1. Title of the project

Insulating Spintronic Principles applied to Inorganic-Organic Hybrids

2. Abstract

Recent experiments have shown the electrical injection and detection of spin currents in ferromagnetic insulating materials which founded the new field of insulating spintronics. This proposed project extends these principles to a new class of materials, the Inorganic-Organic Hybrids. It combines useful properties of both organic materials, like versatileness, cheap and easy preperation and long spin lifetimes, and inorganic materials, like magnetism and conductivity. A known insulating ferromagnetic copper-based hybrid will be used to demonstrate the insulating spintronics experiments. Then these experiments will be optimized for these materials, for example by using newly developed Langmuir-Blodgett films. In the last part the organic component of the hybrid will be changed systematically to provide insight into the spin transport in the organic component. Direct applications for these hybrids are not possible because the ferromagnetic transition temperature is too low. But the advantages of these hybrids, and the model system they can play for purely organic insulating spintronic materials, makes it worth to pursue this research. The most obvious application is the spin Seebeck effect in insulators which can be used to transform heat into electrical power by these principles.

3. Applicant(s)

A. S. Everhardt

4. Key publications of the applicants

- “Spin Seebeck effect in ferromagnetic insulating copper-based Inorganic-Organic Hybrid”, Master thesis, Zernike Insitute for Advanced Materials (in preparation) (2012)
- “Probing Spin-Peierls transition in $CuGeO_3$ by THz time resolved spectroscopy”, Talk at Nanosymposium at the Zernike Insitute for Advanced Materials (2011)
- “Phase transitions and ferroelectricity in Mn hybrid”, Bachelor thesis, University of Groningen (2010)

5. FOM-research group

G14

6. Institute

Zernike Institute for Advanced Materials
Solid State Materials for Electronics
University of Groningen

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The Netherlands
Tel: 0031 50 363 4409
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7. Duration of the project

4 years, starting from September 2012

8. Personnel

8.1 Senior-scientists

Name	Main task	Time
Prof. Dr. T.T.M. Palstra	Supervision	10%

8.2 Junior-scientists and technicians

Name	Main task	Time
1 PhD	Experiments	90%
J. Baas (Technician)	Technical support	10%

9. Cost estimates

9.1 Personnel positions

One PhD position for four years
Budget: 204 k€ (four years)

9.2 - Running budget

Standard expenses for experimental position
Running budget: 4 x 15 k€ (four years)

9.3 - Equipment

Upgrade for a Quantum Design Physical Properties Measurement System (PPMS) with a split-coil 7 tesla transverse magnet. This upgrade will be built into the PPMS system already present in the Solid State Materials for Electronics group.
Cost unknown as price is not readily available. Quantum Design has to specify an offer. This upgrade is expected to not exceed 110 k€.

9.4 - Other support

Support will be given by the Zernike Institute for Advanced Materials and the University of Groningen by providing the positions of the senior scientist and the technician.

9.5 - Budget summary

	2012	2013	2014	2015	2016	TOTAL
Personnel (positions):						
PhD students	1/3	1	1	1	2/3	4
Postdocs	-	-	-	-	-	-
Technicians	-	-	-	-	-	-
Guests	-	-	-	-	-	-
Personnel (costs) (k€)	17	51	51	51	34	204
Running budget (k€)	5	15	15	15	10	60
Equipment (k€)	x*	-	-	-	-	x*
TOTAL requested from FOM (k€)	22 + x*	66	66	66	44	264 + x* (≤ k€ 374)

* is expected to not exceed 110 k€

10. Research programme

10.1 - Introduction

The combination of quantum mechanics and Einstein's relativity by Paul Dirac introduced the concept of 'spin' as an intrinsic property of an electron more than eighty years ago [1]. The discovery of Giant Magnetoresistance used this property of the electon, founding the basis of a revolutionary new field where both charge and spin of electrons are used for transport: Spintronics. [2, 3]

The Giant Magnetoresistance uses the electron spin to change the (electrical) resistance of some multilayer structure dramatically by a change in the magnetization direction in one of the layers. The multilayer consists of a stack of three layers, with the first and the last layer being a ferromagnetic metal and the second layer a metallic spacer (**Fig 1**). The resistance of the multilayer is lower when the ferromagnetic layers are magnetized parallel than when they are magnetized antiparallel. This change is caused by different conductivities for the spin up electrons and the spin down electrons in the ferromagnets. So a spin polarized current is used for this effect. [4]

