DOI: [10.1002/adom.201500474](https://doi.org/10.1002/adom.201500474)

Hybrid light-emitting transistors based on low temperature solution-processed metal oxides and charge injecting interlayers

By Mujeeb Ullah,^{†,*} Yen-Hung Lin,[†] Khalid Muhieddine, Shih-Chun Lo, Thomas D. Anthopoulos,^{*} and Ebinazar B. Namdas^{*}

Dr. M. Ullah, K. Muhieddine and Prof. E. B. Namdas
Centre for Organic Photonics & Electronics, School of Mathematics and Physics
The University of Queensland, Brisbane, Queensland 4072, Australia
E-mail: mujeeb.ullah@uq.edu.au; e.namdass@uq.edu.au

Dr. Y-H. Lin, Prof. T. D. Anthopoulos
Blackett Laboratory, Department of Physics and Centre for Plastic Electronics
Imperial College London, London SW7 2BW, United Kingdom
E-mail: thomas.anthopoulos@imperial.ac.uk

Prof. S-C. Lo
Centre for Organic Photonics & Electronics, School of Chemistry and Molecular Bioscience
The University of Queensland, Brisbane, Queensland 4072, Australia

[†]First two authors contributed equally.

Organic light emitting field effect transistors (LEFETs) evolved from organic field effect transistors (OFETs) and organic light emitting diodes (OLEDs) into a new multifunctional optoelectronic device.^[1-22] LEFETs combine the switching functionality of FETs with light emission of an OLED in a transistor device configuration. This dual functionality has potential for new applications including simplified pixels for high-definition organic-based emissive displays,^[18,20] optical communication devices,^[3,4,17] and potentially electrically driven organic lasers.^[2-8]

Over the past decade, significant progress has been made to improve the brightness,^[7,8,16,21] external quantum efficiency (EQE),^[6,7,15,19,20] charge carrier mobility,^[7,17,21,22] channel current ON/OFF ratio and aperture ratio of LEFETs.^[20] Despite the significant progress, to date there is no single LEFET architecture that exhibits advantages across all of the operational characteristics.^[1-22] For example, single-layer LEFETs suffer from poor charge carrier mobilities^[15-17] and Capelli *et al.* employed all-organic tri-layer heterostructure LEFETs in an attempt to overcome this.^[6] Improved charge carrier mobility and EQE up to 5% was attained by sandwiching the emissive layer between p- and n-type materials. However, the operating voltages remained high (100 V) and the reported high EQE was obtained only at low brightness of $<1 \text{ cd/m}^2$. To achieve high EQE at high brightness, a heterostructure LEFET concept consisting of non-planar source and drain contacts, has recently been demonstrated.^[7] The latter LEFET architecture exhibited enhanced EQEs by a factor of 20 at higher brightness compared to the control planar tri-layer LEFETs. More recently, similar heterostructure LEFETs were employed to give an increased and well-defined light emitting area for display applications. However, these devices still suffered from poor carrier mobility and the light emitting area is heavily dependent on applied gate voltage. Despite of the tremendous progress and technological potential of all-organic heterostructure LEFETs, the carrier mobility values achieved to date remain low ($<1 \text{ cm}^2/\text{Vs}$) while the light emitting area is either too narrow or non-uniform and strongly dependent on the biasing conditions. Finally, the high voltage often required to drive these devices ($\approx 100 \text{ V}$), dramatically increases the overall power consumption which renders the technology unsuitable for display applications.

