Shapeable Magnetoelectronics

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***Abstract* — In our everyday life, we are surrounded by electronic sensing devices designed in a way to meet requirements for a certain application, which is determined primarily by their shape and size. In this respect, the natural question, which surprisingly has only recently been raised, is can one create electronics that can be reshaped on demand after its fabrication? After introducing this ground-breaking paradigm, the so-called shapeable electronics became a dynamically developing research area with already a variety of shapeable devices commercially available: electronic displays, light-emitting diodes, integrated circuitry, to name a few. Special attention has been paid to the family of shapeable electronics which combines advantages of being flexible with the high speed of conventional semiconductor-based electronics. Shapeable electronics and optoelectronics have been developed already for a few years. Very recently, we added a new member to this family – the shapeable magnetic sensor. Shapeable magnetoelectronics on flexible membranes could enable the fabrication of biomedical fluidic systems, where large-angle folding of the micrometer-sized functional elements is a crucial prerequisite for a successful implementation. Furthermore, shapeable magnetic sensors can be directly integrated into already existing flexible electronic systems to realize smart hybrid magneto-electronic devices with the functionality to sense and respond to a magnetic field.**

***Index Terms* — flexible magnetoelectronics, magnetic sensorics, printable magnetoelectronics, stretchable magnetoelectronics.**

I. INTRODUCTION

Research on non-rigid electronics started almost 20 years ago originally motivated by interest in flexible, paper-like displays [1,2]. There are several ways to achieve non-rigid electronics [3]. One is related to the development of organic electronics [4], which is flexible but slow. A good alternative to this approach is stretchable inorganic electronics, which combines advantages of being flexible with the speed and performance of conventional semiconductor-based electronics [5]. Since being first introduced, stretchable electronics has become a dynamically developing research area which is of strong application interest due to the possibility to reshape the functional element on demand after its fabrication. There are already a variety of flexible devices commercially available, i.e. electronic displays [2,6] and integrated circuitry [7] to name a few. Until recently, the main focus was on fabrication of shapeable high-speed electronics [8] and optoelectronics [9] (Fig. 1). However, the family of shapeable electronics is not limited to these two members. Only very recently, we reported for the first time the fabrication of shapeable magnetoelectronics [10-13].

Magnetic sensor devices on elastic substrates could enable fabrication of smart biomedical systems, where large-angle folding of the micrometer-sized functional elements is a crucial prerequisite for a successful implementation. Furthermore, flexible magnetic sensors can be directly integrated into already existing stretchable electronic systems to realize smart hybrid magneto-electronic devices with the functionality to sense and to respond to a magnetic field.

II. STRETCHABLE MAGNETOELECTRONICS

Layered magnetic structures revealing a giant magnetoresistance (GMR) effect are crucial components of magnetic sensor devices. Currently, GMR sensors are fabricated on rigid inorganic substrates. Here, we demonstrate functional stretchable magnetic sensor based on [Co/Cu] and [Py/Cu] GMR multilayers prepared on free-standing elastic PDMS membranes [10,11].

In order to produce magnetic layer stacks on a free-standing rubber membrane, PDMS (Sylgard® 184) was first spin-coated onto silicon wafers. An anti-stick photoresist layer is introduced to assist peeling the PDMS film from the rigid silicon support. The PDMS precursor blend was cured in an oven under continuous nitrogen flow, resulting in a rubber film. To provide the possibility of electrical resistance measurements of the magnetic sensor device on the rubber substrate, the PDMS surface was patterned by means of photolithography before metal deposition. This renders the fabrication process compatible to current microelectronic structuring procedures.

The magnetic sensor layer was grown onto the elastic PDMS surface using magnetron sputter deposition. Afterwards, the PDMS film is peeled from the rigid silicon wafer leading to a free-standing elastic membrane covered with magnetic layer.

