Dispenser Printed Bismuth-Based Magnetic Field Sensors with Non-Saturating Large Magnetoresistance for Touchless Interactive Surfaces

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1. Introduction

Printed electronics is a dynamic research and technology area allowing to obtain on-demand functional elements.[1–3] In recent years, printed electronics with semiconducting,[4] optoelectronic,[5] energy storage,[6] and magnetic[7] properties have been reported. In particular, printed magnetoresistive sensors have proven their relevance as contactless electromagnetic switches[8,9] and touchless interactive on-skin platforms.[10] These magnetically sensitive composites have been produced by incorporating ferromagnetic magnetoresistive (MR) particles or flakes dispersed in various binder solutions of gel-like or thermoplastic nature (Table 1).[9–17] While these contributions have significantly advanced the field in the last decade, the large-scale adoption of these technologies remains unfulfilled due to the complexity and high production costs associated with the constituent particles or flakes. Flakes showing giant magnetoresistance effect (GMR) up to 37% consist of multilayered heterostructures that require sequential deposition of sub-nm-thick films.[9–13] The thickness of the layers require precise tuning to achieve measurable magnetoresistance changes. These result in increased production costs of powders showing GMR. In response to address the scalability problem of GMR powders, particles from commodity available ferromagnetic materials showing anisotropic magnetoresistance (AMR) were employed.[14] However, the measured AMR effect was reduced to 0.34%. Moreover, these MR technologies typically have a linear response at magnetic fields below 500 mT and are almost nonsensitive beyond. A printable commodity scale material that has strong magnetoresistance signal and performs in a wide range of magnetic fields is missing. Targeting a broader range of magnetic fields with printing technologies could enable novel low-cost technological solutions, ranging from non-contact switching applications to industrial monitoring of machinery. Achieving large-scale production and linear response at high magnetic fields with conventional printing methods requires new material developments.

Printed magnetic field sensors enable a new generation of human-machine interfaces and contactless switches for resource-efficient printed interactive electronics. As printed magnetoresistors rely on scarce or hard to manufacture magneto-sensitive powders, their scalability and demonstration of printing with industry-grade technologies are the key material science challenges. Here, the authors report dispenser printing of a commodity scale nonmagnetic bismuth-based paste processed by large area laser sintering to obtain printed magnetoresistive sensors. The sensors are printed on different substrates including ceramics, paper, and polymer foils. It is validated experimentally that the peculiar quantum large orbital magnetoresistive effect remains effective in printed bismuth sensors, allowing their operation in high magnetic fields. The sensors reveal up to 146% resistance change at 5 T at room temperature with a maximum resolution of 2.8 μT. If printed on flexible foils, these sensors show resilience to bending deformation for more than 2000 bending cycles and withstand even thermal forming, as relevant for smart wearables and in-mold electronics. The freedom in the substrate choice and sensor design enabled by dispenser printing allows to implement the proposed sensor technology for different applications focused on touchless interactive platforms, such as advertisement materials, interactive wallpapers, and printed security panels.
We identified bismuth (Bi) powder as a potential non-ferromagnetic filler to produce magnetoresistive pastes. Bi powder is a commodity scale, commercially available, and green alternative to state-of-the-art ferromagnetic MR particles. Bi single crystals and highly ordered thin films have been intensively investigated due to their non-saturating large magnetoresistance (LMR) in a broad range of magnetic fields. We note that large magnetoresistance is also called linear magnetoresistance, extremely large magnetoresistance, or large orbital magnetoresistance. LMR effects appear in semi-metals, with Dirac crossings in their band structure, resulting in extremely high mobilities and low effective mass. LMR is a non-saturating quantum magnetoresistive effect present in bulk Bi, as well as Bi thin films and nanostructures allowing to achieve >300% resistance change at 5 T at room temperature. In terms of the range of detection, the non-saturating behavior of LMR materials contrasts with the previous sensors based on GMR and AMR effect, where the sensing capabilities are restricted to the low field region where the resistance level saturates and does not change for higher magnetic fields (=500 mT, and ≈20 mT for GMR and AMR respectively). Until now, the LMR effect has not been studied in printed materials. The successful implementation of the non-saturating LMR effect on printed magnetic field sensors would mean that the range of detection of magnetic fields could be extended beyond the low field regime with a strong magnetoresistive effect. Bismuth thin films prepared with PVD technologies on polymeric foils have shown their applicability for Hall effect sensors. Pastes containing Bi-powder are non-conductive as printed and dried due to the organic binder residuals and formation of oxide layer around Bi particles and non-continuous particle contacts in the film. Therefore, oven treatment under inert gas or vacuum ambience is needed to achieve sintering with formation of a conductive mesh among the constituent Bi particles. This kind of treatment is not compatible with most types of cost-efficient polymer substrates.

