Impact Objectives

- Embed electronic circuits into glass windows for use in visual display, monitoring and control purposes
- Replace indium with alternative dopants within zinc oxide to enable greener large-area circuit technology at reduced cost and so increase the availability of products
- Open up a new generation of glass window products in buildings, cars and aeroplanes – especially for 'heads-up' displays

Clear as glass

Professors ***Steve Hall*** *and* ***Paul R Chalker*** *discuss their latest work using novel materials to create transparent electronics devices, and share what they believe the future holds for their materials engineering research*

What is the central aim of this work?

PRC: A zinc oxide (ZnO) atomic layer deposition (ALD) technology was developed within a previous project funded by the UK government Technology Strategy Board for energy-saving optical coatings on float glass. The films proved to have good electrical properties, which provided the motivation for the current project. The smart-glass project is fundamental in nature with an aim to develop new manufacturing processes for subsequent application in 'electronics on glass' applications such as windows, screens and displays.

SH: The work has a strong materials focus but is carried out in a framework of simple electronic devices which are used for test purposes. The assessment of the materials properties using devices places the results in a realistic engineering context and provides metrics for comparison with the state of the art.

Can you briefly describe the activities that you have been undertaking through this research?

SH: We have been focusing on the incorporation of additive materials (or 'dopants') to the ZnO films. The industry currently uses indium (In) to enhance the mobility – the ease with which charge carriers move through the films – and gallium (Ga) to help stabilise the electronic properties to allow the production of good quality devices. We have looked at the high-valence elements tantalum, magnesium and niobium so far with promising results. We have made basic transistors and metal-semiconductor (Schottky) diodes of good quality. These devices form the basic building blocks for the production of electronic circuits for the given applications.

Have you faced any obstacles during this work? How have you dealt with these?

SH: The ZnO material on its own contains a very high concentration of free electrons available to carry electric current and this is manifested as a very high conductivity. This large electron concentration arises from the high level of defects in the material. The problem is that it is not possible to turn off a transistor made in such material; a requirement to make digital logic circuits. A related issue is the so-called mobility – the ease with which the electrons can move through the material to supply the current. Thus we need to maximise the mobility and reduce, in a controlled way, the electron concentration to make good transistors which can operate at low voltage for low power operation.

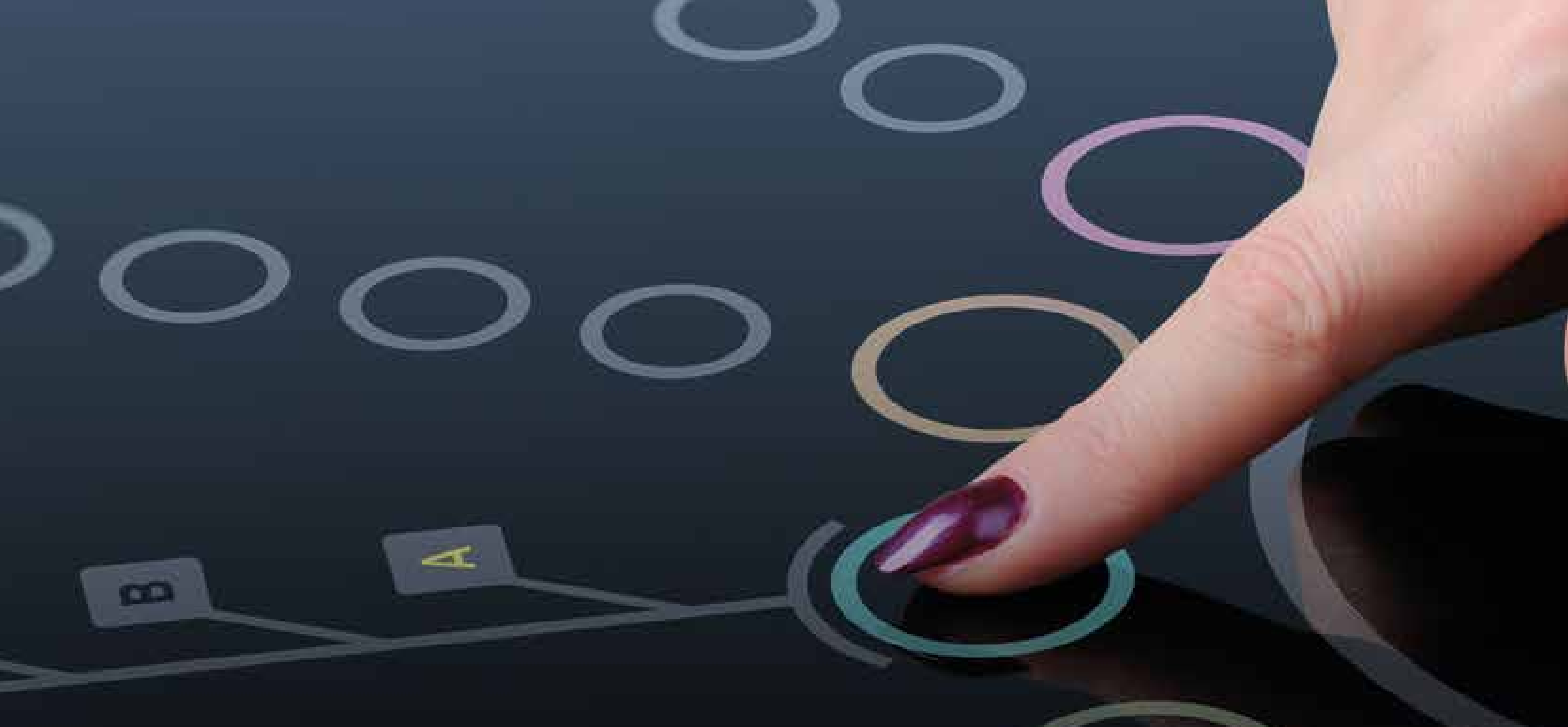
PRC: The addition of dopant atoms to the pure ZnO is to try to control the defects and hence reduce the number of free electrons. Our strategy is based on a good knowledge of materials chemistry and physics to choose suitable dopants combined with the ability to design and realise the device structures to test the ideas. There are also a number of tricks at the film deposition step to control the surface of the material to make good contacts and high quality metal-semiconductor (Schottky) diodes.

