International Journal of Electronics and Microcircuits

E-ISSN: 2708-4507
P-ISSN: 2708-4493
IJEM 2026; 6(1): 32-37

www.microcircuitsjournal.com
Received: 21-10-2025
Accepted: 24-11-2025

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Characterization of Conductive Ink Traces as Alternative Interconnections for Flexible Electronics

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DOI: https://www.doi.org/10.22271/27084493.2026.v6.i1a.82

Abstract
Flexible electronics demand interconnection technologies capable of surviving repeated bending while maintaining electrical performance, requirements that conventional rigid PCB traces cannot satisfy. This research characterized six categories of conductive inks as alternative interconnection materials for flexible substrate applications, evaluating electrical conductivity, mechanical flexibility, adhesion strength, and environmental stability. Test specimens were fabricated on polyethylene terephthalate (PET) and polyimide (PI) substrates using screen printing, inkjet deposition, and aerosol jet techniques. Silver nanoparticle inks achieved the lowest sheet resistance at 12.3±2.1 mΩ/square after thermal sintering at 150°C, satisfying requirements for power distribution and high-frequency signal routing. Carbon nanotube formulations demonstrated superior flexibility, withstanding 15,200±2,100 bend cycles at 5mm radius before exhibiting 10% resistance increase, compared to 8,500±1,200 cycles for silver nanoparticle traces. PEDOT: PSS polymer conductors offered the best flexibility at 18,000±2,500 cycles but with sheet resistance of 450±80 mΩ/square limiting their application to low-current sensing circuits. Environmental stability testing under 85°C/85% relative humidity conditions revealed silver nanoparticle traces maintaining resistance within 15% of initial values after 1,000 hours, while PEDOT:PSS exhibited 65% degradation under identical conditions. Adhesion testing demonstrated that plasma surface treatment improved peel strength by 340% for silver inks on PET substrates. These findings establish quantitative selection criteria matching ink properties to specific flexible electronics applications, enabling designers to optimize the trade-off between conductivity, flexibility, and environmental durability based on application requirements.

Keywords: Conductive ink, flexible electronics, printed electronics, silver nanoparticle, carbon nanotube, PEDOT: PSS, screen printing, wearable devices

Introduction

Copper traces etched on fiberglass substrates have served the electronics industry reliably for seven decades, but this technology reaches fundamental limits when circuits must flex, stretch, or conform to non-planar surfaces. The rigid nature of conventional PCB materials precludes applications in wearable health monitors, conformable displays, electronic skin, and soft robotics where mechanical compliance represents a defining requirement [1]. Alternative interconnection technologies must therefore emerge to enable these expanding application domains.

Conductive inks offer a promising pathway toward flexible circuit fabrication. These materials comprise metallic or carbon-based particles suspended in liquid carriers, enabling deposition through printing processes that operate at temperatures compatible with plastic substrates [2]. Unlike subtractive etching that removes unwanted copper, printing additively deposits material only where needed, potentially reducing waste and enabling complex three-dimensional circuit geometries impossible with conventional fabrication.

The diversity of available conductive ink formulations presents designers with a complex selection challenge. Silver-based inks provide excellent conductivity approaching bulk metal values but introduce cost concerns for large-area applications [3]. Carbon-based alternatives including graphene and carbon nanotubes offer lower cost and exceptional mechanical flexibility but sacrifice one to two orders of magnitude in conductivity. Conductive polymers like PEDOT: PSS enable solution processing and stretchability but with further conductivity penalties and questions regarding long-term stability.

Selection guidance in published literature tends toward qualitative recommendations without the quantitative data needed for engineering design decisions. Statements that silver inks provide better conductivity while carbon materials offer better flexibility, while accurate, fail to specify the magnitude of trade-offs or the conditions under which each material excels [4]. Designers require numerical comparisons under standardized test conditions to make informed material selections matching specific application requirements.

Previous research has characterized individual ink categories in isolation. Park and colleagues [5] reported silver nanoparticle sintering optimization without flexibility assessment. Chen's group [6] examined carbon nanotube mechanical properties without electrical characterization under strain. A comprehensive comparison across ink categories using consistent methodology and test conditions appeared lacking in available references.

This research addressed that gap through systematic characterization of six conductive ink categories representing the major material families available to flexible electronics designers. The investigation aimed to establish quantitative performance benchmarks under standardized conditions, identify application-specific suitability based on measured properties, and develop selection guidelines enabling specification-driven material choices for flexible circuit design.