Here, we present a new material science platform based on bismuth paste that enables the scalable production of dispenser printed magnetic field sensors with LMR effect. A novel approach to large area high-throughput processing of the printed material was explored based upon a micro-optically optimized high-power diode laser array permitting selective sintering of the Bi paste at ambient conditions. We report the paste composition and the laser processing parameters to obtain sensors with strong LMR effect up to 146% resistance change at room temperature at 5 T (exceeds 3900% at 20 K at 7 T). Our methodology allows fabricating high-performance magnetic field sensors on rigid and flexible substrates. Due to their thermal and mechanical stability, the sensors printed on thermoplastic foils can be reformed in a stable 3D shaped object. In this respect, our technology could be applied for in-mold electronics, yielding shapeable custom-made sensors that can be geometrically adapted for lamination over uneven surfaces. Profiting from the high versatility in design and substrate material, we demonstrate magnetically controlled interactive devices based on a printed array of sensors, to be used for interactive advertisement, smart wallpapers, and security input panels.

2. Results and Discussions

2.1. Printed Sensors Revealing Large Magnetoresistive Effect

Printed LMR sensors were fabricated in a two-step process using a paste containing Bi powder (Figure 1a). First, dispenser printing of the paste on a selected substrate allowed facile patterning of the desired layout changing the height and width of the printed layers without changing the paste composition or changing printing masks (Figure 1b). After laser sintering, the printed structure became conductive and performed as a magnetoresistive sensor (Figure 1c). Constituent Bi particles with an equivalent spherical diameter, D(50) of about 2 μm (Figure 1d and Figure S1, Supporting Information) allowed us obtaining a homogenous paste with rheological properties (Figure 1e) suitable for dispenser printing. The latter yields a printed line resolution below 500 μm in width and 75 μm in thickness at printing speeds exceeding 10 mm s⁻¹ (Figure 1f). Stripe-shaped samples with 5 mm contact pitch were prepared to measure the

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Table 1. Comparison of MR and sensing field range of solution-processable magnetic field sensors.

