Wireless Electroluminescence: Polymer Light-Emitting Electrochemical Cells with Ink-jet Printed 1D and 2D Bipolar Electrode Arrays

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ABSTRACT

1D and 2D arrays of conductive micro-discs are printed on glass substrates using a silver nanoparticle (Ag-NP)-based ink. Polymer light-emitting electrochemical cells (PLECs) are then fabricated on top via spin coating and the thermal deposition of aluminum driving electrodes (DEs). The extremely large planar PLECs, with an interelectrode separation of 11 mm, are driven with a bias voltage of 400 V. This causes *in situ* electrochemical doping in the polymer from both DEs and the Ag-NP discs. The latter functions as bipolar electrodes (BPEs) to induce and sustain doping reactions at their extremities. Time-lapse photoluminescence and electroluminescence imaging reveals that p- and n-doping originating from neighboring BPEs can interact to form multiple light-emitting p-n junctions, connected in series by the BPEs. Unexpectedly, the multiple p-n junctions begin to emit well before a continuous pathway of doped polymers is established between the DEs. This observation breaks one of the general rules of PLEC emission. The electroluminescence is therefore wireless in the sense that the emitting junctions are not directly addressed by the DEs. The doping patterns confirm that the 1D vertical arrays of BPE discs can function like a single rod-shaped BPE when individual BPE discs are connected in a series by the light-emitting p-n junctions. Doping induced by an 8 x 8 2D BPE array showed that the electrical field in the PLEC film was initially

highly uniform, but quickly became distorted by the strong doping from the BPE discs. Intense (visible to the naked eye) junction electroluminescence is observed from the 56 light-emitting p-n junctions formed. The demonstration of functional ink-jet printed BPEs and their applications to PLECs allow for easy generation of BPE patterns and probing the complex doping processes in PLECs.

KEYWORDS : Bipolar electrodes ; bipolar electrochemistry ; p-n junctions ; electrochemical doping ; polymer light-emitting electrochemical cell

INTRODUCTION

A light-emitting electrochemical cell (LEC) is a solid-state electroluminescent (EL) device wherein mobile ions play a significant role.¹⁻³ LECs are typically classified based on the types of emitters used, which can be conjugated polymers (CPs),⁴⁻⁶ ionic transition metal complexes,⁷⁻¹³ organic small molecules,¹⁴⁻¹⁶ host/guest systems.¹⁷⁻²⁰ The prototypical polymer-based LECs or PLECs, for example, have an active layer that contains a luminescent CP as well as a solid polymer electrolyte.²¹⁻²² LECs are attractive devices for lighting and display applications owing to their desirable device characteristics and their compatibility with low-cost manufacturing processes.²³⁻²⁵ LECs are also interesting due to an operation mechanism that is unique among organic light-emitting devices.

When a PLEC is operated with a sufficiently large DC voltage or current, charge injection occurs at the driving electrode (DE)/polymer interfaces, causing the polymer to be electrochemically p- and n-doped in the presence of counter ions. The doped CP becomes electronically conductive, causing the doping front to move away from the DEs. Eventually, a p-n or p-i-n junction is formed when the p- and n-doping fronts meet, and electroluminescence (EL) is generated as electrons and holes recombine in the vicinity of the junction formed. Thus, the key reaction in a PLEC is the electrochemical doping of the CP, which is a redox reaction accompanied by the insertion of counterions.

Time-lapsed photoluminescence (PL) imaging of numerous *planar* PLECs establishes four general observations with regards to PLEC emission:²⁶⁻³⁵ (1) EL occurs when and only when p and n-doping fronts make direct contact to form a p-n or p-i-n junction; (2) the p- and n-doped regions behind the doping fronts remain intact during the doping propagation process and become more heavily doped after junction formation. Direct electrical contact with the driving electrodes, in the form of doped polymer, is maintained while the PLEC emits; (3) EL occurs only in the vicinity of the junction, which is narrow compared to the interelectrode spacing. Recent optical beam-induced current (OBIC) imaging of stabilized planar PLECs placed the junction depletion width at only 0.2 % of the interelectrode spacing;³⁶ (4) junction formation and EL are accompanied by cell current turn-on, signifying a transition to electronic conduction from ionic transition. These experimental observations are consistent with the notion that an

emitting PLEC is a forward-biased homojunction. For now we can label these general observations as “rules” of planar PLEC emission, since there have been no exceptions.