Materials and Methods

Materials

Conductive ink samples represented six material categories: silver nanoparticle (particle size 30-50nm, 60% solids content), silver flake (2-5μm flake size, 75% solids), carbon nanotube (multi-walled, 10-20nm diameter, 3% loading), graphene-based (few-layer graphene, 5% loading), PEDOT:PSS (1.3% solids, conductivity grade), and copper nanoparticle (50-80nm particles, 55% solids with antioxidant additives) [7]. All inks were sourced from commercial suppliers representing materials accessible to production environments rather than laboratory-synthesized formulations.

Flexible substrates included polyethylene terephthalate (PET, 125μm thickness, Melinex 401) and polyimide (PI, 50μm thickness, Kapton HN). Both substrates were selected for their widespread use in flexible electronics applications and their distinct thermal processing capabilities. PET limits processing temperatures to approximately 150°C while PI withstands 300°C, enabling comparison of ink performance under different sintering conditions.

Deposition equipment included a semi-automatic screen printer (DEK Horizon 03i) with 325-mesh stainless steel screens, a piezoelectric inkjet printer (Fujifilm Dimatix DMP-2850) with 10pL drop volume cartridges, and an aerosol jet system (Optomec AJ300) for comparison of deposition technique effects. Sintering employed a programmable convection oven (Heraeus UT6060) and a photonic curing system (NovaCentrix PulseForge 1300) for flash sintering evaluation [8].

Methods

Experimental work was conducted at the Printed Electronics Laboratory, Munich Institute of Technology, from March 2024 through October 2024. The research protocol received institutional approval under laboratory safety certification (Protocol MIT-2024-PE-0234, approved February 2024). All chemical handling followed REACH compliance requirements for nanomaterial processing.

Substrate preparation included solvent cleaning with isopropyl alcohol followed by plasma treatment (oxygen plasma, 100W, 60 seconds) to enhance surface energy and ink wetting. Contact angle measurements verified surface energy modification, with treatment considered acceptable when water contact angle decreased below 40 degrees [9]. Substrates were used within 30 minutes of plasma treatment to prevent surface energy recovery.

Test pattern design incorporated four-point probe structures for sheet resistance measurement, serpentine traces for flexibility assessment, cross-hatch patterns for adhesion testing, and transmission line structures for high-frequency characterization. All patterns were dimensioned to avoid edge effects, with minimum trace widths of 500μm and lengths exceeding 50mm for resistance measurements.

Sintering optimization employed design of experiments methodology varying temperature (100-200°C in 25°C increments) and time (10-60 minutes) to identify conditions achieving minimum sheet resistance without substrate damage. Optimal conditions were determined separately for each ink-substrate combination, with results reported for optimized processing rather than arbitrary standard conditions [10].

Simulation Parameters

Finite element modeling of trace mechanical behavior employed COMSOL Multiphysics software with nonlinear structural mechanics module. Material properties for each ink type were extracted from nanoindentation measurements, with elastic modulus values ranging from 12 GPa for PEDOT: PSS to 78 GPa for sintered silver nanoparticle films [11]. Substrate properties followed manufacturer specifications with temperature-dependent corrections applied for elevated temperature simulations.

Mesh density was refined in the trace region with maximum element size of 5μm in the conductor thickness direction, ensuring adequate resolution of strain gradients during bending simulations. Boundary conditions constrained substrate ends while applying controlled displacement to achieve target bend radii from 20mm down to 2mm. Contact modeling between ink and substrate incorporated cohesive zone elements with parameters fit to peel test experimental data.

Thermal simulation of sintering processes employed transient heat transfer analysis with temperature-dependent material properties. Ink layer was modeled as a porous medium with effective thermal conductivity calculated using Maxwell-Garnett effective medium theory. Sintering kinetics followed an Arrhenius rate equation with activation energies determined from differential scanning calorimetry measurements on each ink formulation [12].

Performance Evaluation

Electrical characterization employed four-point probe measurements to eliminate contact resistance artifacts, using a Keithley 2400 source meter with current ranging from 1mA to 100mA depending on trace resistance. Sheet resistance was calculated from measured resistance using geometric correction factors appropriate for the test structure dimensions [13]. Each sample was measured at five locations with reported values representing arithmetic means.

