Improvements at the nano interface

Dr Afshin Ziaei gives an insight into his experiences running nanomaterials research consortia across Europe and highlights the key role of collaboration in overcoming challenges in this cutting-edge field.

Your current projects are Nanotherm and Nano-RF. Could you provide a background to Nanotherm and describe its chief aims?

Nanotherm aims to develop an advanced interface technology to join electronic elements by improving the efficiency of electrical and thermal conductance. Future electronic power devices and packages will need to demonstrate improved performance and functionality at reduced cost, size, weight, energy consumption and thermal budget. Furthermore, demands for increasing reliability have to be met by industry to maintain competitiveness in this growing multibillion-euro market of heterogeneously integrated systems. To respond to these challenges, there is a need for new and innovative nano- and microtechnologies and materials, which are key enablers for advanced thermal and mechanical interfaces, to be developed and integrated to obtain higher electrical, thermal and reliability performance under harsh environmental conditions.

How does the Nano-RF project differ?

Nano-RF is utilising nanotechnology to overcome the current limitations of modern communication. Currently, transmitter/receiver (T/R) modules are key building blocks for communication arrays. The project’s goal is to develop a new approach for future generations of T/R modules by using carbon nanotube (CNT) and graphene technologies, leading to a revolutionary new nano T/R module that works at high frequencies (up to 80 gigahertz). The application spectrum is broad, spanning satellite, aeronautics, and mobile communications and automotive radars.

Can you highlight how your professional experience has prepared you for these projects?

During my career, I have worked on the development, design, fabrication, and characterisation of radiofrequency microelectromechanical system (RF MEMS) and nanoelectromechanical system (NEMS) components such as mechanical switches, transmission lines, etc. I have also been involved with, or in charge of, many European R&D projects. For example, I was Project Coordinator for ARHMS, NANOPACK, SMARTPOWER and NANOTEC. This cumulative experience has allowed me to develop my scientific expertise in the field of RF, particularly concerning the fabrication of different devices. I also developed my skills in managing large projects, including European consortium management, planning and finance, which has enabled me to carry out Nanotherm and Nano-RF effectively.

What are some of the biggest challenges you have faced? How were you able to overcome these difficulties?

The biggest challenge faced by the Nanotherm consortium was to bring together a multi-scale and multi-domain modelling framework that can furnish guidelines for materials design from initiation up to continuum modelling, and verify this using corresponding experimental techniques. Organisation into several small taskforces was necessary to address this challenge.

During the Nano-RF project, it was necessary to simulate devices that do not exist, or model their performance beyond the state of the art. There is little information available on this in the literature, so we had to develop our own software for simulations. Developing quality graphene and CNT for use in different applications was also necessary to achieve the desired performance. Finally, the devices’ manufacturing steps had to be developed without any deterioration of the materials’ properties, particularly for graphene.

The final integration within the demonstrator device has also proven complex. Each technology is optimised and successfully realised independently, so combining them in a monolithic approach is not possible due to the different thermal windows involved. Furthermore, several of the component devices are too sensitive to undergo processing of subsequent demonstrator devices. To address this final step we are exploring two alternative approaches: hybrid integration, where each chip will be fabricated separately and stacked using CNTs to provide signals from one chip to the other, or a multi-chip, module level integration, where each technology will be specifically placed on a printed circuit board with a coplanar waveguide to enable electrical transmission.

To what extent has collaboration proven integral to your line of research?

Collaboration forms the basis of the research carried out in Nanotherm. The consortium, which involves research from eight European countries, is composed of 18 partners from industry, SMEs and academia. This group embodies the necessary excellence and interdisciplinarity to address all tasks successfully.

Collaboration is also a key element of Nano-RF’s success. Each of the 13 partners has been carefully selected and provides the consortium with all the expertise needed for the project. The project is divided into specialities, allowing different partners to utilise their unique skills in the four sections; system architecture and design; graphene and CNT materials, fabrication, and characterisation; and system integration.
ACCoRDINg To MooRe’s Law, the number of transistors that can fit onto a single chip will double every 18-24 months, and this directly correlates to advances in computational power. One of the biggest challenges faced by the technology industry when increasing numbers of transistors is that smaller circuits are less able to dissipate heat, which reduces the efficiency of the device and could damage the chip. The insulation between transistors is constantly being reduced, leading many to predict that the pace of computational advancements will soon be unable to keep up with Moore’s Law.

The unique electronic and mechanical properties of nanomaterials are predicted to play increasingly important roles in the development of smaller, more energy efficient and faster electronic devices. Dr Afshin Ziaei of Thales Research & Technology (TRT), France, is an electronics and microwave engineer who has been involved in many European research projects on thermal interface materials and radiofrequency microelectromechanical systems (RF MEMS). In collaboration with business partner Olivier Prevotat (also of TRT), Ziaei is now coordinating two new, groundbreaking nanomaterials projects, Nanotherm and Nano-RF, which could revolutionise electronics and communication.

NANOTHERM
The Nanotherm project aims to meet market demand for increased performance, smaller size, improved energy efficiency and lower cost computer microchips by researching and improving their thermal management. The multidisciplinary team is investigating the possibility of using nanomaterials to form the interface between different components on chips, improving the thermal conductivity and lowering the electrical resistance at the contact site. "In electronic packaging, interfaces between the different elements – for example, between die and heat spreader – are often a bottleneck in heat dissipation and electrical interconnectivity, a weakness in the system’s reliability," Ziaei elaborates.

Current die attachments and thermal interface materials – metallic solders or adhesives – reach their limits when exposed to high power densities. Existing lead-free solders do not sufficiently withstand thermo-mechanical stresses at temperatures higher than 150°C and lead-based solders are harmful for the environment. Conventional adhesives lack thermal conductivity to dissipate the generated heat properly. "Therefore, enhanced materials are needed for high power density packages, which allow an outstanding bulk heat conduction and low interface resistance," adds Ziaei.

