Research paper

Sub-micron silver wires on non-planar polymer substrates fabricated by thermal nanoimprint and back injection molding

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ABSTRACT

In back injection molding, a polymer film (most commonly a decorative label) is inserted into the mold and fused with the polymer product by injection of the polymer melt from behind. By placing a bendable film into a mold cavity and by injection of polymer melt, the film conforms to the outlines of the cavity, thus enabling the decoration of elements with non-planar surfaces. This technique allows for pre-patterning of films by a planar process, and then convert these into the surface skin of a non-planar molded part. In this research we demonstrate the integration of silver wires onto the surface of a curved polymer part. As an example, we used poly (methyl methacrylate) films of different thicknesses that were pre-structured with micrometer-sized V-grooves, filled with silver nanoparticle ink and placed into the cavity of a commercial injection molding tool. The effect of the back injection molding process on unfilled and filled V-grooves was evaluated for different process parameters. In most cases, the silver wires remained undamaged and their electrical conductivities remained essentially similar to those in planar films. The resulting surface-integrated silver wires were characterized by scanning electron microscopy and electrical resistivity measurements.

1. Introduction

Lithography is essentially a planar patterning process that enables the fabrication of integrated circuits on bulk semiconductors. The same applies for low-cost flexible electronics where polymer films replace wafer-like substrates. Typically, the films are coated with different layers of electronic materials by additive processes. Polymer substrates include poly (ethylene terephthalate) (PET), poly (ethylene naphthalat) (PEN), and polyimide (PI), but also poly (methyl methacrylate) (PMMA), polycarbonate (PC) and cyclo olefin (PEN), and polyimide (PI), but also poly (methyl methacrylate) (PMMA) using nanoimprint lithography (NIL), placing it into the cavity of an injection molding (IM) tool and injecting the polymer melt (e.g. PMMA) into a mold cavity. During this process, typically referred to as back injection molding (BIM) (Fig. 1), the film is pressed against the mold wall by the polymer melt, assuming the shape of the cavity, and the melt solidifies upon contact. Due to interdiffusion of polymer chains the film becomes an integral constituent of the molded part after cooling. During an isothermal process scheme, the temperature of the melt is much higher than its glass transition temperature $T_g$, but cools down rapidly when entering the mold cavity which is usually kept at a temperature substantially lower than $T_g$. Typically, the viscous material is still hot enough that it is not only able to bend the film by pressure, but...
also to deform it permanently by softening. The polymer melt cools down upon contact with the film and the walls of the cavity, starts to solidify, and is cooled down below $T_g$, where no further deformation happens. Thus, the film conforms to the surface outline of the cavity, bonds to the incoming material and becomes an integral part of the bulk element. This process is used on industrial scale for in-mold labeling of polymer parts, and enables to add paper or plastic labels during the manufacturing of polymer parts without gluing, e.g. on plastic containers [7]. It has been reported that by using BIM, a thin polymer element could be created with antireflective structures on both sides of the final element [8]. This was made by placing a pre-patterned film in a cavity that was pressed against a planar cavity wall. Because at the opposite side of the cavity was an insert with the same structures as on the film, the structures on this side were replicated into the final polymer part while the others on the film were bonded on the other side of the part. Since the sub-μm moth-eye structures were imprinted in a hard acrylic material, they did not survive the thermal process undamaged, but could also serve as the scratch-resistant outside of a cell phone window, while the inside was composed of the injected PMMA. In order to investigate different aspects of combination of pre-patterned films and injection molded elements, we choose PMMA with two typical thicknesses used for flexible electronics. For both, film and granulate for injection molding, the raw material and grade of film are the same, however, with some non-disclosed additives. These additives typically facilitate flow during injection molding or film extrusion but do not alter the $T_g$ significantly. As a tool, a cavity with macroscopic concave cylindrical outlines is used. This way, by bending the film in one direction only, stretching of surface structure in the direction perpendicular to the cylinder axis is minimized, and possible warpage due to a 3D deformation is avoided, too. Thermal NIL and IM of surface structures with down to 25 nm has already been demonstrated on planar and crowned surfaces [9,10]. In addition, it has been shown that polymer melts fill the microtopography of polymer foils used as stamps in a cavity [11]. Since we are interested in preserving the surface topographies and maintaining the electrical functionality in the pre-patterned polymer films, we need to minimize the effect of softening of the surface structures. For that we need to investigate process conditions that keep surface structures below $T_g$. At the same time, we need to soften the backside of the film in a way that it bonds to the solidifying polymer and does not delaminate. We therefore put a focus on investigating the influence of the dynamic process on local deformation of topographies of the pre-patterned surface structures. Additionally, we
used grooves filled with metal ink. Once dried, they consist of a dense assembly of metal nanoparticles (NPs) which can be converted into conducting wires. Such wires with sub-micron dimensions, when sintered, have been found to be electrically conducting. Therefore by varying the tool temperature, different regimes are created from a mere bending of a film at low temperatures to the onset of stretching at higher temperatures.