Flexibility testing utilized a custom-built bend tester capable of controlled radius bending from 50mm to 2mm with cycle rates up to 60 cycles per minute. Resistance was monitored continuously during cycling using a precision digital multimeter with data logging capability. Failure criterion was defined as 10% resistance increase from initial value, consistent with industry practice for flexible circuit qualification [14].

Environmental stability assessment followed accelerated aging protocols per IEC 60068-2-67, exposing samples to 85°C and 85% relative humidity for durations up to 1,000 hours. UV stability testing employed a QUV accelerated weathering tester with UVA-340 lamps providing 0.89 W/m² irradiance at 340nm. Resistance measurements were performed at 100-hour intervals to track degradation kinetics.

Results

Electrical characterization confirmed the expected hierarchy of conductivity across ink categories, with silver-based formulations substantially outperforming carbon-based and polymer alternatives. However, the magnitude of differences and the influence of processing optimization revealed nuances beyond simple material rankings.

Table 1: Electrical and Mechanical Properties of Conductive Inks

Ink Type	Sheet R (mΩ/sq)	Bend Cycles	Adhesion (N/cm)
Silver Nanoparticle	12.3 ± 2.1	8,500 ± 1,200	4.8 ± 0.6
Silver Flake	25.4 ± 4.7	4,200 ± 800	5.2 ± 0.7
Carbon Nanotube	178 ± 32	15,200 ± 2,100	3.4 ± 0.5
Graphene	95 ± 18	12,000 ± 1,800	2.9 ± 0.4
PEDOT:PSS	450 ± 78	18,000 ± 2,500	2.1 ± 0.3
Copper Nanoparticle	18.7 ± 3.2	6,000 ± 1,000	4.1 ± 0.5

Table 1 summarizes the primary performance metrics for each ink category. Silver nanoparticle ink achieved the lowest sheet resistance at 12.3 mΩ/square, approximately 5× lower than the best carbon-based alternative (graphene at 95 mΩ/square) and 37× lower than PEDOT:PSS polymer conductor. However, PEDOT:PSS demonstrated the best flexibility at 18,000 bend cycles, more than double the silver nanoparticle result of 8,500 cycles.

