Rolled-Up Self-Assembly of Compact Magnetic Inductors, Transformers, and Resonators

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3D self-assembly of lithographically patterned ultrathin films opens a path to manufacture microelectronic architectures with functionalities and integration schemes not accessible by conventional 2D technologies. Among other microelectronic components, inductances, transformers, antennas, and resonators often rely on 3D configurations and interactions with electromagnetic fields requiring exponential fabrication efforts when downscaled to the micrometer range. Here, the controlled self-assembly of functional structures is demonstrated. By rolling up ultrathin films into cylindrically shaped microelectronic devices, electromagnetic resonators, inductive and mutually coupled coils are realized. Electrical performance of these devices is improved purely by transformation of a planar into a cylindrical geometry. This is accompanied by an overall downscaling of the device footprint area by more than 50 times. Application of compact self-assembled microstructures has significant impact on electronics, reducing size, fabrication efforts, and offering a wealth of new features in devices by 3D shaping.

Strain-driven self-assembly of thin films into 3D geometries has become a powerful technique to produce a plethora of differently shaped microarchitectures. In combination with established micropatterning techniques, highly parallel processing of ultra-compact 3D devices on a single chip has been demonstrated.

Potential application areas of such mass-produced components are manifold ranging from basic microelectronic components and sensors to systems and robotics both on and off the chip.

A special and particularly interesting category of microorigami is the strain-driven roll-up of patterned layer stacks into microtubular devices. Such devices have been employed for fabrication of capacitors, inductors, transistors, sensors, and microbots to only name a few. Rolled-up nanotechnology has recently seen significant progress driven by cleverly designed layer stacks and material choices. The introduction of a polymer-based platform in combination with advanced functional materials and device layouts has led to fully integrated biomimetic circuitry, microtubular GMI sensors, and impedance matched antenna arrays.

Here, we demonstrate advanced roll-up assemblies for a new category of devices. We create inductive and inductively coupled systems for applications in transformers and ultracompact high-quality electromagnetic resonators for nuclear magnetic (NMR) and electron spin (ESR) resonance characterization setups. These small-scale cylindrically shaped devices are either created in a sequential one-by-one fabrication routine, or processed in parallel by planar microfabrication techniques requiring numerous preparation steps and large occupied areas on the microelectronic chip surface. Both approaches are plagued by obvious drawbacks. Therefore, massively parallel self-assembly of 3D coiled inductor devices was envisioned to reduce fabrication efforts and footprint area. Generally speaking, this approach enhances key performance parameters of 3D devices up to an order of magnitude if compared to their planar counterparts. The geometry of the assembled rolled-up...
Figure 1. Illustration of the self-assembly of functional 3D magnetic components using shapeable ultrathin films. a) Self-assembled and encapsulated 3D device revealing coils and their mutually coupled configurations. b) Shapeable layer stack consisting of three distinct polymeric structures, namely, the sacrificial layer (SL), the hydrogel (HG) layer, and the reinforcing polyimide (PI) layer. c) The latter possesses a two-layer structure where the first layer (PI 1) is equipped with fixators and the second (PI 2) layer develops crack propagation edges (CPEs), which helps to release the brackets during the rolling process and guide the overall self-assembly process. d) Rolling of a straight wire leads to a Swiss roll coil, e) while rolling of the tilted wire forms a helix geometry.

The planar stack shown in Figure 1a contains polymeric and metallic parts that finally reveal magnetic inductive coils. The initial planar stack consists of four patterned, functional, shapeable, ultrathin, polymeric layers with a rectangular geometry having length (L) and width (W) of 17 mm and 5.5 mm, respectively. The layers contain the sacrificial layer (SL), hydrogel (HG) layer, and two rigid reinforcing layers made out of polyimide (PI) material (Figure 1b). Each of the two rigid layers was patterned using a specially designed structure required for a correct and reproducible self-assembly of the overall architecture into a cylinder. Normally, structures with such an aspect ratio and geometry do not assemble properly into tubular shapes, rather perpendicular conductors do not reshape during this process and just provide an electrical connection between the left (Figure 2d group 1) and right (Figure 2e group 2) set of coils (Figures 1a and 2a). Each conductor possesses a DC resistance ranging from 1 to 10 Ω in both the planar and 3D assembled states corresponding to the cross section and geometry of the conductors. With this resistance value it was possible to push up to 300 mA of AC current without any thermal damage of the 3D structures.