We pre-structured PMMA films for the fabrication of components covered with a metal wire array (Fig. 2). In contrast to inkjet printing, which is widely used for printed electronics, our process relies on nanoparticle self-confinement in V-grooves enabling sub-μm resolution [12]. For reference purposes, films with open microchannels were back-injection molded, which can be used for microfluidics or post-processing with inks. The shape of the 3.1 μm wide V-grooves is slightly flattened by the process at a low tool temperature, thus enabling capillary filling in an open microfluidic approach [13]. When processed at higher tool temperatures (> 60 °C), the V-grooves start to collapse, resulting in embedded metal wires with a fused thin layer of polymer on top. Sintered wires of this dimensions have been found to be electrically conducting. Such strategies can be applied to various designs of electrical circuits that enable to build complex devices as planned within the project frame in which this project was funded [14]. Potential applications could be electronic labels or pressure sensitive haptic devices, wire generation: (g) dispensing silver ink (Ag NP suspension) onto pre-patterned film; (h) spin coating silver ink, resulting in confined ink in V-grooves; (i) silver NPs merge during drying and form wires after sintering.

2. Experimental section

In order to create stamps for nanoimprinting V-grooves, rigid substrates containing V-grooves with planar areas in between were obtained by anisotropic etching of (100) silicon wafers (Fig. 2 a,b). The process is described in detail in [12–15]. With these methods, 3.1 μm and 5.9 μm wide and 2.2 μm and 4.1 μm deep V-groove lines with an angle of 54.74° between the < 100 > and the (111) crystalline planes were formed in the silicon wafer surface. The corresponding line structures on the mask used for lithography were 2 μm and 5 μm, respectively.

Using UV-assisted imprint, the stamp with V-grooves was inverted into Ormostamp® cast on a Borosilicate float glass wafer and used as a working stamp with Λ-ridges (Fig. 2 c,d). PMMA films were thermally imprinted using a Jenoptik HEX03 thermal imprint machine. Imprinting was performed for 10 min at 180 °C employing a pressure of 2.5 MPa, followed by cooling and subsequent demolding at 80 °C (Fig. 2 e,f). In order to facilitate demolding, Ormostamp® working stamps were coated with fluorinated silanes as anti-sticking layer.

Two films of thickness 50 μm and 175 μm were chosen. For the 175 μm thick film, both Tg and Vicat softening temperature (VST) correlate well with the corresponding values of the granulate used for BIM. We present all values for the materials in Table 1.

Table 1
Comparison of the PMMA polymers used for BIM (granulate) and thermal NIL (films).

| Material                  | PMMA granulate | PMMA film 50 μm | PMMA film 175 μm |
|---------------------------|----------------|-----------------|------------------|
| Supplier                  | Evonik Plexiglas® 7 N | Evonik Plexiglas® film 0F080 | Evonik Plexiglas® film 99,524 |
| Glass transition temp. Tg | 110 °C         | 93 °C           | 93 °C            |
| Vicat softening temperature VST (50 N @ 50 K/h) | 103 °C | 86 °C         | 100 °C          |

1 Evonik Plexiglas® film 99,524 corresponds to the injection molding grade 8 N granulate.
2 For the 50 μm thick Plexiglas® 0F080 PMMA film, the VST is not available. Due to its similarity with the Tg of 93 °C for the pure 0F080 PMMA, we assume the VST to be identical to the 86 °C from given for 53 μm thick Plexiglas® 0F008, which is probably the same PMMA with different loadings of UV-absorbers.
Nanoparticle inks with ~50 nm particle size are commonly used for printed electronic. In our case, the low solid content enables to cover surfaces with such a low density that no conductive film is created due to the sparse distribution of particles. However, in V-grooves, where particles are confined (Fig. 2 h,i), thin wires are created by aggregation upon drying. Spin coating was done with a SmartInk S-CS31506 (Genes’Ink, France), a suspension of silver nanoparticles in alcohol and glycol (nanoparticle loading of 55 w/w%), and diluted with isopropyl alcohol (IPA) at a volume ratio of 1:59, resulting in a NP concentration of 0.17 v/v%. This solution was spin coated on the patterned samples for 120 s at 5000 rpm. More details are presented in [12-15].

