Highly Conducting Nanographite-Filled Paper Fabricated via Standard Papermaking Techniques

Patrik Isacsson, Xin Wang, Andreas Fall, Desalegn Mengistie, Emilie Calvie, Hjalmar Granberg, Göran Gustafsson, Magnus Berggren,* and Isak Engquist*

ABSTRACT: Eco-friendly and cost-effective materials and processes to manufacture functional substrates are crucial to further advance the area of printed electronics. One potential key component in the printed electronics platform is an electrically functionalized paper, produced by simply mixing common cellulosic pulp fibers with high-performance electroactive materials. Herein, an electronic paper including nanographite has been prepared using a standardized and scalable papermaking technique. No retention aid was needed to achieve a conducting nanographite loading as high as 50 wt %. The spontaneous retention that provides the integrity and stability of the nanographite paper, likely originates partially from an observed water-stable adhesion of nanographite flakes onto the fiber surfaces. The resulting paper exhibits excellent electrical characteristics, such as an in-plane conductivity of 10^7 S/cm and an areal capacitance of 9.2 mF/cm^2, and was explored as the back-electrode in printed electrochromic displays.

KEYWORDS: electronic paper, printed electronics, electrochromic display, nanographite, graphene, cellulose, self-assembly

INTRODUCTION

The science and industry of printed electronics have made significant progress over the last decades, although reducing the environmental impact and the material costs are considered increasingly critical issues that must be dealt with. Therefore, biobased and inexpensive cellulosic paper as the substrate for printed electronics has attracted more and more interest from the sector, which is further motivated by the many production protocols that the industries of graphics and printed electronics have in common. Furthermore, it would be of interest to print on papers not only providing a printing substrate but also offering electronic functionality. For example, in electrochromic displays (ECDs), a conductive substrate could simultaneously serve as the flexible rear side substrate, the current collector, and the electrode (Figure 1AB).

Conductive cellulose-based composites have received much attention over the past decade, where cellulose nanofibrils (CNFs) have been successfully combined with nanocarbons. CNFs have an intrinsic attraction to nanocarbons, by which the excellent mechanical properties of CNFs and the high electrical conductivity of various nanocarbons can be exploited to prepare high-performing composites with conductivities approaching 10^7 S/cm. However, CNF-based composites are challenging to produce on a larger scale due to the inherent high dewatering resistance of CNFs. Ordinary papers based on macroscopic cellulosic pulp fibers are, on the contrary, produced in enormous quantities globally. Recently, it has been shown that bulk electronic functionality can be introduced in such papers. For instance, cellulosic pulp can be mixed with conducting graphite, which results in composites exhibiting both conductive and capacitive performance.

Received: July 20, 2020
Accepted: October 2, 2020
Published: October 14, 2020
However, it is not possible to translate the preparation of paper in vacuum funnels with fine filter media, as utilized in the previously mentioned works, into industrial papermaking processes. To realize the potential of electronic papers, we need a fabrication technique that allows for the large mesh size used in traditional paper machines and the demand for high rates of dewatering.\textsuperscript{12} Attempts to use standard papermaking techniques have, in fact, been explored to prepare conducting papers functionalized with conducting polymers;\textsuperscript{13,14} however, the attempts have only resulted in very low conductivities. By instead combining carbon fibers with cellulosic pulp fibers, a relatively high conductivity of 105 S/cm has been achieved,\textsuperscript{15} although for this, a carbon fiber content of 80 wt% was needed. From a printed electronics perspective, the use of carbon fibers gives drawbacks related to poor mechanical performance as well as an open and porous structure not suitable for printing or other common converting steps. Thus there is still no example of a highly conducting paper that is producible in an up-scalable way with standard papermaking methods and exhibits good mechanical properties.