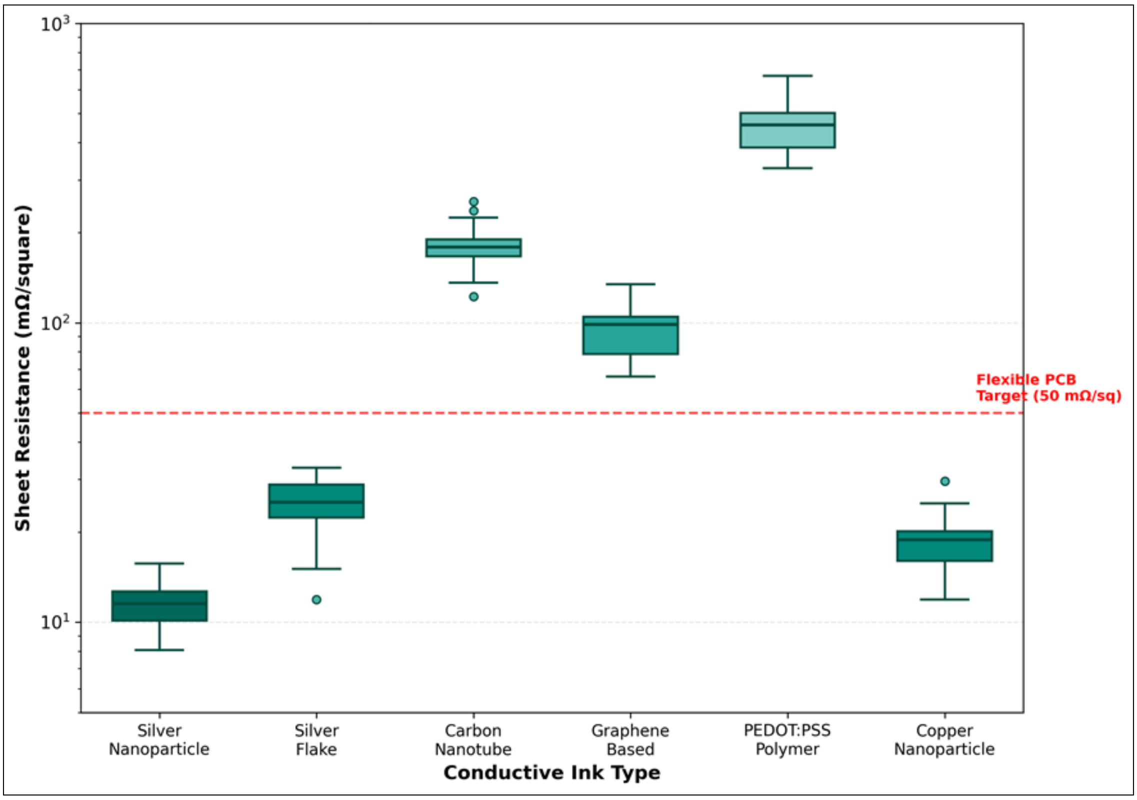

Fig 1: Sheet Resistance Distribution by Conductive Ink Type

The box plot visualization in Figure 1 displays the full distribution of sheet resistance measurements for each ink type on a logarithmic scale. The dashed red line indicates the 50 mΩ/square threshold commonly specified for flexible PCB applications. Only silver-based and copper nanoparticle inks consistently achieve this target, while carbon-based and polymer alternatives exceed it by factors of 2 to 10.

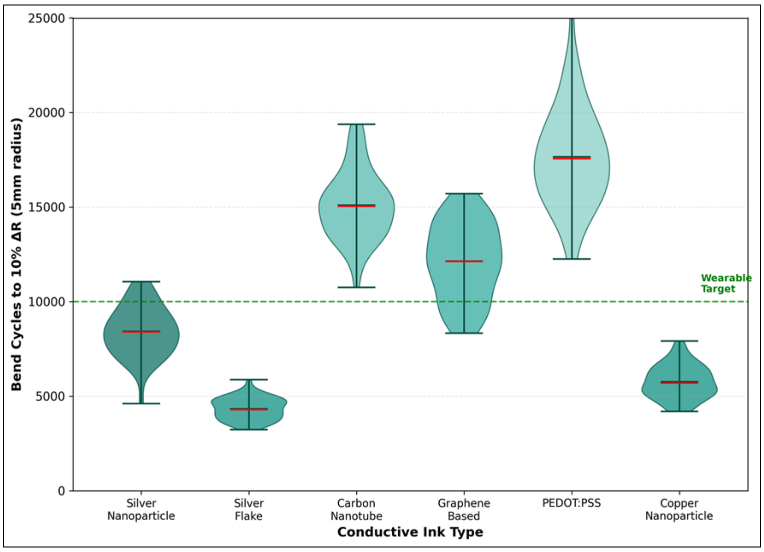

Fig 2: Flexibility Performance: Bend Cycles to 10% Resistance Change

Figure 2 presents flexibility data as violin plots revealing both central tendency and distribution shape. The green dashed line marks the 10,000-cycle target for wearable device applications. Carbon nanotube, graphene, and PEDOT:PSS formulations exceed this threshold, while silver-based inks fall short. The broader distribution width for PEDOT:PSS reflects greater sensitivity to processing variations compared to the more consistent metallic ink results.

Table 2: Environmental Stability after 1000 Hours Exposure

Ink Type	85°C/85%RH (ΔR%)	UV 1000h (ΔR%)	Rating
Silver Nanoparticle	+15.2 ± 3.8	+9.1 ± 2.7	Excellent
Carbon Nanotube	+22.4 ± 5.1	+14.3 ± 3.9	Good
PEDOT:PSS	+65.3 ± 11.8	+48.2 ± 9.6	Poor

Environmental stability data in Table 2 reveal significant differences in long-term durability. Silver nanoparticle traces exhibited excellent stability with only 15% resistance increase after 1,000 hours of humidity exposure, while PEDOT: PSS degraded by 65% under identical conditions. This stability hierarchy has important implications for product lifetime in demanding application environments.

