Dr Shashi Paul

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Personal profile

I graduated from Indian Institute of Science, Bangalore, India and PhD from De Montfort University, Leicester and have previously worked in Cambridge University., Durham University, and Rutgers University. My research interests include manufacturing and analysis of nano-materials and their applications into energy (e.g. photovoltaic solar cells), electronics (emerging electronic memory devices) and biological sensors.

Research group affiliations

Emerging Technologies Research Centre (EMTERC)

Publications and outputs

- **Inkjet Printing of Functional Electronic Memory Cells: A Step Forward to Green Electronics**
  Inkjet Printing of Functional Electronic Memory Cells: A Step Forward to Green Electronics Salaoru, Iulia; Maswoud, Salah; Paul, Shashi Nowadays, the environmental issues surrounding the production of electronics, from the perspectives of both the materials used and the manufacturing process, are of major concern. The usage, storage, disposal protocol and volume of waste material continue to increase the environmental footprint of our increasingly “throw away society”. Almost ironically, society is increasingly involved in pollution prevention, resource consumption issues and post-consumer waste management. Clearly, a dichotomy between environmentally aware usage and consumerism exists. The current technology used to manufacture functional materials and electronic devices requires high temperatures for material deposition processes, which results in the generation of harmful chemicals and radiation. With such issues in mind, it is imperative to explore new electronic functional materials and new manufacturing pathways. Here, we explore the potential of additive layer manufacturing, inkjet printing technology which provides an innovative manufacturing pathway for functional materials (metal nanoparticles and polymers), and explore a fully printed two terminal electronic memory cell. In this work, inkjetable materials (silver (Ag) and poly(3,4-ethylenedioxythiophene)-poly(styrenesulfonate) (PEDOT:PSS)) were first printed by a piezoelectric Epson Stylus P50 inkjet printer as stand-alone layers, and secondly as part of a metal (Ag)/active layer (PEDOT:PSS)/metal (Ag) crossbar architecture. The quality of the individual multi-layers of the printed Ag and PEDOT:PSS was first evaluated via optical microscopy and scanning electron microscopy (SEM). Furthermore, an electrical characterisation of the printed memory elements was performed using an HP4140B picoammeter. open access journal
- **Silicon Rising**
  Silicon Rising Paul, Shashi Silicon, as an electronic material, has played an enormous role in promoting the modern technical evolution in almost all fields. And, needless to say, it will continue its leadership until a better material is found. We are currently going through an exploration period to search out alternative materials. A number of different materials are have been proposed as challengers, but silicon (Si) is still the front runner, as far as complementary metaloxide- semiconductor (CMOS) technologies is concerned. Silicon is widely used in electronic industries in a number of forms, such as the amorphous silicon used in thin-film transistors (TFTs) in liquid-crystal display units, poly-silicon can be found in flash memory structures and photovoltaic solar cells, and single crystals are predominately used in CMOS technologies. Among the various forms of silicon embodiments, silicon nano-structures – for example, silicon nanowires – are also currently being explored, and for the last a few decades, there has been intense interest in how toprepare nanometre scale silicon.
- **Electrical Performance and Stability of ZnO Thin-Film Transistors Incorporating Gadolinium Oxide High-k Dielectrics**
  Electrical Performance and Stability of ZnO Thin-Film Transistors Incorporating Gadolinium Oxide High-k Dielectrics Ngwashi, Divine K.; Paul, Shashi; Devi, Anjana; Cross, R. B. M. This work investigates the performance and gate bias stress instability of ZnO-based thin film transistors (ZnO-TFTs) incorporating amorphous gadolinium oxide, a high-k dielectric material. ZnO thin films produced via radio frequency (RF) reactive magnetron sputtering were used as channel layers. The source/drain electrodes were achieved by the thermal evaporation of aluminium on a bottom gate inverted staggered ZnO TFT structure. Gadolinium oxide (Gd2O3) deposited by metal-organic chemical vapour deposition (MOCVD) served as the gate dielectric. The electrical characterisation of the ZnO-TFTs produced showed improvement in performance and stability in comparison to thermally-grown SiO2-based ZnO TFTs fabricated under the same conditions. The effective channel mobility, on-off current ratio and subthreshold swing of the TFTs incorporating Gd2O3 dielectric were found to be 33.5 cm2 V-1s-1, 107, and 2.4 V/dec respectively when produced. The electrical characterisation of the same devices produced with SiO2 dielectrics exhibited effective mobility, on-off current ratio and subthreshold swing of 7.0 cm2 V-1s-1, 106 and 1.4 V/dec respectively. It is worth noting that, the ZnO active layer was sputtered under room temperature with no intentional heating and post-deposition annealing treatment. On application of gate bias stressing on these thin film transistors, it was observed that threshold voltage instability increased with stress period in all device types. Transistors incorporating Gd2O3 however, were found to exhibit lesser threshold voltage related instability with regards to gate bias stressing in comparison to similar devices incorporating SiO2 as gate dielectric. It was also observed that the effective mobility in both devices tend to stabilize with prolonged gate bias application. In this work, it is demonstrated that Gd2O3 dielectric is a potential alternative to