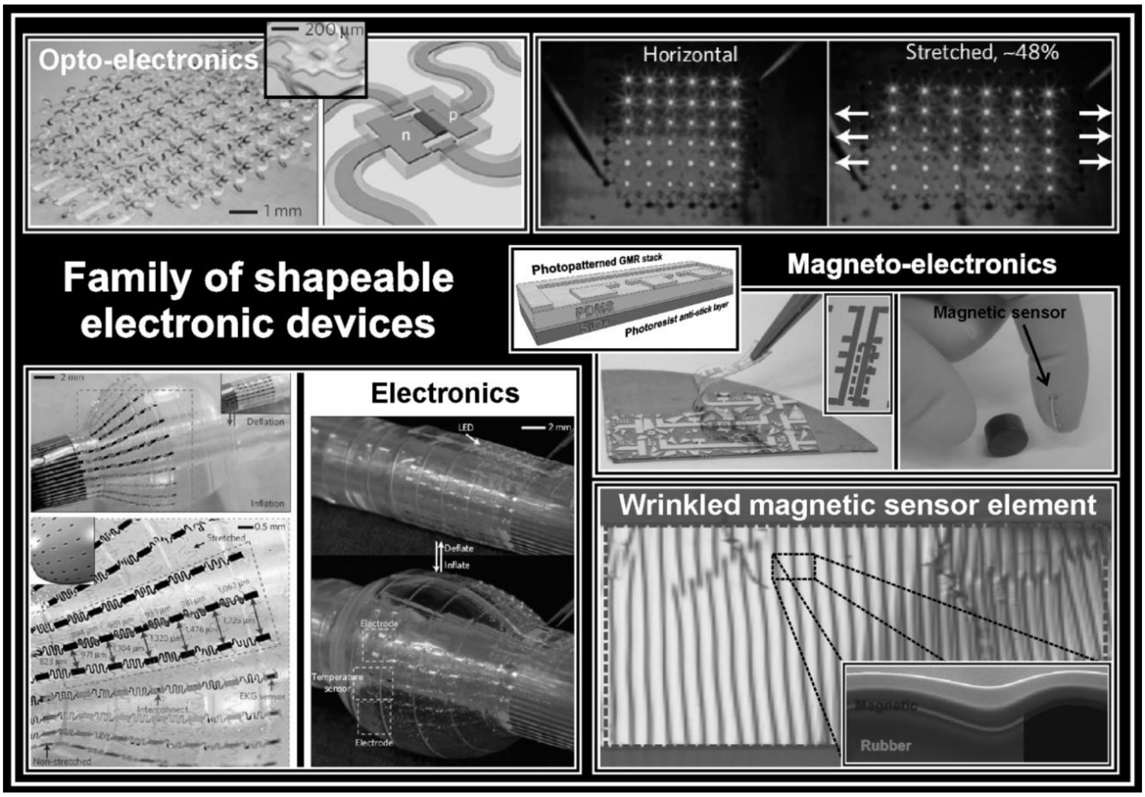

Figure 1: *Family of shapeable electronics: (Top panel) Opto-electronics [11]: array of light emitting diodes (LEDs). (Bottom left) Electronics [10]: Multifunctional inflatable balloon catheters. (Bottom right) New member of the family – shapeable magneto-electronics: giant magneto-resistive (GMR) sensor element on a free-standing rubber membrane. Shapeability of the magnetic sensor element is due to wrinkle formation. The figure is adopted from Melzer et al., Nano Lett. 11, 2522 (2011).*

