Supporting Information

Non-Volatile Capacitive Memory Based on Spiropyran-Derived Copolymers for Multi-Level and Ultralow-Power Data Storage and

Protection

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S1: Characterization



Figure S1. (a) DSC characterization of the pPFPA₁-co-SP_{0.8} film and (b) TGA characterization.



Figure S2. (a) Absorbance spectra of the pPFPA₁-*co*-SP_{0.8} film after 1 min of UV irradiation and 1 min of heating at 70 °C. (b) Changes in absorbance of the pPFPA₁-*co*-SP_{0.8} film after repeated cycles of UV irradiation and heating. Light intensity = 0.32 mW cm^{-2} .



Figure S3. AFM characterization of the pPFPA₁-*co*-SP_{0.8} film at (a) the initial state and (b) after 10 min of UV irradiation, as well as the pPFPA₁-*co*-SP₀ film at (c) the initial state and (d) after 10 min of UV irradiation.

pPFPA₁-co-SP₀



Figure S4. Water contact angle tests of the $pPFPA_1$ -*co*- SP_0 film: (a) at the initial state, (b) after 2 min, (c) 4 min, (d) 6 min, (e) 8 min, and (f) 10 min of UV irradiation.



pPFPA₁-co-SP_{0.8}

Figure S5. Water contact angle tests of the pPFPA₁-*co*-SP_{0.8} film: (a) at the initial state, (b) after 2 min, (c) 4 min, (d) 6 min, (e) 8 min, and (f) 10 min of UV irradiation.



Figure S6. (a) Schematic diagram of $pPFPA_x$ -*co*-SP_y capacitor. (b-j) Capacitance and $\Delta C/C_0$ of $pPFPA_x$ -*co*-SP_y capacitors in initial state and after UV light irradiation (20 Hz-100 kHz, 30% RH, 365 nm UV light intensity = 11.94 mW cm⁻², irradiation time = 10 min).



Figure S7. Capacitance data of pPFPA₁-*co*-SP_{0.8} capacitor at different RH (a) in the frequency range of 20 Hz-100 kHz and (b) at 500 Hz frequency.



Figure S8. Capacitance data of $pPFPA_x$ -*co*-SP_y capacitors in the frequency range of 20 Hz-100 kHz under (a) 30% RH, (b) 70% RH, (c) 80% RH, and (d) 90% RH conditions.



Figure S9. Reversible cycling of capacitance for $pPFPA_1$ -*co*- $SP_{0.8}$ capacitor alternating between 30% RH and 90% RH (a) in the initial state and (b) under UV light irradiation (500 Hz, 365 nm UV light intensity = 11.94 mW cm⁻², irradiation time = 10 min).



Figure S10. Capacitance of pPFPA₁-*co*-SP_{0.8} capacitor under different illumination times (20 Hz-100 kHz, UV light intensity = 11.94 mW cm^{-2}).



Figure S11. Leakage current density of $pPFPA_1$ -*co*-SP_{0.8} capacitive memory device at different humidity levels, initially and after UV light irradiation (365 nm UV light intensity = 11.94 mW cm⁻², irradiation time = 10 min).

Number	Device	P_{\max} (W)	State	Reference
1	transistor	5.50×10^{-3}	8	1
2	transistor	1.00×10^{-5}	8	2
3	transistor	5.00×10^{-5}	4	3
4	transistor	1.10×10^{-8}	\	4
5	transistor	2.50×10^{-5}	4	5
6	transistor	4.19×10^{-5}	\	6
7	memristor	$4.84 imes 10^{-9}$	5	7
8	memristor	3.50×10^{-6}	4	8
9	memristor	5.50×10^{-6}	4	9
10	memristor	1.80×10^{-4}	6	10
11	memristor	4.00×10^{-7}	4	11
12	memristor	2.03×10^{-2}	4	12
13	memristor	1.10×10^{-3}	4	13
14	memristor	1.00×10^{-6}	8	14
15	capacitive memory	4.22×10^{-9}	1	15
16	capacitive memory	1.91×10^{-10}	8	This work

Table S1. Comparison of maximum power consumption (P_{max}) for different types of devices.