SiO2 for the fabrication of ZnO TFTs with improved performance and electrical stability under prolonged use. open access article

- **Stability of Hydrogenated Amorphous Carbon thin films for application in Electronic Devices**
  Stability of Hydrogenated Amorphous Carbon thin films for application in Electronic Devices Alotaibi, Sattam; Manjunathan, Krishna Nama; Paul, Shashi In this study, hydrogenated amorphous carbon (a-C:H) films are investigated for electronic applications as an insulating layer. a-C:H films were deposited using radio frequency-Plasma enhanced chemical vapour deposition (RF-PECVD) technique at room temperature. For the first time, the properties of a-C:H films as a function of annealing temperature is investigated, with a focus on their electrical and optical properties. This study shows that a-C:H films are stable up to 450°C. This investigation will facilitate the use of a-C:H films as an insulating layer where the semiconductor active layers are deposited at higher temperatures (e.g. amorphous silicon deposited around 300°C for thin film transistor TFTs). In addition to understanding the electrical and optical properties of annealed a-C:H films, we have further explored and studied its suitability in Flash-type memory devices. Various forms of diamond-like carbon are considered to have a high chemical resistance; no extensive data are available in the literature on this subject. The stability of a-C: H thin films with various reactive chemicals, commonly used in organic/printable electronic devices, is also investigated in this work. The findings may provide opportunities for adoption/integration of a-C:H in hybrid organic-inorganic electronic devices. The file attached to this record is the author's final peer reviewed version. The Publisher's final version can be found by following the DOI link.
- **A multi-faceted approach to determining the efficacy of metal and metal oxide nanoparticles against bacterial biofilms**
  A multi-faceted approach to determining the efficacy of metal and metal oxide nanoparticles against bacterial biofilms Tejpal, Jyoti; Cross, R. B. M.; Owen, Lucy; Paul, Shashi; Jenkins, R. O.; Armitage, David; Laird, Katie Antibacterial efficacy of nanoscale silver, copper (II) oxide and zinc oxide were assessed against Pseudomonas aeruginosa and Staphylococcus aureus biofilms in solution and on surfaces. Using a Center for Disease Control biofilm reactor, minimum biofilm reduction concentrations, the coefficient of determination (R2) and log(10) reductions were determined. Atomic absorption spectroscopy, scanning electron microscopy and confocal laser scanning microscopy were used to assess the disruption of the biofilms. The efficacy of thin films of zinc oxide and silver deposited via magnetron sputtering and thermal evaporation respectively was also assessed. Minimum biofilm reduction concentrations of zinc oxide or silver nanoparticles were 256 or 50 µg/ml for P. aeruginosa and 16 or50 µg/ml for S. aureus respectively. When tested in combination the nanoparticles concentrations were at least halved resulting in significant ($p \leq 0.05$) biofilm reductions of 3.77 log(10) - 3.91 log(10). Biofilm growth on thin films resulted in reductions of up to 1.82 log(10). The results suggest that nanoparticle suspensions and thin films of zinc oxide and may have potential as antimicrobial treatments for hard to eliminate biofilms in a clinical environment.
- **Inkjet printing of functional materials: a step forward to green electronics**
  Inkjet printing of functional materials: a step forward to green electronics Salaoru, Iulia; Paul, Shashi; Maswoud , S. Nowadays the environmental impact of both used materials and manufacturing process of thin films is a major issue. The usage, storage, disposal protocol and the volume of waste material are also an environmental concern using conventional manufacturing pathway. The current technology to fabricate thin films requires heat generation in a deposition process and hence generation of harmful chemicals/radiation. Additionally, there are environmental limitations, for example, high vacuum equipment requires enormous amounts of electricity, thus creating a larger carbon footprint. Inkjet printing technology is a reliable alternative to traditional manufacturing protocol and most importantly, it is a solution to minimise the deleterious effects on the environment and human health. Here, we explore the potential of Additive Layer Manufacturing – inkjet printing technology to provide an innovative manufacturing pathway for functional materials, both conductive and insulating patterns, on flexible bendable substrates. In this work, ink-jettable materials were printed by a piezoelectric Epson Stylus P50 inkjet printing machine on a flexible substrate. The morphology, surface profile and the thickness uniformity of printed multi-layers were evaluated via Nikon LABOPHOT-2 optical microscope, fitted with Nikon Camera DS-Fi1. Furthermore, the conductivity and its dependency on the number of layers is investigated in this study. Even more, adhesion profile of the ink to the substrate and mechanical flexibility is also studied.
- **Binder-free Sn–Si heterostructure films for high capacity Li-ion batteries**
  Binder-free Sn–Si heterostructure films for high capacity Li-ion batteries Loveridge M.J; Malik, R; Paul, Shashi;