Can you talk about some of the results achieved so far that you are particularly pleased with?

SH: We have successfully incorporated magnesium and niobium into ZnO and thoroughly characterised the materials properties using a suite of physical and electrical measurements. Fabricated transistor structures show good on-to-off current ratios for the digital circuit application. We have also successfully engineered the surface of the ZnO films to realise Schottky diodes. These achievements provide us with the building blocks for realisation of transparent circuits on glass.

What kind of future research opportunities do you think will follow now you have completed this work?

SH: We have a further project at the planning stage. This will be collaborative with another university undertaking similar work. We have more materials engineering ideas to explore and also want to integrate a range of devices to produce some demonstrator circuits with higher functionality, particularly for wireless applications in the internet of things.



Intelligent windows

*Research at the **University of Liverpool** is breaking new ground in building 'intelligence' into glass to support commercial applications and mass production, ultimately supporting reduced energy consumption and greenhouse gas emissions across a number of industries*

The market for introducing electronics capability into glass coatings is potentially huge; however the ability to access this is currently limited by the dependence on expensive and toxic elements used in the thin film circuits. A team at the University of Liverpool is addressing this issue by developing novel processes and materials capable of embedding circuits into glass windows for visual display, monitoring and control purposes. They have come a long way in their efforts and have reached a stage where their technology can now be incorporated into practical applications.

TECHNOLOGICAL ADVANCES

Professor Steve Hall, who is leading this research, observes that this new technology is important because it will enable relatively low start-up cost technologies for the mass production of sensors and displays for a number of industries, including aerospace, architectural glazing and automotive that can benefit from so-called transparent electronics. The team are proposing to embed electronics into glass coatings which should make it possible for the circuits to be self-powered by harvesting energy from the sunlight.

The team have chosen to use the metal-semiconductor field-effect transistor (MESFET) device for this research because it allows lower voltage operation and employs circuit design methodologies developed for gallium arsenide-based technology which can be employed in zinc oxide design. 'Silicon technology is based on so-called CMOS (complementary metal-oxide semiconductor); this is the technology employed in PCs, laptops, phones, games consoles and so on. CMOS requires p-type transistors and these can be done in zinc oxide technology but perform poorly compared to the n-type device where electrons are responsible for the current flow,' explains Hall. Because the slowest device dictates the speed of the circuit in electronics, the team have chosen to use the faster n-type transistors. This has enabled them to develop a technology for so-called large-area electronics where the ability to pack transistors into ever smaller areas is not critical. As a result this project is establishing a MESFET fabrication process, as well as realising basic circuit blocks and gate arrays.

