The SpinTronicFactory roadmap: a European community view

The SpinTronicFactory team present how they want to transform European excellence in spintronics at fundamental research level into a direct benefit for the European microelectronics industry

Since its birth in Europe in the late 1980s, spintronics (the contraction of spin and electronics) has been an extremely vivid area of research and development. Breakthrough discoveries have occurred quite regularly, opening new perspectives for applications. This is illustrated by the two 'sunny diagrams' respectively showing the disruptive phenomena discovered in the field in the past 30 years (see Fig. 1), and the variety of applications already present or emerging right now (see Fig. 2).

From the point of view of fundamental research, Europe is very well positioned in the field. Giant magnetoresistance (GMR) was discovered in Europe by Professor Albert Fert, from Université Paris-Sud (France) and Professor Peter Grünberg, from Forschungszentrum Jülich (Germany), who were awarded the Nobel Prize for this discovery in 2007. The possibility to switch the magnetisation of magnetic nanostructures by spin-orbit torque was first demonstrated in France, as was the possibility to vary the magnetic properties of magnetic thin films by electric field. Recently, the new paradigms of skyrmions, 2D and THz spintronics have emerged in Europe, paving the way for exciting R&D activities all around the world.

Indeed, the European IP portfolio in spintronics is quite strong with several key patents based on European excellence at low technology readiness levels (TRL). This allowed the launch of several European spin-off or start-up companies relating to memories (Crocus Technology Antaios), innovative architectures benefiting from magnetoresistive random-access memory (MRAM) unique assets (Evaderis), RF components (NanOsc ABs), magnetic field sensors (Magnomics CrivaSense), deposition tools (Singulus) and spintronic devices characterization tools (HProbe).

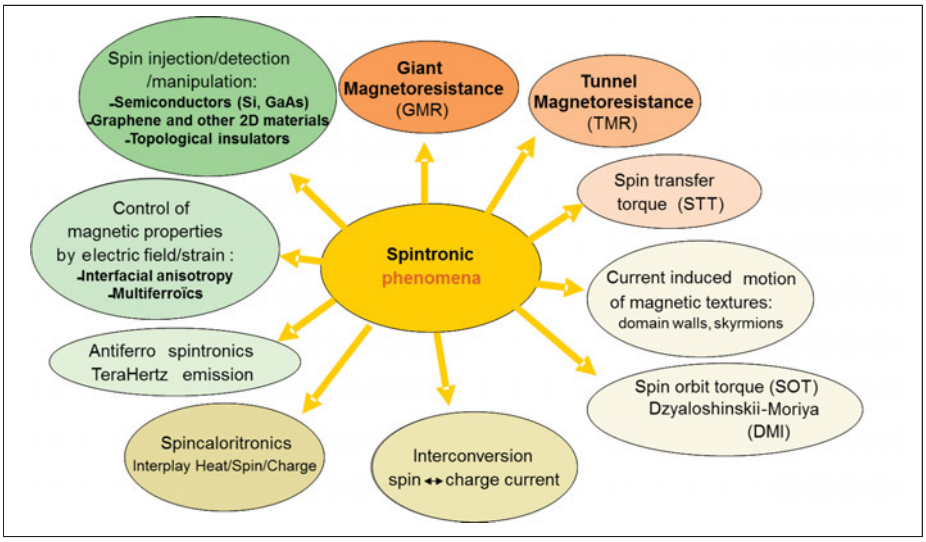

Fig. 1 The wealth of spintronic phenomena discovered since 1988

Applications

Concerning applications, magnetic recording technology has profited of the progress in spintronics by allowing the development of extremely sensitive nanoscale magnetic field sensors based on GMR spin-valves between 1998 and 2004, and later on tunnel magnetoresistance (TMR) since 2004. Unfortunately, and despite the facts that GMR was discovered in Europe, and that Grünberg was the holder of the first patent on GMR sensors, all the subsequent industrial developments in magnetic recording technology took place In Asia and in the USA.

