



Morphological Control of Conjugated Polymer Blends for Elastic Stretchability

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14. ABSTRACT This project was aimed to obtain large, elastic stretchability to conjugated polymers via morphological control of polymer blends, while retaining or even enhancing the high electronic property of the neat conjugated polymers. The project was started on August 01, 2015, for a period of 36 months. A no-cost time extension to February 28, 2019 was requested by UCLA and approved by AFOSR. This report covers the entire project period, from August 01, 2015 through February 28, 2019. Overall, the project team investigated some of the fundamental issues in intrinsically stretchable electronic materials and demonstrated new electronic materials and thin film devices that can be elastically stretched by 100% strain.					
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Morphological Control of Conjugated Polymer Blends for Elastic Stretchability

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The overarching objective of this project was to impart large, elastic stretchability to neat conjugated polymers via morphological control of polymer blends, while retaining or even enhancing their high electronic properties. The project was started on August 01, 2015, and continued for a period of 36 months. A no-cost time extension to February 28, 2019 was requested by UCLA and approved by AFOSR. This report covers the entire project period, from August 01, 2015 to February 28, 2019. Overall, the project team investigated some of the fundamental issues in intrinsically stretchable electronic materials and demonstrated new electronic materials and thin film devices that can be elastically stretched by as much as 100% strain. The project produced 20 peer reviewed papers, including an original research article on Science and an invited extensive review article on Chemical Reviews. One patent application was also filed from the project work. The PI delivered 23 invited lectures on results obtained from this project at international conferences and/or prestigious research institutions. Here we describe the highlights of our research findings. Scientific details of the works can be found in the listed publications.

1. Elastomeric light emitting polymer enhanced by interpenetrating networks

Conjugated polymers containing long-chain alkyl side groups for solubility are generally un-stretchable: large strain induces crack formation, plastic deformation, or fracture. We discovered that an interpenetrating polymer network (IPN) approach could be used to impart elastomeric deformability to a conjugated polymer. A soluble alkyloxy phenyl substituted poly(1,4-phenylene vinylene) (SY-PPV) with bright yellow fluorescent emission was admixed with an ionically conductive medium containing poly (ethylene oxide), ethoxylated trimethylolpropanetriacrylate, and lithium trifluoromethane sulfonate (**Figure 1A**). The spin-cast blend film formed an IPN morphology wherein SY-PPV forms a porous network with pores filled by the ionic medium. PeakForce quantitative nanomechanical mapping (**Figure 1B**) showed that the local Young's modulus was high in the continuous SY-PPV phase while the ionic phase was 2 times softer. Elastomeric deformation of the blend film supported by a polyurethane elastomer substrate was characterized. A high dichroic ratio was observed both for absorption of the ground state and radiative decay of the excited state when the neat SY-PPV was stretched, irreversibly orienting the conjugated chains along the stretching direction. In contrast, global polarization of the blended SY-PPV chains was not observed at strains up to 100% as the dichroic ratio remains close to 1.

Two different light emitting devices based on the blend sandwiched between two stretchable transparent composite electrodes were fabricated. The polymer light emitting electrochemical cell (PLECs) based on the intrinsically stretchable SY-PPV blend, which is uniaxially stretchable up to 140% strain, outperformed the counterpart polymer light emitting diode (PLED) device. The brightness of the PLEC increases with strain up to 50% strain, and then decreases at higher strains

(Figure 2B). The wavelength at the peak of the EL spectrum and its shape does not change upon stretching. The 50% strain was used to investigate the influence of strain on polarized light emitting performance. Figure 2 shows the polarized EL spectra. In the PLEC sample, light intensities in the parallel and perpendicular directions are nearly the same no whether the blended emissive layer is stretched or not. This result differs from the PLED device based on neat SY-PPV, where luminance intensity in the parallel direction is higher than the perpendicular direction.

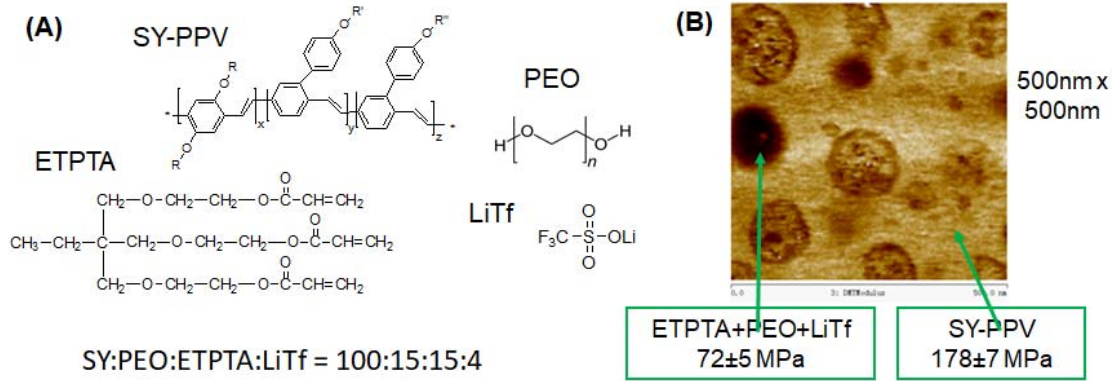


Figure 1. (A) Conjugated polymer (SY-PPV) and additives that render the polymer intrinsically stretchable. (B) Quantitative nanomechanical modulus mapping of the SY-PPV blend.

