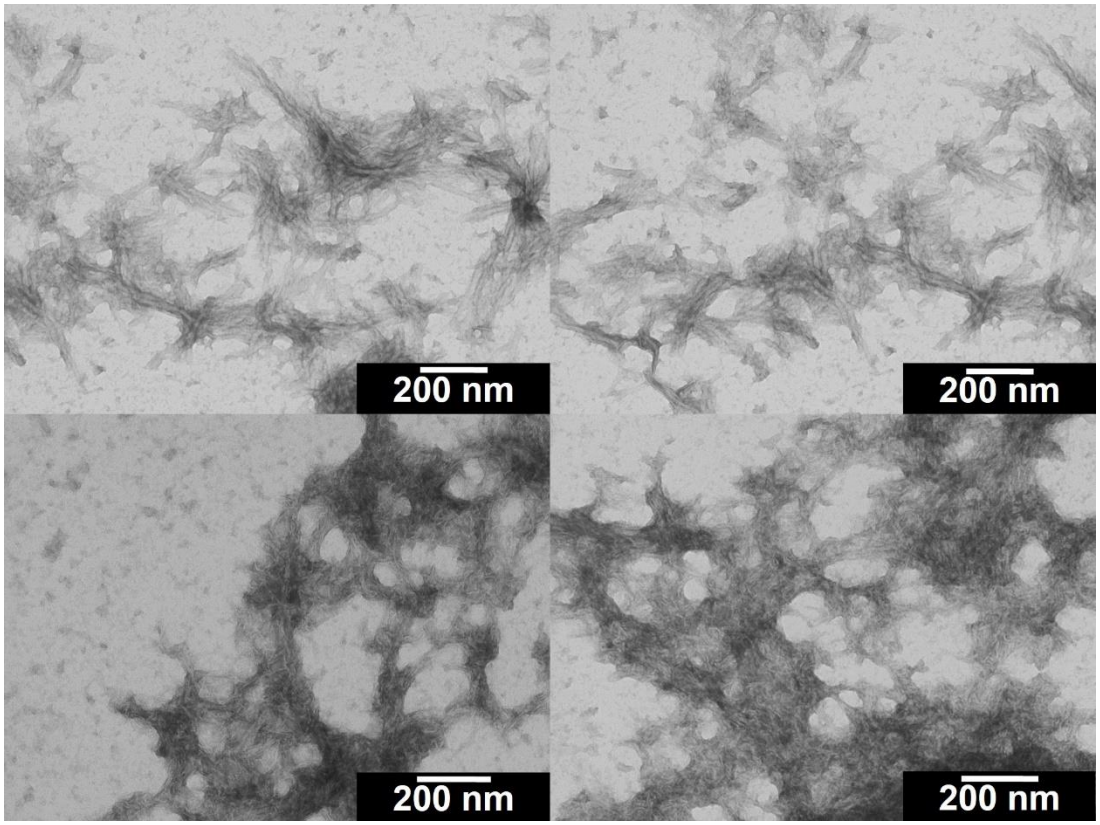

Figure S18. TEM images of 1 wt% DAA-4T peptide gel.