Figure S12. (a) Schematic diagram of the capacitive memory array, where the orange squares labeled 1-13 utilize pPFPA₁-*co*-SP_{0.8} dielectric layer, and the yellow squares labeled 0 utilize PMMA dielectric layer. (b) Capacitance change diagram of the PMMA device in response to different stimuli. The frequency is 500 Hz, 365 nm UV light intensity = 11.94 mW cm^{-2} , and irradiation time = 10 min.



Figure S13. Capacitance change diagrams of the pPFPA₁-*co*-SP_{0.8} capacitive memory devices 1-13 in response to different stimuli. The frequency is 500 Hz, 365 nm UV light intensity = 11.94 mW cm⁻², and irradiation time = 10 min.



Figure S14. Duration of array information retention after encryption with CF₃COOH (2.5×10^{-4} M, 30s).



Figure S15. Comparison of the ¹H NMR spectra of $pPFPA_x$ -*co*-SP_y; the red dashed box "a" represents the characteristic peaks of the SP unit, while the black dashed box "b" represents the characteristic peaks of the PFPA unit.

S2: Device Fabrication

Fabrication Section. We prepared individual capacitive memory devices based on $pPFPA_x$ -*co*-SP_y polymers as the dielectric layer, with feed ratios of x/y being 1:0, 1:0.05, 1:0.1, 1:0.2, 1:0.3,

1:0.5, 1:0.8, 1:1, and 1:2 respectively. The specific fabrication process is as follows: The highly n⁺⁺doped Si substrates were cleaned in soap water, deionized water, acetone, and ethanol using an ultrasonic bath for 20 min, followed by drying with an N₂ stream. The prepared pPFPA_x-*co*-SP_y solution (20 mg mL⁻¹ in chloroform) was sonicated for 10 min to fully dissolve the polymer. Then, 200 μ L of the pPFPA_x-*co*-SP_y solution was drawn using a pipette and vertically dropped onto the cleaned Si substrate. The substrate was immediately spin-coated at 2000 rpm for 60 s, followed by baking at 100 °C in N₂ for 10 min. The thickness of the resulting dielectric layer was approximately 120 nm. Finally, a 50 nm thick Au electrode (1200 × 1200 µm) was deposited onto the dielectric layer through a mask at a rate of 0.5 Å s⁻¹.

Electrical Characterization. The capacitance of the capacitors was measured at room temperature using a TH 2827 LCR meter. Since the test platform is exposed to the environment, controlling the RH in a large space is challenging. Therefore, we constructed a device on the test platform with a transparent top that is not completely sealed. RH adjustment was achieved by introducing dry or humid nitrogen gas into the device, and the RH range was controlled by regulating the gas flow rate. The RH inside the device was monitored using a commercial hygrometer. Additionally, we fixed a UV lamp onto an iron stand, maintaining a constant height for the UV lamp. The leakage current of the devices was measured using a Keithley SCS-4200A parameter analyzer connected to an Everbeing CG-196 probe station.

Array Measurement. In scanning mode (from left to right, top to bottom), the top electrodes are manually probed one by one to obtain the capacitance of each pixel. After obtaining the capacitance values for all pixel points, a heatmap reflecting the capacitance variation is generated using data processing software.

DFT calculation. The geometric optimization and frequency analysis of all molecules were conducted using the DFT method at the B3LYP/6-311G (d, p) level, incorporating Grimme's DFT-D3 correction. Additionally, the visualization of frontier molecular orbitals was performed using the IQmol molecular viewer package, allowing for a clearer understanding of the electronic properties.

