Sensors and Actuators A 253 (2017) 131–135

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

Etch-free addressable organic sensor arrays

Steven A. Rutledge, Amr S. Helmy*

Edward S. Rogers Sr. Dept. of ECE, University of Toronto, 10 King's College Road, Toronto, M5S 3G3, Canada

ARTICLE INFO

Article history:
Received 10 May 2016
Received in revised form 1 September 2016
Accepted 12 November 2016
Available online 19 November 2016

Keywords:
Capacitive sensors
PEDOT:PSS
Organic electronics
Transparent touch screen panel

ABSTRACT

Using a direct UV fabrication technique, an organic transparent 8 × 8 capacitive touch screen panel has been designed, fabricated and characterized. The active electrode material is poly(3,4-ethylenedioxythiophene): poly (styrenesulfonate) (PEDOT:PSS). The UV process provided spatial control over the PEDOT:PSS film conductivity, which was subsequently used to fabricate the touch screen panel. This process does not require external photoresists or secondary development and etch steps. The UV patterning of PEDOT:PSS provided a 3-order-of-magnitude reduction in material conductivity between exposed and unexposed regions. Spatial location of touch events can be accurately identified by monitoring relative changes in capacitance at each of the individual elements of the array. A typical touch event causes a measured capacitance reduction of ~100 fF at the touched intersection. The tested devices exhibit high optical transmission exceeding 80% across the visible spectrum. This technology allowed the device to be realized in a single processing step that is amenable to large scale, high-throughput organic fabrication techniques such as roll-to-roll processing.

1. Introduction

The spiraling appeal and associated demand for lighter, cheaper, and thinner electronic devices have fueled the utilization of organic and polymer materials in emerging generations of electronic circuits [1]. The adoption of these materials in electronics has several advantages including physical flexibility, semi-transparent devices, and the economics of roll-to-roll manufacturing.

In the area of transparent capacitive touch screen panel (TSP) technologies, existing design strategies have regularly used indium tin oxide (ITO) as the primary electrode material. This is because ITO, a transparent conducting oxide, has outperformed other inorganic materials. This is due to its low-temperature deposition, high conductivity and ease of etching. However, ITO suffers from limitations including brittleness, high material cost and vacuum deposition requirements [2]. The loss of electrical performance due to its brittle nature has been acknowledged for over a decade [3]. In order for TSP technologies to be compatible with high-throughput scalable organic electronics produced using roll-to-roll methods, the aforementioned limitations must be circumvented.

There is a pressing need for alternatives to ITO to be developed. The search for a suitable transparent electrode replacement has expanded to non-traditional materials such as silver nanowires, organic polymers, graphene, and carbon nanotubes [4–10]. A common challenge associated with many of these replacement materials is the lack of suitable patterning techniques that afford high-throughput capabilities. Common across all previous demonstrations, regardless of material, is the requirement for the transparent electrode to be amenable to patterning using a variety of micro- or nanofabrication techniques. However, such patterning often requires secondary photoresists, etchants and caustic environments that may preclude integration with underlying organic and CMOS-based devices.

The use of conductive organic polymers as electrodes is becoming increasingly popular. This is not only due to their desirable material properties such as mechanical flexibility, but also because their deposition techniques are intrinsically compatible with organic devices. In particular, poly(3,4-ethylenedioxythiophene): poly(styrenesulfonate) (PEDOT:PSS), a commercially available organic conductor, is attracting interest due to its solubility in water, relatively high conductivity, and environmental stability in comparison to other organic materials [11].

Several fabrication techniques have been previously used to realize capacitive TSPs using PEDOT:PSS including inkjet printing, laser ablation and micromolding; however, only inkjet printing has reported the realization and characterization of a working device [12–14]. Of the reported demonstrations, only micromolding is truly compatible with scalable high-throughput fabrication, whereas both individual inkjet printing and laser ablation approaches are serial patterning processes.

