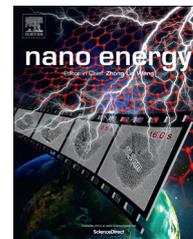


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RAPID COMMUNICATION

Enhanced emission intensity of vertical aligned flexible ZnO nanowire/p-polymer hybridized LED array by piezo-phototronic effect

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Abstract

Flexible optoelectronic device arrays are critically desirable for next-generation digital display, seamless integration of optoelectronics with biomedical and human-machine interactive systems and many other applications. Here we report a flexible patterned ZnO nanowire/PEDOT:PSS LEDs array with very high light-emitting uniformity. A near band edge emission centered at 400 nm and a broad defect-related emission covering the range from 450 to 780 nm is observed in the electroluminescence spectra. Both anneal and H₂O₂ treatment of the ZnO NWs and the optimal thickness of PEDOT:PSS can improve the performance of the as-fabricated device. Furthermore, we demonstrate that the emission intensity of the ZnO nanowire/p-polymer LEDs can be enhanced by applying an external strain owing to the piezo-phototronic effect, which reduces the barrier height for hole transport, leads to an improved balance between electron contributed current and hole contributed current, owing to the piezo-electric charges on the ZnO side created by applying local strain. The simple fabrication process and excellent properties of the device pave the way to cost-efficient LED technology for potential applications in high-resolution optoelectronic device, biomedical implanted devices, artificial electronic skin and smart sensor systems.

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Introduction

Inorganic nanostructures with designed composition, controllable morphology, tunable optoelectronic property and robust chemical stability are regarded as the solution for diverse applications in biomedical implants, environmental monitoring, personal electronics and defense technology. Specifically, Zinc oxide (ZnO), with a direct band gap of 3.37 eV and high exciton binding energy of 60 meV, is one of the most widely studied materials due to its unique electrical and optical properties. ZnO-based light emitting diodes (LEDs) have been considered as a potential candidate for the next generation of blue/near-UV light sources [1], and even as a potential candidate for white light sources [2-5] due to the multi-color emission originated from the visible deep centers which covers the whole visible spectra [6]. Intensive research efforts have been focused on ZnO homojunction LEDs to take the place of GaN LEDs [6-10]. However, the stability and reproducibility of the p-type doping of ZnO are still two main unsolved challenges. As a result, heterojunctions of ZnO devices, typically combined with GaN, are widely used as an alternative approach for LEDs [1,7-9]. However, such GaN/ZnO LEDs are mostly built on rigid sapphire wafers, which make this approach intricate for further applications in flexible and wearable electronic devices. In contrast, organic or organic/inorganic hybridized LEDs are drawing tremendous attention because of their high flexibility. Among them, n-ZnO and p-poly(3,4-ethylenedioxythiophene)-polystyrenesulfonate (PEDOT:PSS) hybridized inorganic/organic LED has aroused great technological and scientific interest due to the excellent optoelectronic properties of ZnO with the high flexibility, low-cost, easy fabrication, potential for large area deposition and commercial availability of PEDOT:PSS. Some groups have demonstrated thin film/thin film diodes based on ZnO/PEDOT:PSS by directly depositing PEDOT:PSS on n-type ZnO film [10,11]. However, many potential applications, such as high resolution pixels electronic display, optical interconnect and high density data storage desire devices with designed patterned arrays, as well as high emission intensity of the LEDs.

In our previous work, we have demonstrated that piezo-phototronic effect can be utilized to largely enhance light emitting intensity (to $\sim 200\%$) of a single ZnO wire inorganic/organic hybrid LED [12], and the results are well supported by a theory proposed for piezo-phototronics for studying the photon emission at a p-n junction with the presence of local

piezoelectric charges [13-18]. However, the piezo-phototronic effect has not been demonstrated in a vertical aligned ZnO wire inorganic/organic hybrid LEDs array, which have greater application than a single lateral NW LED in future. In this work, we demonstrate a flexible large-scale ordered LEDs array composed of PEDOT:PSS and patterned ZnO nanowires (ZnO NWs) array. The patterned ZnO NWs array was prepared by combining a simple low temperature hydrothermal method and convenient photolithography technology. The moderate synthesis conditions ($\sim 80^\circ\text{C}$) allow ZnO NWs to grow on a wide range of substrates, including Si wafers, polymers, and even fabric. Room temperature electroluminescence (EL) spectra of the device are composed of a near band edge (NBE) emission centered at 400 nm and a broad defect-related emission covering the range from 450 nm to 780 nm. The effects of post-treatment of ZnO NWs after hydrothermal synthesis were carried out to improve the quality of ZnO and the emission properties as well. Both H_2O_2 treatment and annealing of ZnO NWs can enhance the near band edge emission of the as-fabricated device. An optimized thickness (~ 200 nm) of the polymer is necessary to achieve the best performance and a high yield of the device. The piezo-phototronic effect was utilized to enhance the light emission intensity by reducing the barrier height for hole transport, leading to an improved balance between electron contributed current and hole contributed current, owing to the piezoelectric charges on the ZnO side created by applying local strain. The simple fabrication process and excellent properties of the device pave the way to cost-efficient LED technology for potential applications in high-resolution optoelectronic device, biomedical implanted devices, artificial electronic skin and smart sensor systems.

