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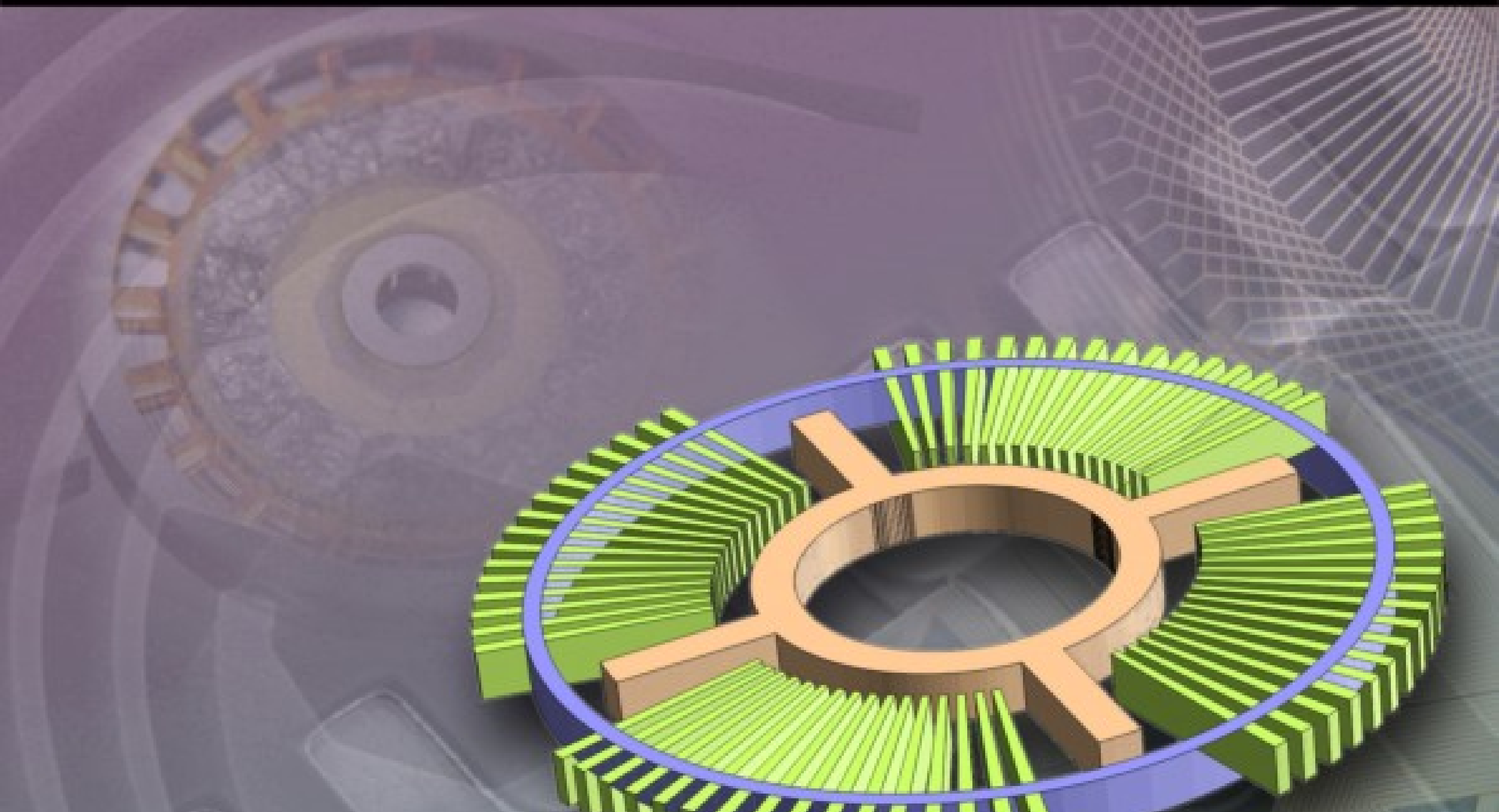

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Novel Synchronous Linear and Rotatory Micro Motors Based on Polymer Magnets with Organic and Inorganic Insulation Layers

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Abstract: In this work, we report on the development of several synchronous motors with rotatory or linear movements. The synchronous micro motors are brushless DC motors or stepper motors with electrically controlled commutation consisting of a stator and a rotor. The rotor is mounted onto the stator and is adjusted by an integrated guidance. Inside the stator different coil systems are realized, like double layer sector coils or special nested coils. The coil systems can be controlled by three or six phases depending on the operational mode. Furthermore, inorganic insulation layers were used in order to reduce the thickness of the system. By this means four layers of electrical conductors can be realized especially for the 2D devices. The smallest diameter of the rotatory motor is 1 mm and could be successfully driven. *Copyright © 2008 IFSA.*

Keywords: Synchronous micro motors, Rotatory and linear actuators, Micro coils, UV depth lithography, Polymer magnets

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1. Introduction

Due to the development of new technologies, more and more complex MEMS applications can be realized. Especially electromagnetic micro actuators have reached a growing interest in micro technology in addition to commercial applications during the last years [1, 2]. Their basic construction exists of electric conductors and coil systems as well as of soft-magnetic and/or hard-magnetic materials that are fabricated in additive technology via UV-depth lithography and electroplating. For

UV-depth lithography photo resists like Epon SU-8, AZ9260, Intervia-3D-N and CAR44 [3, 4] were applied and optimized. Layer thicknesses up to 1 mm and aspect ratios over 60 were achieved (Fig. 1). Special micro composites were developed. This allowed the fabrication of micro magnets with arbitrary shape and properties, ensuring a complete compatibility to existing process chains. With these potential technologies several synchronous motors with rotatory and linear movements were developed. In addition, inorganic insulation layers like silicon nitride or silicon oxide were used. The advantage of these inorganic insulation layers in comparison to organic insulation layers like Epon SU-8 is the reduced thickness, whereby four layers of electrical conductors can be realized especially for 2D devices. Furthermore, inorganic insulation layers are chemically and thermally resistant which can be important for special fields of application.

