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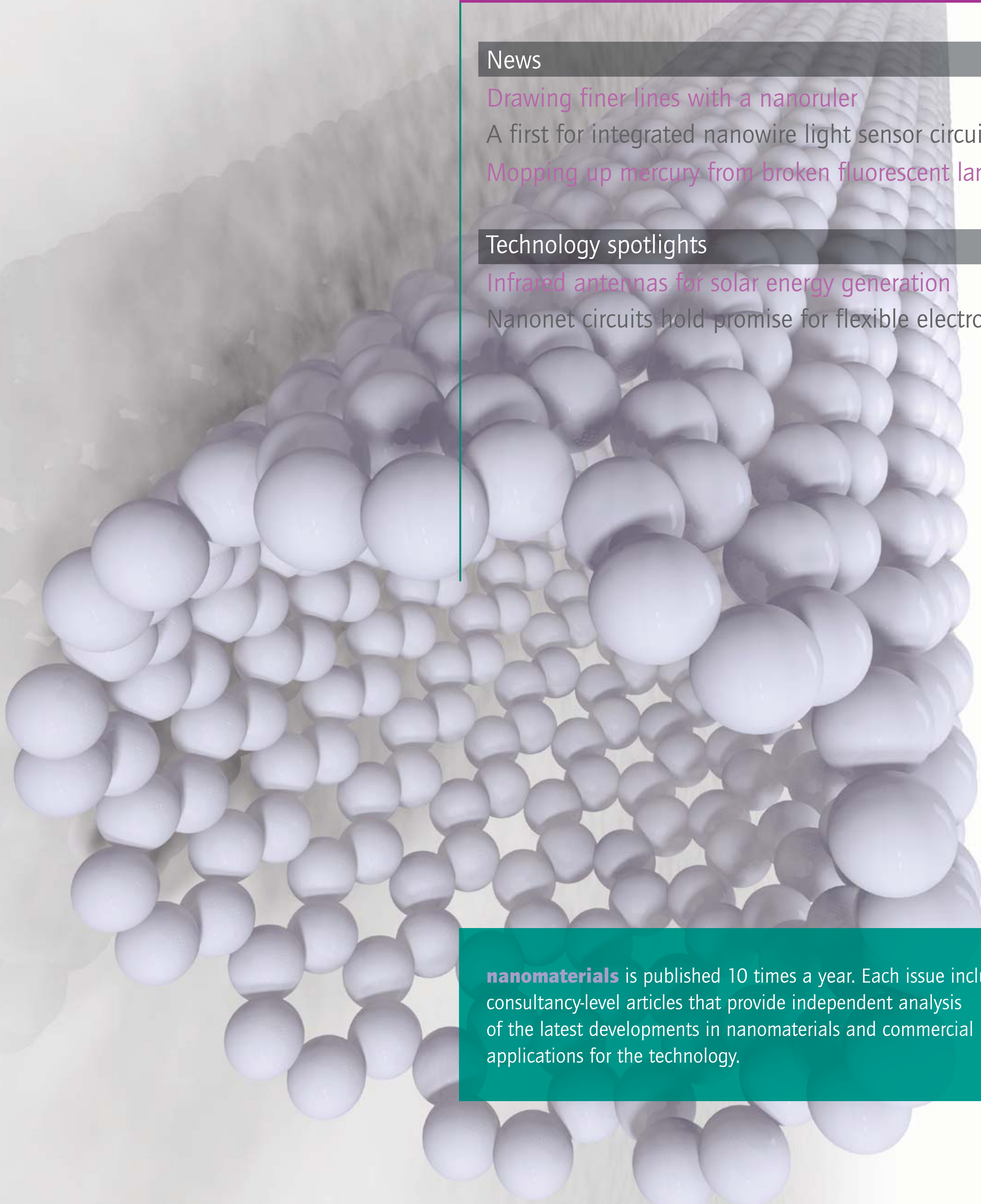

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nanomaterials is published 10 times a year. Each issue includes consultancy-level articles that provide independent analysis of the latest developments in nanomaterials and commercial applications for the technology.