KEEPING CIRCUITS COOL
The Nanotherm consortium consists of 18 partners from eight European countries and is highly interdisciplinary, comprising experts from industry and academic research. This expertise allows the team to investigate the potential use of nanomaterials for improving the thermal regulation of chips in a wide range of industrial applications. In the automotive industry, for example, consumer demand for hybrid and electric-powered vehicles is growing steadily, requiring smaller but more powerful electronic systems to drive the cars, in addition to auxiliary features such as active suspension and air conditioning units, leading to a higher thermal density. These systems have to work in a wide range of ambient temperatures using environmentally friendly technology where possible. As such, Nanotherm is perfectly suited to developing novel thermal regulatory systems from more green nanomaterials.

Another type of application is in light-emitting diode lighting, where thermal performance is a strong limiting factor preventing the technology from achieving its highest potential efficiency. Over 20 per cent of all electricity used goes into lighting, so improving the thermal efficiency of LEDs will result in a huge global energy saving. Almost any type of electronic can benefit from improved thermal and thermo-mechanical properties, which the Nanotherm project team hopes to provide.

DESIRABLE PROPERTIES
Ziaei and his colleagues are investigating several potential nanomaterials for use as thermal interface materials for a variety of applications, using a highly accurate measure of thermal performance. “New functionalised materials with nano-scaled adhesion mechanisms might provide the necessary potential to meet these challenges,” Ziaei elaborates. Therefore, parallel research routes are addressing nano-sinter-adhesive bonding, phonon-coupled vertically aligned carbon nanotubes (VACNT) joining, nano-
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The Nano-RF project is a collaborative effort from 13 partners across eight European countries, focusing on using nanomaterials to improve transmitter/receiver (T/R) modules which are key building blocks for modern communication arrays. In order to be useful in the technologies of the future, next generation T/R modules require several important characteristics, as Ziaei explains: “Next generation T/R modules should be thin and inexpensive to fabricate, test and integrate into radar systems. The frequencies supported will range from microwave through the millimetre wave and maybe even beyond. There is also a need for new technologies allowing the achievement of nano T/R modules with low power, high integration levels for short-range distance applications. These include mobile communications or automotive applications; for example, autonomous cruise control, pre-crash detection systems, blind spot detection, parking aid, side impact detection and stop-and-go traffic radar”. Several alternative approaches to silicon-based CMOSs have been investigated in the past, but Ziaei and his team believe they have found the ideal characteristics in carbon nanotubes (CNTs) and graphene.

**CARBON NANOELECTRONICS**

Graphene and CNTs are carbon allotropes formed into sheets one atom thick, which, in CNTs, is then curved into a cylindrical tube. Both of these nanostructures have unusual thermal-conductive, electronic and mechanical properties that have a wide range of applications in microwave and millimetre wave electronics. For example, CNTs are the best electron emitters ever known, more thermally conductive than most crystals and among the stiffest materials. They can be metallic or semi-conducting depending on their chirality, and are particularly suited for use as both basic building blocks of active T/R module components as well as electrical interconnects for 3D vertically stacked components, which improve performance and reduce size and power consumption.
Graphene is thermally and mechanically robust. Despite being isolated only 11 years ago, it has been used to produce field-effect transistors (FETs) that operate at state-of-the-art level, with room for improvement. Thus, the use of CNTs and graphene-based advanced technologies for nanoelectronics promises significant breakthroughs.

The Nano-RF project aims to develop a revolutionary new wireless nano T/R module capable of working at very high frequencies of up to 80 gigahertz. This will involve the development of several new components. “During the project, we will develop new devices beyond the current state of the art. The CNT technology will address components such as switches, oscillators, filters, mixers, low noise amplifiers (LNAs) and power amplifiers (PAs) based on FET, as well as antennae,” Ziaei describes. “Graphene will be used to develop LNAs targeting ultra-low noise, mixers that act as oscillators, detectors and antennae. At the end of the project, we will unveil the potential of the developed technologies through the realisation of two device demonstrators, one on CNTs and one on graphene.” The demonstrators will exhibit the reconfigurability, system ability, integrability and manufacturability of the developed technologies, and unify advanced More-than-Moore elements and beyond-CMOS devices with existing technologies. The team hopes it could support miniaturised electronic systems for 2020 and beyond.

OUTLOOK
The Nano-RF team has made significant progress since the project began in 2012. Designing the components required the development of software that could simulate technology that does not currently exist, which was achieved by creating a computer model that can simultaneously analyse a variety of parameters to envision components able to function at high frequencies. Ziaei and colleagues have developed a range of techniques to produce CNTs with different morphologies that can be used for the various applications in the project, including thermal chemical vapour deposition and plasma-enhanced chemical vapour deposition. They are currently working to further improve the density and yield of the CNTs for use in T/R module components.

The team has also produced high-quality single layer graphene on silicon carbide, developing novel experimental techniques to measure its thermal conductivity. Once the researchers have succeeded in fabricating the individual components, they will need to be integrated as a whole system to demonstrate the feasibility of a nano T/R module based on CNT and graphene technology. There are a huge range of potential applications here, including future communications arrays in everything from satellites to vehicles to mobile phones.

Ziaei, Prevotat and their teams at Nanotherm and Nano-RF have already developed some groundbreaking materials and resources that are being adapted to novel applications in the fields of chip interface thermal regulation and communications. The next phase is to integrate these developments into new types of nanotechnologies that will have far-reaching implications for improved efficiency in micro- and nanoelectronics and communication systems for the future.