In 2018, Samsung Electronics, first worldwide producer of memories, and TSMC, first worldwide microelectronics foundry, both announced production of embedded STT-MRAM. This marks the adoption of spintronic technology by the microelectronics industry and will greatly help spintronic technology to mature, but it is not clear yet the role that EU industrials will have in such landscape.

Furthermore, the spintronic community in Europe is still fragmented and the effort at intermediate and high TRL levels is weak compared to other macro-regions: for example, huge public investments in spintronics were made in Asia and USA in the past years. At Tohoku University in Sendai (Japan), almost US$1bn has been invested and a complete 300mm back-end magnetic line has been built to enable the fabrication of hybrid CMOS/magnetic circuits. In the USA, large SRC and DARPA initiatives have been launched to investigate the potential of 2D and radio-frequency spintronics few years ago and very recently on skyrmions. Spintronics in EU should be reinforced especially now that the possibility of integrating magnetic materials in microelectronics foundries has been demonstrated. Indeed, spintronics shows excellent perspectives for development of less-power-hungry, more-efficient and reconfigurable electronic circuits which are key building blocks for future applications. EU researchers were motor for launching most of those activities (see Fig. 1 and Fig. 2). It is important not to let actors from outside Europe being the only ones to capitalize from them.

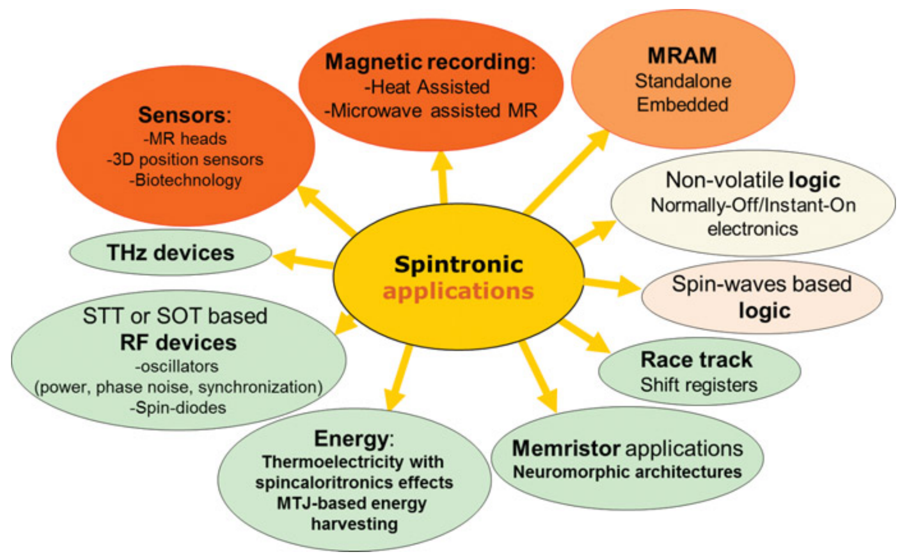

Fig. 2 Spintronic present and foreseen applications

To ease the progression of spintronics towards higher TRL levels in Europe, in 2016, the spintronics community decided to create a co-ordination structure called SpintronicFactory (STF) (see: http://www.spintronicfactory.eu/). Its aim is to federate all EU actors on spintronics and to push the whole community to 'think' applications with the aim of transforming our R&D excellence and IP background into industrial development and economical gain.

STF gathers today 86 European partners (12 private companies, 30 R&D centres, 44 academic entities) active on spintronics from 17 European countries (FR, DE, IT, ES, PL, UK, SE, TR, PT, CH, NL, GR, SK, BE, NO, HU, CZ). STF is itself under the umbrella of a wider European organisation called European Magnetism Association (EMA) which aims at structuring the whole magnetics community (see: http://magnetism.eu).

The network is organized around four axes of research and development:

- Memories
- Magnetic sensors
- Radio Frequency and microwaves devices
- Logic and non-Boolean devices

These pillars are supported by two transverse activities:

- Advanced materials, nanofabrication and tests
- Modelling and design.

The STF structure is illustrated in Fig. 3. The positioning of Europe and foreseen actions along these different pillars and transverse themes are detailed below.