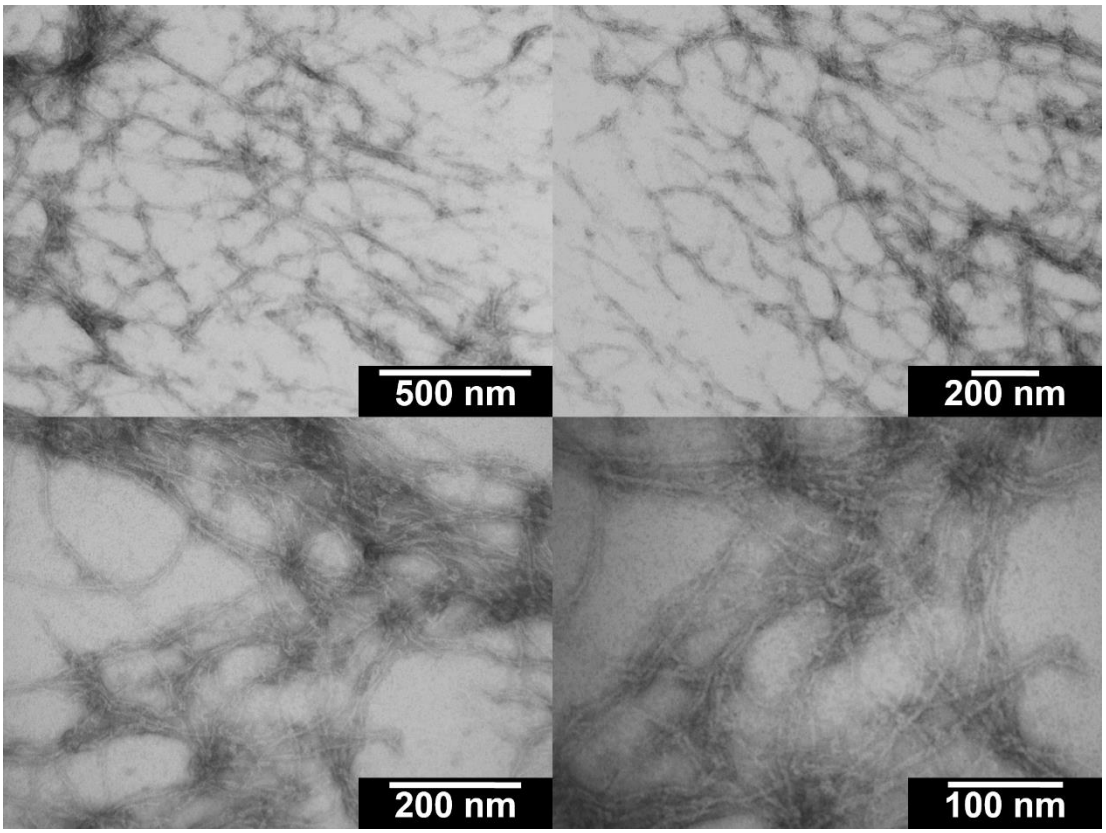

Figure S19. TEM images of 1 wt% DVV-4T peptide gel.

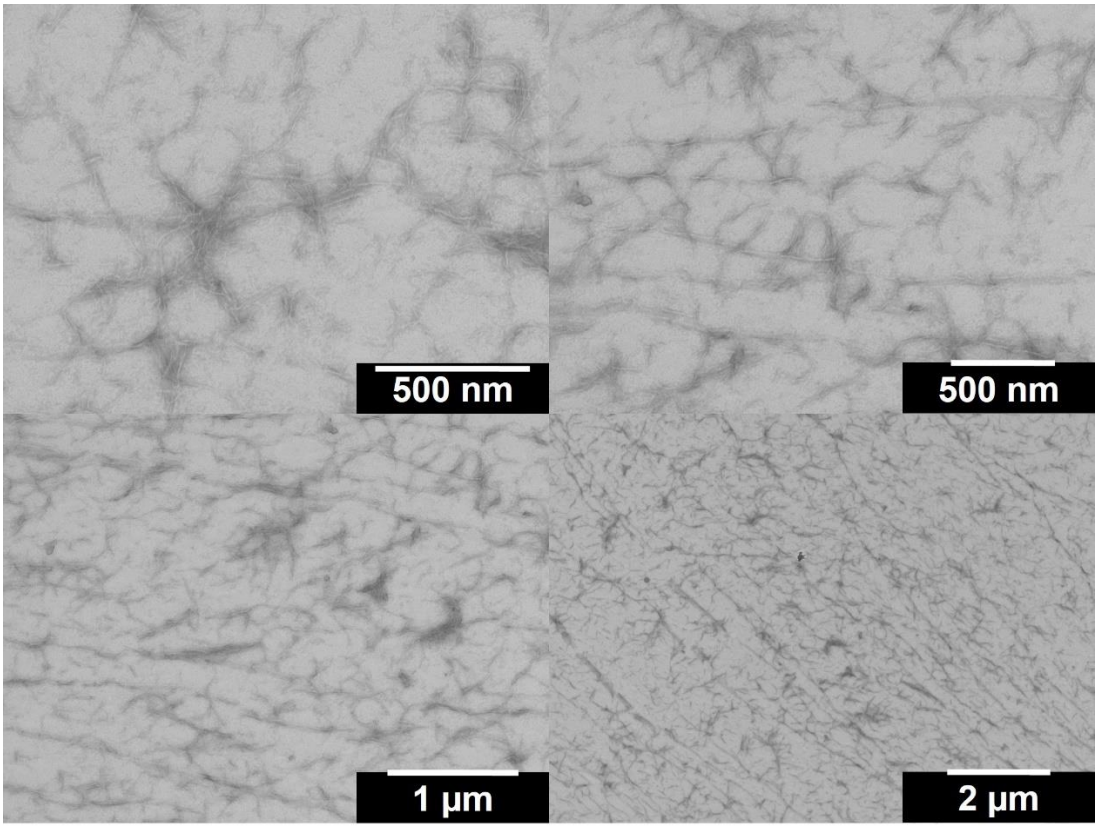

Figure S20. TEM images of 1 wt% DII-4T peptide gel.