In this work, we have focused on exploring the combination of cellulosic pulp fibers and flaky, high-conducting carbon filler material in a standardized papermaking protocol. Instead of using bleached pulp, as was previously utilized in filled conducting papers,\textsuperscript{10,11} we use unbleached pulp of electro-technical grade (treated to remove monovalent metal ions). This is motivated by the fact that the bleaching process significantly reduces the charge density of the fiber surface,\textsuperscript{16} which might lower any dispersing ability of the cellulosic fibers.\textsuperscript{17} In addition, for several reasons, we here select nanographite (NG) flakes in aqueous dispersions stabilized by poly(acrylic acid) (PAA) instead of utilizing carbon fibers or nanotubes as a filler material. First, NG flakes, derived from exfoliated graphite, are a promising low-cost carbon material that exhibits a high conductivity.\textsuperscript{18} Second, because their overall planar shape is expected to provide improved retention,\textsuperscript{19} NG flakes should be preferable as compared with carbon nanotubes and fibers. Third, for the targeted application, it is desired to incorporate a conducting medium that provides enough active surface area for electrical charge storage.

The resulting NG paper exhibited good electrical conductivity and, at the same time, the desired mechanical properties. We explored these properties by utilizing the NG paper as the combined counter electrode, rear current collector, and substrate for an all-printed ECD.

## EXPERIMENTAL SECTION

### Sample Preparation

NG from exfoliated graphite, produced by tube-shear exfoliation in water stabilized by PAA, as described by Blomquist et al.,\textsuperscript{18} was kindly supplied by 2Dfab (Sundsvall, Sweden) with a solid content of 3.3%. Never-dried unbleached kraft pulp (UKP-E) was kindly supplied by Ahlstrom-Munksjö Billingsfors mill (Billingsfors, Sweden). The wet aqueous mix solely contained UKP-E and NG with PAA.

The never-dried UKP-E pulp was diluted to 1.5% fiber content using local tap water and stirred for 20 min before measuring 1.0 g dry weight of fibers into a beaker. Separately, the NG dispersion was stirred for 20 min before pouring an equivalent of 2.0 g dry weight of NG into a beaker. The two dispersions were put into a blender and mixed for 2 min. The UKP-E/NG ratio of 1:2 was chosen arbitrarily, although a ratio of 1:3 also was tested with no clear increase in conductivity.

The papers were made according to a standard protocol for laboratory handsheet preparation (ISO 5269-1) using a Lorentzen & Wettre F1 101 sheet former, followed by wet pressing at 400 kPa between blotters and spanned drying on a slightly convex metal surface. Using the same procedure, reference sample papers were prepared from 1.0 g of UKP-E.

The drainage resistance for the 1:2 UKP-E/NG mix as well as for pure UKP-E was assessed by the Schopper–Riegler method (ISO 5267-1).

### Material Characterization.

WAXS (wide-angle X-ray scattering) measurements were performed on an Anton Paar SAXSpoint 2.0 system equipped with a Microsource X-ray source and a Dectris 2D CMOS Eiger R 1 M detector with a 75 μm × 75 μm pixel size. All measurements were performed with a beam size of ~500 μm diameter and a pressure of about 1 to 2 mbar at a temperature of 25 °C. The evaporated NG dispersion was measured in a sealed cell with Kapton windows. The sample-to-detector distance (SDD) was 110.0 mm. Scattering data recorded on Kapton foils with the same experimental setup were used for background subtraction. The UKP-E and the NG paper were mounted on an open sample holder with SDD = 110.6 mm.

According to paper testing standards (ISO 536, ISO 187), the handsheets were conditioned at 23 °C and 50% RH for 24 h before the grammage, thickness, and mechanical properties were determined. The thickness was measured with a Lorentzen & Wettre Micrometer 251 apparatus.

Strips of NG paper and reference paper were cut and tested in a Lorentzen & Wettre tensile tester 066 to measure the tensile strength, tensile stiffness, and Young’s modulus. The tensile strength and the tensile stiffness were also indexed against the grammage.