Sintering of wires was done on a hotplate with the following process: 3 min heating up to 95 °C, holding for 2 min at 95 °C (for solvent evaporation), then heating up to 150 °C in 5 min (for sintering); keeping at 150 °C for 1 min, then cooling back to room temperature before taking the samples from the hotplate. For height measurements of the silver nanoparticles (AgNPs) deposited V-grooves, the samples were analyzed using a scanning electron microscopy (SEM, Zeiss Supra VP55) and a 3D laser scanning confocal microscope (VK-X1000, Keyence Corp., Osaka, Japan). For cross-sectional SEM imaging, the entire BIM part needed to be broken to obtain a cleaved facet at the desired location of the film. First, a notch was sawn into the concave backside of the element. Then the film was broken by hands at room temperature. Planar PMMA films or films which could be detached from the polymer element were cleaved after cooling the samples in liquid nitrogen for at least 3 min in order to enhance the brittleness of PMMA and minimize deformity.

For evaluating electrical conductivity, diluted ink with a volume ratio of 1:19 (ink: IPA, resulting in 0.51 v/v% Ag concentration) was used for spin coating onto substrates. The samples for electrical measurement contain channels (V-grooves) which have a square cavity (0.5 × 0.5 mm², a few micrometers deep) serving as contact pad on each channel end. In order to measure the resistance of the Ag wires in V-grooves, we used a capillary tube to dip a small volume of undiluted Ag ink onto the contact pad area. The solvent in the undiluted Ag ink wetted the surface and brought the AgNPs into contact with the Ag wire in the V-grooves. However, the ink was not able to fill further into the V-grooves channel by capillary force, as the solvent in the undiluted ink dried quickly after dipping. The sample was then sintered. In this way, we make contact to the Ag wires with the probes of a standard multi-meter, and preform the electrical measurement. The electrical resistivity was calculated according to the equation: $\rho = \frac{R l}{A}$, where $R$ is the resistance of the silver wires, calculated from the readout voltage and the constant current (9.96 μA) provided by a microampere source, $A$ is the cross-sectional area calculated from the cross-section SEM images of the wires, and $l$ is the length of the wires. The microampere source of 10 μA was used for the measurement, since it is very important to not generate electrical sintering due to a too high current.

The molding tool was fixed in a HASCO ‘handy mold’ (Fig. 1), with the concave cylinder on the left side enabling the use of ejector pins and the convex cylinder on the right side with the injection nozzle. Back injection molding was performed on an Arburg 320 Allrounder (Arburg, Lossburg, Germany) with a maximum clamping force of 600 kN. Molding trials were conducted at constant mold temperatures varying between 40 and 80 °C (controlled by circulating water).

The pre-patterned PMMA films (Evonik Plexiglas® film 99,524 or 0F080) were placed on to the concave (ejector) side of an injection molding tool that constitutes a cylinder with an outside radius of 28 mm, with a convex cylinder at the opposite nozzle side. Viscous polymer (Evonik Plexiglas 7 N) was injected onto the backside of the film, pressing the film onto the concave surface. The tool temperature (e.g. 40 °C) was low enough that the 250 °C hot melt was cooled down to slightly below Tg when it reaches the film upon entering the mold cavity, thus it was able to deform the thermoplastic film without completely erasing its topography.

A polyimide (PI) film (DuPont™ Kapton® 200HN, 50 μm thick) was used as cover sheet facing to the unpolished surface of the concave side. This film is stable up to high temperatures and does neither bond to the tool surface nor to the PMMA film. It prevents any replication of roughness from the steel tool onto the thermoplastic film (Fig. S1) and is removed together with the polymer part. After demolding, the PI film can be readily delaminated from the polymer part.

