Structuring Methods of Polymers for low Cost Sensor Manufacturing

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***Abstract*—A new manufacturing technique for low cost sensor production was developed at the Institute of Micro Production Technology at the Leibniz University Hanover. The herein described manufacturing technique uses common injection molding processes to pre-structure thermoplastic polymers such as Polycarbonate, which can subsequently be used as a substrate to build up sensor structures. The sensor structures are generated by sputter deposition and a following chemical mechanical polishing step. The realized sensor structure can be manufactured neglecting any lithography processes and therefore eliminates expensive clean room technology. This work investigates and optimizes injection molding parameter using design of experiment methods. Following the parameter studies, a manufacturing process designed to realize a micro technologically fabricated injection mold inlay was performed, and the performance of an electroplated Ni based injection mold master form for sensor structure manufacturing evaluated. A temperature sensor on a thermoplastic substrate (polycarbonate) prototype was realized, which was able to prove the feasibility of the manufacturing technique and the robustness of polymers as a substrate material.**

Keywords—injection molding; manufacturing technology; polymer substrate; Pt sensor

I. Introduction

In the field of Industry 4.0, “the internet of things“ is a major part of the new industry revolution [1]. The surveillance of products in terms of “the internet of things” demands a cost efficient manufacturing of sensors, which can be applied in industrial and consumer products. Therefore, the production technology has to be simplified and reduced in terms of manufacturing steps for sensors as well as the use of expensive clean room technology and lithography processes. The idea at this point is, to combine substrate and housing material as well as the structuring process of the sensor itself in order to reduce the manufacturing steps for structuring, housing and connecting. Common sensor systems are based on silicon substrates and have to be manufactured using clean room technology in addition to standardized micro production technologies like photolithography. Silicon based sensors are usually housed after steps of photolithography, deposition of the sensor layer, and dicing. New approaches to package integrated circuits show the need of flexible and cheap materials. Polymers offer good possibilities regarding material choice and mass production. The use of injection molding for more complex three-dimensional substrates, housings, circuit structures, and even sensors can be a solution for simplified production processes in comparison to the current state of the art in micro production technology [2] [3] [4]. At the Institute of Micro Production Technology (IMPT) at the Leibniz University Hanover, the development of a new manufacturing strategy is developed, to produce pre-structured substrates/housings, which can be used for sputter deposition and electroplating. The goal is to realize a cost efficient mass production manufacturing process for sensors. Important process steps are injection molding, sputter deposition, and chemical mechanical polishing (CMP). These manufacturing processes are not in need of clean room technology and abstain from any lithography processes. Therefore, the concept offers a promising solution for a low cost sensors production. Preliminary results investigating a transformer layout based on this manufacturing technique were published by the IMPT in 2016 [5].

II. Process Development

A. Process Steps

The manufacturing process steps are summarized in figure 1 (cross section) and figure 2 (top view). At the IMPT, we started with a simple sensor layout, which is a demonstrator in shape of a Wheatstone Pt-Sensor-bridge. The sensor prototype was produced to establish whether or not the manufacturing processes can offer an alternative to the common substrates and lithography processes usually used for strain gauge, AMR-(anisotropic magneto resistive effect), or Pt-sensors. Ideally, the sensor structure is formed directly into the substrate material by an injection molding process; in our case the substrate is polycarbonate. Other substrate materials such as high temperature stable thermoset plastics (e.g. PEEK) could offer higher application temperatures for the sensors. Considering thermoset plastics for instance, our manufacturing approach could be combined with LDS (Laser Direct Structuring). Following the injection molding, a thin layer of Pt is created onto the substrate by sputter deposition. Sputter deposition onto polycarbonate substrates is a state of the art process in compact disc (CD) manufacturing. As an alternative, evaporating deposition could be performed, which could be beneficial in terms of lower process temperatures. After the steps of master forming/substrate structuring and thin film deposition, the process makes use of chemical mechanical polishing (CMP). At this point, structure housing is an option, through spin coating or another injection molding. Overall, this new combination of well-known fabrication processes and easy-to-handle substrate materials offers an alternative cost efficient and reliable kind of packaging of integrated circuit technology for sensor systems.