S3: Experimental Section

Materials and instruments. Unless otherwise noted, all chemicals were commercially

available and used without further purification. ¹H and ¹⁹F NMR spectra were recorded on a Bruker AVANCE III NMR 400 M instrument. DSC measurements were tested on DSC25 instrument, from -50 °C to 200 °C at a heating/cooling rate of 10 °C min⁻¹ under a nitrogen flow. TGA measurements were performed on a Netzsch STA449F3 analyzer at a heating rate of 10 K min⁻¹. UV-vis absorption spectra were performed on Shimazu UV-2600 UV-NIR Spectrometer. AFM measurements were performed on a Digital Instrument Multimode Nanoscope IIIA in the tapping mode under ambient conditions. The thickness of the dielectric layer film was measured using a Dektak 6M surface profilometer. The contact angle was measured using the tangent method with the contact angle analysis software DSA1.92.

Synthesis



Scheme S1. Synthesis of pPFPA-co-SP monomer.

2-(3',3'-dimethyl-6-nitrospiro[chromene-2,2'-indolin]-1'-yl)ethan-1-ol (4). Compound 4 was synthesized according to the literature procedures.^{16 1}H NMR (400 MHz, DMSO-d6, δ): 8.22 (d, J = 2.8 Hz, 1H), 8.02 (dd, J = 9.0, 2.9 Hz, 1H), 7.30 (d, J = 10.4 Hz, 1H), 7.14 - 7.11 (m, 2H), 6.88 (d, J = 9.0 Hz, 1H), 6.77 (t, J = 7.3 Hz, 1H), 6.65 (d, J = 8.0 Hz, 1H), 6.00 (d, J = 10.4 Hz, 1H), 3.58 (m, 2H), 3.23 - 3.12 (m, 2H), 1.20 (s, 3H), 1.12 (s, 3H).

2-(3',3'-dimethyl-6-nitrospiro[chromene-2,2'-indolin]-1'-yl)ethyl acrylate (5). Compound 5 was synthesized according to the literature procedures.¹⁶ ¹H NMR (400 MHz, Chloroform-*d*) δ 8.03 - 8.00 (m, 2H), 7.20 (t, J = 7.7 Hz, 1H), 7.00 (d, J = 7.0 Hz, 1H), 6.92 - 6.88 (m, 2H), 6.75 (d, J = 8.6 Hz, 1H), 6.69 (d, J = 7.8 Hz, 1H), 6.38 (m, 1H), 6.09 - 6.02 (m, 1H), 5.88 - 5.81 (m, 2H), 4.31 (t, J

= 6.3 Hz, 2H), 3.59 - 3.40 (m, 2H), 1.28 (s, 3H), 1.16 (s, 3H).



Scheme S2. Synthesis of PFPA.

Pentafluorophenyl acrylate (PFPA). PFPA was synthesized according to the literature procedures.¹⁷ ¹H NMR (400 MHz, Chloroform-*d*) δ 6.70 (dt, *J* = 17.3, 1.5 Hz, 1H), 6.36 (dd, *J* = 17.3, 10.5, 1.6 Hz, 1H), 6.16 (dt, *J* = 10.5, 1.5 Hz, 1H). ¹⁹F (376 MHz, CDCl₃, δ): -152.65 (d, *J* = 17.0 Hz, 2F), -158.04 (t, *J* = 21.7 Hz, 1F), -162.42 (dd, *J* = 17.0, 21.7 Hz, 2F).