Results and discussion

Schematic representation of the ZnO nanowire/p-polymer LEDs is shown in Figure 1a. The device was fabricated by using a transparent ITO/glass or ITO/PET substrate as negative electrode for electron injection and a metal contact as positive electrode for hole injection. Figure 1b shows a photograph of an as-fabricated flexible device and corresponding optical image when the device was electrically lit up. The dimension of the whole device is about $1.5\text{ cm} \times 2\text{ cm}$, which was divided into nine discrete areas.

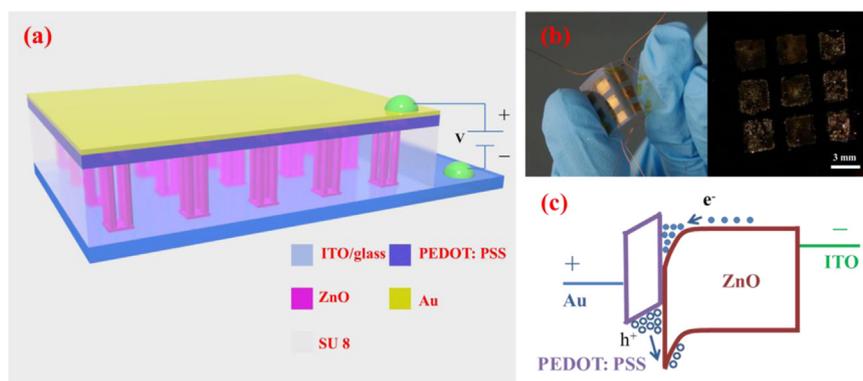


Figure 1 (a) Schematic illustration of the device based on ITO/glass substrate. (b) Photograph of the ZnO nanowire/p-polymer LEDs based on flexible substrate and corresponding optical image when the device was electrically lit up. (c) Schematic band diagram of the ZnO nanowire/p-polymer LEDs under forward bias.

Figure 1c shows the energy band diagram of the ZnO nanowire/p-polymer LEDs. There is a 0.9 eV barrier for electron injection from the conduction band of ZnO into LUMO of PEDOT:PSS. The hole injection barrier is approximately 2.4 eV for hole transfer from HOMO of PEDOT:PSS into valence band of ZnO (Figure S1) [19]. So electron and hole accumulation at the ZnO/PEDOT:PSS interface will be substantial under forward bias [20], leading to a light emission by electron-hole recombination.

Figure 2a shows the detailed step by step fabrication process of the ZnO nanowire/p-polymer LEDs. Patterned arrays of the ZnO NWs with diameter of 300 nm and length of 4 μm were obtained where the ZnO seed patterns locate, with a side length of 20 μm and pitch of 100 μm (Figure 2b). Notably, ZnO NWs can be grown with a broad concentration variation of the nutrient solution, from 5 mM to 100 mM. The concentration of the nutrient solution will control the growth speed, NWs' length, diameter and size distribution [21]. After the growth of patterned ZnO NWs, a layer of SU 8 was spun coated to wrap around the ZnO NWs. Then an oxygen plasma was applied to etch the top of SU 8 to expose the heads of ZnO NWs. Figure 2c clearly shows that all of the nanowire arrays are wrapped in SU 8 with their heads exposed after oxygen plasma etching, while the bottoms and main bodies of the nanowire arrays are still fully enclosed, which greatly improves the stability and robustness of the structure. At last, a layer of PEDOT:PSS was spun coated on the top of the ZnO NWs and a 40-nm layer of Au was then sputtered as the top electrode of the device. Figure 2d shows the cross-section SEM image of the ZnO nanowire/p-polymer LEDs (false color for a better identification).

A typical *I-V* characteristic of the ZnO nanowire/p-polymer LEDs, which consists of nine positive electrodes, is presented

in Figure 3a, demonstrating a good rectification behavior with a turn on voltage of 12 V. The corresponding digital image of the device before and after electrically light up at a bias voltage of 20 V is shown in the inset in Figure 3a. The optical image of the LEDs array with high uniformly light-emitting is shown in Figure 3b, in which a pixel is consisted of a bundle of ZnO NWs. The enlarged image of five adjacent representative LEDs (marked with a red dashed rectangle in Figure 3b) is given in Figure 3c, together with the corresponding line profile of their emission intensity, in which no crosstalk between adjacent light-emitting pixels is observed. Room temperature electroluminescence spectra (EL) of an LED under different bias voltages are shown in Figure 3d. A broad defect-related visible emission ranging from 450 nm to 780 nm as well as a weak near band emission (NBE) peak at 400 nm is observed, which may be associated with the poor crystallinity and high defect concentration of ZnO nanowire synthesized through the low-temperature hydrothermal method [22]. EL intensity increases as the voltage increases, while the peak does not show any obvious shift.