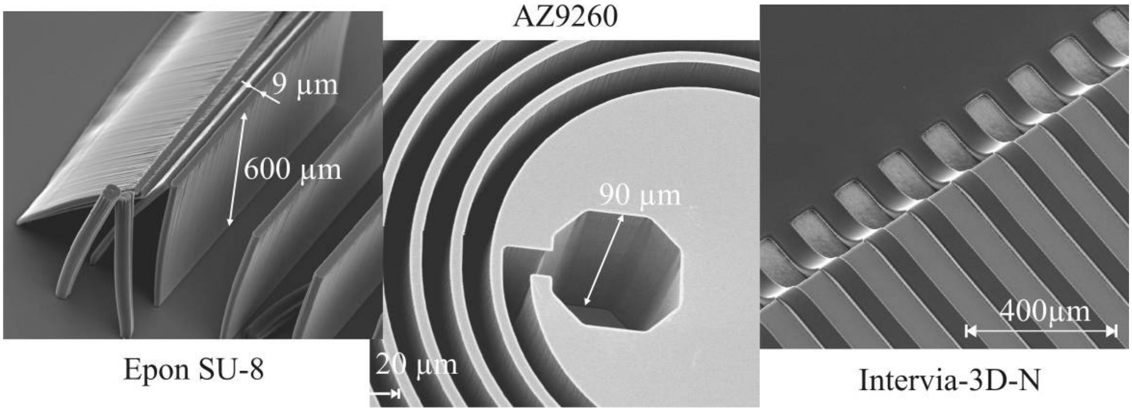

Fig. 1. SEM-pictures of Epon SU-8, AZ9260 and Intervia-3D-N photo resist structures.

2. Concept and Design

The synchronous micro motors are brushless DC motors or stepper motors with electrically controlled commutation. In Fig. 2 the basic setup of an electric motor with disc-shaped rotor consisting of a stator and a rotor is shown. The rotor is made of an SU-8 form, which contains alternate magnets. These magnets were realized by polymer magnets [5, 6] or commercial magnets. Both magnet types feature an axial magnetization. The stator consists of double layer coils, which were arranged as sector coils or nested coils. The coils have 6-30 windings per phase depending on the motor size and number of poles. The arrangement of the coils and magnets allows driving by three or six phases. For the adjustment of the rotor and the stator a centrically arranged circular guidance is integrated.

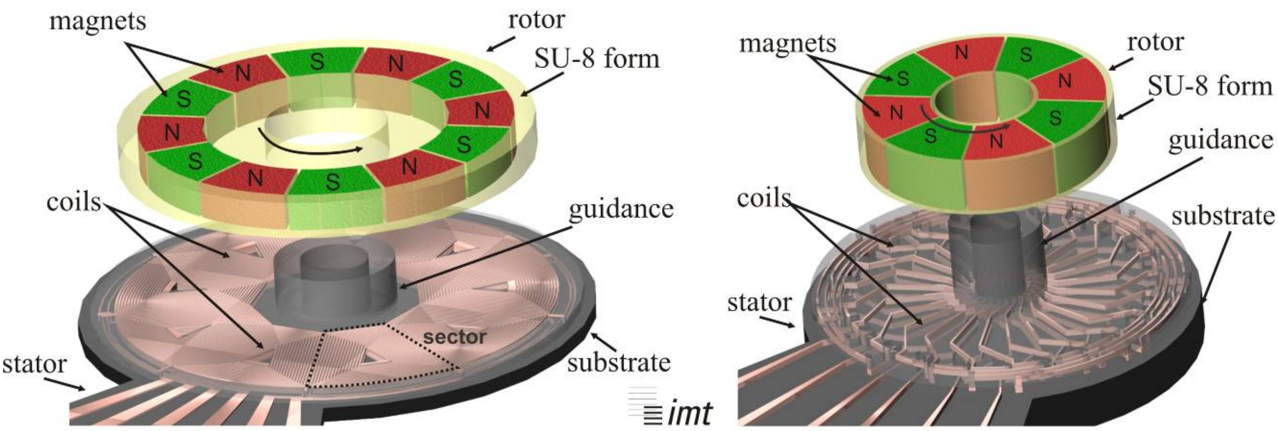

Fig. 2. Concept of rotatory synchronous motors with sector coils (left) and nested coils (right).

3. Polymer Magnets

Polymer magnets are micro composite materials which are fabricated by embedding powdery, magnetically hard materials in a polymer matrix. During the past few years we have developed three different techniques (Fig. 3, left) for micro scale structuring of these composites: direct structuring (a), lift-off process (b) and soft lithographic molding (c) [7]. Different qualities and properties can be obtained depending on the used technique. In comparison to electroplated or sputtered layers the lift-off process provides magnetically hard structures with high thicknesses of some 100 µm combined with high edge quality and high aspect ratios. For this process the polymer powder composite was filled in a patterned resist form and baked out. After that, overlaying residues could be removed and the structures were be leveled by means of burnishing. Depending on the following process steps the resist form either is removed or remains on the substrate with the micro structured polymer magnet. The advantage of this technique to produce the polymer magnets is the possibility to fabricate structures with arbitrary shapes and any thickness.

