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*L. Rissing, A. Belski, T. Creutzburg, T. Griesbach,
M. Kaiser, A. Wienecke, M. Wurz*

MAGNETIC MEMS

Magnetic MEMS (Micro Electro Mechanical Systems) gained much of importance during the past 25 years. Today for example magnetic MEMS are part of the sensor network in cars. Magnetic sensors measure the rotation of the wheels to generate the information necessary for the ABS (anti-lock brake system) or for stabilization systems like ESC (Electronic Stability Control). They are also used to measure the angle of the stirring wheel as a basic part to implement the drive by wire concept. Another important field of application is the consumer electronic. MEMS are used as a part of an electronic compass. There are many more examples for magnetic sensors and actuators. We will present some examples for magnetic sensors and actuators developed during the last four years at the Institute for Micro Production Technology (IMPT) in Hanover.

MEMS; MAGNETIC SENSORS; MAGNETORESISTIVE DEVICES; MODULAR SYSTEM; EDDY CURRENT SENSOR; WRITE HEAD; HEARING AID IMPLANT; ACTIVE MICROOPTICAL SYSTEM.

*Л. Риссинг, А. Бельски, Т. Грицбург, Т. Грисбах,
М. Кайзер, А. Винеке, М. Вюрц*

МАГНИТНЫЕ МЭМС

В течение последних 25 лет магнитные микроэлектромеханические системы (МЭМС) приобрели важное значение в различных областях. Сегодня, например, магнитные МЭМС являются частью сенсорной сети в автомобилях. Так, магнитные датчики измеряют скорость вращения колес и генерируют информацию, необходимую для антиблокировочных систем или для электронных систем стабилизации. Магнитные датчики также используются для измерения угла перемещения колеса в качестве чувствительного элемента в системах привода проводного типа. Другой важной областью применения является отрасль бытовой электроники. Датчики МЭМС используются как часть электронных компасов. Существует много других примеров применения магнитных датчиков и исполнительных механизмов. Мы представим некоторые примеры для магнитных датчиков и исполнительных механизмов, разработанных в течение последних четырех лет в Институте производственных микротехнологий (IMPT) Университета Ляйбница в Ганновере.

МЭМС; МАГНИТНЫЕ ДАТЧИКИ; МАГНИТОРЕЗИСТИВНЫЕ УСТРОЙСТВА; МОДУЛЬНАЯ СИСТЕМА; ДАТЧИК ТОКА EDDY; ЗАПИСЫВАЮЩАЯ ГОЛОВКА; ИМПЛАНТЫ ДЛЯ ПЛОХОСЛЫШАЩИХ; АКТИВНАЯ МИКРООПТИЧЕСКАЯ СИСТЕМА.

I. Introduction

During the last four years the research activities at the IMPT in Hanover have been focused on the following topics. An important issue has been to find new fields of application for magnetic MEMS. Today, the basic principles of magnetic sensing and actuation are investigated in detail and in most cases well understood. But there is an ongoing demand to develop not only a simple sensor but a complete system to facilitate the application of the sensor. As a consequence other areas of technology have to be covered. For example data processing is very important and normally electronics is an essential part of MEMS. One of the key steps to realize a microsystem successfully is the packaging of the system. The advanced packaging technologies are relevant to achieve connectivity, robustness, and reliability and to allow an easy handling. It has to be taken into consideration that not only the thin-film processing is relevant for the costs. Packaging and testing is an important cost factor in the production process of MEMS.

It is necessary to concentrate not only on the thin-film processes to fabricate the sensor and actuator elements, but also on the packaging technologies to consider all these aspects during the design phase. To realize MEMS systems starting with the design from scratch it is also essential to develop the fabrication process in a holistic approach simultaneously.

Nowadays, microsystems are known for very low prices per system. The low price level is caused by low production costs for high volume production. The batch fabrication allows low costs per component, because the production costs are divided by the number of systems simultaneously produced. This argumentation is true if the number of produced MEMS is high. As a result it is normally much more difficult to start a low volume production. Therefore, it is necessary to find production processes to fabricate individualized sensors at an affordable cost level.

II. Industrial Applications

A. Industry 4.0 – Gentelligent components

Currently, the buzzword "industry 4.0" is very popular. Starting the Collaborative Research Center (CRC) 653, that is funded by the German Research Foundation (DFG), in 2005 the group of researches addressed many of those topics which are of importance also for the industry 4.0 today. The novel approach targeted the aim to enable the components to make experiences themselves during their life time, to collect and store information, and to pass this information to improve the next generation of components. A new word has been created and the components being able to collect and store information in their life time become genetically intelligent (short "gentelligent") [1]. This term has been chosen according to the transfer of information by genes in biology, although this technical process shows significant differences.

An important issue is that the components have to be able to gather data and to store the information. Accordingly, sensors have to be part of or have to be fused with the components. The IMPT has developed a variety of various sensors which have been directly attached to the surface of the respective component. Strain gauges, eddy current sensors, strain gauges, and anisotropic magnetoresistive sensors have been realized. These sensors have been developed to equip machine parts and tools with sensors to implement the sensing machine. As a consequence the volume is limited and a modular concept has been designed to reduce costs [2]. In the beginning a conventional process was applied. Silicon was used as a substrate material and after the thin-film processing the wafers were diced and thinned. The drawback of this procedure is that the sensor elements have been separated from the surface of the machine part or tool by the remaining silicon. The next approach was to use sacrificial layers. These sacrificial layers were dissolved using etchants. The sensor layers were embedded into a flexible polymer used as a handling framework. Summarizing the results it could be shown, that dissolving is possible, but the handling of the sensor foil has been a high challenge. If the sensors are separated from the silicon wafer in a ensemble, the polymer membrane unfurls and the sensors cannot be separated by dicing and handled afterwards. Separating the sensors before starting the dissolving process allows to dicing the wafer but handling of the sensor foils is still a challenge. In the context of the CRC 653 a new approach was developed taken all process steps starting with the thin-film process, the sensor separation, and the handling and application into account. In Fig. 1 the process for substrateless sensors is described.