As such, there remains a real need and an unmet demand for materials and associated fabrication processes that can replace ITO

---

* Corresponding author.
E-mail address: a.helmy@utoronto.ca (A.S. Helmy).

http://dx.doi.org/10.1016/j.sna.2016.11.016
0924-4247/

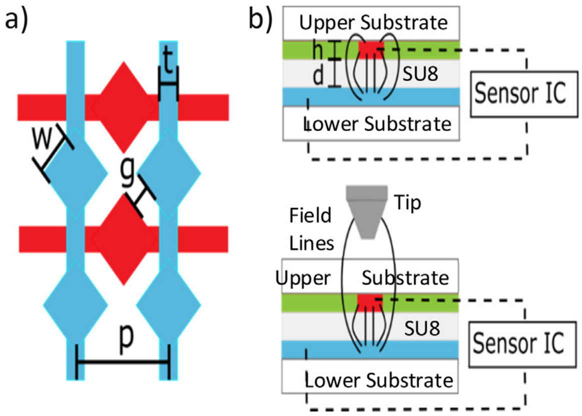

Fig. 1. a) Schematic of electrode design with interlocking diamond structure. The vertical and horizontal electrode lines (blue and red respectively) reside at different heights within the device. b) A schematic depiction of the fields associated with mutual capacitance sensing, showing the shunting of the electromagnetic fields between electrode pads upon introduction of a conductive stylus (bottom). The electrical connections to the sensing electronics are also shown. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

while mitigating the aforementioned drawbacks to enable competitive, inexpensive organic electronic devices. It is crucial that in order to create commercially viable technologies, the materials and fabrication process be compatible with large scale, high throughput processing such as roll-to-roll methods.

In this work, a fabrication process and the associated device architecture for mutual-capacitance organic PEDOT:PSS-based TSPs with high spatial resolution is proposed, demonstrated, and characterized. The devices are realized using a novel processing technique that selectively tailors the material conductivity in the planar spatial dimension by utilizing a UV-induced polymer scission process. In contrast with other patterning mechanisms, direct UV scission does not have any inherent material compatibility constraints. The technique has been developed, characterized and implemented to pattern the output emission of an organic light emitting diode [15]. This direct, etch-free spatial patterning technique is compatible with scalable, high-throughput and roll-to-roll manufacturing, where it is spatially limited only by the critical dimension of the UV shadowmask.

2. Capacitive touch sensor panel design

To demonstrate the application of the etch-free patterning technique, a commonly used TSP electrode layout, is designed and adopted for the devices reported within. Due to the relatively low sensitivity of the employed mutual capacitive sensing technique, an interlocking diamond parallel-plate structure shown in Fig. 1a) has been designed to increase the fringing field between electrodes. The row and column electrodes shown in Fig. 1a) are fabricated on separate substrates and isolated using a dielectric medium as shown in Fig. 1b). For such a design, the measured capacitance between a specified row and column electrodes can be expressed as [16]

$$C_{\text{element}} = \frac{t^2\varepsilon}{d} + \frac{8\pi w\varepsilon}{\log(\frac{4d}{h})}, \qquad (1)$$

where t is the electrode trace width, ε is the permittivity of the dielectric interlayer, d is the thickness of the dielectric, h is the thickness of the electrode material, and w is the length of the side of the diamond. The fabricated structure has values of $t = 0.5$ mm, $w = 0.9$ mm, $g = 0.5$ mm, $h = 100$ nm, $d = 5$ µm, $p = 2.5$ mm, and $\varepsilon = {\sim}4\,\varepsilon_0$. Together with Eq. (1), these give an estimated value of 1.92 pF for the unperturbed capacitance between a row and column electrode.

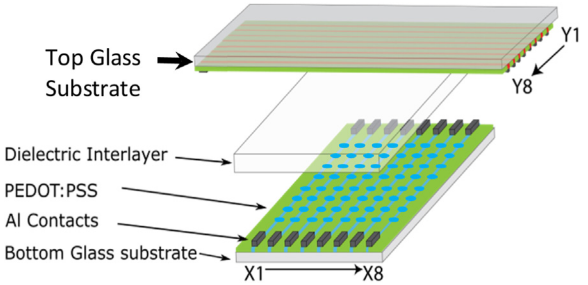

Fig. 2. Generalized assembly of the 8 × 8 capacitive sensing array made from dual UV-patterned substrates, allowing for addressable contact to each of the 64 capacitive elements.

In comparison to ITO panels which often implement electrodes with a trace width of 20 µm, a wider 0.5 mm trace is required due to the relative lower conductivity of PEDOT:PSS. This results in a larger crossing overlap between the rows and columns, thereby sacrificing some of the spatial sensitivity in order to allow for high conductivity through the unexposed PEDOT:PSS trace. The lower conductivity of PEDOT:PSS also makes it necessary to deposit metal contacts on opposing edges of the capacitive sensor to ensure that, during bias while sensing, a minimum resistance from the trace to the element under test is maintained.

