1. Introduction

Sensors have become integral to our daily lives and are in continuous and ubiquitous use: They automatically switch on the lights when a person enters a house,[3] operate in moving vehicles to recognize pedestrians at the roadside,[2] and help to control smartphones.[3] In industry, sensors are implemented to control and optimize production processes. This reduces both costs and the emissions of greenhouse gases and improves the ecological footprint of the products. The same benefits are achieved by using wooden elements in building construction[4] and fiber-reinforced composites in the automotive industry to make cars lighter and more efficient.[5] Adhesive bonds play a major role both in the production of wooden structures and in fiber composites. The performance of a bond is highly dependent on the key parameters of the curing process of the adhesive such as, for example, temperature, pressure, and time. In order to characterize this process, sensors are inserted directly into the adhesive bonds. [6,7] Ideally, the sensor is not only a powerful tool for optimizing the production process by tracking the curing data, but remains in the component for its entire lifetime, providing data for structural health monitoring (SHM)[8,9] related to various parameters of surrounding materials in its vicinity (humidity, temperature, cracks), and for building information modeling (BIM).[10] In warranty cases, the data obtained from production can also be used to confirm correct manufacturing of the parts. As a permanent part of the component, the sensor should be integrated seamlessly and influence the component as little as possible and not act as a structural defect.[11] Previous work in this field has demonstrated sensors printed on paper which are able to measure humidity, however, the substrates used have very limited permeability.[12,13] Poly(vinyl alcohol)-based nanomesh conductors employed as on-skin sensors are permeable to water vapor,[14,15] but may have insufficient mechanical strength to withstand harsh operating conditions.

Here, we present imperceptible sensors (iSens) on porous substrates, more specifically, on ultra-thin paper (Figure 1a) and glass fiber sheets (Figure 1b). The sensors are designed to perform dielectric analysis for continuous in-process monitoring of the curing of an adhesive and to measure its temperature.
The entire technology is non-destructive, operates in situ and in real-time, and is data compatible with the Internet of Things. Our iSens are fabricated by coating fibers with a metal to form individual and electrically conductive paths (Figure 1c). Although the substrates used (e.g., cellulose fiber papers) are lightweight and extremely permeable, allowing a drop of water to penetrate within 160 ms (Figure 1d), electrical components such as light-emitting diodes (LEDs) can be soldered onto them (Figure 1e) and then embedded in epoxy (Figure 1f). Several soldered connectors, a microchip, a resistor, and an LED show the possibility of complex circuits on the substrates (Figure 1g). Here, solder connections to a fiber substrate are superior to their counterparts on flat, non-porous substrates (i.e., flexible copper-coated printed circuit boards, PCB) because the solder does not attach to the surface only, but permeates and fills the fiber structure volume of the substrate around the soldering location. As a result, the solder is robustly connected and cannot be removed without rupture of the fibers and the entire system (Figure S1, Supporting Information). The paper sensors are highly flexible; repeated bending to radii of 6 mm for more than 2400 times leaves the conductivity of the metal traces nearly unchanged (<0.6% variation) and they even endure multiple “hard” folds (Section S1.4 and Figure S2, Supporting Information). This readily allows for insertion into 3D wood-glue joints (Figure 1h). Our glass fiber sensors do not act as defects in the fiber composite material and can be integrated seamlessly (Figure 1i). The paper sensors are very thin and are also easily penetrated by a transparent varnish, which allows, for example, touch sensors to be realized on wooden surfaces (Figure 1j and Figure S3, Supporting Information). These enable wipeable and therefore germ-free electrical switches in medical areas.

