Line-patterning of polyaniline coated MWCNT on stepped substrates using DC electric field

Young Gun Ko1, Tae Gu Do2, Hyun Chul Oh2, Hyun Jeong Lee2, Hung-gu Han2, Choong Hyun Kim3 & Ung Su Choi2

1Environmental Radioactivity Assessment Team, Korea Atomic Energy Research Institute, 989-111 Daedeok-daero, Yuseong-gu, Daejeon 305-353, Korea, 2Center for Urban Energy Systems, Korea Institute of Science and Technology, Hwarangno 14-gil 3, Seongbuk-gu, Seoul 136-791, Korea, 3Center for Bionics, Korea Institute of Science and Technology, Hwarangno 14-gil 3, Seongbuk-gu, Seoul 136-791, Korea.

Printing electronic components on a chip edge and a stepped substrate with functional inks are an attractive approach for achieving flexible and inexpensive circuits for applications such as flexible displays and large-area chemo/bio/radioactivity sensors. However, it is still challenging because a sufficient cover of the 100 μm high step at the chip edge with a high-resolution pattern is the hardest part of the layer assembling by inkjet printing. Herein, we present a simple and effective strategy to generate electrically conductive line-patterns on stepped substrates by applying the DC electric field. On the surface of flat polyimide substrate, the fine line-pattern (less than 850 nm in line width) is achieved with a polyaniline coated MWCNT dispersed ink. Furthermore, 9.9 μm of line width is successfully patterned on the high stepped poly(dimethylsiloxane) substrate, higher than 100 μm, by printing only 1 time.

In recent years, a great deal of effort has been expended in the study of the development of inkjet printing technology because of its various applications such as organic thin film transistor, radio-frequency identification devices (RFIDs), light-emitting diodes (LEDs), photovoltaic cells, displays, chemo/bio/radioactivity sensors, etc1. This technology has also attracted significant attention as an enabling technology for the rapid, low-cost, scalability to large-area, material-saving, and energy-conserving manufacture of flexible electronics2. One of key issues toward "flexible electronics" is to develop the high resolution line-patterning techniques using conducting materials3. Therefore, numerous efforts from both scientific and industrial communities have been made to achieve high resolution inkjet-printed features by shrinking the nozzle size4 or control of interfacial tension between ink and substrate or nozzle material5. However, the high resolution, less than 1 μm in line width, has not been achieved with conducting ink such as silver, copper, carbon nanotube (CNT), conducting polymers and indium tin oxide (ITO) by the common inkjet printing technique6–8 although various materials are patterned one-dimensionally by techniques of several process steps9,10. Recent advance in inkjet printing techniques such as electrostatic autofocussing11, electrohydrodynamic jet12, electrified liquid jet13, and dielectrophoretic nanoprinting14 allows the fabrication of high resolution line-pattern which is less than 1 μm of line width. Despite the rapid developments in inkjet printing of a conducting ink, printing technology for the step-coverage lateral interconnection over a chip on flexible circuit board still remains a challenging task because the line-patterning is not printed at the side wall of the step. If the standard wire bond process can be replaced by the inkjet technology, we can expect advantages of downsizing possibilities for the chip with better cost performance and shorter interconnects, realization of very complex modules between chips and board connections at small geometric sizes, and easy change of designs for assembling different chip sizes and interconnects by just alterations of the printed program.