Various magnet powders were used and characterized for applications as polymer magnets, like rare earth materials (neodymium iron boron, samarium cobalt) and ferrites (barium-, strontium-ferrites). Depending on the material the grit sizes of the powders are between 0.8 µm and 9 µm whereas ferrites have finer grits. The fabricated polymer magnet structures were characterized regarding their magnetic properties with a vibrating sample magnetometer. In Fig. 3 (right) the magnetization curves are shown for various used polymer magnets with 80%wt powder ratio. The results show that the achievable residual magnetism augments with increasing powder ratio or structure thickness, whereas the coercive field strength stays constant.

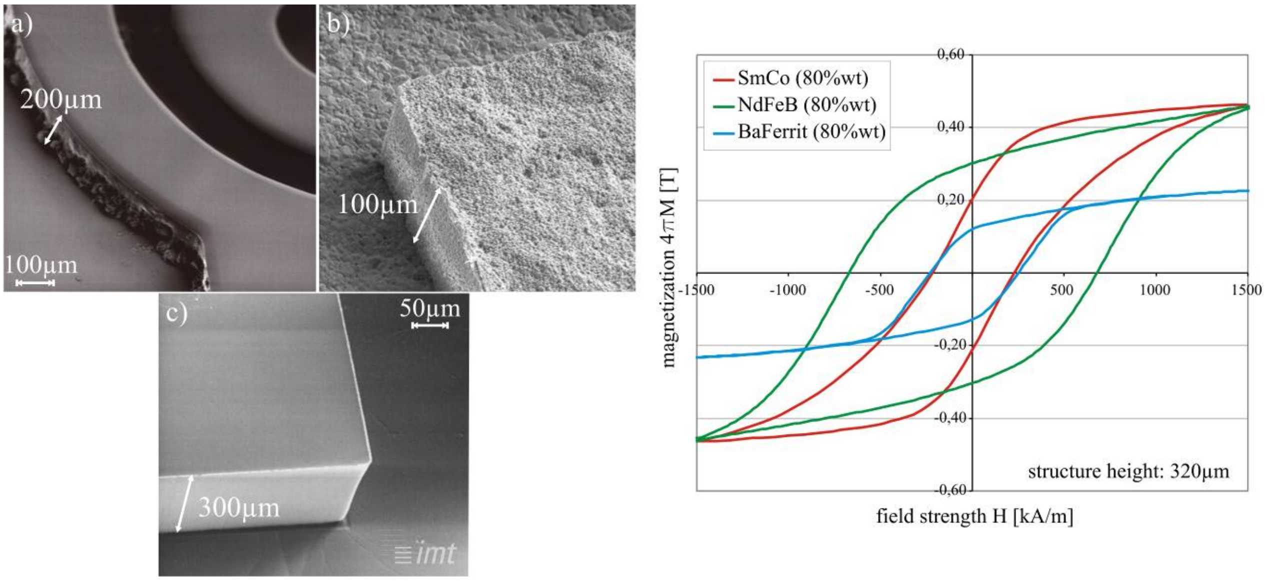

Fig. 3. Polymer Magnets: fabrication methods (left) and characterization of different materials (right).

4. Fabrication

The principle process chain for the fabrication of stator and rotor consists of an iteration loop of single process steps for in layers built-up for complex 3D micro structures. The fabrication process includes UV-depth lithography using AZ9260 of electroforming and Epon SU-8 for insulation, planarization and embedding. Inorganic materials like silicon oxide and silicon nitride where used alternatively to SU-8 for insulation of the different coil layers.

4.1. Stator

The process sequence (Fig. 4) for the fabrication of the stator with organic insulation layers starts with the lower conductors of the double layer coil. A mold of AZ9260 is patterned and filled with 15 µm thick copper by electroplating. After stripping the AZ9260 mold, an SU-8 layer is spun onto these structures as insulation. This layer provides openings for through connections to the upper coil layer.

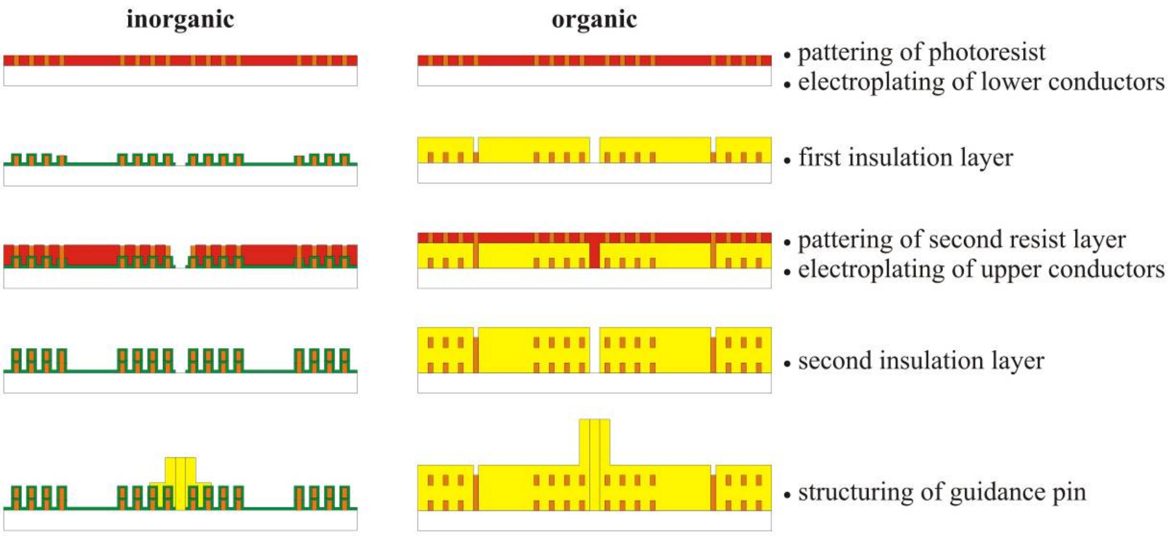

Fig. 4. Schematic stator fabrication sequence.