2. Results and Discussion

Fabrication of the iSens comprises only three process steps. First, metal layers are thermally evaporated onto the front side of the porous substrate (Figure 2a). We used a 3 nm thick adhesive chromium (Cr) and a 300 nm conductive copper (Cu) or gold (Au) overlayer. The same metal layers are then evaporated onto the back to ensure optimal metallization of the fibers. Finally, custom sensor designs are realized by spatial laser ablation (Section S1.6 and Figure S4, Supporting Information). Due to fast temperature homogenization of the fibers, the ablation from one side also removes the metal from the other side, thus drastically reducing fabrication complexity and processing time. We present two different substrate materials (Figure S5, Supporting Information) for different applications. An optical cleaning paper and a textile glass fiber. All sensor materials, parameters, and designs used throughout this work are listed in Table S1, Supporting Information. A 300 µm wide...
Cr/Cu electrode on this paper is shown in Figure 2b,c. The Cu thickness of 300 nm provides sufficient conductivity for reproducible sensor behavior. Laser ablation yields clean edges, few residual copper particles, and little debris, thus avoiding short-circuiting between adjacent electrodes (300 µm gap). A 500 µm wide Cr/Cu electrode on the glass fiber is shown in Figure 2d,e. Again, a 300 nm-thick Cu layer provides sufficient conductivity. Various measurements were carried out to find suitable electrode geometries. The resistance $R$ of a Cr/Cu electrode of width $w$ and length $l$ (Figure S6a, Supporting Information, corresponding conductance $G = R^{-1}$) was measured by a 4-point scheme. We found a linear behavior ($R \propto l$, Pouillet’s law) on paper (Figure 2f) and glass fiber (Figure 2i). Further, the conductance was linear in $w$ (Figure 2j), but only above some...
minimum width \( w_{\text{min}} \) (\( G \propto w - w_{\text{min}} \)). These data suggest that, for reliable electrical conductivity, an electrode should be at least 300 and 500 \( \mu \)m wide on paper and on glass fiber, respectively (for detailed information on geometry and error bars see Section S2, Supporting Information). On some substrates, the conductance also showed in-plane anisotropy (\( x \) or \( y \), Figure S6b,c, Supporting Information). In accordance with the literature, the interdigital electrode (IDE) sensors (Figure S7a, Supporting Information) exhibited a linear increase in capacitance \( C \) with increasing electrode length \( l \) (\( C \propto l \), Figure 2h)\(^{[7,18]} \). The capacity of the glass fiber sensors was slightly higher than that of the paper sensors due to substrate material properties (thickness, fiber density, and permittivity). Furthermore, there was an almost linear relation between the capacitance and the number of electrodes \( n \) (\( C \propto n - 1 \), Figure 2k). With one electrode (i.e., \( n = 1 \)) parasitic capacitances during measurement were small. In summary, we have demonstrated that individual iSens can be created easily and simply on our permeable substrates. Note that the electrodes must be sufficiently wide to guarantee good functionality and conductance.

To understand the influence of paper substrate porosity and electrode functionality, we simulated both porous and solid electrodes using the finite element method (FEM). Two Cr/Cu electrodes on a paper substrate were read into CAD software from a 2D microscope image (Figure 3a) and then digitally extruded to imitate the 3D network structure. This porous model (Figure 3b) was compared to conventional interdigital electrodes (solid model, Figure 3c). In both CAD models the electrodes were about 4.86 mm long, had width and spacing equal to 300 \( \mu \)m, and had a thickness \( h \) of 20 \( \mu \)m. The cross-sectional view of the normalized electrical potential distribution (similar to that in reference [19]) shows no noticeable difference between the two models (Figure 3d). The electric fields midway between the electrodes \( E = E_{\text{mid}}(x = 0, z) \) differs only slightly (Figure 3e). For the conventional electrodes (solid model), \( E_z \) is marginally higher for small \( z \). The theoretical curve assumes a periodic set of infinitely thin solid electrodes (\( h = 0 \)) with equal gap and width; see Equation (9) in the Supporting Information, based on reference\(^{[20]} \) and references therein. It explains the results and the logarithmic slope of the FEM simulations; the field values are slightly lower than for FEM simulations with finite electrode thickness \( h \). The charges, fields, and capacitance of the system increase with thickness \( h \) (about linearly for the capacitance) due to the presence of additional surfaces. However, the difference in capacitance between the porous and the solid structures remains small (Figure 3f). Here, the theoretical results again lie slightly below the simulated values, see Equation (12) and (13) in the Supporting Information, based on reference\(^{[21]} \). Further physical implications and theoretical aspects of the fibrous structure of the paper sensors are also discussed in Section S1.5, Supporting Information.