The doping and emission profiles of a PLEC, however, can be dramatically altered by the introduction of electrically floating conductors into the active layer. An aluminum disc coated on top of the polymer layer, for example, can induce electrochemical p- and n-doping at its opposite ends despite the fact that it was not directly connected to the driving electrode. Doping from the BPE and the driving electrodes interact to form four, rather than one light-emitting p-n junction.³⁰

The floating conductors in a PLEC functioned as bipolar electrodes (BPEs) from which doping is induced wirelessly.³⁷ A BPE, by definition, is a floating conductor that can simultaneously drive reduction and oxidation reactions when polarized in an electrochemical cell.³⁸⁻⁴³ Bipolar electrochemistry is an active area of fundamental research as well as a versatile technique for many applications that are either inconvenient or impossible to achieve with conventional wired electrodes.⁴⁴⁻⁴⁹ BPE arrays, in particular, are extremely useful for high throughput, multiplexed detection or screening applications.⁵⁰⁻⁶⁰

PLECs offer a brand new platform for bipolar electrochemistry research. The solid-state nature of PLECs allows for the formation of BPEs using techniques that are otherwise impossible in a liquid cell. Bipolar electrochemistry, in return, offers new insight into complex PLEC processes. In model PLECs containing evaporated aluminum discs of various sizes, the doping reaction (or lack thereof) from the floating discs was found to be strongly dependent on the size of the discs as well as on the applied potential difference.³⁰ The observations confirmed that bipolar electrochemistry was at play and that the floating conductors were indeed BPEs. Moreover, conducting polymers, either free-standing or created by *in situ* electrochemical doping within a PLEC, have been shown to function as BPEs.⁶¹⁻⁶² Recently, a linear BPE array was introduced for the first time to a planar PLEC.⁶³ The BPE array, consisting of eight evaporated aluminum discs of about 0.3 mm in diameter, was parallel to the applied electric field. Under an applied potential of 100 V, all individual discs in the BPE array were able to induce doping at their extremities. The contact by the moving doping fronts led to the simultaneous formation of light-emitting p-n junctions in series and caused a cell current turn-on. The

study offered the first glimpse of how doping from individual BPEs can interact to form multiple junctions in series, and in the process alter the cell current and local electric field. One of the study's limitations had to do with the way the BPE array was formed: it was coated on top of the polymer film by thermal evaporation through a machined shadow mask. This made it difficult to change the BPE patterns and sizes. As a result, only one linear array with a fixed BPE size and separation was studied. The thickness of the shadow mask also led to a shadowing effect that deformed the BPE discs.

In this study, a standard inkjet printing technique was used to print BPE arrays of various designs using silver nanoparticle (Ag-NP)-based ink. 1D verticals arrays of 21 and 8 discs, a solid rod BPE and an 8 by 8 2D BPE arrays were printed directly on glass substrates onto which planar PLECs were applied. The BPE arrays were printed in minutes under ambient conditions. The various BPE patterns yielded some highly unexpected results which will be discussed in detail.

