Small science, great achievements

Professor Michael J Naughton and Dr Fan Ye discuss some technical aspects, innovative discoveries and potential applications of their research on nanomaterials and nanostructures, particularly concerning interesting electron density oscillations known as surface plasmon polaritons.

How did your academic career guide you to your current research endeavours?

MJN: I entered small science driven by the idea that “necessity is the mother of invention”. While investigating something called spin density waves in 1D organic conductors in high magnetic fields, my thesis advisor and I found that existing probes of magnetism were inadequate for the small samples we had and in the tight confines of our low-temperature (below 1 K) apparatus. Thus, my research on organic conductors led me to the world of microelectromechanical systems (MEMS), using silicon microfabrication techniques for magnetometry.

When the nanotube era began in the 1990s I, like many others, began studying their properties and using nanoscale tools to fabricate novel structures, actuators and sensors. More recently, in collaboration with Boston College colleagues including Professor Kris Kempa, we have been fabricating multilayer structures onto nanowires, forming what we call nanocoaxes, which resemble the coaxial cable used for cable TV, only 10,000 times smaller. A number of technologies and devices have emerged from this nanocoax and related nano-architectures.

What are surface plasmon polaritons (SPPs)?

MJN: SPPs are oscillations of electron density that are confined to, and can move along, a metal-nonmetal interface. They are primarily excited by light or by a beam of electrons. Interest in SPPs is exploding (and is unlikely to have peaked yet) mainly due to the realisation that their energy-momentum relation is nonlinear such a way that they can be propagated on size scales far smaller than their free space wavelength. This enables one to create structures that move information on the nanoscale in unique ways, or that respond to exposure to biomolecules in readily detectable ways.

Do you use any innovative experimental or theoretical methods in your investigations?

MJN: We are playing with some new concepts in the field of optical microscopy, including fabricating new probes that may be useful for single cell-level interrogation of optogenetically modified neurons. The fact that the nanocoax can propagate visible light as well as measure electrical signals opens the opportunity to fabricate a high-resolution neurointerface that can optically stimulate and electrically record the activity of such neurons. In fact, the 2014 Nobel Prize in Chemistry, won by a trio of physicists, was for pioneering work in sub-diffraction-limited optical microscopy, used primarily in the life sciences. Our efforts were inspired by that work, and may someday help to advance it.

FY: Moreover, I have developed an aperture-restricted critical illumination technique, which allows precise measurement of absolute reflectance of a sample with micron-sized area under normal incidence. The aim is to experimentally characterise the reflectionless directional coupling between free photons and surface plasmon polaritons, but this technique could have value to other researchers working on imaging of small samples.

Could you explain the major challenges faced during your research and how you overcame them?

MJN: Scientific research almost always presents challenges. That is what makes it intellectually stimulating and makes us wake up at three in the morning thinking about our work. The best challenges are the intellectual ones. How do we understand that observation? How do we interpret those data? If I imagine myself the size of an electron, will it help me contemplate how electrons move in magnetic fields?

Once a particular problem is chosen to be addressed or pursued, more practical challenges arise, such as a need to invent a new measurement technology, or to devise a ‘smoking gun’ experiment that settles an important issue. One of my biggest challenges right now is finding a way to execute on a concept for large-scale interrogation of neural activity with nanoscale precision.

Is funding an issue that you have to regularly deal with or is your field appropriately supported?

MJN: The issue of obtaining funding is something we deal with on a nonstop basis. In recent years, much funding has gone into photovoltaics and disease monitoring and detection, but we still obtain our energy from fracking gas and digging coal, we still have too many people dying from cancer after late diagnoses, and we still experience emerging viral outbreaks that can threaten global health. Therefore, society as a whole needs to continue to recognise the value of fundamental science and support it as best it can.

This means nonscientifically trained citizens of every country need to increase their scientific literacy, to not be afraid of science, but to recognise its intrinsic good. And emerging, low-resource nations need to set STEM education as a national priority. One can look at Rwanda as such a nation – fantastic progress only two decades out from a devastating genocide, in large part due to national priorities on public health and scientific literacy.
Better together

In the spirit of integrated science, researchers from the Department of Physics, Boston College, explore the potential technological applications of nanoscience combined with insights from neuroscience and biology, with the goal of addressing society’s greatest challenges – making breakthrough discoveries along the way.

**WHILE PROGRESS IN** basic science is in itself a worthy Endeavour and the primary goal for most researchers, it is a particularly thrilling outcome when scientific discoveries find practical applications that are able to meaningfully improve the human condition and increase quality of life.

Materials physics is an exciting field of research precisely because its value goes beyond that of expanding knowledge; it has the potential to advance our technologies and develop devices and strategies to address some of the most pressing global issues, such as the energy crisis, water scarcity and public health threats.

**MULTIDISCIPLINARY MAGIC**

However, it is when the discoveries of materials science are integrated with those from other scientific disciplines, and experts with different backgrounds and outlooks join their efforts, that the greatest technological advancements are made and society’s biggest challenges can be met: “Modern, materials-based integrated science opens a world of opportunity and potential for improving the human condition,” enthuses Professor Michael J Naughton from Boston College, USA. “Physicists, engineers, biologists, chemists, neuroscientists – each give a specific contribution to common projects that cannot be conceived or completed without multiple discipline involvement.”