In the production of wood-based composites, hot pressing is a commonly used process that is very energy-consuming and cost-intensive.\(^{[22]} \) For this reason, it is important to minimize both curing time and the amount of adhesive by optimizing the pressing conditions, such as temperature, pressure, and...
pressing time. In our case, it is a simple and practical method to put a flat and small IDE sensor between the wooden plates.\textsuperscript{6,23} For in situ investigation of the cross-linking reactions in wood glue, the sensor SenPZ1 was placed directly into the glue joint (Figure 4a). SenPZ1 is a sensor on a paper substrate that is used to measure the impedance $Z$ (Table S1, Supporting Information). The boards were pressed together by a hot press at a stable temperature of 140 °C and a force of 10 kN (corresponding to 10 bar in the glue joint). To verify, that glue can permeate the iSen, the adhesive was applied only to one side of the lower board. A thin type K thermocouple was inserted into the glue joint to monitor the temperature. The paper sensor response was measured with an impedance spectrometer. The spectrometer and thermocouple readings were fed into a computer for further processing (Figure 4b). At the beginning of the experiment, the wooden sample with the embedded sensors...
was placed in the hot press, which closes completely in about 10 s. The time $t = 0$ in Figure 4c corresponds to the closed press and marks the beginning of the measurement. The heat diffused through the 5 mm thin beech wood into the glue joint, where the temperature reached 104 °C after 2 min. At this temperature, short-term temperature stabilization occurred. Evaporation of water is endothermic, which is reflected in a plateau in the curing temperature curves. Although the experiment was performed under atmospheric ambient pressure, the additional build-up of high pressure within small regions of the glue layer due to locally trapped water vapors increased the boiling temperature to above 100 °C. Similar experiments by Sernek et al. have shown that the plateau temperature increases when a warmer hot press is used. After the plateau, the temperature rose again and slowly stabilized at the hot press temperature of 140 °C. During the entire pressing time of 35 min, the impedance $Z$ of the paper sensor within the glue joint was recorded (Figure 4d). Starting from a dominant resistive behavior over the whole frequency range (slope $= 0$) at $t = 0$, the impedance changed to an almost ideal capacitive behavior (slope $= -1$) at $t = 35$ min. Thus, it is reasonable to analyze these results within the framework of a parallel resistor-capacitor element (Section 1.7 and Figure S7b, Supporting Information). In the beginning, the glue was still liquid and provides high mobility for both electrons and ions. The mobile electrons cause a high ohmic conductance (Figure 4e), and the large amounts of highly mobile ions, results in electrode polarization, with high capacitance values, especially at low frequencies (Figure 4f). An increase in temperature first reduced the viscosity of the glue, and conductance and capacitance continued to rise slightly, reaching a maximum at about $t = 1$ min (Figure S7c, Supporting Information). At this point, the temperature was sufficiently high to induce cross-linking reactions within the glue, and mobility and number of ions decreased. As a result, conductance and capacitance then exhibited a trend reversal, and in the course of further cross-linking and water evaporation (drying), both values decreased. After 35 min the rate of change in the measured data was very small and the glue almost completely hardened. This experiment shows that the porous iSen presented here is suitable for continuous in situ monitoring of the curing process of wood glue in the manufacturing of wood-based composites. It withstands harsh conditions over the entire measurement period and delivers stable and reliable values that are comparable to those achieved with commercial sensors made of plastic or paper.