Our approach for overcoming the challenging task of printing technology for the step-coverage lateral interconnection over a chip is to apply a DC electric field along the desired direction around an ink-jetted droplet on the substrate. The key of our manufacturing concept is the introduction of electrorheological (ER) phenomena for conductive line-patterning. The ER fluid is a colloidal suspension composed of an insulating liquid medium embodying either a polarizable particulate material or a polarizable liquid material15. Application of an electric field to ER particles induces the formation of chains of particles in the colloidal suspension along the field direction16. Galliker et al. applied the electric field perpendicularly to the substrate for the fabrication of the high...
Carbon nanotube (CNT) composites have drawn much attention for the alignment of MWCNT@PANI particles under DC electric fields. The perpendicular electric field produces complex patterns and multiple chips on flexible substrates. Although our developed technique is an immature technology, this technique has the potential to be broadly utilized to enable the delivering subfemtoliter ink volumes and the high control of ink spreading on the substrate. This method allows the line-pattern width down to 1 μm. However, the printing of the lateral line-pattern on the stepped substrate had not been tried by the method. Here, based on the ER phenomena, we demonstrate the fabrication of polyaniline coated multi-walled carbon nanotube (MWCNT@PANI) line-patterning with line width of less than 1 μm, and with various step heights on the flexible substrates using a commercial needle nozzle. Under the electric field, MWCNT@PANI particles in the dropped ink on the substrate align along the direction of the electric field with fast evaporation of ink solvent, and finally form the conductive line-pattern.

To the best of our knowledge, this is the first report on the conductive line-patterning on the stepped substrate by the inkjet printing technique. Although our developed technique is an immature technology, this technique has the potential to be broadly utilized to produce complex patterns and multiple chips on flexible substrates for a wide variety of applications, including in optical, electronic, optoelectronic, and biomedical devices.

**Results**

**Alignment of MWCNT@PANI particles under DC electric fields.** Carbon nanotube (CNT) composites have drawn much attention for the high electric conductivity. Although the drop-on-demand technology, such as inkjet printing, is powerful to approach fine-electronic devices with high resolution, the technology demands nanometer-sized particles as a dispensing material for small dispensing nozzle diameter. Therefore, a micrometer-length CNT cannot be printed on the circuit-substrate with sub-micrometer scale. In this study, to circumvent this problem, a DC electric field is applied parallel to the substrate for dispensing CNT on the substrate with a commercial needle nozzle. For homogeneous dispersion of CNTs in the ink, CNT was coated with polyaniline (PANI) which is one of the most prominent members of the family of intrinsically conducting polymers. The polyaniline coated multi-walled carbon nanotube (MWCNT@PANI) was prepared by the following procedure (Supplementary Fig. S1). MWCNTs are hydrolyzed for the adsorption of monomer (aniline). And then, oxidative PANI polymerization occurs on the surface of MWCNTs. Without the use of surfactants or stabilizers, our method allows the uniform thickness of PANI layer on the surface of MWCNTs. Without the use of surfactants or stabilizers, our method allows the uniform thickness of PANI layer on the surface of MWCNTs. The thickness of the PANI layer of the prepared MWCNT@PANI was ca. 3 ~ 7 nm (Supplementary Fig. S2).

The behavior of MWCNT@PANI in the fluid against DC electric fields was observed using an optical microscope with 5 vol% of MWCNT@PANI/silicone oil suspension (Fig. 1a). The experimental cell was assembled by mounting two parallel electrodes with a 1.5 mm gap on a glass slide, in which a drop of well-mixed MWCNT@PANI suspension was dispersed. The presence of fibrils is obvious as the electric field increases, although they are not always linear and even have double loops in some cases. This suspension is called as an electrorheological (ER) fluid. Generally, two different mechanisms have been proposed to explain the ER phenomena. The electrostatic polarization mechanism, proposed originally by Winslow, attributes the origin of the ER effect to the field-induced polarization of the disperse phase particles relative to the continuous phase (Supplementary Fig. S3).

Based on this result, we have tried to confirm the behavior of MWCNT@PANI particles in the droplet of MWCNT@PANI/chlorobenzene under the DC electric field. A conductive line-pattern on the glass substrate has been fabricated as described schematically in Fig. 1b. A suspension is prepared by dispersing MWCNT@PANI in chlorobenzene (0.5 wt%). A droplet of the suspension is dropped between the two-electrodes using a commercial needle nozzle. Experiments were carried out with two cases: case 1) evaporation of the droplet without the application of DC electric field, and case 2) evaporation of the droplet after the application of DC electric field.