Scheme S3. Synthesis of pPFPA-co-SP.

pPFPA-co-SP was synthesized according to the literature procedures.¹⁶

	PFPA (x)	SP (y)	$pPFPA_x$ - co - SP_y (x:y)
Stoichiometric ratio	1	0%	1:0
	1	5%	1:0.05
	1	10%	1:0.1
	1	20%	1:0.2
	1	30%	1:0.3
	1	50%	1:0.5
	1	80%	1:0.8
	1	100%	1:1
	1	200%	1:2

Table S2. Stoichiometric ratio of pPFPA_x-co-SP_y.

pPFPA₁*-co-***SP**_{0.05}. Under nitrogen atmosphere, to a solution of a **PFPA** (1 g, 4.2 mmol) and **5** (0.09 g, 0.22 mmol) in 1,4-dioxane (5 mL) were added dibenzyl carbonotrithioate (0.003 g, 0.01 mmol, RAFT agent) and AIBN (0.001g, 0.006 mmol, initiator). The mixture was stirred at 80 °C for 3 days. After cooling down to room temperature, the resulting mixture was added dropwise to hexane, and

the produced white solid was collected by centrifugation. The crude polymer was dissolved in THF, precipitated in hexane and centrifuged again, which was repeated twice. Finally, drying in a vacuum oven at 25 °C offered a corresponding polymer. ¹H NMR (400 MHz, CDCl₃) δ 7.90 (m, 0.05H), 7.01 (m, 0.06H), 6.89 (0.05H), 6.71 (0.03H), 6.50 (m, 0.02H), 5.90 (0.02H), 4.22 - 4.15 (m, 0.04 H), 3.65 (m, 0.12H), 3.07 (0.93 H), 2.50 (m, 0.35H), 2.13 (m, 1.63H), 1.20 (m, 0.10 H), 1.05 (m, 0.08H).

pPFPA₁*-co-***SP**_{0.1}. Under nitrogen atmosphere, to a solution of a **PFPA** (1 g, 4.2 mmol) and **5** (0.17 g, 0.42 mmol) in 1,4-dioxane (5 mL) were added dibenzyl carbonotrithioate (0.003 g, 0.01 mmol, RAFT agent) and AIBN (0.001g, 0.006 mmol, initiator). The mixture was stirred at 80 °C for 3 days. After cooling down to room temperature, the resulting mixture was added dropwise to hexane, and the produced white solid was collected by centrifugation. The crude polymer was dissolved in THF, precipitated in hexane and centrifuged again, which was repeated twice. Finally, drying in a vacuum oven at 25 °C offered a corresponding polymer. ¹H NMR (400 MHz, CDCl₃) δ 7.93 (m, 0.05H), 6.98 (m, 0.06H), 6.83 (0.05H), 6.65 (0.03H), 6.59 (m, 0.02H), 5.85 (0.02H), 4.29 - 4.13 (m, 0.04 H), 3.69 (m, 0.12H), 3.05 (0.93 H), 2.48 (m, 0.35H), 2.11 (m, 1.63H), 1.21 (m, 0.10 H), 1.09 (m, 0.08H).

pPFPA₁*-co-***SP**_{0,2}. Under nitrogen atmosphere, to a solution of a **PFPA** (0.5 g, 2.1 mmol) and **5** (0.18 g, 0.43 mmol) in 1,4-dioxane (5 mL) were added dibenzyl carbonotrithioate (0.003 g, 0.01 mmol, RAFT agent) and AIBN (0.001g, 0.006 mmol, initiator). The mixture was stirred at 80 °C for 3 days. After cooling down to room temperature, the resulting mixture was added dropwise to hexane, and the produced white solid was collected by centrifugation. The crude polymer was dissolved in THF, precipitated in hexane and centrifuged again, which was repeated twice. Finally, drying in a vacuum oven at 25 °C offered a corresponding polymer. ¹H NMR (400 MHz, CDCl₃) δ 7.95 (m, 0.05H), 7.00 (m, 0.06H), 6.80 (0.05H), 6.72 (0.03H), 6.60 (m, 0.02H), 5.80 (0.02H), 4.27 - 4.13 (m, 0.04 H), 3.68 (m, 0.12H), 3.08 (0.93 H), 2.45 (m, 0.35H), 2.10 (m, 1.63H), 1.19 (m, 0.10 H), 1.00 (m, 0.08H).