EXPERIMENTAL METHODS

The BPE arrays were printed with a SonoPlot Microplotter II and a Ag-NP metallic ink. The Ag-NP ink (UT Dots, Inc.) consisted of surface stabilized 10 nm (average size) Ag-NPs dissolved in a hydrocarbon solvent mixture. The Microplotter deposited the ink onto glass substrates, without contact, at a speed of 15 dots per minute. The printed patterns were cured at 130°C for 2 hours in a nitrogen filled glove-box. The glass substrates, measured at 16 mm by 16 mm by 1 mm, were cleaned with detergent, acetone and isopropanol in an ultrasonic bath for 5 min each and blown dry with nitrogen gas. Before use, the glass substrates were subjected to UV-ozone treatment for 15 minutes. The extremely large planar PLECs were fabricated using materials and procedures described in a previous publication.⁶³ All PLECs were made with an orange/red emitting luminescent polymer, poly[2-methoxy 5-(2-ethylhexyloxy)-1, 4-phenylenevinylene], MEH-PPV. The PLEC active layer also contained polyethylene oxide and potassium triflate, which together constitute a solid polymer electrolyte. The PLEC film was spin cast from a cyclohexanone solution. The thickness of the PLEC was measured with a stylus profiler to be several hundred nm in thickness. The cast polymer film was subsequently dried at 50 °C for at least 5 hours to remove any residual solvent. A pair of

aluminum driving electrodes at a thickness of 100 nm was thermally evaporated onto the polymer film to complete the device. The BPE arrays were printed in air in a Class 1000 cleanroom. The PLECs were fabricated in a nitrogen-filled glove box/evaporator system to prevent exposure to oxygen and water. The finished PLECs were placed in a sealed glass vial and transferred into a *Janis ST-500* micro-manipulated cryogenic probe station for testing under vacuum ($\sim 5 \times 10^{-4}$ torr). A LabVIEW-controlled *Keithley 237* high-voltage source measurement unit was used to apply a voltage bias to the driving electrodes and simultaneously measure the cell current. The PLECs were imaged with a computer-controlled *Nikon D300* digital SLR camera equipped with a Tamron 90 mm 1:1 macro-lens. A UV ring lamp provided illumination to the polymer film through the quartz window of the sample chamber. The PLECs were heated to 360 K during testing under a constant applied voltage bias of 400 V between the driving electrodes.

RESULTS

Figure 1(a) is a schematic representation of the BPE printing and device fabrication steps. The finished PLECs had a planar configuration with two Al DEs contacting the top surface of the polymer film. The separation between the inner edges of the DEs was 11 mm for all PLECs in this study. Figure 1(b) is an optical micrograph of an 8x8 BPE array before the polymer layer was coated, showing only six discs. The printed discs are 122 ± 2 μm in diameter and 607 ± 10 nm in height with a depressed center about 300 nm high.

Figure 1. (a) Schematic representation of the ink-jet printing of BPEs and PLEC fabrication on a glass substrate. (b) Micrograph showing images of a printed Ag-NP BPE array on a bare glass substrate. Only part of the 8x8 array is shown. The same printed array is used to fabricate Cell 4 in this study.

Figure 2 shows a PLEC with a linear BPE array of 21 discs. This PLEC is referred to as Cell 1 throughout the text. The discs were 0.5 mm apart and $178 \pm 3 \mu\text{m}$ in diameter. The PLEC film thickness was $567 \pm 7 \mu\text{m}$. Figure 2(a) shows the cell current in