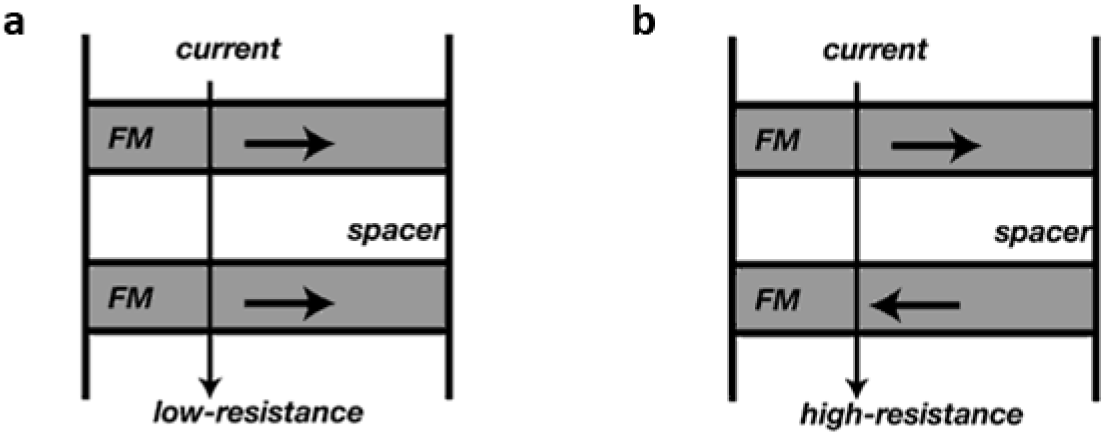

Fig 1 Giant Magnetoresistance principle. **a** The magnetization of both ferromagnetic layers is parallel. A current throught multilayer faces low resistance because one spin orientation has low resistance in both layers. **b** The magnetization of both ferromagnetic layers is antiparallel. A current through the multilayer faces high resistance because the resistance of both spin orientations is high in the different ferromagnetic layers. [5]

Spintronics has large potential for new devices. This potential has been shown best by the commercialization of the Giant Magnetoresistance in hard disk drives ten years after its discovery. [5, 6]

The use of spin currents instead of conventional electrical currents has advantages like nonvolatility, increased processing speed and low power consumption due to the fact they are *dissipationless* because they are time invariant [1]. But spin currents are not *conserved*: the conservation of a spin current can be broken by mechanisms like magnetic impurity scattering, spin-orbit coupling or hyperfine interactions [7, 8]. This limits the spin conservation lengths to several nanometers to microns [1, 9, 10].

Until recently all spintronics research has focused on metals and semiconductors [6]. Reports in 2010 have opened the way to new spintronic physics by showing electrical control of spin transport in ferromagnetic insulators [11, 12].

Different kinds of spin transport, which is effectively transport of angular momentum, are shown in **Fig 2**. Angular momentum is generally carried by spin polarized conducting electrons in conducting materials. In insulators angular momentum is proposed to be transported by spin-wave currents since there are no conduction electrons that can be responsible for transport. [11]

It is possible to have electrical detection and injection of spin currents in insulators. Detection is possible by angular momentum transfer from the insulator to the metal (called spin pumping) and subsequent use of the inverse spin Hall effect in the metal (**Fig 3 a**). The inverse spin Hall effect transforms a spin current in an electrical currents. Electrical injection is possible by making use of the direct spin Hall effect (**Fig 3 b**) to transform electrical current into a spin current in a metal. The angular momentum of the spin current can then be transferred to the insulator (called spin transfer torque). [11]

Spin currents in insulators have been demonstrated by using these and other methods to inject and detect spin currents in the insulating ferromagnet Yttrium Iron Garnet, $Y_3Fe_5O_{12}$ (YIG) [11]. The electrical injecton and detection is shown in **Fig 3 c**.