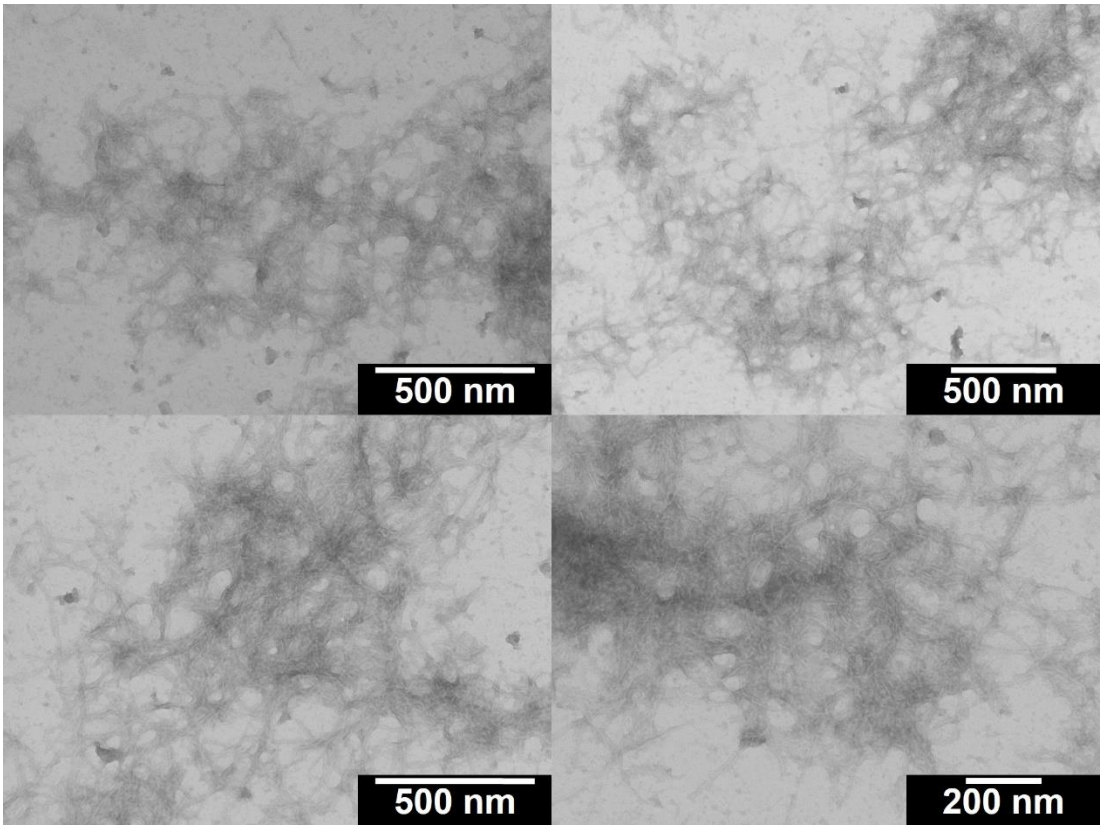

Figure S21. TEM images of 1 wt% EGG-4T peptide gel.