the first 60 s after a 400 V bias was applied to the driving electrodes. The initial cell current was mainly ionic and barely changed in the first few seconds. This was followed by a sharp turn-on after which the cell current quickly reached nearly 10 μA . A turn-on time of $t=10.9$ s was determined by performing exponential fits to data points marked as solid circles and subsequently solving the fit equations. At $t=60$ s, the cell current had reached 40.7 μA , a 35 fold increase over the initial value of 1.12 μA . The cell current increase was caused by *in situ* electrochemical doping of the polymer film. Figures 2(b)-(h) show that the PLEC film was indeed doped in a progressive fashion. In PLECs, doping is easily visualized because significant PL quenching occurs when the luminescent polymer is electrochemically doped *in situ*.²⁷ For simplicity, we refer doping originated from the driving electrodes as DE doping and from the BPEs as BPE doping throughout the text. Note that in Figure 2 (h), the DE p- and n-doping fronts were still millimeters apart. Therefore, the expansion of DE doping could neither account for the 35-fold increase nor the cell current turn-on. Rather, it is the presence of a vertical BPE array that is solely responsible for these key events. As shown in Figures 2(b) and (c), individual BPEs from the array were able to induce p- and n-doping at their top and bottom ends. The opposing doping fronts only needed to propagate for a short distance to form a p-n junction. When a linear array of p-n junctions was formed between the DEs, as shown in Figure 2 (d), the cell current underwent a sharp turn-on due to the creation of a continuous pathway for the flow electronic currents via doped polymers and forward-biased p-n junctions. This scenario is strongly supported by the fact that the junction formation time ($t=12 \pm 2$ s), identified from PL imaging, matches the current turn-on time. For the junction formation time, an uncertainty of ± 2 s was assessed to account for the exposure time (1/3 s) and any time delay of the first image relative to the time when the voltage bias was applied. From $t=12$ s onwards, the current passing through the region containing the BPE array continued to increase, causing the p-n junction EL to become brighter.

Figure 2. (a) Cell 1-current as a function of elapsed time after a 400 V bias voltage was applied to the driving electrodes. The dashed lines are exponential fits to the highlighted (solid dots) data points. The intersection of the fit lines gives rise to a turn-on time of $t=10.9$ s (b)-(h) Cell 1-time-lapsed fluorescence images of Cell 1 under bias. The elapsed times are 3 s, 9 s, 12 s, 18 s, 30 s, 52 s and 60 s, respectively. The BPE array in Cell 1 consists of 21 discs with an average diameter of 178 ± 3 μm and a center-to-center separation of 0.5 mm.

The general behavior of Cell 1 described above is similar to that of PLECs in a previous study which used BPE arrays made of evaporated aluminum discs.⁶³ However, a

few important differences exist. The p-n junctions formed in the current study, as inferred from junction EL, are mostly uniform in size and horizontally orientated. In the previous study, however, the junctions were nearly vertical due to the tilt of the elongated BPEs. Based on the observations showings significant branching of the BPE doping, it was postulated that the linear BPE array functioned collectively as a single, rod-shaped BPE when the p-n junctions became highly conductive. The branching of BPE doping is once again observed in the current study. For a rod BPE oriented along the direction of an applied electric field, COMSOL simulation showed that the electric field was nearly perpendicular to the rod at its middle region and also at its weakest.⁶³ In this region, the BPE doping should be absent due to an insufficient potential difference to drive any redox reactions. Such a region, which was not observed in the previous study, is clearly identified by the blue arrow in Figure 2 (h). Above, a single, merged n-doped region envelopes the BPEs and the much smaller, individual p-doped regions before branching out near the top. Below, the same behavior is observed for BPE p-doping. An unexpected observation can be seen in Figure 2 (c) which shows that a p-n junction, formed between the bottom-most BPE and the negative driving electrode, was already emitting. This happened while the n-doping front from the upper-most BPE was still nearly 0.5 mm away from the top DE. This observation is clearly in violation of afore-mentioned rule #2 for PLEC emission. By employing a different design for the BPE array, as shown below, this highly unexpected behavior is accentuated and confirmed without any doubt.

Figure 3 shows a PLEC (Cell 2) with a more compact BPE array. With only eight $133 \pm 2 \mu\text{m}$ discs and a center-to-center spacing of $300 \mu\text{m}$, the BPE array in Cell 2 was designed to be well-separated from the DEs, as shown in Figure 3(a). This geometry allowed for the formation of p-n junctions between the BPE discs, well before the BPE doping fronts could make contact with the DE doping fronts. In Figure 3(b), the BPE doping had grown to a significant size at the tips of the array, but were still millimeters away from the nearest doping fronts. Astonishingly, the p-n junctions formed between the BPEs were emitting clearly. An expanded view of Figure 3(b) shows that all seven junctions were already emitting at $t=30 \text{ s}$, with the bottom three being the brightest. In Figure 3 (c)-(e), EL from the junctions became brighter and more uniform in intensity.