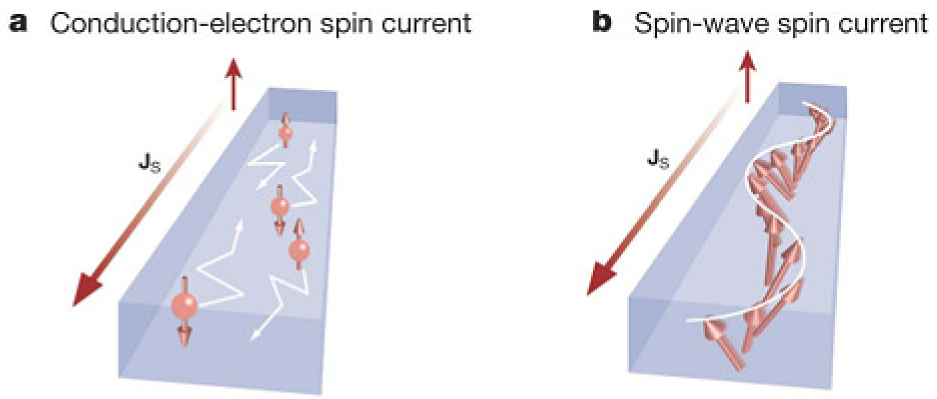

Fig 2 a Spin currents in conducting materials. Spin polarized conduction electrons conduct spin currents. Electrons carry angular momentum in their spins. **b** Spin current in insulators. The electrons are not mobile so angular momentum cannot be conducted by electrons. The angular momentum is proposed to be carried by collective magnetic-moment precession, a spin-wave. [11]

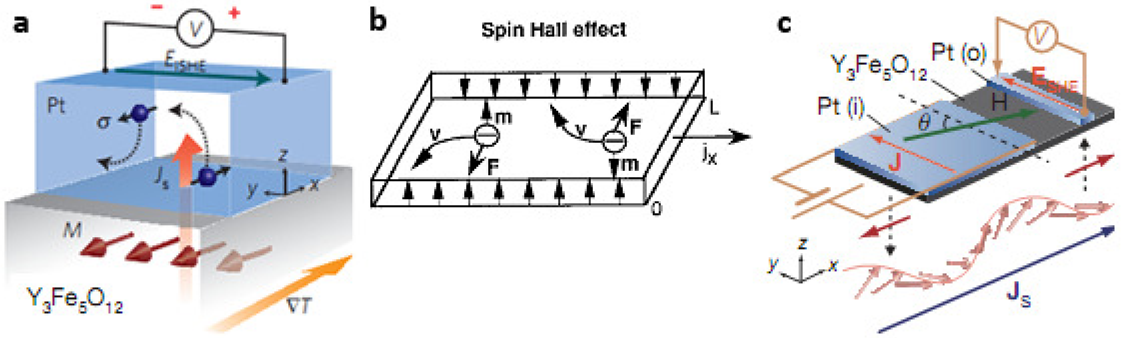

Fig 3 a A spin-wave in the ferromagnetic insulator like $Y_3Fe_5O_{12}$ can be transferred to a spin current in a nonmagnetic metal by a process called spin pumping. A spin current in a nonmagnetic metal with high spin-orbit interaction like platinum can be transformed into an electrical current by the inverse spin Hall effect. The electric charge $\boldsymbol{E_{ISHE}}$ is generated according to $\boldsymbol{E_{ISHE}} \propto \boldsymbol{J_s} \times \boldsymbol{M}$ where $\boldsymbol{J_s}$ is the spin current in the platinum layer and $\boldsymbol{M}$ is the spin magnetization. [11, 12] **b** The direct spin Hall effect. An electrical current j_x is passed through a material and the spin-up and spin-down with magnetization m electrons get scattered with velocity v by a force F to the opposite sides of the material to create a spin current. [13] **c** Generation and detection of spin-waves in YIG. An electric current is passed trough the first platinum layer and is converted into a spin current by the direct spin Hall effect. This spin current is transferred to the second platinum layer by a spin-wave current in the YIG. In the second platinum layer the inverse spin Hall effect converts the spin current in a detectable electrical voltage. A magnetic field H must be applied for this measurements. The angle θ can be changed to prove the dependence of the measurement on the magnetic field and exclude some artifacts. [11]

The demonstration of spin currents in insulators broadens the scope of spintronics to allow more progress in the field. [11] The long spin current transmission length is one of the most important advantages for spin currents in insulators. The mechanisms to break the conservedness of spins is more efficient for electrons than for spin-waves. Phonons can also couple to the spin-waves to allow more long range transport and also other advantages like transport in nonmagnetic materials [9]. That advantage allows spin transport even in nonmagnetic insulators. Millimeter and centimeter transportation lengths have been obtained for insulators. [11]

The main challenge when using spin transfer torque and spin pumping to inject and detect spin currents is the efficiency of injection across the interface between the insulator and the nonmagnetic metal. These processes depend heavily on the interface and the quality of the interface between the two materials and has to be optimized for the specific interface and for every material couple [11, 12].

Spin currents in insulators have yielded only few applications. But one application has already gained large momentum and is researched throughout the world, like in the German Priority Program SpinCat (Spin Caloritronic Transport) [14]: the Spin Seebeck effect [12].