Pillar 1: Memories

Among all technologies of non-volatile memories, the microelectronics industry is particularly excited by the magnetic memory called Spin-Transfer-Torque Magnetic Random Access Memory (STT-MRAM). Indeed STT-MRAM gathers a unique combination of assets: write speed, low density, low electrical consumption, and very importantly, an extremely long write endurance which is not the case of the alternative technologies of non-volatile memories (phase change RAM, resistive oxide RAM). Europe played a very important role in these developments and owns key patents in the STT-MRAM technology which is now entering into production (see an example of chip integrating magnetic materials on CMOS in Fig. 4a).

European researchers also launched a whole new field which is very exciting from fundamental and applied points of view: spinorbitronics. This is a variant of spintronics in which quantum mechanical spin-orbit phenomena are used. In particular a new class of magnetic memory called spin-orbit-torque MRAM (SOT-MRAM) was invented in Europe based on these phenomena. They have the advantage to be writable at nanosecond time scale which makes them promising for cache memory applications (as SRAM) in microprocessors. Further efforts now aim at reducing the electrical power consumption for writing by two orders of magnitude thanks to new write approaches based on electric field rather than current. Similarly for the reading, the power consumption can be reduced by an order of magnitude by changing the readout approach from a resistive approach based on the tunnel magnetoresistance to a readout based on spin-orbit phenomenon. These technologies have the potential to become mainstream in microelectronics and therefore deserve intense efforts in Europe.

STF laboratories are also very active in the development of storage shift register devices called 'race track memories'. The information is stored in the form of tracks of polarised spin-textures (domain walls or skyrmions) representing the logic 0 and 1 which can be moved by an electrical current along the tracks. Such storage devices could reach extremely high storage densities without any moving parts. This, together with the field of memory devices based on magnetic skyrmions, is a more exploratory research but can have a high impact considering the exponentially growing amount of data which needs to be stored.

Pillar 2: Magnetic sensors

Spin-based magnetic sensor technology has seen a rather strong development in the past 10-15 years with the advent of tunnel magnetoresistance (TMR) sensor technology (see example in Fig. 4b), gradually replacing giant magnetoresistance (GMR), anisotropic magnetoresistance (AMR), and conventional Hall effect technologies in applications where higher output and signal-to-noise ratio, good thermal stability, compatibility with CMOS integration, reduced cost and minimum features (< 1mm^2) are required. Major markets today include smart phones (3D magnetometers/digital compasses), the automotive sector (angular, speed, current, position/switch sensors), Industry 4.0 with current

The aims of the STF network:

1) To construct and continuously update a business-oriented roadmap for spintronics with related SWOT analysis for each application segment
2) To promote synergies and collaborations across Europe between universities, research facilities and industries, eventually leading to collaborative proposals where some of the most promising spintronic concepts developed in academic laboratories will be pushed towards proofs-of concept, functional demonstrators, chips prototypes
3) To work towards the potential launching of large EU actions, i.e., missions, gathering academic and industrial partners for a common goal
4) To federate activities and coordinate actions in Brussels: a common voice representing the spintronic community
5) To mutualise resources and facilities across Europe with nodes of excellence becoming innovation hub
6) To organise activities (joint workshops, summer schools, etc.) aiming at reducing the cultural gap between magnetics and microelectronics communities and to strengthen the relationship between the two communities