pPFPA₁*-co-***SP**_{0.3}. Under nitrogen atmosphere, to a solution of a **PFPA** (0.5 g, 2.1 mmol) and **5** (0.255 g, 0.63 mmol) in 1,4-dioxane (5 mL) were added dibenzyl carbonotrithioate (0.003 g, 0.01 mmol, RAFT agent) and AIBN (0.001g, 0.006 mmol, initiator). The mixture was stirred at 80 °C for

3 days. After cooling down to room temperature, the resulting mixture was added dropwise to hexane, and the produced white solid was collected by centrifugation. The crude polymer was dissolved in THF, precipitated in hexane and centrifuged again, which was repeated twice. Finally, drying in a vacuum oven at 25 °C offered a corresponding polymer. ¹H NMR (400 MHz, CDCl₃) δ 7.94 (m, 0.05H), 7.08 (m, 0.06H), 6.80 (0.05H), 6.65 (0.03H), 6.55 (m, 0.02H), 5.85 (0.02H), 4.22 - 4.12 (m, 0.04 H), 3.68 (m, 0.12H), 3.05 (0.93 H), 2.50 (m, 0.35H), 2.12 (m, 1.63H), 1.25 (m, 0.10 H), 1.05 (m, 0.08H).

pPFPA₁*-co-***SP**_{0.5}. Under nitrogen atmosphere, to a solution of a **PFPA** (0.5 g, 2.1mmol) and **5** (0.425 g, 1.04 mmol) in 1,4-dioxane (5 mL) were added dibenzyl carbonotrithioate (0.003 g, 0.01 mmol, RAFT agent) and AIBN (0.001g, 0.006 mmol, initiator). The mixture was stirred at 80 °C for 3 days. After cooling down to room temperature, the resulting mixture was added dropwise to hexane, and the produced white solid was collected by centrifugation. The crude polymer was dissolved in THF, precipitated in hexane and centrifuged again, which was repeated twice. Finally, drying in a vacuum oven at 25 °C offered a corresponding polymer. ¹H NMR (400 MHz, CDCl₃) δ 7.96 (m, 0.05H), 7.65 (m, 0.06H), 6.80 (0.05H), 6.70 (0.03H), 6.57 (m, 0.02H), 5.85 (0.02H), 4.27 - 4.15 (m, 0.04 H), 3.66 (m, 0.12H), 3.00 (0.93 H), 2.48 (m, 0.35H), 2.12 (m, 1.63H), 1.22 (m, 0.10 H), 1.09 (m, 0.08H).

pPFPA₁*-co-***SP**_{0.8}. Under nitrogen atmosphere, to a solution of a **PFPA** (0.5 g, 2.1 mmol) and **5** (0.685 g, 1.68 mmol) in 1,4-dioxane (5 mL) were added dibenzyl carbonotrithioate (0.003 g, 0.01 mmol, RAFT agent) and AIBN (0.001g, 0.006 mmol, initiator). The mixture was stirred at 80 °C for 3 days. After cooling down to room temperature, the resulting mixture was added dropwise to hexane, and the produced white solid was collected by centrifugation. The crude polymer was dissolved in THF, precipitated in hexane and centrifuged again, which was repeated twice. Finally, drying in a vacuum oven at 25 °C offered a corresponding polymer. ¹H NMR (400 MHz, CDCl₃) δ 7.93 (m, 0.05H), 7.02 (m, 0.06H), 6.85 (0.05H), 6.75 (0.03H), 6.55 (m, 0.02H), 5.80 (0.02H), 4.25 - 4.15 (m, 0.04 H), 3.70 (m, 0.12H), 3.05 (0.93 H), 2.55 (m, 0.35H), 2.10 (m, 1.63H), 1.15 (m, 0.10 H), 1.00 (m, 0.08H). ¹⁹F (376 MHz, CDCl₃, δ): –152.67 (s, J = 17.0 Hz, 2F), –156.56 (s, J = 21.7 Hz, 1F), –161.76 (s, J = 17.0, 21.7 Hz, 2F).