Thermogravimetric analysis (TGA) was performed to define the mass ratio of NG and UKP-E fibers in the paper. Samples of dried NG dispersion, dried UKP-E, and NG paper were heated from 30 to 900 °C using a Mettler Toledo apparatus at a heating rate of 20 K/min in an ambient atmosphere. The revealed mass ratio of NG and UKP-E fibers was combined with the oven-dry grammage and the wet mix mass ratio to calculate the retention of the NG.

Cross-section samples of the paper were prepared using a Leica histological microtome. The cross-sections were imaged using a scanning electron microscope (SEM) (Zeiss, EvoS0 Lab6Tip) and energy-dispersive X-ray spectroscopy (EDX) (Bruker, Quantax 200 SDD 30 mm\textsuperscript{2}). On the obtained X-ray maps, oxygen was used as a marker for the UKP-E fibers, and carbon was used as a marker for the NG.

Individual fibers from an NG paper sample dispersed in distilled water were studied using a Sigma 500 Zeiss scanning electron microscope. The NG paper suspension was washed repeatedly in distilled water to remove the released NG. Individual fibers from this suspension were put onto an SEM sample holder, dried in oven for 5 min at 100 °C, and cooled to room temperature before being mounted into the microscope.

The surface roughness was assessed with surface imaging using a Sensafer (PLux neox) profilometer with 20x magnification confocal lens. Both the NG paper as well as a reference paper were studied.

The surface free energy of the paper was derived from contact-angle measurements with water and diiodomethane using a Krüss mobile surface analyzer.

### Preparation of the ECD.

The ECDs were prepared by screen-printing electrolyte ink and conducting ink. The screen with a 77 × 48 mesh size was masked with aluminum foil and distanced 10 mm from the printing substrate with rubber pads. Ink containing poly(3,4-ethylenedioxythiophene) (poly(styrenesulfonate)) (PEDOT:PSS), purchased from Heraeus Clevios (Germany), was printed onto an indium-tin-oxide (ITO)-coated polyethylene terephthalate (PET) substrate and cured in oven (110 °C, 5 min). The electrolyte ink, kindly supplied by Rise Acreo (Sweden), was printed onto the smoother side of the NG paper using a screen with a mesh size of 54 × 64. The two printed substrates were mounted with PEDOT:PSS toward electrolyte.
**Electrical Measurements.** Using a 3D four-point probe measurement technique, the in- and through-plane electrical conductivity of the paper sheet were measured. The measurements were carried out on a 30 × 30 mm piece. A set of currents was applied in each of the two different planes, and the output voltage was measured. The calculated resistance was combined with the thickness measurements to calculate the conductivity of the paper.

Because a possible application of the NG paper could be flexible electronics, the electrical response to bending or folding was investigated. Using an ohmmeter with clip probes, the electrical resistance of the paper was measured before, during, and after bending and folding.

The durability toward different pH values and solvents common in inks and coating formulations was tested. Strips of the NG paper were bent down into five separate 50 mL beakers. Each beaker was then filled with 10 mL of 0.25 M citric acid (CA), distilled water, 0.1 mM potassium hydroxide (KOHaq), ethanol, and cyclopentanone, respectively. After 10 min of immersion, the paper strips were collected and dried on a hot plate heated to 70 °C. Using an ohmmeter with pointed probes, the resistance of the paper was measured with a probe distance of 5 cm before and after the treatments with liquids.

The specific capacitance of the NG paper was measured by cyclic voltammetry, using a set of scan rates in a three-electrode setup with carbon felt as a counter electrode, silver/silver chloride (Ag/AgCl) as a reference, and 1 M aqueous sodium chloride (NaCl) as an electrolyte. A potential window of 0–600 mV versus Ag/AgCl was used to minimize the interference from unwanted electrochemical redox reactions in the electrolyte.

The display performance was measured using an Ivium potentiostat. The switch time of the display was visually assessed in both directions, and the current-voltage characteristics were graphically recorded. The stability of the display was assessed by recording the current-voltage characteristics in an open circuit after the initial reduction. The device capacitance was characterized by chronopotentiometry (charge-discharge measurements) using a constant current of 0.1 mA and driving the cell voltage to 1 V.