The GMR ratio is defined as the magnetic field dependent change of the sample's resistance, $R(H_{\mathrm{ext}})$, normalized to the value of resistance when the sample is magnetically saturated, R_{sat}: $\mathrm{GMR}(H_{\mathrm{ext}}) = [R(H_{\mathrm{ext}}) - R_{\mathrm{sat}}] / R_{\mathrm{sat}}$. Figure 2(left panel, top) shows the GMR ratio measured for $[\mathrm{Co/Cu}]_{50}$ multilayers grown on different substrates. The GMR curves obtained from the samples prepared in the same deposition run on a rigid silicon wafer without (open square symbols) and with PDMS coating (open circle symbols) are very similar. A maximum GMR value of more than 50% is obtained on both substrates. Furthermore, the GMR signal does not change after the PDMS is peeled off the silicon wafer (compare curves with open and close circle symbols). Although the GMR performance of the devices on free-standing PDMS membranes and on PDMS-coated silicon wafers is similar, the morphology of the samples is found to be substantially different due to appearance of thermally induced wrinkles (Fig. 2(left panel, middle)). The height profile of the sample reveals a wrinkling period of about 17 µm and a mean amplitude of about 0.5 µm. Upon stretching the wrinkles are smoothened out and prevent the sensor from cracking, allowing for superior stretchability. Figure 2(left panel, bottom) shows the measured electrical resistance while the sample was stretched. For strains of up to about 4% only a slight increase of the samples resistance is observed. For higher strains the resistance abruptly increases and finally the electrical contact is lost at a strain of about 4.5% (gray-shaded area). Please note that flat metal films on top of a rubber substrate without surface wrinkling withstand tensile strains of only below 1%.

The GMR sensor element is remarkably stable against cyclic loading. Figure 2(middle panel) shows the resistance of a GMR multilayer on a rubber membrane during 10 stretching cycles from 0 to 1% and back. A permanent magnet was employed to measure the GMR performance. The magnetic field was chosen to be 300 mT to assure that the sample is magnetically saturated. When the magnetic field is applied, the resistance of the sample drops (Figure 2(middle panel, top), red curve) as expected for [Co/Cu] multilayers. The resistance of the sample (with and without applied magnetic field) remains unchanged even after the sample was reversibly stretched and relaxed for 10 times. Figure 4(middle panel, bottom) shows the GMR ratio in dependence of the tensile strain for the cyclic loading measurements. The GMR ratio remains at a constant value of ≈ 53% with low deviations (±0.2%) for tensile strains up to 1% and therefore is well-suited for magnetic sensor applications in environments where deviations from a flat geometry are required.

To demonstrate the performance of the elastic GMR sensor element, the sensor was attached to a plastic foil shaped into a ring geometry to track the magnetic field of a rotating permanent magnet (Fig. 2(right panel, top)). The change of the resistance of the GMR multilayer was recorded versus time: When the magnet is in the proximity of the sensor, a decrease of the resistance is detected. The dynamic response is illustrated by sensing the rotating magnetic field at higher frequency, which is easily traced with the GMR sensor (Fig. 2(right panel, bottom)).