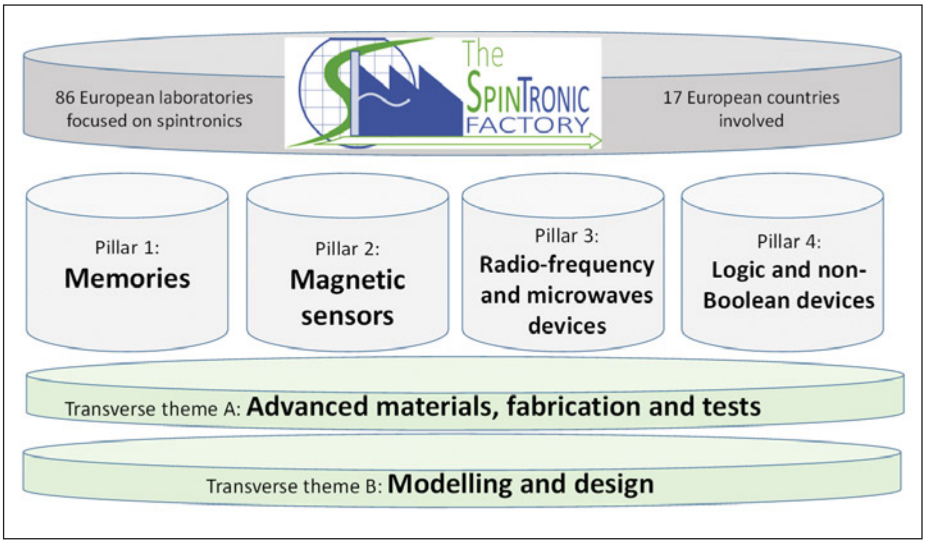

Fig. 3 SpinTronicFactory structure

and power sensors, linear and angular encoders, scanners. Novel applications are emerging in the Internet of Things (IoT) and biomedical arenas with the development of low consumption, reliable devices on silicon or flexible substrates.

Europe has had a long standing activity in magnetic sensors, both at the industrial level (Infineon, NXP, Sensitec, Melexis, LEM, to name a few) as well as at the academic level (INESC MN, CEA, INL, Crocus/Spintec, FhG) and at tool manufacturer level (Singulus, Nordiko Tech). Competition from the USA (Allegro), Japan (TDK, Alps, etc.), and China is growing strong. With Europe speeding up the transition to electrical vehicles (cars and grids), increasing renewable energy sources (solar and wind generators and associated invertors), and further exploiting Industry 4.0 and IoT concepts, our need for smarter and more advanced magnetic sensors is growing. The search for basic phenomena and architectures that can be used for the next generations of sensing devices is pressing. The need to keep our leadership in these technologies is critical, and will depend first on increasing our market share in major sensor categories, as well as on better funding opportunities at EU level for these topics.

Pillar 3: Radiofrequency and microwaves devices

Spintronics concepts in nano-sized magnetic structures enable two basic radiofrequency (RF) functions that give promise for low cost, low power and compact microwave components:

- Conversion of a *DC* into an RF voltage signal for frequency tunable, nano-scale microwave oscillators that can be modulated (amplitude, frequency and phase), injection locked to an external RF source or mutually synchronised
- Conversion of an *RF* into a DC voltage signal for frequency selective, passive or active microwave signal detectors, filters and demodulators. Device design allows covering more than two decades of frequencies (0.1 – 60GHz)

A first target application is short distance (~10 m) wireless communication for IoT such as wireless sensor networks, electronic smart systems or flexible electronics. Spin-based RF power harvesters as well as ultra-low power (< 1µW) wake-up radios address the central issue of power consumption. Demonstrated operation in phase locked loops as well as communication based on amplitude and phase modulation over 1-10m distance, provide compact multi-frequency solutions for transmission modules. A second target application is neuromorphic computing exploiting networks of synchronized spintronic oscillators with first demonstration of voice recognition.

These demonstrations are just the start to push these RF spintronics concepts towards applications. Achieving the required milestones will pass via the realisation of networks of devices as well as the implementation of advanced concepts such as non-reciprocal elements, large arrays of synchronised oscillators and the use of novel excitation schemes (non-local injection).

European laboratories are at the forefront of this research. European Commission-funded projects permitted in the past 10 years to establish multidisciplinary teams between spintronics and microelectronics communities (CEA-LETI, TUDresden, CNRS, etc.) and companies (THALES, Singulus, NanOsc, Sivers IMA, etc.) enabling significant progress on the fundamental concepts and to explore the applicative potentials (see Fig. 4c). The next steps will aim at bringing these concepts from the present TRL 1-3 to higher ones (4-5) in the next five years and higher afterwards.