The sensors are fabricated starting with a silicon substrate. As a first step the contact pads are deposited followed by an embedding layer of a polymer. On the polymer layer made of polyimide, the sensor layers are deposited and structured by photolithography and lift-off processes. The design presented in Fig. 1 shows an eddy current sensor. A single-turn excitation coil of copper generates the magnetic field. The sensing element is an AMR (Anisotropic Magneto Resistive) sensor realized as a meander-type resistor made of NiFe. Finally, the sensor is covered by a second polymer layer. After finishing the thin-film process, the backside material is etched and as a result the sensor membrane is only fixed to a frame of

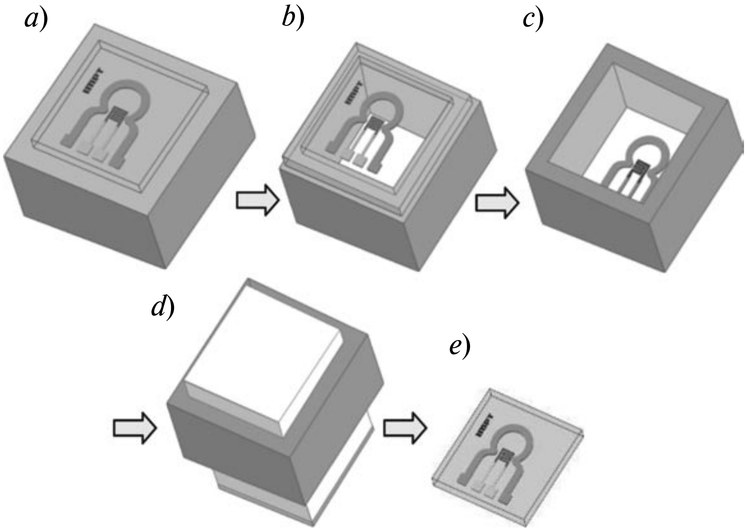

Fig. 1. Process for substrateless sensors

silicon (Fig. 1 *b*). In Fig. 1 *c* the wafer is turned. Using a stamp, the sensor can be solved from the carrier and attached to the machine part or tool (Fig. 1 *d*). In Fig. 2 the processed wafer is shown. The detail is revealing the structure of the eddy current sensor.

Fig. 3 depicts a sensor fixed to the frame provided by the silicon grid and the sensor after the stamping process.

The sensor design offers the possibility to realize four different kinds of sensors using the same set of photolithography masks and by depositing different materials [2]. In addition to the eddy current sensor, a temperature sensor, a sensor to measure the magnetic field, and a strain gauge sensor can be fabricated. This increases the flexibility and reduces the costs if only small piece numbers of sensors are produced.

The design and fabrication of the eddy current sensor was presented previously [3]. The measurement results were presented before as well [4]. The basic principle of the sensor is depicted in Fig. 5. The sensors are shown in Fig. 6. The eddy current sensor was used to measure the surface topography of a machined sample and the results were compared to the data gained by a confocal measurement. The qualitative comparison of the measured signals shows a very similar curve progression (Fig. 7).

The principle design has also been used to realize a strain gauge sensor. Only the meander-type sensor has been taken for this purpose. Although the layout is not optimized for a strain gauge, because the length and width of the sensing wire does not differ much from the connecting elements, the sensitivity

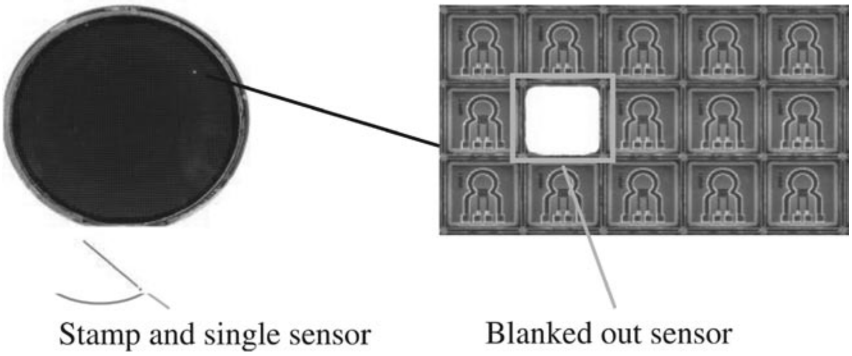

Fig. 2. Wafer with stamping tool, enlarged view of the wafer

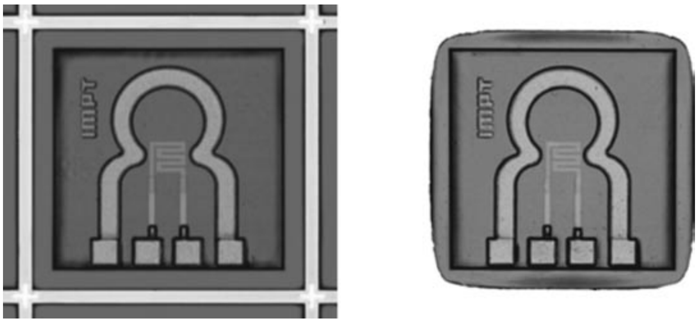

Fig. 3. Sensor fixed to the silicon frame and after the stamping process.
The size of the sensor is about 1 mm^2

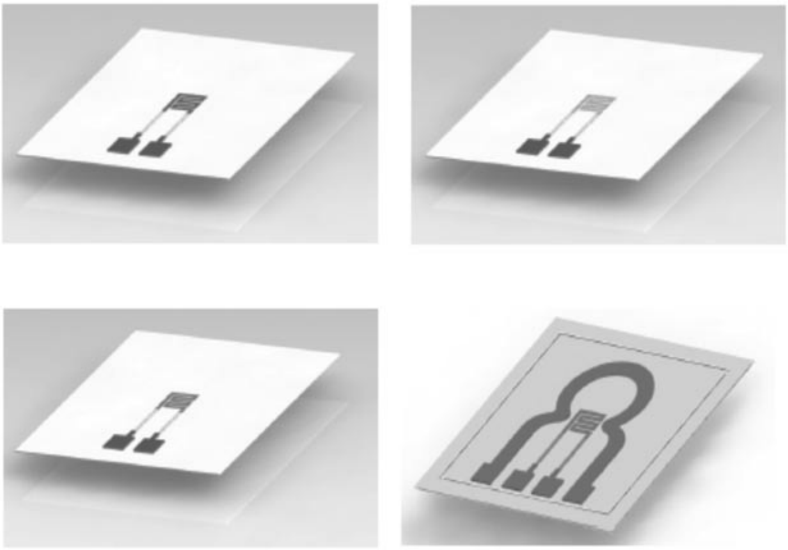

Fig. 4. These four different sensor types can be fabricated with the same set of photolithography masks