The observation of EL in the interior of a PLEC without a doped polymer contacting either driving electrodes totally broke rule #2 of PLEC emission.

Figure 3. (a)-(f) Cell 2-time-lapsed fluorescence images under a 400 V applied bias. The elapsed times are 18 s, 30 s, 42 s, 54 s, 120 s and 144 s, respectively. The blue arrow in (f) indicates the location of least doping along the BPE array. The BPE array consists of eight discs with an average diameter of $133 \pm 2 \mu\text{m}$ discs and a center-to-center spacing of $300 \mu\text{m}$. (g) Current as a function of elapsed time after a 400 V bias voltage was applied to the driving electrodes. The labels (a)...(f) indicate the time at which the images are taken. The polymer film thickness was $397 \pm 8 \text{ nm}$

When the doped regions did finally connect, as shown in Figure 3(d), the cell current once again underwent an exponential turn on, as shown in Figure 3(g). In Cell 2, the current turn-on occurred at $t=43.3 \text{ s}$, much later than in Cell 1. This is caused by the longer distance the doping fronts must travel to reach the opposing doping fronts. The onset of EL, on the other hand, occurred as early as $t=18 \text{ s}$, when faint EL is discerned in the bottom three junctions, shown in Figure 3(a). This is yet another unexpected result

that indicates, for the first time, that the onset of junction EL need not be accompanied by a turn-on in cell current. In other words, the observation in Cell 2 also broke Rule #4 of PLEC observation.

The short and closely packed linear BPE array in Cell 2 behaved in a way that is the most similar to a rod BPE yet. For the purpose of comparison and validation, a PLEC with an actual rod BPE was also fabricated. Figure 4 shows the time evolution of doping and of cell current in such a device (Cell 3). The printed rod BPE had an average thickness of 118 μm and the same length (2.26 mm) as the BPE array in Cell 2. It is easy to observe that the doping patterns of Cell 3 and Cell 2 are remarkably similar. Both BPEs were able to induce strong, fast propagating doping from their ends. The BPE doping, as seen in both Figure 3(f) and Figure 4(f), had the shape of an hourglass. At the top and bottom were two long and jagged light-emitting junctions. The waist of the hourglass represents a doping-free region, as indicated by the blue arrows in both figures. Doping-free regions can also be identified in earlier images. Interestingly, this region shifted toward the lower tip of the BPE array or BPE rod with time. This is likely caused by the continued expansion of the various doped regions, which altered the electric field distribution of the cell. These observations confirm that the linear BPE array in Cell 2, once connected by a doped light-emitting p-n junction, behave collectively as single rod BPE.

The BPE array, however, was not as conductive as the silver rod BPE. This led to some observable differences between Cell 2 and Cell 3. Most notably, the long light-emitting junctions in Figure 4(f) were brighter and longer than the corresponding ones in Figure 3(f). The more conductive rod BPE was also responsible for the faster initial doping propagation and a larger angular divergence. As a result, the current turn-on in Cell 3 occurred earlier, at $t=36$ s (vs. $t=43.3$ s for Cell 2). At $t=150$ s, the currents of Cell 3 and Cell 2 were 105.4 μA and 22.6 μA , respectively. Since the DE doping fronts in both cells were still well-separated and at about the same distance, the 4.7-fold difference in cell current can only be attributed to the conductivity difference of the BPEs. Since the emitting junctions were connected in series by the BPE rod or array, a larger cell current is responsible for the higher EL output observed in Cell 3. It is interesting and significant to note that in Figure 2(e), junctions formed between the BPEs are visibly brighter than

the long junctions above and below. This is because the current density along the narrow BPE array was higher than at the long junctions. Here we see that EL intensity can be used to compare the local current density of the vast planar cell.