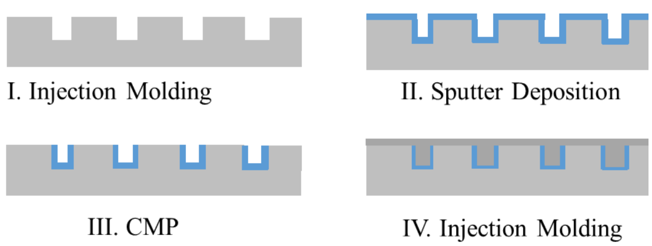

Fig. 1. Process steps for sensor array (cross section)

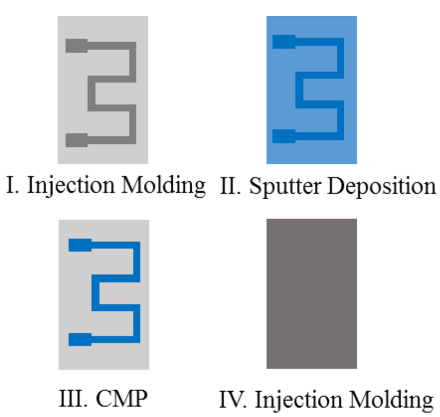

Fig. 2. Process steps for sensor array (top view)

B. Process Feasability

At first, dummy structures were processed to determine the structure quality with respect to planarity, surface roughness, and reproducibility of the injection-molded substrates. These structures were fabricated with electrical discharge machining [EDM]. Initial tests showed that the dummy mold could realize the necessary surface quality for sensor structures. However, additional reproducibility tests and several design of experiments (DOE) using the EDM fabricated dummy mold lead to sufficient parameter settings to achieve the required planarity. Fig. 3 and fig. 4 show the planarity results before and after the DOE. For injection molding, these parameters are crucial: extrusion temperature or screw temperature, pressure, injection speed, cooling time, mass of the material controlled by the displacement of the screw, and its diameter. To reach the goal of extremely low roughness values on plane surfaces as well as high precision in form tolerances, the material has to be injected as quickly as possible with the lowest possible viscosity, and therefore being processed at the highest possible temperature. In our experiments, Apec 1897® by Bayer® was used, having a maximum processing temperature of 330 °C. Table I defines the applied parameters in accordance with the data sheet.

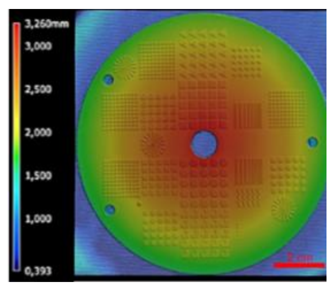

Fig. 3. Planarity before DOE

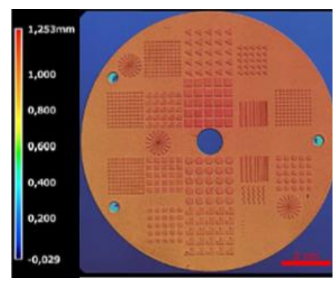

Fig. 4 Planarity after DOE

TABLE I. Initial Injection Molding Parameter

Parameter	Values
Pressure	10 bar
Closing Force	550kN
Injection Speed	180mm/s
Screw Temperature	330,325,320,320,310°C
Cooling Time	12 sec
Changeover Point Dwell Pressure	5mm
Injection Pressure	180-140 bar
Displacement of Screw	25mm

Besides an increase of planarity values, the results in molding precision were enhanced (fig. 5, fig. 6). Unfortunately, the dummy mold molding precision does not result in the precision needed for reproducible sensor structures.

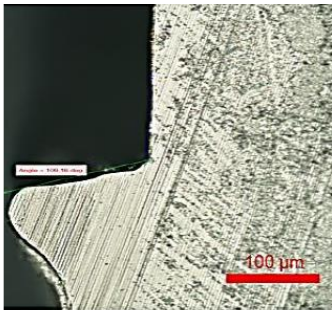

Fig. 5. Precision before DOE

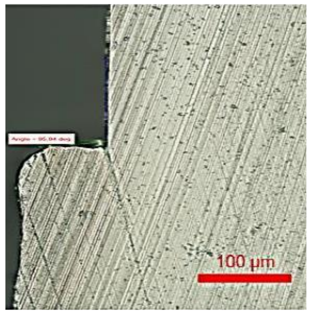

Fig. 6. Precision after DOE

Following the parameter determination for planarity, new manufacturing technologies regarding mold fabrication were evaluated. Considering state of the art mold fabrication of injection master forms used for compact disc manufacturing, electroplated Ni structures were developed and fabricated, so that these could be used as structures for injection molds. Steel (C45) inlays were milled and polished (using chemical mechanical polishing) to create very high surface qualities for a subsequent lithography process. After structuring the steel inlay, the created structures were deposited using Ni electroplating. Structure heights between 13 and 26 µm were measured and tested using an injection molding machine type BOY 55EV™. The detailed process for the mold inlay fabrication is laid out in fig. 7.