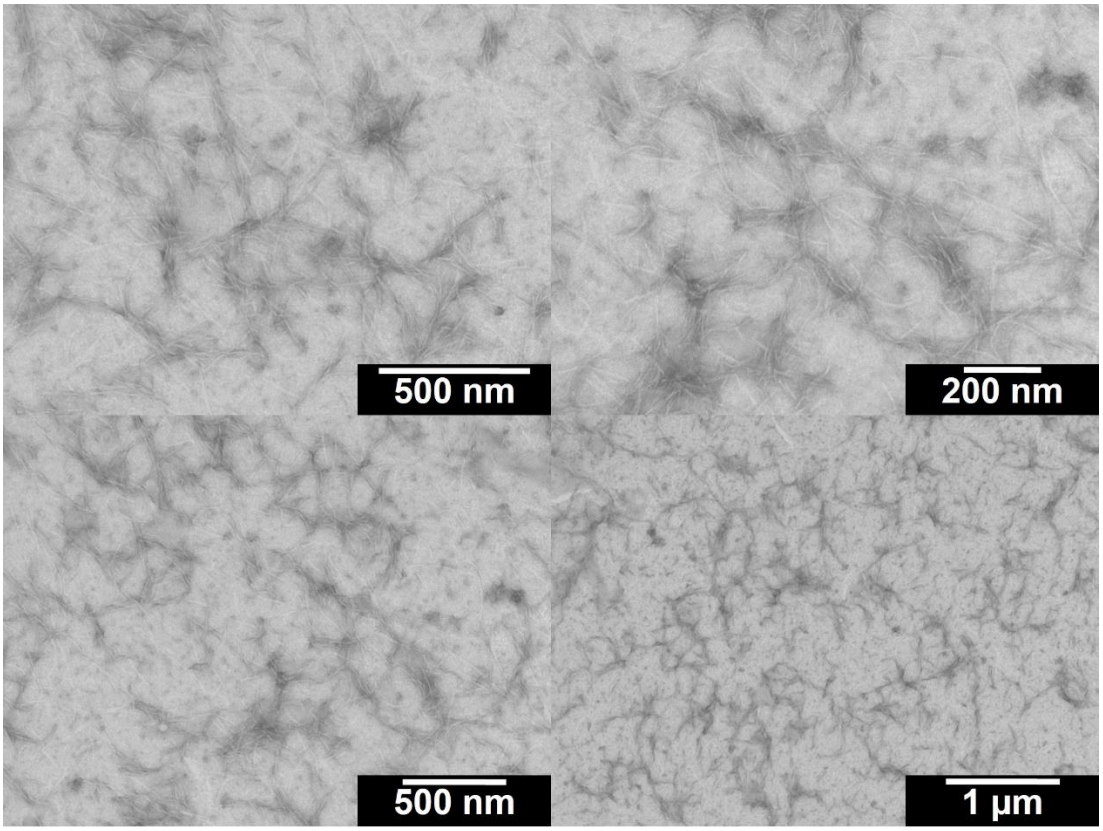

Figure S22. TEM images of 1 wt% EAA-4T peptide gel.