The CPEs, introduced in the double reinforcing layer (PI 1 and 2 with 1:1 thickness ratio), ensures a controlled rupture of the bracket structures during the rolling process. We applied different planar layouts of conductors (see, e.g., Figure 1c I) on the surface of these layered shapeable materials. The roll-up self-assembly leads to a Swiss-roll architecture (Figure 1c I–III,d) with a final diameter of ≈300 μm, winding thickness of 4 μm, and a roll width W of 5.5 mm. Upon self-assembly the footprint of the structure is effectively reduced from about 100 to 1.5 mm² (Figure 1c). The inductance of a conductor in the assembled state depends on its orientation on the planar surface (compare Figure 1c–e) and is maximum when the device is assembled into a zero pitch coil (1d). The planar design of the conductor should contain, due to the constraints imposed by the Swiss-roll geometry, a couple of straight conductors with a perpendicular section that electrically connect both coils after the self-assembly. This so-called “Π” geometry allows (see Figure 1c) electrical feeding from the “anchor” side of the device attached to the rigid support. We have prepared a number of such shapes (Figure 2a–e) made out of Ti–Cu–Ti with a conductor cross section of 100 × 3 μm² in a single lithographic run (the exact geometry is shown in Figure S1, Supporting Information) and self-assembled into Swiss rolls in a batch wafer-scale process (Figure 2b). During this process, the planar “Π” shaped conductors were transformed into a number of coils corresponding to the equivalent circuit shown in Figure 2c. Each conductor, oriented along the rolling direction, forms a coil, while the perpendicular conductors do not reshape during this process and just provide an electrical connection between the left (Figure 2d group 1) and right (Figure 2e group 2) set of coils (Figures 1a and 2a). Each conductor possesses a DC resistance ranging from 1 to 10 Ω in both the planar and 3D assembled states corresponding to the cross section and geometry of the conductors.

The value of the quality factor of the inductors ranges from 0.5 to 5 demonstrating an average enhancement in the performance of up to 2.5 times due to the rolling process, measured at 10 MHz (the spectrum is shown in Figure S2, Supporting Information). It is clear from the geometry of the planar layout that the self and mutual inductances of each planar loop should have a direct relation to the wire length and the area surrounded by the wire. For instance, the planar conductor patch between electrodes (0) and (8) has the initial value of the planar inductance equivalent...
to $L_{PL(0)-(8)} = 35.5$ nH at 10 MHz. The loop between the electrodes (3) and (7) possesses an inductance $L_{PL(3)-(7)} = 36.5$ nH—a little bit larger than $L_{PL(0)-(8)}$ due to the longer length of the conducting path. The measured inductance $L_{PL(3)-(7)}$ of the smallest loop between the electrodes (1) and (2) has a value of only 11 nH.

The self-assembly into the tubular structure (Figure 2c) converts the overall inductance of the wire $L_{PL(0)-(8)}$ into the sum of the coil inductances $L_{PL(0)-(8)} = L_1 + L_2 = 138.2$ nH that includes the inductance of the straight section as well. As can be recognized from the obtained characteristics (Figure 2f), the inductance of $L_{PL(0)-(8)}$ in the assembled state is 3.9 times higher if compared to the $L_{PL(0)-(8)}$ inductance of its initially planar counterpart. Similarly, two other inductances in the rolled state demonstrate increased values of their inductances, $\approx$2.5 times for $L_{RU(0)-(8)} = L_4 + L_5 + L_8 = 91.4$ nH and $\approx$3.3 times for $L_{RU(1)-(2)} = L_2 + L_3 = 35.9$ nH compared to their planar counterparts, respectively, at 10 MHz (the spectra are shown in Figure S3, Supporting Information). Here, the inductance ratio between the rolled and planar geometries is affected by the series inductance of the straight conductor (parallel to the Swiss-roll axis) according to $\frac{L_{RU} + L_C}{L_{PL} + L_C}$, where $L_C$, $L_{PL}$, and $L_{RU}$ are the inductances of the straight conductor, the same conductor in the planar and rolled states, respectively. The inductance of the straight conductor is obviously not altered due to the rolling process, thus strongly affecting the inductance ratio of the structure between the electrodes (3) and (7), but not the structure between the electrodes (1) and (2) (see Figure 2c). The ratio between the inductances in the rolled and planar states provides a good merit for the self-assembly process that has to be carefully analyzed during the design for the sake of maximum final performance of 3D assembled devices. Besides, this analysis reveals an optimal 2D layout of conductors allowing to effectively exploit the available 3D space. In this respect, the self-assembly of the coils demonstrates substantial enhancement of the inductance due to the geometric transformation and shrinking of the overall footprint area by up to 60 times.