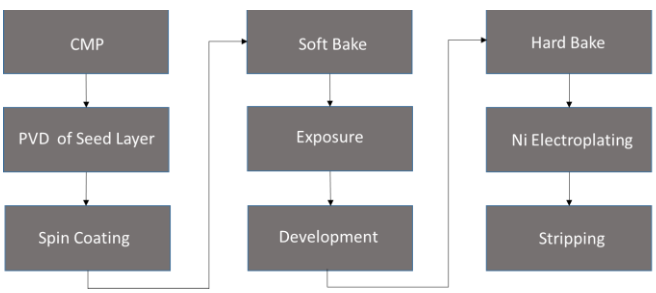

Fig. 7 Process steps of mold inlay

The surface quality of the electroplated Ni structures show highly promising values. Measured using confocal laser microscopy and tactile surface technology, the average surface roughness of the Ni structure was 25.1 nm. Additionally, the surface quality of the mold inlay was improved using a second CMP process step to polish the electroplated Ni. The resulting surface qualities were below the resolution of the confocal laser microscope as well as tactile measurement tools and had to be confirmed by atomic force microscopy. Average roughness values below 10 nm could be achieved after a second CMP step. Surface roughness values of the electroplated Ni injection mold inlays are listed in Table II.

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TABLE II. SURFACE ROUGHNESS OF ELECTROPLATED NI

Sample	Surface Roughness Values		
	***R_a* [nm]**	***R_q* [nm]**	***R_z* [nm]**
1	22.6	28.8	116.8
2	31.6	31.5	143.2
3	23.1	28.9	108.8
4	23.2	29.2	98.4
Arithmetic Average	**25.1**	**29.6**	**116.8**

Feasibility tests regarding structure size and height of the used injection molding machine (BOY 55EV™ (fig. 11) in combination with the polycarbonate Apec 1897® (Bayer®) and the manufactured mold inlays were performed. Structures of 200 nm, 13 µm, and 26 µm height were easily realized, as well as structure sizes down to diameters of 20 µm and sensor array footprints (of Wheatstone bridge) of 200µm x 200µm are possible. Since a different amount of material, the injection molding parameters were adjusted accordingly. Another DOE was used to determine the parameters to successfully yield sufficient planarity and surface quality. Experimental results show a surface quality on the transferred sensor structures of R_a = 35 nm, considering the injection mold which had not been polished after electroplating. The table below (Table III) shows the average surface roughness (of the PC) of two different parameter settings of the injection-molding machine.

TABLE III. SURFACE ROUGHNESS OF MOLDED SUBSTRATES

Sample	Surface Roughness Values		
	***R_a* [nm]**	***R_q* [nm]**	***R_z* [nm]**
Arithmetic Average Setting I	35.93	47.30	194.23
Standard Deviation I	4.72	3.59	4.82
Arithmetic Average Setting II	34.75	42.40	151.65
Standard Deviation II	0.85	0.40	9.95

After the fabrication of the injection mold inlay for sensor structures and the determination of the injection molding parameters, the PC substrates were tested with regard to sputter deposition capability. Polycarbonate (PC) as a substrate material can generally be sputter deposited with Cu, Ni or NiFe with 200 nm or more using a 50 nm Cr adhesion layer. Temperatures during the sputter deposition process are critical and should not exceed 140 °C for the examined polycarbonate due to the PC's mechanical stability limit. Cooled substrate holders proved to be beneficial. Following the sputter deposition evaluation, PC was tested regarding its ability to expose the sensor structures during the subsequent CMP process. Chemical mechanical polishing using PC as substrate material was simple to realize. High abrasion rates are achieved due to the low surface hardness. With respect to the MSW 1500© solution, the abrasive particles are aluminum oxides particles with a diameter between 225 to 250 nm.