To improve the charge carrier mobility, hybrid non-planar LEFETs architectures employing different charge transporting inorganic semiconductors such as CdS and metal oxides (*e.g.*, ZnO, ZTO) have been developed to offer a much higher mobility of up to 19

cm^2/Vs and a high channel current ON/OFF ratio ($>10^6$) with a lower EQE (typically $\sim 0.01\%$).^[21-26] Although respectable electrical device performance has been demonstrated, it has remained challenging to achieve a high EQE and brightness simultaneously, especially at lower operating voltages ($<25\text{ V}$). Furthermore the major drawbacks of reported hybrid LEFETs are; i) very high processing temperatures (typically $>500\text{ }^\circ\text{C}$) necessary for sintering metal oxides, which are incompatible with processing on plastic substrates, and ii) edge light emission zone leading to low (2.5%) aperture ratios (defined as the ratio of light emitting area over total device area). Such narrow edge emission zone restricted to the edge of the emitting electrode in the reported hybrid heterostructure LEFETs is not suitable for application in display technologies.^[6-8,17,21-25] To overcome this issue, we recently showed that incorporation of the solution processed interlayer ethoxylated-polyethylenimine (PEIE) can modify the surface energy of the inorganic charge transporting layer resulting in enhanced carrier injection and uniform light-emission across the electrode area.^[26] However the EQE value obtained from these devices remained low ($10^{-2}\%$ - $10^{-1}\%$), and the operating voltages high (100V). Furthermore, the processing temperatures required for the deposition of the inorganic layer was high ($500\text{ }^\circ\text{C}$) and incompatible with inexpensive, temperature-sensitive substrate materials.

Here we report hybrid LEFETs fabricated with low temperature and solution-processed organic and inorganic metal oxide semiconductors. Furthermore, we demonstrate a strategy to significantly enhance the key performance parameter of LEFETs namely; the operating voltage, aperture ratio, EQE and brightness in a simultaneous fashion. The hybrid LEFETs were comprised of the bilayer oxide heterojunction $\text{In}_2\text{O}_3/\text{ZnO}$ (OHJ-I) and the multilayer oxide heterojunction $\text{In}_2\text{O}_3/\text{Ga}_2\text{O}_3/\text{ZnO}$ (OHJ-II) structures prepared using different metal oxide precursors.^[27-28] In addition, Cs_2CO_3 and poly(*p*-phenylene vinylene) based copolymer, Super Yellow (SY), PDY-132, were used as the work-function

modification for electron injection^[29-31] and emissive layer, respectively. The devices were fabricated and processed at temperatures lower than 200 °C^[27,29] and exhibited excellent n-channel transistor characteristics operating at <25 V with high electron mobilities of ≈ 3.5 cm²/Vs, and high EQEs up to 0.5% at a high brightness of ≈ 1800 cd/m², exceeding previously reported performances of hybrid LEFETs. Remarkably, we found that when the Cs₂CO₃ was incorporated as a work modification layer, the EQE was enhanced by approximately one order of magnitude and the devices exhibit a large spatially stable light emitting area (V_g -independent emission area) with an aperture ratio of 38%. These results represent a significant advancement over previously reported hybrid LEFETs and can be seen as an important milestone towards next generation display technologies.

Figure 1 shows the device structures of the hybrid light emitting field effect transistors (LEFETs). The pixelated light emitting transistor (pix-LET) and control LEFET were fabricated using solution-processed metal oxide layers with Cs₂CO₃ and without Cs₂CO₃ layer, respectively. Multilayer In₂O₃/Ga₂O₃/ZnO (OHJ-II) and bilayer In₂O₃/ZnO (OHJ-I) oxide structures were used as the charge transport layer and devices were fabricated using 400 nm thick SiN_x as the gate dielectric (**Figures 1a** and **b**). The electron injecting Al source electrode was thermally evaporated directly onto the metal oxide layers. In the case of the pix-LETs a 10 nm thick layer of Cs₂CO₃ was deposited in high vacuum directly onto the oxide layers, exactly under the drain electrode (see **Figure 1a**). This thickness was found to yield the best and most reproducible results. The light-emitting polymer Super Yellow was then spin-coated onto the oxide/Cs₂CO₃ in the all pix-LETs and onto the oxide/Cs₂CO₃ in control LEFETs. Finally, MoO_x/Au was deposited under high vacuum to form the hole-injecting drain electrode. For direct comparison, control devices were also prepared without Cs₂CO₃ (**Figure 1b**). Full details of fabrication and testing protocols including error analysis are presented in Materials and Methods.