Manjunathan, Krishna Nama; Gallanti, S; Tan, C; Lain, M; Roberts, A.J; Bhagat, R This study fabricated and demonstrated a functional, stable electrode structure for a high capacity Li-ion battery (LIB) anode. Effective performance is assessed in terms of reversible lithiation for a significant number of charge–discharge cycles to 80% of initial capacity. The materials selected for this study are silicon and tin and are co-deposited using an advanced manufacturing technique (plasma-enhanced chemical vapour deposition), shown to be a scalable process that can facilitate film growth on 3D substrates. Uniform and hybrid crystalline–amorphous Si nanowire (SiNW) growth is achieved via a vapour–liquid–solid mechanism using a Sn metal catalyst. SiNWs of less than 300 nm diameter are known to be less susceptible to fracture and when grown this way have direct electrical conductivity to the current collector, with sufficient room for expansion. Electrochemical characterisation shows stable cycling at capacities of 1400 mA h g 1 (>4 the capacity limit of graphite). This hybrid system demonstrates promising electrochemical performance, can be grown at large scale and has also been successfully grown on flexible carbon paper current collectors. These findings will have impact on the development of flexible batteries and wearable energy storage. Open access article

- **3-D Printing of Flexible Two Terminal Electronic Memory Devices**
  3-D Printing of Flexible Two Terminal Electronic Memory Devices Salaoru, Iulia; Paul, Shashi; Maswoud , S. Recent strategy in the electronics sector is to ascertain the ways to make cheap, flexible and environmentally friendly electronic devices. The 3D inkjet printing technology is based on the Additive Manufacturing concept and it is with no doubt capable of revolutionising the whole system of manufacturing electronic devices including: material selection; design and fabrication steps and device configuration and architecture. Thus, 3D inkjet printing technology (IJP) is not only one of the most promising technologies to reduce the harmful radiation/ heat generation but also achieve reductions in manufacturing cost. Here, we explore the potential of 3D – inkjet printing technology to provide an innovative approach for electronic devices in especially information storage elements by seeking to manufacture and characterise state-of-art fully inkjet printed two terminal electronic memory devices. In this work, ink-jettable materials (Ag and PEDOT:PSS) were printed by a piezoelectric Epson Stylus P50 inkjet printing machine on a flexible substrate. All components of the memory cells of a simple metal/active layer/metal structure were deposited via inkjet printing. The quality of the printed layers was first assessed by Nikon LABOPHOT-2 optical microscope, fitted with Nikon Camera DS-Fi1. Furthermore, an in-depth electrical characterisation of the fabricated memory cells was carried out using HP4140B picoammeter.
- **Birth of silicon nanowires covered with protective insulating blanket**
  Birth of silicon nanowires covered with protective insulating blanket Paul, Shashi; Manjunathan, Krishna Nama Core–shell silicon–silicon oxide nanowires are synthesized at low temperatures using inorganic and organic compounds of a tin as a catalyst. In situ simultaneous one-dimensional growth of pristine silicon nanowires (SiNWs) using alloy catalyst is reported here. Such a development process generates a high-quality SiNW that is not determined by other atomic species in the plasma. A possible growth model is discussed to understand the synchronized precipitation of a SiNW core and an oxide shell. Nanowires grown here eliminate the additional fabrication steps to deposit anticipated oxide shell that is achieved by precipitation from the same catalyst that precipitates core nanowires. The file attached to this record is the author's final peer reviewed version. The Publisher's final version can be found by following the DOI link.