Finally, abrasive cutting (dicing) using diamond dicing blades was employed to analyze the deposited structures and to examine the abrasive behavior of the polycarbonate. Comparable to the CMP process, the abrasive behavior proved to be sufficient. To investigate the mold behavior of the PC in terms of the Ni microstructures, cross section views of the transferred structures were obtained. Fig. 8 shows a 200 nm layer height transferred into polycarbonate substrate. Fig. 9 shows a 13 µm layer height transferred into PC substrate.

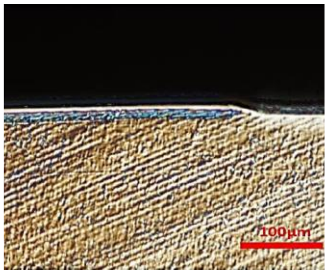

Fig. 8 Cross section of 100 nm structure height (reflected-light microscope)

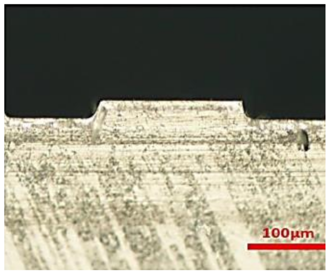

Fig. 9 Cross Section of 13 µm structure height (reflected-light microscope)

In summary, the results of the process feasibility investigation show positive deposition, adhesion, and mechanical behavior of the different layers. Injection molding can successfully be combined with electroplated Ni structures.

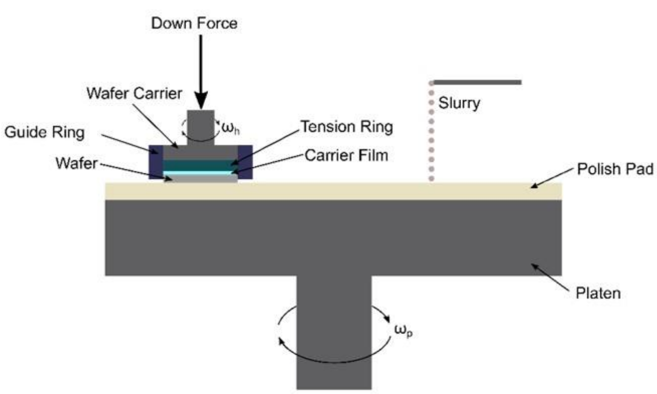

Fig. 10 Schematic CMP process

Fig. 11 Injection molding machine Dr.BOY 55EVV©

III. Demonstrator System

To create the demonstrator set-up, a simple temperature sensor layout was chosen. The injection molding form inlay was processed from a CMP polished steel substrate (C45). In the next step, a 50 nm Cr seed layer and a 200 nm NiFe layer were sputter deposited. Afterwards, the steel substrate was spin coated with AZ9260® resist and structured via lithography. Subsequently, the cavities created by the lithography process were filled in an electroplating step. The deposited material was 13 µm Ni. Lastly, the AZ9260® resist was stripped. The process steps are identically to the ones described in fig. 7. The realized injection-molding inlay is shown in fig. 12 and an injection molded structure sample in fig. 13.

Fig. 12 Manufactured injection molding inlay

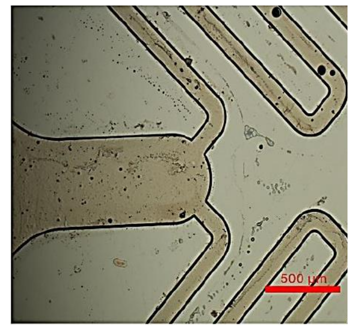

Fig. 13 Electroplated Ni structure on injection mold inlay

The micro-technologically manufactured injection molding form was examined in the injection molding machine at the IMPT. Injection molding parameters were evaluated and promising results regarding injection molding quality and surface quality were achieved. Important machine parameters are: injection pressure, reprint, injection mass, process time, form temperature, and melt temperature profile of the substrate.

After realizing the demonstrator injection molding inlay, the manufacturing steps of the sensor demonstrator were the following (fig. 14).

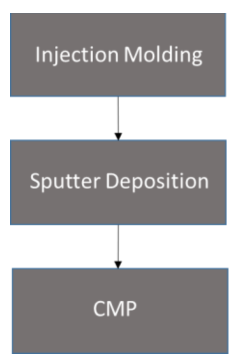

Fig. 14 Sensor manufacturing process steps (demonstrator)

Furthermore, it was possible to use the produced substrates for sputter deposition purposes. As already examined in prior experiments, a sputter deposition layer of Pt is realizable. The next process step is the chemical mechanical polishing to exposure the Pt-sensor structure. Afterwards, the structures are separated by dicing. The polished structures and the surface quality of the sputtered sensor layer are shown in figure 15 and 16.