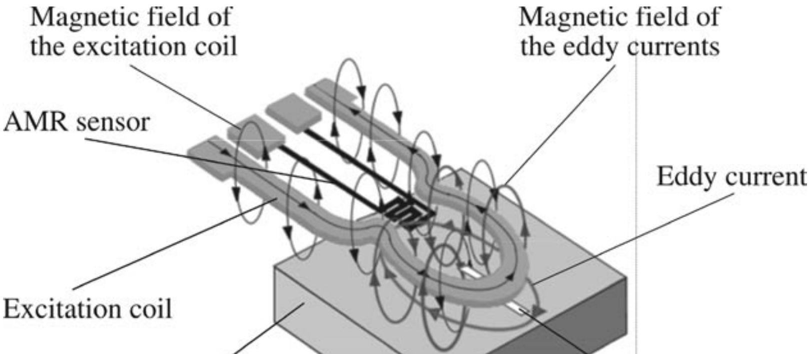

Fig. 5. Working principle of the modular eddy current micro sensor [4]

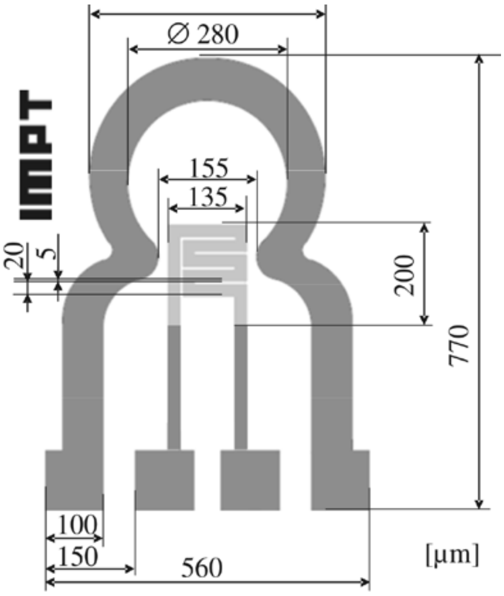

Fig. 6. Sensor dimensions [4]

is astonishing. Because of the thin polymer encapsulation layer, the sensing element is positioned in a close distance to the surface of the loaded part. The sensing structure is separated by less than a 8 µm polyimide film and a thin adhesive layer. 28 of these sensors have been integrated in the z-axis of a machining center and deliver strain and elongation values during the machining process.

In the framework of the CRC 653, the IMPT also designed a write head to store information magnetically in the surface of magnesium. Magnesium typically is not hard magnetic. The Institute for Material Science (IW, Hanover University) developed a new material for this purpose. To do so, hard magnetic material was embedded into a magnesium matrix.

The first approach used ferrite material to pattern a conventional write head [5]. The head has been fabricated applying a dicing process. This is a grinding process used for profiling. The coil is wound around the magnetic core.

Because the surface of the parts to carry the information is not flat, the challenge is to build a flexible and adaptable write head. Another desired feature is a direct control of the written data. This requires the implementation of a read-after-write procedure.

The first flexible head design was presented in [5]. The schematic view of the write head is shown in Fig. 8.

First a copper foil-cladded polymer is processed. The copper coils are fabricated by etching the copper layer. Holes are drilled into the foil. Then a pre-structured NiFe foil is bonded to the backside of the polyimide by a double-sided adhesive tape. NiFe creates a softmagnetic backside layer. Fig. 9 shows the process to form the first part consisting of polyimide carrier and Cu coils.

In the second step, the NiFe foil is bonded to the Cu module. This is depicted in Fig. 10.

The assembly group is flipped over and the gap area is realized by electroplating into a photoresist form Fig 11.

The finished assembled head is shown in Fig. 12. Also depicted is a detailed view of the air gap region.

It is important to mention, that the heads are produced in a batch fabrication process. The processed foils have been clamped to a holder. The substrate size is 4 inch.

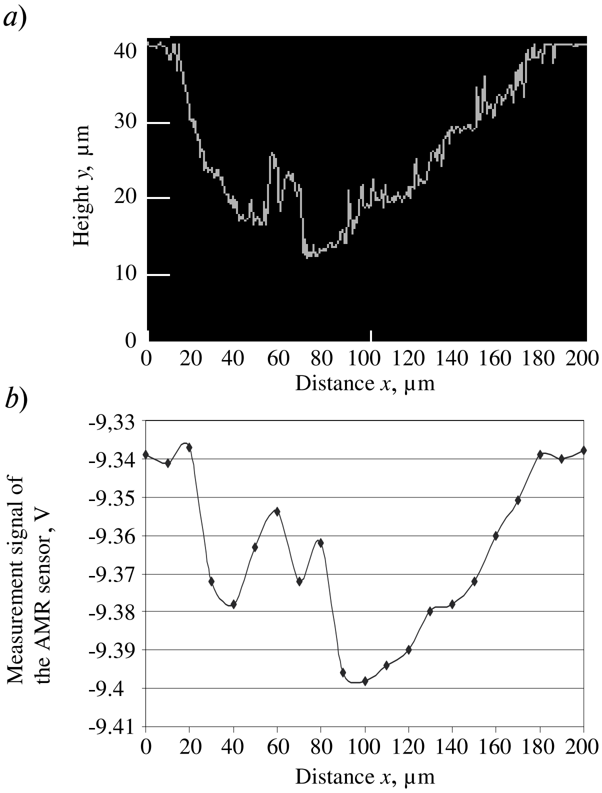

Fig. 7. The surface profile measured with *a* – a confocal microscope; *b* – the eddy current sensor [4]