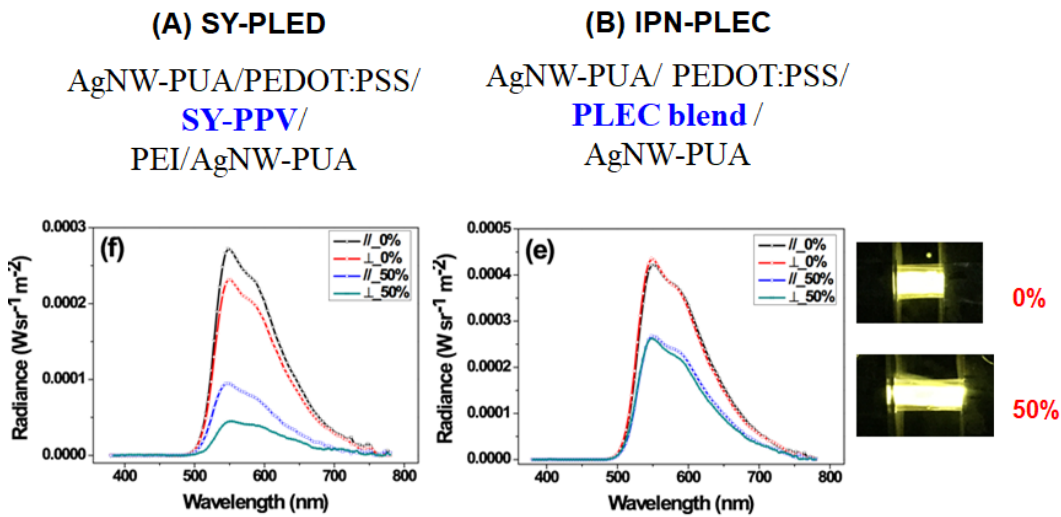


Figure 2. Sandwich architecture and emission intensity in parallel and transverse directions of stretching of (A) SY-PPV-based light emitting diode and (B) SY-PPV blend-based light emitting electrochemical cell with additives that renders the polymer intrinsically stretchable.

Based on the dichroic behaviors of the optical absorption, photoluminescent emission, and electroluminescent emission from a number of samples and various stretching ratios, we argue that the SY-PPV blend has an interpenetrating polymer network microstructure as illustrated in Figure 3. The SY-PPV forms a continuous network while the ionic mediums fill the pores. The pores inside the film can accommodate large strain without undergoing plastic deformation. The dichroic ratio of the PLEC blend remains around 1 up to 100% strain, which reveals that SY-PPV polymer chains remain random. Both the conjugated polymer network and ionic phase are amorphous, hence, stretching does not induce polymer chain orientation.

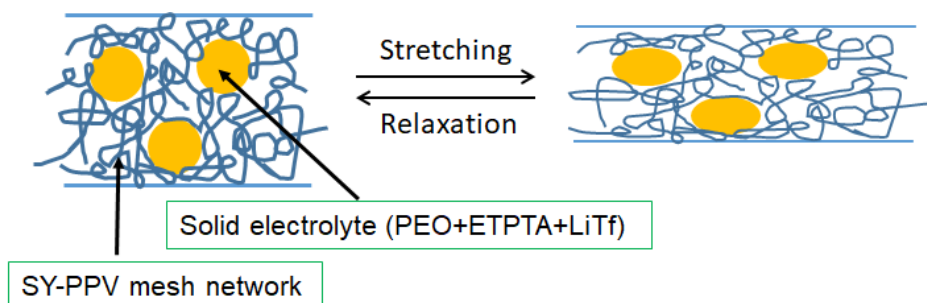


Figure 3. Schematic illustration of a SY-PPV:ETPTA:PEO:LiTf blend film upon stretching and subsequent relaxation.

2. A nano-grain blend morphology as a stretchable photovoltaic system

Another good example of organic conjugated polymer systems being typically rigid and un-stretchable is the photovoltaic blend of poly(thieno[3,4-b]-thiophene/benzodithiophene) (PTB7) and phenyl-C71-butyric acid methyl ester (PC₇₁BM). PeakForce quantitative nanomechanical mapping (**Figure 4**) shows that the PC₇₁BM grains (100-200nm diameter) are dispersed in the PTB7 matrix. Plastic deformation is induced in the thin films at low strain, typical of fullerene-based systems. UV absorption and PL emission analysis confirmed irreversibility of the deformation. When diiodooctane (DIO) was added in the spin-coating solution, the PC₇₁BM grains were reduced to only a few nanometers in diameter. The removal of the residual DIO creates free volumes in the blend, and thus un-jams the nano-grain packing. The resulting blend is mechanically compliant and allows for large-strain reversible deformation, analogous to beach sand that is soft even though the sand grains themselves are stiff.

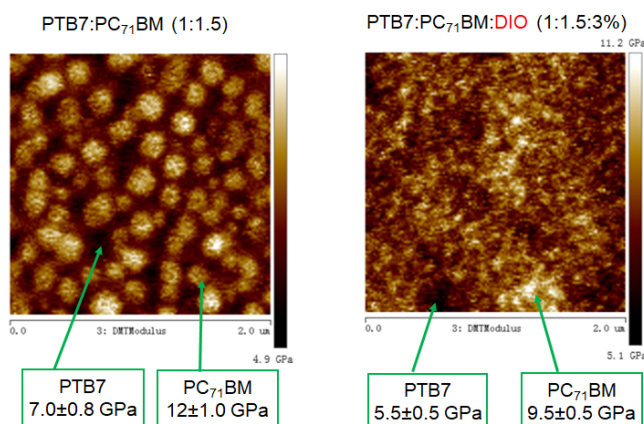


Figure 4. Quantitative nanomechanical modulus mapping of PTB7:PC₇₁BM blend without (*Left*) and with (*Right*) DIO added in the spin coating solution.