To study the work function evolution in the semiconducting materials, Kelvin Probe (KP) measurements were carried out after each metal oxide layer deposition. **Figure 1d** shows the results for the OHJ-I layers used in our approach. After the deposition of the first In_2O_3 layer, a reduced work function of 4.6 eV was obtained and a further reduction of ≈ 4.2 eV was achieved after depositing a second ZnO layer, which has good agreement with literature.^[26,28] In our pix-LETs configurations, a 10 nm Cs_2CO_3 layer was selectively deposited onto the oxide film stacks. From KP measurements, it was found that the work function of the oxide layers was effectively modified to ≈ 3.7 eV (see **Figure 1d**). This can in principle enable efficient electron injection into the light emitting layer of the device, *i.e.*, SY, since the values for the lowest unoccupied molecular orbital (LUMO) and the highest occupied molecular orbital (HOMO) energies of SY are known to be -2.9 eV and -5.3 eV, respectively.^[19] Similarly, for the OHJ-II layers, the work function was reduced to ≈ 3.7 eV after the deposition of the Cs_2CO_3 layer (see **Figure 1e**). Here, insertion of the Ga_2O_3 layer helps to passivate the interfacial electron traps present in In_2O_3 and enhance the effective electron mobility of the layer.^[28] In addition, atomic force microscopy analysis (**Figure S2**, Supporting Information) show that the surface roughness of the multilayer stack can be further reduced by inserting the Ga_2O_3 layer (root mean square surface roughness R_{RMS} reduces from 0.23 for OHJ-I to 0.21 nm for OHJ-II).

Figure 2a and 2b show a comparison between the electrical transfer characteristics of the pix-LET and control LEFET fabricated using OHJ-II and OHJ-I charge transporting films, respectively, while the corresponding output characteristics are shown in **Figure S3** (Supporting Information). All pix-LETs and control LEFETs showed excellent n-channel transistor characteristics with negligible hysteresis and operating voltages < 25 V. All LEFET devices exhibited high ON/OFF ratio ($> 10^7$) as shown in **Figures 2a and 2b**. The control devices exhibited a negative threshold shift compared to the devices with Cs_2CO_3 layer. The

threshold shift was more pronounced in OHJ-I compared to OHJ-II as a larger V_g bias is required to turn-off the channel current in the control samples as compared to the pix-LETs. This is most likely attributed to the suppression of the bulk charge carriers by the insertion of an additional Ga_2O_3 layer in-between the In_2O_3 and ZnO layers. Most importantly, the tri-layer OHJ-II device outperforms that of the bilayer OHJ-I transistors; something most likely attributed to the improved electron transport characteristics.^[29]

The Cs_2CO_3 layer, on the other hand, was found to reduce the mobile charge carrier density in the oxide films. This is most likely due to extra oxygen released during the evaporation of Cs_2CO_3 .^[30,32] As a result pix-LET devices showed a lower turn-off voltage and a shift in the threshold voltages compared to control samples. The field-effect electron mobility values were calculated from the transfer characteristics of the pix-LETs and control LEFETs yielding values in the order of $\approx 3 \text{ cm}^2/\text{Vs}$ and $\approx 6 \text{ cm}^2/\text{Vs}$, respectively for tri-layer OHJ-II-based devices, and $\approx 3.5 \text{ cm}^2/\text{Vs}$ and $\approx 4 \text{ cm}^2/\text{Vs}$ respectively, for bilayer OHJ-I-based devices. **Table 1** provides a summary of the obtained results. To the best of our knowledge, these results represent the state-of-the-art for hybrid LEFETs processed from solution at $<200^\circ\text{C}$.