The spin Seebeck effect is a method to generate electrical voltages from a temperature gradient. A temperature gradient creates a spin current in a magnetized ferromagnetic material (**Fig 4 a**) and this spin currents can be detected electrically by the inverse spin Hall effect in an attached nonmagnetic metal (**Fig 4 b**). The spin Seebeck effect is a spin analogue of the conventional Seebeck effect and can thus be used to transform temperature gradients into electrical power. This spin Seebeck effect, unlike the conventional Seebeck effect, can be generated in insulators. This is mainly advantageous because the thermal conductivity can be decreased more in insulators than in conductors by the Wiedemann-Franz law [12]. So the power generation efficiency from temperature gradients can be increased. Currently that efficiency is still low, but more research should be able to increase it. [12]

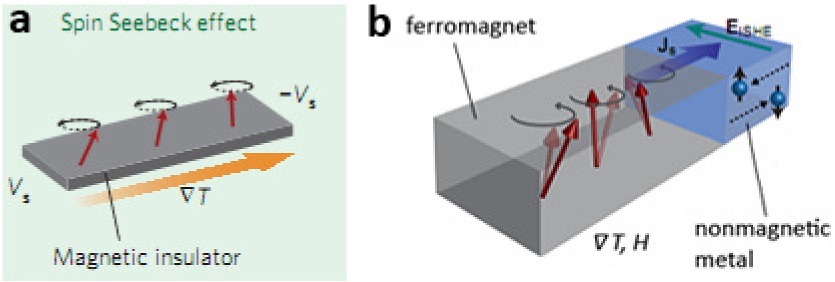

Fig 4 a Spin Seebeck effect in ferromagnetic insulators. A temperature gradient applied over a material induces spin voltages at both sides of the material. The spin voltages create spin-wave currents in the material. [12] **b** Device structure to generate electrical voltages from the spin Seebeck effect in insulators. A temperature gradient creates a spin current in a magnetized ferromagnetic material. Angular momentum is transferred at the interface between the ferromagnetic insulator and a nonmagnetic metal. The inverse spin Hall effect creates an electrical voltage. [15]

10.2 - Motivation

It has been claimed that all ferromagnetic materials can display the insulating spintronics effects [16]. So this field should be able to be broadened to new materials. But most ferromagnetic materials are metals so there are not many materials to choose for insulating spintronics materials. When trying to broaden the scope to organic materials to get advantages like low spin-orbit coupling, the choice of ferromagnetic insulators is even smaller. [17] One good class of materials which can display ferromagnetism and which also have large structural freedom, is the class of Inorganic-Organic Hybrids (hereafter called ‘hybrids’).

The aim of this proposed project is to transfer the principles established in the inorganic insulating spintronics research to this class of materials. It can provide knowledge about spin transportation in these hybrids in particular and in organic components in general.

Hybrids combine both organic and inorganic elements in one material. So it can benefit from the advantages of both organics and inorganics in one material to get useful combinations or completely new phenomena.

The macroscopic effects of inorganic materials are typically characterized by covalent and ionic interactions. They offer the potential for high carrier density and mobility, a wide range of band gaps, magnetic interactions (for example ferro- or antiferromagnetic), ferroelectric transitions and thermal stability. Organic materials typically have their macroscopic effects dominated by weaker interactions like hydrogen bonds and vanderwaals interactions. They provide nearly unlimited flexibility of structural diversity, cheap and easy preparation and good polarizability. [18, 19]

Hybrids can have several properties and applications. Useful properties can be transparency, flexibility, durability [20], multiferroicity [21] and even new electronic and optical properties which do not belong to the organic and inorganic building blocks [22]. Several applications have already been found, including bonding of hydrogen [23], contact lenses, coatings [21], energy-storage applications, photovoltaics and sensors [24].