This model is supported by UV-vis absorption and PL emission spectroscopy. It is well understood that the optical transition dipole moment (π - π^*) in a conjugated polymer is aligned with the polymer backbone. Thus, a transition to uniaxially aligned polymer chains due to tensile elongation results in detectable anisotropic optoelectronic properties. Polarized optoelectronic behavior under mechanical deformation was investigated by placing a polarizing prism between the photo detector and sample, so that only light from the selected direction is collected. The absorption spectra of the PTB7:PC₇₁BM blend measured with linearly polarized light parallel and perpendicular to the strain direction have a PTB7 photosensitizing peak at 680 nm and a PC₇₁BM peak at 460 nm. The DIO additive does not shift the position of these peaks. When the films were stretched, the optical absorbance is enhanced in the strain direction, and reduced in the orthogonal

direction. Both films without and with DIO exhibit this polarization effect.

Note that the polarization of polymer chains along the stretching direction has been widely observed for soluble conjugated polymers with relatively low glass transition temperature and is often accompanied by concurrent increases in electrical conductivity and field-effect mobility along the stretching direction. The reorientation of the polymer chains after stretching is, for the most part, irreversible. This is observed in the PTB7:PC₇₁BM film without DIO; the molecular orientation is retained after strain relaxation. The blend film with DIO, however, shows almost complete recovery; the molecular reorientation during stretching is reversible.

The dichroic data reveals some insightful observations that are not immediately clear (**Figure 5**). One is that the dichroic ratio observed for the blend without DIO is smaller than the blend with DIO at the same strains. For instance, the PTB7 DR in the blend without DIO at 100% strain is 1.74, whereas in the blend with DIO, it is 2.09 at 100% strain. The DR of 1.74 at 100% strain at 680 nm is rather small for such large elongation. This is due to the cracking of the blend film without DIO at small strains, and that further elongation of the cracked film would not induce as much molecular reorientation compared to the crack-free blend film with DIO. The other observation is that as the stretched films are relaxed, the DR for the blend without DIO is mostly unchanged. While this irreversibility can be explained by plastic deformation upon stretching, the crack formation during stretching plays a relatively dominant role. For the blend film with DIO, the DR returns to close to unity when the stretched film is relaxed to 0% strain. Both peak absorptions for PTB7 and PC₇₁BM show similar total recovery in the blend film with DIO.

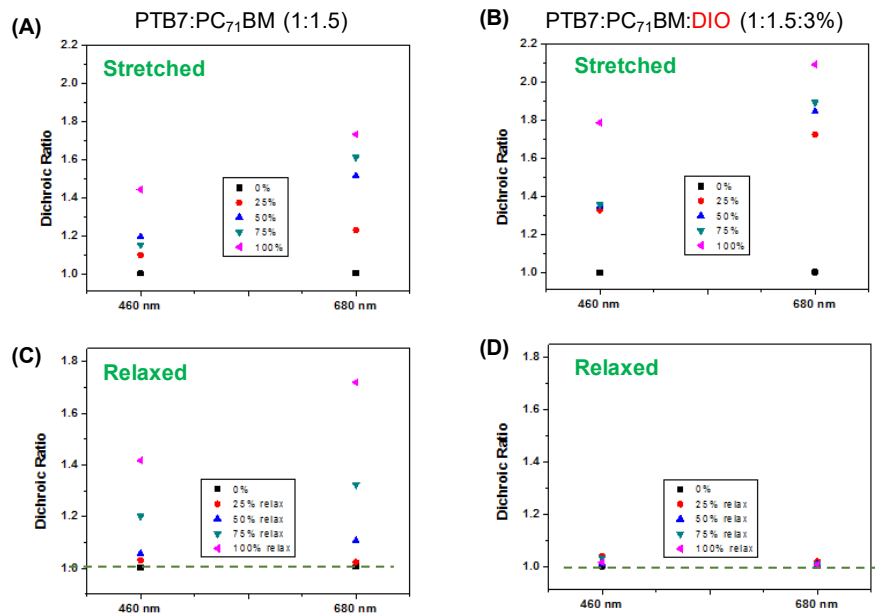


Figure 5. Dichroic ratios of a PTB7:PC₇₁BM blend without DIO (A,C) and with DIO (B,D), being stretched to the specified strains (A,B) and relaxation after the specified strains (C,D). Peak absorbances at 460nm and 680nm correlate to the PC₇₁BM moiety and PTB7 moiety, respectively.

Polymer solar cells based on the un-jammed nano-grain blend were fabricated employing a layer of the PTB7:PC₇₁BM:DIO blend sandwiched between a pair of stretchable transparent electrodes each comprising a stack of a silver nanowire percolation network and single wall carbon nanotube network bilayer embedded in the surface of a poly(urethane acrylate) elastomer film. A thin layer of PEDOT:PSS and ethoxylated polyethyleneimine (PEIE) were used as the interfacial layers to enhance hole and electron collection, respectively. The solar cells were semitransparent and could be stretched like a rubbery film by as much as 100% strain (**Figure 6**). The measured

power-conversion efficiency was 3.48%, which was increased to 3.67% after one cycle of stretching to 50% strain and lowered to 2.99% after 100 stretching cycles. The total power generation from the cells was significantly increased thanks to the expanded active area as the cells were stretched.