pPFPA₁-co-SP₁. Under nitrogen atmosphere, to a solution of a PFPA (0.2 g, 0.84 mmol) and 5

(0.34 g, 0.84 mmol) in 1,4-dioxane (5 mL) were added dibenzyl carbonotrithioate (0.0015 g, 0.005 mmol, RAFT agent) and AIBN (0.0015g, 0.009 mmol, initiator). The mixture was stirred at 80 °C for 3 days. After cooling down to room temperature, the resulting mixture was added dropwise to hexane, and the produced white solid was collected by centrifugation. The crude polymer was dissolved in THF, precipitated in hexane and centrifuged again, which was repeated twice. Finally, drying in a vacuum oven at 25 °C offered a corresponding polymer. ¹H NMR (400 MHz, CDCl₃) δ 7.99 (m, 0.05H), 7.03 (m, 0.06H), 6.85 (0.05H), 6.76 (0.03H), 6.57 (m, 0.02H), 5.83 (0.02H), 4.24 - 4.15 (m, 0.04 H), 3.42 (m, 0.12H), 3.02 (0.93 H), 2.85 (m, 0.35H), 1.91 (m, 1.63H), 1.23 (m, 0.10 H), 1.09 (m, 0.08H). ¹⁹F (376 MHz, CDCl₃, δ): –153.04 (s, J = 17.0 Hz, 2F), –157.10 (s, J = 21.7 Hz, 1F), –162.06 (s, J = 17.0, 21.7 Hz, 2F).

pPFPA₁*-co-SP*₂. Under nitrogen atmosphere, to a solution of a **PFPA** (0.1 g, 0.42 mmol) and **5** (0.34 g, 0.84 mmol) in 1,4-dioxane (5 mL) were added dibenzyl carbonotrithioate (0.0015 g, 0.005 mmol, RAFT agent) and AIBN (0.0015g, 0.009 mmol, initiator). The mixture was stirred at 80 °C for 3 days. After cooling down to room temperature, the resulting mixture was added dropwise to hexane, and the produced white solid was collected by centrifugation. The crude polymer was dissolved in THF, precipitated in hexane and centrifuged again, which was repeated twice. Finally, drying in a vacuum oven at 25 °C offered a corresponding polymer. ¹H NMR (400 MHz, CDCl₃) δ 7.92 (m, 0.05H), 7.04 (m, 0.06H), 6.85 (0.05H), 6.65 (0.03H), 6.64 (m, 0.02H), 5.81 (0.02H), 4.25 - 4.15 (m, 0.04 H), 3.80 (m, 0.12H), 3.05 (0.93 H), 2.55 (m, 0.35H), 2.10 (m, 1.63H), 1.24 (m, 0.10 H), 1.07 (m, 0.08H). ¹⁹F (376 MHz, CDCl₃, δ): –152.35 (s, J = 17.0 Hz, 2F), –156.56 (s, J = 21.7 Hz, 1F), –160.54 (s, J = 17.0, 21.7 Hz, 2F).



Scheme S4. Synthesis of pPFPA.

pPFPA(pPFPA₁-*co***-SP₀).** pPFPA was synthesized according to the literature procedures.¹⁷¹H NMR (400 MHz, CDCl3, δ): 3.08 (br, 1.00 H), 2.48 (br, 0.42 H), 2.10 (br, 1.75 H).

NMR spectroscopy



Figure S16. ¹H NMR spectrum of SP in CDCl₃.



Figure S17. ¹H NMR and ¹⁹F NMR spectrum of PFPA in CDCl₃.



Figure S19. ¹H NMR spectrum of pPFPA₁-co-SP_{0.05} in CDCl₃.



Figure S21. ¹H NMR spectrum of pPFPA₁-co-SP_{0.2} in CDCl₃.



Figure S23. ¹H NMR spectrum of pPFPA₁-co-SP_{0.5} in CDCl₃.