Both connections and upper conductors are likewise structured by copper electroplating. A second SU-8 layer serves both as insulation between upper conductors and traveler magnets and as a bearing layer for the traveler. In the last step the circular or linear guidance structures are made by pattering a 200 µm thick SU-8 layer. The fabricated stators are shown in Fig. 5.

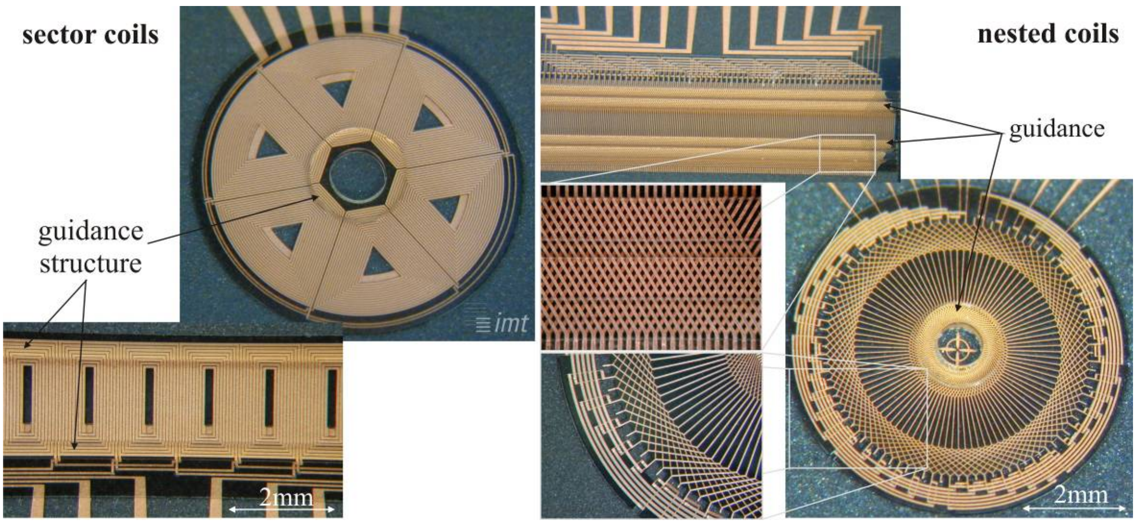

Fig. 5. Photograph of different fabricated stators.

For the application of inorganic insulation layers, instead of organic SU-8, investigations with silicon oxide and silicon nitride were carried out. Both films were deposited by a PECVD process with thicknesses of 600-1000 nm for oxide and 100-200 nm for nitride, respectively. These layers were masked by patterned AZ9260. Both wet and dry etch were tested. In the wet etching process large undercut could be observed. The pattering of silicon nitride could be improved by using dry etching in a barrel etcher avoiding any undercuts (Fig. 6).

The advantage of the implementation of the inorganic insulation layers is given on the one hand by reducing the thickness of the coil system and on the other hand by a better thermal conductance. Therefore, heat produced by powering the micro motor can faster dissipate out of system. Furthermore, these layers feature a better aging stability in comparison to SU-8 which is useful for long time applications.

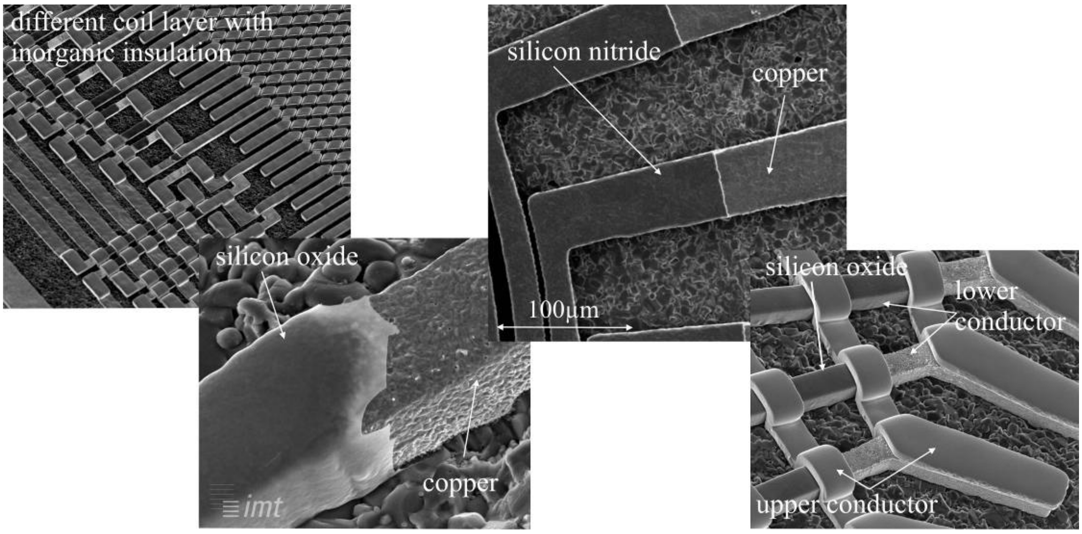

Fig. 6. SEM-pictures of lower conductors covered with inorganic insulation layers.