Fig. 15 Polished sputtered micro structure I

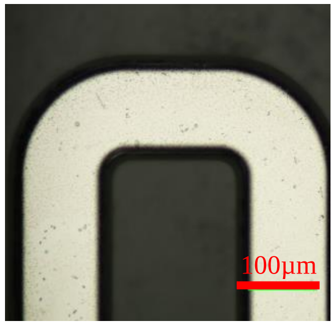

Fig. 16 Polished sputtered micro structure II

An important factor for the quality of a Pt sensor is the surface quality of its substrate material and depends on the injection molding form inlay and process parameters. Therefore, the substrate material was analyzed by light microscopy, confocal measurements, as well as tactile measurements. Electroplated Ni-structures are commonly used in the compact disc manufacturing process and can achieve very high roughness qualities. The surface roughness of the electroplated Ni structures of the manufactured injection molding form was R_a=25 nm. The high surface quality of the injection molding form creates a suitable polymer substrate for sputtering purposes. For the sensor manufacturing, 50 nm Cr and 200 nm Pt were deposited onto the PC via PVD processes and afterwards

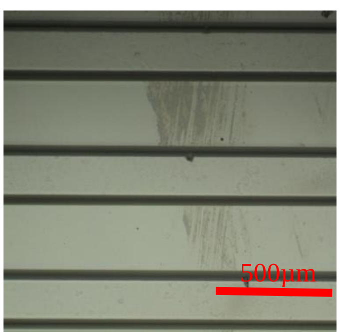

Fig. 17 Injection molded PC structure

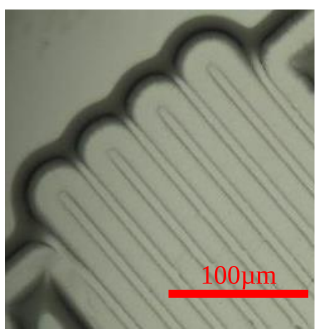

Fig. 18 minimal Pt-sensor structure resolution manufactured

polished by a CMP process using a MSW 1500® solution. The structures were exposed after approximately 5 minutes of polishing. Figure 18 displays the lowest resolution of Pt-sensor structure manufactured and transferred into the PC substrate. Figure 19 is an example of a tested Pt-sensors and figure 20 shows a Wheatstone bridge comprised of these sensors. Three sensors were fabricated and evaluated. To qualify the sensors, the relationship between change in temperature and change in resistance were determined and compared to conventional Pt-sensors. The quality factor are described with the equation below.

$$k = \Delta R / \Delta T \qquad \text{(Eq. 1)}$$

Where ΔR defines the change in resistance [Ω] and ΔT defines the change in temperature [K]. According to Eq. 1, the manufactured sensors will display the following K-factors:

$$k1 = 10.16 \Omega / K$$

$$k2 = 6.67 \Omega / K$$

$$k3 = 6.3 \Omega / K$$

The trend of the three evaluated sensor demonstrators is shown in fig. 21.

