Project title: Compliant Magnetosensory Systems: Enabling magnetic functionalities for e-skins, soft robots and healthcare

Projektnummer/Aktenzeichen: J21/2017

Executive Summary

Flexible and imperceptible electronics are key for today's digital technology era. Flexible and printable sensory systems such as gas sensors, temperature sensors, strain gauges and magnetic sensors have gained significant attention and importance due to their noteworthy applications in soft robotics, electronic skins, wearable electronics, smart textiles and future bio-integrated consumer electronics. A special role goes to magnetosensorics, with its possibility for contactless monitoring mechanical movements, or for implementing navigation and orientation capabilities. Thus, integrating magnetic sensorics with flexible, stretchable and printable electronics is essential for magneto-electronic systems. While the field of flexible electronics has progressed exponentially in the last decade, very few studies addressed the integration of magnetic sensors with flexible electronics.

The foremost important goal of the project was the development of a novel type of magnetic sensors with integrated electronic system. Developed on thin polymer membranes, this system allows for operation on a human skin. In order to achieve this state of art, it was important to specifically design and integrate thin-film microelectronics with magnetic sensors. We have successfully developed and tested this imperceptible system, integrating giant magneto resistive sensors and electronics based on p-type organic thin film transistors (OTFTs) that included switches, bootstrap shift registers, and signal amplifiers on an ultrathin polymer substrate. In addition, we have also addressed such challenges as low voltage operation and signal degradation associated with OTFT based electronic system. We were able to achieve a low power consumption of the device by applying the bootstrap design of shift register, which avoids DC power dissipation. Low power consumption, reduced signal degradation and high-speed operation of the system will be valuable in next generation flexible and wearable system. Proving this, we also demonstrated that the achieved imperceptible magnetoelectronics system can be utilized as a compliant magneto-electronic e-skin, that can follow deformation without degrading the performance of the device.

1. Achievement of objectives and milestones

The foremost important goal of the project was the development of active Thin Film Transistor (TFT)-based electronic circuitry on shapeable and imperceptible supports to be integrated together with previously developed giant magnetoresistance (GMR) sensors. The combination of both components on the same compliant platform allows for soft, smart and multifunctional magneto-responsive systems with advanced signal processing capabilities, to be utilized in electronic skin, soft robots or novel medical healthcare systems. This demanding objective was tackled in a scientific work program with 7 individual work packages that are listed again in the following, together with four milestones.

We were able to successfully complete all work packages but for WP7 and achieved all milestones except for M4. Hereby, we closely followed the initial work plan. Modifications arose from a stronger focus on large-scale fabrication of GMR multilayers and strategies for printed magnetoelectronics in the final project year, which led to the derogation in WP7 and its associated milestone M4. Additional modification arose from necessary personnel changes in the project management (see Point 2), which nonetheless guaranteed the successful completion of the project.

In WP1, indium gallium zinc oxide (IZGO) TTFs have been successfully prepared and optimized with state-of-the-art performance concerning high ON-OFF ratio of more than 10^7 and approximately 0 V cutoff gate voltage with threshold voltage of about 1.5 V. The overall transfer and output curves (Figure 1) demonstrate that the transistors can operate with 5 V supply and even lower, allowing for standard and flexible battery supply. Moreover, the high ON current of 100 µA is beneficial when driving relatively high-power devices, such as LED`s or sensors, or capacitive loads i.e. cables and chemical sensors. Thus, **WP 1: Preparation and optimization of IGZO TFTs** has been successfully completed. The TTF layer stack consists of polyimide support, metallic gate (Ti), gate dielectric material (Al_2O_3/HfOx), n-type IGZO semiconductor, passivating polyimide layer and metallic (Ti/Au) source drain connections, all prepared on a glass support, from which the ultrathin electronics can later be delaminated and transferred to i.e. skin. With this successful packaging strategy, we furthermore completed **WP 5: Packaging strategies**.