In the case 1 of Fig. 1b (electric field: 0 V mm⁻¹), a ring composed of MWCNT@PANI was observed in the field-emission gun-scanning electron microscope (FEG-SEM) image (Fig. 1c, left image). Most of solute (MWCNT@PANI) is deposited at the periphery of the dispersed ink due to the strong evaporation flux at the contact line. When the sessile droplet is pinned during the evaporation process, the evaporation flux gradient induces a strong radial outward convective flow, which forces most of the particles to be deposited near the contact line (formation mechanism of a ring-like deposit in Fig. 1b, top inset). This phenomenon is known as the coffee-ring effect. In the case 2 experiment of Fig. 1b, the pattern composed of MWCNT@PANI depended on the strength of the DC electric field. The diagram of electric field lines around the droplet of MWCNT@PANI suspension is depicted with vector arrows in Fig. 1b, bottom inset. At 250 V cm⁻¹, the pattern followed the curvature of the electric field lines (Fig. 1c, middle image). The similar pattern was reported that the domain orientation in the diblock copolymer thin film can be obtained by the application of DC electric field. However, we firstly report that the large pattern is also able to mimic the DC electric field lines on millimeter-length scale. At the higher electric field (500 V mm⁻¹), the thick line pattern composed of MWCNT@PANI was fabricated (Fig. 1c, right image). The strongest electric field line forms at the shortest distance between electrodes. Thus, MWCNT@PANI locate on the the shortest distance between electrodes and form the straight line. In this work, only chlorobenzene was used as an ink medium. In addition to this solvent, various solvents can be used as the ink medium. However, the dielectric constant and electric conductivity of the solvent should be lower than those of MWCNT@PANI. The negative electrorheological (ER) effect occurs when the dielectric constant and electric conductivity of the host fluid are higher than those of the dispersed particle (eg. MWCNT@PANI in this work). In the negative ER fluid, the suspended particles do not form the strong fibillation parallel to the electric fields because of two phenomena of negative ER fluids; Quincke rotation (electrorotation) and phase separation (electromigration). The dielectric constant of the used host fluid (chlorobenzene) and particle (polyaniline/MWCNT) are 5.69 and 100 ~ 600, respectively. The electric conductivity of the used particle is also significantly higher than that of host fluid. The host fluid should be evaporated at the room temperature and the atmospheric pressure to fabricate line-pattern in the DC electric field. Supplementary Figure S4 shows the 3D reconstructed images and the height profiles (red lines in the 3D reconstructed images) of the patterns composed of the MWCNT@PANI on the glass substrate at the application of 0, 250, and 500 V cm⁻¹. At 500 V cm⁻¹, the line cross-sectional profile became a roughly convex shape with a high height while other cross-sectional profiles exhibited a low height. The resistivity of the patterns decreased with the increase of the applied electric field because the MWCNT@PANI became the denser nanostructure and connected well with each other with increasing the applied electric field as shown in two magnified FEG-SEM images (Supplementary Fig. S4). This dense nanostructure strongly influenced the resistivity. The electric field forced the electrostatically polarized MWCNT@PANI to be very close to each other, and made them the dense nanostructure. The resistivity of the line-pattern fabricated at 500 V cm⁻¹ is 854 ± 99 μΩ cm. This value is significantly lower than that of PANI nanofiber pattern (ca. 1 Ω cm), and locates between those of bulk of PANI/PANI salts (ca. 2000 ~ 10⁵ μΩ cm) and carbon nanotubes (5 ~ 50 μΩ cm) (Fig. 2).