Presence of the embedded paper sensor should impair the bond strength of the glue joint as little as possible. To quantify its effect on the joint, tensile shear tests were performed (Figure 4g and Figure S8, Supporting Information). The wooden test samples with glued-in sensors were prepared and produced as in the previous hot-press experiment (pressure, temperature, amount of glue, etc.). In the center of the sample, both upper and lower wooden plates were notched to create a preferential breaking point at the sensor position. Every sample was pulled apart by a universal tensile testing machine until failure. The quality of a glue joint is characterized by the wood failure percentage (WFP), which is a visual estimation of the percentage of wood fibers covering the tested adhesive surface after the tensile test. For 8 samples, the wood broke completely while the glue joint remained intact: an excellent WFP of 100% (Figure S8c, Supporting Information). Only one sample broke at the glue joint: a poor WFP of 0% (Figure 4h); only very small pieces of wood stuck to the sensor embedded in the yellow glue (Figure 4i). Thus, in the overwhelming majority of cases, and with a very high average WFP of 81%, the glue joint with the built-in sensor was stronger than the wood itself. The shear strength is the maximum shear stress $\tau = F/A$ before a sample breaks, where $F$ is the applied load and $A$ is the shear area (10 × 20 mm²). We compared the tensile test results of our porous sensor with those of three additional material configurations. All measurement results are listed in Table S2, Supporting Information. Polyimide as a sensor substrate did not result in appreciable bonding and exhibited a WFP of 0% because the glue could not penetrate it (Figure 4j). Standard copy paper was also not suitable as a sensor substrate, because shear strength and WFP were too low and varied too widely. The adhesive joint without a sensor (control sample) achieved a very high shear strength of 13.5 MPa and an average WFP of 100%. This WFP value shows that the shear joint is stronger than the wood, and the shear strength characterizes the glue itself, rather than the glue. The measured shear strength of our porous sensor showed moderate standard deviation, and all values were above 10 MPa, which corresponds to quality class C1 according to European Standard DIN EN 12765-2001 and is within the range of values achieved without any sensor. After the tensile tests, the broken wood samples were cut to analyze the microscopic condition of the glue joint in a cross-section (Figure 4g). The adhesive joint was trimmed by microtome cuts and investigated with an optical microscope. For good contrast, fluorescence microscopy with appropriate filters was used, which showed the wood in blue color. The glue layer without a sensor was very thin (Figure 4k) and exhibited a glue distribution as seen in other papers. More vessels were filled with yellow glue in the lower board than in the upper one, probably because the glue was applied only to the lower plate before hot pressing. The glue joint with embedded sensor was equally thin and exhibited a similar glue distribution (Figure 4l). This is important because penetration of the glue into the wood is crucial for good adhesion. In previous work, we found that the porosity of conventional paper was not sufficient for the glue to permeate it, which is no longer the case for the improved porous paper sensor presented here.