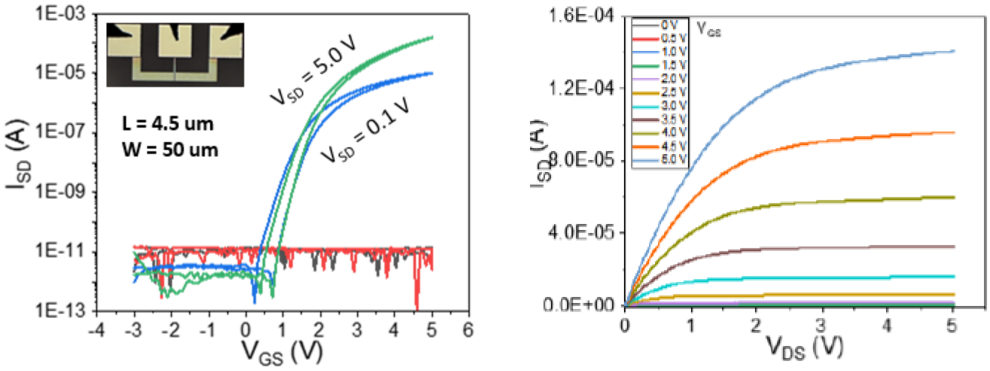


Figure 1: Transfer (left) and output characteristics (right) of an individual IGZO based TFT encapsulated in polyimide, demonstrating successful operation.

In a fruitful collaboration with one of the leading research groups for compliant organic circuitry in Osaka, Japan, we were able to design, fabricate and test an imperceptible magnetosensory system, featuring active multiplexing and signal amplification of a distributed GMR sensor array, as shown in Figure 2. This system demonstrates the on-site addressing, power supply and

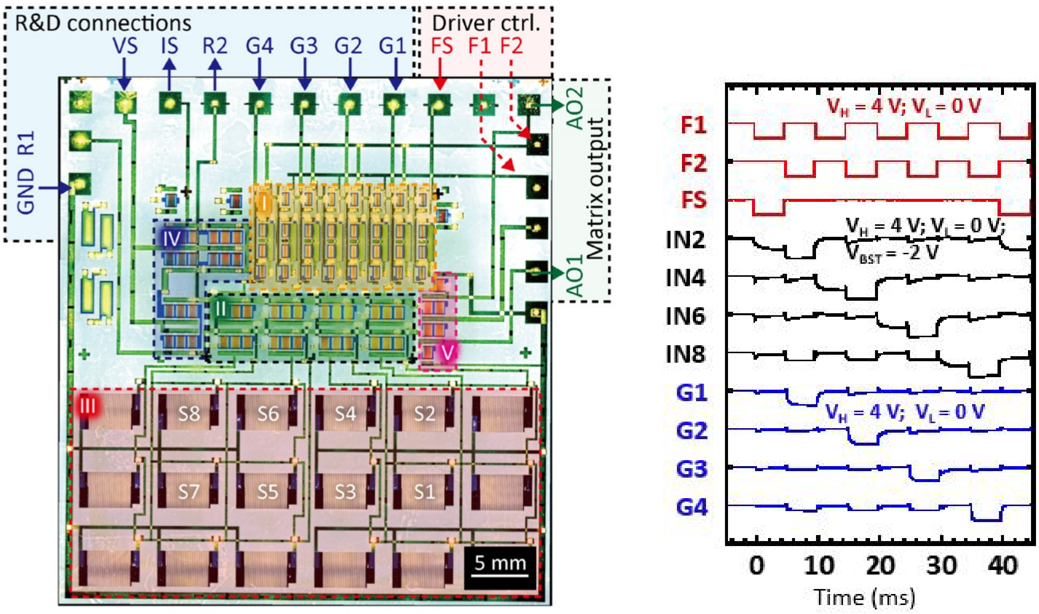
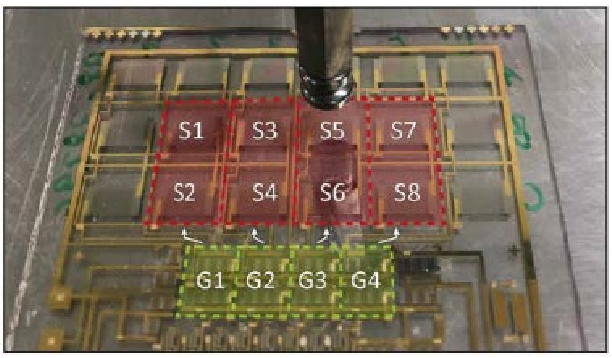


Figure 2: Left: imperceptible magneto sensory system prepared on parylene, consisting of five main building blocks (labeled I to V, see text). **Right**: shift register in operation, with input (F1, F2, FS) and output gate signals (G1 – G4) in time.

signal conditioning of eight magnetic sensor elements using only five wires in total. The magnetosensory system consists of five major building brocks: I - a four-stage bootstrap organic shift register to drive the switching OTFTs; II - switching matrix transistors (switching OTFTs) for addressing each of the sensor cells; III - the 2 x 4 GMR sensor array; IV - a current mirror providing a stable bias current for each of the matrix rows; V - organic inverters explored as common source amplifiers. This results in a simple but effective circuit representing all necessary components for an active matrix integrated electronics, fabricated on an ultrathin (~3 μm) parylene membrane.