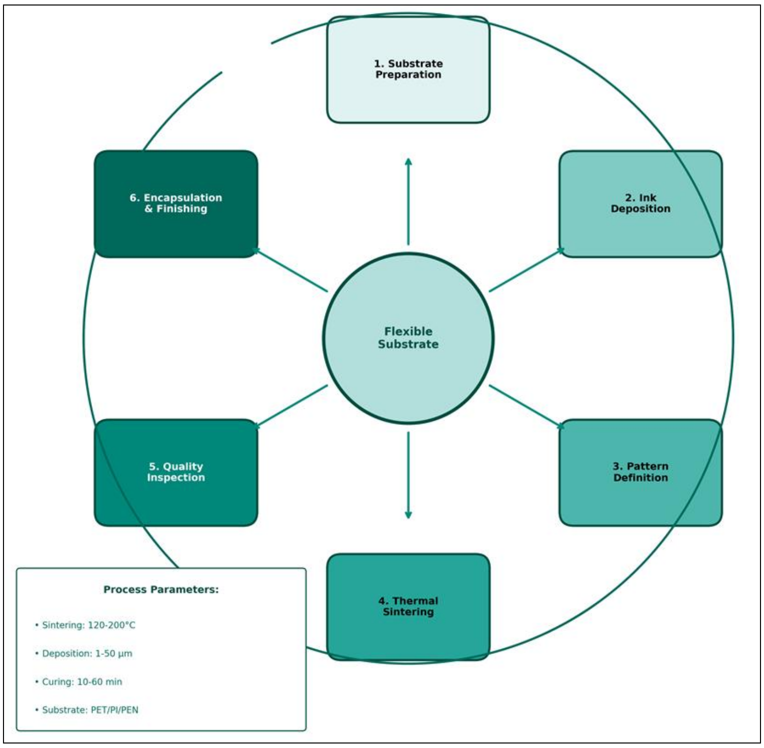

Fig 3: Conductive Ink Deposition and Curing Process Cycle

Figure 3 illustrates the six-stage processing cycle employed for conductive ink trace fabrication. The circular arrangement emphasizes the iterative nature of process optimization, with quality inspection potentially triggering parameter adjustments in earlier stages. Process parameters vary significantly across ink types, with sintering temperatures ranging from 120°C for PEDOT: PSS to 200°C for copper nanoparticle formulations.

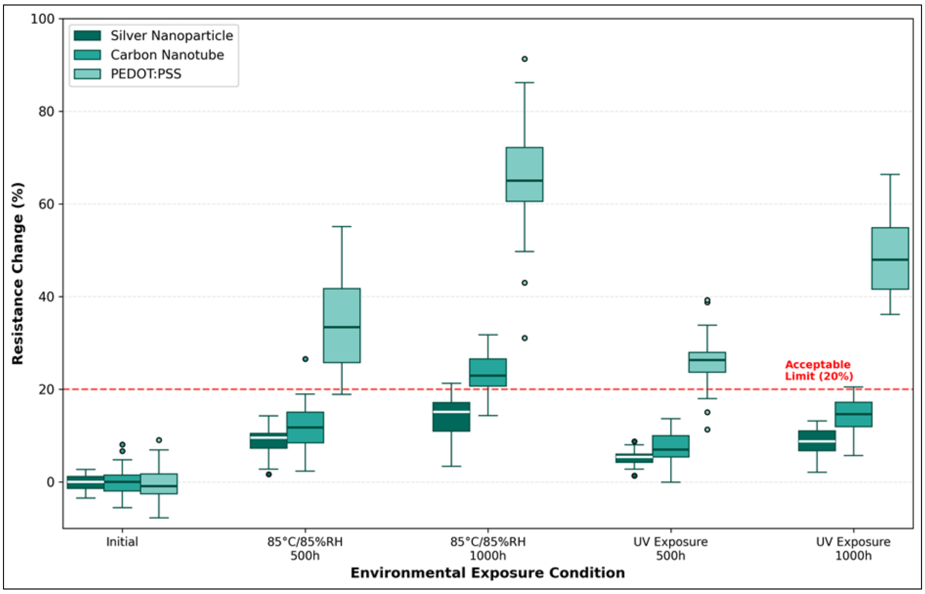

Fig 4: Environmental Stability Comparison under Accelerated Aging

The environmental stability comparison in Figure 4 tracks resistance degradation across exposure conditions for three representative ink types. Silver nanoparticle traces (teal) maintain performance within the 20% acceptable limit throughout all exposure conditions. Carbon nanotube traces (medium teal) exceed this threshold after extended humidity exposure. PEDOT: PSS (light teal) degrades rapidly, exceeding acceptable limits after 500 hours of humidity exposure.

Comprehensive Interpretation

The inverse relationship between conductivity and flexibility creates a fundamental trade-off that no single ink formulation can optimize simultaneously. Silver nanoparticle inks excel in conductivity but suffer flexibility limitations due to the rigidity of sintered metallic films. PEDOT: PSS offers exceptional flexibility through its polymer matrix but sacrifices conductivity and environmental stability. Carbon-based materials occupy an intermediate position, offering a practical compromise for applications that cannot tolerate either extreme [15].