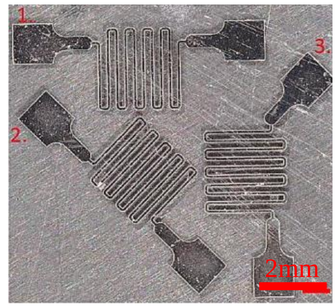

Fig. 19 Manufactured Pt-sensors

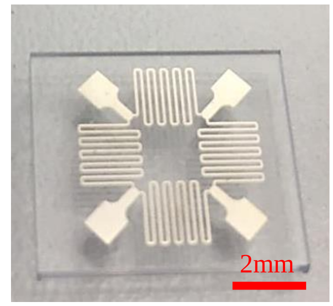

Fig. 20 Wheatstone bridge on PC-substrate

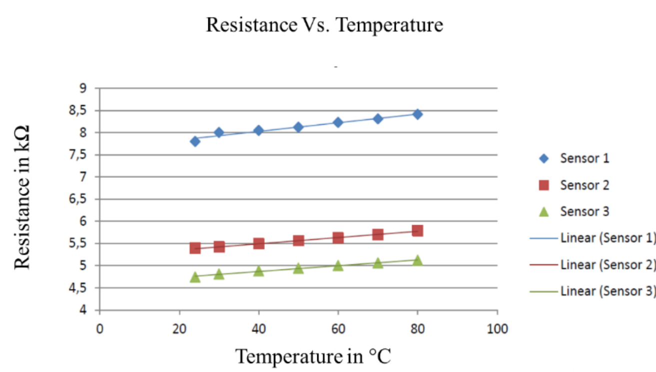

Fig. 21 Resistance vs. Temperature behavior of the Pt-sensors

Considering conventional Pt-sensors and their behavior towards change in temperature, 100 Ω resistances will offer 0.4 Ω/K. [6] To compare the fabricated sensors, the values are standardized to a nominal resistance of 100 Ω. Subsequently, the following K-factors were determined for the sensors:

$$k1 = 0.13 \Omega / K$$

$$k2 = 0.12 \Omega / K$$

$$k3 = 0.10 \Omega / K$$

In comparison, the fabricated sensors can only supply a maximum of 32.5% of the performance of conventional Pt-sensors. Therefore, the PC-substrate based Pt-sensors are not yet as accurate as conventionally manufactured, lithography based Pt-sensors. So far, only surface qualities of R_a= 35 nm (PC substrate) have been evaluated. More precise surface qualities are technically possible as discussed earlier, but have not yet been evaluated.

IV. Conclusion and Outlook

A simplified manufacturing process based on injection molding, sputter deposition and chemical mechanical polishing was introduced. It has been shown that it is possible to structure a polymer substrate material with injection molding processes and proceed with a sputter deposition, a dicing, and chemical mechanical polishing process without damaging the substrate material. Injection molding parameters were investigated in order to realize the required planarity for ongoing processing using an EDM manufactured dummy mold. After the evaluation of several DOEs, form inlay manufacturing methods were discussed. Eventually, a lithography-based manufacturing process was chosen to create a form inlay yielding higher structure resolution and surface qualities in comparison to EDM machined dummy molds. The sensor structure forms on the injection mold inlay were created using Ni electroplating. Structure heights between 13 µm and 26 µm as well as structure footprints down to 200 µm x 200 µm were realized. Surface qualities were analyzed, and improved through an additional second CMP process step. Average surface roughness values of 25.1 nm were realizable without polishing the electroplated structures. The minimal average roughness values reached the resolution limits of the tactile and optical measurement equipment, below 10 nm. In comparison, common Si-wafer reach Root Mean Square, „RMS“ values below 1 nm. After investigating the manufacturing process and process parameters, an injection mold inlay was fabricated using CMP, lithography, and electroplating. The mold inlay was subsequently employed to pre-form PC substrates. The transferred structures show average roughness values of 35 nm, therefore the injection molding process parameters have to be optimized, to increase the surface quality of the substrate.

A simple sensor demonstrator based on a Pt thin film showed the effect of change in resistance by applying temperature. K-factors were determined to compare the process technology with common thin film based Pt sensors. The results of the temperature tests show that there is room for future improvements on this process. The K-factor only reaches 32.5% of the values for common manufactured sensors. Thus, an increase of surface roughness may lead to better performance of the sensitive thin film layers. In terms of Pt-sensors, the different coefficients of thermal expansion of polymer substrates in comparison to Si substrates probably influence the results on the K-factor and should be evaluated in future works.

Additional research will estimate the minimal size of such a sensor layout using injection molding and will focus on the optimization of the tool manufacturing process for injection molding forms to create a sufficient mass production process for Pt-sensors, strain gauges, AMR sensors, and other micro technological systems. This manufacturing technique is potentially more beneficial for the production of other thin film based sensors, such as AMR sensors, due to the negative influence of the thermal expansion coefficient. Future research is focused on these technologies. Nevertheless, benefits regarding polymer substrate materials concerning costs, flexibility, and less infrastructure potentially outweighs the lack in performance of the sensor, especially since common housing steps and connecting technology like soldering or wire bonding can be omitted.

Standardized connectors can theoretically also be realized via special injection molding forms. One can simplify the sensor connection without any complicated bonding techniques. The analysis of the process steps shows the feasibility of the manufacturing of sensors as well as e.g. transformer set-ups. This manufacturing concept creates a new low cost micro technological fabrication process independent of clean room technology.

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