Figure 6. Schematic illustration of a PTB7:PC₇₁BM:DIO blend film upon reversible stretching and relaxation.

The PTB7:PC₇₁BM blend film has a phase separated morphology, like the IPN microstructure in the PLEC, but the much larger stiffness of the PTB7:PC₇₁BM blend indicates a different mechanism governing the stretchability. The fundamental difference is that the dispersed electrolyte phase in the PLEC blend is soft; the mechanical deformation of the PLEC blend can be compared to a sponge soaked with water. On the other hand, the dispersed phase in the PTB7:PC₇₁BM blend without DIO is made of PC₇₁BM and is stiffer than that of the PTB7 mesh network. This microstructure is analogous to cement-rock concrete, where the dispersed rocks stiffen the concrete matrix. DIO is added into the blend, and its evaporation at a later stage of film formation leaves behind free volumes that facilitate the relative sliding of the rigid nano-grains upon deformation (**Figure 7**). This is analogous to beach sand where the sliding of the rigid sand grains renders the sand soft and highly deformable.

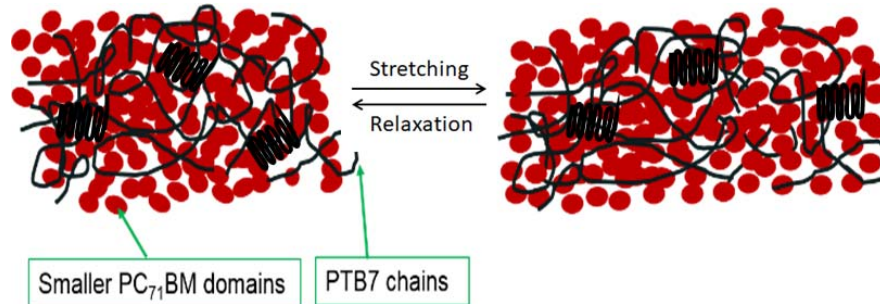


Figure 7. Schematic illustration of a PTB7:PC₇₁BM:DIO blend film upon reversible stretching and relaxation.

3. A screen-printable conductive ink and elastomeric conductor

To create stretchable printed electronics, a major material challenge is to develop printable and stretchable conductors or electrodes. Existing printed conductors either lack high conductivity or elastomeric deformability. We developed a screen printable ink based on silver nanowires (AgNW) that can be printed onto various substrates. The water-based AgNW ink, which contains a low solid content of 6.6 wt%, had a viscosity as high as 405.8 Pa·s at 0.1 s⁻¹ shear rate and appropriate rheological behavior suitable for screen printing (**Figure 8**). Uniform and sharp-edged lines with resolution achieving 50 μm were obtained by screen printing the AgNW ink. Moreover, a low thermal annealing temperature of 150°C was required to post-treat the printed patterns to recover the conductivity to as high as 4.67 × 10⁴ S cm⁻¹. When embedded in the surface layer of a polyurethane elastomer (PUA), the screen printed AgNW/PUA composite conductor behaves like

a rubbery conductor. The retention in conductivity of the composite conductor was up to $>10,000$ S cm^{-1} at 70% tensile strain. **Table 1** compares this elastomeric conductor with competing materials reported in the literature.

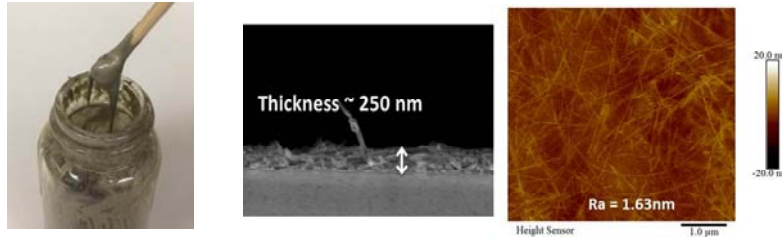


Figure 8. (From left to right) Photograph of a screen printable AgNW ink, SEM image of printed AgNWs on glass, and AFM image of an elastomeric conductor comprising the printed AgNWs (note the surface roughness is only 1.63nm).

Table 1. Comparison of electrical conductivity and stretchability of the present work with various previous research concerning intrinsically stretchable conductors.

Conductive components	Process	Conductivity at 0% strain (S cm^{-1})	Conductivity at 70% strain (S cm^{-1})	Reference
Silver flake Silver-CNT hybrid	Printable	5,710	~800	Literature
Silver nanoparticle	Printable	5,450	~3,700	Literature
Silver flake	Printable	3,570	~1,200	Literature
Silver particle Silver-CNT hybrid	Wet spinning	~6,000	~260	Literature
Gold nanoparticle	Layer-by-layer deposition	11,000	~5,000	Literature
Silver flake	Printable	738	~400	Literature
AgNWs	Printable	16,500[a]	8,002[a]	Our work
AgNWs	Printable	46,000[b]	10,064[b]	Our work

[a] Printed line width of 250 μm . [b] Printed line width of 50 μm .

4. Stretchable thin film transistors

We fabricated fully stretchable field effect transistors by solution-based processes (**Figure 9**). The elastomeric conductor from the previous section was successfully used as the stretchable gate/source/drain electrodes, semiconducting single walled carbon nanotubes (SWCNTs) were used as the channel material, and an elastomeric polymer developed in house as the dielectric. The fabrication of the fully-printed and wearable 10×6 TFT array had a yield of 91.7%, an average mobility of 33.8 ± 3.7 $\text{cm}^2\text{V}^{-1}\text{s}^{-1}$, and high stability during 1,000 cycles of wearing on-peeling off a glass tube with 5 mm diameter. The transistors could also be stretched by 30% strain. **Figure 10** shows that the TFT can effectively switch an OLED when unstretched, or stretched to 10%, 20%, and 30% strain.