The bootstrap circuit design of the shift register in particular, overcomes several limitations imposed by the utilization of organic semiconductor materials in TFT architectures. It allows the usage of p-type only transistors in manageable amounts and balances any unavoidable distributions of transistor parameters by means of specified capacitors integrated into the circuit. This results in a very low power consumption of the active matrix system (<10 μW) at relatively high operation frequencies (100 Hz). The entire circuit can be battery powered with only 4 V directly supplied via the clocking signal of the shift register. The onboard amplifiers provide a gain factor of 87.5 and boost the signal from the GMR multilayers sensor elements to a total sensitivity of 400 V/AT. This completes **WP2: Circuit and system design and modelling** and achieves milestone **M1: GMR sensor circuit with high amplification or multiplexing**.

Another activity concerned the design and integration of multilayer-based giant magnetoresistive sensors made of Py ($Ni_{81}Fe_{19}$)/Cu bilayers. We successfully realized this goal in a long meander design of the GMR sensor, possessing resistance in the range of 25 kOhm suitable for operation with *i.e.* OTFT switches, amplifiers and moderate bias currents of 200 μA. These GMR sensors possess high value of the GMR response ~12 %, comparable to similar elements prepared on rigid silicon supports. For testing compliance in imperceptible applications, the GMR multilayer on perylene substrate the magnetoresistance characteristics were obtained in the flat state and while it was bent to a radius of 2 mm. A maximum resistance variation of 1% indicates that the GMR sensors are sufficiently compliant for use in flexible electronics. In total, GMR performance and insensitivity to deformation demonstrate the applicability of the GMR sensor circuitry. Thus, we have successfully completed **WP3** and **WP4** and achieved milestone **M2: Encapsulated sensory circuits with minimum performance deviations upon deformation**.



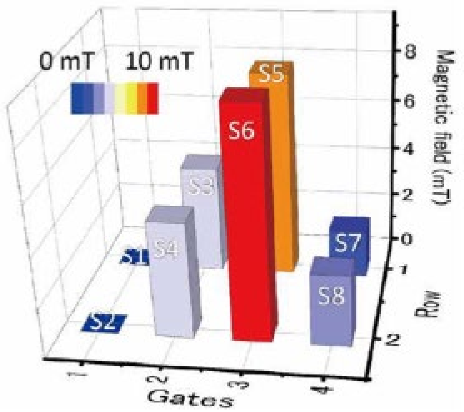


Figure 3: Left: weak permanent magnet (max 40 mT) on top of sensor matrix position S5 and S6. **Right:** response of magnetosensory matrix system displayed as a 2D field map.

In order to demonstrate the multiplexing capability of the magnetosensory matrix system, we performed real time magnetic mapping experiments using the imperceptible MSM system to detect the stray field of a weak permanent magnet placed above (Figure 3). The position of the permanent magnet is traced with the sensor matrix (see labels S1 to S8) with high precision through the clearly measured field signal. In a further experiment we demonstrated finger motion sensing by fixing permanent NdFeB magnets on separate finger tips and moving the fingers towards the e-skin magnetosensory matrix system attached to the inner palm of a hand

(Figure 4). These successful experiments account for the achievement of **WP6: Magneto-electronic skin** and **M3: Magnetosensory electronic skin with a distributed GMR sensor array and signal condition**.