Within the field of materials science, the study of nanomaterials and nanostructures is especially fruitful in terms of practical applications, as it deals with low-dimensional systems like molecular organic conductors which are liable to be transformed into superconductors, metals, semimetals or insulators – magnetic or nonmagnetic – simply by applying different temperature, pressure or magnetic field.

Moreover, some organic conductors such as nanotubes and fullerenes – the discovery of which fuelled the development of nanoscience – display on the nanoscale many peculiar physical, electrical and mechanical properties that do not apply in nature on the large scale and can therefore be utilised in unique ways in a number of technologies.

**THE POTENTIAL OF NANOSCIENCE**

Exploiting the potential of nanomaterials and inspired by the collaborative, transdisciplinary approach of integrated science, Naughton and his laboratory have made important discoveries in the sub-fields of plasmonics and photonics, which may ultimately contribute to addressing societal issues.

The construction of nanocoax architectures is one of the team’s latest achievements, from which technologies like solar cells, biosensors and plasmonic waveguides may be developed. This is thanks to nanoscale coaxes sharing many properties with conventional macro coaxial cables, such as the capacity to propagate electromagnetic radiation with a wavelength larger than the wire’s diameter.

More recently, as the lab started focusing on devices like electrochemical biosensors, neuroelectronic interfaces and nanoscale optical microscopes, the need arose to delve into surface plasmons and design nanostructures specifically with plasmonics in mind.

**BREAKTHROUGH DISCOVERIES**

It is in this context that some breakthrough discoveries were made. In particular, Naughton’s graduate student Fan Ye, now a postdoctoral researcher at Cornell University, USA, discovered and systematically described the novel phenomenon of plasmonic halos, which can be conceived as the electrooptical analogue to surface waves on a musical drumhead.

Surface plasmons were excited by light on circular microcavities integrated with step gaps to form confined plasmon drumhead modes. The latter, under resonant conditions, were shown to modulate photon scattering into the far electromagnetic field and emanate colourful plasmonic ‘halos’, which can be modified by tuning geometric and/or material parameters. A peculiar feature is that part of the energy contained in the plasmon is reconverted to light that, being modulated by the surface waves, results in specific colour filtering.

The phenomenon may have significant technological applications; for instance, in discrete optical filtering and biomedical plasmonics. A molecular biosensor may be developed that exploits the halo’s peculiar properties. “Since the details of the light transmitted from a halo are altered by plasmons, it may be possible to further modulate this light by attaching biomolecules, such as disease biomarkers, to the surface,” Naughton explains. “Given the size of the device (~1 μm diameter), a small number of such molecules could lead to a sizeable change in the optical signal, and the device could be portable.”

**LIGHT TO PLASMON**

Ye further discovered that asymmetric, periodic, two-element metal-insulator-metal structures can serve as reflectionless directional converters between freely propagating visible photons and surface plasmon polaritons. While the structure was not originally conceived for the purpose of specific applications, the finding opens a number of possibilities in optical and biomedical technology.
The lack of reflection means light can be converted into plasmons very efficiently, while plasmons’ directionality feature guarantees they can be steered in a specific direction with a high degree of precision. This will have useful applications in optically driven information technology on sub-wavelength size scales: “Due to the much larger effective resonance mode volume, this asymmetric, periodic plasmonic structure has a much higher quality factor (Q) than conventional symmetric structures,” notes Ye. “One can potentially leverage this high-Q resonance for accurate biomedical detection and sensing.”

NEUROELECTRONICS, PHOTOVOLTAICS AND BEYOND

In line with the overall integrated science approach, Naughton’s team is collaborating with other Boston College research groups, like that of Professor Tom Chiles of the Biology Department and Professor John Christianson’s team in the Department of Psychology, to explore further exciting applications of their discoveries.

In the field of bioelectronics, researchers are designing a high-sensitivity, high-specificity sensor which, by exploiting arrays of vertical nanocoaxes that function as electrochemical detectors of biomolecules, can simultaneously identify multiple molecular indicators. This will help to specify those diseases that have not one but many biomarkers, and will also optimise point-of-care disease diagnostics. Vertical nanocoaxes are also being used to fabricate a high spatial resolution neuroelectronic interface. The device will have a number of applications, ranging from understanding neuron networks to monitoring cell neurodegeneration, on size scales unavailable with other technologies or devices.

Naughton's research on nanostructures is also going to be exploited in photovoltaics, thanks to a collaboration with Professor Kris Kempa of the Department of Physics. The two scientists are developing a plasmon-enabled hot electron solar cell, wherein metamaterial structures are going to be used to orthogonalise optical absorption and electric current collection, and with plasmons extracting so-called ‘hot electron energy’ before it can be lost to heat, thus making an improved solar cell.

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SPREADING THE WORD

Results of these collaborative efforts will be disseminated through specialist publications, web pages, university colloquia and international conferences, such as the 2014 Materials Research Society Fall Meeting in Boston on 30 November-5 December, and the American Physical Society March Meeting 2015 in San Antonio, Texas.

Dissemination is crucial in order to spread the word among scientists as well as society at large that it is through an integrated approach to science that technology may be advanced in truly innovative ways and lives improved. “Smartphone-integrated diagnostics that exploit novel physical phenomena like plasmonics are envisioned and can be fabricated by physicists, but real implementation of such devices is next to impossible without the know-how of biologists and biochemists,” Naughton insists. “Similarly, neuroscience stands to benefit greatly from new tools that enable scalable interrogation of neuronal activity in networks – tools that physicists working at the nanoscale may be able to make.”