To increase the crystallinity as well as the light emission performance of the ZnO NWs array LEDs, H_2O_2 surface treatment and annealing in oxygen are carried out to modify surface defects and improve crystallinity of the as-grown ZnO NWs, respectively. Figure 4a shows the room temperature photoluminescence (PL) spectra of the ZnO NWs grew on ITO/glass substrate with and without H_2O_2 treatment. Compared with the untreated NWs, the device has an enhanced NBE emission and weakened defect-related emission, indicating the improved crystallinity and reduced defects of ZnO NWs after the H_2O_2 surface treatment (dipped in a 30% H_2O_2 solution at 70 $^\circ\text{C}$ for 30 min) [23,24]. An NBE emission at around 400 nm can be

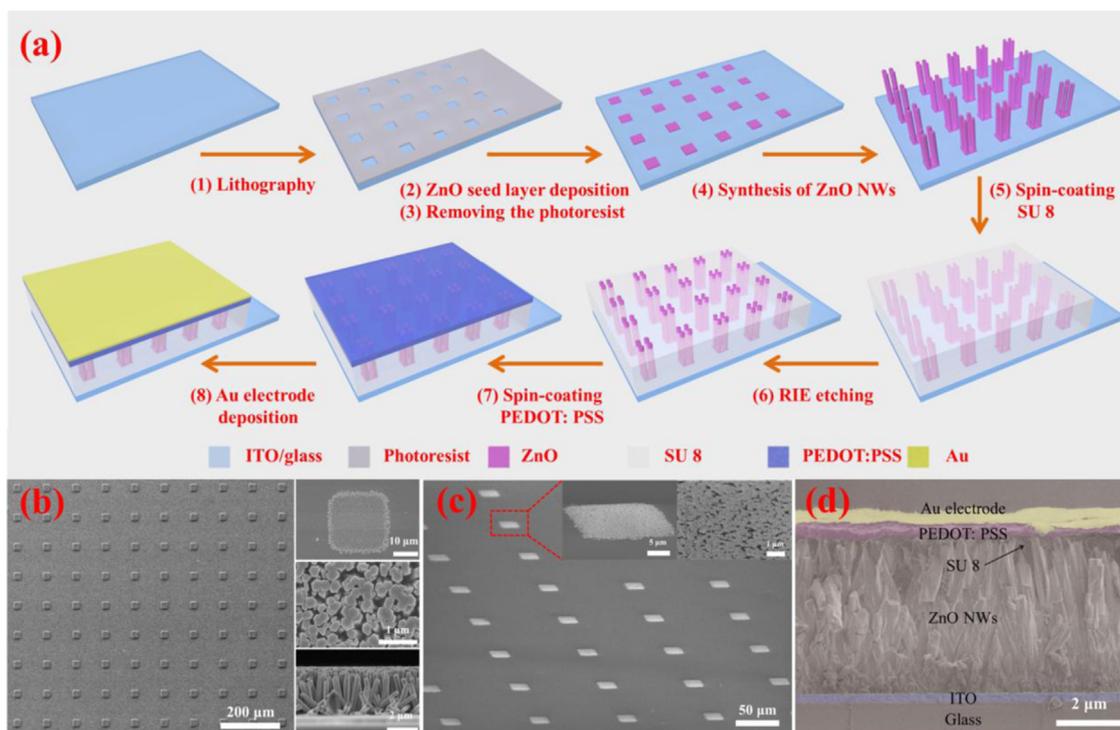


Figure 2 (a) The schematic process for fabricating ZnO NWs/p-polymer LEDs. (b) SEM images of the as-grown ZnO NWs. (c) 25° tilt SEM images of the as-grown ZnO NWs with their heads exposed. (d) Cross-section SEM image of the ZnO nanowire/p-polymer LEDs device (false color for a better identification).