The resulting back injection molded cylinder-like part consists of the pre-structured film as a skin covering the top of the 3 mm thick polymer element. Two different process variants were addressed: a) When the patterned surface of the film faces to the mold surface (with PI foil in between), in which case the resulting cylinder features the surface topography of the film at its surface. b) When the patterned surface of the film points towards the injecting polymer, in which case the surface structures are embedded within the part. The latter case is particularly interesting for films that are already processed, e.g., covered with electrodes.

3. Results and discussion

3.1. Empty V-grooves facing towards the outside the polymer element

The deformation of blank V-grooves that were pressed against the PI-covered concave mold was evaluated at five different tool temperatures (40, 50, 60, 70, and 80 °C). 40 °C was chosen as the lowest temperature where sufficient bonding to the polymer body was expected, and 80 °C as the highest temperature where the film was expected to be mechanically stable enough so that it would not rupture. At all temperatures, we expected the film to bend rather than to be stretched, since the film was only fixed at one side of the mold cavity. SEM images of the V-groove deformation (Fig. 3) revealed that at low tool temperatures (< 50 °C), the vertex of the V-grooves is reduced in depth but retained, despite that the upper corners of the grooves (between sidewalls and planar surface areas) are rounded due to thermomechanical deformation. For example, at 40 °C the depth of the V-grooves in the BIM element is reduced from 2.1 μm in the original pre-patterned PMMA film to 1.1 μm. This means that the confinement strategy in [12] can still be employed on the surface of this BIM element, with some restrictions of flattened-out tops of the V-grooves. However, since spin coating on solid cylindrical substrates becomes critical, we only demonstrate here the general feasibility for fabricating wires on non-planar (post-BIM) elements, but do not intend to pursue this further. A more suitable method for non-planar surfaces would be spray coating or aerosol jet printing [3,17]. In this case, sintering of the silver wires will be critical, since higher temperatures may lead to deformation of the molded element, while sintering at a low temperature (e.g. 100 °C) may result in higher resistance since some metal nanoparticles will remain unconnected. Flash sintering could be an alternative method for the post-BIM coated silver wires, as it is done at room temperature, and the short UV-exposure duration of the PMMA surface does not result in damages of the polymer chains in PMMA [12]. As the tool temperature rises, the PMMA film becomes softer, and hence more sensitive to the injection pressure. Instead of flattening the V-grooves from the top, as it is seen in the case of 40 °C, at higher temperatures the sidewalls of the V-groove walls are squeezed from the side and the V-grooves start to collapse, forming a deep trench. The depth seems to be similar to the reduced height of the V-groove at 40 °C, i.e., ~1 μm. At a tool temperature of 80 °C, the V-grooves almost collapse completely and the capillary cannot be observed or measured from the top surface anymore.

3.2. Filled V-grooves facing towards the outside the polymer element

A more common case would be pre-processed films, with an electrical element already patterned on the surface of the film. Similarly to the previous section, films with spin coated silver wires were integrated onto the BIM elements at different tool temperatures, and characterized...
Fig. 3. Profile of the V-grooves on BIM parts processed at different tool temperatures. PMMA film thickness: 175 μm. Scale bar: 1 μm.

with SEM from both cross-sectional and top view (Fig. 4). The 175 μm PMMA films with silver wires follow the similar trend as observed in the blank V-groove films: Collapsing of the V-grooves happens at tool temperatures of 50 °C and more (Fig. 4, left column). This results in wires located at ~1 μm depth from the PMMA surface. This is interesting for applications in electronic devices as it demonstrates the possibility of embedding wires during the fast BIM process. For 0.17 v/v % ink solution spin coated on the 175 μm PMMA films, the wire embedding starts from a tool temperature of 50 °C, but only at 80 °C we observed complete closing of the groove, i.e. causing full embedding of the wires. An even higher tool temperature could in principle further enhance the embedding by improving the adhesion between the collapsing sidewalls, however, it should not be too close or higher than the Tg of the film considering the deformation and stress in the film could damage the sub-μm wires. As can be seen from the top view images, the sparsely distributed AgNPs remain on the surface of the BIM part due to the spin coating process, however, this low loading of the nanoparticles cannot form a conductive layer and therefore not interfere with the electrical properties of the films. Nevertheless, the sparse AgNPs can be reduced when using a lower ink concentration, in case long wires (in millimeter range) are not necessary for specific applications.