The sensors demonstrated here consist of 8 individually addressable rows and columns, effectively creating 64 separate capacitive sensing elements. With the parallel-plate interlocking diamond structure, the mode of operation is based on sensing the mutual capacitance between the row and column traces. When a conductive stylus or human finger is near or in contact with the top glass substrate, a portion of the fringing field lines is shunted away from the mutual capacitors between the X and Y traces with a subsequent change in capacitance as shown in Fig. 1b) [16].

The spatial definition of the PEDOT:PSS electrodes in the capacitive sensor is achieved by using a direct UV patterning technique. As opposed to traditional methods of physically defining separated TSP electrodes, this novel fabrication technique selectively modulates the conductivity of regions within the thin film by up to 4 orders of magnitude when compared to the pristine polymer [15]. This approach allows new capabilities of for micron-scale precision patterning of electronic devices in a single processing step without the requirement of additional deposition, development, or etch steps.

3. Methods and materials

PEDOT:PSS was spun onto cleaned boroaluminosilicate glass slides. The resultant film thickness was approximately 100 nm prior to UV exposure. The films were irradiated by a Spectroline XL-1500 Crosslinker through an electroformed Ni shadow mask. A total exposure energy of 75 J/cm^2 at 254 nm was irradiated onto the films. Following the UV patterning, aluminum contacts were thermally evaporated onto both ends of the PEDOT:PSS electrodes. Employing this direct UV exposure patterning necessitated a design in which the row and column electrodes are separated by a dielectric interlayer. The capacitive array is comprised of two identically patterned PEDOT:PSS films that are oriented 90° with respect to each other and secured using an SU8 interlayer. The SU8 interlayer was spun onto one of the substrates using SU8 2000.5 at a final spin speed of 3000 RPM resulting in an approximate thickness of 5 um. Upon appropriate alignment of the top substrate, the completed device was then baked at 60 °C for 1 h under a 1 kg weight to ensure appropriate adhesion of the substrates. The generalized design and of the capacitive structure is shown in Fig. 2. It should be noted that the individual diamond structures patterned on each conductive

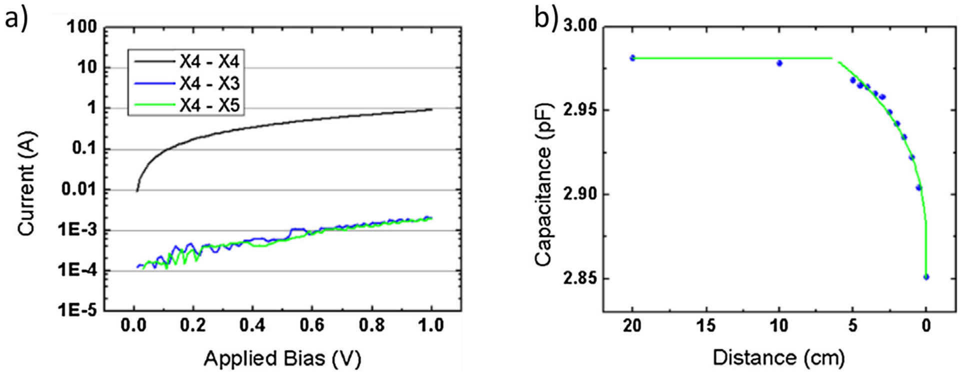

Fig. 3. a) IV characteristics between common contacts (X4-X4) and UV-isolated (X4-X3 and X4-X5) electrical contacts across the transparent active sensing region, confirming the efficacy of the patterning process. b) Measured change in raw capacitance with respect to stylus height above the glass substrate (blue circles) and subsequent mathematical fit to data (green lines). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

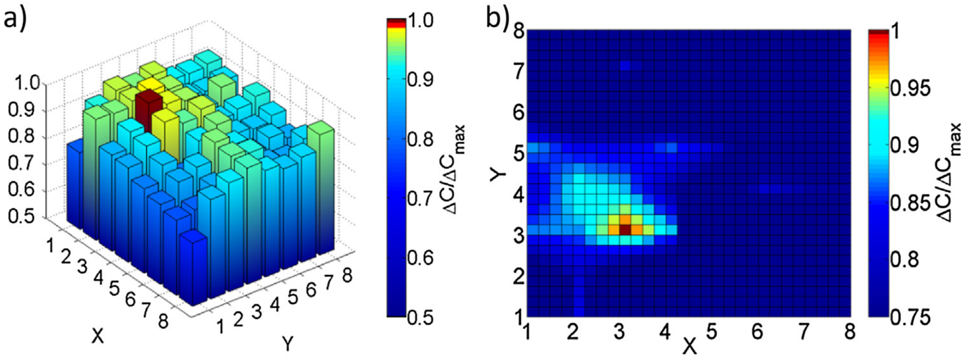

Fig. 4. a) Measured change in capacitance at each intersection with a touch event occurring at X = 3, Y = 3. b) Corresponding 2D interpolated spatial map of capacitance change across the entire active array allowing for determination of stylus location in which the color scale has been reduced for clarity.

