

Next Generation Antennas Based on Screen-Printed and Transparent Silver Nanowire Films

Yash Goliya, Almudena Rivadeneyra, José F. Salmeron, Andreas Albrecht, Josef Mock, Michael Haider, Johannes Russer, Bruna Cruz, Philipp Eschlwech, Erwin Biebl, Markus Becherer, and Marco R. Bobinger*

The advent of mobile communication has made antennas omnipresent. Conventional methods of antenna manufacturing cannot address the growing demands for novel applications requiring transparent and flexible antennas. In this paper, transparent silver nanowire films are studied with respect to their high-frequency properties. Transparent silver nanowire (AgNW)-based antennas that are screen printed onto flexible polyethylene terephthalate (PET) substrate are reported. Transparent films with a low sheet resistance of $8.5 \Omega \text{ sq}^{-1}$ and a high transmittance of 85%, at a wavelength of 550 nm, are characterized as bowtie antennas with a radiation efficiency of 52%. This combination of efficiency and transmittance rivals the ones that are commonly reported for conductive-oxide based transparent antennas and paves their use for any automobile window, liquid crystal display, or organic-light-emitting-diode display.

techniques that require wet etching or lithography steps for the structuring, and often also vacuum systems for the metalization via sputtering or evaporation. These fabrication methods bear some severe disadvantages that require their replacement by novel materials and alternative deposition techniques. The decisive drawbacks are (i) only a low to moderate level of scalability, (ii) restrictions for the size as well as the material of the substrate due to high-vacuum processes at elevated temperatures, (iii) a lack of mechanical flexibility and (iv) optical transparency.

A few of these obstacles have been overcome with the emergence of novel materials such as carbon nanotubes (CNTs),

graphene,^[2] graphene oxide,^[3] poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS),^[4] metal nanomeshes,^[5] silver-coated polyester films (AgHT),^[6] silver flakes,^[7] silver nanoparticles,^[8] copper oxide nanoparticles^[9] as well as metal nanowires.^[10,11] For the majority of these materials, scalable and high-yield synthesis protocols or fabrication techniques exist and these materials can potentially be deposited at almost arbitrary scale and under ambient conditions. Due to the cost-effectiveness, the ease-of-processing and the scalability, deposition methods such as inkjet printing,^[12] direct laser writing,^[13] spray coating^[14] or screen printing^[15] have become increasingly popular over the last years and raised academic and industrial interest.

A high optical transparency of the deposited films is already a requirement for numerous antenna applications including solar cells,^[16] sun shields on satellites,^[17] radio-identification tags (RFIDs),^[18–21] smart glasses,^[22] bandstop filters to reduce the interference from wireless local area networks (WLANs)^[23] as well as for energy harvesting.^[24,25] Due to this broad application spectrum and the commercialization potential, notable technology companies including the so-called Big Techs, have recently filed several patents related to transparent conductive films and their use for antennas.^[26–28]

The conducting and transparent films presented in this work were made of a commercially available silver nanowire (AgNW)-based screen print paste. The use of screen printed AgNWs for antennas has already been reported in 2014 by Song et al.^[29] However, in that work, the antenna films were fully opaque, which is a criterion for exclusion in many applications. In this work, as transparent electrode (TE) material, AgNWs were selected since this material is currently considered as the most

1. Introduction

Since the digitalization of the world is progressing rapidly and is accompanied by a vast amount of generated data,^[1] the demand for novel and innovative transmission systems including wireless solutions is increasing alongside this trend. Conventional antennas are commonly fabricated by subtractive

Y. Goliya, Dr. A. Albrecht, J. Mock, M. Haider, Dr. J. Russer,
Prof. M. Becherer, Dr. M. R. Bobinger

Chair of Nanoelectronics
Technical University of Munich
80333 Munich, Germany
E-mail: marco.bobinger@tum.de

Dr. A. Rivadeneyra, Dr. J. F. Salmeron
Pervasive Electronics Advanced Research Laboratory (PEARL)
Department of Electronics and Computer Technology
University of Granada
18071 Granada, Spain

B. Cruz, P. Eschlwech, Prof. E. Biebl
Associate Professorship for Very High-Frequency Technology
Technical University of Munich
80333 Munich, Germany

 The ORCID identification number(s) for the author(s) of this article can be found under <https://doi.org/10.1002/adom.201900995>.

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DOI: 10.1002/adom.201900995

promising alternative to the prevailing TE material, i.e., indium tin oxide (ITO),^[30] with regard to the electro-optical performance as well as the chemical and the mechanical stability.^[31] The antennas presented in this work show a high optical transmittance of 85% at a wavelength of 550 nm and a low sheet resistance of $8.5 \Omega \text{ sq}^{-1}$. As an advancement to the previous antenna related publications on ITO-free material systems, the antennas exhibit a high radiation efficiency above 50%, which promotes the AgNW-based transparent antennas to a serious competitor to the current opaque antennas. Besides the efficiency, the antennas are also robust to mechanical bending and prolonged exposure to the ambient air or harsh moisture levels.