With the successful demonstration of both intrinsically stretchable OLEDs and TFT, our next step would be to vertically integrate OLEDs onto a TFT array to achieve an intrinsically stretchable active matrix OLED display panel. As significant engineering effort is required to accomplish this,

further funding is required to develop this ambitious yet important technology.

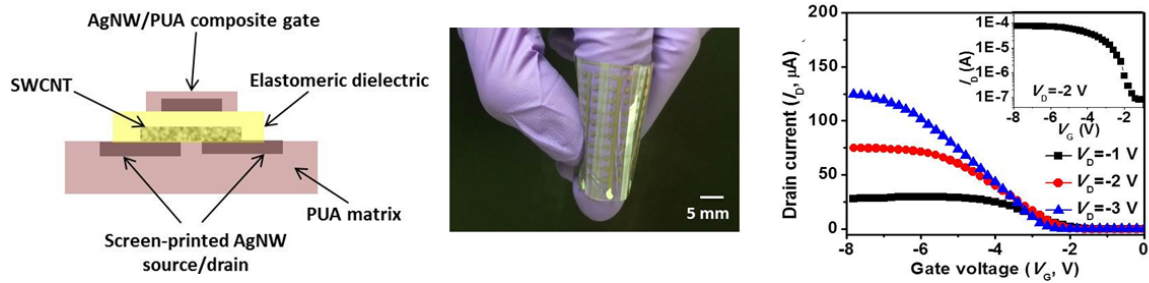


Figure 9. *Left:* Schematic illustration of the configuration of a fully printed TFT. *Center:* Photograph of the 10×6 TFT array contorted around a finger. *Right:* Transfer (I_D - V_G) characteristics of the transistors with V_D from -1.0 to -3.0 in 1.0 V step (Inset, I_D - V_G curve at V_D =-2.0 V on a logarithmic scale).

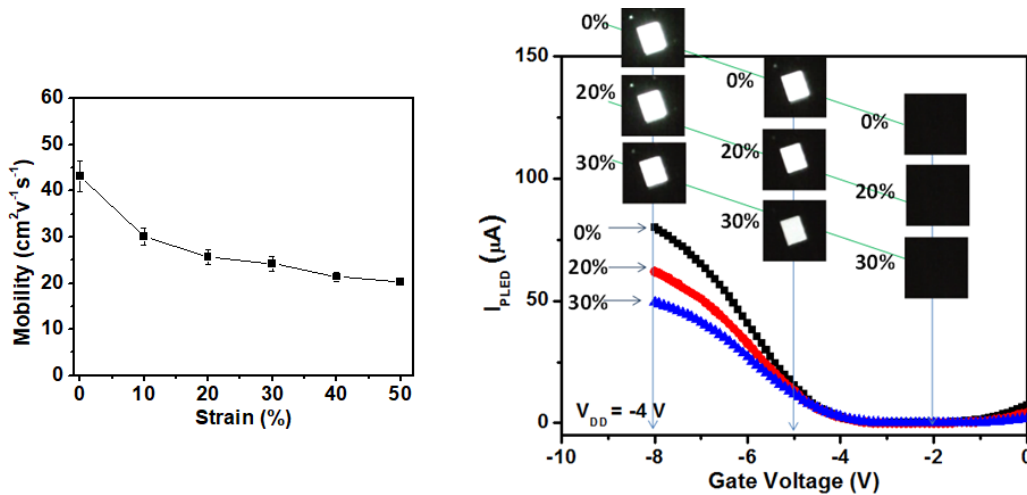


Figure 10. *Left:* Carrier mobility of the printed TFT as a function of stretching strains. *Right:* An OLED is switched by the TFT at 0, 10%, 20%, and 30% strains.

5. Electrolyte gated light emitting diodes

Considering the complexity of the AMOLED display architecture, we also investigated polymer light emitting transistors (LETs) that could simplify the display architecture and consequently the fabrication process of intrinsically stretchable displays. This work was done in collaboration with Atom Nanoelectronics, Inc. The LET is a thin film sandwich structure comprising, from the substrate upward, an OLED anode, OLED stack, a nanoporous layer of aluminum electrode as the OLED cathode, a solid electrolyte gate dielectric, and a top gate electrode. A voltage applied on the gate facilitates the electron injection from the cathode into the OLED stack, and thus switches on the OLED. Phosphorescent blue, green, red, and white LETs have all been demonstrated. In future studies, we would replace the nanoporous aluminum cathode with a stretchable electrode such as single-wall carbon nanotubes to achieve stretchable LETs.