<table>
<thead>
<tr>
<th>Type</th>
<th>Magnetoresistive material</th>
<th>Microstructure of magnetosensitive particles</th>
<th>Max MR at RT [%]</th>
<th>Sensing field range [T]</th>
<th>Fabrication</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>GMR</td>
<td>Co NPs</td>
<td>Core-shell Fe-C NPs</td>
<td>260</td>
<td>0.2</td>
<td>Casting</td>
<td>[11]</td>
</tr>
<tr>
<td>GMR</td>
<td>Co/Cu flakes</td>
<td>50 bilayers of Co(1.0 nm)/Cu(1.2 nm)</td>
<td>8</td>
<td>2</td>
<td>Painting</td>
<td>[9]</td>
</tr>
<tr>
<td>GMR</td>
<td>Co/Cu flakes</td>
<td>50 bilayers of Co(1.0 nm)/Cu(1.2 nm)</td>
<td>37</td>
<td>0.6</td>
<td>Painting</td>
<td>[12]</td>
</tr>
<tr>
<td>GMR</td>
<td>Py/Cu flakes</td>
<td>30 bilayers of Py(1.5 nm)/Cu(2.3 nm)</td>
<td>2</td>
<td>0.02</td>
<td>Stencil painting</td>
<td>[10]</td>
</tr>
<tr>
<td>GMR</td>
<td>FeCoNi/Cu nanowires</td>
<td>1300 bilayers of FeCoNi(25 nm)/Cu(8 nm)</td>
<td>14</td>
<td>0.6</td>
<td>Stamping</td>
<td>[13]</td>
</tr>
<tr>
<td>AMR</td>
<td>Py flakes</td>
<td>Bilayer of Ta(5 nm)/Py(100 nm)</td>
<td>0.34</td>
<td>0.4</td>
<td>Stencil painting</td>
<td>[14]</td>
</tr>
<tr>
<td>Magnetically driven stress</td>
<td>Magnetite μPs in PDMS</td>
<td>Ag coated magnetite particles</td>
<td>7.5</td>
<td>0.3</td>
<td>Casting</td>
<td>[15]</td>
</tr>
<tr>
<td>Magnetically driven stress</td>
<td>Carbonyl-iron μPs in PDMS</td>
<td>Carbonyl-iron μPs</td>
<td>3.6</td>
<td>0.15</td>
<td>Casting</td>
<td>[16]</td>
</tr>
<tr>
<td>AMR</td>
<td>Carbonyl-iron μPs in PDMS</td>
<td>Carbonyl-iron μPs</td>
<td>25</td>
<td>0.04</td>
<td>Spin coating</td>
<td>[7]</td>
</tr>
<tr>
<td>LMR</td>
<td>Bi</td>
<td>Bi μPs</td>
<td>146</td>
<td>5</td>
<td>Dispenser printing</td>
<td>This work</td>
</tr>
</tbody>
</table>

The basic magnetoresistive material, their microstructure, the maximum measured MR, the maximum measured sensing field range, and the solution-processable fabrication method are summarized.
magnetoresistive effect after the laser processing (Figure 1g, inset).

Our Bi sensors printed on alumina achieved 146% MR at 5 T at room temperature (Figure 1g, graph, and Figure S2, Supporting Information) and 3900% at 7 T at 20 K, giving the first experimental demonstration of the non-saturating large magnetoresistance effect with printed materials. The non-saturating behavior implies that the resistance grows up to the measured available fields. Our printed LMR sensors expand the detectable magnetic field range by a factor of more than 10 with respect to the previously reported printed sensors. The noise performance (Figure S3, Supporting Information) and sensitivity characteristics (Figure 1h) resulted in a sensing resolution of 14 µT at 100 mT. The design flexibility of the dispenser printing method demonstrates that MR sensors, based on Bi pastes, can be integrated in various application scenarios, like interactive advertisement devices (Figure 1i), smart paper, and wearable electronic platforms.