**High resolution conductive line-patterning on polyimide films.** Between two parallel electrodes, single high-resolution line was not obtained due to overlapped electric field lines between the electrodes (see Fig. 1a,c). To address this problem, we did same experiment with...
Figure 1 | Fabrication of MWCNT@PANI pattern under DC electric field. (a) Optical microscope images of aligned polyaniline-coated multi-walled carbon nanotube (MWCNT@PANI) between two electrodes after application of DC electric fields (gap between electrodes: 1.5 mm, concentration of suspension: 5 vol% of MWCNT@PANI in silicon oil). (b) Schematic illustration of patterning of MWCNT@PANI on a substrate under DC electric fields. (c) Patterns of MWCNT@PANI on glass substrates under various DC electric fields.
using two needle electrodes instead of two parallel rod-electrodes. In 
this experiment, single MWCNT@PANI line formed between the 
electrodes in the silicone oil (Supplementary Movie 1). Inspired 
by this experimental result, we dropped the MWCNT@PANI/ 
chlorobenzene solution (1.5 × 10⁻³ wt%) between the sharp-edged 
copper-electrode patterns on the flexible polyimide film, and then 
applied 20 mV μm⁻¹ of DC electric field (Supplementary Fig. S5). 
A high-resolution conductive line has been fabricated on the flexible 
polyimide film, and its width and length were 800–900 nm and ca. 
100 μm, respectively (Fig. 3). The each MWCNT@PANI tube in the 
fabricated line aligned well along the direction of the electric field 
line. This alignment was not observed in high concentration 
MWCNT@PANI/chlorobenzene (see Supplementary Fig. S4). In the 
low concentration, tubes stretch along the direction of electric 
field, and then adhere each other between two electrodes. However, 
in the high concentration, tubes agglomerate together first due to 
their polarization and then adhere each other. Due to the dense 
structure, the fabricated line-pattern showed very low electrical 
resistivity (142 μΩ cm).

In addition, we fabricated a long conductive line-pattern on the 
glass substrate with MWCNT@PANI. The conductive line-pattern 
has been fabricated by repeating steps of 1) dropping of the 
MWCNT@PANI/chlorobenzene solution, and 2) evaporation of 
benzene with the application of DC electric field, as described in 
Supplementary Fig. S6a. To form the long conductive line-pattern, 
the electro-de of the needle type is used, and one electrode is fixed on 
the glass substrate while another moves in the designed pattern dir-
rection. The applied DC electric field for the needle electrodes was 
50 V mm⁻¹. It is lower than that for the rod electrode type (copper 
electrodes in Fig. 1b). At the same DC electric field, the electric field 
line between the needle electrodes is stronger than between the rod 
electrodes, because only one strong-straight electric-field-line forms 
between two points while many strong-straight electric-field-line 
form two between lines. The dimension of the contact between 
the needle electrode and the glass substrate is zero (point) while 
the rod electrode is one (line). With the described instrument 
(Supplementary Fig. S6b), the first initials of the institute (KIST, 
Korea Institute of Science and Technology) were written on the glass 
substrate as shown in Supplementary Fig. S6c. The dense structure 
of MWCNT@PANI in the formed “KIST” is observed 
(Supplementary Fig. S6d). To see the letters with naked eyes, high 
concentration of MWCNT@PANI/chlorobenzene (0.5 wt%) was 
used to fabricate the initials.