Figures 2c and 2d show the brightness (cd/m^2) *versus* gate voltage for the pix-LETs and control LEFETs fabricated using OHJ-II and OHJ-I films, respectively. The brightness of both pix-LET devices increases with increasing V_g and reached up to $\approx 1800 \text{ cd}/\text{m}^2$ at $V_g < 25 \text{ V}$. Both control LEFETs showed a lower brightness of $\approx 1200 \text{ cd}/\text{m}^2$. The measured EQEs for pix-LETs were $0.5 (\pm 0.1)\%$ at $1800 \text{ cd}/\text{m}^2$ and $0.5 (\pm 0.1)\%$ at $1700 \text{ cd}/\text{m}^2$ for OHJ-II and OHJ-I-based devices, respectively, as shown in **Figures 2e and 2f**. The EQE was significantly higher than that in the control LEFETs (**Table 1**) and the best performing hybrid LEFETs previously reported (**Table S2**, Supporting Information). It is important to note that the high EQEs and brightness were achieved at the much lower gate voltage of $<25 \text{ V}$.

Figures 3a and **3b** show the micrographs of the emission from the pix-LET and control LEFETs based on OHJ-I electron transport layers. An important observation was that the total area of the semi-transparent MoO_x/Au electrode was observed to emit light during pix-LET operation. The area emission of the MoO_x/Au electrode was spatially stable and independent of the gate voltage and can be clearly seen in the series of images shown in **Figure 3a** for OHJ-I films and **Figure S4a** (Supporting Information) for OHJ-II-based devices. In contrast, control devices, *i.e.* without the Cs₂CO₃ layer, only showed edge emission close to the edge of MoO_x/Au electrode instead of spatially uniform emission features seen in pix-LETs (**Figure 3b** and **Figure S4b**, Supporting Information). Furthermore, in control devices, the width of the edge emission depends on the applied *gate voltages* (V_g) in a similar fashion to previously reported results.^[16,19,20,21] Otherwise, the emission area can only be enlarged under the condition of a higher gate bias applied to the devices, and the edge emission can further spread under the MoO_x/Au electrode.

The details of the operating mechanism along with energy levels are shown in **Figure 4a**. In all the devices the electrons were injected from the Al (−4.1 eV) source electrode into the oxide layers (−4.2 eV, *i.e.* the work function of the whole oxide film stacks). Incorporation of the Cs₂CO₃ interlayer further lowered the electron injection barrier from the electron transporting oxide layer to the LUMO of SY. From the MoO_x/Au (≈−5.4 eV) drain electrode, holes are injected into the HOMO of SY (−5.3 eV) and recombine with injected electrons in the channel. Light emission occurs at the hole injecting MoO_x/Au electrode as illustrated in **Figure 4b**. Previous studies demonstrated that the use of a thin layer of Cs₂CO₃ shifts the work function of metals and semiconductors.^[30-32] This is consistent with our observation of lowered light turn-on voltages and higher EQE for pix-LET devices as

compared to control devices. The light turn-on voltages of pix-LET devices were 3 V and 4 V for OHJ-II and OHJ-I films, respectively, which are both significantly lower than control devices (≈ 6 V). The calculated maximum radiative recombination efficiencies of the pix-LET and control LEFETs are calculated to be on the order of 15% and 1.5%, respectively – see **Table S3**, Supporting Information. The far superior recombination efficiency of pix-LET is attributed to the enhanced electron injection from the electron transporting metal oxide layer into the LUMO of SY in the presence of Cs_2CO_3 .