The same experiment was performed with 50 μm PMMA films (Fig. 4, right column). The 50 μm thick film is more sensitive to the injection pressure of the BIM, and since it has a lower Tg (93 °C) than the 175 μm film, the heat softens the 50 μm thick film more when it dissipates through the film. Sidewalls already start to collapse at 40 °C, and the grooves are almost completely closed when the tool temperature is above 60 °C, and only a seam line is visible. Again, the wires are located at ~1 μm depth, except for samples at 80 °C where the wires seem to be embedded closer to the surface. This indicates that the 50 μm film is much softer at 80 °C and is compressed due to the injection pressure. The measurement of the surface topography of the BIM part by 3D laser scanning confocal microscopy in Fig. S2 (b) shows that no distinct depth difference can be seen among the samples processed at 60, 70 and 80 °C.

For the PMMA films used as substrate in this work, the recommended sintering temperature for the AgNPs (150–180 °C) is far above the Tg of PMMA. While for spin coated PMMA films used in [12] this leads to an almost complete removal of the surface topography. In previous research it has been found that at 150 °C the V-grooves in the 175 μm film are preserved, with only some rounding of the upper corners. The V-grooves flatten out completely when the film is treated at 180 °C for 30 min [15]. As a result, the wires are integrated into the surface of the film, and the triangular cross-section of the wires level out with the reflowed surface.

In order to evaluate the electrical conductivity of the silver wires on the curved BIM part, we used a higher AgNPs concentration (0.51 v/v %) for spin coating. This results in wider silver wires (1–2 μm range) depending on the dimension of the V-grooves. For example, long silver wires in 5.9 μm wide and 14.2 mm long V-groove channels were measured, in order to compare the conductivity of the silver wires before (on planar PMMA film) and after (on cylinder-shaped PMMA film) the BIM process at a tool temperature of 40 °C (Table 2). Results show that the calculated resistivity of the silver wires on the BIM parts lies within the same order of magnitude (10−5 Ω·m) as those on planar films. Furthermore, these values are also comparable with our previous results on narrow silver wires (~467 μm wide after sintering, 200–400 μm long) which were sintered at the same condition [12]. The larger wire width in the BIM part is to compensate the risk of disconnection in the millimeter-long wires, as for narrower wires the risk for wire disconnection due to formation of big grains during sintering is substantially higher over such a long distance.

The conductive condition of the silver wires are related to several factors: (1) wire dimensions: Thinner, narrower, and longer wires (especially in sub-μm range) are generally more challenging to process, as they are more sensitive to disconnection of the sintered silver grains, hence a higher risk of breaking; (2) thermal properties of polymer films: The polymer film undergoes softening and experiences high compressive forces due to the high pressures, which can cause deformations and reflow. This becomes more pronounced for thinner films. For example, the heat dissipation proceeds faster in the 50 μm thick PMMA film than in the 175 μm thick PMMA film. Furthermore, its Tg (93 °C) is considerably lower than that of the injected polymer (110 °C) and that of the 175 μm film (113 °C). Consequently, the plastic deformation of the 50 μm film during the BIM process is more pronounced than for the 175 μm film. This could cause disconnection within the wires, resulting in a higher resistance or even non-conductive wires. (3) BIM tool temperature: The parameters of BIM should be optimized according to the properties of the polymer materials, as well as the conditions of the wires. Excessive conditions such as a tool temperature near Tg or high injection pressure may lead to problems discussed in (1) and (2) and therefore result in a higher resistance. Fig. 5 compares the silver wire resistivity in the 175 μm thick PMMA film on the BIM elements made at different tool temperatures. Measurements were performed on silver wires in 2.9 μm wide and 1.8 μm deep V-groove channels. The results indicate that the wires can be considered stable for these three tool temperatures, as the resistivity remains within the same order of magnitude. A slight tendency of increasing resistivity is observed as the tool temperature rises, especially for the case of the longer wires.
The reason for this could be that the wire width is disturbed at certain area by the increasing tool temperature, which is difficult to detect by microscopy over such a long distance. The processing of AgNPs wires with sub-μm dimensions remains a challenge. If individual grains (~100 nm size) are disconnected by mechanical stress, it can result in the failure of an entire wire. As for the 50 μm thick PMMA film, the resistance of the wires increases more than 10 times as the tool temperature rises. Already at 40 °C, about 50% of the measured samples are not conductive. As a consequence, for these films either lower tool or melt temperatures should be applied, or films with higher Tg should be used.