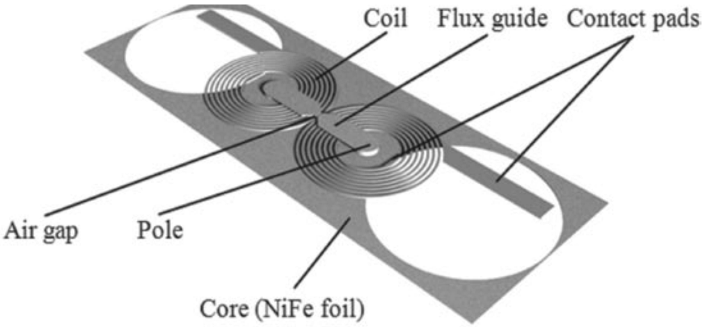

Fig. 8. Schematic view of the flexible write head [5]

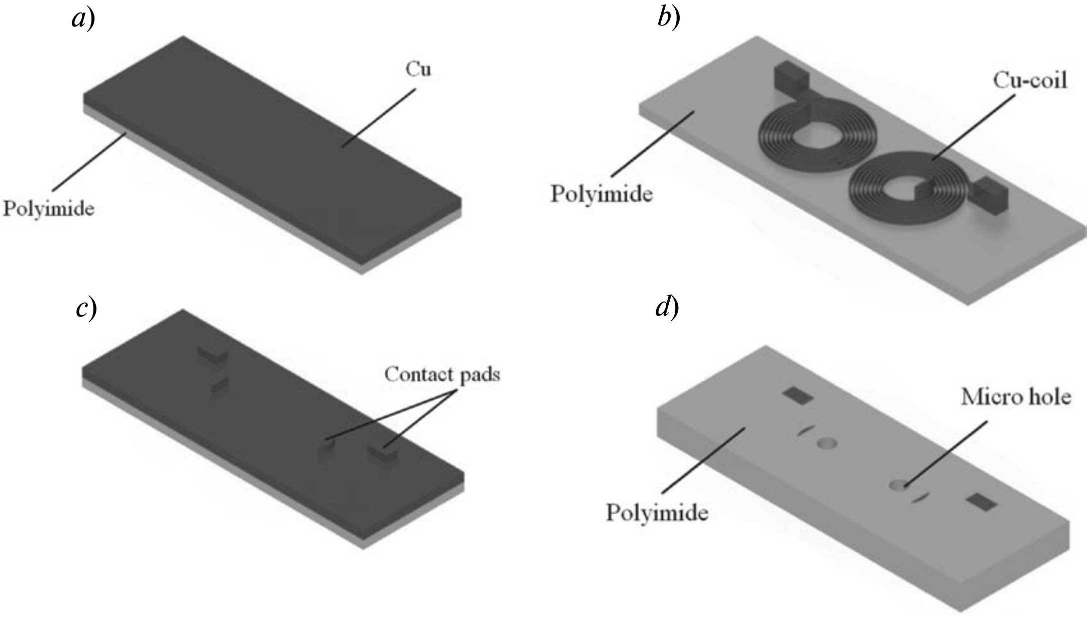

Fig. 9. Processing of the first side of the polyimide foil:
a – Cu foil-cladded polyimide; *b* – reinforcement of the contact pads;
c – etching of the Cu coils; *d* – embedding in polyimide [5]

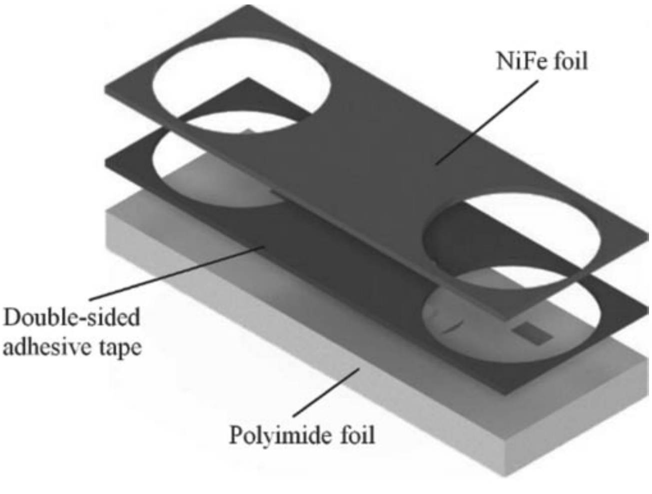

Fig. 10. Assembly of NiFe foil and coil module [5]

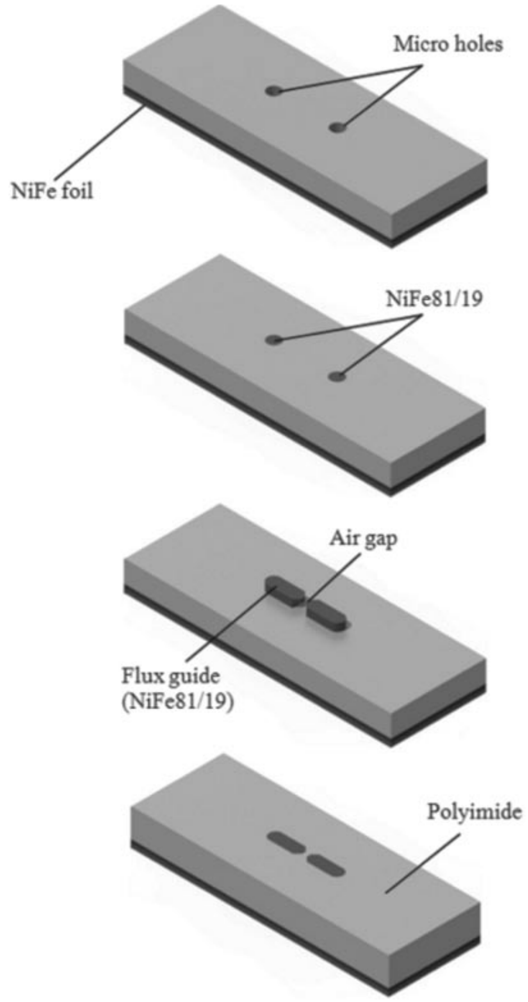

Fig. 11. Electroplating to form the air gap [5]

B. Highly sensitive earth magnetic field sensor

The goal of the project called Gebo funded by the German State of Lower Saxony is to develop new technologies necessary for geothermal drilling activities. To reach zones of exploitable thermal energies in Lower Saxony it is necessary to drill into a depth up to 6,000 m. The task of the IMPT was to design new magnetic sensors to measure magnetic fields in that depth. The challenges are the extreme temperatures, the low magnetic field strength, and the necessary robustness of the sensor. The sensors have to operate at temperatures up to 250 °C.