This contribution is organized as follows. In the Experimental Section, the screen printing of the transparent films and their characterization as electrodes and antennas are described. In Section 2, the fundamental properties of the films such as sheet resistance, optical transmittance, and roughness are analyzed. Using this knowledge, transparent antennas are then designed, simulated, fabricated, and characterized. In the end, we benchmark our results with a comprehensive summary on transparent antenna publications.

2. Results

2.1. Transparent Film Characterization

In this section, key properties of the screen-printed films such as the sheet resistance, thickness, roughness, conductivity, and transmittance values are presented. The figure of merit (FoM) of the films, i.e., the combination of sheet resistance and optical transmittance at a wavelength of 550 nm, is compared with the literature for transparent electrodes. As described in the Experimental Section, the films were deposited using different meshes that are illustrated in the microscope recordings depicted in **Figure 1** for a thread count of (a) 120T (T = threads per cm), (b) 90T, and (c) 32T.

A mesh with a lower thread count allows for selecting a thread with a larger diameter that in turn leads to thicker films. The SEM images for an increasing number of screen-printed layers using the 120T mesh are illustrated in **Figure 1** for (d) 1 layer, (e) 2 layers, and (f) 4 layers. No increase in wire density that should scale linearly with the number of layers can be seen from these SEM images since the wires are buried within the up to 500 nm (4 layers, 120T mesh) thick films. For the highest number of deposited layers, i.e., for 4 layers, charging can be observed in the SEM-images, which is attributed to the non-conductive polymers in the screen print paste. After evaluating the SEM recordings with the free image-processing software Gwyddion, a mean diameter and a mean length of $33 \pm 4 \text{ nm}$ and $16 \pm 4 \mu\text{m}$, respectively, were extracted for the wires. For this estimate, a total of 150 wires have been considered. As shown in **Figure 2**, the screen printed films were characterized comprehensively for an increasing number of layers with regard to their (a) sheet resistance R_s , (b) transmittance T evaluated at a wavelength of 550 nm, (c) thickness as well as (d) their electro-optical FoM. The FoM is defined as $\text{FoM} = T^{10}/R_s$, in accordance with the widely used and accepted Haacke's definition^[32] from 1976.

From these plots, it can be seen that R_s decreases gradually to a minimum value of $1.40 \pm 0.05 \Omega \text{ sq}^{-1}$ (4 layers, 32T mesh), for an increasing number of layers and a decreasing mesh count. The resistivity of the films lies in a range of $(3\text{--}4) \times 10^{-6} \Omega \text{ m}$, as depicted in **Figure S1** of the Supporting Information, and exhibits no dependency on thickness or the utilized mesh count. Compared with the resistivity that is commonly reported for bulk silver, i.e., $1.59 \times 10^{-8} \Omega \text{ m}$, the values presented in this work are increased by a factor of around 180–250, which can mostly be ascribed to the use of nonconducting components in the screen print paste and wire-to-wire resistances in the random network.^[33] The transmittance evaluated at a wavelength of 550 nm shows a linear decrease for an increasing number of layers, which is accompanied by a linear increase in

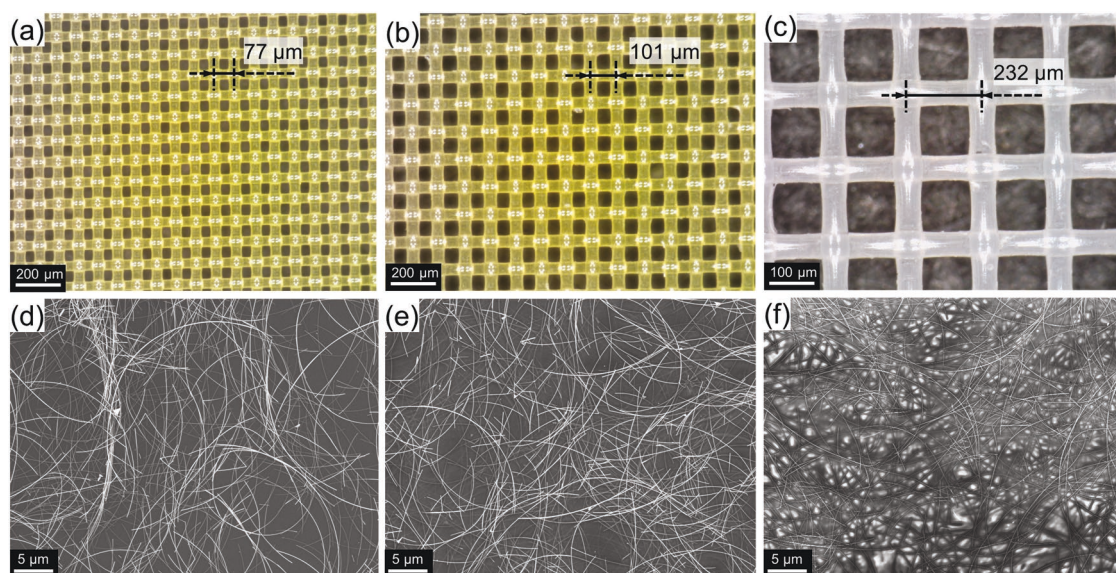


Figure 1. Optical microscope images of polyester-based screen print meshes with a decreasing mesh count of a) 120T, b) 90T, and c) 32T. The thread-to-thread distances for each mesh are indicated in the recordings. SEM-images for an increasing number of d) 1, e) 2, and f) 4 screen printed AgNW layers on a silicon substrate.