**RESULTS AND DISCUSSION**

**WAXS Characterization.** The measurements on the NG samples gave a distinct signal at 2θ = 26.3° (q = 18.5 nm⁻¹) (Figure S1), characteristic of the (002) plane in graphite, indicating a highly crystalline material. The WAXS data recorded on the UKP-E sample showed a similar diffractogram as previous reports on unbleached kraft pulp, with characteristic diffraction peaks of cellulose I at 2θ = 22.3° (q = 16.0 nm⁻¹) of the (200) plane and at 2θ = ~15° (q = ~11 nm⁻¹) of the (110) plane (Figure S1).

The NG paper sample displays both the (002) signal from the NG and the (200) and (110) signals from the UKP-E sample (Figure S2). Hence the paper-making process has not significantly altered the crystal structure of the starting components.

**Mechanical Properties and Retention Behavior.** The resulting NG paper had a grammage of 78.8 g/m² and a thickness of 98.5 μm. It appeared as a dark-gray paper having a metallic-shining surface appearance, which did not dust and had the typical flexibility expected from an ordinary sheet of paper (Figure 2A).

Using a paper tensile tester, the mechanical properties of the NG paper were compared with a reference paper that was prepared using the same process but without containing any NG filler. As expected, the tensile index was lower when using a filler (16.75 vs 32.40 N/m for the reference paper) and is in line with the existing theory in paper mechanics. Interestingly, we observed a sharp increase in stiffness (Young’s modulus reached 2.56 vs 1.02 GPa for the reference paper), which is surprising because stiffness otherwise typically has an inverse correlation with the content of mineral fillers.

From the cross-section elemental mapping images of the NG paper using SEM/EDX (Figure 2B,C), we found the NG flakes to appear as rather soft and flexible flaky structures that tend to bridge the cellulosic fibers. The NG flakes were clearly found to be located in between the fibers. Because the integrity in papers results from bonding between cellulosic fibers, the NG flakes should consequently considerably decrease the number of fiber–fiber bonding sites. This further makes the increase in tensile stiffness surprising, as the tensile stiffness should decrease with a lower number of fiber–fiber bonding sites.

Still, it was initially assumed that parts of the fiber surfaces could potentially expose spots free from NG flakes, which then would provide available bonding sites between the cellulosic fibers.
To investigate the presence of the NG-free fiber surface area available for direct fiber–fiber bonding, single fibers of the NG paper were imaged using SEM (Figure 2D–F). The dispersed and washed fibers from the NG paper appeared to the eye as tiny black needles. The SEM images reveal that the washed fibers are completely coated by the NG flakes, with a surface morphology totally different from that of the reference fibers (Figure S3). Because the coating of the fibers remained after the washing step, the NG flakes have a strong water-stable adhesion to the cellulosic fiber surfaces.

Several previous reports have presented stable formulations between CNFs and conducting nanocarbons; however, to our knowledge, no previous reports have described stable amalgamations between ordinary pulp fibers and carbon conductors. In the case of CNFs, several different explanations have been reported for the adhesion phenomena. One suggested mechanism is van der Waals forces operating between hydrophobic sites of the CNFs and the carbon material, whereas another suggestion is an interlocking effect caused by the induced polarization along the nanocarbons generated from the charged groups of the CNFs and their counterions. We view it as probable that the NG–fiber adhesion is of similar origins.

Regardless of what explains the NG–fiber adhesion, the extensive degree of NG coating around the cellulosic fibers shows that direct fiber–fiber bonding in the paper is at a very low level and implies that the integrity of the paper must result from mechanisms involving the NG coatings rather than direct fiber–fiber bonding. One plausible explanation could include restacking of the exfoliated graphite flakes to form strong interflake bonds, which hold the paper bulk together. This theory is supported by the considerable increase in the stiffness of the NG paper in at least two ways. First, graphite has a high inherent stiffness, which could be expressed in the paper properties. Second, given that the NG flakes form a strong adhesion to the fibers, the NG flakes could bridge the individual fibers and act as a cross-linker, indirectly increasing the fiber–fiber bonding degree. An increase in the fiber–fiber bonding degree is a common explanation for the increase in the tensile stiffness of papers when, for example, adding carboxy-methyl cellulose or a formula of cationic starch with mineral fillers.