While introducing an additional Cs_2CO_3 layer in the pix-LET devices resulted in an order of magnitude higher EQE and a lower turn-off voltage of the LEFETs, the more profound effect was the gate voltage and drain current independent area emission under the drain electrode (MoO_x/Au). This is most likely attributed to the doping-like effect induced by the evaporated Cs_2CO_3 onto the oxide and light-emitting polymer.^[30,32] The latter effect leads to the formation of an electron rich region at the inorganic semiconductor/polymer interface directly under the MoO_x/Au drain. At high source-drain voltages ($V_{ds} = 25$ V), the increasing V_g from 0 V to 22 V assists the hole injection from MoO_x/Au electrode and the electron injection into SY from the electron reservoir present at the oxide/SY interface. The electrons are accumulated in the LEFET channel that is composed of the carefully-engineered heterojunction/quasi-superlattice based oxide layers with increasing gate voltage and moves across the channel while providing mobile electrons to the oxide/SY interface. The holes injected from the MoO_x/Au electrode lead to significant hole density under the MoO_x/Au electrode, leading to the formation of excitons and subsequent recombination with incoming electrons from the Cs_2CO_3 doped oxide/SY interface region. As a result, a uniform light-emission area is formed. The equivalent circuit of a pix-LET device can be approximated with an OLED connected in series with a FET – reminiscent of the nature and intent of the LEFETs operation. In the control sample, and in the absence of the Cs_2CO_3 layer, electrons

are injecting into the SY layer from the oxide layer close to the MoO_x/Au electrode and light emission is observed initially only at the edge of electrode and spatially extends with increasing charge carrier density towards the centre of the electrode.

In summary, we have demonstrated low-temperature, solution-processed hybrid light emitting transistors using two types of electron transporting metal oxide semiconducting heterojunctions. The average electron mobilities of the control LEFETs and the proposed pix-LETs were high and in the range of 3–6 cm²/Vs with channel current ON/OFF ratios >10⁷. The incorporation of a thin Cs₂CO₃ layer at the oxide/polymer interface has enabled the development of a LEFET structure that exhibits superior operating characteristics, including large-area and uniform light-emission, and significantly enhanced EQE. In particular, the OHJ-I and OHJ-II-based pix-LETs showed a maximum brightness of ≈1700 cd/m² and 1800 cd/m² with EQE values of ≈0.5% for both device architectures. These results demonstrate the viability of using the low-temperature superlattice n-type metal oxides for the development of high-performance hybrid LEFETS hence paving the way for the application of this rather promising technology in future generation high definition displays.

Experimental Method

Heterostructure pix-LETs and control LEFETs used in this study were fabricated using with a 400 nm SiN_x dielectric layer grown by low pressure physical vapor deposition technique LPCVD, which were purchased from Silicon Quest, International, Inc. as shown in **Figures 1a**, and **1b**. These wafers were precisely diced in 15 x 15 mm² size of substrates and cleaned in a Class 1000 clean room by ultra-sonication in acetone for 15 min, and followed by 15 min

in 2-propanol. Substrates were dried using pressurized nitrogen and ready for materials depositions. ZnO precursor was prepared by dissolving ZnO nanopowder (>97% Sigma-Aldrich) in ammonium hydroxide (Alfa Aesar, 50% V/V) to the concentration of 10 mg/mL. As-prepared solutions were then stirred rigorously at room temperature for 15 h. This process yielded a clear transparent Zn-ammine complex based solution. For solution-processable indium oxide (In_2O_3) and gallium oxide (Ga_2O_3), the In_2O_3 and Ga_2O_3 precursor solutions were prepared by dissolving anhydrous indium nitrate ($\text{In}(\text{NO}_3)_3$, 99.99% Indium Corporation) and gallium nitrate hydrate ($\text{Ga}(\text{NO}_3)_3 \cdot x\text{H}_2\text{O}$, 99% Sigma-Aldrich) in 2-methoxyethanol ($\text{CH}_3\text{OCH}_2\text{CH}_2\text{OH}$, anhydrous, 99.8%, Sigma-Aldrich) at the concentration of 30 mg/mL and 10 mg/mL, respectively. The solution was subjected to rigorous stirring at room temperature for 15 h before use. Oxide layers were deposited from the as-prepared precursors via spin-coating at 4000 rpm for 30 s, and following by thermal-annealing process (200 °C for 1 h) for each oxide layer. Both of the deposition and thermal calcination processes were performed in ambient environment. Following this the substrates were transferred into a nitrogen glove box (O_2 and H_2O level <0.1 ppm), where rest of the fabrication and testing was performed.