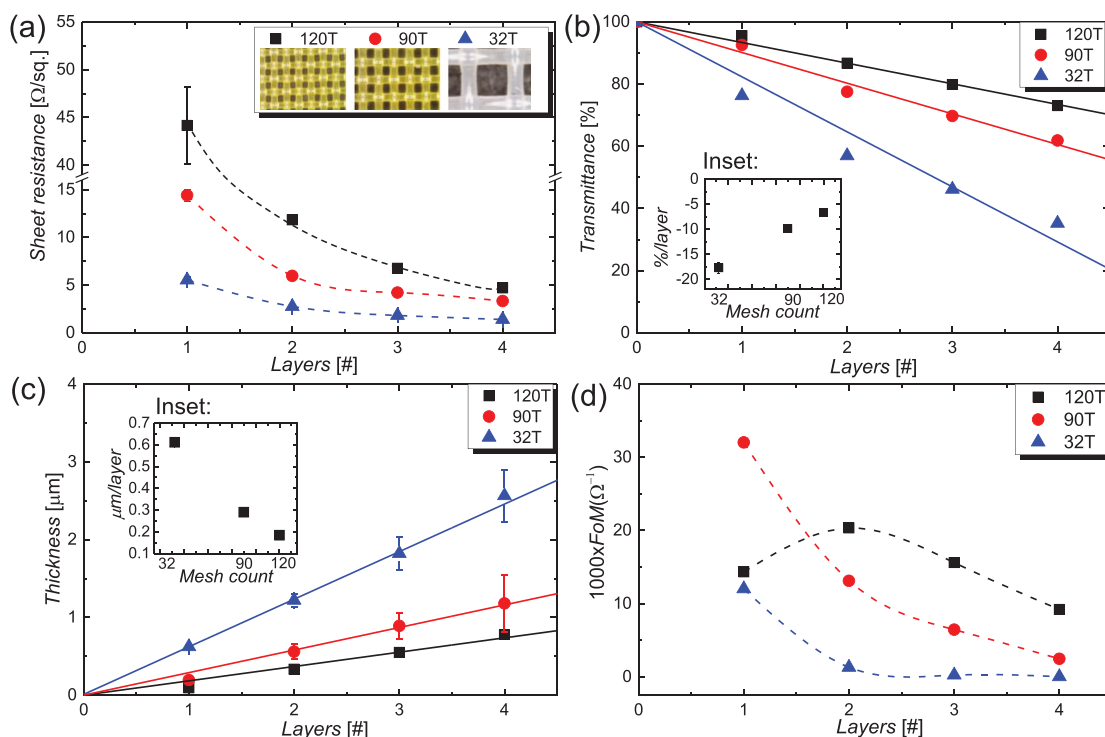


Figure 2. a) Sheet resistance and b) optical transmittance at a wavelength of 550 nm. c) Thickness and d) figure of merit for an increasing number of layers as well as three different meshes with a thread count of 120T, 90T, and 32T, respectively. The insets in (b) and (c) show the decrease in transmittance and increase in thickness per screen printed layer as a function of the different mesh counts. The solid lines represent linear fits to the experimental data, whereas the dashed lines serve as a guide to the eye. Error bars are included for each data point and often smaller in size than the symbol. The bars represent a mean value averaged over five samples from different batches.

the film thickness. The transmittance spectra for the films that show the AgNW typical plasmon-induced dips are illustrated in Figure S2 (Supporting Information) over a wavelength region of 350 to 800 nm. Utilizing the mesh with the lowest thread count, the highest film thickness of $2.5 \pm 0.3 \mu\text{m}$ at a transmittance of 35% could be achieved. With respect to the TE performance, the highest FoMs in the range of $1000 \times \text{FoM} = 14\text{--}32$ were achieved using a 120T or a 90T mesh with 2 deposited layers. These values compare well to the best FoMs for AgNW-based TEs that have been reported in the literature in a range of 30–34^[34–36] and also approach the performance of ITO with highest FoMs of around 50.^[37]

2.2. Antenna Design

Dipole and bowtie type configurations were selected for the fabrication of the antennas due to their simple RF model. Further, the RF performance of these antennas depends largely only on their length and the conductivity of the material.^[38] The antennas were designed to resonate at a frequency of 2.45 GHz using well-studied equations for the center-fed half-wavelength dipole antennas and bowtie antennas, as described by Stutzman and Thiele^[39] and Balanis.^[38] These designs are simulated and optimized in CST Microwave Studio. All antennas were designed based on the material properties of our previous work for solution-based AgNP antennas, i.e., for

a conductivity of 9.4 MS m^{-1} and a thickness of 237 nm .^[40] Polyethylene terephthalate (PET) was selected as a flexible and transparent substrate with great popularity in the industry that offers versatile use. The dielectric constant of PET is set as 3 and the loss tangent as 0.002, in agreement with the literature.^[41] Using profilometry, the thickness of the PET was found to be $114 \mu\text{m}$. The antennas are fed with a 1.13 mm U.FL cable of 50Ω impedance and simulations take this connector into account.