The basic structure for one class of hybrids is shown in **Fig 5**. It is composed of an inorganic layer of octahedra with organic molecules stacked in between. The octahedron is composed of a metal in the middle with halogens ordered around the metal. The organic molecules have an ammonium group which interacts with the inorganic layer. Some of these hybrids are ferromagnetic. [19, 21, 25, 26]

Hybrids have some advantages over conventional inorganic materials for spintronics. The inorganic components can introduce magnetism in the system. The use of organic materials introduces low molecular weight elements that have very small spin-orbit coupling [7, 8]. So the spin currents are more conserved in organics than they are in high molecular weight inorganics. Another advantage is the possibility to make low dimensional structures. **Fig 5** shows a two-dimensional structure with inorganic and organic planes. Different transportation physics can be found in such low dimensional structures [27]. The spin Seebeck effect is expected to profit from low dimensionality as in analogy some of the highest conventional Seebeck effects have been realized in those kind of structures. [28]

These hybrids also have disadvantages compared to other materials. The main disadvantage is the low Curie temperature for the known ferromagnetic hybrids. The transition temperature is in the order of 10 K [18, 29] which makes direct implementation into practical room temperature devices impossible. A disadvantage that the hybrids share with normal organic materials is that the surface properties are generally not homogeneous [30]. So the spin injection across an interface is very dependent on the interface properties and quality. So the spin injection between the ferromagnetic material and a nonmagnetic metal is expected to be lowered. The spin injection is also most probably less optimized for the interface between a hybrid and a nonmagnetic metal than for an inorganic material and a nonmagnetic metal as the material’s properties are more different.

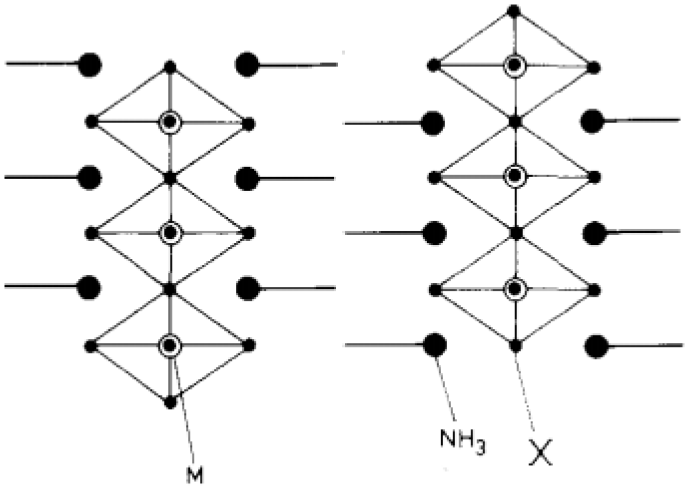

Fig 5 General structure of hybrids. It consists of inorganic and organic layers. The inorganic layer is composed of octahedrons with a metal M in the middle and halogens X around it. The organic layer is composed of molecules with an NH_3-group at the end which bonds to the inorganic layer. [26]

Next to the interesting properties the hybrid systems have, they can also serve as a model system for insulating spintronics in organic materials. The current organic ferromagnetic materials have a rather fixed structure so the possibilities are limited [31]. Hybrids have much more structural freedom to provide much more options for initial research. The inorganic components in the hybrids can introduce magnetism in the material so spin currents are possible, mostly irrespective of the organic component chosen [32]. This allows good research of the influence of different organic components on spin transport.

Using organic materials could bring the same kind of impact to spintronics as organic materials did to electronics which has grown into a huge field the last decade. The performances of organic electronics are often inferior to the inorganic counterparts. But the advantage is that it is possible to build cheap, light-weight and sometimes even flexible devices. Several electronic elements like switchers, sensors and rectifyers have already been made and applications like LEDs and solar cells have already been commercialized. [33, 34]

Research that is related to, but still different than this proposed project has been performed on conducting nonmagnetic organic materials. [7, 8] Most research is focused on magnetoresistance with a nonmagnetic organic component as a spacer between two inorganic ferromagnets. Several organic components have been used in those structures like small molecules, polymers [35], graphene [36] and carbon nanotubes [8]. Magnetoresistance has even been observed in organic materials without the use of any ferromagnetic materials [35]. That is a demonstration of the unique new capabilities organic materials can show.

The basic principles in inorganic insulating spintronics have just been discovered and much research remains to be done. That means it is wise to already start exploring the principles in new materials to deliver new knowledge to the field and help it mature faster. Transferring these principles to the hybrids can show new insights and possibly new unexpected phenomena just like organic electronics and spintronics have shown new phenomena. Proving spin currents in hybrids can start a completely new field of spin currents in insulating hybrid and organic materials. Since the large majority of those materials are in fact insulators [8] this can prove to be quite a large field. There is still a long road from this initial research to practical devices so in order to be able to benefit from the possible devices it is requried to start this new field as soon as possible.

10.3 - Goals

The proposed project has two main goals.

1. Transfer the principles and experiments used in insulating inorganic spintronics research to the class of Inorganic-Organic Hybrids.
2. Optimize spin currents in the Inorganic-Organic Hybrids.