Figure S25. ¹H NMR and ¹⁹F NMR spectrum of pPFPA₁-co-SP₁ in CDCl₃.



Figure S26. ¹H NMR and ¹⁹F NMR spectrum of pPFPA₁-co-SP₂ in CDCl₃.

References

- 1. X. Wu, S. Feng, J. Shen, W. Huang, C. Li, C. Li, Y. Sui and W. Huang, *Chem. Mater.*, 2020, **32**, 3641-3650.
- Z. Chen, S. Chen, T. Jiang, S. Chen, R. Jia, Y. Xiao, J. Pan, J. Jie and X. Zhang, *Nanoscale*, 2024, 16, 3721-3728.
- 3. S. K. Hwang, I. Bae, R. H. Kim and C. Park, *Adv. Mater.*, 2012, 24, 5910-5914.
- 4. S. H. Kim, S.-G. Yi, M. U. Park, C. Lee, M. Kim and K.-H. Yoo, *ACS Appl. Mater. Interfaces*, 2019, **11**, 25306-25312.
- M. Kang, Y.-A. Kim, J.-M. Yun, D. Khim, J. Kim, Y.-Y. Noh, K.-J. Baeg and D.-Y. Kim, Nanoscale, 2014, 6, 12315-12323.
- X. Chen, S. Zheng, B. Liang, X. Wu, D. Wang, Y. Dong, W. Huang, Y. Liu, X. Yu, J. Shen, S. Feng, C.-C. Chang and W. Huang, *Chem. Mater.*, 2023, 35, 2808-2819.
- T. Aziz, Y. Sun, Z.-H. Wu, M. Haider, T.-Y. Qu, A. Khan, C. Zhen, Q. Liu, H.-M. Cheng and D.-M. Sun, *Journal of Materials Science & Technology*, 2021, 86, 151-157.
- B.-L. Hu, X. Zhu, X. Chen, L. Pan, S. Peng, Y. Wu, J. Shang, G. Liu, Q. Yan and R. W. Li, J. Am. Chem. Soc., 2012, 134 42, 17408-17411.
- 9. W. Wang, K. L. Kim, S. M. Cho, J. H. Lee and C. Park, *ACS Appl. Mater. Interfaces*, 2016, **8**, 33863-33873.
- S. K. Hwang, I. Bae, S. M. Cho, R. H. Kim, H. J. Jung and C. Park, *Adv. Funct. Mater.*, 2013, 23, 5484-5493.
- 11. H. Tan, G. Liu, X. Zhu, H. Yang, B. Chen, X. Chen, J. Shang, W. D. Lu, Y. Wu and R.-W. Li,

Adv. Mater., 2015, 27, 2797-2803.

- 12. V. K. Nagareddy, M. Barnes, F. Zipoli, K. Lai, A. Alexeev, M. Craciun and D. Wright, ACS Nano, 2017, **11**, 3010-3021.
- 13. B. Lu, J. Du, J. Lu, S. Li, R. Yang, P. Liu, J. Huang, L. Chen, F. Zhuge and Z. Ye, *ACS Mater*. *Lett.*, 2023, **5**, 1350-1358.
- P. Hou, J. Wang, X. Zhong, Y. Zhang, X. Zhang, C. Tan and B. Li, *RSC Adv.*, 2016, 6, 80011-80016.
- 15. M. Kumar and J. Dhar, J. Mater. Sci.: Mater. Electron., 2024, 35, 1-11.
- X. Zhang, R. Yang, Y. Dong, C. Zhang, S. Feng and W. Huang, *Angew. Chem. Int. Ed.*, 2024, 63, e202403973.
- 17. S. Feng, L. Zhu, D. Wang, C. Li, Y. Chen, X. Chen, J. Liu, W. Huang, Y. Ling and W. Huang, *Adv. Mater.*, 2022, **34**, 2201337.