4.2. Rotor

The rotor is realized by SU-8 creating a form for polymer magnets or commercial magnets with high precision adjustment (Fig. 7). For the fabrication of the rotor a sacrificial copper layer is electroplated onto the substrate followed by a thin patterned SU-8 layer as base plate. After that, a 400 µm high SU-8 layer is structured to provide the filling form. The commercial magnets were directly mounted inside of this form and hold by a fit. In contrast, for rotors with polymer magnets the above mentioned lift-process was applied. Therefore, the not required areas around the SU-8 mould were filled with a solvable resist like AZ9260. The liquid polymer magnet was inserted into the mold and baked out. After baking, a polishing process followed to level the compound structure and to remove waste residues. By etching the sacrificial layer the rotors were detached from substrate. Subsequently the rotors and travelers were alternatingly magnetized by special developed magnetization equipment and then mounted onto the stator. The adjustment of the elements was facilitated by the integrated guidance structures. The applied polymer magnets consist of 80wt% barium-strontium ferrite or 90wt% neodymium-iron-boron.

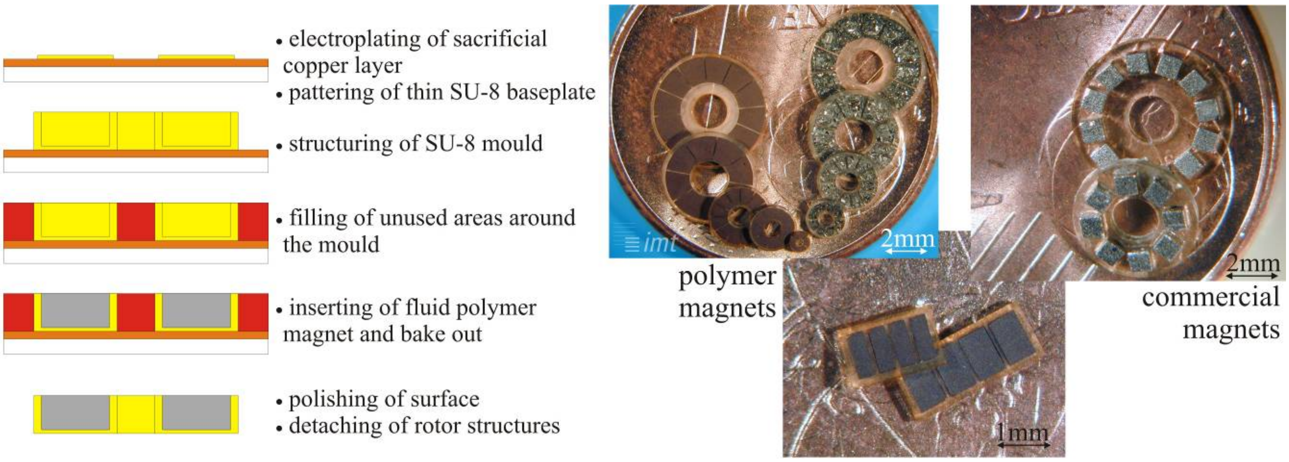

Fig. 7. Rotor fabrication sequence (left) and photographs of different rotors and travelers with integrated polymer magnets or mounted commercial magnets (right).

Both rotor types were fabricated to compare their influence of motor properties and performance. The structured polymer magnets show comparatively lower magnetization than the commercial magnets. However, the advantage is the flexible formation so that higher area fillings could be achieved. Furthermore, smallest structures down to several tens micrometers are producible with polymer magnets. By that, rotors with a smallest diameter of 1 mm could be realized. In Table 1 the realized rotors configurations are shown. For the linear motors, travelers with different pitches from 850 µm down to 150 µm were realized.

Table 1. Overview of realized rotor configurations.

Diameter [mm]	2p	Weight [mg]	Magnets
5,5	12	45	commercial
5,5	12	24	polymer magnet
4,5	8	30	commercial
4,5	8	17	polymer magnet
3,0	12	6	polymer magnet
2,0	8	2	polymer magnet
1,0	8	<1	polymer magnet

5. Magnetization

A special magnetization equipment was designed in order to alternatingly magnetize the polymer magnet sectors in axial direction (Fig. 8 left). It consists of a ferromagnetic core with a yoke in which special magnetization adapters (Fig. 8 right) can be placed. In these adapters milled sectors and stripes are located for magnetization of the rotors and linear travelers, respectively. A flat coil with 445 windings wound around the core serves for generating magnetic flux.

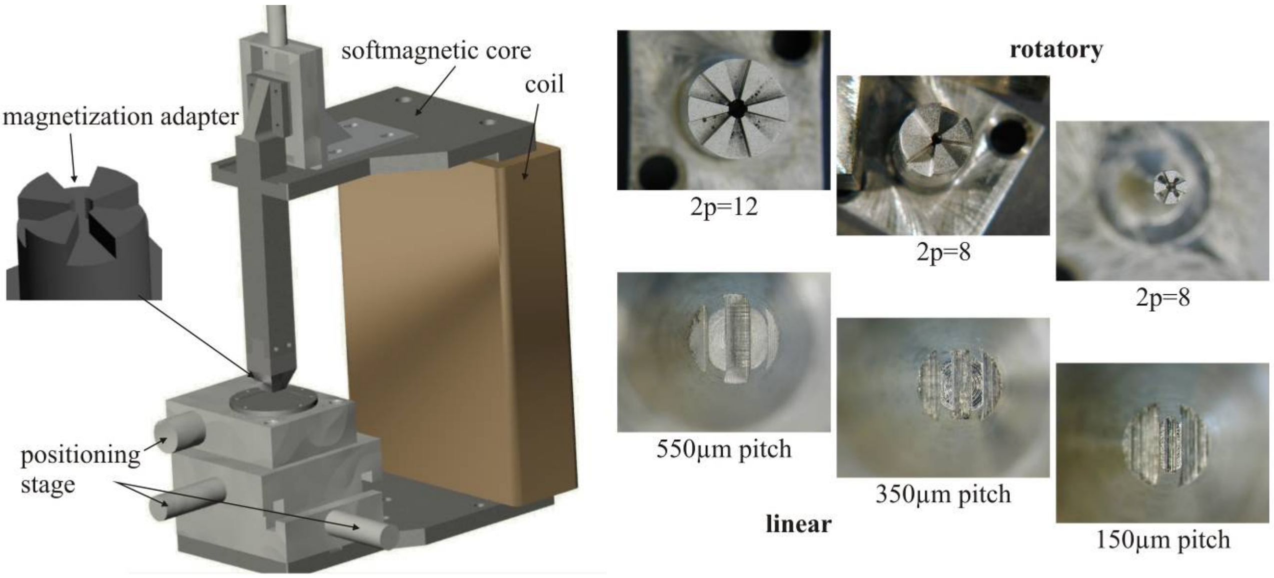

Fig. 8. Magnetization equipment (left) and different adapters (right).