- **Stability study: Transparent conducting oxides in chemically reactive plasmas**
  Stability study: Transparent conducting oxides in chemically reactive plasmas Manjunathan, Krishna Nama; Paul, Shashi Effect of plasma treatment on transparent conductive oxides (TCOs) including indium-doped tin oxide (ITO), fluorine-doped tin oxide (FTO) and aluminium-doped zinc oxide (AZO) are discussed. Stability of electrical and optical properties of TCOs, when exposed to plasma species generated from gases such as hydrogen and silane, are studied extensively. ITO and FTO thin films are unstable and reduce to their counterparts such as Indium and Tin when subjected to plasma. On the other hand, AZO is not only stable but also shows superior electrical and optical properties. The stability of AZO makes it suitable for electronic applications, such as solar cells and transistors that are fabricated under plasma environment. TCOs exposed to plasma with different fabrication parameters are used in the fabrication of silicon nanowire solar cells. The performance of solar cells, which is mired by the plasma, fabricated on ITO and FTO is discussed with respect to plasma exposure parameters while showing the advantages of using chemically stable AZO as an ideal TCO for solar cells. Additionally, in-situ diagnostic tool (optical emission

spectroscopy) is used to monitor the deposition process and damage caused to TCOs. The file attached to this record is the author's final peer reviewed version. The Publisher's final version can be found by following the DOI link.

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Key research outputs

Memory effect in thin films of insulating polymer and C60 nanocomposites, Paul, S., Chhowalla, M. and Kanwal, A., Nanotechnology (2006), 17(1), pp. 145-151.

Langmuir-Blodgett film deposition of metallic nanoparticles and their application to electronic memory structures, Paul, S et al, Nano letters (2003), 3, 191-195.

Realisation of Non-volatile Memory Devices using Small Organic Molecules and Polymer", S. Paul, IEEE Transaction on Nanotechnology, 2007, 6 , 191-195.

Ferroelectric nanoparticles in polyvinyl acetate (PVAc) matrix-A method to enhance the dielectric constant of polymers. D Black, I Salaoru, S Paul, Nanoscience and Nanotechnology Letters (2010), Volume 2, Issue 1, March 2010, Pages 41-45.

Prime, D. and Paul, S. (2010) First contact-charging of gold nanoparticles by electrostatic force, Applied Physics Letters, 96 (4) 043120.

Research interests/expertise

Cheap and Flexible Electronics

Emerging Memory Devices (e.g. Molecular, Organic and low temperature Si memory devices)

Spin Valves

Growth Nano-structures (e.g nanoparticles, nanowires, nanotubes) and their applications in emerging areas of electronics (e.g healthcare and THz generation)

Self Assembly

Instrumentation Development for growth of nano-materials and understanding their physical properties

Green Growth Processes for Electronics Materials

Photovoltaic

Biological Sensors

Areas of teaching

Physics of Semiconductor Devices (ENGT5128)

Research Methods (ENGT5244)

Biosensors (ENGT5257)

Nanomaterials and Nanoelectronics (ENG5242)

Research Method (REST7013)

Research Method (EMTERC)

Qualifications

MSc, PhD

Courses taught

MSc in Micro Electronics and Nano Technology

MSc in Electronics Engineering

Membership of external committees

The 4th International Conference “Smart Materials, Structures and Systems”- a part of CIMTEC2012 conference organising programme committee

Dr S Paul is member of international programme committee for the forthcoming Conference on Renewable Energies and Power Quality (ICREPQ) by the European Association for the Development of Renewable Energies, Environment and Power Quality (EA4EPQ)", (**http://www.icrepq.com/**), 28-30 March, 2012, Santiago de Compostela, Spain.