Conductive line-patterning on stepped PDMS films. The drop-on-
demand technique offers high technology for the fabrication of 
modules with multiple chips on a board by printing multilayers on 
the board with functional inks35. However, the technique does not 
allow the 3D printing on the stepped surface for the interconnection 
between chips and board because the printed conductive line 
connects at the sidewall of chip. Our printing technique has 
been applied to a stepped PDMS substrate (Fig. 4a). The line-
pattern was fabricated by dropping the MWCNT@PANI/ 
chlorobenzene solution on the step using a commercial needle 
nozzle, and applying a DC electric field with two copper needle 
electrodes. One was located on the top floor of the stepped film, 
and the other was on the bottom floor (Fig. 4b). Line widths of 9.9, 
50.3 and 70.9 μm were fabricated on the stepped PDMS substrates 
(step height: 105.1, 201.1 and 326.6 μm) at the MWCNT@PANI/ 
chlorobenzene concentration of 2.5 × 10⁻³, 5 × 10⁻³ and 8 × 
10⁻³ wt% under DC electric fields of 30, 40 and 50 mV μm⁻¹, 
respectively. The data in the graph were obtained by adjusting 
MWCNT@PANI/chlorobenzene concentration and DC electric 
field during line-patterning and measuring the line width of the 
best fine line-pattern. It is noteworthy that the line width shows 
the repetition of linear increase in range [1] and plateau in range 
[2] with increase of the step height. In the case of the fabrication of 
line-patterning on the substrate, applied DC electric field for the 
patterning is influenced by the electric properties of substrate 
surface and air. On the other hand, in the case of the stepped 
substrate, the DC electric field is influenced not only by the 
substrate surface and the air but the substrate material because the
DC electric field should penetrate through the substrate due to the step of the substrate. Thus, a step-height threshold forms due to the resistivity from the substrate, and can be broken by increasing the DC electric field. During increasing the DC electric field, the MWCNT@PANI/chlorobenzene concentration is adjusted to avoid the line-pattern disconnection and fabricate the fine line-pattern. From this result, to apply our technique to other substrates, the electric properties of the substrates should be considered because the exhibited linear increase (range [1]) and plateau (range [2]) in the graph depend on the electric properties of the substrates. The fabricated line-patterns exhibit well interconnection at the sidewall of the step with low resistivity (ca. 150, 200 mV cm) to allow the lateral interconnection between chips and board (Fig. 4c–e). Hence, the current shortcomings (the high-step-coverage lateral interconnection between chips and board) that plague the application of the drop-on-demand or inkjet technology to industrial fields are eliminated by this innovative approach.

**Discussion**

Although the inkjet printing technology is simple, cost-effective, scalable and energy-savable compared with other patterning technologies, it has not been applied for the step-coverage lateral interconnection over a chip or the wiring between semiconductor chips stacked due to the risk of short circuits. Several researches were reported for the step-coverage lateral interconnection over a chip with the inkjet printing technology. However, they did not show a printed line with narrow width over a 100 μm high step. Herein, we have demonstrated a simple and effective strategy for the first time to generate electrically conductive MWCNT@PANI line-patterns on the stepped substrate by applying the DC electric field. The applied DC electric field kept the line-pattern during evaporation of the ink solvent without its disconnection, and made the fine pattern at the edge of the step of substrate. If the conductivity or the dielectric constant of the material for the patterning is lower than the ink host fluid, Quincke rotation (electrorotation) or phase separation (electromigration) occurs and prevents the formation of the fine line-pattern. Therefore, MWCNT was coated with PANI to increase its dielectric constant although it is a high conductive material. In this study, on the surface of flat polyimide substrate, the line-pattern having the line width of 821.7 nm and conductivity of 142 μΩ cm was achieved by applying the DC electric field of 20 mV μm⁻². The each MWCNT@PANI tube in the fabricated line aligned well along the direction of the electric field line. It is noteworthy that a line width of 70.9 μm was fabricated on the stepped PDMS substrate (step height: 326.6 μm). A sufficient cover of the 100 μm high step at the chip edge is the hardest part of the layer assembling by inkjet printing. Especially, using our method, line width of 9.9 μm was patterned on the 105.1 μm high stepped PDMS substrate without the cutoff of the MWCNT@PANI line.

In conclusion, the high-resolution line-pattern can be fabricated by the DC electric field assisted inkjet printing technique with the conductive and dielectric material dispersed ink. The technique allows the high step-coverage lateral interconnection over a chip or the wiring between semiconductor chips stacked with the narrow line width. Compared to recent-advanced inkjet printing techniques for the fabrication of the flexible devices, great advantages of our technique are (a) the fabrication of fine pattern with a large particles dispersed ink, (b) the sufficient cover of the high step at the chip edge by printing only 1 time, and (c) the use of commercial printing-nozzle (needle nozzle) without adjustment of its size or wettability. It is assumed that with proper optimization of the nanotube concentration, process temperature and applied DC electric field, our suggested method will become a mature and competitive technology for fabricating future fast and low-cost devices, for example, flexible electronic devices and complex chemo/bio/radioactivity sensors.