Complementary shadow masks were used in combination to form source and drain electrodes through evaporation giving asymmetric, interdigitated, hole-injecting and electron-injecting metal contacts (**Figure S1**, Supporting Information). The electron injecting Al electrode was positioned directly on top of the oxide layer from the first mask. From second mask, a 10 nm thick layer of Cs_2CO_3 was deposited on the oxide layer. Then a 120 nm layer of emissive polymer, Super Yellow (purchased from Merck under name PDY-132) with a concentration of 7 mg/mL in toluene ($\geq 99.5\%$) was spin coated onto the substrates at 2500 rpm for 30 s, followed by 3000 rpm for 10 s. After this, the substrates were annealed on a hotplate at 150 °C for 30 min. The film thicknesses were measured using a Dektak 150

profilometer. Finally, the MoO_x/Au (2/12 nm) hole injecting electrode was deposited on top of the SY films as shown in **Figures 1a, 1b** and **S1** (Supporting Information).

Electrical characterization of the devices was performed using an Agilent B1500A Semiconductor Device Analyzer and an SA-6 Semi-Auto Prober station and optical characterization was achieved with a calibrated photomultiplier tube (PMT) positioned over the device. The source-drain current in the transistor channel and photocurrent in the PMT were recorded to determine the device parameters. Brightness was calculated from the photocurrent in the PMT by comparing with a super yellow OLED device of known brightness and light emission area, and then corrected according to the measured emission area of the LEFET.^[7,17,19-21] A digital camera connected to an optical microscope was used to image the device emission area. The image was then analyzed by taking an intensity profile across the emission region to calculate the width of the emission zone, estimated by taking the full width at half maximum of the image intensity profile. The EQE was calculated (assuming Lambertian emission) using the brightness, source-drain current and emission spectrum of the device previously reported.^[3,7,9,18-21]

The charge carrier mobility and threshold voltage were calculated from the electrical transfer characteristics in the saturation regime of transistor operation, using the equation:

$$I_{ds} = \frac{W C_i}{2 L} \mu (V_g - V_{th})^2 \quad (1)$$

where I_{ds} is the source-drain current, W is the channel width, L is the channel length, μ is the field-effect mobility, C_i is the geometric capacitance of the dielectric, V_g is the gate voltage and V_{th} is the threshold voltage.

Work function energies were measured using a KP Technology scanning Kelvin Probe system SKP5050 in nitrogen environment at room temperature. The samples were

prepared using the same processing parameters on ITO glass substrates. For atomic force microscopy (AFM) measurements, atomic force micrographs of the films were taken in the tapping mode using an Agilent 5500 AFM in air, and the oxide films were deposited on Si/SiO₂ wafer substrates with the same parameters as aforementioned.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

Acknowledgements

This work was funded by the Australian Research Council (FT110100216 and DP140101088). EBN is the recipient of an Australian Research Council Future Fellowship. KM is funded by an Australian Postgraduate Award. This work was performed in part at the Queensland node of the Australian National Fabrication Facility Queensland Node (ANFF-Q) - a company established under the National Collaborative Research Infrastructure Strategy to provide nano- and micro-fabrication facilities for Australia's researchers.

References

1. Hepp, H. Heil, W. Weise, M. Ahles, R. Schmechel, H. Von Seggern, *Phys. Rev. Lett.* **2003**, *91*, 157406.
2. J. Zaumseil, R. H. Friend, H. Sirringhaus, *Nature Mater.* **2006**, *5*, 69.
3. A. J. Heeger, N. S. Sariciftci, E. B. Namdas, "Semiconducting and Metallic Polymers", Oxford University Press, London 2010.
4. J. Zaumseil, C. L. Donley, J.-S. Kim, R. H. Friend, H. Sirringhaus, *Adv. Mater.* **2006**, *18*, 2708.
5. J. Zaumseil, C. R. McNeill, M. Bird, D. L. Smith, P. Ruden, M. Roberts, M. J. McKiernan, R. H. Friend, H. Sirringhaus, *J. Appl. Phys.* **2008**, *103*, 064517.