The 3rd International Conference “Smart Materials, Structures and Systems” held in Acireale Catania District), Sicily, Italy, on June 8 to 13, 2008. Organised a special session on “Recent Development in Electrical Writable Organic Memory Devices”.

The 4th International Conference “Smart Materials, Structures and Systems” will be held in Acireale Catania District), Sicily, Italy, on June 8 to 13, 2008. Dr S Paul is organising a special session on “Emerging Non-volatile Memory Devices”.

Visiting Professor in the Physics department of Alexandru Ioan Cuza University of Iasi, Romania. From 24/12/2011 to 24/12/2013.

Membership of professional associations and societies

Association Name, period start, period end, description

Member IEEE (January, 2012 to December 2012)

Member Materials Research Society

Forthcoming events

Organising a special symposium on Emerging Memory Devices in CIMTEC2012

Conference attendance

Attended a number of international conferences (e.g.: IEEE, MRS, CIMTEC)

Current research students

First supervisor for:

Nare Gabrielyan
Sultan Alotaibi
Faleh Alotaiby
Keith McGrath
Khalid Mahood
Konstantina Saranti

Second supervisor for:

Jyoti Tejpal

Externally funded research grants information

EPSRC funding (#EP/E047785/1) on “Nano-Scale Re-Writable Non-Volatile Polymer Memory Arrays” (from 08/07/2007 to 08/11/2009) – PI (£207k).

EPSRC funded CASE studentship for new academics (~£57k) from October, 2005 to March, 2009.

National Physical Lab funding for understandin “Electrical Charging Mechanism in C60”, (from October-2005 –July-2011 – PI (~£20k).

Low-temperature Si Nonvolatile memory- PI, European Integrated Activity of Excellence and Networking for Nano and Micro- Electronics Analysis (ANNA) (FP6), http://www.anna-i3.org, NCSR 'Demokritos' – IMEL funded (5500 Euros) directly to use their facilities (December, 2010).

Internally funded research project information

RIF project: A Cleaner, Greener, Low Carbon Fabrication Process for Photovoltaic (PV) Solar Cells (PI). Start date: 01/04/10; End date: 01/07/10.

DMU PhD Bursary on Plastic compatiable Electronic Memory Devices, October-2011 to September 2014.

Professional esteem indicators

Guest editor of the issue of the Philosophical Transaction of the Royal Society A, on the theme of “Making Nano-Bits Remember: A Recent Development in Organic Electronic Memory Devices”. Volume 367, Issue 1905, 28 October 2009.

Reviewer for a number of journals in the field of electronic materials and devices.

Visiting Professor, Faculty of Physics, Alexandru Ioan Cuza University of Iasi, Romania.

Case studies

Nano-bits Enabled Application in storing electronic information and creating electrical energy:

Ribbon award – MRS Fall Meeting 2004, Boston, USA

News in Science -2004:
http://www.sciencenews.org/view/generic/id/5717/title/Buckyballs_store_1s_and_0s_in_new_memory_device

Gold nanoparticles for memory storage: **http://www.theengineer.co.uk/news/gold-nanoparticles-for-memory-storage/1001480.article**

Organic electronic memory chip to be demonstrated in the UK

Huge breakthrough in tiny technology by DMU: **http://www.findaphd.com/custadverts/dmu/2010.asp**

De Montfort University Shows the Benefits of Gold Nanoparticles for Organic Electronics:
http://nanopatentsandinnovations.blogspot.com/2010/03/de-montfort-university-shows-benefits.html

De Montfort University Shows the Benefits of Gold Nanoparticles for Organic Electronics:
http://nanopatentsandinnovations.blogspot.com/2010/03/de-montfort-university-shows-benefits.html

Flexible memory has wide ranging application