Figure 4. (a)-(f) Cell 3- time-lapsed fluorescence images under a 400 V applied bias. The elapsed times are 6 s, 18 s, 30s, 42s, 72s, and 147s, respectively. The blue arrow in (f) indicates the location of least doping along the BPE. The BPE is a single printed rod with a length of 2.26 mm and an average thickness of 118 μm . (g) Current as a function of elapsed time after a 400 V bias voltage was applied to the driving electrodes. The labels (a)...(f) indicate the time when the images are taken. The polymer film thickness was 394 ± 7 nm.

Figure 5. (a)-(f) Cell 4- time-lapsed fluorescence images under a 400 V applied bias. The elapsed times are 3 s, 27 s, 36 s, 51 s, 117 s, and 147s, respectively. The BPE is an 8x8 array, part of which is shown in Figure 1 (b). (g) Current as a function of elapsed time after a 400 V bias voltage was applied to the driving electrodes. The labels (a)...(f) indicates the time at which the images are taken. The polymer film thickness was 384 ± 8 nm

A PLEC with a single rod BPE, however, was neither the brightest nor the most conductive. Figure 5 shows a PLEC (Cell 4) with an 8x8 BPE array. Part of the 2D BPE array was shown in Figure 1(b). The BPE discs had a diameter of 123 ± 2 μm and were 0.5 mm apart from their nearest neighbors. Cell 4 was tested under the same conditions as Cells 1-3. At $t=3$ s, all four types of doping were visible: p- and n-doping from DEs as well as p- and n-doping from all 64 BPEs. While DE p- and n-doping were comparable in size, as seen in the magnified boxes of Figure 4(a), the BPE p-doping was significantly larger than the BPE n-doping. At $t=27$ s, all doped regions had grown in size, as shown in Figure 5(b). DE doping and BPE doping had yet to make contact, but light-emitting p-n junctions had already formed between the neighboring BPEs. Once again, the observation of EL well before the formation of a continuous pathway of doped polymers is in

violation of Rule 2. The unexpected EL is apparently a common occurrence now that it has been observed in Cells 1, 2 and 4. At $t=36$ s, tips of BPE doping first made contact with DE doping, as shown in Figure 5(c). At $t=51$ s, EL is observed in parts of the long junctions above and below the BPE array. Meanwhile, EL from the BPE junctions grew stronger. Figure (e) is an EL-only image of Cell 4 at $t=117$ s with the UV illumination turned off. Note the faint EL at the top left of each emitting junction was caused by the reflection from the bottom surface of the glass substrate. At $t=147$ s, strong EL is observed in both DE and BPE junctions, as shown Figure 5(f). In Figure 5(g), the time evolution of cell current exhibits similar shapes to those of Cells 1-3. A sharp turn on occurs at $t=29.2$ s. At $t=150$ s, the cell current reached $165.8\text{ }\mu\text{A}$, the highest among the four cells tested.

DISCUSSION

The PLECs described in the previous section demonstrate the feasibility and versatility of ink-jet printed BPE arrays. New BPE designs allowed for the observation of some highly unexpected doping and EL patterns/behaviors that are previously unseen in any PLECs, with or without a BPE array. Of the four aforementioned “rules” of PLEC emission, rules 1 & 3 still hold. In other words, EL in a PLEC requires junction formation, which allows for the PLEC to operate as a forward-biased homojunction. Rules 2 & 4, however, are no longer valid when BPEs of certain geometries are introduced.