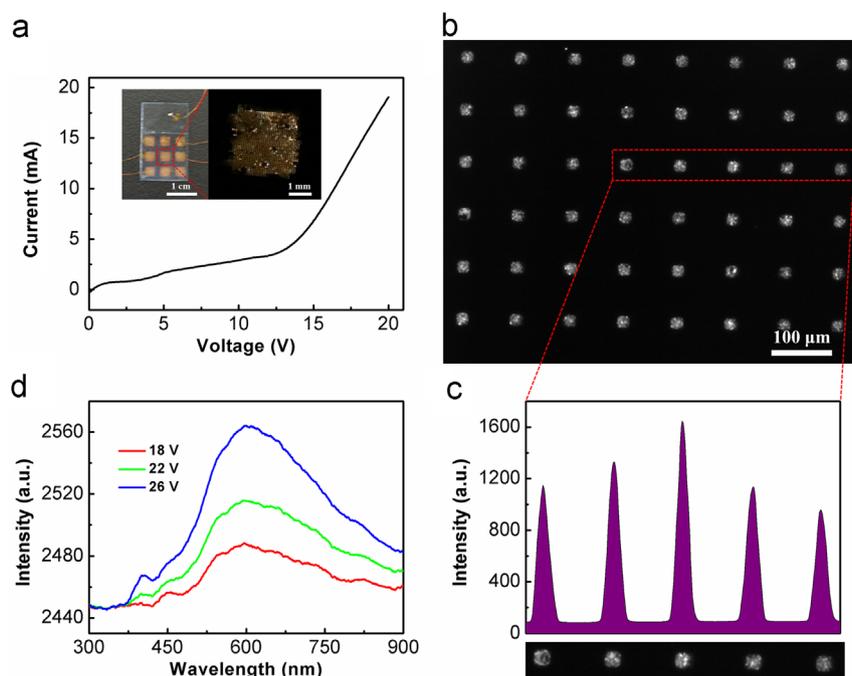


Figure 3 (a) *I-V* curve of the ZnO nanowire/p-polymer LEDs. Inset: Digital photographs of the LED based on ITO/glass before and after being lit up. (b) The optical image of the ZnO nanowire/p-polymer LED array when electrically emitting light. (c) Five representative ZnO nanowire/p-polymer LEDs (marked with a red dashed rectangle in (b)) and the corresponding emission intensity profile. (d) Room temperature EL spectra of the ZnO nanowire/p-polymer LEDs under different biased voltages.

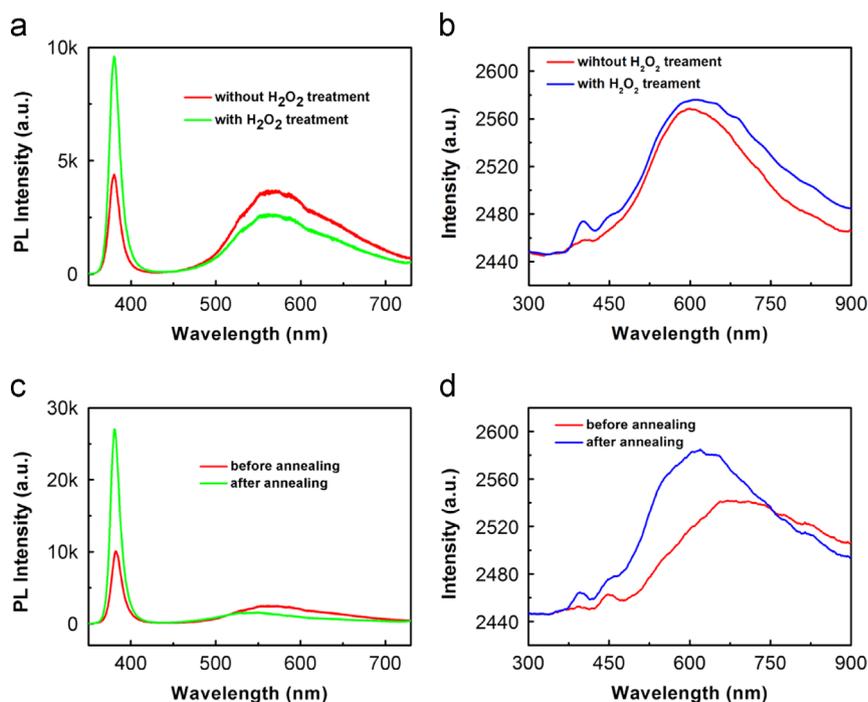


Figure 4 (a) PL spectra of ZnO NWs with and without H_2O_2 treatment. (b) EL spectra of the as-fabricated LEDs with and without H_2O_2 treatment of ZnO NWs. (c) PL spectra of ZnO NWs before and after annealing. (d) EL spectra of the as-fabricated LEDs before and after annealing of ZnO NWs.

obviously observed in the EL spectrum of the device fabricated with H_2O_2 -treated ZnO NWs, which can hardly be observed before the H_2O_2 surface treatment, as shown in Figure 4b.