6. R. Capelli, S. Toffanin, G. Generali, H. Usta, A. Facchetti, M. Muccini, *Nature Mater.* **2010**, *9*, 496.
7. M. Ullah, K. Tandy, S. D. Yambem, M. Aljada, P. L. Burn, P. Meredith, E. B. Namdas, *Adv. Mater.* **2013**, *25*, 6213.
8. E. B. Namdas, P. Ledochowitsch, J. D. Yuen, D. Moses, A. J. Heeger, *Appl. Phys. Lett.* **2008**, *92*, 188304.
9. H. Nakanotani, M. Saito, H. Nakamura, C. Adachi, *Appl. Phys. Lett.* **2009**, *95*, 033308.
10. F. Cicoira, C. Santato, A. Dadvand, C. Harnagea, A. Pignolet, P. Bellutti, Z. Xiang, F. Rosei, H. Meng, D. F. Perepichka, *J. Mater. Chem.* **2008**, *18*, 158.
11. M. Schidleja, C. Melzer, H. von Seggern, *Appl. Phys. Lett.* **2009**, *94*, 123307.
12. C. A. Di, G. Yu, Y. Q. Liu, X. J. Xu, D. C. Wei, Y. B. Song, Y. M. Sun, Y. Wang, D. B. Zhu, *Adv. Funct. Mater.* **2007**, *17*, 1567.
13. Rost, D. J. Gundlach, S. Karg, W. Riess, *J. Appl. Phys.* **2004**, *95*, 5782.
14. S. Z. Bisri, T. Takenobu, K. Sawabe, S. Tsuda, Y. Yomogida, T. Yamao, S. Hotta, C. Adachi, Y. Iwasa, *Adv. Mater.* **2011**, *23*, 2753.
15. M. C. Gwinner, D. Kabra, M. Roberts, T. J. K. Brenner, B. H. Wallikewitz, C. R. McNeill, R. H. Friend, H. Sirringhaus, *Adv. Mater.* **2012**, *24*, 2728.
16. B. B. Y. Hsu, J. Seifter, C. J. Takacs, C. Zhong, H. R. Tseng, I. D. W. Samuel, E. B. Namdas, G. C. Bazan, F. Huang, Y. Cao, A. J. Heeger, *ACS Nano* **2013**, *7*, 2344.
17. M. Ullah, K. Tandy, J. Li, Z. Shi, P. L. Burn, P. Meredith, E. B. Namdas, *ACS Photonics* **2014**, *1*, 954.
18. K. Nakamura, T. Hata, A. Yoshizawa, K. Obata, H. Endo, K. Kudo, *Jpn. J. Appl. Phys.* **2008**, *47*, 1889.
19. M. Ullah, K. Tandy, S. D. Yambem, K. Muhieddine, P. Meredith, P. L. Burn, E. B. Namdas, *Org. Electron.* **2015**, *17*, 371.
20. M. Ullah, A. Armin, K. Tandy, S. D. Yambem, P. L. Burn, P. Meredith, E. B. Namdas, *Scientific Reports* **2015**, *5*, 8818.
21. K. Muhieddine, M. Ullah, B. N. Pal, P. L. Burn, E. B. Namdas, *Adv. Mater.* **2014**, *26*, 6410.
22. B. Walker, M. Ullah, G. J. Chae, P. L. Burn, S. Cho, J. Y. Kim, E. B. Namdas, J. H. Seo, *Appl. Phys. Lett.* **2014**, *105*, 183302.
23. H. Nakanotani, M. Yahiro, C. Adachi, K. Yano, *Appl. Phys. Lett.* **2007**, *90*, 262104.