6. A lightemitting touch-responsive device

During our exploration of mechanical deformation effects on semiconductor device behavior, we

invented a new light emitting touch-responsive device (LETD) for instantaneous visualization of pressure mapping (**Figure 12**). The LETD integrates an organometal halide perovskite polymer composite emissive layer and a flexible silver nanowire-polyurethane composite transparent electrode. The composite emissive layer contains methylammonium lead bromide (MAPbBr₃) nanocrystals uniformly dispersed in a polyethylene oxide (PEO) matrix and emits an intense green luminescence. The PEO matrix promotes the formation of small perovskite grains (~20 nm) composing a pinhole free composite film with a smooth surface. The composite transparent electrode is separated from the emissive layer with a 100 μm thick spacer. When a local pressure is applied, a Schottky contact is formed instantaneously between the metal and the emissive layer, and electroluminescence is produced at low voltages, reaching 1030 cd/m² at 6 V. The transparent LETD has approximately 68% transmittance. It can be bent to a 6 mm radius when polyethylene terephthalate is used as the substrate. The perovskite LETD has fast response and can be pixelated to offer potential applications in robotics, motion detection, finger print devices, and interactive wallpapers.

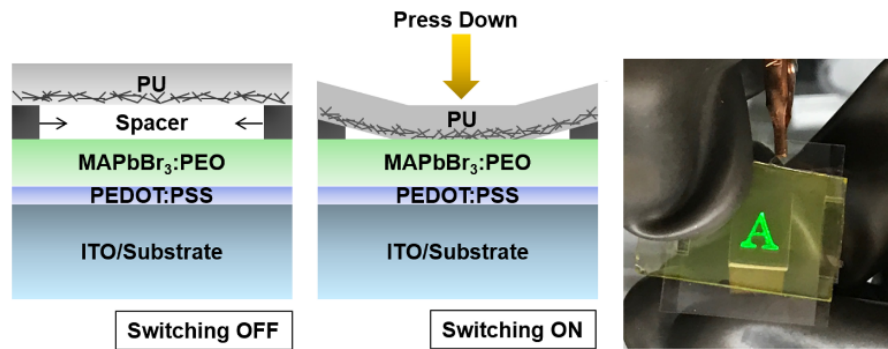


Figure 12. Schematic illustration of the cross-sectional structure of an LETD, and the light emitting pattern produced using a stamp labeled 'A'.

7. A compact flexible cooling device

On a joint effort with a project funded by the ARPA-E which focused on personal thermal management, we demonstrated the first solid-state cooling device. Relaxor ferroelectric P(VDF-TrFE-CFE) terpolymer had been proposed as a potential electrocaloric material for cooling. No functional cooling device had been designed because of the unsolved need to transport the polymer film and simultaneously exchange heat between a heat source and sink. We invented an electrostatic actuation mechanism that rapidly transported a flexible electrocaloric polymer film between heat source and heat sink, ensuring a high heat flux of transfer at the interfaces. This actuation did not add significant weight, volume, or power consumption needs to the device (**Figure 13**). The temperature change obtained was 3.8 K with a coefficient of performance (COP) of 13 which far surpasses any thermoelectric devices. To further improve the cooling performance, we investigated stretching of the P(VDF-TrFE-CFE) terpolymer film to re-orient the nanocrystallite microstructure in the amorphous polymer matrix. Terpolymer film stretched to 500% of its original length exhibits induced polarization much higher than its un-stretched state, which can be directly transformed into stronger electrocaloric effect. Meanwhile, the stretched sample also appears to display higher breakdown electric field strength. Work is in progress to integrate the strained terpolymer films into an improved cooling device.

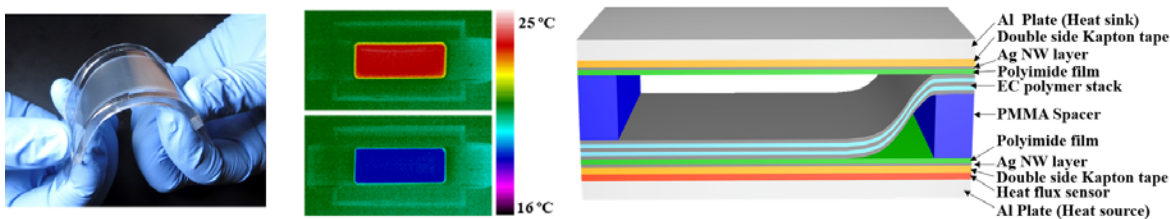


Figure 13. (from left to right) A flexible cooling device, heating of the electrocaloric polymer film upon voltage applied ON and cooling when voltage is turned OFF, schematic of the cooling device comprising an electrostatic actuation mechanism to transport the electrocaloric polymer film between the heat source and sink.

8. A rewritable paper based on photonic crystal

Paper has remained a widely accessible information medium even as sustainable and reusable paper replacements have attracted increasing attention. Building upon the new functional polymer materials developed in our group, we devised an ink-free rewritable paper concept in which the functions of photonic crystals, shape memory polymers, and electroactive polymers are combined in a nanocomposite for long-term information storage and display. The re-writable paper matches the benefits of paper as a zero-energy, long term medium, but provides the additional advantage of rewritability (**Figure 14**). The rewritable paper consists of a ferrous ferric oxide-carbon ($\text{Fe}_3\text{O}_4@\text{C}$) core-shell nanoparticle (NP) based photonic crystal embedded in a bistable electroactive polymer (BSEP). Electrical actuation induces large deformation in the z-axis of the nanocomposite, creating distinct color change in the actuated area. This nanocomposite stored high fidelity color images without inks which remained stable after more than a year of storage in ambient conditions, and the stored images could then be re-written over 500 times without degrading. A seven-segment numerical display was also demonstrated.