**Methods**

**Synthesis of MWCNT@PANI.** 1.5 g of MWCNT (Aldrich) is dissolved in 250 ml of diethyl glycol dimethyl ether (anhydrous, Sigma-Aldrich) and sonicated for 1 h. 8 g of 3-sulfone (Tokyo Chemical Industry) is added into the solution and sonicated.
1. Singh, M., Haverinen, H. M., Dhtagat, P. & Jabbour, G. E. Inkjet printing - Process and its applications. Adv. Mater. 22, 673–685 (2010).

2. Ha, M. et al. Printed, sub-3V digital circuits on plastic from aqueous carbon nanotube inks. Adv. Mater. 24, 4348–4395 (2012).

3. van Osch, T. H. J., Perelaer, J., de Laat, W. M. & Schubert, U. S. Inkjet printing of narrow conductive tracks on untreated polymeric substrates. Adv. Mater. 22, 343–345 (2010).

4. Derby, B. Inkjet printing of functional and structural materials: Fluid property requirements, feature stability, and resolution. Annu. Rev. Mater. Res. 40, 395–414 (2010).

5. Dong, Z., Ma, J. & Jiang, L. Manipulating and dispensing micro/nanoliter droplets by superfertrophic needle nozzles. ACS Nano 7, 10371–10379 (2013).

6. Li, J. et al. Efficient inkjet printing of graphene. Adv. Mater. 25, 3985–3992 (2013).

7. Caironi, M., Gili, E., Sakanooue, T., Cheng, X. & Sringraigh, H. High yield, single droplet electrode arrays for nanoscale printed electronics. ACS Nano 4, 1451–1456 (2010).

8. Zhang, Z. et al. Controlled inkjetting of a conductive pattern of silver nanoparticles based on the coffee-ring effect. Adv. Mater. 25, 6714–6718 (2013).

9. Su, B., Wu, Y. & Jiang, L. The art of aligning one-dimensional (1D) nanostructures. Chem. Soc. Rev. 41, 7582–7586 (2012).

10. Kuan, X., Su, B. & Jiang, L. Precisely patterning graphene sheets through a liquid-bridge induced strategy. Small 10, 2570–2577 (2014).

11. Galliker, P. et al. Direct printing of nanostructures by electrostatic autofocusing of ink nanodroplets. Nat. Commun. 3, 890 (2012).

12. Park, J. et al. High-resolution electrohydrodynamic jet printing. Nat. Mater. 6, 795–799 (2007).

13. Park, J. et al. Nanoscale, electrified liquid jets for high-resolution printing of charge. Nano Lett. 10, 584–591 (2010).

14. Schirmer, N. C. et al. On ejecting colloids against capillarity from sub-micrometer openings: On-demand dielectrophoretic nanoprinting. Adv. Mater. 22, 4701–4705 (2010).

15. Ko, Y. G. & Choi, U. S. Gelation of natural polymer dispersed suspensions under electric field. Soft Matter 8, 253–259 (2012).

16. Halsey, T. C. Electrotheroeological fluids. Science 258, 761–766 (1992).

17. Lau, P. H. et al. Fully printed, high performance carbon nanotube thin film transistors on flexible substrates. Nano Lett. 13, 3864–3869 (2013).

18. Lee, S. Y. et al. Scalable complementary logic gates with chemically doped single conductingcarbon nanotube transistors. ACS Nano 5, 2369–2375 (2011).

19. Kordas, K. et al. Inkjet printing of electrically conductive patterns of carbon nanotubes. Small 2, 1021–1025 (2006).

20. Park, S., Vosguerchian, M. & Bao, Z. A review of fabrication and applications of carbon nanotube film-based flexible electronics. Nano Letters 13, 3864–3869 (2013).

21. Chiang, J.-C. & Macdardm, A. G. ‘Polyaniline’: Protonic acid doping of the emeraldine polaron form to the metallic form of the polymer. J. Phys. Chem. B, 1021–1025 (1998).

