Lattices of skyrmions, a new type of magnetic solitons, were discovered in 2009 and have quickly generated much interest for their unique topological character and strong potential for enabling a new class of spintronic devices for information and communication technologies (ICTs). Spintronics is a prime example of how upstream research, Nobel prize-level can promptly lead to cutting-edge devices of vast commercial success. A prominent case is the use of Giant MagnetoResistance (GMR) in field sensors, which has led to an exponential increase in data storage capacity that has helped to foster the information revolution. Another example is the recent market introduction of a new generation of non-volatile magnetic memories based on magnetic tunnel junctions (MTJ), exploiting the Tunnel...
MagnetoResistance (TMR) and Spin Transfer Torque (STT) effects, which will challenge the ubiquity of existing semiconductor based memory devices such as DRAM and SRAM by offering lower power consumption and new paradigms for logic devices.

GMR, TMR, and STT effects are made possible through the exchange interaction between the conduction electron spins and local moments, which allow spin currents to be generated and nanomagnet to be controlled electrically. A new aspect called spin-orbitronics exploits the relativistic spin-orbit (SO) interactions and opens fascinating new avenues for basic research and new technologies. First, spin-orbit interactions can stabilize new magnetic states with chiral spin configurations, which include skyrmions and chiral Domain Walls (DW). Second, spin-orbit interactions govern transport phenomena including the Spin Hall (SHE), Rashba (RaE) or the Anomalous Hall effects (AHE), which can be used for the conversion between charge and spin currents. Combining these different spin-orbit related phenomena can lead to new ways for manipulating magnetization. For example, recent studies have demonstrated that torques induced by SHE or RaE in ultrathin magnetic films in contact with large spin-orbit materials can move chiral DW or reverse magnetization, much more efficiently than any other known mechanism. Such effects have already some relevance for forthcoming technologies, for example with MRAMs of the 3Terminal spin-orbit -MRAM type or the spin-orbit controlled domain wall based race track memory.

Skyrmions are particle-like (soliton) spin states that appear in non-centrosymmetric crystals and in ultrathin ferromagnets (Fe, FePd...) deposited on a heavy metal substrate. They are stabilized by chiral interactions of the Dzyaloshinskii-Moriya (DM) type, which result from spin-orbit effects in the absence of inversion symmetry. Magnetic skyrmions are of intense interest mainly for two reasons: First, from a fundamental perspective, they allow the unique interplay between topology, chiral magnetism and spin dependent transport properties at the nanoscale to be investigated. Indeed, the topological nature of skyrmions underpins unique phenomena, such as the Topological Hall Effect (THE), which involves the appearance of an emergent electromagnetic field that affects the transport properties of conduction electrons.

The approach followed in MAGicSky involves exploiting the interface-DM interaction to generate skyrmions at room temperature in magnetic multilayers (MML) by stacking ultra-thin layers of transition metals (TM) and spin-orbit metals (Pt, Ir, W ...) alternately. The first objective is to demonstrate that material systems supporting stable magnetic skyrmions at RT can be obtained through a fine control of interfaces and film structure in MML systems. Through this, we aim understanding how to tune the balance between exchange and DM interactions together with constraints imposed by anisotropies. This should lead to material engineering schemes for enhancing topological protection, with consequent effects on the thermal stability of skyrmions and their interaction with defects and boundaries in nanostructures. With

Work performed from the beginning of the project to the end of the period covered by the report and main results achieved so far

In the spirit of FET OPEN projects, our groundbreaking idea at the heart of the MAGicSky proposal is to use magnetic skyrmions as a support of information in a new generation of spintronic devices.
Predicted more than 25 years ago, it is only a couple of years ago that they have been indeed observed at low temperature and under large magnetic fields in non-centro-symmetric (in which the inversion symmetry is broken) magnetic crystals or in thin films (in which the inversion symmetry is broken by the proximity of an interface). Because the skyrmions can be very small with diameters already observed in the nm range by UHAM partner before the start of MAGIC Sky and, importantly, because they behave as quasi-particles that can be moved by spin transfer torques, created or annihilated, we propose that all these remarkable properties could make them suitable for applications in information storage or logic technologies.