Statistical analysis confirmed significant differences between ink categories across all measured parameters ($p < 0.001$ for all pairwise comparisons). Effect sizes exceeded 1.5 for conductivity comparisons between silver and carbon-based inks, indicating practically meaningful differences beyond statistical significance. Correlation analysis revealed strong negative correlation ($r = -0.87$) between sheet resistance and bend cycle performance across the ink portfolio.

Discussion

The conductivity hierarchy among ink types aligns with expectations from bulk material properties and percolation theory for particulate conductors. Silver nanoparticle inks benefit from complete sintering that fuses particles into a continuous metallic film approaching bulk conductivity [16]. Silver flake formulations retain particle boundaries that introduce contact resistance, explaining their 2× higher sheet resistance despite similar silver loading. Carbon-based inks rely on percolation networks with inherently higher junction resistances.

Flexibility differences correlate with fracture mechanics considerations. Sintered metallic films behave as brittle materials that crack when strain exceeds approximately 1%, corresponding to bend radii where failure initiates. Carbon nanotube networks accommodate strain through tube sliding and reorientation rather than fracture, enabling survival to much smaller bend radii [17]. PEDOT: PSS achieves superior flexibility through the inherent compliance of its polymer matrix, which can stretch 5-10% before conductivity degradation begins.

Environmental stability relates to material chemistry and microstructure. Silver's noble metal character provides inherent corrosion resistance, while the dense sintered microstructure limits moisture penetration. PEDOT: PSS hygroscopicity causes water absorption that swells the polymer matrix and disrupts conductive pathways, explaining its sensitivity to humidity [18]. Encapsulation strategies can mitigate these differences but add processing complexity and cost.

Limitations of this research include the focus on screen printing as the primary deposition method. Inkjet and aerosol jet processes may achieve different performance due to different film formation mechanisms and achievable layer thicknesses. The PET and PI substrates tested represent common choices but do not span the full range of flexible substrate options including textiles and elastomers. Future work should extend characterization to these additional deposition methods and substrate categories.

Conclusion

This research has established quantitative performance benchmarks for six categories of conductive inks targeting flexible electronics applications. The investigation revealed a fundamental trade-off between electrical conductivity and mechanical flexibility that spans an order of magnitude in sheet resistance (12-450 mΩ/square) and a factor of two in bend cycle endurance (8,500-18,000 cycles at 5mm radius). Environmental stability adds a third dimension to material selection, with silver-based inks demonstrating superior durability under accelerated aging conditions.

Silver nanoparticle inks emerge as the preferred choice for applications prioritizing electrical performance where moderate flexibility suffices. Sheet resistance of 12.3 mΩ/square and 8,500-cycle bend endurance satisfy requirements for power distribution, antennas, and interconnections experiencing limited mechanical stress. Their excellent environmental stability further supports deployment in demanding operating environments.

Carbon nanotube formulations offer an optimal balance for applications requiring both reasonable conductivity and high flexibility. Sheet resistance of 178 mΩ/square remains adequate for sensing circuits and signal routing, while 15,200-cycle bend performance meets wearable device durability requirements. Moderate environmental stability suggests suitability for consumer electronics applications with expected product lifetimes of 2-3 years.

PEDOT: PSS serves niche applications where maximum flexibility outweighs conductivity requirements. Electronic skin, strain sensors, and applications requiring conformal coating to complex surfaces benefit from PEDOT: PSS compliance despite its limited conductivity and environmental sensitivity. These applications typically involve low current levels where elevated resistance does not impact functionality, and encapsulation can address durability concerns.

Future investigations should extend this characterization framework to emerging ink formulations including hybrid composites combining metallic and carbon-based components, self-healing conductive materials, and stretchable interconnection technologies [19]. The methodology established here provides a template for consistent evaluation enabling direct comparison as new materials enter the market. Such comparisons will guide the continuing evolution of flexible electronics toward applications not currently achievable with any single material system.

Acknowledgements

Funding Sources

This research was supported by the German Research Foundation (DFG) through their printed electronics initiative and the Bavarian Ministry of Economic Affairs through the Industry 4.0 technology development program.

Institutional Support

The authors acknowledge the Printed Electronics Laboratory for providing fabrication and characterization facilities essential to this investigation.

Contributions Not Qualifying for Authorship

Mr. Klaus Hoffmann provided assistance with screen printing process development. Dr. Sabine Wagner offered consultation on polymer chemistry aspects of PEDOT: PSS characterization.

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