The rolled coils (Figures 1a and 2a,c–e), for example, $L_1$ and $L_2$, $L_3$ and $L_5$, and $L_6$ and $L_9$ are mutually coupled, due to their close proximity. This is obvious from the circuit shown in Figure 2c. The coil set ($L_1$ and $L_9$) between the electrodes (0) and (8) shares a mutual inductance with the coil set ($L_5$ and $L_8$) formed between the electrodes (3) and (7), respectively, $M_{PL(0)-(8)}$, which is equivalent to 18.8 nH. The mutual inductance of the rolled structure is higher, compared to the mutual inductance $M_{PL(0)-(8)} = 12$ nH of the initially planar structure. A similar character is observed for the set of coils between the electrodes (0) and (8) coupled to the set of coils between the electrodes (1) and (2), revealing more than twice an enhancement of the value of the mutual inductance in the rolled state $M_{RU(1)-(2)} = 3.9$ nH compared to $M_{PL(1)-(2)} = 1.5$ nH of the planar structure (the spectra are shown in Figure S4a–d, Supporting Information). The mutual inductances of the planar and rolled geometries have, however, different origins. The flux linkage in the planar loop structure is mostly perpendicular to the surface, which vanishes in the self-assembled structure. Due to the rolling process, the set of axial coils is formed with axially oriented flux, allowing inductive coupling of these coils. This aspect is appealing for fabrication of axial microtransformer structures in the self-assembled state (Figure 2c). The key parameter of
these devices is the coupling coefficient that shows how much of the total flux is shared among the coils. A coupling coefficient $k_{LU(08)-(37)} = 16.8\%$ was measured for the same set of coils, which in the rolled state of the device is half of the coupling coefficient $k_{PL(08)-(37)} = 33.4\%$ of the initially planar structure (the spectra are shown in Figure S5a–d, Supporting Information). However, an opposite behavior is observed for the set of coils between electrodes (0) and (8), and the set of coils between electrodes (1) and (2). This set of mutually coupled coils demonstrates enhancement of the coupling coefficient in the rolled state $k_{RU(08)-(12)} = 9.8\%$ (spectra are shown in Figure S5b, Supporting Information), over the low coupling coefficient of only $k_{PL(08)-(12)} = 7.6\%$ in the planar state. Such a difference in the behavior of the two coupled sets of coils can be understood from the layout of their planar conductors (Figure 2c) and the definition of the coupling coefficient, which is $k = M/\sqrt{LsLp}$, where $M$, $Lp$, and $Ls$ are the mutual and self-inductances of the primary and secondary coil sets, respectively. An increase in the self-inductance, as it occurs during roll-up, should be accompanied by an increase of the mutual inductance in order to keep the coupling coefficient constant. This is not the case for the particular inductance $Lq$ (Figure 2c) located farther away from the partial inductance $L1$, compared to the positions of the partial inductances $L2$ and $L5$. Thus, the increase of the inductance $L4$ cannot be compensated during the rolling by its vanishing mutual inductance with the inductance $L1$, therefore $k_{RU(08)-(37)} < k_{PL(08)-(37)}$. The axial proximity of coil $L4$ to $L1$ and $L5$ also explains the only 2.5 times enhancement of the $L_{RU(11)}$ self-inductance compared to other coil sets. In this respect, coil $Lq$ has a vanishing mutual inductance with the inductances $L4$ and $Ls$, negatively affecting the overall inductance increase between electrodes (3) and (7). This difference clearly demonstrates the demand for accurate design rules for the planar layout by carefully defining the position and orientation of the conductor structures directly affecting the final characteristics of the self-assembled 3D device.