Simulations and measurements were carried out for characterization of the magnetization equipment: it was to verify if the magnetic flux is high enough to drive the polymer magnets in saturation for achieving a magnetic remanence as high as possible. Both simulations and measurements were performed with an unstructured adapter with a square area and an air gap of 400 µm corresponding to the rotor or traveler thickness. By increasing the coil current the resulting magnetic flux could be simulated and measured. The results of both (Fig. 9, left) differ slightly because of small air gaps between the real components which were not considered in simulation. The flux density increases further by using structured adapters, so that it is high enough to reach a high magnetic remanence in the structured polymer magnets of the rotor or traveler.

For the magnetization process a rotor is inserted and oriented to the adapter (Fig. 9, right) by means of a multi axis positioning stage. Every second segment is magnetized with the first current feed. After that the rotor is rotated at an angle, which corresponds to the pole pitch. With a second current feed the other segments are magnetized in the opposite direction.

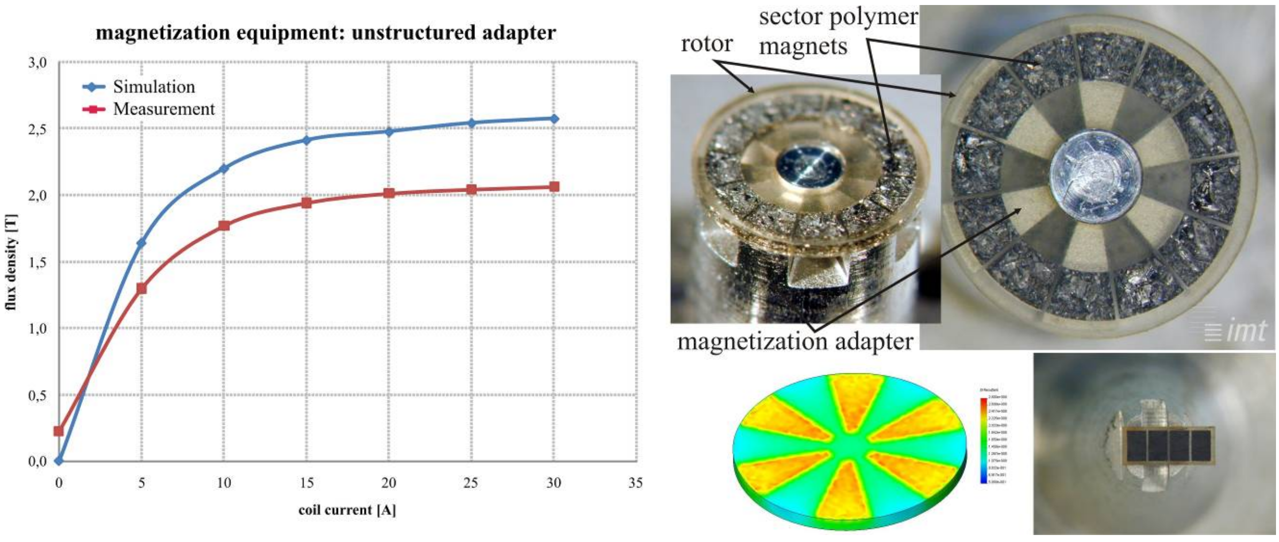

Fig. 9. Comparison of simulated and measured flux density (left) and rotor magnetization (right).

6. Results

By the use of the described process sequences, stators and rotors or travelers were successfully fabricated. By means of the guidance structures the components could be mounted (Fig. 10) and first tests were carried out. The smallest diameter of the rotatory motor is 1 mm and driving currents between 50-300 mA are necessary depending on the magnet type. In first test the motor could be successfully driven over a long period with a rotating speed over 7000 rpm. Generally, the motors with nested coils indicate a smoother movement due to their finer pitch.

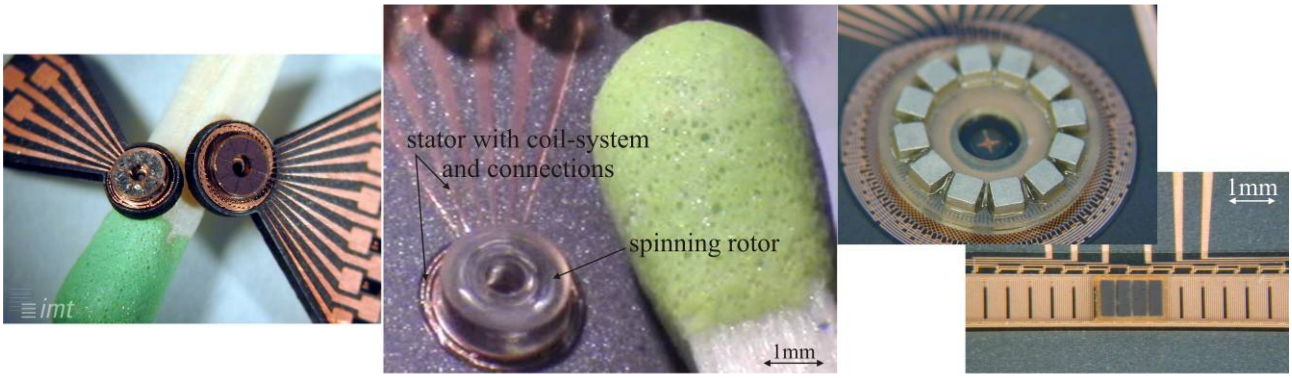

Fig. 10. Photograph of different mounted synchronous motor.