As sensor principle a GMR (Giant Magneto Resistive sensor) was chosen. The design of choice is that of a spin valve sensor. The layer sequence can be seen in Fig. 14.

The spin valve has been tested up to temperatures of 250 °C and it could be proven that the system is stable for several hundreds of hours.

The complete sensor layout is shown in Fig. 15. The system consists of four GMR sensors connected to a wheatstone bridge. Two of the sensors are covered with softmagnetic material to protect them against the magnetic field. They are used to compensate the influence of the temperature. The softmagnetic layer is also used to concentrate the field near to the measuring spin valves.

The sensor has been tested to evaluate the reliability. As a test sequence a thermal shock according to the MIL Std. 883 d was applied. The temperature has been alternated from −70 °C to 205 °C and vice versa in 10 s

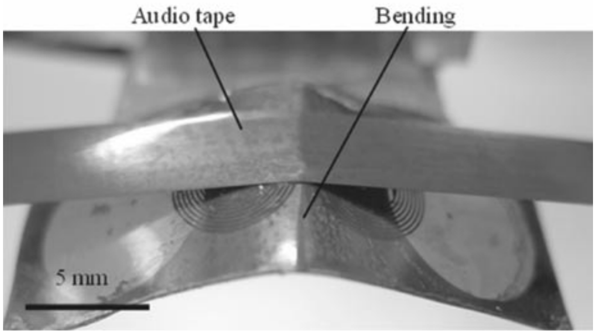

Fig. 12. Flexible write head writing data on an audio tape [5]

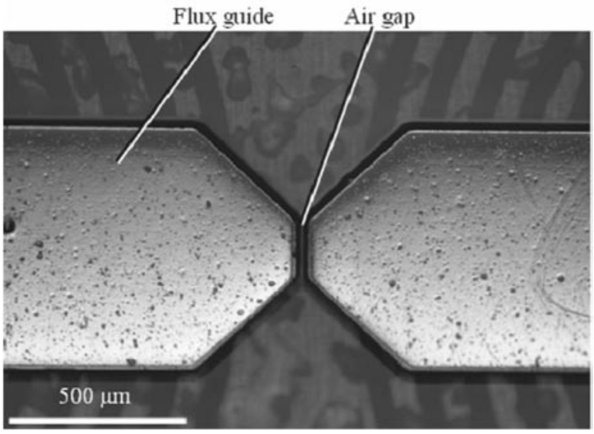

Fig. 13. Detail showing the air gap between the electroplated flux guides [5]

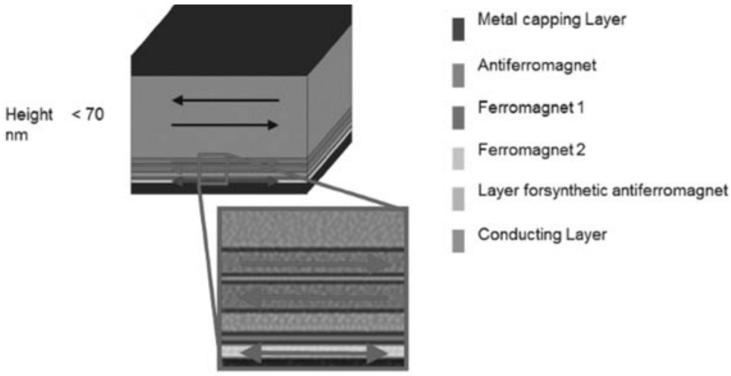

Fig. 14. Layer sequence of the spin valve system [6]

shifting time. The completed sensor is shown in Fig. 16.

III. Medical applications

A. Pole row for stem cell Transfection

The central topic of the CRC Transregio 37 was the investigation and development of micro and nanosystems for medical applications. Within the scope of the cooperative research in cooperation with the The Department of Cardiac Surgery, University of Rostock, Germany, the IMPT developed a pole row to transport nanoparticles. The nanoparticles were filled with genetic material. Shifting the magnetic field from one pole to the next by powering the poles sequentially, the nanoparticles are transported to the last pole in the row. A stem cell was placed at this point. When the stem cell is brought into contact with the genetic material the probability is high that a transfection takes place as intended.

The basic principle of the sensor function and its fabrication was presented in [8]. The small sensor was integrated in a PCB board and a well structure was added to the board to allow an easier handling [Fig. 17].

To improve the system capability, the silicon substrate was replaced by a substrate made of glass. The advantage of this approach is that glass is transparent and microscopic methods