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>
> John Rogers, chemist, Universtiy of Illinois

Technology spotlight

Nanonet circuits hold promise for flexible electronics

Creating integrated circuits on flexible sheets of plastic will lead to electronic devices that are difficult or impossible to realise using traditional semiconductor wafers or rigid glass substrates. Organic small molecules and polymer-based materials are currently the most widely-used semiconductor materials in plastic electronics, but these materials have relatively modest performance characteristics. The performance of these materials may be sufficient for electrophoretic displays, for example, but it severely restricts their wider application potential.

Other materials are under investigation, including stretchable silicon substrates. But given that the characteristics of semiconducting carbon nanotubes would make them an ideal material for high-performance applications, it makes sense to look seriously at the possibility of using nanotubes in flexible electronics. Especially in larger-scale applications for which they may be well-suited.

Researchers at Purdue University and the University of Illinois at Urbana-Champaign recently reported that they have overcome a major obstacle to producing transistors from networks of carbon nanotubes. This could make it possible to print large-scale circuits on plastic sheets, for applications ranging from flexible displays to sensing skins on aircraft that monitor the formation of potentially catastrophic cracks. ‘The findings represent the culmination of four years of collaborative efforts between the Illinois and Purdue groups,’ says Illinois chemist John Rogers.

The so-called ‘nanonet’ technology developed by a team led by Rogers and Purdue electrical engineer Ashraf Alam consists of circuits made from networks of carbon nanotubes randomly overlapping in a fishnet-like structure. But the problem with such networks is that industrial-scale production methods tend to yield a mixture of semiconducting and metallic nanotubes, with up to a third being metallic.

Engineers would prefer to go for a high density of nanotubes in their circuits in order to achieve high ‘on’ currents and fast switching times. But with the presence of relatively large numbers of metallic nanotubes in the mix, conducting pathways can form between the source and drain electrodes of transistors. These make it impossible to turn the transistors off, thereby rendering them useless.

The ideal solution to this problem would be to use only purely semiconducting nanotubes from the start. In the real world, however, with currently available nanotube synthesis methods, this simply isn’t possible. A more practical remedy might be to remove the metallic nanotubes by burning them off or washing them away in a chemical process. But this is messy, and it adds complexity and cost to circuit fabrication.

Alam, Rogers and their colleagues have opted instead for a more creative approach. Using theory and computer simulation, the researchers found that the short-circuits can be eliminated by dividing

Developers of the ‘nanonet’ technology

Ashraf Alam

Muhammad Ashraf Alam is a professor of electrical engineering at Purdue University in West Lafayette, Indiana, US.

Alam’s research interests are in the theory, simulation, characterisation, and compact modelling of semiconductor electronic, optoelectronic, and bio-electronic devices. He is currently working on four research topics relevant to the continued evolution of the semiconductor industry over the next 20–30 years:

- Reliability physics of MOSFETs for microelectronic applications;
- Novel DRAMs cells as memory elements beyond the International Technology Roadmap for Semiconductors (ITRS);
- Performance limits of nanocomposite thin films for macroelectronic applications;
- Functionalised sensor arrays for biomedical and electrochemical applications.

John Rogers

John Rogers is a professor of chemistry, and Founder Professor of Materials Science and Engineering at the University of Illinois at Urbana-Champaign, US. Rogers leads a research group specialising in high-performance materials for flexible electronics. Current work focuses on soft materials for flexible macroelectronic circuits, photonic structures, microfluidic devices and micro-electromechanical systems. Recent highlights include:

- Stretchable silicon for flexible electronics;
- High-frequency transistors on plastic substrates;
- Molecular-scale lithography;
- Plasmonic crystals for bio-sensing and imaging.

Single-crystal silicon and organic semiconductor technologies developed by the Rogers Research Group for photovoltaic and display backplane applications are being commercialised through Semprius, Inc.

> ‘The researchers who created these circuits say that they have overcome a major obstacle in producing transistors from networks of carbon nanotubes.’

Technology spotlight

Photographs of flexible circuits based on carbon nanotubes. The researchers who created these circuits say that they have overcome a major obstacle in producing transistors from networks of carbon nanotubes. The technology could make it possible to print circuits on plastic sheets for applications such as flexible displays and a sensing skin for aircraft that monitors crack formation

Source: University of Illinois at Urbana-Champaign

nanonets into strips just a few microns wide. Each nanonet transistor consists of numerous strips of nanotubes separated by fine lines created using optical soft lithography and reactive-ion etching. Both are well-established semiconductor industry processes.

