Spin, graphen, THz and electronics

International cooperation nurtures scholarship and revolutionary research…

Electronics is all around us. PCs, PDAs, laptops, video mobile phones, digital cameras, or MP3 players are just a few examples that have become a part of our daily lives. Electronics depends largely on semiconductor devices like transistors that work by switching flows of electrons on and off. Many recent technological and conceptual breakthroughs have made electronic devices smaller, smarter and more powerful. The discovery of the giant magnetoresistance (GMR), which has provided increased sensitivity for measuring miniscule magnetic fields, has enabled further shrinkage of hard drives, thus fostering new applications. In these GMR devices, not only the charge of electrons but also their spin is used. The spin is the electron's magnetic moment and is responsible for ferromagnetic properties of matter. The simultaneous use of charge and spin in electronics has opened a new scientific field, called spintronics. Many believe that the integration of the spin in electronics has the potential for reduced power consumption, higher speed or added functionality such as non-volatile memory. Besides the spin, monoatomic sheets of carbon, called graphene (see Fig. 1), have recently entered the stage and might revolutionise electronics. This hope rests largely on the much higher electron velocities in this new material. Graphene has been heralded as an important discovery with the potential to revolutionise electronics in the same way that silicon did.

Both fields – semiconductor spintronics and graphene electronics/spintronics – are still in their infancy and constitute the hottest area in basic semiconductor research. In all of these research areas, the

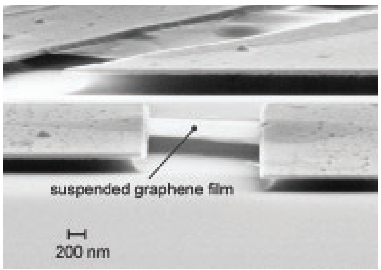

Fig. 1. Electron micrograph of a graphene film suspended between two metallic contacts (courtesy of B Söll and J Eroms, University of Regensburg)

condensed matter section of the physics department of the University of Regensburg is involved. According to the funding ranking 2009 of the German Science Foundation (Deutsche Forschungsgemeinschaft, DFG), condensed matter physics at Regensburg University belongs to the three top players in Germany. Below we give a short profile of the institution and describe some of its activities.

The Collaborative Research Centre SFB 689 on 'Spin Phenomena in Reduced Dimensions' focuses on semiconductor-, molecular- and graphene-spintronics. The centre, funded by the DFG, is coordinated by experimental physicist Dieter Weiss and addresses the storage, transport and manipulation of spins for novel electronic devices and concepts. Ferromagnetic semiconductors, graphene and carbon nanotubes as well as magnetic molecules and materials with strong spin-orbit interaction form a broad material basis for the realisation of new spin-effects and their application for novel functionalities. In particular, magnetic semiconductors are interesting hybrids as they are both ferromagnetic and semiconducting. This can simply be achieved by incorporating manganese atoms into the conventional optoelectronic material gallium arsenide (GaAs): ferromagnetic (Ga,Mn)As results. The main problem with this material, limiting currently device perspectives, is that the Curie-temperature at which ferromagnetism sets in is still well below -70°C. At present we are checking how coupling of the well known ferromagnet iron and (Ga,Mn)As might open prospects for device operations at ambient temperature conditions. The newest addition in the family of ferromagnetic nanostructures are (Ga,Mn)As nanowires (see Fig. 2), which are grown by a combination of self-organisation and conventional molecular beam epitaxy. Other hybrid systems like molecules, carbon nanotubes or graphene with ferromagnetic contacts, explored in Regensburg and other places, expand the spintronics concept to molecular and carbon-based systems. Molecules as electronic devices represent the ultimate level of the miniaturisation of electronic/spintronic circuits. The formation of electric contacts, the control of the electronic and optical properties of single molecules, as well as the processing and storage of information at the molecular level represent novel challenges for nanoscience.

Electronics is based on the flow of electrons (electric current). As the electrons carry a magnetic moment that has, due to the rules of quantum mechanics, only two possible values, called spin-up and spin-down, one can also envision a situation in which a spin current but no charge current flows. This is indeed experimentally possible and the physical properties – as well as the application potential of this new type of current – is being intensively investigated. Spin currents can also be excited by means of tera-