trace have not been included for clarity purposes. Current–voltage (IV) measurements were obtained using an HP4145A semiconductor probe analyzer. Capacitive measurements were obtained using an HP4284A LCR meter. Touch events were introduced using a grounded conductive stylus with a rounded tip having a diameter of ~1.5 mm, connected in series to a 100 pF capacitor and a 1.5 kΩ resistor to model a human body.

4. Characterization and discussion

4.1. Electrical resistivity patterning

To verify the reduction of electrical conductivity with UV exposure, IV measurements were taken between pairings of opposing contacts across the transparent active area, and comparison was made between connected contact pads and those separated by the UV-exposed film. These results are shown in Fig. 3a). With an applied 1 V bias, approximately 1 μA of current can be measured across connected pads. In contrast, for the UV-isolated contacts the measured current is 3 orders of magnitude lower. This degree of resistive decrease is sufficient for adequate capacitive TSP device functionality.

4.2. Capacitive sensing operation

Upon fabrication, the mean value of all 64 measured raw capacitances was 2.10 pF with a standard deviation of 1.26. This is within 10% error of the expected unperturbed capacitance value of 1.92 pF. The variability in the initial capacitances of the addressable elements can be attributed to dielectric interlayer thickness variations as well as measurement error due to resistive losses along the PEDOT:PSS conductive traces.

The change in capacitance as a function of the stylus distance from the top substrate was also characterized. The measurement results are shown in Fig. 3b). The initial capacitance value of 2.981 pF, when the stylus is 20 cm from the surface of the top substrate, decreases to 2.851 pF when the point is in contact with the glass at the measured location. Above a separation distance of 6 cm, the capacitance is essentially constant at 2.98 pF. Below 6 cm, the capacitance is well-described by the fitting function $C = (0.351 – 0.009s^{0.31})^{-1}$, where s is the height of the stylus from the substrate surface [12]. From Fig. 3b), the nominal sensitivity ($\Delta C/C_0$) of the measured electrode can is found to be 4.4%. This level of capacitance change is slightly lower than that other similar demonstrations that implement mutual capacitive sensing which are found to induce a change of 10% or greater [12,17]. Future improvements to the sensitivity could be achieved through design considerations such as thinning the top substrate to enhance the interaction between the stylus and the fringing electric field, or adjusting the interlocking diamond design to minimize direct electrode overlap, yet maximize a fringing field between conductive traces. Both of those approaches do have their drawbacks however, including structural stability, alignment tolerance, and maintaining appropriate carrier conduction along the entire length of the electrode.

Fig. 4a) depicts the capacitance change ΔC measured at each electrode intersection due to a touch event at X = 3, Y = 3. The data has been normalized by the largest-measured capacitive change, $\Delta C_{\max}$. From these measurements a spatial capacitive map can be interpolated to allow for a precise localization of the touch event, as shown in Fig. 4 b). Neighboring elements, and in

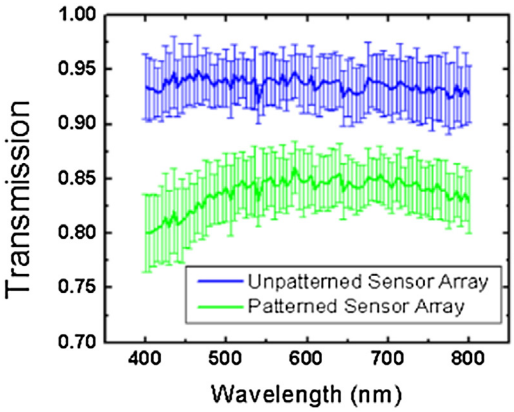

Fig. 5. Comparison of transmission between unpatterned multilayer films and the UV-patterned capacitive array across the visible spectrum.