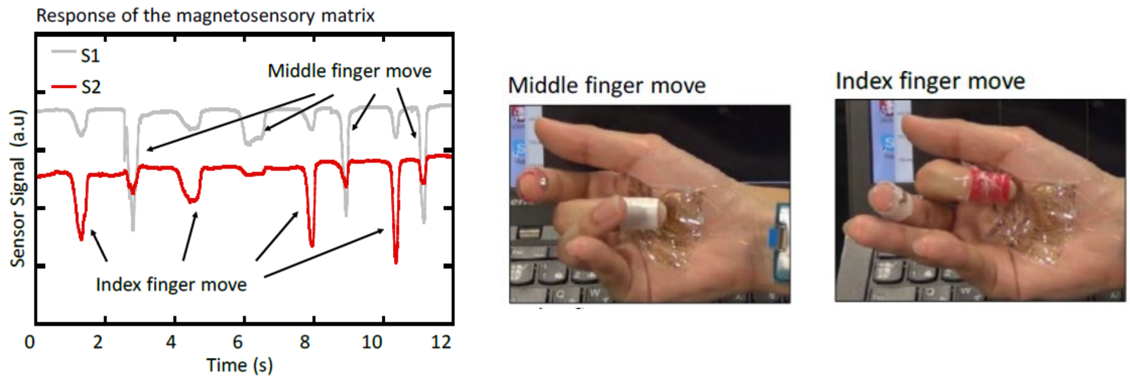


Figure 4: Real-time response of magnetosensory e-skin to different finger motions.

In an extension to above, activities additionally focused on solving an important fabrication hurdle for imperceptible magnetosensory systems, namely the large-scale production of GMR materials on flexible substrates with large GMR response. For that, a high throughput roll-to-rol sputter deposition system was installed and launched, which allows preparation of GMR multilayers on 200 mm wide and 100 m long webs of flexible substrates, such as polyethylene terephthalate (Figure 5). Optimizing the sputter power and hence layer architecture of a [Co/Cu]25 GMR multilayer we achieved a GMR ratio of around 40% in a large portion of the 100 m long web. The large-scale production now allows the formulation of magnetoresistive inks, which is another strategy towards compliant magnetosensory systems, as it allows the printing of magnetic sensing elements at predefined positions on a flexible electronic circuitry. Within the project, the full process of preparing the magnetoresistive ink, printing of mm-sized magnetic sensing elements and contacting them via printed Ag contacts has been established.

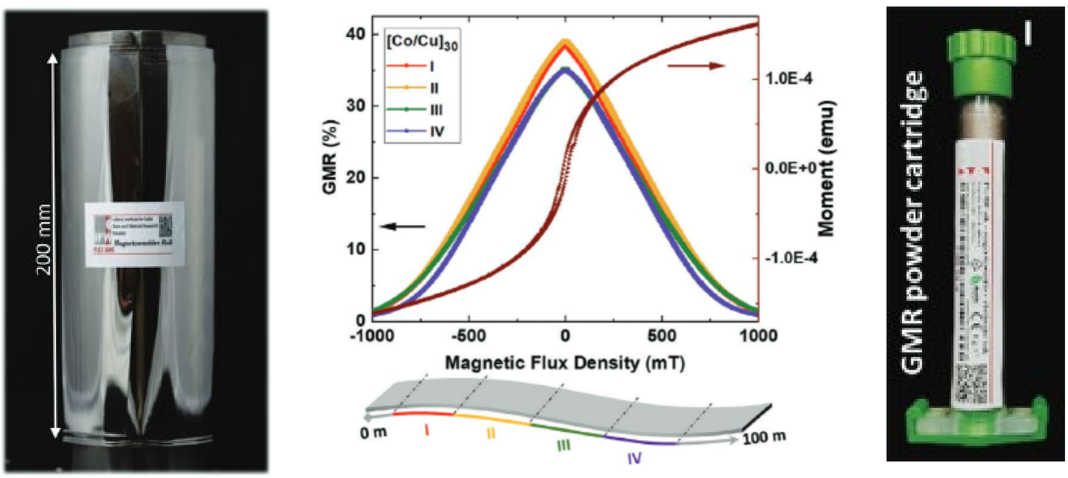


Figure 5: Left: 100 m long PET web with [Co/Cu] multilayer. **Middle**: Large GMR in a large fraction of the web. **Right**: GMR powder prepared from shredded GMR flakes dissolved in hexaflouroiso-propanol.

2. Activities and obstacles

After leading the Leibniz- Junior Research Group for 17 months, the promoted speaker, Dr. M. Melzer, has found a proceeding employment at the Bundesanstalt für Materialforschung und -prüfung (BAM) in Berlin. The supervision and scientific leadership at the host institution was taken over by Prof. Oliver G. Schmidt for a successful continuation of the project. With Prof. Schmidt taking the directors position of the Research Center for Materials, Architectures and

Integration of Nanomembranes (MAIN), Chemnitz, in September 2021, the leadership at IFW Dresden was taken over by Prof. Dr. Bernd Büchner for a successful completion of the project.