The effect of annealing in oxygen on the emission property of the device is also investigated, with the corresponding PL and EL spectra given in Figure 4c and d, respectively. Here, sapphire

substrate is employed instead of glass in order to withstand the high annealing temperature (700 °C). Figure 4d shows the EL spectra of the device fabricated using the ZnO NWs with and without annealing. We find that the NBE emission of the EL spectra is obviously enhanced after annealing, as indicated by the peak centered at 400 nm. The defect-related visible emission exhibits blue-shift after annealing, and a similar feature is also observed in the PL spectra. It is possible that the observed shift is due to the reduction of the red component of the emission [25]. Note that there is an obvious shift of defect-related EL emission between devices fabricated with as-grown ZnO NWs on ITO/glass (Figure 4b, red solid line) and those on ITO/sapphire substrate (Figure 4d, red solid line), which perhaps due to the difference of substrates [26]. Studies on the treatment of ZnO NWs with H₂O₂ and annealing indicate that both approaches lead to the enhanced NBE emission. Since most flexible substrates cannot survive the high temperature for effective annealing treatment, H₂O₂ treatment is more favorable for fabricating devices on flexible substrates due to its low operating temperature, mild environment and convenient process.

Flexibility is another important characteristic for wearable electronics. To build nanowire LEDs array with great flexibility and low cost for wearable electronics applications, a thinner device is desired. Here, we investigated the luminescence performance of the ZnO nanowire/PEDOT:PSS LEDs at different thicknesses of PEDOT:PSS varying from 180 nm to 550 nm. The cross-section SEM images of the ZnO nanowire/p-polymer LEDs with thicknesses of 550 ± 10 nm (device A, left), 370 ± 10 nm (device B, middle) and 180 ± 10 nm (device C, right) are shown in Figure 5a, and the corresponding EL spectra of these devices are shown in Figure 5b. We can find

that the EL spectra of device B and device C exhibited a broad defect-related emission peak while it is hardly to observe the emission peak from the EL spectrum of device A, which indicates that the thickness of PEDOT:PSS plays a critical role in the electroluminescence of the ZnO nanowire/p-polymer LEDs. By extracting the peak intensity from the EL spectra and plotting in Figure 5c, we can find that the peak intensity of the LEDs increases as the thickness of PEDOT:PSS decreases, when the thickness is larger than 180 nm. The reason maybe that the hole mobility of PEDOT:PSS [27] is much lower than the electron mobility of ZnO NWs [28,29]; as a result, the electron-hole recombination is limited by hole injection of PEDOT:PSS. When the PEDOT:PSS layer is thicker, the less holes can reach the interface between ZnO NWs and PEDOT:PSS to recombine with electrons, leading to a lower electroluminescence intensity. However, when the thickness of the PEDOT:PSS film keeps decreasing, it cannot totally wrap the heads of all the ZnO NWs, which will lead to a current leakage or short-circuit of the device between the top and the bottom electrodes (purple zone in Figure 5c). Therefore, an optimized thickness of the PEDOT:PSS film (~200 nm in our device) is achieved in our experiment to ensure the electroluminescence properties of the device. It is worth mentioning that LED of water-resistance and flexibility has great prospect for applications in biomedicine and moist environment [30-32]. Figure S4 shows the water-resistant test of the ZnO nanowire/p-polymer LEDs based on PET substrate. The excellent light emission performance of the device does not alter even after the device was immersed in the water over 2 h.

To demonstrate the strain-controlled light-emitting intensity of the ZnO nanowire/p-polymer LEDs by the piezo-phototronic effect, different pressures were applied