2.3. Transmission Line Characterization

The frequency-dependent behavior of AgNWs is studied by constructing microstrip transmission lines exhibiting a characteristic impedance of 50Ω . Ideally, a perfect conducting line made on lossless dielectric substrate would transfer 100% of the incident power, i.e., no power would be lost if a microstrip line would be inserted into a system. For this work, Rogers RO3003 was selected as it offers superior dielectric performance, which ensures that the transmission line losses depend on the conducting material and not the substrate itself. Besides this advantage, it provides a stable support for the connection of subminiature version A (SMA) connectors. Since AgNWs have limited conductivity, we expect AgNW lines to have an “insertion loss,” dependent on the signal frequency. Using standard equations^[42] and considering the properties of

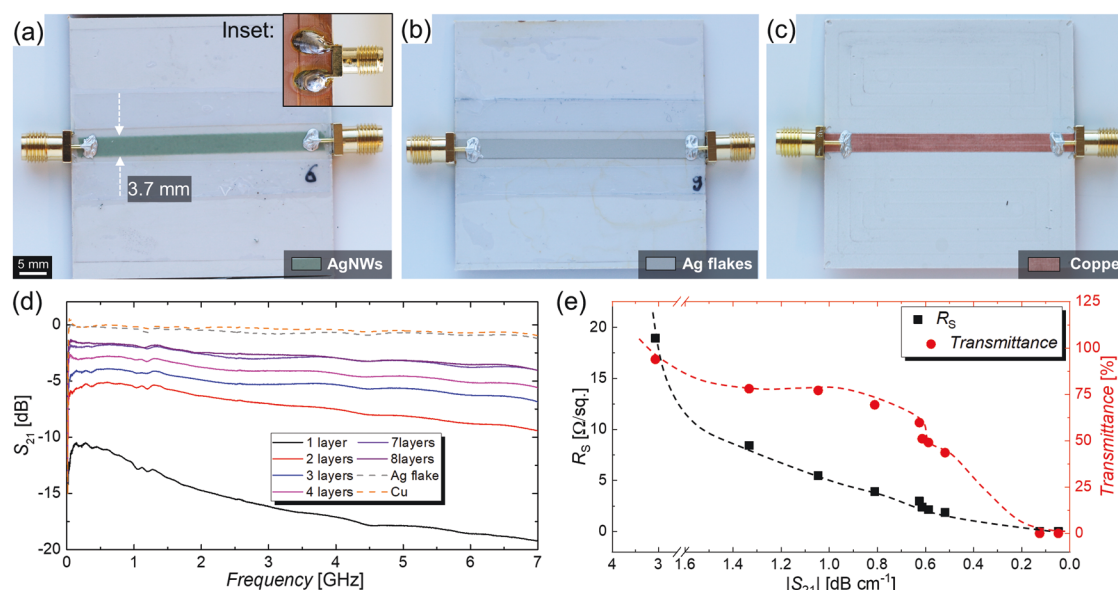


Figure 3. Photos for the three types of transmission lines on 1.52 mm thick Rogers RO3003 substrate ($5.0 \times 5.0 \text{ cm}^2$) that were fabricated for the insertion loss measurements. a) AgNW film with 6 screen-printed layers, b) opaque screen printed silver flakes film, and c) a copper line. The width of all conductive lines was 3.74 mm, as indicated in (a). d) Insertion loss spectra of the transparent AgNW-based transmission lines for an increasing number of layers. The insertion loss spectra for the opaque Ag flake line and the copper stripe, respectively, are plotted as dashed lines. e) Sheet resistance and transmittance of the films evaluated at a wavelength of 550 nm for the achieved insertion loss per cm at a frequency of 2.45 GHz.

RO3003 substrate, the dimensions of the 50Ω microstrip line are fixed to width $\times$ length = 3.74 mm $\times$ 50 mm.