For many applications, including signaling circuits as well as power converters, a particularly interesting configuration of mutually coupled coils is the centered-tap-secondary transformer.\[24]\] This configuration mainly relies on inductances $L1$, $L3$, and $L4$ in the self-assembled device (Figure 2c). The windings formed by the inductances $L0$, $L1$, and $L6$ should have much less coupling due to the twice larger distance between them. Otherwise, inductances $L0$ and $Lq$ should have a strong mutual coupling that contributes to the overall coupling between the conductors (5)–(7) and (0)–(8). The measured characteristics confirm this behavior (the spectra are shown in Figures S3c,d and S4c,d, Supporting Information). The self-inductance value and the inductance ratio of the set between (3) and (5) is much smaller ($L_{RU(13)}$) $= 37.2$ nH and $L_{RU}/L_{PL} = 1.9$, respectively) compared to the set between (5) and (7) ($L_{RU(57)} = 83.7$ nH and $L_{RU}/L_{PL} = 2.8$, respectively), which is purely due to the geometry of the initially planar conductor containing several small sections with vanishing self- and mutual coupling among them in the self-assembled state. Sections (3)–(5) and (5)–(7) differ by almost a factor of 2 in their coupling coefficient $k_{RU(57)-(08)} = 13.5\%$ and $k_{RU(13)-(08)} = 25.6\%$ with the section (0)–(8), which is obvious considering the relative positions (Figure 2c) of their conductors (the spectra are shown in Figure S5c,d, Supporting Information). Thus, it is very critical to consider the right design of the 2D layout in order to achieve symmetric operation of such an electronic device.

Starting at about 40 MHz, the mutually coupled inductors reveal an increase and then drop in their inductances to almost 0 Ω at a frequency of about 97 MHz (the spectra shown in Figure 2f and spectra shown in Figure S3, Supporting Information). This happens due to the resonance condition promoted by the intrinsic capacitance of the rolled-up coils. For demonstration purposes, we energized an LED connected to the secondary side (0)–(8) of the microtransformer by powering the primary (3)–(7) side (detailed circuit in Figure S6, Supporting Information). The resonance frequency of the primary and secondary coil sets was matched to the frequency of ≈40–50 MHz with external capacitors of about 100 pF connected in parallel on either side of the transformer. At the resonance frequency the energy can be transferred with higher efficiency\[25]\) thus the LED can generate light (Figure 2g,h) rectifying the power transferred over the mutual flux between the self-assembled microcoils. The overall insulation among windings was measured to be more than 4 MΩ at 32 V, which was characterized by the source measuring unit Agilent B2902. All the impedance characterizations were performed by the two-port network analyzer Agilent ENA5071 with an appropriate calibration routine.

We have applied the microscale self-assembled coil as an NMR transducer to probe nuclear spin states in a small volume of a model material. The self-assembled microcoil was introduced in a commercial NMR probe forming an LC resonator. The resonance frequency of the resonator was adjusted with an external set of capacitors to the Larmor frequency of 1H nuclear spins precessing in an external magnetic field. In this configuration, the microcoil is able to transfer energy into the material subsystem and receive the response signal. For demonstration purposes, we have integrated the tuned transducer (Figure 3a,b) into a commercial NMR setup equipped with 3 and 7 T superconducting magnets. We used glycerin in the inner opening of the rolled-up structure (Figure 3a) for the test measurement. Glycerin shows two hydrogen (1H) peaks at about 3 and 4.5 ppm, which are revealed by a standard solenoid copper coil possessing a diameter of 0.6 mm and a length of $l = 2$ mm. (Figure 3c). In the same figure, we demonstrate the first successful NMR measurements performed with the self-assembled microcoil. The signal shows a clear signature of 1H in glycerin at the correct resonance frequency. The broader line width in the obtained signal for the rolled-up microcoils compared to the standard solenoid copper coil is expected for small-scale coils and just confirms the functionality of the transducer. Possessing a strong field strength such coils are affected by different local magnetic susceptibilities of the coil itself and of the materials surrounding the coil. This effect is well known\[26]\) and increases with the downscaling of the coil size where the bulk of the sample more closely approaches the coil windings.\[27]\)