Pillar 4: Logic and non-Boolean devices

The intrinsically very low energy of magnetic excitations renders spintronics not only of great interest for memory applications but also for the heart of today's computers itself, the information processor. We believe that spintronics will enable future ultra-low energy non-volatile computing technologies that will benefit both economy and ecology. Europe is clearly a leader in spintronic logic and the chances that major technological breakthroughs will be developed in Europe are rather high.

Compared to spintronic memories, spintronic logic technology is still at the level of fundamental research and several approaches are still explored in parallel. Information coding in nanomagnets, spin waves, or domain walls has been proposed and working logic gates have been reported (see Fig. 4d).

Novel physical phenomena such as spin-orbit torques or magnetoelectricity are currently intensely pursued to further lower energy consumption of devices and enable hybrid systems combining spintronics and conventional CMOS. Efficient spin information transport, a key issue for logic, has been mastered in Europe either through 2D graphene or spin waves. At the same time, unconventional computing systems,

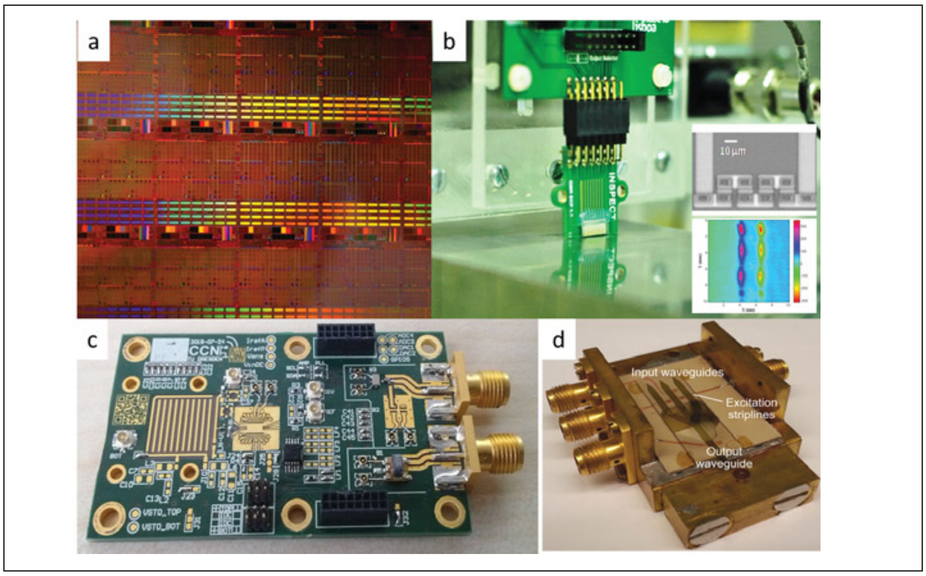

Fig. 4 Realisations from SpintronicFactory labs: a) Integrated chip of CMOS and magnetic technology; b) MTJ sensors array used for non-destructive testing; c) Example of PCB card for spin-transfer-torque RF emitters; d) Spin wave majority gate prototype

STF Roadmap: message in a nutshell

Memories: New ultra-low power write and read schemes; 300mm integration towards high TRL

Sensors: Launch large industrial projects (derisking phase); conquer larger market segments

RF devices: Reach specifications for wireless communication apps (power, phase noise, energy)

Logic & non-boolean: Benchmark existing solutions; scaling-up and new architecture; path finding

Materials: New materials, heterogeneous integration; flip-chip; 300mm lines for higher TRL

Modelling: Multiscale approach, design tools for spintronic functions; Innovative architectures

which are inspired by the operational principle of the human brain, are attracting more and more attention and spintronics can play a major role in such approaches. These include neuromorphic networks, stochastic, or/and reservoir computing. The STF roadmap envisions the down-selection of all these potential technologies in the next five years towards commercially viable solutions that have the potential to complement, and in the long term eventually rival, conventional CMOS.

Transverse theme 1: Advanced materials, fabrication and tests

Spintronics devices use magnetic materials as spin-polarisers and analysers or spin-orbit phenomena to separate the different populations of spins and thereby create spin-polarised electrical currents. As a result, spintronic steadily requires the development of new functional materials exhibiting specific properties such as high spin polarisation, large spin-orbit coupling, high magnetic anisotropy, weak damping of magnetic excitations, weak temperature dependence and so on.