From a retention point of view, the attraction between the fibers and the NG filler is an attractive feature that enables high loadings without retention aid. Although the white water (i.e., the papermaking filtrate) was colored black from the excess NG, the thermogravimetric characteristics of the resulting NG paper revealed a 50% mass loading of NG (Figure 3). The observed adhesion of the NG flakes to the fibers should be one explanation for such a high loading, although more factors must also be considered such as NG flake interactions and agglomeration as well as a filtration mechanism provided by the cellulosic bulk fibers during the manufacturing process. However, although the loading is impressively high, the retention of the NG filler during the fabrication is only 50%. To scale up the process, the filler recovery with white water recirculation, as done in commercial processes, should be more closely investigated to secure good production economics.

In papermaking, low drainage resistance is a key attribute to enable high production speed. The drainage resistance of the wet mix (49°SR) was higher compared to the reference pulp (19°SR), indicating that the NG flakes significantly contribute. Nonetheless, a drainage resistance of 49°SR for the NG/UKP-

![Figure 3. TGA graph for the NG paper and its components. The plateau for the NG paper starting at 500 °C corresponds to the more thermally stable NG filler.](https://dx.doi.org/10.1021/acsami.6b13086)

E wet mix is still viewed as moderate (100°SR is equivalent to no drainage at all) and is not uncommon in papermaking.

Using an optical profilometer, the surface characteristics of the NG paper were compared with those of the reference paper. As expected, the NG flakes contribute to a smoother paper surface (Table S1). For the NG paper, the magnitude in roughness reduction depended on which side of the paper was measured, a difference not seen for the reference paper. The observed difference in the roughness of the NG paper should not be explained by the manufacturing procedure as such. Instead, these observations probably result from a nonuniform distribution of the NG filler in the vertical direction of the paper. In fact, this is a normal characteristic of filled papers, which is related to the unilateral dewatering direction in the drainage, rendering the filler material more concentrated toward one side of the paper. This indicates that fiber infiltration was a contributing mechanism to the NG flake retention, amid the good adhesion of the NG flakes to the UKP-E fiber surfaces.

**Electrical Properties.** Because graphite flakes are inherent 2D electronic systems, macroscopic conductors based on such conducting fillers could potentially exhibit anisotropic conductivity, although previous works on pulp/graphite composites have not encompassed this aspect. When measuring the electrical conductivity of the plain NG paper using a 3D four-point probe measurement setup, the out-of-plane conductivity is 12 S/cm, which is similar to values in previous reports describing pulp/graphite composites. On the contrary, the measured in-plane conductivity reaches a value of 107 S/cm, thus showing that a clear anisotropic conductivity is obtained. From the SEM/EDX images of the NG paper cross-section, we find a preferential orientation of the NG flakes along the in-plane direction (Figure 2C). Apparently, this in-plane orientation of the NG flakes has a crucial impact on the conductivity anisotropy in the resulting NG paper.

A conductive paper should be interesting for printed electronics. However, this depends on whether or not the paper can maintain its good conducting properties after being exposed to the pH and solvent conditions common in inks and coating formulations. For example, printed electrolytes could
have a low pH, coatings could be alkaline, and solvents such as plain water, alcohols like ethanol, or nonpolar solvents like cyclopentanone are common. Therefore, the electrical resistivity in strips of the NG paper was measured before and after being subjected to each of these conditions. Whereas no NG leaked into the solvents (Figure S4), the results show an increase in NG paper resistance for the aqueous solutions, with indications of an increased sensitivity toward a higher pH (Figure S5). This could be attributed to the swelling and shrinking of the pulp fibers upon wetting and drying, resulting in a rearrangement of the fibers. This could possibly also reorient and decouple the NG flakes, leading to the increased resistance. However, ethanol and cyclopentanone did not affect the electrical resistance of the paper. These solvents do not swell the fibers, so the paper integrity should be stable, which is manifested in the unchanged resistance of the NG paper.

