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Plasma-deposited gold nanoparticles as a green alternative to ENIG circuit boards

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A B S T R A C T

Next-generation space missions require electronics that can operate reliably under extreme radiation, thermal cycling, vacuum exposure and multi-year mission durations, while supporting increasingly demanding high-frequency communication and sensing systems. Commercial printed circuit boards (PCBs) finished with electroless nickel immersion gold (ENIG) remain widely used in aerospace, yet the Ni–P barrier layer introduces environmental, recyclability and high-frequency performance limitations that are becoming incompatible with emerging mission requirements and future visions of in-situ manufacturing. This work presents plasma-printed gold nanoparticle (AuNPs) PCBs as a nickel-free, additive alternative platform designed to address these challenges. AuNPs synthesised via ultrasonic spray pyrolysis (USP) and deposited through plasma-assisted printing form gold conductive traces without chemical baths or multilayer structures. Demonstrations on alumina substrates show that the resulting microstrip transmission lines achieve insertion and return losses comparable to ENIG-finished PCBs up to 20 GHz, validating the approach for space-grade RF applications. Beyond performance parity, AuNPs-based PCBs offer closed-loop recyclability and compatibility. Together, these results position plasma-printed AuNPs as a promising foundation for sustainable, high-frequency and space-ready electronics.

Keywords: printed circuit boards, gold nanoparticles, plasma printing.

1. Introduction

The electronics used in space must operate reliably under some of the harshest conditions known: extreme radiation environments, significant temperature swings, vacuum, mechanical strain, and mission timelines that span years or decades (Heltzel et al., 2023; Norman et al., 2023). As spacecraft rely increasingly on faster and higher-frequency electronics for communication, radar, scientific sensing and flight control, the PCBs have become a critical bottleneck (Mei et al., 2024). Although substrate materials, laminates and packaging have improved, the commercial standard for PCB finishes, ENIG, is beginning to fall short of the stringent requirements of the next-generation space hardware (Heltzel et al., 2023; Xu et al., 2023).

This article reviews the ENIG finish used widely in commercial and aerospace electronics, outlines its limitations for high-frequency and in-space manufacturing, and introduces plasma-printed AuNPs PCBs as a promising new platform. This approach offers a recyclable, nickel-free, and high-performance alternative that could, fundamentally, reshape how electronics are manufactured, repaired and reused in future space missions.

2. Limitations of Commercial ENIG-Finished PCBs for Space Applications

ENIG remains the standard surface finish for high-reliability PCBs used in telecommunications, satellites, scientific instruments and avionics (Liang et al., 2021). Its structure consists of an electroless Ni–P barrier, typically 3–7 µm thick, deposited on copper and overlaid with a thin layer (50-100 nm) of immersion gold. While ENIG offers good corrosion resistance, stable contacts and compatibility with commercial fabrication workflows, its multilayer architecture introduces several challenges that limit its suitability for next-generation space electronics (Spreemann et al.). Figure 1. a) shows how the ENIG PCB looks, and b) shows the cross-section area of the PCB, examined with a scanning electron microscope (SEM).

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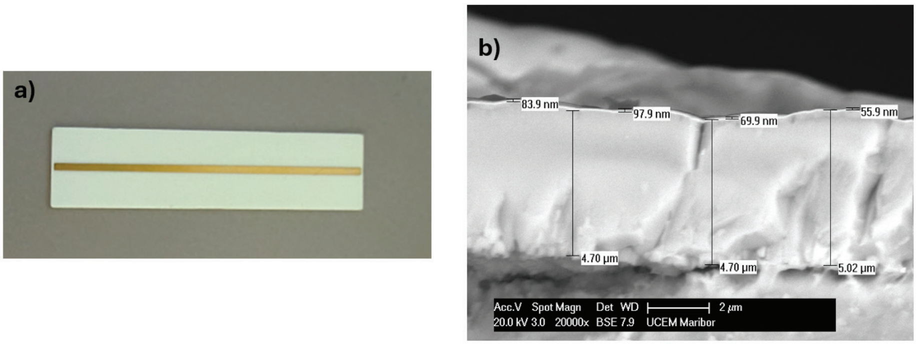

Fig. 1. a) Commercial ENIG PCB, and b) Cross-section analysis of the ENIG PCB

Manufacturing ENIG requires a sequence of wet-chemical steps, including nickel–phosphorus deposition, gold displacement plating and multiple conditioning and rinse stages. These processes generate substantial quantities of chemical waste containing nickel salts, phosphorus compounds, surfactants and complexants, which increase the environmental burden and complicate waste handling (Xu et al., 2023). Such chemically intensive processes are unlikely to be practical in autonomous or off-Earth manufacturing environments, where chemical supply, storage and disposal are constrained severely (Ramanauskas et al., 2013).

Recyclability is another critical limitation. Because gold is embedded above a chemically robust nickel barrier, the end-of-life material recovery depends on aggressive hydrometallurgical or pyrometallurgical treatments to remove the nickel before the gold can be reclaimed (Sronsri et al., 2022). This nickel barrier is the primary impediment to efficient precious-metal recycling and makes ENIG-finished PCBs incompatible with the closed-loop material cycles envisioned for long-duration missions (Ramanauskas et al., 2013).