‘Striping is the key enabling step,’ says Alam. ‘The idea of striping – which is grounded in the theory of heterogeneous asymmetric percolation – breaks the metallic paths that cause the shorts, and restores the on/off capability of transistors. Semiconducting nanotubes are also striped, but given their higher density they have many more percolating paths remaining to connect the source and drain. The idea of striping is to remove the effects of metallic nanotubes on transistor performance without physically removing the nanotubes.’

With their technique the researchers produced a flexible circuit containing more than a 100 transistors. This, they say is the largest nanonet produced to date, and the first demonstration of a working nanonet circuit.

In the nanonet circuit, a 50µm thick sheet of polyimide serves as the substrate, and random networks of single-walled carbon nanotubes grown by chemical vapour deposition are transfer printed onto the substrate, forming a semiconductor layer. Source and drain electrodes made of gold serve as low-resistance contacts to the networks.

Each 100µm-long transistor in the circuit is divided into several strips, each 5–10µm wide. The separation between the source and drain electrodes of each transistor is around 100µm, and the network contains tens of nanotubes per square micron. The network strips are oriented along the overall direction of transport, and their widths are calculated to reduce the formation of conducting paths to below a practical level without significantly lowering the effective thin-film mobility of the network.

'Now, there is no fundamental reason why we couldn't develop nanonet technologies,' says Alam. 'If you can make a flexible circuit with 100 transistors, you can make circuits with 10,000 or more transistors.'

As for device performance, the transistors created by the Purdue and Illinois scientists have high mobilities (up to $80cm^2V^{-1}s^{-1}$), low sub-threshold slopes, operating voltages of less than 5V, on/off ratios as high as 10^5, switching speeds in the kilohertz range even for the coarsest device geometries, and good mechanical flexibility. The results of the researchers' experimental investigations and theoretical calculations suggest that sub-monolayer films of single-walled nanotubes could be attractive materials for flexible integrated circuits in diverse application areas.

'The process of etching the networks into stripes aligned between the transistor source and drain dramatically reduces the probability of all-metallic pathways without significantly reducing the overall performance of the device,' says Rogers. 'This approach is important for obtaining in a reliable way the sort of performance needed to support circuit implementation.'

One major advantage of carbon nanotube-based circuits is that they can be produced at low temperatures. A number of research groups around the world are currently working on low-temperature deposition of metal-oxide films and structures onto plastic substrates, but the bonding of conductors to semiconductor substrates tends to be done at temperatures high enough to melt plastic.

Many of the applications being spoken of for flexible electronics will require large-scale and low-cost fabrication methods. For displays integrated into car windscreens, electronic paper and solar cells, for example, the aim is to rapidly stamp the circuits onto plastic sheets, much like in the printing of newspapers and magazines. 'The next challenge is to determine whether devices with performance in this range can be achieved in a roll-to-roll printing process,' says Rogers. 'We believe that interest in solution-deposited networks of nanotubes as transparent conductors will help to develop the necessary techniques.'

'Scaling up the system is the obvious next step, but it is perhaps best done in industry,' says Alam. 'We are now establishing a precision connection of the technique to percolation theory that may allow a more efficient striping method. It would be wonderful if we can find a way to reduce the metallic-tubes to begin with, so that striping becomes even more effective than it is now.'

'This new achievement is a major step towards real nanotube devices that can be made in large enough numbers to be practical,' says chemist Jie Liu at Duke University in Durham, US. It is a development that the whole research field is waiting for. The levels of uniformity and reproducibility are the most impressive part of the results.'

The research at Purdue University was funded by the US National Science Foundation (NSF) through the Network for Computational Nanotechnology at the Birck Nanotechnology Center in the university's Discovery Park. The University of Illinois contribution was funded and supported by the NSF, DoE and Motorola, and the university's Frederick Seitz Materials Research Laboratory, Center for the Microanalysis of Materials and Department of Chemistry.

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T +44(0)1372 802080
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Reporter
Dr Francis Sedgemore

Editor-in-chief
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