Breaking of rule #2 creates an electroluminescent analog of wireless electrochemiluminescence (ECL) in solution.^{47, 57} Here wireless EL, much like wireless ECL, creates a scenario in which the emitting entity is not directly addressed by the wired driving electrodes. In PLECs lacking any BPE (although the light-emitting junctions are formed in the interior of the cell), direct electronic contact is maintained, via doped polymers, with the driving electrodes. In Cells 1, 2 and 4, however, the p-n junctions formed between the BPEs begin to emit well before conductive “wires”, here doped polymers, connect them to the driving electrodes. Therefore, the current in a PLEC is initially carried by the electrolyte. This creates a situation similar to a conventional electrochemical cell containing a liquid electrolyte. Under the correct operating

condition, the electrolyte could supply a large enough current to the already formed p-n junctions, leading to observable EL, even against a strong PL background. When ionic charges reach the doping fronts, they participate in the doping process, causing the doping fronts to propagate. It should be emphasized again that any EL observed in a PLEC is junction/injection EL. This key fact distinguishes the emission in Cells 1, 2, and 4 from ECL.

Breaking rule 4 has to do with the fact that the onset of wireless EL is not accompanied by any turn-on in cell current. In Cells 2 and 4, cell current turn-on occurred at a much later time when DE and BPE doping fronts first made contact to form a continuous pathway for electronic conduction. The breaking of rule 4 suggests that the onset of wireless EL has a negligible effect on the overall cell current. This is consistent with the fact that wireless EL occurs while the cell current is still dominated by an ionic current. When wireless EL is observed, however, the presence of BPE arrays did have an observed effect on DE doping propagation. As shown in Figure 3(c) and Figure 5(b), DE doping closest to the BPE array were accelerated due to local field enhancement. This observation is consistent with COMSOL simulation results.

Cells 2, 3, and 4 had similar initial cell currents of around 0.8 μA . This makes it possible to compare and extract information from the magnitude of the cell current. At $t=150$ s, all three cells had strongly emitting DE and/or BPE junctions. The cell current is dominated by a flow through the BPE region, since the DE p- and n-doping fronts had yet to make contact in the rest of the device. The magnitude of current at this particular moment is therefore a measure of the conductance of the various BPEs. The current of Cell 2, at 22.6 μA , was significantly lower than that of Cell 3 at 105.4 μA . This is not surprising considering that the conductance of a single metallic rod BPE should be higher than that of a BPE array connected by doped polymers. A single BPE array is roughly 1/5 as conductive as a single Ag rod BPE. Cell 4 has eight parallel BPE arrays, and the current reached 165.8 μA at $t=150$ s-about 8/5 of the Cell 3 current. As a reference, a control device without any BPE reached only 0.9 μA at $t=150$ s. These results underscore the dramatic effects of BPE array to PLEC conductance and PLEC currents. BPE arrays offer simple and flexible ways of controlling both EL and current flow in PLECs, without the need to modify the constituents and overall cell structures of PLECs.

CONCLUSIONS

In this study, we have fabricated extremely large planar PLECs containing 1D and 2D BPE arrays of various designs. The micro-disc BPE arrays are ink-jet printed using a Ag-NP-based ink and a computer-controlled microplotter. The PLECs have been investigated via temperature-controlled, time-lapsed PL/EL imaging and cell current measurements. This study fully demonstrates the feasibility and versatility of ink-jet printed BPE arrays. In addition, new BPE designs allow for the observation of some highly unexpected doping and EL patterns/behaviors previously unseen in any PLECs. Of the four well-established “rules” of PLEC emission, two were violated during the first demonstration of wireless EL in PLECs. The doping patterns confirm that 1D vertical arrays of BPE discs can function like a single rod-shaped BPE when the individual BPE discs are connected by light-emitting p-n junctions. Cell current measurements estimates the conductance of a linear BPE array at about 1/5 of a solid, printed rod BPE of the same length. A PLEC with an 8x8 2D array exhibits intense (visible to the naked eye) junction EL from 56 light-emitting p-n junctions formed between the BPEs and the largest cell current measured. The demonstration of functional ink-jet printed BPEs and their applications onto PLECs facilitates easier generation of BPE patterns as well as probing the complex doping processes in PLECs.

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