Carbon nanocreations

Scanning tunnelling microscopy pioneer and co-founder of technology company Tiptek, Professor Joseph W Lyding discusses his work on 2D materials and carbon nanotubes

Why did you choose to explore carbon nanotubes (CNTs) at the start of the century, and can you outline the most significant discoveries you have made since then?

It is very difficult to fabricate atomically perfect nanoscale structures. However, in the case of CNTs, nature does the job for us. That said, it is important to understand how nanotubes interact with their environment, which includes their electrical contacts and the surfaces they contact.

We set out to explore these effects, first by developing a method to deposit nanotubes onto atomically clean surfaces. We were then able to observe subtle effects; for example, what happens when you alter the alignment of a nanotube with the underlying atomic lattice of the substrate.

Can you give examples of carbon nanotube network (CNN) devices and provide an insight into what triggered your interest in finding a way to improve current conduction between nanotubes?

CNN devices are attractive in that they are quite easy to fabricate and have numerous potential applications, for example, in low-cost wearable flexible electronics. The key device is the transistor, whose speed and power efficiency critically depends on how well electrons can flow through the nanotube network.

Unfortunately, in these nanotube networks the electrons must jump from nanotube to nanotube as they pass from one end of the transistor to the other. These 'jumps' are very inefficient and slow down the performance of the transistor by a factor of 10 to 100. It simply occurred to me one day that the nanotube-nanotube junction problem could be solved via nanosoldering.

Beyond CNT research, what other areas does the Lyding Research Group explore?

We are exploring the fabrication of devices based on the 2D atomically thin materials graphene and boron nitride, as well as the layered transition metal dichalcogenides like molybdenum disulphide. There is a worldwide effort to study these and related materials to replace silicon in future integrated circuit chips.

In addition, we are investigating the atomically precise fabrication of semiconducting graphene nanoribbons by combining bottom-up chemical synthesis with top-down fabrication driven by electrons from our scanning tunnelling microscope (STM). We are also developing nanometre-scale metal wires that can be used to make connections to ultra-small structures like CNTs and graphene nanoribbons.

An offshoot of our work in microscopy has been the development of a patented tip sharpening process that now serves as the basis for a startup company, Tiptek, LLC, which was founded to commercialise this process.

How do you involve undergraduate students in your nanotechnology projects? Is your aim to inspire the next generation of nanoscience thought leaders?

Undergraduates are heavily involved in our research. It is important to immerse them in open-ended problems that they do not see in their classroom curriculum. This is how I got my start in research and I found it to be enlightening and inspiring. A number of our undergraduate researchers have been authors on our papers and presented their research at major conferences.

In which areas do you see your investigations progressing in the next five to 10 years?

We are just beginning to obtain some very interesting results in our graphene nanoribbon experiments, so I expect this effort to grow in the near future. We are also exploring the effect of the nanosoldering process on mechanical strength and thermal conductivity of nanotube networks.
40 YEARS AGO, many scientists would most likely have thought that there was little, if anything, more to learn about carbon, seeing as it had been known, used and analysed throughout human history in the form of coal and diamonds. However, an unplanned experiment in 1985 led to the discovery of a new molecule made purely of carbon – the buckyball. Arranged in the shape of a football and consisting of 60 carbon atoms, the buckyball was actually the first of a brand new class of molecules, later named the fullerenes.

Numerous arrangements were subsequently proposed but one in particular caught the imagination of scientists worldwide – the carbon nanotube (CNT). Cylinders only a few nanometres wide, CNTs’ unique molecular structure furnishes high tensile strength, electrical conductivity, ductility, heat conductivity and relative chemical inactivity. Since the later isolation of graphene – carbon arranged into a one atom-thick honeycomb sheet – in 2004, single-walled CNTs have been described as 1D cylinders of monolayer graphene.

With such stunning properties, it is little surprise CNTs have been proposed as components for future nanoelectronics. However, primitive synthesised (as-grown) CNTs are a mixture of metallic and semiconducting types, an arrangement which often hinders their practical application.

Many have attempted, with limited success, to isolate metallic or semiconducting CNTs to form a more useful structure. But an alternative approach is to find ways to enhance the performance of random as-grown carbon nanotube networks (CNNs) – made up of many CNTs randomly laid across one another. CNNs are easy to fabricate and transfer to arbitrary substrates, which make them attractive for applications in integrated circuits and display drivers on flexible or transparent substrates, particularly as transistors.