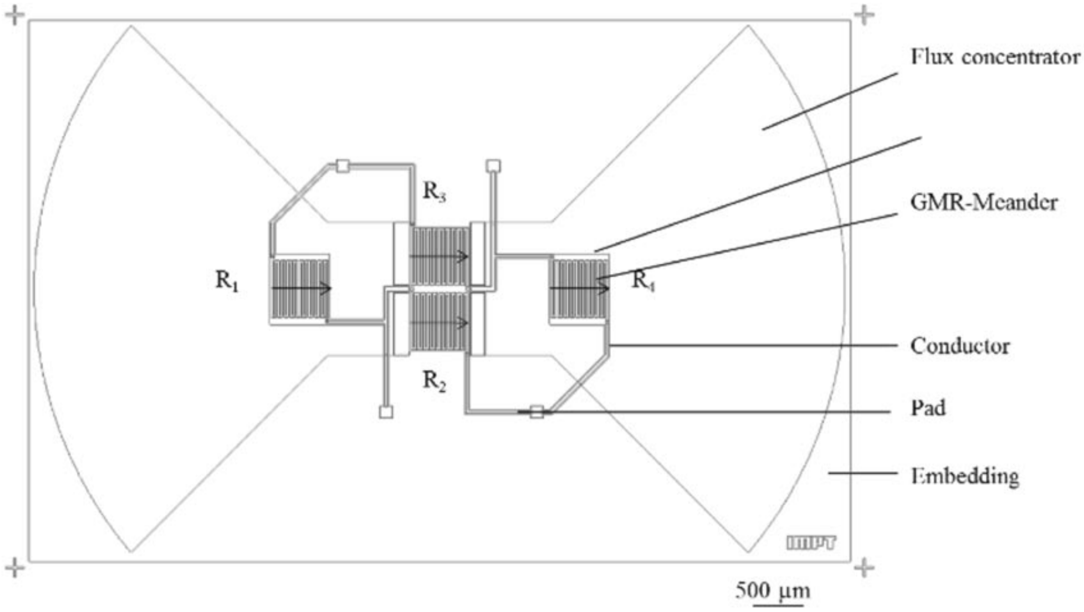

Fig. 15. Sensor design [7]

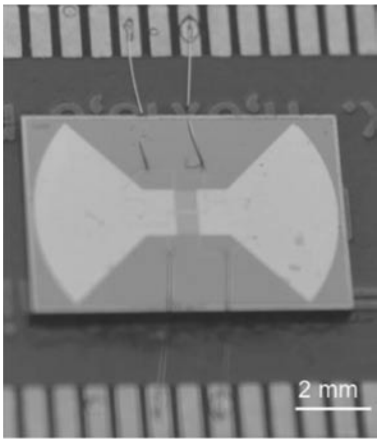

Fig. 16. Magnetic sensor for measuring low magnetic fields [7]

using transmitted light could be brought into action. To observe the transfection process, it was necessary to redesign the magnetic pole in the center of the coils. It could be shown that although the flux concentrator was missing the function of the pole row was still present. Another improvement was that the feed cables were covered with a thick layer of a polymer to suppress the influence of the magnetic field surrounding the powered lines. In Fig. 18 the new design is depicted as a schematic. In Fig. 19 a photo of the system is presented.

The pictures in Fig. 20 show that the material is transparent for the wavelengths 405 nm, 488 nm, and 561 nm, respectively.

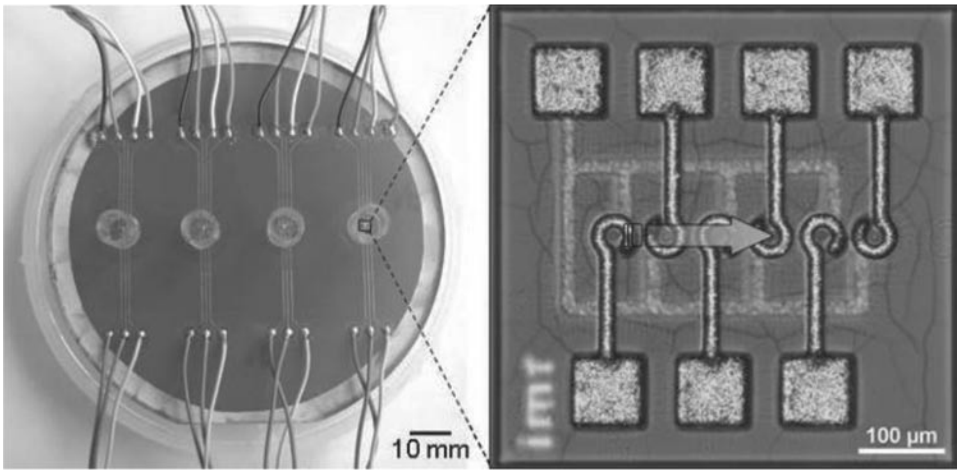

Fig. 17. PCB wafer with pole rows and well structures, detailed view of the system fabricated on a silicon substrate [8]

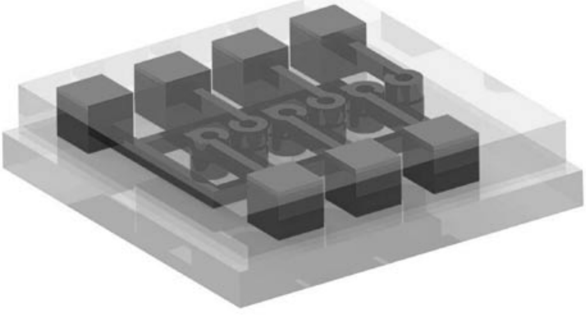

Fig. 18. Schematic view of the pole row fabricated on a glass substrate [8]

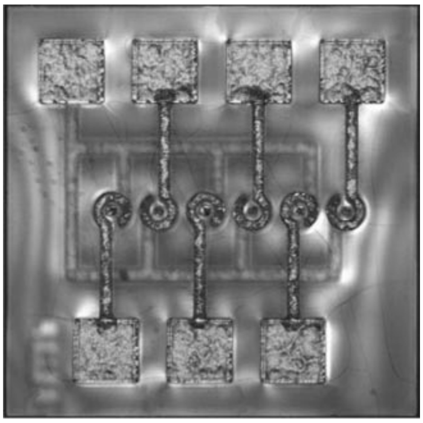

Fig. 19. Pole row fabricated on glass [8]

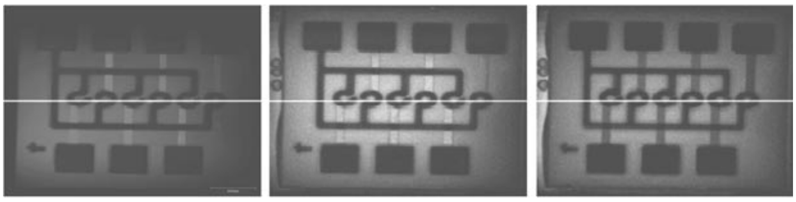

Fig. 20. Illumination of the pole row with blue, green, and red light, often used to visualized marked material [8]

B. Hearing aid implant

The partial or complete loss of the hearing ability of an adult represents a strong cut into the person's quality of life. For children this can have direct consequences on the development of the ability to learn to speak. Hearing aids can help to minimize the influences of a loss of the hearing ability. In cooperation with the Hannover Medical School a new implantable hearing aid has been developed. The hearing aid consists of an electro-mechanical microactuator, which is connected to the round window of the perilymph. The vibration is transferred to the membrane and the signal is transported to the hair cells. To reduce the costs a batch fabrication process has been chosen.