Furthermore, force measurements are performed to determine the achievable torques of the motors. They are carried out with a 3D micro force sensor which is generally based on piezo-resistive silicon membrane with a stylus. For the measurements the rotor was mounted on the stator. By current feed of phase 1 the rotor is turned and centered on this phase. Then the stylus of the force sensor was brought in contact with the rotor (Fig. 11, center). After that, current amplitudes of phases 2 and 3 were changed with the same amount but in opposite direction (Fig. 11, left). Firstly, the current was increased and then decreased stepwise and the forces in x- and y-direction were measured. The resulting force was calculated (Fig. 11, right). These measurements have shown, that a torque up to 20 µNm and higher was reachable depending on the used magnets and size of the motor.

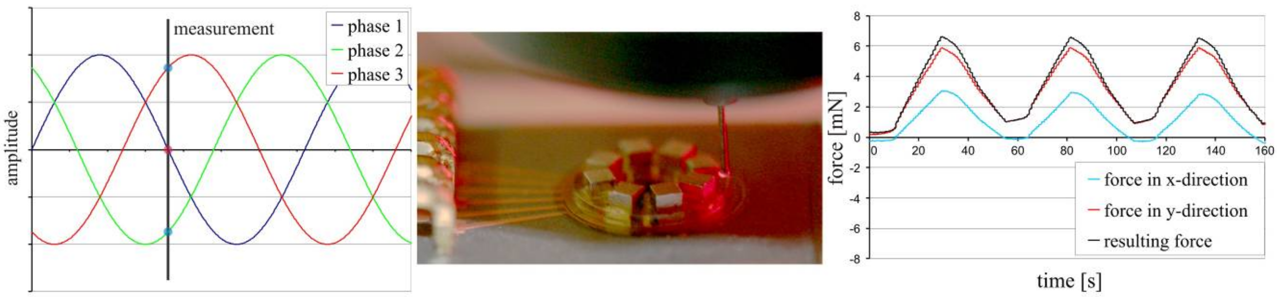

Fig. 11. Force measurements.

7. Application

The synchronous motor principle can be applied for example in micro fluid systems such as biochemical or biomedical devices. Particular interest is laid on the fabrication of complex systems composed of several micro devices like fluidic channels, valves, pumps, mixers, reactors and analysis systems. The development and fabrication of micro pumps is one of the main topics in microfluidic research. Several pumping principles have already been described in literature [8-10]. One of them is a gear pump which uses the centrifugal force to transport a fluid from inlet to outlet. Mostly these pumps are driven externally. By using the developed synchronous motor set up, a full integration of the pump unit as well as the electromagnetic drive unit is realized. The basic setup of the pump is shown in Figure 12 (left). On the one hand a pump chamber with inlet and outlet channels made of 400 µm thick SU-8 is implemented on the stator (Fig. 12, right). On the other hand the rotors feature gears with different diameters. After mounting the gear into the pump chamber a glass cover with etched openings is adjusted above and fixed with an adhesive. The pumps are designed and fabricated with diameters ranging between 1 mm and 6 mm and therefore holding different pump volumes. Furthermore, the pump volume can also be set by the height of the pump chamber and the gear. The presented pump reveals a promising basic concept for other micro rotary pumps like spiral, impeller or other forms of gear pumps.