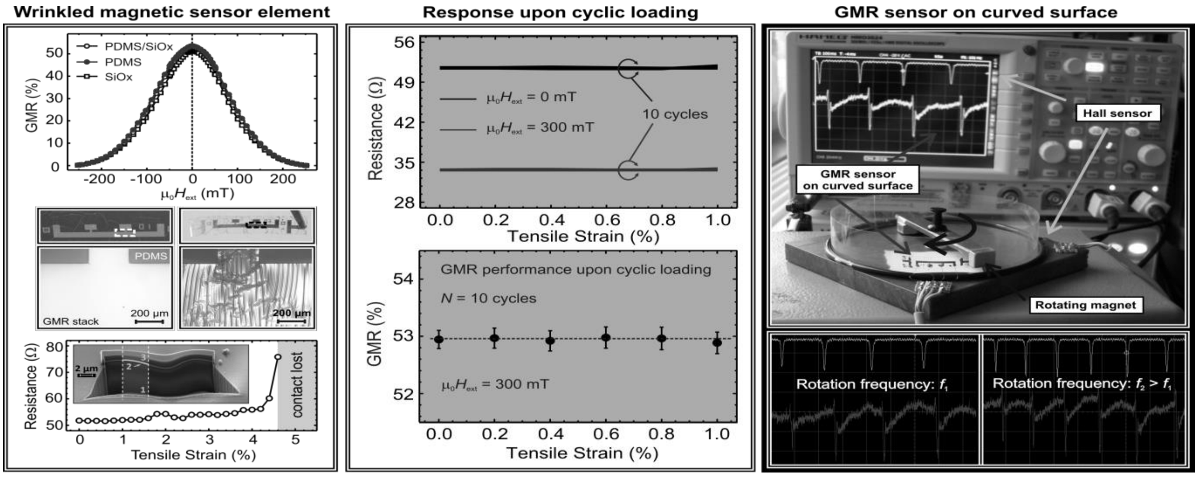

Figure 2: *(Left panel) Stretchable magnetoelectronics: giant magnetoresistive (GMR) sensor element on a free-standing PDMS membrane. Even after the sample is peeled from the SiOx wafer, the GMR performance remains unchanged. Optical microscopy images taken from the photolithographically patterned GMR multilayers on PDMS/SiOx and free-standing PDMS membrane revealing wrinkle formation. Electrical resistance of the wrinkled GMR multilayer upon tensile strain. Only gradual increase in the sample resistance is observed up to 4.5% strain. The inset shows SEM image of a FIB cut through the sample (1: PDMS; 2: [Co/Cu] multilayers; 3: carbon protective layer). (Middle panel) Response of the sensor to cyclic loading. (Right panel) Measurement of the magnetic field of a rotating magnet using an elastic GMR sensor attached to the curved surface of a foil. The figure is adopted from Melzer et al., Nano Lett. 11, 2522 (2011).*