The principle design is shown by the model in Fig. 21.

The system consists of two basic parts, the substrate carrying a coil system and a second wafer providing the membrane and the boss. The boss is holding the plunger which is coupled to the membrane of the cochlea.

Fig. 22 presents the coil system which is generating the magnetic field. Powering the coil, the force is attracting the membrane carrying the magnetic back iron.

The bottom substrate is made of aluminium oxide and the top part is based on silicon. The silicon is etched using a deep reactive ion etching process to create a free-standing membrane. The complete system is shown in Fig. 23. The footprint of the system is 2.3×2.5 mm. The dimensions of the plunger are (0.4×0.4×2.5) mm^3.

To improve the system properties the system has been redesigned. The next generation was built as a hybrid system. The coil is conventionally wound around a machined softmagnetic core. The membrane, the back-iron and the boss are realized in applying process steps persued in

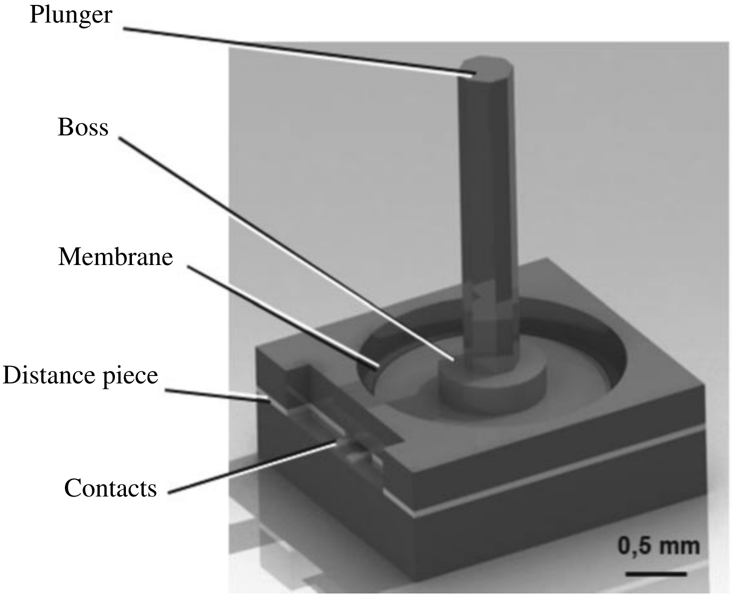

Fig. 21. Model of the hearing aid [9]

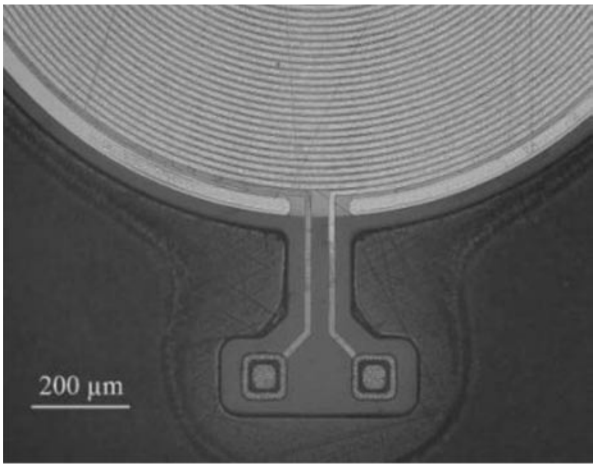

Fig. 22. Coil system [9]

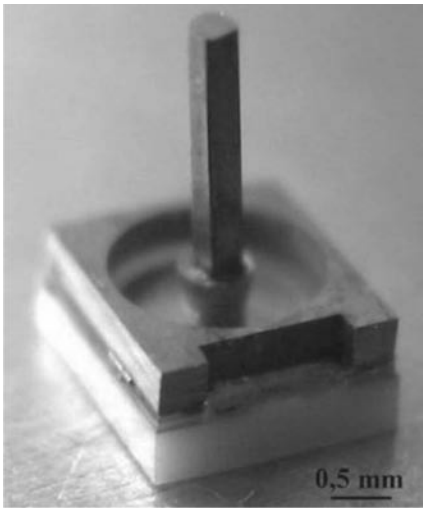

Fig. 23. Completed system of the hearing aid implant [9]

microsystem technologies. A picture of the new actuator system can be seen in Fig. 24.

C. Active microoptical system

There exists a demand for actuators which can be used to change the focal length by adapting optical lenses. These systems can be an essential part in autofocus systems or confocal microscopes. Together with the Hanover Centre for Optical Technologies (HOT) the IMPT has developed an actuator system to form a liquid lens. The coils of the microactuator generate a magnetic field and the magnetic force moves a ferrofluid in a microchannel. The movement of the ferrofluidic piston shifts a transparent fluid and a liquid lens is formed at the end of the channel. Fig. 25 shows a schematic drawing of the system.