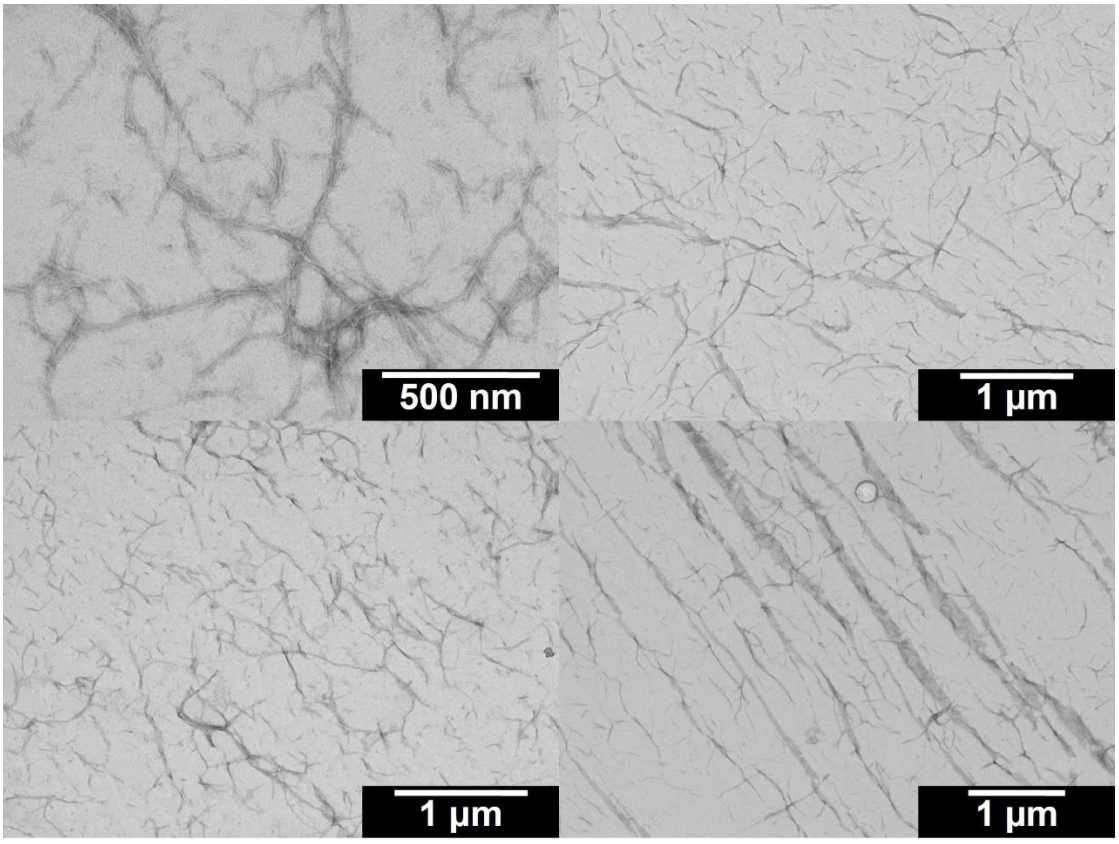

Figure S23. TEM images of 1 wt% EVV-4T peptide gel.

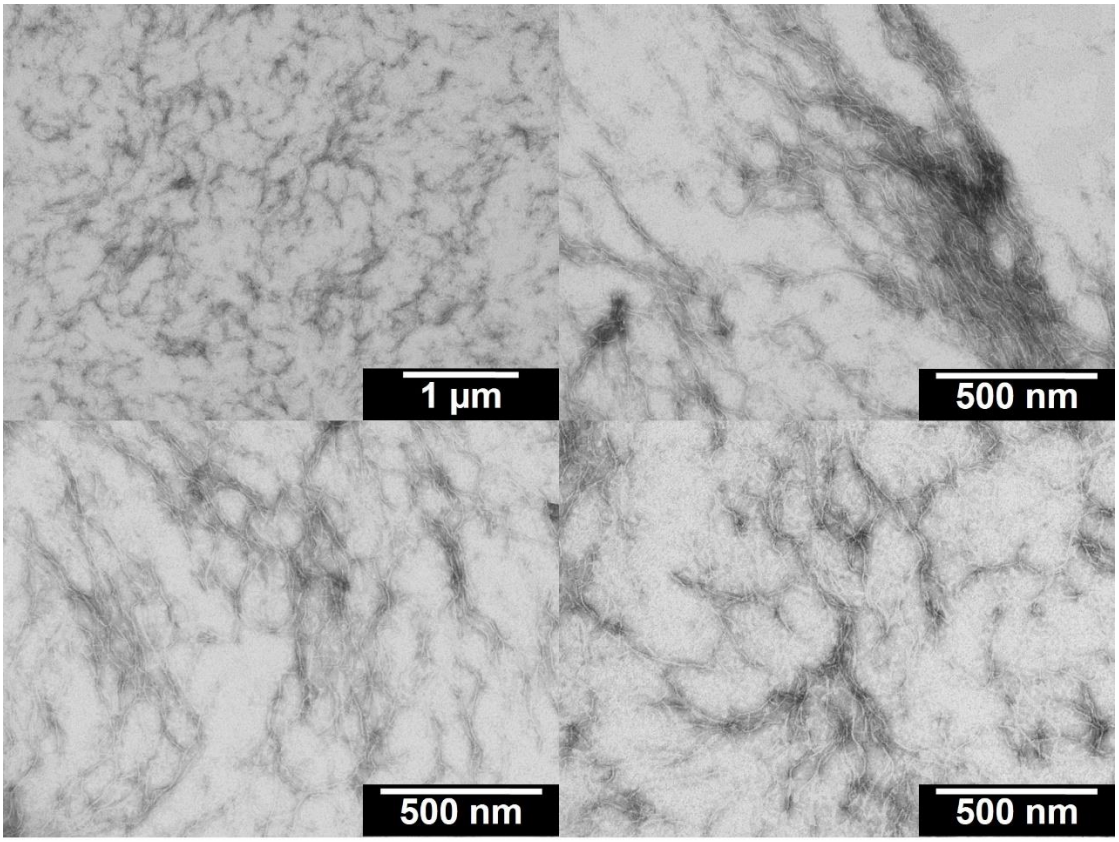

Figure S24. TEM images of 1 wt% EII-4T peptide gel.