2.2. Large Area Laser Sintering of Bismuth-Based Paste Enables Processing on Rigid and Flexible Substrates

Emphasizing the design flexibility of the dispenser printing method, we demonstrated the parallel processing of the magnetic field sensors on large area foils with 25-mm-long stripe elements (Figure 2a and Movie S2, Supporting Information) and free design layouts (Figure 2b and Movie S3, Supporting Information). A study of the printing parameters required to print the Bi-based paste is described in Supporting Information (Figures S4 and S5, Supporting Information and the corresponding discussion). The fabrication of magnetic field sensors was enabled by a diode laser array source operating in the near infrared (NIR) (wavelength λ = 980 nm) with dwell time on the millisecond scale. This processing technique allowed the sintering of samples not only on thermally stable rigid substrates like alumina, but also on thermally sensitive and flexible polymer foils like polyimide (PI; Figure 2a,c) and polyethylene terephthalate (PET; Figure 2b,d). We studied the effect of the paste composition and the laser processing parameters, on the magnetoresistive performance of the sensors printed onto reference Al₂O₃ ceramic substrates, by quantifying the measured...
MR response at 500 mT. The appropriate concentration of the Bi powder in the paste was chosen at the level of 88 wt% allowing to achieve MR up to about 7% at 500 mT in case of the sensors processed on Al₂O₃ ceramic substrates (Figure 2e). This paste composition was chosen for further experiments, where the effect of the laser sintering parameters on the MR effect and conductivity was addressed. As shown in Figure 2f (upper axis), electrical conductivity was observed for the samples processed on Al₂O₃ ceramic substrates with the laser fluence in the range of 20 to 100 J cm⁻². The MR performance of the sensors is found to stay at the observed highest values of approximately 7% and to be independent of the fluence within the range from 60 to 100 J cm⁻². Beyond the fluence window of 20 to 100 J cm⁻², the samples were non-conductive. A scanning electron microscopy (SEM) characterization and separate analysis of the laser parameters provide insight into the mechanism of achieving conductivity of the printed sensors (Figure S6, Supporting Information). We observed that low fluence did not favor the formation of a continuous layer as there are no effective conductive paths formed due to the remaining polymer binder and oxide around the particles (Figure 2g). In the laser fluence range between 20 and 100 J cm⁻², conduction was achieved by a continuous Bi conductive path formed along the printed area (Figure 2h). This effect demonstrates the suitability of the laser processing to achieve locally the melting and sintering temperature of Bi microparticles. On the other hand, increasing the fluence above 100 J cm⁻² caused physical delamination of the material (Figure 2i), hindering conductivity of the sensors.

The sintering process is qualitatively similar to the discussion above when carried out for Bi sensors printed on polymeric foils (Figure 2f, bottom axis). Thermal damage of the polymer substrate during the laser treatment was minimized because the Bi-based printed structures have substantially stronger optical absorption in the NIR compared to that of the employed polymer foils. Considering processing dwell time on the millisecond scale (2–12 ms for PET substrates), the laser-induced heating is mainly confined to the printed structures, because heat transfer into the substrate is limited in this case by a few tens of micrometers at most. The morphological changes in Bi and PET films during the laser processing indicate that temperature exceeds the Bi melting point of 271 °C but remains below PET ignition temperature of 400–600 °C at the contact areas between Bi-structures and the substrate. Simplified estimations based upon solving heat conduction equation for thermal parameters of PET and bulk Bi support this assumption suggesting the temperatures at the surface of the printed layer to be within the range 300–400 °C and below 300 °C at the interface to the substrate, decreasing below 100 °C at the depth of >20 µm in the PET.
substrate. Since the polymer foils have approximately one order of magnitude lower thermal conductivity compared to the ceramic Al₂O₃ substrates, much lower laser fluence was sufficient to enable sintering of Bi particles and achieve the highest MR values of 6% (18 J cm⁻²) for the samples on PET and 7% (22 J cm⁻²) in those on PI foils. Also, the range of laser fluences resulting in functional Bi sensors on PET substrates is observed to be shifted to lower values (7–21 J cm⁻²) compared to those for the sensors on Al₂O₃ ceramic substrates. The proposed dispenser printing was found to be suitable for flexible design of printed magnetic field sensors, over diverse substrates, and prospectively for parallel processing and sintering over large areas (Figure S7, Supporting Information).