Fig. 24. Picture of the redesign actuator

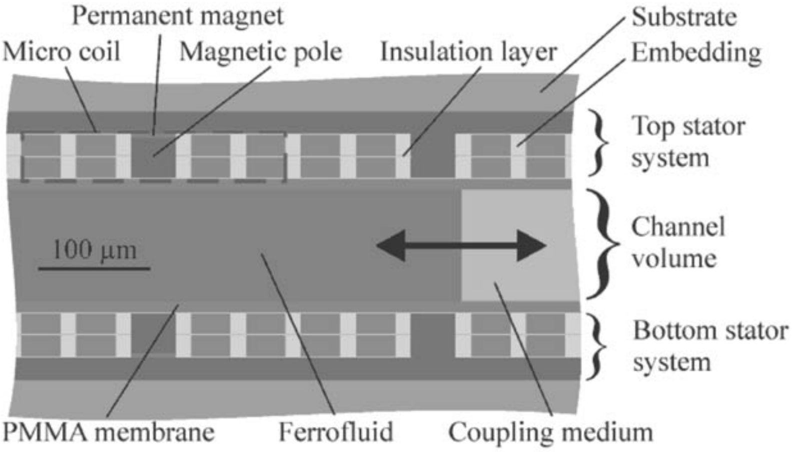

Fig. 25. Schematic drawing of the adaptive microoptical system [10]

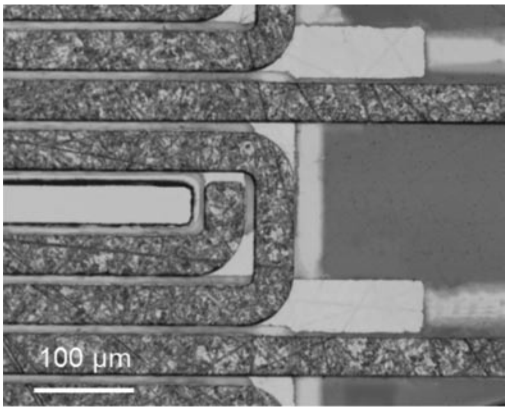

Fig. 26. Picture of the microcoils of the actuation system [11]

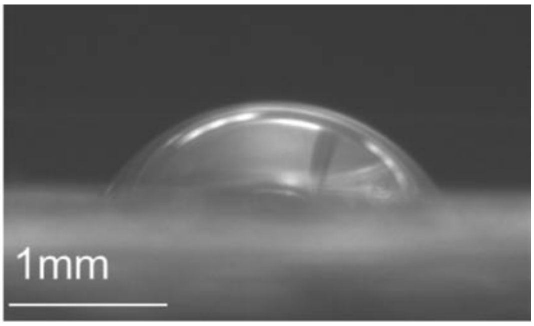

Fig. 27. Formation of the liquid lens [12, 13]

In Fig. 26 a magnified picture of the microcoils can be seen. The formed liquid lens by shifting the ferrofluidic plug is shown in Fig. 27.

Acknowledgment

This research has been sponsored in part by the German Research Foundation (DFG) within the Collaborative Research Center (CRC) 653 "Gentelligent Components in their Lifecycle", the CRC TR37 "Micro and nanosystems for medical applications", and the Priority Program 1337 "Active Micro-optics" and by the Gebo Project funded by the German State of Lower Saxony.

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RISSING, L. *Institut für Mikroproduktionstechnik, Leibniz Universität Hannover, Garbsen, Germany.*
An der Universität 2 30823 Garbsen, Germany.
E-mail: impt@impt.uni-hannover.de

РИССИНГ Лутц — *Prof., Institut für Mikroproduktionstechnik, Leibniz Universität Hannover, Garbsen, Germany, D.Eng.*
An der Universität 2 30823 Garbsen, Germany.
E-mail: impt@impt.uni-hannover.de

BELSKI, A. *Institut für Mikroproduktionstechnik, Leibniz Universität Hannover, Garbsen, Germany.*
An der Universität 2 30823 Garbsen, Germany.
E-mail: impt@impt.uni-hannover.de

БЕЛЬСКИ Александр — *сотрудник, Institut für Mikroproduktionstechnik, Leibniz Universität Hannover, Garbsen, Germany.*
An der Universität 2 30823 Garbsen, Germany.
E-mail: impt@impt.uni-hannover.de

CREUTZBURG, T. *Institut für Mikroproduktionstechnik, Leibniz Universität Hannover, Garbsen, Germany.*
An der Universität 2 30823 Garbsen, Germany.
E-mail: impt@impt.uni-hannover.de

ГРИТЦБУРГ Том — *сотрудник, Institut für Mikroproduktionstechnik, Leibniz Universität Hannover, Garbsen, Germany.*
An der Universität 2 30823 Garbsen, Germany.
E-mail: impt@impt.uni-hannover.de

GRIESBACH, T. *Institut für Mikroproduktionstechnik, Leibniz Universität Hannover, Garbsen, Germany.*
An der Universität 2 30823 Garbsen, Germany.
E-mail: impt@impt.uni-hannover.de

ГРИСБАХ Тим — *сотрудник, Institut für Mikroproduktionstechnik, Leibniz Universität Hannover, Garbsen, Germany.*
An der Universität 2 30823 Garbsen, Germany.
E-mail: impt@impt.uni-hannover.de

KAISER, M. *Institut für Mikroproduktionstechnik, Leibniz Universität Hannover, Garbsen, Germany.*
An der Universität 2 30823 Garbsen, Germany.
E-mail: impt@impt.uni-hannover.de

КАЙЗЕР Маттиас — *сотрудник, Institut für Mikroproduktionstechnik, Leibniz Universität Hannover, Garbsen, Germany.*
An der Universität 2 30823 Garbsen, Germany.
E-mail: impt@impt.uni-hannover.de

WIENECKE, A. *Institut für Mikroproduktionstechnik, Leibniz Universität Hannover, Garbsen, Germany.*
An der Universität 2 30823 Garbsen, Germany.
E-mail: impt@impt.uni-hannover.de

ВИНЕКЕ Аня – *сотрудник, Institut für Mikroproduktionstechnik, Leibniz Universität Hannover, Garbsen, Germany.*
An der Universität 2 30823 Garbsen, Germany.
E-mail: impt@impt.uni-hannover.de

WURZ, M. *Institut für Mikroproduktionstechnik, Leibniz Universität Hannover, Garbsen, Germany.*
An der Universität 2 30823 Garbsen, Germany.
E-mail: impt@impt.uni-hannover.de

ВЮРЦ Марк – *сотрудник, Institut für Mikroproduktionstechnik, Leibniz Universität Hannover, Garbsen, Germany.*
An der Universität 2 30823 Garbsen, Germany.
E-mail: impt@impt.uni-hannover.de