The photos of the fabricated transmission lines are shown in **Figure 3** for the three utilized materials: (a) screen printed silver nanowires (6 layers, 90T mesh), (b) screen printed silver flakes (1 layer, 90T mesh), and (c) copper on RO3003 PCB substrate. The transmission lines on the PCB substrate were attached to standard SMA connectors, as shown in the inset in **Figure 3a**, using silver conductive paint. The copper-based ground plane on the backside of the PCBs was contacted by soldering, as shown in the inset of **Figure 3b**. The measured insertion losses in dB per length of the transmission line in cm over frequency are depicted in **Figure 3d** for an increasing number of screen printed AgNW layers. To allow for a comparison, the data for the opaque silver flake and copper lines was also included. It can be seen that the insertion loss ($|S_{21}|$) per cm (dB cm^{-1}) at 2.45 GHz is decreasing in a range from 3 to 0.5 dB cm^{-1} , for an increasing number of layers from 1 to 8, respectively. These results are in accordance with the expectation that low-resistance lines offer lower attenuation than high-resistance lines. The lowest transmission line losses with 0.13 and 0.05 dB cm^{-1} are achieved for the silver flake and the copper line, respectively. The insertion loss curves decrease slightly at higher frequencies, which is typical for a transmission line. However, the steep decrease at higher frequencies for a single-layered AgNW microstrip line were previously ascribed to surface roughness and the microstructure of the films.^[43,44] Since the mean surface roughness extracted from atomic force microscopy (AFM) images lies in the region of 7.1 nm and is much lower than the skin depth for all frequencies it can be concluded that the frequency behavior stems either from the mesh-like structure of AgNW films or from polymers that were added to the screen print paste from the manufacturer to stabilize and tailor the viscosity of the paste.

Since transparency is a crucial film property for this work, the transmittances of the films at a wavelength of 550 nm along with their associated sheet resistances are plotted over the insertion loss at a frequency of 2.45 GHz in **Figure 3e**. A clear trade-off between a low (absolute values) transmission loss and a high transmittance becomes visible.

2.4. Antenna Characterization

After characterizing the films as transmission lines, which has provided an insight into the loss values as well as the behavior for an increasing number of layers, the transparent films will be tested as antennas. The transparent antennas are characterized with regard to their S-parameters as well as efficiencies and compared with opaque antennas that are either made of screen-printed silver flakes or standard PCB-based milled copper antennas.

As outlined in Section 2.2, three types of antennas that are depicted in **Figure 4** were fabricated, namely (a) Type A: thin dipole antenna, (b) Type B: thick dipole antenna, and (c) Type C: a bow-tie antenna. These antennas were simulated and designed to work at a resonance frequency of 2.45 GHz. The $|S_{11}|$ return loss parameters for all antennas including the opaque silver flake and copper-based ones are illustrated in **Figure 4d–f**. With an increasing number of layers, the $|S_{11}|$ value decreases, which is associated with a reduction in sheet resistance. The lower film resistance improves the matching of the antenna to the 50Ω impedance of the vector network analyzer (VNA) port, which in turn reduces the reflection losses and leads to a decrease in $|S_{11}|$. It should be noted that the antenna design plays a role for the S_{11} parameter. As the antenna area increases from Type A to Type B and Type C, the DC loss resistance