In contrast to our paper sensor in wooden structures, our permeable glass fiber sensor is fabricated directly on the construction material, which makes it an additional, intelligent feature of the glass fiber itself. Dielectric analysis using IDE sensors is well suited for the characterization of adhesive curing. We chose Ag instead of Cu as the main electrode material to prevent oxidation during the high-temperature experiments (Figure S9a, Supporting Information). The experimental setup consisted of two glass fiber sensors (SenGZ1 and SenGR1, Table S1, Supporting Information) placed in a small molding frame (Figure 5a,b). SenGZ1 is an IDE sensor for measuring the impedance of the surrounding epoxy during curing (a process similar to the curing of wood glue). The smaller SenGR1 is a resistance sensor which monitors temperature changes after curing (Figure S9b, Supporting Information). A thin type K thermocouple was inserted into the frame to record
the temperature. The entire experimental setup was placed on a hot plate to provide the heating necessary for tempering the epoxy. SenGZ1 was measured with an impedance spectrometer. In addition, a digital multimeter measured the resistance of SenGR1. The readouts from the spectrometer, the multimeter, and the thermocouple were sent to a computer for further processing. At the beginning of the experiment (t = 0), the mixed liquid epoxy was filled into the molding frame. Following the instructions from the datasheet of the epoxy system, it was cured for 24 h at 23 °C and then tempered twice for 15 h at 82 °C (Figure 5c). A small temperature increase (+1 °C) occurred in the first hours due to exothermic polymerization. The impedance Z measured by SenGZ1 showed a clear resistive behavior at lower frequencies (slope ≈ 0) during the first 4 h of measurement (Figure 5d). At higher frequencies, capacitive behavior (slope ≈ −1) was observed, which dominated across the whole frequency range after 6 h. Therefore, it was possible to apply the parallel resistor-capacitor model for these results as well (Section S1.7 and Figure S7b, Supporting Information). Initially, the epoxy was liquid, and both conductance and capacitance were very high (Figure 5e and Figure S10a, Supporting Information). Due to progressive hardening in the first 24 h, both values decreased continuously. An increase in temperature during the first tempering caused conductivity and capacitance to rise again. The small peak at the beginning of the first tempering reflects a short hardening period of the epoxy (further polymerization), which did not occur during the second tempering. This confirms that the epoxy was almost completely cured already towards the end of the first tempering, where the values stabilize (see also curing kinetics in the Figure S10b,c, Supporting Information). If the temperature changes significantly afterward, the impedance just tracks these changes reversibly. These results demonstrate, that our glass fiber iSen is suitable for measuring and characterizing the curing of a commercial epoxy resin. It provides stable and reliable measurement data comparable to those from other...
3. Conclusion

We have presented a simple and straightforward method for producing permeable sensors on flexible and porous substrates (paper and glass fiber). Fabrication includes physical vapor deposition and laser ablation. Conveniency, removal of the electrode materials can be achieved by laser ablation from only one side. The electrodes thus created should be sufficiently wide to ensure good functionality and conductance. Soldering various electrical components onto the sensor substrates and creating circuit boards is also possible. Theoretical and finite element method (FEM) analyses found only very small differences between conventional solid and porous electrodes. We have demonstrated that our paper sensor can withstand harsh conditions (140 °C, 10 bar) during hot-processing of wooden constructions and provides data on the glue curing. The adhesive joint with the built-in paper sensor exhibited high mechanical stability. The glass fiber sensor, which is directly evaporated onto the construction material, provided stable data for epoxy curing during high-temperature phases. The characteristics of the resistance sensor make it suitable for use as a temperature sensor and as a heating element. We believe that our iSens platform will contribute to a new generation of flexible, permeable, and imperceptible sensors seamlessly integrated into various smart composite materials, further increasing their functionality in a wide variety of applications, from automotive and construction industries to renewable energy production and healthcare.

4. Experimental Section

**Paper substrate:** Thorlabs Premium Optical Cleaning Tissue with a size of 124 × 73 mm², a thickness of 49 µm, and a grammage of 9.39 g m⁻². Its organic fibers, which are free from contaminants and adhesives, have a diameter of about 5–15 µm, and the wide-meshed fabric guarantees good permeability for liquids. This tissue meets the U.S. Government Lens Tissue Specification A-A-50177B.

**Glass Fiber Substrate:** Johns Manville Glass Fiber Nonwoven type FH 0.30/50 with a size of 210 × 297 mm² (DIN A4), a thickness of 0.32 mm, and a grammage of 48 g m⁻². The fibers are 8 µm in diameter, have random orientations, and are bonded together with a urea-formaldehyde resin.

**Thermal Evaporation Materials:** All metals were evaporated at a rate of 0.3 nm s⁻¹ and at a pressure below 0.8 mPa in a vacuum chamber. Cr: Kurt J. Lesker Chrome-Plated Tungsten Rods EVSCRW1 (0.07 diameter, 2″ long, 99.9% purity). Cu: Kurt J. Lesker Copper Pellets EVMCU40EXQ (1/4" diameter, 1/4" long, 99.99% purity). Ag: Ögussa Fine gold granulate (99.98% purity).