24. Z. E. Ooi, T. R. B. Foong, S. P. Singh, K. L. Chan, A. Dodabalapur, *Appl. Phys. Lett.* **2012**, *100*, 093302.
25. K. Yamada, T. Yamao, S. Hotta, *Adv. Mater.* **2013**, *25*, 2860.
26. K. Muhieddine, M. Ullah, F. Maasoumi, P. L. Burn, E. B. Namdas, “Hybrid Area Emitting Transistors: Solution Processable and with High Aperture Ratios”. *Adv. Mater.* 2015 (in press).
27. A) Yu et al., *Proc. Natl. Acad. Sci.* **112** 3217-3222 (2015); B) Rim et al., *Chem. Mater.* **27** 5808-5812 (2015); C) Lin et al., *Adv. Sci.* **2** DOI: 10.1002/advs.201500058 (2015)
28. Y. H. Lin, H. Faber, K. Zhao, Q. Wang, A. Amassian, M. McLachlan, T. D. Anthopoulos, *Adv Mater.* **2013**, *25*, 4689.
29. Y. H. Lin, H. Faber, J. G. Labram, E. Stratakis, L. Sygellou, E. Kymakis, N. A. Hastas, R. Li, K. Zhao, A. Amassian, N. D. Treat, M. McLachlan, T. D. Anthopoulos, **2015**, *Adv. Science* doi: 10.1002/advs.201500058.
30. J. Huang, Z. Xu, Y. Yang, *Adv. Funct. Mater.* **2007**, *17*, 1966.
31. M.-H. Chen, C.-I Wua, *J. Appl. Phys.* **2008**, *104*, 113713.
32. J. Zhao, Y. Cai, J.-P. Yang, H.-X. Wei, Y.-H. Deng, Y.-Q. Li, S.-T. Lee, J.-X. Tang, *App. Phys. Lett.* **2012**, *101*, 193303.

Figure 1. Device and chemical structures: (a) pix-LET, (b) control LEFET, (c) SY. The work function evolution measured using the Kelvin Probe system for each layer in d) OHJ-I and e) OHJ-II as well as the work function obtained after depositing the Cs₂CO₃ layer.

Figure 2. Electrical transfer characteristics of pix-LET and control LEFETs based on a) OHJ-II layer and (b) OHJ-I layer. Optical transfer characteristics of pix-LET and control LEFETs based on (c) OHJ-II layer and (d) OHJ-I layer. External quantum efficiency (EQE) of pix-LET and control LEFETs based on (e) OHJ-II layer and (f) OHJ-I layer.

(a) pix-LET - OHJ-I **(b) Control - OHJ-I**

Figure 3. Micrographs of light emitting area at different gate voltages: (a) a uniform aerial emission under the electrode in a pix-LET device, (b) gradually increasing edge emission under the electrode in a control device fabricated utilizing OHJ-I as chart transport layer. Red dot line represents the spacing between L=channel length, S = source and D = drain.

Figure 4. (a) Charge injection mechanism and energy levels of emissive and charge transport layers. (b) Schematics of charge transport mechanism, injection and emission in pix-LET. (c) Electroluminescence of control and pix-LET device and photoluminescence spectra of SY film.

Table 1. Comparison of results of control LEFETs and pix-LET using both oxide transport layers. The plus / minus represent the standard deviation on the mean as derived from the averages of multiple devices.

Metal oxide	OHJ-I		OHJ-II	
Device structure	Control	pix-LET	Control	pix-LET
Work function	−4.2	−3.7	−4.2	−3.7
μ_e (cm ² /Vs)	4 (±1)	3.5 (±0.5)	6 (±1)	3 (±1)
ON/OFF ratio	$\approx 10^3$	$\approx 10^7$	$\approx 10^7$	$\approx 10^7$
Brightness (cd/m ²)	1200 (±100)	1700 (±200)	1200 (±100)	1800 (±200)
EQE (%)	0.05 (±0.05)	0.5 (±0.1)	0.1 (±0.05)	0.5 (±0.1)