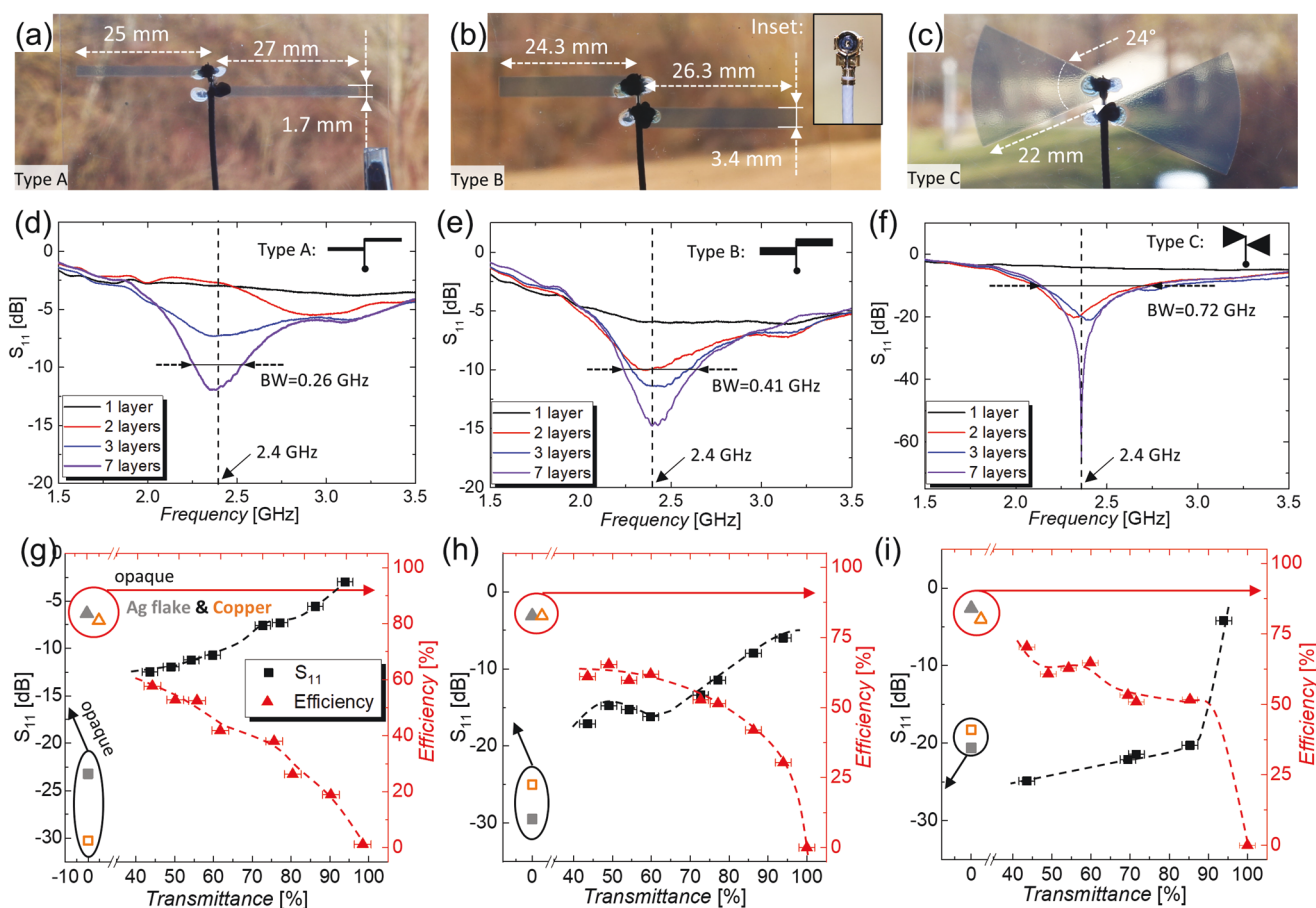


Figure 4. Photos for the three utilized types of antennas: dipole antenna with a) small width of 1.7 mm (Type A) and b) a large width of 3.4 mm (Type B) and c) bow tie antenna (Type C). The dimensions are indicated in the images. Return loss parameters S_{11} for the three types of antennas: d) Type A, e) Type B, and f) Type C. The bandwidths that are defined as the widths at a return loss of -10 dB are indicated in the graphs. g–i) The measured S_{11} parameters along with the measured efficiencies for the three types of antennas. The hollow and filled symbols indicate the values for the opaque antennas based on Ag flakes and copper stripes. The legend in (g) also applies to (h) and (i). The dashed lines serve as a guide to the eye.

decreases, which leads to an improved 50Ω matching, in agreement with the work of Sidén et al.^[45] and Nikitin et al.^[46]

The efficiency of the antennas alongside with their S_{11} parameters over the transmittances is illustrated in Figure 4g–i for all types of antennas including the silver flake and copper reference antennas. As described in the Experimental Section, the Wheeler Cap method was used to measure the efficiencies. From the graphs, it can be seen that a lower transmittance and thus a lower sheet resistance results in a higher efficiency, which is in accordance with other works.^[45,47–49] The $|S_{11}|$ values, as well as the efficiencies, improve from Type A to Type B and Type C attributed to the increase in area, which leads to a lower DC resistance and a better 50Ω matching. For the bow-tie type antenna, an efficiency of 52% is achieved for a transparency of 85%. The efficiency achieved for the transparent antennas compares well to the ones measured for silver flake and copper-based antennas with an efficiency of 81% and 79%, respectively.

The best optical performing AgNW antennas of design A achieved a radiation efficiency of 41.86% with $R_s = 2.98 \Omega \text{ sq}^{-1}$ and $T = 59.82\%$, whereas Ag flake and copper antennas exhibited radiation efficiencies of 80.76% and 77.9%,

respectively. Type B AgNW antennas performed better with an efficiency of 51.39% with $R_s = 5.53 \Omega \text{ sq}^{-1}$ and $T = 77.15\%$, while Ag flake and copper antennas exhibited radiation efficiencies of 80.18% and 82.06%, respectively. Type C AgNW antennas performed the best with an efficiency of 51.7% with $R_s = 8.45 \Omega \text{ sq}^{-1}$ and $T = 85.29\%$, while Ag flake and copper antennas exhibited radiation efficiencies of 80.8% and 79%, respectively.

Since the presented antennas can be deposited at large-scale, the stability of the films that is later discussed is high and the costs of AgNW-based pastes are dropping due to their ongoing commercialization, this work represents a promising alternative to replace conventional antennas, with the additional feature of transparency.

2.5. Film and Antenna Robustness

This section briefly addresses the degradation of the AgNW films for a prolonged exposure to the ambient air as well as the robustness of the antennas in a bent state. AgNWs are well-known for their chemical stability in air, at room