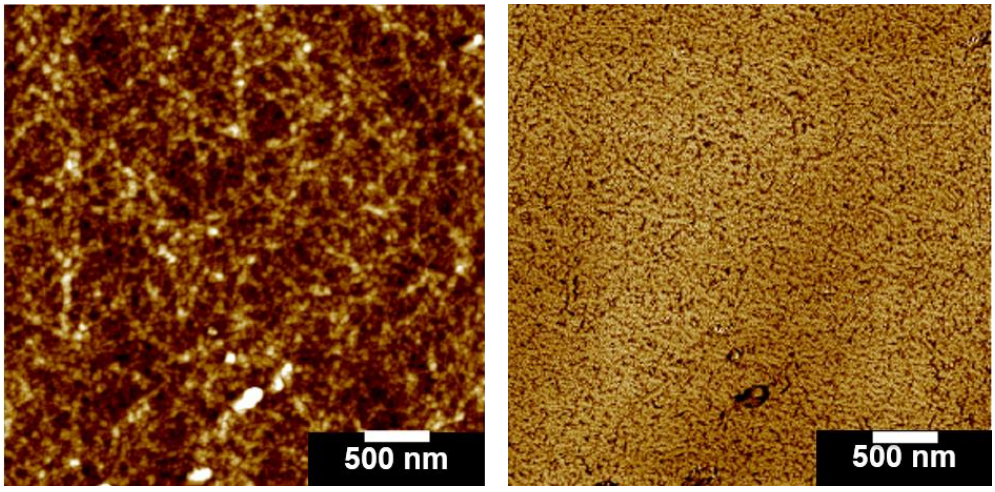

Figure S25. Representative AFM image for acidified 0.1 mg/mL EVV-4T dropcast film; height (*left*) and phase (*right*) profiles.