REDUCING COST AND ENVIRONMENTAL IMPACTS

Hall describes that the work of the team is mainly on the materials science level at this stage, which 'concerns the possibility of replacing the expensive, toxic and low-abundant elements indium and gallium with alternative dopant materials for controlling the stability and electronic properties of zinc oxide based technology'. He points out that replacing indium as a dopant in zinc oxide is so beneficial because, in addition to having an environmental impact from its toxicity, indium is expensive, non-abundant and the price is volatile because it is subject to political influence.

Professor Paul R Chalker, who is based within the University's Centre for Materials Science and Engineering, says that the potential value of this new technology to Europe's green building industry is significant: 'The advantages of green buildings have been recognised by national governments and the EU have a mandate for higher efficiency standards for new construction and renovations.' It is hoped that a number of environmental benefits will be realised through this research, including reducing energy consumption and minimising greenhouse gas emissions. Chalker notes that one of the main advantages of the new technology is the heating control offered by the 'intelligent window'. In addition, the identification of less toxic materials is important to achieving such goals.

> *The technology offers lower cost and greener routes to stable and competitive electronic materials compared with those in current use*

INDUSTRIAL RELATIONS

The team fully realise the importance of sharing the knowledge they have gained through this work. So far they have produced a number of conference papers which they consider as the best way to disseminate early results. A publication has appeared in a highly regarded academic journal with several more already submitted; other papers are emerging as the work develops. Hall hopes that this will help inform the ultimate end users of this new technology of their progress, such as the glass and display industries as well as mainstream electronics manufacturers who are supplying Europe's automotive, aeronautical and building sectors. 'The technology offers lower cost and greener routes to stable and competitive electronic materials compared with those in current use,' concludes Hall. It is hoped that this work will also open up opportunities for a new generation of glass window products by technological innovators.

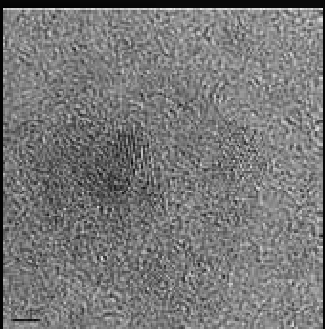


Fig.1: Micrograph showing atomic scale crystalline domains in semiconducting ZnO grown by ALD.

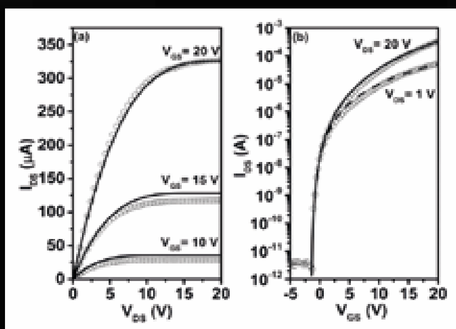


Fig.2: Electrical characteristics of a typical Nb-doped ZnO thin film transistor. The solid line shows a theoretical fit to the data.

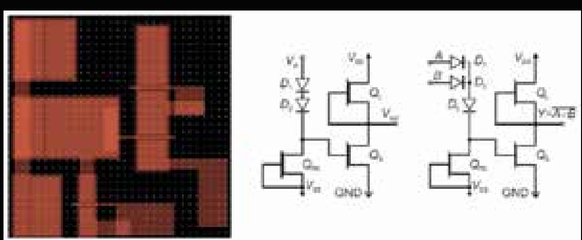


Fig.3: Layout and schematic diagrams of ZnO depletion-model MESFET logic circuits: an inverter and a two-input NOR gate.

Project Insights

FUNDING
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PROJECT LEADER BIO
Professor Steve Hall has a background in semiconductor materials, devices and circuits. He has worked on silicon devices for many years, including the novel materials aspects for engineering lower power, faster devices. He has also designed circuits in novel silicon-based technologies for low power and neuromorphic applications. Hall has studied technological oxides for many years for use in silicon devices and has served on the steering and technical programme committees of major European conferences.

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