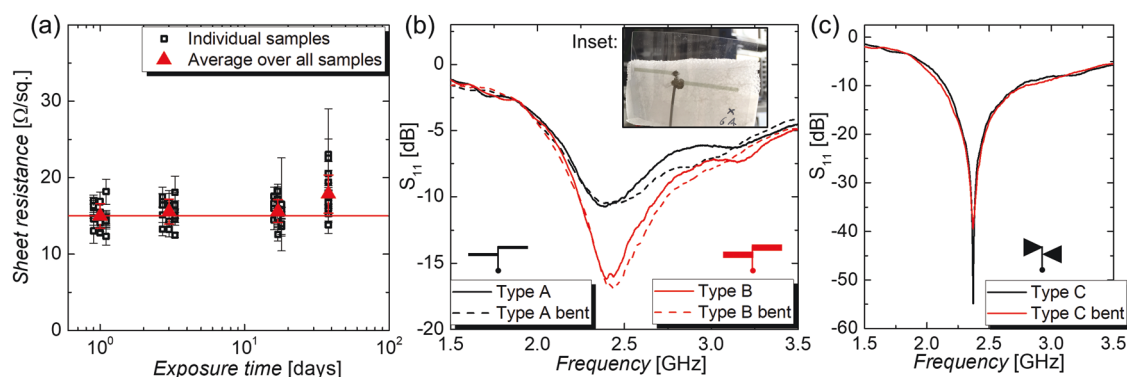


Figure 5. a) Sheet resistances of screen printed AgNW films (1 layer, 90T mesh, 15 samples in total) as a function of the exposure time to the ambient air. The red triangles represent the mean values averaged over all sample. Return loss parameter S_{11} as a function of the frequency for AgNW-based antennas (5 layers, 90T mesh) for b) the Type A and the Type B design as well as c) Type C. The inset in (b) shows an AgNW antenna with Type A geometry that is bent to a radius of 4.4 cm using a cylindrical foam.

temperature.^[11] However, under high electrical DC current densities, electromigration and sulfurization of silver to silver sulphide nanoparticles have been identified as the two main degradation mechanism.^[50,51] For a selection of antenna applications including wireless sensor nodes the current densities are too low to play a role for the degradation of the films. To provide an example, the power consumption of a smartphone antenna that establishes a Wi-Fi access point is around 100 mW (20 dBm). Considering the antenna with the lowest area, i.e., Type A, this power corresponds to a power density of 1.1 kW m⁻² and depending on the resistance of the film to a current density in the region of 65–90 mA cm⁻². This current density lies well below the values that were reported to lead to a non-negligible degradation of the films.^[50]

In this study, the transparent AgNW films were tested for their stability when exposed to the ambient air for a duration of 40 days, as shown in **Figure 5a** that depicts the averaged sheet resistance for each as well as for all samples as a function of the exposure time. It can be seen that the increase in resistance with respect to the value for the as-deposited films lies below 13% even for the film with the highest initial resistance and lowest network density that, in accordance with the literature, is more prone to degradation.^[50]

The flexibility of the antennas was tested with regard to their S_{11} performance when bent to a radius of 4.4 cm that is applicable, for, e.g., wearable electronics. As shown in the inset in **Figure 5b**, the antenna was bent circularly using a foam. The foam structure has a relative dielectric constant close to 1.0 and therefore does not alter the behavior of the antenna. The return loss parameters of the antennas are shown in **Figure 5b** for the two types of dipole antennas, i.e., Type A and Type B, respectively, as well as in **Figure 5c** for the bowtie antenna. The antenna performance of the dipole antennas at the resonance frequency is almost unaffected by the bending. This reduction in return loss is due to an interference of the connector with the altered antenna geometry that leads to an impedance mismatch and thus an increased reflection of the input signal. However, all return loss parameters are still well below a value of -10 dB, which means that less than 10% of the input signal is reflected.^[40] It should be

mentioned that, for a comprehensive stress test, the AgNW antenna characteristics have to be tested for repeated bending cycles. These tests have already been performed in previous studies, where the stretchability for antenna operation^[52] and the bendability with a radius of 2 mm up to 10 000 cycles for touch panels^[53] were shown.

2.6. Antenna Literature Review

As outlined in Section 1, numerous TE materials have been explored and some were also tested for their use as transparent antennas. Most of the literature related to transparent antennas that are flexible and fabricated under the ambient air and thus not made of metal oxides such as ITO employ silver-coated polyester films (AgHT) as the TE material.^[6,23,24,54–60] Besides for AgHT, there are a number of publications on transparent antennas using materials such as metal-doped oxides,^[17–19,61–68] thin silver and gold films,^[69] multilayer systems composed of metal oxide/metal/metal oxide stacks,^[70,71] metal meshes,^[72–74] and organic conductors including PEDOT:PSS^[21] and graphene.^[75] In this section, the performances of the presented screen printed antennas are benchmarked with regard to their efficiency and transmittance to the aforementioned materials. The efficiency of transparent antennas that was presented in previous publications for different materials such as AgHT,^[6,76,77] ITO,^[77,78] IGZO/Ag/IGZO^[79] (IGZO = indium gallium zinc oxide) multilayer systems, metal meshes^[77] and AgNWs^[80] is shown in **Figure 6** over the transmittances of the films at a wavelength of 550 nm. The plot also includes the values achieved in this work for all types of antennas, i.e., Type A, B, and C. From this summarizing plot it can be seen that the screen printed AgNW films with antenna design B and C outperform most of the other materials except the metal oxide-based films. Better performing ITO^[78] and AgHT^[6] antennas have gold nanolayer deposition and high conductivity layer deposition, respectively. In particular, for higher transmittances above a value of 80% that are acceptable for RFID, window or touch panel applications, our antennas still exhibit a remarkably high efficiency of around 50%.