10.4 - Plan of work

In the proposed project four years work will be carried out by one PhD student. The available time will be divided among several goals for this project.

The **first year** will be devoted to transferring the principles and experiments in insulating spintronics to the class of Inorganic-Organic Hybrids, research that has never been done before.

The well-established hybrid $CuCl_4(C_6H_5CH_2CH_2NH_3)_2$, bis(phenyl ethyl ammonium) tetrachlorocuprate(II), hereafter called Cu PEA, will be used as a model system. The crystal structure of this hybrid is shown in **Fig 6** and follows the schematic structure of **Fig 5**. It consists of inorganic layers of copper-chloride octahedra with two organic layers of phenyl ethyl ammonium molecules stacked in between. The layers are bonded by hydrogen bonds between the organic ammonium group and the inorganic chloride. [29] Interesting properties of this molecule are its insulating nature [37], ferroelectricity caused by the ammonium-group hydrogens and ferromagnetism [29]. The ferromagnetic order is a two-dimensional order caused by 90 ° superexchange between the copper atoms in a d^9-state. The transition temperature is only 13 K because of the weak superexchange interaction and the (quasi-) two-dimensional order. [29]

Flat Cu PEA single crystals can be grown easily by self assembly of the starting materials copper chloride and 2-phenyl ethyl ammonium chloride. The starting materials are dissolved in a solvent like ethanol and they crystalline upon the evaporation of the solvent. High quality millimeter to centimeter crystals can be obtained by this method. [37]

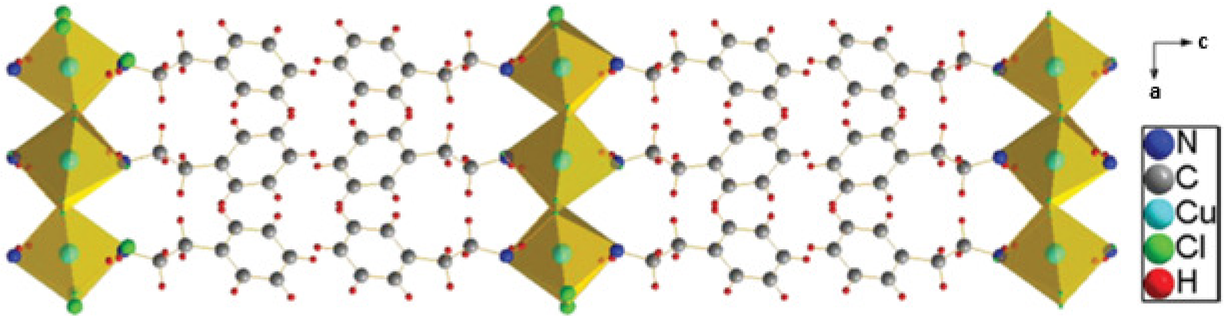

Fig 6 Crystal structure of $CuCl_4(C_6H_5CH_2CH_2NH_3)_2$ (Cu PEA). It consists of inorganic layers of copper-chloride octahedra with two organic layers of phenyl ethyl ammonium molecules stacked in between. [29]

The experiments that will be transferred from the inorganic insulating spintronics research to these hybrids are the electrical injection and detection of spin currents and the spin Seebeck effect. These experiments are the easiest experiments and hold most promise. So the key elements that will be carried out are the direct spin Hall effect and subsequent spin transfer torque, spin pumping followed by the inverse spin Hall effect and the generation of spin current from a temperature gradient. The requried conditions for these experiments are a magnetic field, a thin nonmagnetic metal on top of the material and for the spin Seebeck effect a temperature gradient.

The contacts to the inorganic materials in literature were made using sharp tungsten needles that are pressed onto the surface. These hybrid materials are fragile and will probably break when sharp needles are pressed onto the surface. So the contacts to the hybrids will be made by solvent-based silver paste to create contacts gently. The solvent evaporates after some time to give a solid and stable contact. The measurements will be carried out in a Physical Properties Measurement System (PPMS), a cryostat built for accurate measurements. It allows the application of a magnetic field in the longitudinal direction. The experiments require the ability to change the angle of the magnetic field to prove the relationships between the magnetic field and the measurement. In order to change this angle it is needed to upgrade this PPMS with a transverse magnet which can rotate freely in the transverse directions.