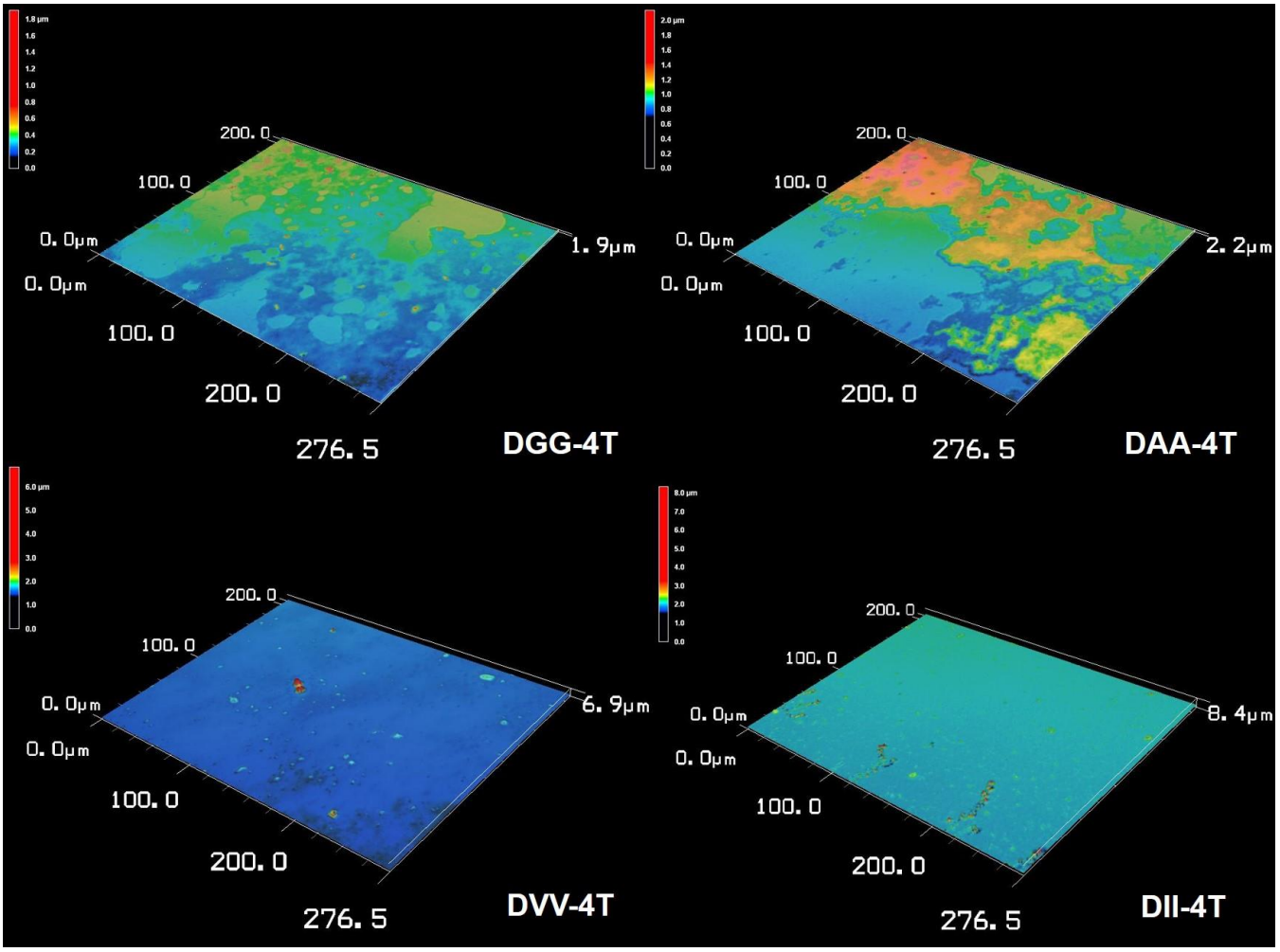

Figure S26. 3D surface profiles of 1 wt% DXX-4T peptide films generated from laser microscopy observations.