2.3. Mechanical Stability of LMR Sensors Printed on Polymeric Foils

When printed on flexible substrates, Bi-based magnetic field sensors show potential for applications in flexible electronics. We study the mechanical stability of Bi sensors printed on 125-µm-thick PET foils. Adding a ~50-µm-thick polyvinyl-alcohol (PVA) encapsulation layer on top of the printed area provided mechanical resilience with the effective displacement of the neutral mechanical plane closer to the printed Bi layer (Figure S8, Supporting Information). Figure 3a shows the stability of the MR response upon deformation to different bending radii. After bending the sample down to 3.5 mm radius and flattening back, the MR effect at 500 mT was stable around 4.2%. Additionally, we tested the stability of the MR effect upon repetitive bending (Figure 3b). The resistance change in the signal has two components, the cyclic bending strain due to the typical gauge factor in conductive materials, and the larger resistance change in the signal that corresponds to the LMR effect after approaching a magnet. Even after 2300 cycles, the magnetoresistor was operational and responded to the magnetic field of a permanent magnet (350 mT). The measured MR effect of 1.9% is consistent with the initial sensor performance (before bending) in the field of 350 mT (Figure 3c and Figure S9, Supporting Information). The mechanical stability of the encapsulated sensors on flexible foils renders them attractive for integration in mechanically moving flexible parts and wearable devices.

The printed sensors reveal stable operation even after heating up to temperatures of 130 °C in air without encapsulation (Figure S10, Supporting Information). The thermal stability enables an appealing possibility to change the shape of the printed sensor foils permanently after their fabrication on flexible PET foils. In this respect, PET as a thermoplastic can be reformed. This offers a possibility to perform 2D printing process on a flat foil, which can be afterward reformed to a more complex 3D shape (Figure 1k). This result demonstrates that our technology could prospectively be combined with the fabrication of in-mold electronics, yielding shapeable custom-made sensors that can be geometrically adapted for lamination over uneven surfaces.

![Figure 3. Performance of PVA encapsulated magnetoresistors printed on a flexible PET foil. a) MR signal stability after bending a printed magnetic sensor down to 3.5 mm (blue symbols) and flattening it back (orange symbols). b) The change of the electrical resistance of the sensor printed on PET during a cyclic bending test between 30 mm and 15 mm bending radii. The higher resistance levels contained in the shadowed area correspond to the magnetoresistive effect occurring after approaching a permanent magnet (350 mT) to the sensor. c) Prevalence of the MR effect calculated before bending trials and at specific cycles of the bending test.](image-url)
A permanent magnet applied to the finger (Figure 4a). The magnetic field easily passes through the cover layers and reaches the sensing units. Each of the sensing areas (two areas in total; Figure 4b) was assigned to different outputs: the upper one was assigned to change the “next” content section and the lower to change “back” in the sequence (Figure 4c). When the respecting sensing area was activated by the user, the wallpaper showed additional content. Figure 4d shows the time evolution of the signal output voltage for both sensing areas where a “next” keystroke was registered at ≈ 6 s and a “back” command happened at ≈ 16 s. These events resulted in a change in the content that was displayed on the interactive wallpaper (Figure 4e).
We expanded the concept of the usage of printed magnetic field sensitive panels to safety input devices for smart home applications. We placed a printed panel on a door entrance as an input keyboard for introducing a password key (Movie S5, Supporting Information).

Figure 5a shows the schematics of the safety panel construction, consisting of a plastic cover where the printed magnetoresistive panel was attached with additional light-emitting diode (LED) indicators. The input keyboard consisted of four sensing units (half-Wheatstone bridges), each of them corresponding to a digit (1 to 4) from the keyboard (Figure 5b). The assembly was attached at the door entrance functioning as a hidden input keyboard (Figure 5c), the faint overlayed image illustrates the position of the panel below the cover. Sequentially approaching a permanent magnet over the sensing areas (Figure 5d) resulted in the independent activation of the keystrokes as shown in the output signal in the Figure 5e. This application example illustrates one of the possible configurations for wall-mounted terminals and magnetically controlled touchless interactive surfaces.