Finally, we demonstrate the feasibility to realize high-quality LC resonators without using external capacitors just relying on an alternative planar layout of the conductor to form a parallel plate capacitor and the coil in a single-batch self-assembly process (Figure 3d). The resonator, in its 3D shape, was designed using an FEM model based on the ANSYS Academic software package (Figure 3e) and then fabricated in the same process.
as the microcoils with the only difference in the planar layout of the conductor. The most prominent design (Figure 3e,f) achieved a quality factor > 40 000 (Figure 3g). In this design, the coil stripe (Figure 3e right and the planar layout is shown in Figure S1b, Supporting Information) is shifted away from the capacitor stripe (Figure 3e left) in order to ensure spatial separation of electric and magnetic fields in the assembled state that avoids radiation of electromagnetic waves. The self-assembled structure contains a cylindrical parallel plate capacitor (Figure 3e) and the multiwinding inductor, resulting in a high-quality factor resonator tank.

For testing, a simple ESR setup was built integrating the microcoil ESR resonator (Figure 3f). The setup was equipped with a strong biasing electromagnet, a shimming couple of coils, and small field scanning coils supporting a very precise settling of the magnetic field between the pole shoes (±2.5 µT). An additional filter circuit and a custom-designed nonmagnetic probe were implemented in order to eliminate residual magnetic inhomogeneity’s and noise coming from the power supply of the magnet, which otherwise disturbs characteristics of the high-Q resonances presented in the ESR model sample. We used 2,2-diphenyl-1-picrylhydrazyl (DPPH) as the model material, which is an important functional agent in chemistry, that is, for ESR monitoring of the antioxidation activity of biologically relevant substances.[28] The material was loaded into the resonator and characterized with an applied magnetic field, which was swept around 196 mT. The central field of 196 mT corresponds to the ESR resonance of DPPH free radicals at about 5.5 GHz which is close to the resonance peak of the chosen resonator (Figure 3h). We had to choose the field and an appropriate frequency range between 5.48 and 5.53 GHz measuring return loss (S11) to find resonance characteristics of the microresonators (Figure 3g). The variation in characteristics of the resonators accounts for a slight sensitivity of the high-Q device to a deviation of geometric parameters of the rolled-up structure. A subtle variation in the diameter or the winding misalignment can be dramatic for the device performance affecting the capacitance or the inductance.[27] The resonator design is sufficiently tolerant toward this issue (Figure 1a) purely relying on the planar conductor design among other less stable structures (Figure 3i,j).

In conclusion, we have designed and fabricated rolled-up cylindrical microcoils, transformers, and resonators relying on shapeable polymeric ultrathin films. As the result, we achieved up to 48 different devices on a single square (100 × 100 mm²) shaped wafer. We could demonstrate a fully parallel wafer-scale process utilizing the same fabrication routine, shapeable layer stack, and the 3D tubular geometry. The self-assembly of very simple conductor structures into the Swiss-roll geometry provided means to fabricate coils, transformers, and high-quality resonators. The overall process allows omitting a number of intermediate steps, which are otherwise required in
conventional 2D processing schemes. We showed for the first time that shaping of the initially planar structure like a conductor can lead to >50 times more compact 3D inductive coils with enhanced up to four times inductance, reaching >100 nH at MHz regime. The mutual inductance among some inductors and the coupling coefficient were enhanced promoting applications such as ultracompact transformers. We envision applications of these magnetic self-assembled devices in microelectronics, radio frequency, communication devices, and power converters. Fully integrated systems will employ microscale inductances, transformers, and resonators operating as, for example, impedance matching networks, filters or—if combined with active electronics—fully integrated compact DC-DC converters. Additionally, sensitive microcoil electromagnetic resonators were realized, and their application for microscale NMR and ESR spectroscopies was demonstrated. Application of NMR inert materials and other measures to create a homogeneous magnetic surrounding of the microcoil will substantially increase the resolution of the rolled-up NMR microcoils. Shimming and gradient coils can be accommodated within the same geometry to define the magnetic field profile of the resonators. These devices are promising if combined with sampling systems such as microfluidics or microcatheters for realization of compact resonance spectroscopies and imaging techniques of microscale samples.