particular those sharing a common contact with the expected touch, also exhibited significant capacitive change, resulting in the color map displayed. With appropriate signal processing and filtering through the use of backend controllers, it is expected that spatial errors could be efficiently detected and compensated for as this is a separate realm of ongoing research interest [1,17]. In comparison to current implementations using ITO in TSPs, the device produced has a finer electrode pitch of 2.5 mm in comparison to ~6.5 mm [18]. Due to this finer pitch, the crosstalk effects of a touch event on the capacitance change of are magnified, as interference with neighboring elements will undoubtedly occur. While this crosstalk may be of concern in terms for direct unambiguous resolution, this effect is in fact utilized to locate touch events that may not occur directly on one of the intersecting capacitive elements through the interpolation and application of back end controllers [19]. The finer grid structure does offer higher resolution without excessive back end computing, however at the cost of increased number of measurements and increased crosstalk between sensing elements. For future optimization, and implementation with commercial sensing circuitry, a balance of processing computations, cross talk, and the resolution requirements will need to be considered for specific applications.

4.3. *Transparency*

Transparency across the visible regime from 400 to 800 nm was measured through both a completed, patterned device and one having not undergone patterning. The transparency data shown has been normalized to transmission through the glass substrates and is shown in Fig. 5. The potential suitability for integration with an underlying information display is evident, since after fabrication the transmission is still greater than 80% across the visible spectrum.

5. Conclusion

Through utilization of a novel etch-free UV induced polymer scission pattering technique, spatial control of the conductivity of a PEDOT:PSS film is achieved to implement a transparent capacitive TSP. The processing technique enables the spatial patterning of film conductivity to define the sensor electrodes and their crossings. The 2D sensing array, which is designed with an interlocking diamond shape structure, operates on the basis of projected mutual capacitance. By using a parametric analyzer to measure the change in the level of capacitance between each of the individual row and column electrodes upon the introduction of a touch event, a spatial map of relative capacitance change could be generated, and the corresponding touch event could be located within the active sensing array. This approach allows for a single material and single processing step active layer patterning. Further performance improvements are expected through standard signal processing. The TSP is inherently compatible with the large scale fabrication of organic electronic devices through processing technologies such as roll-to-roll systems.

References

[1] G. Walker, A review of technologies for sensing contact location on the surface of a display, J. Soc. Inf. Display 20 (September) (2012) 413–440, http://dx.doi.org/10.1002/jsid.100.

[2] D. Angmo, F.C. Krebs, Flexible ITO-Free polymer solar cells, J. Appl. Polym. Sci. 129 (2013) 1–14, http://dx.doi.org/10.1002/app.38854.

[3] R. Paetzold, K. Heuser, D. Henseler, S. Roeger, G. Wittmann, A. Winnacker, Performance of flexible polymeric light-emitting diodes under bending conditions, Appl. Phys. Lett. 82 (2003) 3342–3344, http://dx.doi.org/10.1063/1.1574400.

[4] W. Cao, J. Li, H. Chen, J. Xue, Transparent electrodes for organic optoelectronic devices: a review, J. Photon. Energy 4 (2014) 040990, http://dx.doi.org/10.1117/1. JPE.4.040990.

[5] K. Ellmer, Past achievements and future challenges in the development of optically transparent electrodes, Nat. Photon. 6 (December) (2012) 809–817, http://dx.doi.org/10.1038/nphoton.2012.282.

[6] D.-J. Kim, H.-J. Kim, K.-W. Seo, K.-H. Kim, T.-W. Kim, H.-K. Kim, Indium-free, highly transparent, flexible $Cu_2O/Cu/Cu_2O$ mesh electrodes for flexible touch screen panels, Sci. Rep. 5 (November) (2015) 1–10, http://dx.doi.org/10.1038/srep16838.

[7] S. Hong, J. Yeo, G. Kim, D. Kim, H. Lee, J. Kwon, J. Lee, P. Lee, S.H. Ko, Nonvacuum, maskless fabrication of a flexible metal grid transparent conductor by low-temperature selective laser sintering of nanoparticle ink, ACS Nano 7 (June) (2013), 5024–4031.

[8] S.-J. Woo, J.-H. Ko, D.-G. Kim, J.-M. Kim, A tin all-elastomeric capcitive pressure sensor array based on micro-contact printed elastic conductors, J. Mater. Chem. C 2 (2014) 4415–4422, http://dx.doi.org/10.1021/nn400432z.

[9] Y. Kim, C.-H. Song, M.-G. Kwak, B.-K. Ju, J.-W. Kim, Flexible touch sensor with finely patterned Ag nanowires buried at the surface of a colorless polyimide film, RSC Adv. 5 (2015) 42500–42505, http://dx.doi.org/10.1039/C5RA01657F.