Flexible electronics should also maintain their properties upon bending or even folding. The electrical resistance in a NG paper strip was therefore measured before and after folding it with an estimated bending radius of 1 mm (Figure S6). Interestingly, the resistance of the paper remained unchanged, demonstrating the suitability of this material for flexible electronics.

The specific double-layer capacitance of the NG paper, calculated from the responses in cyclic voltammetry, gave a resulting unit area capacitance of 9.20 mF/cm² (Figure 4A). In relation to the grammage of the paper, this corresponds to a gravimetric capacitance of 1.17 F/g. For energy-storage applications, this is low compared with other carbon-based electrodes, whereas the electrical conductivity is unusually high. Applications for the NG paper should therefore be sought where this combination of properties is useful and, in particular, where mechanical stability and up-scalable production are of interest.

**Printed Electronics Application.** Printed ECDs are devices that could be considered as a good example fit to the properties of this paper. High conductivity is needed for a fast switch time, a reasonable capacitance is desired for display bistability, and a smooth surface is required for a fair printing performance. To explore the paper as a functionalized substrate according to the scheme in Figure 1B, the ECDs were prepared following a screen-printing manufacturing protocol. The aqueous polyelectrolyte ink wetted the paper surface well, indicating a hydrophilic surface. This was supported by surface energy measurement results from a mobile surface analyzer/goniometer, which revealed the NG paper to have a 76.8° static contact angle to water and a surface free energy of 47.3 mN/m (polar component 3.79 mN/m, dispersive component 43.55 mN/m). The PEDOT-based electrochromic ink was printed onto a transparent ITO-coated PET foil, which then was manually laminated toward electrolyte-coated NG paper, with the electrochromic layer facing the electrolyte.

The electrochromic switching performance of these ECDs were evaluated using a potentiostat setup, operated in a constant voltage mode. The top PEDOT-based electrochromic electrode was reduced by applying a potential of −2 V, with respect to the NG paper counter electrode, for 10 s. Following this, the PEDOT was then oxidized by applying 1 V for 10 s (Figure 4B). The time it took to switch from semitransparent (oxidized state) to dark blue (neutral state) was ∼1 s, which corresponds to a drop in the current of ~80%. This is in good agreement with the current switching behavior of archetypical organic-based ECD devices.
Using charge–discharge measurements with a constant current of 0.1 mA, recorded from the square-shaped ECD, the net unit area capacitance of the ECD device was found to be 1.04 mF/cm² (Figure 4C). The shape is not exactly triangular due to the iR drop, which is caused by the internal resistance of the device. Considering the NG paper unit area capacitance of 9.20 mF/cm², the capacitance of the PEDOT-based top electrode can then be calculated to 1.17 mF/cm². Thus the NG paper has a relatively much higher capacitance than the PEDOT-based electrode, meaning that the NG paper electrode does not capacitively limit the switch contrast of the PEDOT phase of the manufactured ECD.

Using the same equipment, the color and charge bistability of the ECD were evaluated. When the circuit was left open, the voltage instantly dropped to about −1.5 V due to the internal resistance of the device, followed by a relatively much slower voltage loss (Figure 4D). According to the eye, the coloration of the displays seemed stable without any major fading in coloration and with no crosstalk between neighboring ECDs (Figure 5). We conclude that the capacitance of the NG paper is large enough to provide an ECD with good switching properties.

**CONCLUSIONS AND OUTLOOK**

Highly conducting papers can be easily prepared by using a standardized papermaking protocol with an acceptable drainage rate using electrotechnical unbleached pulp and an aqueous dispersion of NG flakes. The resulting paper also exhibits a reasonable specific capacitance, making it suitable as the backplane electronic paper for printed and flexible electronics, here demonstrated to perform well as the combined counter electrode, conductor, and substrate in a printed ECD. Owing to the excellent electrical and printability characteristics of the paper, the total number of layers to produce the resulting functional display component was reduced from seven to five.