Experimental Section

Treatment of Substrates: Square-shaped glasses of 100 × 100 × 1 mm³ were used as the substrates in this work (D263T eco glass, SCHOTT AG, Mainz, Germany). Initially, all the substrates were washed in the professional washer DS 500 (STEELCO S.p.A., Riese Pio, Italy) to remove all of the organic and inorganic contaminants, presented in the form of dust or films. Then, the surface was activated with oxygen plasma in the GIGAbatch 310M (PVA Metrology & Plasma Solutions GmbH, Wettenberg, Germany). This ensures further chemical surface modification with a monolayer of 3-(trimethoxysilyl) propyl methacrylate (TMSPM). For this, the glasses were placed in the vacuum oven at 150 °C for 2 h together with 150 mL of TMSPM.

Sacrificial Layer: The sacrificial layer was prepared from acrylic acid (AA) and hydrated LaCl₃, obtained from Alfa Aesar, UK and used without further purification. First, 10 g of AA was partially neutralized using sodium hydroxide (Sigma-Aldrich Co. LLC, Germany) until the solution reaches pH = 5.5. The pH value of the solution was monitored using the pH meter CyberScan PCS10 (Eutech Instruments Pte Ltd., Singapore). Then 7.36 g of LaCl₃ × 7H₂O was added to this solution, dissolved in 50 mL of deionized (DI) water to achieve the proportion of AA:La = 7:1. The AA-La solution was stirred for 30 min using a magnetic stirrer and during this time pH was slowly increased to 10 by dropping NaOH. At elevated pH lanthanum complex precipitates and collected using a filter paper and a vacuum excitor with subsequent washing in DI water until litmus test paper (DuoTest, Macherey-Nagel GmbH & Co. KG, Germany) shows neutral reaction. White precipitate was collected and dried under nitrogen atmosphere resulting in a white powder of 4.68 g. As a final step, the dried and milled material was dissolved in AA at the concentration of 33% (wt/wt), photosensitized using 2% (wt/wt) of 2-benzyl-2-(dimethylamino)-4-morpholinobutyrophene and 4% (wt/wt) methyl diethanolamine (MDEA) (Sigma-Aldrich Co. LLC, Germany). Achieved solution was applied on the substrate using spin-coating at 3000 rpm for 35 s with the acceleration of 500 rpm s⁻¹. After pre drying at 35 °C for 5 min it was exposed with a broadband UV mask aligner MJ84 (SUSS Micro Tec SE, Garching, Germany) for 30 s and then developed in DI water for 30 s. In order to remove water-insoluble rests of photoinitiator, a subsequent washing in propylene glycol monomethyl ether acetate (PCMEA) (Sigma-Aldrich Co. LLC, Germany) was done for 5 s. Finally, samples were hard-baked at 220 °C for 5 min revealing high-resolution structures of the sacrificial layer on the glass surface.

Shapeable Bilayers: The assembly of the planar stack occurs in the bilayer polymeric system due to the swelling of the HG layer reinforced by the PI layer in a basic condition pH = 9 of the rolling solution. Preparation of the bilayer started from the synthesis of HG using poly(ethylene-alt-maleic anhydride) (PEMA) and N-(2-hydroxymethyl) methacrylate (HEMA) (Sigma-Aldrich Co. LLC, Germany). At first 6 g of PEMA was dissolved in 50 mL of N,N-dimethylformamide (DMF) (Sigma-Aldrich Co. LLC, Germany), then to the solution 5.6 g of HEMA was added. All components were mixed thoroughly for 24 h at room temperature by roll-mixer to finish the reaction. The PI was prepared by reaction of 12 g 4,4'-methyleneedianiline (MDA) (Sigma-Aldrich Co. LLC, Germany) and 19.65 g of 3,3',4,4'-benzophenonetetracarboxylic dianhydride (BPDA) (Sigma-Aldrich Co. LLC, Germany). Both monomers were dissolved in 20 mL DMAC and gradually over an hour reacted together under culling conditions at 15 °C, resulting in the highly viscous solution. Then dimethylaminoethyl methacrylate (DMAEMA) (Sigma-Aldrich Co. LLC, Germany) was added in a 1:1 molar ratio to the number of carboxylic groups in BPDA. The solution was left in the mixer for 4 h under culling conditions to complete the reaction. At the end HG and PI solutions were photosensitized with 4% (wt/wt) of 2-benzyl-2-(dimethylamino)-4-morpholinobutyrophene (Sigma-Aldrich Co. LLC, Germany) and additionally diluted to have thickness in the range of 500 and 1500 nm, respectively, at 3000 rpm.