22. Parhasarathy, M. & Klucznge, D. J. Electrorheology: Mechanics and models. Mater. Sci. Eng. R. 17, 57–103 (1996).

23. Deegan, R. D. et al. Capillary flow as the cause of ring stains from dried liquid drops. Nature 389, 827–829 (1997).

24. Kawase, T., Sringraigh, H., Friend, R. H. & Shimoda, T. Inkjet printed via-hole interconnects and resistors for all-polymer transistor circuits. Adv. Mater. 15, 1601–1605 (2003).

25. Kirkup, L. Computer simulation of electric field lines. Phys. Educ. 20, 142–145 (1985).

26. Morkved, T. L. et al. Local control of microdomain orientation in diblock copolymer thin films with electric fields. Science 273, 931–933 (1999).

27. Ramon-Tejada, M. M., Arroyo, F. J. & Delgado, A. V. Negative electrorheological behavior in suspensions of inorganic nanoparticles. Langmuir 26, 16833–16840 (2010).

28. Ko, Y. G. & Choi, U. S. Negative electrotheroeological fluids. J. Rheol. 57, 1655–1667 (2013).

29. Lide, D. R. Handbook of Organic Solvents 77–77 (CRC Press, Boca Raton, 1995).

30. Zhang, Y. et al. Dielectric percolative composites with high dielectric constant and low dielectric loss based on sulfonated poly(arylether ketone) and a-MWCNTs coated with polyaniline. J. Mater. Chem. C, 1, 4035–4041 (2013).

31. Shi, S.-L., Zhang, L.-Z. & Li, J.-S. Electrical and dielectric properties of multilayer carbon nanotube/polyaniline composites. J. Polym. Res. 16, 395–399 (2009).

32. Zhang, X. et al. Synthetic process engineered polyaniline nanosystems with control morphology and physical properties. Polymer 53, 2109–2120 (2012).

33. Mark, J. E. Polymer Data Handbook 271–275 (Oxford University Press, New York, 1999).

34. Mittal, V. Carbon nanotubes: An introduction. Polymer Nanotube Nanocomposites: Synthesis, Properties, and Applications, Mittal, V. (ed.) 1–13 (Scrivenior Publishing, Salem, 2010).

35. Sringraigh, H. et al. High-resolution inkjet printing of all-polymer transistor circuits. Science 290, 2123–2126 (2000).

36. Mantysalo, M. et al. System integration of smart package using printed electronics. IEEE Electro. Components and Tech. Conf. (ECTC) 629, 997–1002 (2012).

37. Mengel, M. & Nikitin, I. Inkjet printed dielectrics for electronic packaging of chip embedding modules. Microelectro. Eng. 87, 593–596 (2010).

Acknowledgments
This work was supported by the Green City Technology Flagship Program funded by the Korea Institute of Science and Technology (KIST-2014-2E25084).

Author contributions
Y.K. designed experiments and interpreted the experimental findings. T.D. and H.O. contributed to the fabrication of the patterns. Y.K. and U.C. wrote the manuscript, which was revised by all authors. U.C. was responsible for project coordination.
Additional information

Supplementary information accompanies this paper at http://www.nature.com/scientificreports

Competing financial interests: The authors declare no competing financial interests.

How to cite this article: Ko, Y.G. et al. Line-patterning of polyaniline coated MWCNT on stepped substrates using DC electric field. Sci. Rep. 4, 6656; DOI:10.1038/srep06656 (2014).
ERRATUM: Line-patterning of polyaniline coated MWCNT on stepped substrates using DC electric field

Young Gun Ko, Tae Gu Do, Hyun Chul Oh, Hyun Jeong Lee, Hung-gu Han, Choong Hyun Kim & Ung Su Choi

The original HTML version of this Article contained a typographical error in the spelling of the author Tae Gu Do which was incorrectly given as Tae Gu. This has now been corrected in the HTML version of the Article.