[10] S. Bae, H. Kim, Y. Lee, X. Xu, J.-S. Park, Y. Zheng, J. Balakrishnan, T. Lei, H.R. Kim, Y.I. Song, Y.-J. Kim, K.S. Kim, B. Özilmaz, J.-H. Ahn, B.H. Hong, S. Iijima, Roll-to-roll production of 30-inch graphene films for transparent electrodes, Nat. Nano 5 (August) (2010) 574–578, http://dx.doi.org/10.1038/nnano.2010.132.

[11] Y.H. Kim, C. Sachse, M.L. Machala, C. May, L. Müller-Meskamp, K. Leo, Highly conductive PEDOT:PSS electrode with optimized solvent and thermal post-treatment for ITO-free organic solar cells, Adv. Funct. Mater. 21 (2011) 1076–1081, http://dx.doi.org/10.1002/adfm.201002290.

[12] S. Ma, F. Ribeiro, K. Powell, J. Lutian, C. Møller, T. Large, J. Holbery, Fabrication of novel transparent touch sensing device via drop-on-demand inkjet printing technique, ACS Appl. Mater. Interfaces 7 (September) (2015) 21628–21633, http://dx.doi.org/10.1021/acsami.5b04717.

[13] S.-F. Tseng, W.-T. Hsiao, K.-C. Huang, D. Chiang, Electrode patterning on PEDOT:PSS thin films by pulsed ultraviolet laser for touch panel screens, Appl. Phys. A 112 (July) (2013) 41–47, http://dx.doi.org/10.1007/s00339-012-7172-3.

[14] S.-K. Lim, E.-M. Park, J.-S. Kim, S.-H. Na, H.-J. Park, Y.-S. Oh, S.-J. Suh, Fabrication of a touch sensor for flat panel displays using poly(3,4-ethylenedioxythiophene):poly(styrene sulfonate) with dimethylsulfoxide by soft lithography, Jpn. J. Appl. Phys. 51 (August) (2012) 096501, http://dx.doi.org/10.1143/JJA51.096501.

[15] S.A. Rutledge, A.S. Helmy, Etch-free patterning of poly(3, 4-ethylenedioxythiophene)-poly(styrenesulfonate) for optoelectronics, ACS Appl. Mater. Interfaces 7 (January) (2015) 3940–3948, http://dx.doi.org/10.1021/am507981d.

[16] T.-H. Hwang, W.-H. Cui, I.-S. Yang, O.-K. Kwon, A highly area-efficient controller for capacitive touch screen panel systems, IEEE Trans. Consum. Electron. 56 (May) (2010) 1115–1122, http://dx. doi. org/10. 1109/TCE. 2010. 5506047).

[17] S. Heo, H. Ma, J.J. Kim, F. Bien, Dynamic range enhanced readout circuit for a capacitive touch screen panel with current subtraction technique, Proc. 40th European Solid-State Circuit Conference (ESSCIRC 2014) (2014) 327–330, http://dx.doi.org/10.1109/ESSCIRC.2014.6942088.

[18] K. Lim, K.-S. Jung, C.-S. Jang, J.-S. Baek, I.-B. Kang, A fast and energy efficient single-chip touch controller for tablet touch applications, J. Display Technol. 9 (July) (2013) 520–526, http://dx.doi.org/10.1109/JDT.2013.2243900.

[19] I.-S. Yang, O.-K. Kwon, A touch controller using differential sensing method for on-cell capacitive touch screen panel systems, IEEE Trans. Consum. Electron. 57 (August) (2011) 1027–1032.

Biographies

Steven A. Rutledge is a Ph. D. Candidate in the Helmy lab at the University of Toronto in Electrical and Computer Engineering. He obtained a B. Sc. from the University of Alberta in 2007, and completed an M. A. Sc. from the University of Toronto in 2009. His research interests include polymer and colloidal nanoparticle optoelectronic materials, applied optical spectroscopy, and micro- and nano-fabrication techniques and processes.

Amr S. Helmy is a professor with the department of Electrical and Computer engineering of the University of Toronto. He received an M.Sc. (9/1995) and Ph.D. (11/1998) degrees from the University of Glasgow, Scotland, in the field of photonics. He was a European Union-sponsored research fellow on project to study difference frequency generation in III–V heterostructures using Quantum well intermixing in 1999. His research Interests include; Photonic device physics and characterization techniques, non-linear optics in III–V semiconductors, applied optical spectroscopy for III–V optoelectronic devices and materials, III–V fabrication and monolithic integration techniques.