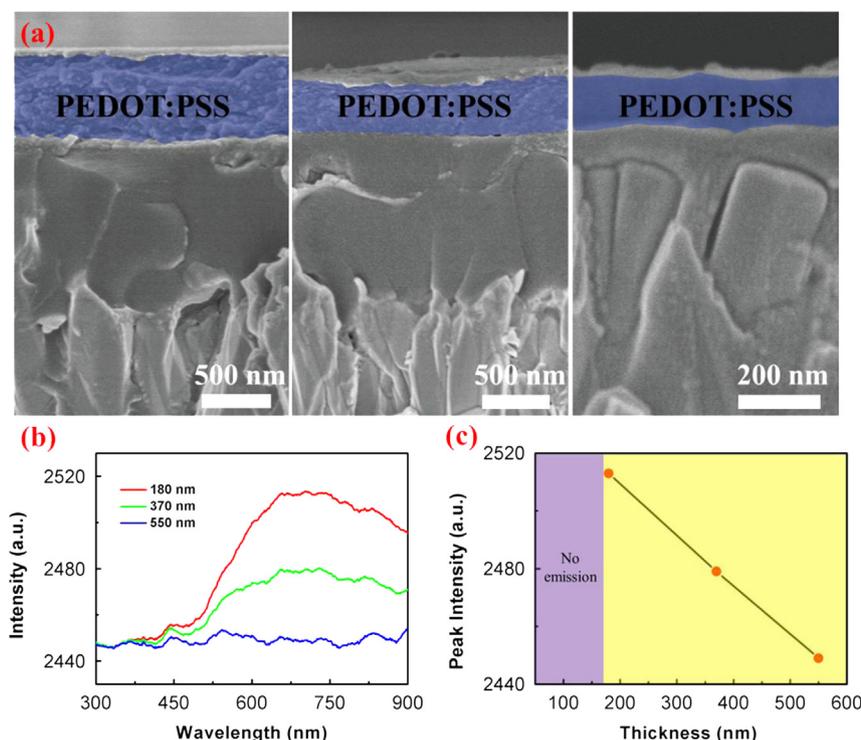


Figure 5 (a) Cross-section SEM images of the ZnO nanowire/p-polymer LEDs with different thicknesses of PEDOT:PSS (false color for a better identification). (b) EL spectra of the ZnO nanowire/p-polymer LEDs with different thicknesses of PEDOT:PSS at the same bias voltage of 24 V. (c) Dependence of the peak intensity on the thickness of PEDOT:PSS.

onto the device and the corresponding optical images were recorded by a CCD camera. Under a fixed forward bias of 14 V, the light-emitting intensity of the four representative LEDs increased by applying a step-by-step compressive strain, which can be directly observed from the inserted CCD images in Figure 6a. The enhancement factor E of the LED intensity is defined as $E = (I_p - I_0)/I_0$, where I_0 and I_p are the intensities of the LED extracted from the optical images taken by a CCD camera at zero applied strain and corresponding certain strain, respectively. Figure 6a shows that the E factor is approximately linearly dependent on the pressure. The intensity enhancement by the piezo-phototronic effect in the ZnO nanowire/p-polymer LED before (dashed line) and after (solid line) applying a pressure can be explained schematically in Figure 6b. The low mobility and high barrier height of 2.4 eV for hole transport and injection largely limit the radiative recombination in the device. When the ZnO nanowire is under compressive strain, a piezopotential is created in the nanowire, assuming that the concentration of free carriers is low in the nanowire. When the c -axis of the ZnO nanowire is pointing to the p-polymer [33] and the NW under c -axis compressive strain, the local negative piezoelectric charges at the p-n junction region will raise the energy band in the ZnO nanowire near the junction region [16], leading to a reduced barrier height for hole injection. The modified band can increase the hole injection rates from PEDOT:PSS into ZnO, which increases the recombination rate of electrons and holes, leading to an enhancement of the light emission intensity.

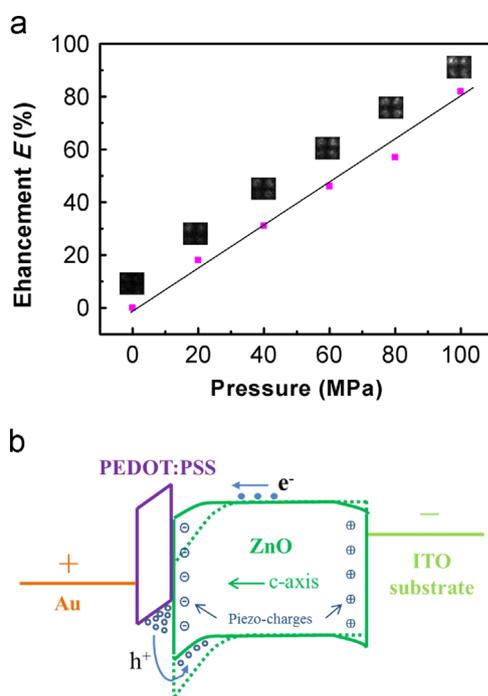


Figure 6 (a) Enhancement factor E of the ZnO nanowire/p-polymer LEDs as a function of the applied pressure with the corresponding optical images in the inset. (b) Schematic band diagram of the ZnO nanowire/p-polymer LEDs before (dashed line) and after (solid line) applying a pressure.

Conclusions

In summary, we have demonstrated an inorganic/organic hybrid LEDs array consisting of ordered ZnO NW array and PEDOT:PSS hole transfer layer. The device is flexible and exhibits high uniformly light-emitting intensity. Room temperature electroluminescence shows a near band edge emission centered at 400 nm and a broad defect-related emission covering the range from 450 to 780 nm. Both H_2O_2 treatment and annealing of ZnO NWs can effectively enhance the near band edge emission of the as-fabricated devices. An optimized thickness of PEDOT:PSS (~ 200 nm) is achieved to ensure that the electroluminescence properties of the device due to the electron-hole recombination are limited by hole injection of PEDOT:PSS. The piezo-phototronic effect was introduced to modify the band structure at the interface of the p-n junction by applying a compressive strain, which increases the recombination rate of electrons and holes, leading to an enhancement of the light emission intensity. Such strain-controlled light-emitting intensity of the LEDs offers a novel approach for next generation pressure mapping technology, touchpad technology, artificial electronic skin and smart sensor system. Furthermore, a water-resistant test of the device was conducted to demonstrate its good stability in the moist environment. Our results show great potential as cost-efficient LED technology for applications in high-resolution optoelectronic devices, biomedical implanted devices and wearable electronic devices.