**Laser Ablation:** A Trotec Speedy 300 laser engraver was used together with a fiber laser and a 2.85" lens.

**Permeability Measurements:** To visualize the high permeability of the paper-based sensor, a video was recorded with a frame rate of 50 Hz. The time between the deposition of the water droplet onto the sensor and complete droplet seepage to the opposite side was found from the frame by frame analysis and is about 160 ms (Figure 1d). This time gives an upper limit for the water permeation time, the wetting of the sensor occurs faster. In addition, electrical measurements were made with an experimental setup similar to the one described in reference [23] and found permeation times for wood glue-paper to be <1 s, water-glass fiber to be <2 s, and viscous epoxy resin-glass fiber less than 6 s. In practical application, the time scale relevant for permeability analysis and monitoring is typically significantly larger than these values.

**Soldering on Porous Substrates:** A standard non-RoHS solder was used (Sn60Pb39Cu1, RS Components) for soldering the electronic components (e.g., LED Driver: TLEC9116IPWR Texas Instruments and Red LEDs: 150004RSJ1240, Würth Elektronik) onto the porous substrates (Figure 1e–g). Direct contact between substrates and the soldering iron was avoided by prior application of the solder to the contact pads of the components. The components were then positioned and soldered onto the substrate by tipping the contact pads with a fluid flux (428 332, Multicore) and heating the pads with the soldering iron (300 °C). In addition, low-temperature soldering was also performed (solder IND282, indium corporation).

**Touch sensor under transparent varnish:** The medium-density fiberboard used had a thickness of 18 mm, a size of 10 × 10 cm², and was dried and conditioned at 23 °C and 50% rH for seven days before the experiment. The fiberboard, the paper sensor SenPZ2 (Table S1, Supporting Information) and 1.34 g of the powder coating (Drylac Wood Series 530, TIGER Coatings GmbH & Co. KG) were pressed together for 15 min by a hot press (LabEcon 300 Fontijne Presses) at a stable temperature of 150 °C and a force of 5 kN. This resulted in a pressure of 5 bar (0.5 MPa) and a desired powder application of 134 g m⁻². The capacitance of the paper sensor was measured with an impedance spectrometer at 1 MHz and a signal voltage of 2 V.

**Scanning Electron Microscope (SEM) pictures:** Measurements were taken using a Zeiss CrossBeam 1540 XB SEM at 3 kV acceleration voltage. Samples were prepared by thermally evaporating (0.1–0.5 nm s⁻¹, 1 × 10⁻⁶ bar) about 20 nm Cu, which provides good contrast in the SEM pictures.

**Microscope Pictures:** The optical microscope images were produced with a Nikon Industrial Microscope ECLIPSE LI100ND, a Zeiss Axioplan 2 Universal Microscope, and a KEYENCE VHX-7000 Digital Microscope.
**Supporting Information**

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

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**Conflict of Interest**

T.S., and D.W. are co-founders of sendance, a start-up company developing sensor systems. T.S., U.M., R.S., and M.K. are listed as inventors on an Austrian patent application (AT323450) that describes a permeable electrode for sensor applications.

**Author Contributions**

T.S., U.M., R.S., B., and M.K. conceived the research project; T.S. prepared the materials with input from M.S. and F.E.; T.S. fabricated the sensors, conducted the experiments and analyzed the data; S.D. recorded the SEM images; R.P. soldered the electronic components; G.M. conducted the FEM simulation; N.A. developed the theoretical models; T.S., D.W., and M.D. designed the figures; T.S., D.W., N.A., and M.K. wrote the manuscript; all authors contributed to editing the manuscript; M.K. gave input at all stages and supervised the research.

**Data Availability Statement**

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

**Keywords**

glass fibers, laser ablation, papers, porous materials, sensors

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