Technical issues during the project concerned the movement of the carrier web in the roll-to-roll system, which partly led to wrinkling of the foil and wrong positioning. The problem was solved with a modified motor control leading to a constant foil tension, and with installing a barcode scanner inside the system that monitors the position of the foil.

3. Results and successes

We have successfully fabricated, characterized and tested an imperceptible magnetosensory (MSM) system, that operates at low voltage, with low power consumption and in real time, and demonstrated its suitability for e-skin applications. Key to the performance is the integration of a magnetic sensor with high GMR, which was achieved by optimizing sputtering parameters and growth conditions in a large-scale roll-to-roll sputter deposition system.

The work has been published in highly reputed journals

- M. Melzer, D. Makarov, O.G. Schmidt, „A review on stretchable magnetic field sensoric", *J. Phys. D: Appl. Phys*. **53**, 083002 (2020).
- M. Kondo *et al., "*Imperceptible magnetic sensor matrix system integrated with organic driver and amplifier circuits", *Sci. Adv.* **6**, eaay6094 (2020).
- P. Gupta *et al., "*Large scale exchange coupled metallic multilayers by roll-to-roll (R2R) process for advanced printed magnetoelectronics", *Adv. Mater. Technol*. **7**, 2200190 (2022).

and has also been addressed and highlighted in various press releases, such as e.g. in ScienceDaily and Nanowerk News.

4. Equal opportunities, career development and internationalisation

The applicant of the Leibniz-Competition program and leader of the Leibniz-Junior Research Group, Dr. M. Melzer, has found a proceeding employment at the Bundesanstalt für Materialforschung und -prüfung (BAM) in Berlin. The new permanent position denotes a significant career advancement.

Equal opportunity is the fundamental right of every individual, irrespective of gender. IFW is committed to gender equality and encourages and promotes women in science, especially with regard to academic leadership positions. This is implemented in job announcements and the selection of applicants. The IFW objective of equal opportunity is being observed by the equal opportunity commissioner since 2002. In the present project a female scientist, Dr. Preeti Gupta, has been employed as a postdoc for two years, allowing her to gain significant expertise for her future carrier.

5. Structures and collaborations

Within this project we had an extensive collaboration with the group of Prof. Dr. Tsuyoshi Sekitani, ISIR, Osaka University, PhotoBIO-OIL, Japan. During this collaboration we had an exchange of PhD students and numerous samples. Furthermore, the outcome of the project arose interest from an expert group on magnetoresistive sensors in Beijing, Prof. Dr. Quenwen Leng from the School of Microelectronics at Beihang University. A PhD student from his group is performing part of her experimental work on flexible magnetoelectronics at IFW Dresden in the framework of a Chinese State Scholarship, and the fruitful collaboration is planned to be continued.

6. Quality assurance

IFW Dresden follows the rules for good scientific practice by the Leibniz Association (WGL) and the German Research Society (DFG), with regulations governing relations with colleagues and cooperation, regulations governing publication of results and regulations governing a proper review process, and instructs employees about these regulations through tutorials. Experiments are documented in laboratory books and all primary and meta data are stored in a central IFW archive and are accessible upon reasonable request. Results are published in well reputed, peer-reviewed journals, one of three in open access format.

7. Additional recources

No other resources than planned have been used in the project. The co-funding of the host institute (IFW Dresden) to the total project budget was 47%.

8. Outlook

The field of flexible and imperceptible electronics is most importantly dependent on the feasibility of large-scale production of electronic components on flexible substrates. The activity at IFW to successfully install and launch a roll-to-roll sputter deposition system is an important step into that future development. We were able to prepare GMR multilayers on 200 mm wide and 100 m long webs of flexible substrates with state-of-the-art magnetoresistive performance. Future work will focus on evaluating large-scale preparation of other magnetioresistive material systems, such as tunnelling magnetoresistance architectures, of roll-to-roll preparation of polymers for encapsulation and for preparation of other functional material systems, such as solar cells and thermoelectric materials, to be integrated into flexible sensorics and electronics.