Europe is very well positioned on these developments and has even key patents, such as for instance related to the perpendicular anisotropy at magnetic metal/oxide interfaces nowadays used in all magnetic memory devices (STT-MRAM). But Europe is also a leader in developing new paradigms based on materials such as magnonics, skyrmions, 2D-MTJs, etc. We are particularly strong at the fundamental level thanks to a large and strong community and the availability in Europe of very nice tools dedicated to basic research enabling the growth of complex stacks by combining different deposition techniques (e.g. TUBE-DAUM Nancy). However, we still need to strengthen our effort on the acquisition of state-of-the-art deposition tools on 200mm and 300mm industrially relevant wafers to move to higher TRLs. In terms of economic impact for Europe, it is worth mentioning that a German company SINGULUS is producing industrial tools for the deposition of magnetic stacks for spintronics.

In terms of nanofabrication, a few fabrication lines for spintronic devices exist in Europe dedicated to basic research (e.g., PTA in Grenoble) or to prototyping on large wafers (IMEC in Belgium, INL in Portugal). However, here too this effort must be reinforced considering the rising importance of spintronics for the silicon-based microelectronics industry.

The various laboratories involved in STF encompass a unique worldwide set of characterisation techniques which are at the basis of the European excellence at the fundamental level in this field. These include structural, magnetic, magneto-optical and electrical characterisation techniques. The industrial development of spintronic devices and circuits also requires the availability of industrial characterisation tools enabling on-line quality control in production. There are a lot of opportunities for European industry here based on the excellent know-how in characterisation techniques of European spintronics. Start-ups companies in this area are emerging in Europe such as HPROBE and NanOsc.

Transverse theme 2: Modelling and design

The modelling activity is of utmost importance in the development of spintronic devices due to the complex phenomenology of spintronics, which is the result of an intricate interplay among the nanostructure of materials arranged in complex stacks and the associated interface effects, the magnetisation dynamics and the electron transport dynamics at the nanoscale. The role of modelling can be identified at different stages of the R&D process and, in general, can be used to significantly reduce the prototyping cost.

The first level concerns the description of the fundamental physical mechanisms arising in spintronic materials and systems. Modelling at this level definitely requires the adoption of theoretical and computational tools addressing the relevant physics at different spatial scales ranging from electronic and atomistic levels to several microns. In this respect, one of the main challenges is to bridge the gaps among existing theories and models valid at different length scales by developing appropriate multi-scale approaches. In addition, the continual discovery of new phenomena in spintronics requires prompt development of novel theoretical models/tools capable of describing the physics of new materials and systems.

The second level is device-oriented and answers the industrial demand to have design tools for electronic circuits incorporating spintronic devices (e.g. magnetic random access memories, nanomagnetic logic, microwave filters, etc.). In this respect, the main objective is the integration of models of spintronic devices/magnetic materials in the standard design suites of CMOS-integrated electronics using a PDK (Process Design Kit). To this end, the development of compact and efficient electrical circuit models based on the fundamental physical models of spintronics is required. In this framework, another challenge is to go towards standardisation of modelling approaches, as it is the case, for instance, of BSIM for CMOS electronics. The STF network gathers EU partners (from both academia and industry) very active in modelling at both the aforementioned levels.

To summarise, spin-electronics is at the verge of becoming a mainstream technology in microelectronics. The launch of magnetic memory production in 2018 at major microelectronic foundries marks the adoption of spintronics by microelectronics industry. The whole ecosystem still has to be built in terms of design tools and characterisation tools, education of students in electrical engineering, etc.

Lots of opportunities exist for Europe and the number of start-ups created in the field in the past five years illustrates that. But this is not enough. STF target is to transform the European excellence in spintronics at fundamental research level into a direct benefit for European microelectronics industry. Europe should not miss this train. SpinTronicFactory is set to co-ordinate this effort.

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