3. Conclusions

Laser sintered Bi-based pastes open the path for scalable, cost-efficient, on-demand fabrication of flexible fully printed magnetic field sensors. Our results suggest that, even at ambient conditions, the laser processing on the millisecond time scale leads to simultaneous removal of the binder polymer from the surface of Bi particles and sintering of the particles without formation of the oxide layers, which blocks electrical conduction in the layers. The employed dispenser printing excels in the research and personal use scale, as it allows flexibility in
the design and precise large-area patterning on flat and uneven surfaces with the benefit of minimal material waste. We also foresee the use of screen printing with dedicated screen layouts to mass-production environments. The state of the art in-mold electronics mainly rely on capacitive proximity sensing for interactivity. Such technology combine in a single foil functional printed track with embossed integrated circuits. In this respect, our material and printing approach could be applied as a novel fully-printed layer for touchless interactivity relying on interaction via magnetic fields. Our results, showing the thermal molding capabilities of the printed magnetic field sensors, are promising for extending the usual capacitive input gestures with orientation and tilting information that is intrinsic to magnetic fields.

This work could be extended to study multilayer structures to enhance the device sensitivity in the low magnetic field region. Furthermore, our results motivate follow-up research on the development of feedstock materials for 3D printing of magnetic field sensors. Additionally, we note that this work constitutes the use of topological material properties of bismuth to realize non-saturating LMR in printed sensor devices. Using non-saturating LMR-based printed sensors, we increased the range of magnetic field detection by a factor of more than 10 compared to the state of the art printed magnetic field sensors, with quasi-linear sensitivity and strong magnetoresistive effect. We are convinced that this demonstration will stimulate further research on the use of quantum topological materials in different fields of printed electronics with the latter benefiting from their advanced optical and transport properties. Examples may come from the printing of topological optical elements for holography,[39] to increasing the power efficiency of printed solar cells with topological materials.[40]

The demonstrators shown in this work illustrate promising novel applications of magnetically sensitive printed devices. A seamless integration of wide range magnetic sensing into dedicated experimental setups and personal dosimeters, might find direct applications in research and clinical environments. Bi-based sensors, being non-magnetic, might be useful for continuous exposure monitoring during magnetic resonance imaging, nuclear magnetic resonance, and prospective magnetically controlled interventional procedures. From smart home applications, through interactive entertainment electronics, to interactive wallpapers, magnetically responsive devices open new paths for user interactivity. Interactivity via magnetic fields is attractive for prospective smart textiles in wetsuits or winter clothing, for gaming controllers, and even to contain pandemics propagation introducing non-contact terminals. These possibilities resulting from the intrinsic action-at-a-distance of magnetic fields are essential for the broad acceptance of on-site printed sensing arrays and large-scale interactive surfaces.

4. Experimental Section

**Paste Formulation:** A pure (99.9%) Bi powder (Haines & Maassen GmbH) was used for the preparation of the paste. The equivalent spherical diameter of the bismuth powder was measured by laser diffraction with a Mastersizer 2000 (Malvern Panalytical Ltd, United Kingdom). A printable paste compound was obtained by using a speedmixer DAC 150SP (Hauschild GmbH und Co. KG, Germany) to mix the components. The paste composition was based on a butylmethacrylate-type binder, solvents, and Bi powder (82 to 90 wt%). After the mixing process, a three roll mill W550 (Exakt Advanced Technologies GmbH, Germany) was used to ensure dispersing of the paste components. The viscosity parameters of the paste were tested with a cone plate rheometer (Haake Mars II Rheometer, Thermo Fisher Scientific Inc., USA) at room temperature.

**Dispenser Printing:** Dispenser printing of the formulated paste was done with a VCI1000 dispenser (VIEWEG GmbH, Germany) using a DV-5005DFS screw valve of the same company. 25-mm-long lines with variable width and thickness were printed on 500-μm-thick aluminum oxide ceramic (Ceramtec GmbH, Germany). For printing on flexible substrates, 125-μm-thick PET foils (Optimont MF-AS, Bleher Folientechnik GmbH, Germany), 175-μm-thick paper foils (p_e:smart paper Type 3, Felix Schoeller Group, Germany), and 50-μm-thick polyimide foils (Kapton HN200, DuPont, USA) were used. After the printing process, the structures were dried in a box oven (FT6060, Heraeus GmbH, Germany) at 80 °C for 30 min in nitrogen. The discussion of the printing parameters is provided in Figure S5, Supporting Information, where the dispenser printing mechanism, the importance of an appropriate cannula diameter, optimization of the rotation speed of the spindle, and optimization of the spindle pitch are addressed.