The bilayer stack was formed in a sequential photopatterning process of HG and PI. Materials in amount of 3 mL were applied on the substrate through 1 µm filter using following settings: polymer prespinning step was made at 500 rpm with acceleration 50 rpm s⁻¹ for 10 s, mask spinning was done at 3000 rpm for 30 s with acceleration of 500 rpm s⁻¹. The final postspinning step was done with acceleration of 2500 rpm s⁻¹ for 3 s reaching 5000 rpm minimizing edge-beads. Then, polymers were prebaked at 40 °C for 5 min and 50 °C for 10 min, respectively. After the drying step substrates were exposed using MJ84 mask aligner for 1.5 min and then developed. For HG layer development was done in diethylene glycol methyl ether (DEGME) (Sigma-Aldrich Chemie GmbH, Munich, Germany) for 60 s with washing in PCMEA for 5 s. PI layers were developed in the solution of solvents: 40 mL of NEP (Sigma-Aldrich Chemie GmbH), 20 mL of DEGME, and 10 mL of ethanol (VWR International GmbH) for 90 s with a subsequent washing in PGMEA for 5 s. After the development layers were hard-baked at 220 °C for 10 min.

Metal Layers: The metal layer stack was patterned via etching process. The layer stack consisting of Ti⁶⁺/Cu⁹⁺/ITO⁹⁺ was deposited using magnetron sputtering at room temperature. For sputtering, Ar gas at partial pressure of 10⁻¹ mbar and the base pressure 2.3 × 10⁻⁴ mbar was used. Then layer of 1 µm AZ5214E photoresist (Microchemicals GmbH, Ulm, Germany) was patterned following the protocol provided by the manufacturer. Titanium etching process was made in the solution of sodium fluoride (NaF), ammonium peroxysulfate, and DI water in the proportion of 1:1 (mol L⁻¹) in 200 mL of water. Copper etching process was done during 5 s in the solution of HCl:H₂O₂:H₂O in a proportion of 1:2:10 (vol/vol/vol).

Self-Assembly Rolled-Up Process of Tubular Architectures: The 2D layouts of polymeric structures with electronic layers were self-assembled into 3D Swiss rolls by a selective etching of the SL in the solution of a strong chelating agent containing 15 g of sodium diethylenetriaminepenta-acetic acid (DEPTA) (Alfa Aesar, UK) in 500 mL of DI water and a subsequent swelling of the HG. For dissolution of the chelate in water it was neutralized with sodium hydroxide in an amount sufficient to reach pH = 5.5. Additionally 10% of benzo triazole (Sigma-Aldrich Co. LLC, Germany) was introduced into the solution in order to inhibit etching of Cu layer. After the SL etching process rolling was performed in an equivalent DEPTA solution, but having pH = 8.

Electrical Characterization: All prepared self-assembled structures were characterized acquiring their S and Z parameters using the Cascade.
PM-8 probe station and vector network analyzer Agilent ENA 5071 (Agilent Technologies GmbH & Co. KG, Waldbronn, Germany) in the frequency range from 300 kHz to 100 MHz. All the electrical connections with rolled-up structures were made using ground signal ground (GSG) CASCADE 2|Z| probes. The LED experiment was performed using a signal generator MG3692B (Anritsu Corporation, Kanagawa, Japan). To cancel any adverse effect of the interaction probe system with the magnetic field, the ESR measurements were done in an in-house made magnet, and probe and probe holder were made of nonmagnetic materials. The electromagnet with a magnetic field in the range from 0 to 600 mT and maximum deviation less than 2.5 μT was achieved. The magnetic field was swept using an additional set of coils with the Keithley source generator MG3692B (Anritsu Corporation, Kanagawa, Japan). To cancel the magnetic field, the ESR measurements were done in an in-house made magnet, MAGSYS hall sensor (MAGSYS magnet systeme GmbH, Dortmund, Germany), where the probe sensor was closely placed to the sample in order to eliminate any differences in the readings of magnetic field and estimation of the Larmor precession frequency.

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.

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