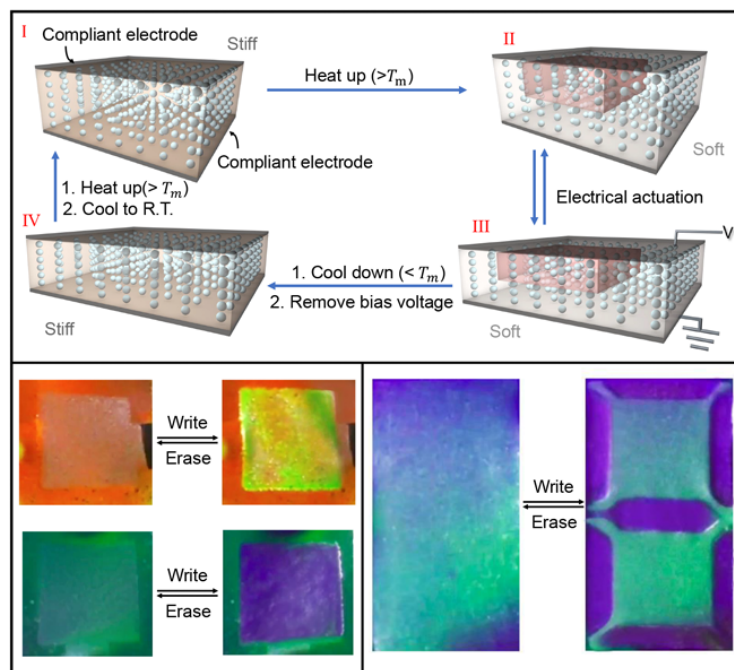


Figure 14. (Upper) Illustration of the writing/refreshing of a photonic nanocomposite containing 6 wt% $\text{Fe}_3\text{O}_4@\text{C}$ via bistable actuation. (Lower) Two different papers switching between orange-green and green-blue, and a paper electrically actuated to show numerical digits.

9. List of Publications in the past 12 months supported by the grant

1. Li, Y.F., Chou, S.Y., Huang, P., Xiao, C., Liu, X., Xie, Y., Zhao, F., Huang, Y., Feng, J., Zhong, H. and Sun, H.B., Pei, Q., Stretchable organometal - halide - perovskite quantum - dot light - emitting diodes. *Adv. Mater.*, DOI: 10.1002/adma.201807516 (2019).
2. Ma R, Chou SY, Xie Y, Pei Q. Morphological/nanostructural control toward intrinsically stretchable organic electronics. *Chemical Society Reviews*. DOI: 10.1039/C8CS00834E, pp 1-46 (2019).
3. Xie, Y., Meng, Y., Wang, W., Zhang, E., Leng, J. and Pei, Q., Bistable and reconfigurable photonic crystals—electroactive shape memory polymer nanocomposite for ink - free rewritable paper. *Adv. Func. Mater.*, **28**, 1802430 (2018).
4. Bae, J. S., Lee, Y. S., Li, J., Liang, J., Chen, D., Pei, Q., & Lee, S. B., The feasibility of healable electronics and mechanical behavior of silver nanowire (AgNW)/healable polymer composite. *Advanced Materials Technologies*, **3**, 1700364 (2018).
5. Gao, H., Youssef, K., Li, L., Zhu, X. and Pei, Q., Morphological study of an intrinsically stretchable photovoltaic bulk heterojunction. *J. Polymer Science Part B: Polymer Physics*, **56**, 814-820 (2018).
6. Liu, H., Li, M., Kaner, R.B., Chen, S. and Pei, Q., Monolithically integrated self-charging power pack consisting of a silicon nanowire array/conductive polymer hybrid solar cell and a laser-scribed graphene supercapacitor. *ACS Applied Materials & Interfaces*. **10**, 15609-15615 (2018).
7. Liu, J., Zhao, F., Li, H. and Pei, Q., 2017. Electrolyte-gated light-emitting transistors: working principle and applications. *Materials Chemistry Frontiers*. **2**, 253-263 (2018).
8. Chou, S.Y., Ma, R., Li, Y., Zhao, F., Tong, K., Yu, Z. and Pei, Q., 2017. Transparent perovskite light-emitting touch-responsive device. *ACS Nano* **11**, 11368–11375 (2017).
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10. Ma, R.* , Zhang, Z.* , Tong, K., Huber, D., Kornbluh, R., Ju, Y. S., & Pei, Q. Highly efficient electrocaloric cooling with electrostatic actuation. *Science*, **357** (6356), 1130-1134 (2017)
11. Liu, J., Oliva, J., Tong, K., Zhao, F., Chen, D. and Pei, Q., Multi-colored light-emitting electrochemical cells based on thermal activated delayed fluorescence host, *Scientific Reports*, **7**, 1524 (2017).
12. Liu, J., Chou, S. Y., Tong, K., Luan, X., Zhao, F., Pei, Q., & Li, H., Study of white electroluminescence from single-component polymer using electrolyte-gated diode. *J. Phys. Chem. C*. **121**, 10112–10118 (2017).
13. Liu, J., Chen, D.Y., Luan, X., Tong, K., Zhao, F., Liu, C., Pei, Q. and Li, H., Electrolyte-gated red, green and blue organic light-emitting diodes. *ACS Applied Materials & Interfaces*. **9**, 12647–12653 (2017).
14. Liang, J., Tong, K., Sun, H. and Pei, Q., Intrinsically stretchable field-effect transistors. *MRS Bulletin*, **42**, 131-137 (2017)
15. Zhao, F., Chen, D., Chang, S., Huang, H., Tong, K., Xiao, C., Chou, S., Zhong, H. and Pei, Q., Highly flexible organometal halide perovskite quantum dot based light-emitting diodes on a silver nanowire–polymer composite electrode. *J. Mate. Chem. C*. **5**, 531-538 (2017).
16. Gao, H., Chen, S., Liang, J., & Pei, Q. Elastomeric light emitting polymer enhanced by

- interpenetrating networks. *ACS Applied Materials & Interfaces*, **8**, 32504-32511 (2016).
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 20. D. Chen, J. Liang, Q.Pei, “Flexible and stretchable electrodes for next generation polymer electronics: a review”, *Science China: Chemistry*, **59**, 659-671 (2015).