**Laser Sintering:** After drying, the printed samples were transferred to the continuous wave LIMO900 Line Laser (Focuslight/Limo GmbH, Germany) system for treatment in air. A 30 × 0.1 mm² laser beam (λ = 980 nm) was generated by microoptically optimized high-power diode laser array. The resulting line-shaped laser beam had “top hat” homogeneous intensity profile along the line with the laser radiation intensity variation below 5% and Gaussian profile across the line. The description of this type of laser sources is given elsewhere.[41,42] The laser beam was swept along the printed lines (Figure 1c) to remove the organic phase and sinter Bi particles of the paste. The laser treatment speed varied between 100 mm min⁻¹ and 18 000 mm min⁻¹ with the laser in focus. The dwell time was defined as the ratio of the laser beam width to the treatment speed yielding the values in the range from 60 to 0.33 ms. The laser output intensity was changed within the range 833–8267 W cm⁻² by varying the drive current applied to the diode laser. Finally, the laser fluence was determined as a product of the laser radiation intensity and the corresponding dwell time. The effect of the individual parameters was studied to determine their influence on the MR performance for Al₂O₃ and PET (Figure S6, Supporting Information). Knowing the thermal diffusivity, α, of the substrate material, and the dwell time, t, it is possible to make an estimation of how deep the thermal front will propagate in the substrate during the laser treatment with the dwell time t: z = − ct. This estimate is an upper bound of the thermally affected layer thickness due to laser treatment. Thermal diffusivity α = k(ρ c) can be estimated based on the thermal conductivity, k, of the polymer foil (typically about 0.15 W m⁻¹ K⁻¹ at 100 °C),[43] its heat capacity (c = 1650 J kg⁻¹ K⁻¹) at 100 °C,[44] and density (ρ = 1350 kg m⁻³).[45] For the PET foils used in this study, the value of α was about 7 × 10⁻⁴ m² s⁻¹ resulting in a thermally affected layer thickness z of about 12–30 μm for dwell time 2–12 ms.

**SEM:** SEM microscopy images were acquired using the backscattered electron detector of the Phenom XL Desktop SEM (Thermo Fisher Scientific, United States) with 10 kV acceleration voltage and 0.1 Pa pressure. SEM study addresses the modification of the sensor morphology upon laser sintering (Figure S6, Supporting Information).

**Magnetoresistance Characterization:** The electrical resistance of the printed magnetoresistors was measured via 4-point configuration. Silver ink (Elektrodag 1415 M, PLANO GmbH, Germany) was applied by brush onto the sintered bismuth layer as contacts to a dedicated printed circuit board (PCB) connector. The resistance of the sensors was measured with a Tensortester (HZDR Innovation GmbH, Germany) with an applying current of 0.01 mA. A computer uniform magnetic field produced by electromagnet coils was swept up to 2.3 T perpendicular to the substrate plane.
Additionally, low-temperature measurements (Figure S2, Supporting Information) were performed with a Hall Measurement system (775, Lakeshore – W, United States) coupled with a superconducting magnet supply (625, Lakeshore, United States) and a He temperature controller (340, Lakeshore, United States). The MR effect percentage was calculated as a relative resistance change:

$$MR = 100\% \left( R_{H} - R_{0} \right) / R_{0}$$  \hspace{1cm} (1)

where $R_{0}$, is the electrical resistance of the sensor exposed to the magnetic field $H$; $R_{H}$ is the electrical resistance of the sensor at zero magnetic field.