An electric bond

The Lyding Research Group within the University of Illinois brings together experienced, distinguished researchers with undergraduate students. Aiming to uncover atomistic-level information, the team provides insight into, and innovative new methods to improve, important nanotechnology systems.
“During current flow these junctions get hot, so we expose the CNN to a gaseous chemical that thermally decomposes at the hot junctions, leaving behind a metal deposit.” As the metal deposition continues to build up, it forms a conducting bridge between the nanotubes. Current then starts to flow efficiently across the junction, which causes the junction to cool down and thus prevents further metal deposition, essentially acting as solder between the nanotubes.

This technique – developed by Lyding and colleagues, and led by graduate student Jae Won Do – has provided a staggering improvement in CNN conduction: “In our first published experiments, we observed close to an order of magnitude improvement in the conduction efficiency of our nanotube array transistors,” Lyding enthuses.

PUSHING TOWARDS THE MARKET

Lyding’s nanosoldering method relies on chemical vapour deposition (CVD), a process well-established in the semiconductor industry to produce high-purity, high-performance thin films. Not only does this mean the industry is accustomed to the technique, making nanosoldering more easily transferrable to market, but it also means a wide range of metal precursor molecules are available.

However, the Lyding Research Group is not one to rest on its laurels: “We are trying an alternative method to CVD, which requires a vacuum system and gas handling apparatus,” Lyding illuminates. “In this method, we simply coat the nanotube array transistors with a thin layer of the CVD chemical, either by simple drop casting or by a spin-on process.”

Asked how close the Group’s innovations are to making it into commercial technology, Lyding replies: “I could see this happening over the next three to five years”. The Group is not currently working with commercial partners, but initial discussions with potential industrial collaborators are underway that Lyding hopes will lead to a development process.

Evidence of this continuing ethos can be seen in the makeup of the Group, which consists of graduate research assistants, PhD students and undergraduates, all engaged in research alongside Lyding and his world-leading collaborators.

HOLISTIC COLLABORATION

Lyding’s distinguished academic career began under the tutelage of twice Nobel Prize for Physics winner Professor John Bardeen. “At first I was in complete awe just to be near someone of his stature, but then I realised that he was not at all egotistical about his accomplishments,” recalls Lyding. “Bardeen’s lasting influence on me has been to embrace challenges and take the risks that can lead to discoveries, but above all make sure that people come first.”

Evidence of this continuing ethos can be seen in the makeup of the Group, which consists of graduate research assistants, PhD students and undergraduates, all engaged in research alongside Lyding and his world-leading collaborators.

INTELLIGENCE

NANOSOLDERING CARBON NANOTUBE JUNCTIONS BY LOCAL CHEMICAL VAPOR DEPOSITION FOR IMPROVED DEVICE PERFORMANCE

OBJECTIVES

• To determine atomistic-level information that provides insight into important nanotechnology systems, utilising the ultra-high vacuum scanning tunnelling microscope (STM) as an atomic-resolution imaging, spectroscopic and fabrication tool

• To enhance the performance of as-grown carbon nanotube networks through a novel nanosoldering technique

KEY COLLABORATORS

Professor Narayana Aluru; Jae Won Do; Professor Greg Girolami; Professor Martin Gruebele; Professor Karl Hess (emeritus); Professor Bill King; Professor John Rogers, University of Illinois • Professor Mark Hersam; Dr Joshua Wood, Northwestern University • Dr Phaedon Avouris, IBM T J Watson Research Center • Professor Salvador Barraza-Lopez, University of Arkansas • Professor David Estrada, Boise State University • Dr Scott Lockledge, CEO, Tiptek, LLC • Professor Eric Pop, Stanford University • Dr John Randall, Zyvex Laboratories • Dr Scott Schmucker, Naval Research Laboratory • Professor Yang Xu, Zhejiang University, China

FUNDING

US Office of Naval Research
US National Science Foundation

CONTACT

Professor Joseph W Lyding
Head, Lyding Research Group
Electrical and Computer Engineering
3065 Beckman Institute MC 251
405 North Mathews
Urbana, Illinois 61801, USA
T +1 217 333 8370
E lyding@illinois.edu
http://bit.ly/1vmcB0Q
http://bit.ly/1yw6Dc

PROFESSOR JOSEPH W LYDING received his PhD in Electrical Engineering from Northwestern University in 1983. Since being recruited to the University of Illinois in 1984 by Professor John Bardeen, Lyding has risen to Professor of Electrical and Computer Engineering. Most recently, he has developed ultra-clean nanotube deposition and STM spectroscopic methodologies to understand the interaction of carbon nanotubes and graphene with technological substrates.