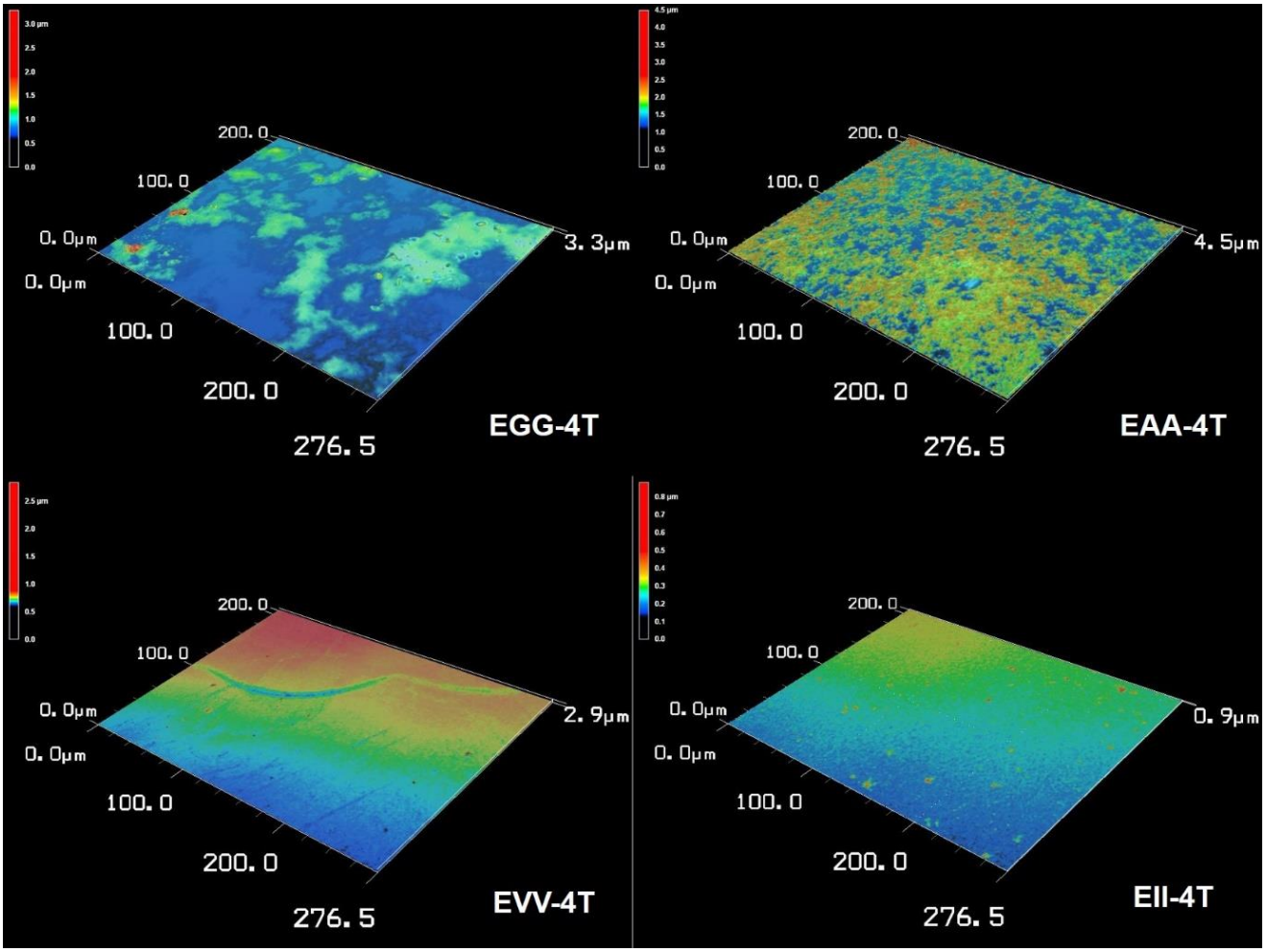

Figure S27. 3D surface profiles of 1 wt% EXX-4T peptide films generated from laser microscopy observations.

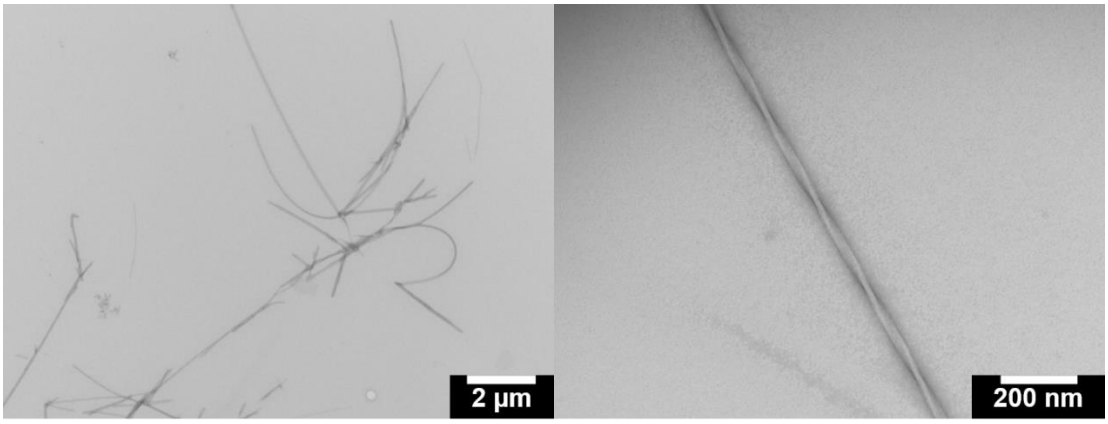

Figure S28. TEM images of 0.1 wt% solution of DVV C10 peptide.

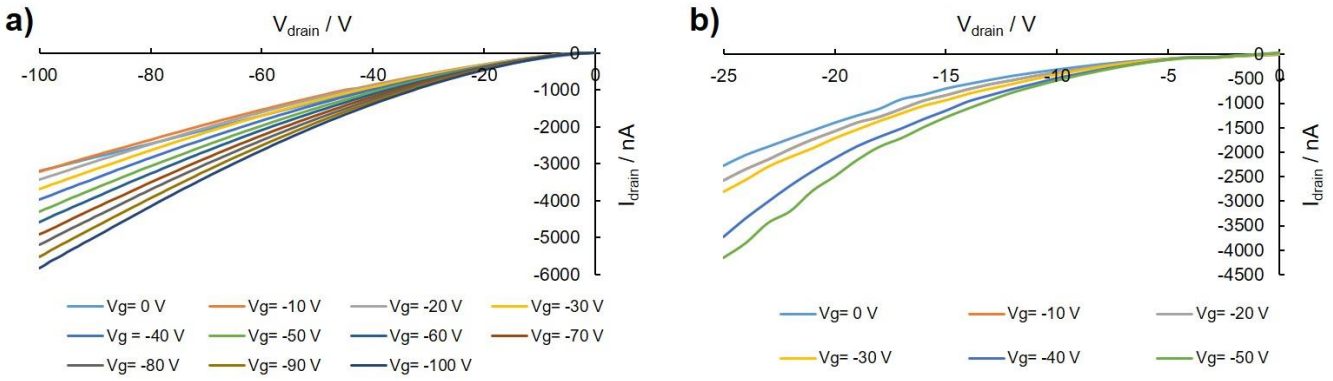

Figure S29. Output curves for devices with 1 wt% EAA-4T as gate, 40-nm pentaerythritol as dielectric and a) PQT-12 (poly(3,3"'-didodecylquaterthiophene)) and b) pentacene as the semiconducting layer.

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