Experimental section

Fabrication of the device

The fabrication procedure of ZnO nanowire/p-polymer LEDs is shown in Figure 2a. The substrates were cleaned ultrasonically in acetone, isopropyl alcohol and deionized water for 10 min, respectively, and then blown dry with nitrogen gas. A SU 8 (from MICROCHEM) photoresist layer, with patterned pore diameter about $4 \mu\text{m}$ and $100 \mu\text{m}$ pitch, was prepared by photolithography (PL). Subsequently, a 50 nm thickness ZnO seed layer was deposited onto the as-fabricated substrate by RF magnetron sputtering. By removing the photoresist, a substrate with patterned ZnO seed layer was obtained. Then, the patterned substrate was put into the nutrient solution, containing 50 mM zinc nitrate and equal concentration of hexamethylenetetramine (HMTA), for ZnO growth at 85°C for 3 h. After the growth of patterned ZnO NWs, a layer of SU 8 was spun coated wrap around the ZnO NWs. Then an oxygen plasma etching was applied to etch away the top part of the SU 8 and expose the heads of ZnO NWs. At last, a layer of PEDOT:PSS was spun coated on the top of the ZnO NWs and a 40-nm layer of Au was then sputtered as the top electrode of the device.

Characterization

A field-emission scanning electron microscope (FE-SEM, Hitachi SU8020) was used to characterize the morphology of ZnO NWs and the cross-section of the device. The optical images and lighted-up image of the LED array were obtained by a Zeiss Observer Z1 inverted microscope equipped with

an HQ2 camera. Current-voltage characteristics were measured by the Keithley 4200 SCS system. Electroluminescence spectra (EL) were collected by an Ocean Optics QE65000 spectrometer, while the photoluminescence spectra (PL) were collected by a confocal micro-Raman spectroscope (Horiba Jobin-Yvon LabRAM HR Evolution) with a He-Cd laser (Kimmon IK3301R-G) of 3 mW at 325 nm.

Acknowledgments

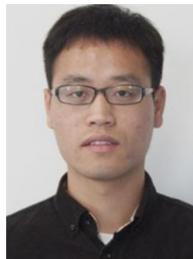
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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at <http://dx.doi.org/10.1016/j.nanoen.2014.11.033>.