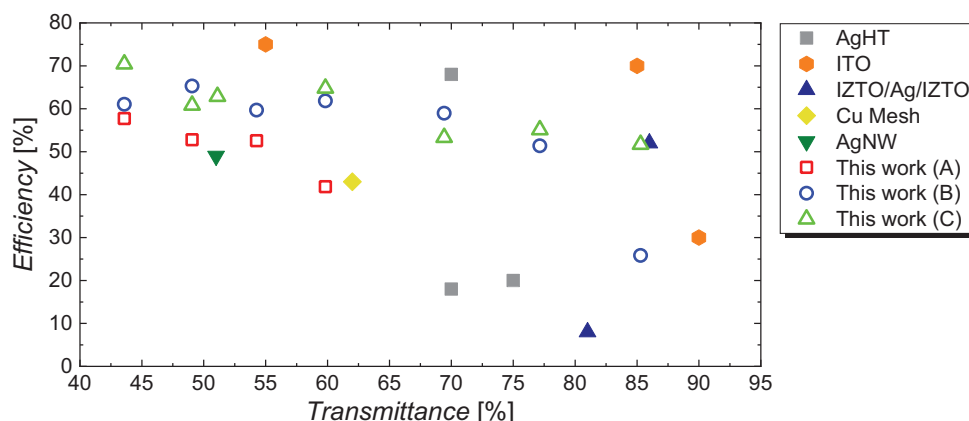


Figure 6. Efficiency of transparent antennas based on different materials (see legend) over the transmission of the films at a wavelength of 550 nm. The references are provided and discussed in the text.

3. Conclusion

For the first time, in this contribution, screen printed and optically transparent AgNW-based antennas have been presented. The antennas exhibit a remarkably high radiation efficiency of around 50% with transparencies over 85%. The high efficiency combined with an acceptable transmittance can enable the use of the antennas for commercial purposes such as transparent RFID tags or transparent antennas on windows including car, aircraft, and other types of windows as well as for touch panels. Since the antennas can be deposited by a facile and scalable process, they could in principle replace all types of conventional flat antennas such as on PCBs, with the additional features of low thickness, flexibility, and the transparency.

4. Experimental Section

Film Fabrication and Post Treatments: The utilized screen print paste is commercially available and was provided by Loctite (Hartford, Connecticut, USA) (product name: LOCTITE ECI 5005 E&C). Multiple as well as stacked layers of the paste were printed using a high precision screen printer (model: Nino) from Coruna Printed Electronics (Bettwil, Switzerland). In accordance with the manufacturer recommendations, the films were dried in a UF55 oven from Memmert (Schwabach, Germany) at a temperature of 85 °C for a duration of 3 min. After the deposition of the final layer, the films were annealed in an oven at a temperature of 120 °C for a duration of 5 min.

DC Electrical Characterization: The sheet resistances were measured using a four-point probe head from Jandel (Germany) connected to a B2901A source measuring unit from Keysight Technologies (USA). A constant DC current of 100 μ A was sourced for all measurements.

Optical Characterization: The transmittance spectra were recorded in the visible range using a 300 W xenon arc lamp, chopped at a frequency of 210 Hz. The light passes through an Oriol Cornerstone 260 $\frac{1}{4}$ monochromator and a silicon-based photodiode with a transconductance amplifier that is connected to a 70105 Oriol Merlin digital lock-in amplifier. The calibration of the photodiode was performed with a glass substrate to determine the pure transmission of the AgNW films.

Morphology and Thickness Characterization: AFM images were recorded using an MFP-3D Origin from Asylum Research (UK). Field-emission scanning electron microscope images were recorded with an NVision40 from Carl Zeiss (Germany) at an extractor voltage of 5.0 kV and an acceleration voltage of 7.0 kV. Profilometer measurements were conducted with a DekTak XT from Bruker (USA).

Antenna Design and Characterization: The S-parameters were measured using a ZVA40 vector network analyzer VNA from Rohde & Schwarz. The VNA is calibrated with an automatic calibration kit ZV-Z53. The antenna efficiencies were determined by the Wheeler Cap method^[81–83] using a custom built setup and considering the constant power method.^[83] A balun was not used for the antenna measurements since the simulations consider the effect of the coaxial feed cable. The antennas and the transmission lines were simulated using CST Microwave Studio.

Supporting Information

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

Acknowledgements

The authors thank Loctite (a subsidiary company of Henkel) for providing with free samples of their Loctite5005 transparent silver nanowire screen print paste. The authors are also grateful to Rogers Corporation for providing with RO3003 samples.

Open access funding enabled and organized by Projekt DEAL.

Conflict of Interest

The authors declare no conflict of interest.

Keywords

antennas, flexible, screen-printed, silver nanowires, transparent

Received: June 13, 2019

Revised: July 5, 2019

Published online: August 8, 2019

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