The methods to build devices for these measurements in a probe system are reported in literature [15]. Similar devices will be built but then for use in the PPMS. The devices will allow the application of magnetic fields in the right directions and a temperature gradient for the spin Seebeck effect. Deposition of a thin metal layer on the material can be done by standard techniques like sputtering or e-beam evaporation available within the insitute.

Initial attempts at these measurements might not be optimal. So a lot of effort has to be devoted to the optimization of this process. Different, more efficient measurement methods have to be established. This optimization will take place in the **second year**.

The most important optimization will be the improvement of the interface between the hybrid and the nonmagnetic metal. This interface is very important for the spin transfer by spin transfer torque and spin pumping as shown in the introduction. The surfaces of the flat hybrids are parallel to the two-dimensional planes and terminated by organic layers. Organic materials, and the hybrids share those properties, are generally soft, more fragile and have a rougher surface than inorganic materials. This can lead to interfaces such as shown in **Fig 7 a** for an organic material. So the optimization of the interface requires much more engineering than for conventional inorganic materials. [30, 38] The most visible methods to improve such interfaces are by growing higher quality single-crystals by optimizing the chemical conditions or surface cleaning methods such as gentle polishing or cutting a crystal in half to produce two clean surfaces. Some, but not a large improvement can be expected from these methods.

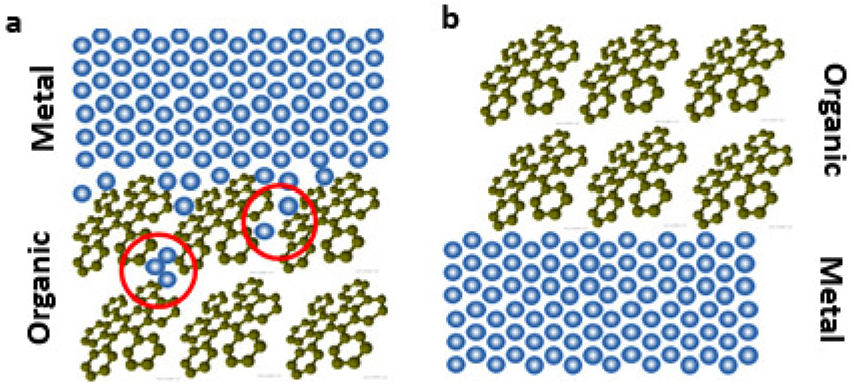

Fig 7 a Schematic drawing for an interface between an organic and a metal deposited on top of the organic. The organic surface is not perfect so many defects can be formed on the interface. **b** Schematic drawing for an interface between a metal and an organic deposited on top of the metal. Less defects will be produced because they can not be introduced by the deposition of a metal on the organic. [38]

More improvement can be expected by trying other methods to synthesize the hybrids. The most notable methods are spin coating which has been demonstrated on other hybrids [39] and Langmuir-Blodgett synthesis. Both methods allow the deposition of a thin layer of hybrid on a substrate. One advantage is the ability to deposit the metal films before the deposition of the hybrid which can result is much better interfaces between the materials as shown in **Fig 7 b**. Another advantage is the ability to get thin films which have more potential for practical devices. [39, 40]

Langmuir-Blodgett synthesis is a method where several single layers of material are deposited on a substrate. It makes use of amphiphilic molecules, molecules that have a polar and a nonpolar part in one molecule. Those molecules can be packed at a water surface with the nonpolar parts aligned away from the water. By dipping a nonpolar substrate in this water, the surface molecules in the water start to bond to the substrate to form a monolayer. A double layer will be formed by bonding of the polar groups when taking the substrate out of the water. This process can be repeated for a multilayer. Work on Langmuir-Blodgett synthesis of hybrids has been carried out in this institute based on similar work on lead titanium stearic acids [41]. Copper chlorides were used as inorganics and $C_{18}H_{35}NH_2$ as organic molecules. Preliminary results showed that hybrid-like structures with hints of ferromagnetism were observed.

The Langmuir-Blodgett films show great promise to solve the interface quality and give devices with thin layers. But the Langmuir-Blodgett synthesis of these magnetic hybrids are still largely unexplored so it is far from known if the obtained results are good enough to use for these kind of measurements.

The **third and first half of the fourth year** will be used to determine the influence of the organic component on the spin conduction. Hybrids are very flexible materials in the sense that it is very easy to replace one component by another component. This property will be used in this part of the research to synthesize hybrids with different organic parts while all other properties stay the same.