The NG filler provides a reduction in the surface roughness and an increase in Young’s modulus. The good retention of the NG filler is explained with infiltration by the fibers, but SEM images also reveal a water-stable adhesion of NG to cellulosic fibers. This coating of the fibers with NG challenges the established paper physics, as the paper integrity cannot be explained by ordinary fiber–fiber bonding. Although the interactions need to be better understood and optimized, our findings demonstrate a successful pathway to realize biobased electronic materials using standard manufacturing protocols.

We believe that NG paper will find its way into numerous large-volume applications in flexible and printed electronics due to its up-scalability, favorable mechanical properties, and stability and the combination of high conductivity along with charge-storage ability. For instance, it can potentially be used as a large-area and porous electrode in various electrocatalytic and electrochemical setups targeting the production of fuels, and in fuel cells, it can act as the dually conducting and capacitive electrode in transistors, and it can also serve as the electrodes in batteries and supercapacitors, especially because it maintains a high conductivity at different potentials.

**ASSOCIATED CONTENT**

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsami.0c13086.

- WAXS results, SEM images of reference and NG paper pulp fibers, solution resistance results, folding test, topography imaging, and surface roughness (PDF)
- Switching of the printed ECD (MP4)

**AUTHOR INFORMATION**

Corresponding Authors

Isak Engquist — Laboratory of Organic Electronics, Department of Science and Technology, Linköping University, 601 74 Norrköping, Sweden; orcid.org/0000-0001-5365-6140; Email: isak.engquist@liu.se

Magnus Berggren — Laboratory of Organic Electronics, Department of Science and Technology, Linköping University, 601 74 Norrköping, Sweden; Email: magnus.berggren@liu.se

Authors

Patrik Issacsson — Laboratory of Organic Electronics, Department of Science and Technology, Linköping University, 601 74 Norrköping, Sweden; orcid.org/0000-0002-7488-3788

Xin Wang — RISE Digital Systems, Department of Smart Hardware, 601 74 Norrköping, Sweden
Andreas Fall — RISE Bioeconomy and Health, Department of Pulp, Paper and Packaging, 114 86 Stockholm, Sweden
Desalegn Mengistie — Laboratory of Organic Electronics, Department of Science and Technology, Linköping University, 601 74 Norrköping, Sweden
Emilie Calvie — Ahlstrom-Munksjö Research Center, 38140 Apprieu, France
Hjalmar Granberg — RISE Bioeconomy and Health, Department of Pulp, Paper and Packaging, 114 86 Stockholm, Sweden
Göran Gustafsson — RISE Digital Systems, Department of Smart Hardware, 601 74 Norrköping, Sweden

Complete contact information is available at: https://pubs.acs.org/10.1021/acsami.0c13086

Author Contributions
The manuscript was written through contributions of all authors.

Funding
This work was funded by the Digital Cellulose Centre, a competence center set up by the Swedish Innovation Agency VINNOVA and a consortium of Swedish forest industries. Additional funding has been provided by the Wallenberg Wood Science Center (Knut and Alice Wallenberg Foundation), the VINNOVA “EPIC” project (2017-05413 Electro- och fotokatalys inducerat i papper), and the Karl-Erik Önnesjö Foundation.

Notes
The authors declare no competing financial interest.

ACKNOWLEDGMENTS
The pulp was kindly supplied by Ahlstrom-Munksjö Billingsfors mill, Sweden, which also let us use their papermaking equipment and provided the measurement of the drainage resistance. SEM/EDX analysis was done by the Ahlstrom-Munksjö analysis team in Apprieu, France. The NG used was kindly supplied by 2D fab in Sundsvall, Sweden. The WAXS characterizations were carried out at RISE Bioeconomy by Anita Teleman. We also acknowledge the support from Treesearch, a collaboration platform for Swedish forest industrial research.

REFERENCES