References

- [1] S. Xu, C. Xu, Y. Liu, Y. Hu, R. Yang, Q. Yang, J.-H. Ryou, H.J. Kim, Z. Lochner, S. Choi, R. Dupuis, Z.L. Wang, *Adv. Mater.* 22 (2010) 4749-4753.
- [2] Z. Lichun, L. Qingshan, Q. Chong, Z. Zhongjun, H. Ruizhi, Z. Fengzhou, *J. Opt.* 15 (2013) 025003.
- [3] D.I. Son, B.W. Kwon, D.H. Park, W.-S. Seo, Y. Yi, B. Angadi, C.-L. Lee, W.K. Choi, *Nat. Nanotechnol.* 7 (2012) 465-471.
- [4] M. Willander, O. Nur, S. Zaman, A. Zainelabdin, N. Bano, I. Hussain, *J. Phys. D: Appl. Phys.* 44 (2011) 224017.
- [5] N. Bano, S. Zaman, A. Zainelabdin, S. Hussain, I. Hussain, O. Nur, M. Willander, *J. Appl. Phys.* 108 (2010) 043103.
- [6] M. Willander, O. Nur, Q.X. Zhao, L.L. Yang, M. Lorenz, B.Q. Cao, J.Z. Pérez, C. Czekalla, G. Zimmermann, M. Grundmann, A. Bakin, A. Behrends, M. Al-Suleiman, A. El-Shaer, A.C. Mofor, B. Postels, A. Waag, N. Boukos, A. Travlos, H.S. Kwack, J. Guinard, D.L.S. Dang, *Nanotechnology* 20 (2009) 332001.
- [7] Q. Yang, W. Wang, S. Xu, Z.L. Wang, *Nano Lett.* 11 (2011) 4012-4017.
- [8] O. Lupan, T. Pauporté, B. Viana, *Adv. Mater.* 22 (2010) 3298-3302.
- [9] Y. Hu, Y. Zhang, L. Lin, Y. Ding, G. Zhu, Z.L. Wang, *Nano Lett.* 12 (2012) 3851-3856.
- [10] B.K. Sharma, N. Khare, S. Ahmad, *Solid State Commun.* 149 (2009) 771-774.
- [11] D.-H. Lee, D.-H. Park, S. Kim, S.Y. Lee, *Thin Solid Films* 519 (2011) 5658-5661.
- [12] Q. Yang, Y. Liu, C. Pan, J. Chen, X. Wen, Z.L. Wang, *Nano Lett.* 13 (2013) 607-613.
- [13] Z.L. Wang, *Nano Today* 5 (2010) 540-552.
- [14] Y. Zhang, Y. Liu, Z.L. Wang, *Adv. Mater.* 23 (2011) 3004-3013.
- [15] Z.L. Wang, *Adv. Mater.* 24 (2012) 4632-4646.
- [16] Y. Zhang, Z.L. Wang, *Adv. Mater.* 24 (2012) 4712-4718.
- [17] W. Wu, C. Pan, Y. Zhang, X. Wen, Z.L. Wang, *Nano Today* 8 (2013) 619-642.
- [18] Y. Liu, S. Niu, Q. Yang, B.D.B. Klein, Y.S. Zhou, Z.L. Wang, *Adv. Mater.* 26 (2014) 7209-7216.
- [19] Z. Wang, J. Qi, X. Yan, Q. Zhang, Q. Wang, S. Lu, P. Lin, Q. Liao, Z. Zhang, Y. Zhang, *RSC Adv.* 3 (2013) 17011-17015.
- [20] X.W. Sun, J.Z. Huang, J.X. Wang, Z. Xu, *Nano Lett.* 8 (2008) 1219-1223.
- [21] S. Xu, Z. Wang, *Nano Res.* 4 (2011) 1013-1098.
- [22] M. Riaz, J. Song, O. Nur, Z.L. Wang, M. Willander, *Adv. Funct. Mater.* 21 (2011) 628-633.
- [23] S.-H. Yang, Y.-J. Lin, H.-C. Chang, Y.-H. Chen, *Thin Solid Films* 545 (2013) 476-479.
- [24] L.E. Greene, M. Law, J. Goldberger, F. Kim, J.C. Johnson, Y. Zhang, R.J. Saykally, P. Yang, *Angew. Chem. Int. Ed.* 42 (2003) 3031-3034.
- [25] A.B. Djurišić, Y.H. Leung, K.H. Tam, L. Ding, W.K. Ge H.Y. Chen, S. Gwo, *Appl. Phys. Lett.* 88 (2006) 103107.
- [26] A. Nadarajah, R.C. Word, J. Meiss, R. Könenkamp, *Nano Lett.* 8 (2008) 534-537.
- [27] Q. Wei, M. Mukaida, Y. Naitoh, T. Ishida, *Adv. Mater.* 25 (2013) 2831-2836.
- [28] H. Liu, R. Peng, S. Chu, S. Chu, *Appl. Phys. Lett.* 105 (2014) 043507.
- [29] J. Goldberger, D.J. Sirbuly, M. Law, P. Yang, *J. Phys. Chem. B* 109 (2004) 9-14.
- [30] S.-I. Park, Y. Xiong, R.-H. Kim, P. Elvikis, M. Meitl, D.-H. Kim, J. Wu, J. Yoon, C.-J. Yu, Z. Liu, Y. Huang, K.-c. Hwang, P. Ferreira, X. Li, K. Choquette, J.A. Rogers, *Science* 325 (2009) 977-981.
- [31] R.-H. Kim, D.-H. Kim, J. Xiao, B.H. Kim, S.-I. Park, B. Panilaitis, R. Ghaffari, J. Yao, M. Li, Z. Liu, V. Malyarchuk, D.G. Kim, A.-P. Le, R.G. Nuzzo, D.L. Kaplan, F.G. Omenetto, Y. Huang, Z. Kang, J.A. Rogers, *Nat. Mater.* 9 (2010) 929-937.
- [32] S.Y. Lee, K.-I. Park, C. Huh, M. Koo, H.G. Yoo, S. Kim, C.S. Ah, G.Y. Sung, K.J. Lee, *Nano Energy* 1 (2012) 145-151.
- [33] C. Pan, W. Guo, L. Dong, G. Zhu, Z.L. Wang, *Adv. Mater.* 24 (2012) 3356-3361.



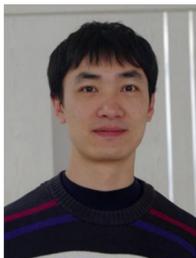
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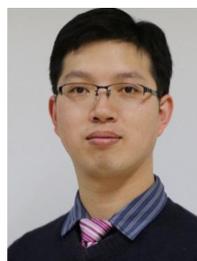
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