Conjugated systems show highest electrical conductivity in organic materials. They are systems with delocalized p-orbitals like for example a phenyl ring (**Fig 8**). Conduction can take place within or between such conjugated systems. Conduction between two conjugated systems depends stronly on the electronic overlap between the systems. Spin-wave conduction should also be promoted by conjugated systems since they are more tolerant to spin distortions. [32] So the best option to increase spin conduction in the organic part of the hybrids is to increase conjugated systems and their overlap.

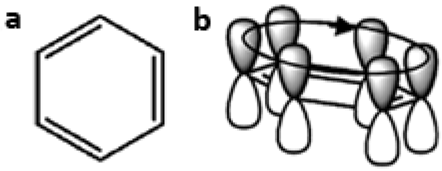

Fig 8 a A phenyl ring drawn in chemical representation. It has three double bonds which are delocalized over the ring. **b** Orbital representation of a phenyl ring. The p-orbitals on the carbon atoms are aligned out of plane. [32]

Those goals can be achieved by synthesizing hybrids with other organic molecules. The single crystal synthesis is fairly straightforward as it is similar for all these hybrids apart from the optimization of the chemical conditions. The synthesis of Langmuir-Blodgett films with different organic molecules is more demanding. Molecules without conjugated components were used in the current synthesis and replacing them by conjugated components makes them less amphiphilic which makes the process harder.

The new materials should be characterized by magnetic measurements to determine their (ferro-)magnetic properties and XRD to determine their crystal structure. These facilities and a lot of knowledge about these characterizations are present in the group.

Cu PEA has conjugated elements in the form of phenyl rings as was shown in **Fig 6**. The angle between the phenyl rings in the crystal structure is 77 °. This head-to-tail alignment of the phenyl rings give very bad overlap between the conjugated systems in Cu PEA. A better overlap can be achieved by introducing steric hindrance and anisotropy in newly synthesized hybrids which forces the conjugated systems to align head-to-head. 1-ethyl ammonium naphthalene was suggested as a molecule that will allow good overlap between the conjugated systems by these principles. This is supported by electronic band structure calculations which have shown a much higher organic valence band than for Cu PEA. [32]

The spin conduction of the different hybrids synthesized here will be determined. There will be a contribution of spin transport of both the inorganic and the organic components. The organic contribution will change for all hybrids while it should give a constant contribution for the inorganic part. The constant inorganic spin conduction could obscure signals from organic components with (much) lower spin conduction and make it hard or even impossible to distinguish the differences between different organics. But the inorganic spin conduction will at least allow reliable measurements in all hybrids and can give clues about the ratio of spin conduction in organics compared to inorganics.

The time for the **last half year** will be used to write the PhD thesis, write publications and visit conferences.

11. Infrastructure

Most infrastructure that could be required for the proposed research is already present in the group. The major infrastructure includes, but is not restricted to:

- Chemistry lab with fumehoods and other chemical tools
- Glove box
- Bruker d8 powder diffractometer
- Bruker Apex single crystal diffractometer
- Quantum Design Magnetic Properties Measurement System (MPMS)
- Quantum Design Physical Properties Measurement System (PPMS)
- Atomic Force Microscopy

Other infrastructure required is available within the institute:

- Langmuir-Blodgett thin film fabrication in collaboration with the Surfaces and Thin Films group of Prof. dr. Rudolf
- Clean room facilities with e-beam evaporation and sputtering system in collaboration with the Physics of Nanodevices group of Prof. dr. Van Wees.

12. Application perspective in industry, other disciplines or society

The field of insulating spintronics has started only very recently and little is known about it yet. This proposed project will extend this new field to a much broader perspective by transferring the principles to Inorganic-Organic Hybrids instead of the inorganic used up to now. No special applications are envisioned yet for this new class of materials in this field since no research has been done in the field.

This research can also be a starting point for insulating spintronics in organic materials. A similar transfer from inorganic to organic electronics has gained huge impact and is being commercialized by companies as Hitachi [42].

Now already one application has been found for insulating spintronics research: the spin Seebeck effect [12]. This effect generates a voltage induced by a temperature gradient over a material. The practical aspect of this effect is for example shown by a spin-current-driven thermoelectric coating [40] where an insulating ferromagnet deposited on several substrates, including glass, can yield this effect. This means that electrical power can be generated from temperature differences in something as simple as a glass plate.

Practical devices with the current hybrids are not possible because the ferromagnetic transition temperature is far below room temperature. Further research should focus on improving this transition temperature to make practical applications possible. The advantages of these hybrids, easy and cheap preparation and a long spin lifetime, make it worth to investigate these materials for future applications.

13. References

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