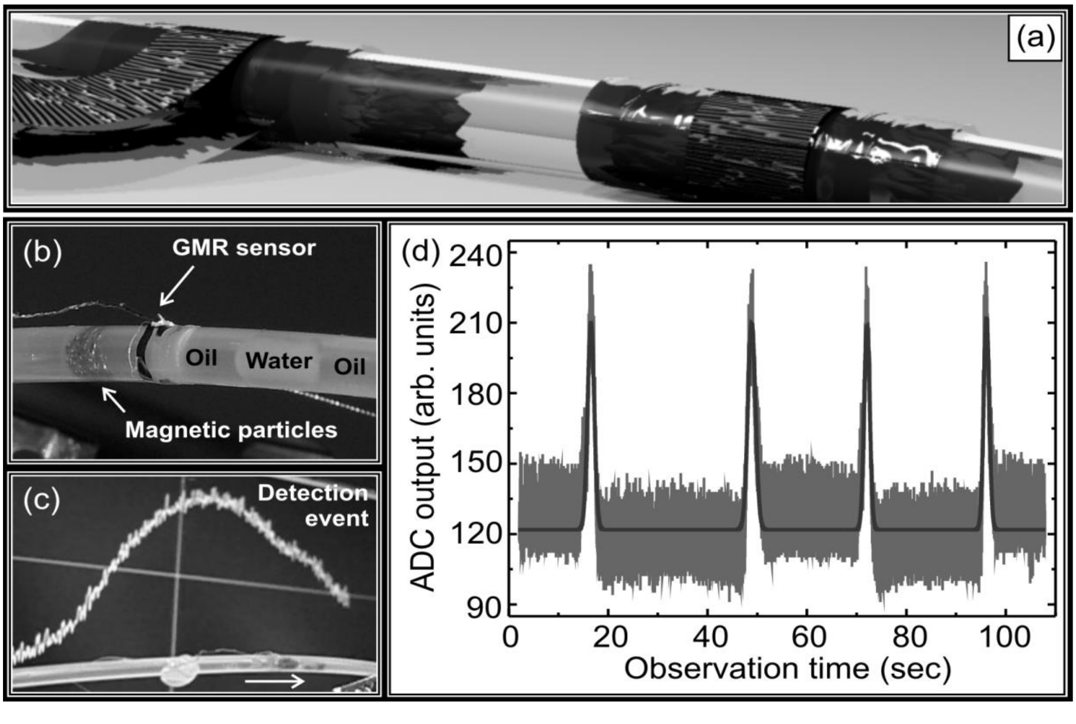

Figure 3: *(a) Sketch demonstrating the application of stretchable magnetic sensors for in-flow detection of magnetic objects in fluidics: the elastic sensor can be tightly wrapped around a fluidic channel allowing for an enhanced and isotropic sensitivity. Detection of magnetic particles in a fluidic channel: (b) optimized [Py/Cu]*$_{30}$ *elastic GMR sensor wrapped around the circumference of a Teflon tube. Agglomerate of FeNdB particles suspended in oil and separated by colored water droplets inside the tubing is shown. The magnetic particles are approaching the GMR sensor. (c) Signal of the elastic GMR sensor on a screen (background) as the magnetic cluster is passing the sensor (foreground). (d) Several consecutive detection events of particles passing the elastic GMR sensor. The figure is adopted from Melzer et al., RSC Adv. 2, 2284 (2012).*

III. IN-FLOW DETECTION OF MAGNETIC OBJECTS USING STRETCHABLE GMR SENSORICS

Furthermore, we proposed a new concept for in-flow detection of magnetic particles in millifluidics using elastic GMR sensors [11]. Due to their stretchability, GMR sensors can be wrapped tightly around a fluidic channel (Fig. 3(a, b)). This strategy offers the following advantages: (i) sensing of the magnetic stray fields in virtually all directions (isotropic sensitivity), which is unique compared to the rigid planar counterparts; (ii) simplicity of the sensor integration into a fluidic circuit; (iii) possibility of being reused. As magnetic stray fields to be detected in fluidics are small, the strong emphasis was on the enhancement of the sensitivity of the sensor on elastic membranes to small magnetic fields. For this purpose, we fabricated different GMR multilayer systems, including [Co/Cu] and [Py/Cu] stacks coupled in the 1st or 2nd antiferromagnetic (AF) maximum. Even when prepared on elastic 40-μm-thick free-standing rubber membranes, [Py/Cu] multilayers coupled in the 2nd AF maximum reveal a remarkable sensitivity of 106 T^{-1} (magnetic field: 0.8 mT); this value is almost 30 times larger than for the [Co/Cu] stack coupled in the 1st AF maximum. We successfully demonstrate the performance of this elastic sensor wrapped around a fluidic channel (diameter of 3 mm) for in-flow detection of assemblies of magnetic FeNdB particles (Fig. 3(c,d)).

Our approach potentially opens an exciting possibility for stretchable magnetoelectronics to be applied in the field of biology and chemistry. Indeed, in combination with magnetic particles as biomarkers, this elastic magnetic sensor can be considered as a new generation of biosensors for cells or even biomolecules evading many difficulties of traditional optical detection methods like low speed, excitation, bulky and expensive equipment, biomolecular amplification and the need for transparent packaging.

REFERENCES

[1] G. Gustafsson et al., *Nature* 357, 477 (1992).
[2] J. A. Rogers et al., *PNAS* 98, 4835 (2001).
[3] D. H. Kim et al., *Adv. Mater.* 22, 2108 (2010).
[4] T. Sekitani et al., *Adv. Mater.* 22, 2228 (2010).
[5] F. Cavallo et al., *Soft Matter* 6, 439 (2010).
[6] I. J. Chung et al., Molecular Crystals and Liquid Cristals 507, 1 (2009).
[7] T. W. Kelley et al., *Chemistry of Materials* 16, 4413 (2004).
[8] D. H. Kim et al., *Nature Mater.* 10, 316 (2011).
[9] R. H. Kim et al., *Nature Mater.* 9, 929 (2010).
[10] M. Melzer et al., *Nano Letters* 11, 2522 (2011).
[11] M. Melzer et al., *RSC Adv.* 2, 2284 (2012).
[12] D. Karnaushenko et al., *Adv. Mat.* 24, 4518 (2012).
[13] M. Melzer et al., *Adv. Mater.* 24, 6468 (2012).