10. List of Invited Presentations supported by the grant

1. “Toward Flexible and Intrinsically Stretchable Polymer Electronics”, Materials Research Society (MRS) 2018 Fall Meeting, Symposium PM, Boston, MA, November 25-30, 2018.
2. “Compact and Flexible Electrocaloric Cooling Devices”, 2018 International Symposium on Solid-State Cooling Materials and Devices, 11-15 November 2018, Guangzhou, China.
3. “From Driving Ions to Driving Polymers”, Symposium on Organic Electronics in Sweden During 30 Years and Future Promises. Linkoping, Sweden, October 18-19, 2018.
4. “A Transparent Light Emitting Touch-Responsive Device”, SPIE Photonics and Optics 2018, Symposium on Organic Light Emitting Materials and Devices XXII, San Diego, CA, August 19-23 (2018).
5. “Light Emitting Touch-Responsive Devices and Stretchable Electronic Materials”, Society for Information Display annual conferences and exhibition, Los Angeles, CA, May 22, 2018.
6. Keynote: “Morphological Controls Toward Intrinsically Stretchable Organic Electronics”, Photonics and Electronics Conference 2017, Swedish Foundation for Strategic Research, Lund, Sweden, September 7-8 (2017).
7. Plenary: “Morphological Controls Toward Intrinsically Stretchable Organic Electronics”, 10th Conference on Organic Electroluminescence and Optoelectronics”, Taiyuan, China, July 7-10.
8. “Novel Flexible Transparent Electrodes Based on Silver Nanowires”, 9th International Conference on Materials for Advanced Technologies (ICMAT 2017), Symposium J, June 18-23, Singapore.
9. “Intrinsically Stretchable Electronics Based on Silver Nanowires, Carbon Nanotubes, Conjugated Polymers, and Rubbery Dielectric Polymers”, 9th International Conference on Materials for Advanced Technologies (ICMAT 2017), Symposium R, June 18-23, Singapore.
10. “Stretchable Transparent Electrodes Based on Silver Nanowires”, The Society of Information Display (SID) Display Week Symposium & Seminars: May 21 – 26, 2017, Los Angeles, CA
11. “Dielectric elastomer and bistable electroactive polymer materials and devices”, The 53rd Society of Engineering Science (SES) Technical Meeting, Track C: Mechanics of Bioinspired Soft Machines, College Park, MD, October 2-5, 2016.

12. “Intrinsically-Stretchable, Transparent Thin Film Transistors”, PRiME 2016/230th Electrochemical Society Meeting, H03: Thin Film Transistors 13 (TFT 13). Honolulu, Hawaii, October 2-7, 2016.
13. “Synthesizing Elastomeric Electronic Materials for Intrinsically Stretchable Devices”, 252nd American Chemical Society National Meeting & Exposition, PMSE: Polymer & Polymer Hybrid Electronics & Biosensors, Philadelphia, PA, August 21-25, 2016.
14. “Low-Cost Approach to High-Efficiency Flexible and Stretchable OLEDs”, 2016 International Conference on Synthetic Metals, 26-July 1, 2016, Guangzhou, China, June
15. “Intrinsically Stretchable Polymer Electronic Materials and Devices”, Nature Conference on Flexible Electronics — Challenges and Opportunities, June 6–8, 2016, Nanjing, China.
16. “Stretchable polymer electronic materials and thin film devices”, University of Akron, College of Polymer Science and Engineering, April 22, 2016.
17. “Elastomeric Electronic and Electromechanical Materials”, 2016 IEEE Haptics Symposium, Philadelphia, PA, April 8-11, 2016.
18. Invited Keynote presentation, “A Transparent Composite Electrode for Flexible and Stretchable OPVs”, American Chemical Society Annual Conferences, Division of Solar and Fuel, San Diego, CA, March 13-16, 2016.
19. “Intrinsically Stretchable Polymer Electronics Based on Silver Nanowire Composite Electrode”, Materials Research Society (MRS) 2015 Fall Meeting, Symposium B: Responsive Polymers and Composites for Electronics, Energy, and Medicine, Boston, MA, Dec 1-5, 2015.
20. Plenary speech, “Highly Flexible Electronics”, International Forum on Organic and Nano Electronics, organized by Chongqing University of Science and Technology, November 06-07, Chongqing, China.
21. Plenary speech, “High Performance Flexible Organic Electronic Materials and Devices”, Joint Symposia on Organic Electronic Processes and Solid State Electroluminescence, October 11-14, Nanjing, China.
22. “Silver Nanowire Composite Electrode for High Efficiency Flexible OLEDs”, European Materials Research Society Fall 2015 Conferences, Warsaw, Poland, September 14-17, 2015.
23. “Stretchable Polymer Electronic Materials Devices”, Changchun Institute of Applied Chemistry, Chinese Academy of Science, Changchun, China on July 8, 2015.

11. List of patent applications

1. “Electrocaloric cooling with electrostatic actuation”, PCT Patent Application, Appl No. PCT/US2018/031410, filed on 07 May 2018.