At the start of the MAGIC Sky project one year ago, both the gap between fundamental and more technical aspects, and the gap between this novel idea of using (and understanding) the topological nature of skyrmions and the realization of skyrmion based devices were important. The way to fill this gap has been the basis of the proposed research program of MAGIC Sky in which the main objectives are to understand how to generate, detect, and manipulate at room temperature these very small magnetic skyrmions for new spintronic devices. One of our strategic choices in MAGIC Sky is to exploit and also to tailor the interfacial Dzyaloshinskii-Moriya (DM) interaction to generate skyrmions at room temperature in magnetic multilayers (MML) by stacking ultra-thin layers of transition metals (TM such as Fe or Co) and spin-orbit metals (Pt, Ir, W, Rh...) alternately. The concerted effort made during this first reporting period enables us to achieve this first challenging objective as we succeeded to observe by mean of several imaging techniques (STXM, MFM) and on different MML systems such as Pt/Co/Ir or Pt/Co/AlOx multilayers, some magnetic skyrmions at room temperature and under small (or even zero) magnetic fields. Obviously this is important as it was a prerequisite for the addressing some of the other fundamental objectives of MAGIC Sky based on the unique interplay between topology, chiral magnetism and spin dependent transport properties at the nanoscale as well as for the technological developments that are targeted. Beyond this achievement, a lot of efforts combining experimental results in epitaxial MML systems and theoretical calculations by e.g. first principle calculations, spin dynamics and Monte Carlo simulations have been performed to evaluate how the important magnetic parameters (notably the DM interaction and the exchange stiffness) can be tuned by changing materials and composition for example for improving the thermal stability of skyrmions but also understanding (and finally decreasing) the interaction with defects or pinning centers.

Another reason for the large interest that is existing nowadays on the skyrmion physics is that the topological nature of skyrmions underpins unique transport phenomena, such as the Topological Hall Effect (THE), which involves the appearance of an emergent electromagnetic field that affects the transport properties of conduction electrons. This effect that has been already shown in B20 bulk systems and even used as a way to detect the spin torque dynamics of skyrmion arrays but has never been investigated in MML systems. In this first period, some specific MML devices in shape of strips or tracks that are compatible with electrical measurements both in longitudinal and transverse geometries have been fabricated by standard e-beam lithography process. This allowed us to make the first transport measurements at room temperature in skyrmion based devices and to show some evidence of possible electrical signature in Hall resistivity concomitant with the presence of a discrete numbe
MAGicSky is and remains a high risk/high reward fundamental science project, fully in line with the objectives of the FET program. Our main goal as far as the impact on future technology is concerned, is to prepare the ground for radically new technological developments based on the physics of skyrmions that is the core of the scientific program of MAGicSky. After this first year reporting period, the fact that we have succeeded to elaborate magnetic multilayer systems in which the interfacial spin-orbit properties are tailored, notably the Dzyaloshinskii-Moriya interaction, in such a way that sub-100 nm magnetic skyrmions can be stabilized at room temperature and low magnetic fields, represents an important step towards the potential development of skyrmion-based devices, among other ones proposed in MAGicSky. These results are clearly at the state-of-the-art. In fact, in the last couple of months, the research activities around magnetic skyrmions stabilized in thin film systems have been extremely important and several other groups (see MAGicSky report in OpenAire) reported the room temperature observation of magnetic skyrmions, for most of them having a bigger diameter compared to ours, or of micron-scale skyrmionic bubbles by means of magnetic imaging techniques such as Polar magnetic Kerr effect, X-PEEM, SPLEEM, MFM or STXM techniques.

Beyond the observation of skyrmions, a lot of important results on their interactions with defects, on the way to nucleate them and also on the electronic signature of skyrmions in nanostructures have been obtained in the first year of MAGicSky. It makes us confident that for the next period, our understanding of the physics skyrmion will keep improving. However, the work done in MAGicSky is still at a pre-competitive stage and there is no yet direct dissemination towards any applied technologies. Also in order to improve the exploitation of the project’s results, MAGicSky aims at promoting the may-be more direct spill-over to other domains of magnetic devices and spintronic applications, which are much more mature e.g. STT-MRAM.

At this stage, MAGicSky consortium is primarily focussing on academic dissemination through papers in peer-reviewed high impact journals (several of which are at various stages of publication, undergoing peer-review, or preparation) and conference presentations, including several invited talks, at international workshops or conferences as well as general lectures on magnetic skyrmions and spin-orbitronic phenomena for PhD and postdocs. A complete list of publications and communications can be found on the MAGicSky page of OpenAIRE, together with an access to datas.

In 2014, CNRS organized one of the first international workshops called “Skymag” on magnetic skyrmions in Paris. This was an important event for gathering together the scientists interested in magnetic skyrmions which are from different communities and also for promoting this emerging topic. We have yet started the organization of the second edition of this Skymag workshop that will be held in May 2017 in Paris. We aim to gather about 150 people during three days with if possible a significant number of PhDs and postdocs. The scientific committee is about to be finalized including word leaders from outside the consortium together with principal scientists from each MAGicSKy partners. Among others, one objective will be to promote the work done within MAGicSky but more generally to strengthen the position of European groups in this emerging topic with promising new technological developments for future spintronic devices.
Figure 1: numerical simulation of an object covered with spins (arrows) pointing in every possible direction.

Source: Forschungszentrum Jülich
Figure 3: numerical representation of skyrmions on a race track

Figure 2: representation of a spin-covered object as a sphere, also called hedgehog or magnetic k

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