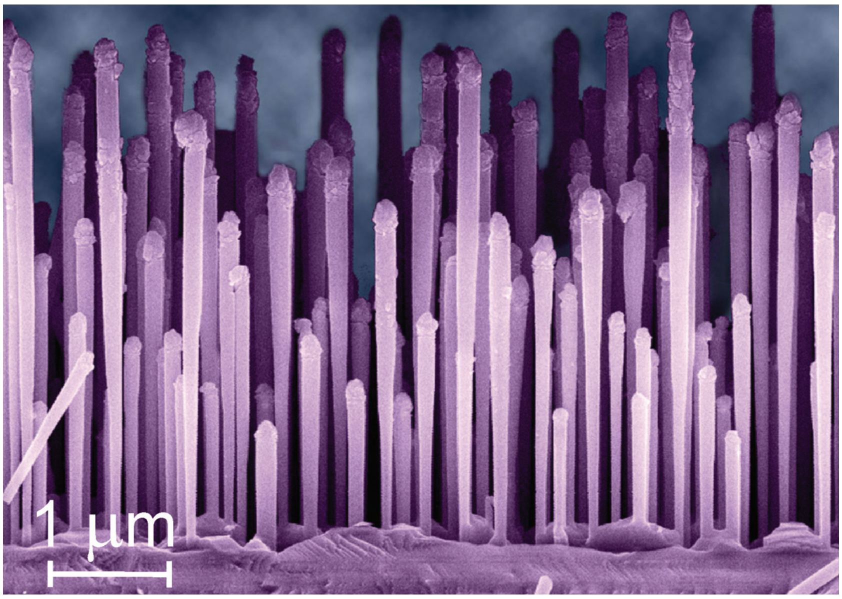

Fig. 2. Electron micrograph of (Ga,Mn)As nanowires (courtesy of E Reiger, A Rudolph and C Butschkow, University of Regensburg)

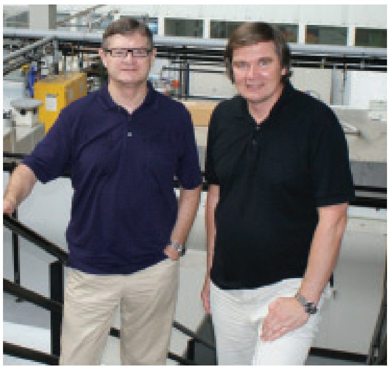

Fig. 3. Dieter Weiss (left), Coordinator of the collaborative research centre SFB 689 and Sergey Ganichev (right), Director of TerZ

hertz (THz) radiation. The physics and application of terahertz radiation is in the focus of the Regensburg Terahertz Centre (TerZ), directed by Sergey Ganichev. Terahertz radiation with frequencies between the microwave regime and visible light has low energy and is thus biologically nonhazardous, penetrates conventionally opaque materials like textiles or organic tissue and has a high chemical sensitivity due to molecule specific absorption. This invisible light is not only a powerful tool to study spin-orbit interaction for spintronics research but also has wide application potential in material characterisation, medicine, chemistry, environment monitoring, security, biomedical imaging, and chemical/biological sensors. At present we are investigating, amongst others, photocurrents in graphene using terahertz radiation.

All the described activities take place in a university environment. The role of universities in society is on one hand to 'produce' knowledge, ie. doing research, and on the other hand to educate young people. As Humboldt's idea of unity of research and education is dwarfed by the reality of undergraduate education in Germany, it is partly still alive in graduate programmes. Only graduate students working on topics at the forefront of current research can convey new developments into society. In Regensburg we offer what is so far the only coordinated PhD programme on carbon-based electronics in Germany involving many projects on graphene. The DFG funded Research Training Group GRK 1570 is coordinated by Milena Grifoni. In GRK 1570 we explore electric, magnetic and also mechanical properties of graphene, nanopatterned graphene and carbon nanotubes, consisting of 'rolled up' graphene. Before carbon-based electronics could take over from silicon, many fundamental physical challenges need to be addressed. One is the absence of an energy gap in graphene monolayers, which prevents switching on and off electric currents easily.

Basic research, as conducted here, rests to a large extent on international cooperation. Hence all three institutions SFB 689, GRK 1570 and TerZ focus on international teamwork. Apart from many individual contacts, an institutionalised cooperation between the Ioffe Institute and the Polytechnic University, both in St Petersburg, as well as the Lomonosov University in Moscow, are most notable. Cooperation is funded by the International Bureau of Germany's Federal Ministry of Education and Research (BMBF). The resulting establishment of the German-Russian Terahertz Centre is an important step in joining forces between Europe and Russia in the field of semiconductor research. Quite recently the DFG also established, together with the Japanese funding agency JST, a joint German-Japanese Research Unit (Fogru 1483) on new electronic concepts in which the universities in Würzburg, Regensburg, Tokyo and Sendai closely work together, involving also the authors of this article as principal investigators.

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