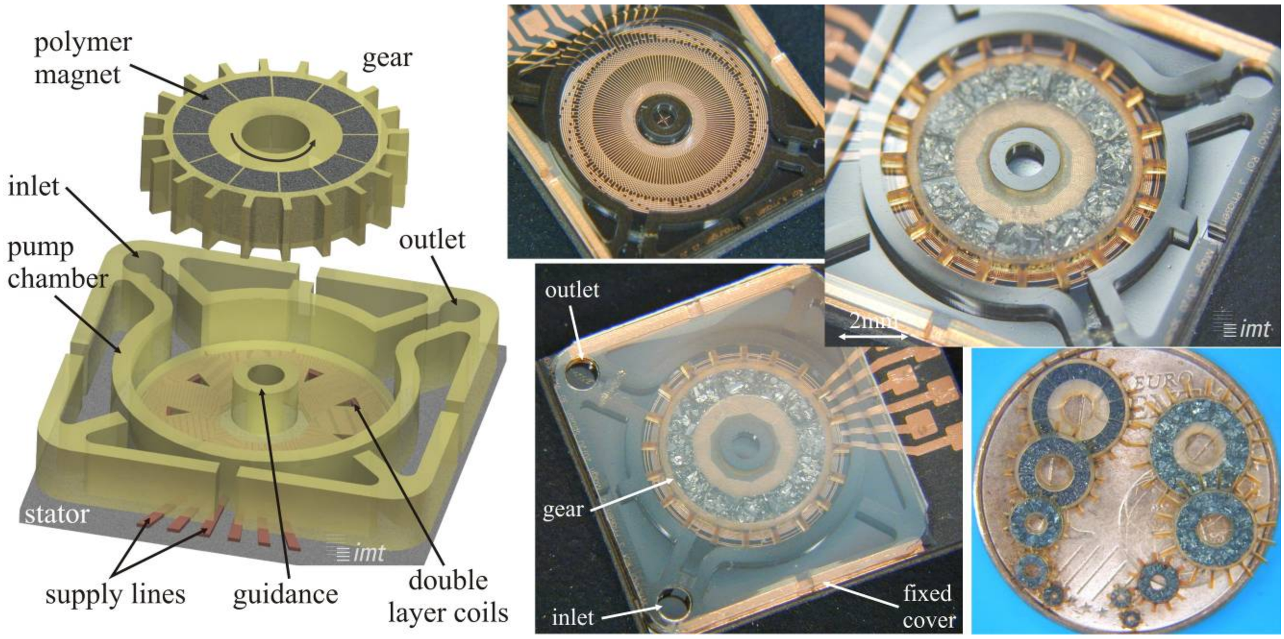

Fig. 12. Schematic view of the set-up of the gear pump (left) and photographs of the fabricated components (right).

8. Outlook

The presented micro synchronous motors and the fabrication concept possess a variety of new applications and options. One intention is the double-sided assembly of the rotatory motor. The coil systems are arranged on both sides of the substrate connected by contacting via through holes. According to this the rotors are mounted on both sides and jointly attached by an axle which passes through a laser cut guidance in the center. The double-sided configuration features an enhancement of the active area and therewith an enhancement of maximal torque. Another possibility could be to combine several single actuators to one stack motor for further improvement of the performance.

A further application lies in the enhancement of the 1D linear motor to a 2D motor. The coil system will become more complex. A 90° rotated double layer coil system for the second drive direction is processed onto the first double layer coil system. Furthermore, the traveler design has to be modified.

Another objective is the integration of a contactless position detection system for a closed-loop control. A first concept is developed (Fig. 13 left) which consists of fixed commercial magnetic sensors, such as Hall or AMR sensors and a movable part with integrated micro structured polymer magnets (Fig. 13 left). The magnetic sensors are assembled on the substrate and integrated into the micro fabrication process chain, thereby allowing high precision adjustment and electrical contacting by the combination of UV-depth lithography and electroplating. On top of the sensor device, the polymer magnet is adjusted via guidance. Due to the varying geometry of the polymer magnets, the strength of the magnetic field can be altered by moving them over the magnetic sensors, resulting in the detection of the geometric structures as well as the measurement of their corresponding position or angle. Different designs (Fig. 13 center) have been developed and were successfully tested in the first experiments. In Fig. 13 (right) a measurement of a complete rotation of a double cotter over one Hall sensor is shown.

Fig. 13. Contactless magnet sensor: concept (left), geometric variations (center) and a first measurement (right).

9. Conclusions

The purpose of this work was to develop linear and rotatory synchronous motors. Both motor types could be realized successfully by means of UV-depth lithography, electroplating and by using polymer magnets. The integration of polymer magnets made it possible to miniaturize synchronous motors down to 1 mm of rotor diameter. All devices are currently under further investigation to optimize and characterize the operating behavior. In addition, a special packaging is being developed. Also first concepts for the integration of magnetic sensors were developed for closed loop control, which allow micro-/nano stepping and rotating. Further investigations will have the aim to exactly measure the magnetic flux densities generated by the polymer magnet segments.

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References

[1]. C. Yang, X. Zhao, G. Ding, C. Zhang, B. Cai, An Axial Flux Electromagnetic Micromotor, *Journal of Micromechanics and Microengineering*, 11, 2001, pp. 113-117.

[2]. S. Kleen, W. Ehrfeld, F. Michel, M. Nienhaus, H.-D. Stölting. Penny-Motor: A Family of Novel Ultraflat Electromagnetic Micromotors, in *Proceedings of Actuator 2000*, Bremen, Germany, 2000, pp. A6.4.

[3]. M. Feldmann, A. Waldschik, S. Büttgenbach, Technology and Application of Electrodepositable Photo Resists to Create Uniform Coatings needed for Complex 3D Micro Actuators and Sensors, *Microsystem*

Technologies, 13, 5-6, 2006, pp. 557-562.
[4]. M. Feldmann, S. Büttgenbach, The Potential of Novel Photo Resists in MEMS Applications – Technology and Characterisation of Electrodepositable Photo Resists and CAR44, in *Proceedings of Apcot 2006*, p. 148f.
[5]. M. Feldmann, S. Büttgenbach, Novel Fabrication Processes for Polymer Magnets and their Utilization to Design Versatile Electro Magnetic Micro Actuators, in *Proceedings of Eurosensors 2005*, 2005, pp. WC6f.
[6]. M. Feldmann, S. Büttgenbach, Novel Versatile Electro Magnetic Micro Actuators with Integrated Polymer Magnets: Concept, Fabrication and Test, in *Proceedings of Actuator 2006*, Bremen, Germany, 2006, pp. 709-712.
[7]. M. Feldmann, S. Büttgenbach, Novel monolithical micro plunger coil actuator using polymer magnets and double layer micro coils, in *Proceedings of XVIII. Eurosensors*, Rome, Italy, 2004, pp. 34-35.
[8]. C. H. Ahn, M. G. Allen, Fluid micropumps based on rotatory magnetic actuator, in *Proceedings of 8th IEEE Int. Workshop on MEMS*, 1995, pp. 408–412.
[9]. N.-T. Nguyen, X. Huang, T. K. Chuan. MEMS-Micropumps: A Review, *Transactions of the ASME*, 124, 2002, pp. 384-392.
[10]. B. D. Iverson, S. V. Garimella, Recent advances in microscale pumping technologies: a review and evaluation, *Journal of Microfluid Nanofluid*, Vol. 5, 2008, pp. 145-174.

Guide for Contributors

Aims and Scope

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- Sensor instrumentation;
- Virtual instruments;
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