A hot plate stage was used for measuring the MR effect after heating the sample. The sample was heated up to 130 °C. Before and after this heating process, the magnetoresistive effect was measured (Figure S10, Supporting Information).

**Noise Characterization:** The noise performance was tested after applying currents in the range between $1 \times 10^{-3}$ and $1.9 \times 10^{-2}$ A. The time evolution of the electrical resistance was measured over 30 s and sampled at 50 Hz for each current level. After applying a fast Fourier transform to the time-dependent datasets, the noise spectral density of the signals was obtained (Figure S11, Supporting Information).

**Encapsulation of the Printed Magnetic Field Sensors:** An aqueous solution (100 µL, 10 wt%) of poly(vinyl alcohol) (PVA MW 115 000 ≥ 89%, hydrolyzed, VWR, Germany) was drop casted over the printed sensing area. The solution was dried on a hot plate at 100 °C for 30 min. This resulted in a 50-µm-thick encapsulation layer that provided additional mechanical resilience to bending to these printed magnetic field sensors (Figure S8, Supporting Information). All the samples subjected to static and dynamic bending experiments (Figure 3 and Figure S9, Supporting Information) were encapsulated using this method.

**Performance Characterization during Bending:** Static bending experiments were performed using a dedicated holder that allowed to change the curvature radius based on the compression between the opposite edges of the flexible sensor. The electrical resistance of the samples was measured with a Tensormeter (HZDR Innovation GmbH, Germany). Cyclic bending experiments were carried out by a Phenom XL Tensile Tester (MTI0821, Thermo Fisher Scientific, United States) through the Microtest (Deben, UK) interface. Copper wire cables were fixed onto the contacts on the sensor with silver ink and connected to a dedicated PCB connector outside the bending stage. The electrical resistance of the samples was measured continuously with a digital multimeter (34461A, Keysight, United States). After about 1000 training cycles, the resistance value converged and the resistance response experiment was carried out. The measured dataset shows a typical periodic pattern corresponding to the changes of the resistance due to strain. The change of the electrical resistance of the printed sensor exposed to the magnetic field of a permanent magnet (350 mT field strength at the sensor location) was recorded to determine the respective MR performance upon cyclic bending. The prevalence of the MR effect calculated from the moving average resistance level over ten cycles before and after a permanent magnet is approached to the sensor during the cyclic bending test was registered (Figure 3 and Figure S9, Supporting Information).

**Printed Panels for Interactive Demonstrators:** An array of four magnetoresistive sensing units arranged in a half-Wheatstone bridge configuration was printed (Figure S11, Supporting Information). The silver interconnects on PET foil for the demonstrator were printed by inkjet. An inkjet-compatible and low-temperature sintering nanoparticle silver ink (Ag-LT-20, Fraunhofer IKT, Germany) with a solid content of 20 wt%, particle size <200 nm, viscosity of 10 mPa (22 °C, 100 s⁻¹), and surface tension of 35 mN/m (22 °C) was used. The silver ink was printed by Dimatix Material Printer DMP-2850 (Fujifilm Dimatix, USA) with a 10 µL printhead feed rate of about 100 mT. When magnets approach the sensors, their electrical resistance is modified due to the MR effect. If the change of the electrical resistance overcomes the pre-defined threshold, this triggers the external electronics to switch off an LED for a defined time. The LED was installed in the center of the rotating plate. The LED is otherwise switched permanently on and highlights the advertisement piece.

**Supporting Information**

Supporting Information is available from the Wiley Online Library or from the author.

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**Conflict of Interest**

The authors declare no conflict of interest.

**Data Availability Statement**

The data that support the findings of this study are available from the corresponding author upon reasonable request.

**Keywords**

dispenser printing, high-power diode laser array processing, magnetoresensitive bismuth paste, printed electronics, printed magnetic field sensors

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