3.3. Filled V-grooves facing inside towards the polymer element

For V-grooves facing inside, the topography is directly getting in touch with the viscous polymer melt, and while the grooves are filled like a microstructured stamp, the structures are prone to thermomechanical deformation. In case of ink pre-coated film, the wires are embedded into the BIM part (Fig. 6 a). The 175 μm thick PMMA films back injection molded at a tool temperature of 40 °C could be easily delaminated from the polymer element. Actually, this delamination was even easier if the V-grooves were pre-filled with wires. When delaminated, the wires remain in the V-grooves of the film, and the film shows no specific deformation except for a slight rounding on the upper corners between the sidewall and the planar area. The topography of the film was copied into the PMMA element formed by the melt (Fig. 6 b). This demonstrates that the melt is not able to induce a strong bonding nor a significant reflow as it cools down too fast. Only at a tool temperature of 60 °C, the bonding between film and substrate was strong enough that stripping-off the film could not be done without destroying all the wires.

As an alternative, pre-embedded metal wires in two bonded thin PMMA films can be inserted into the mold, e.g. two 175 μm thick films with silver wires sandwiched between them. At a bonding temperature of 60 °C, the flow of polymer could be observed, and the border between the two films is not visible anymore in a cross sectional SEM micrograph (Fig. S3). Similar as the samples discussed in section 3.2, the conductivity of the wires was comparable before and after the BIM process.

The main reason for bonding the film is the incoming hot melt, which first heats it up and then, jointly with the film, cools rapidly when touching the cold cavity wall behind it. It is obvious that a trade-off needs to be found for every kind of material and structure. Heating of the film above Tg needs to be short enough to avoid excessive deformation. At the same time the film surface towards the needs to be...
heated up long enough by the solidifying melt to allow out-of-plane mobility of polymer chains and interfacial diffusion to achieve a strong bonding. This might be facilitated by the heat gradient within the film which serves as an insulator between the tool surface and the melt. Taking PMMA as an example, at 40 °C tool temperature, the structures are well preserved for thin and thick films, however, bonding of thicker films with pre-processed electrical element towards the polymer element is limited. From a tool temperature of 60 °C on, the structures tend to vanish for both thicknesses but the bonding is strong and irreversible. Since the heat gradient can be more controlled for thicker films, topographical structures facing outwards can be preserved more easily, while the tool temperature needs to be low (between 40 and 50 °C).

For the cylindrical mold structures used here, the main strain on the wires comes from the bending of the film in one direction, which would result (for the 30 mm radius cylinder and 175 μm film thickness) in <1% elongation of the wires. More complex 3D surface topographies, such as a spherical lens, would require an additional deformation of the film in two dimensions which might lead to extensive warpage and strain. A gentle pre-deformation into the shape of the mold, e.g. by thermalforming the film prior to insertion, could help to alleviate local excess of strain. More process variations could be achieved using concepts of compression injection molding and variothermal molding [18]. The first process could enable faster injection into a larger cavity; the latter would enable to soften thick foils to conform to more complex surface geometries. In all cases, the functionality of electronic structures needs to be tested. Here, the main question for filling cavities with inks was whether the vertex of the V-grooves could be preserved after BIM. This has been demonstrated and confinement was even possible for slightly deformed V-grooves.

4. Conclusion

We have demonstrated the fabrication of sub-micrometer scale metal wires on a curved surface using lithography-based pre-patternning of thermoplastic polymer film, which were bent and bonded on a solid polymeric element using back injection molding. Conductive millimeter-long wires can be achieved on a cylinder surface. Embedded wires are feasible as well. Choosing the right melt and tool temperature is a prerequisite for both, a preservation of surface structures and a good bonding of films to the bulk element. For the surface structures in the micrometer range investigated here, and for different materials and thicknesses of films, optimum conditions could be found, so that the films could be permanently bonded and the surface structures preserved for further processing. This paves the way for molding more complex 3D surface topographies by BIM.

AUTHOR CONTRIBUTIONS

Sijia Xie was preparing, performing and evaluating all the experiments. Barbara Horvath created the concept of the confinement of nanoparticle inks in V-grooves, prepared electrical measurements and validated results. Jerome Werder performed all injection molding experiments. Helmut Schift was responsible for the concept and prepared the original draft. All authors performed writing, review and editing of the manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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