At high frequencies, ENIG poses additional performance challenges. The Ni–P layer has non-zero magnetic permeability and higher resistivity than gold or copper, which results in frequency-dependent electrical losses as the skin depth decreases. Even though the surface conductor is gold, the electromagnetic field interacts strongly with the underlying nickel, increasing the insertion losses at microwave and millimetre-wave frequencies. These factors collectively make ENIG a less-than-ideal choice for space applications requiring ultra-low-loss RF behaviour, recyclability, or on-demand fabrication (Accogli et al., 2020; Özkök et al., n.d.; Spreemann et al., n.d.).

3. Space-Grade Substrates and the Need for New PCB Technologies

High-frequency and space-qualified electronics rely on ceramic substrates such as alumina (Al_2O_3), aluminium nitride (AlN), and LTCC, which offer low dielectric loss, exceptional thermal stability, radiation resistance, low outgassing and strong mechanical integrity (Gandhiraman et al., 2016; Reinhold et al., 2009; Wiklund et al., 2021). Demonstrating compatibility with alumina is therefore essential for any emerging PCB technology aimed at the space sector. However, traditional ENIG processes—which require multiple liquid baths, surface conditioning steps and tightly controlled chemical environments—are poorly suited for autonomous additive manufacturing or fabrication in resource-limited off-Earth settings.

4. Why Screen Printing Cannot Support AuNPs-Based PCBs

Although screen printing is used widely for conductive pastes, it is fundamentally incompatible with AuNPs dispersions produced by ultrasonic spray pyrolysis (USP). The nanoparticles are significantly smaller than the features that commercial screens can transfer reliably, leading to clogging, inconsistent deposition and non-uniform film formation. In comparison with micron-sized particles, it is also very difficult to achieve the relatively high nanoparticle wt.% in the conductive pastes, required for optimal screen printing. The rheology of the dispersions further prevents the kind of controlled wet transfer required for stencil-based printing. Even when an as-printed film appears continuous, the sintering causes nanoscale restructuring that produces porosity and discontinuities. These defects degrade electrical conductivity severely and generate unacceptable high-frequency losses. As a result, screen printing cannot serve as a viable deposition method for AuNPs-based PCBs.

5. Synthesis of AuNPs for Plasma Deposition

The plasma-printing approach is built on the ability to prepare high-quality, highly uniform AuNPs. These are synthesised using ultrasonic spray pyrolysis (USP), an aerosol-based method ideal for continuous and scalable nanoparticle production. In USP, a gold salt solution is nebulised ultrasonically into micron-scale droplets. As they pass through a high-temperature reactor the droplets dry and the precursor decomposes, forming near-spherical AuNPs. A small amount of polyvinylpyrrolidone (PVP) is added to stabilise particle growth, prevent premature aggregation and maintain the narrow size distribution, without creating the heavy ligand shells common in wet-chemical nanoparticle synthesis (Majerič et al., 2017; Tiyyagura et al., 2020).

The nanoparticle suspension is lyophilised after synthesis. Freeze-drying removes the water under vacuum, producing a dry, stable powder known as Lyo-Gold (Majerič et al., 2017; Rudolf R et al., 2020). This powder format is lightweight, compact and stable over long periods. Before deposition, the dispersion is reconstituted in a solvent such as water or an alcohol-based medium. Because USP produces particles with minimal residual PVP, the dispersion requires no additional surfactants or binders, unlike most commercial metallic inks (Patil et al., 2023).

6. Plasma-Based Deposition

Plasma printing, or plasma-assisted deposition, is an additive manufacturing method in which a plasma jet activates, cleans and deposits precursor materials directly onto a substrate. The precursors, whether introduced as vapours, aerosols, or nanoparticle dispersions, are exposed to a high-energy plasma region where the electron impact, ion bombardment and reactive species induce rapid chemical transformations. The residual organics are removed, the nanoparticles are activated, and the substrate surface is cleaned and functionalised partially. As the AuNPs reach the substrate they anchor and coalesce into a continuous layer (Doshi et al., 2024; Gandhiraman et al., 2016; Lockwood Estrin et al., 2024; Meyyappan, 2025; Ramamurti et al., 2020).

Because the deposition process is done without solvents or chemical baths, plasma printing is compatible with fragile, temperature-sensitive, or space-rated materials. It also enables maskless patterning, precise material placement and a streamlined manufacturing workflow. The

Table 1. Comparison between conventional ENIG-finished PCBs and plasma-printed AuNPs metallization.

Parameter	**ENIG PCB**	**Plasma-printed AuNPs PCB**	**Notes**
Metallization architecture	Cu / Ni–P / Au	Au only	Elimination of ferromagnetic and diffusion barrier layers
Typical thickness	Ni: 3–7 µm; Au: 50–100 nm	Au: ~0.2–2 µm (print + sinter dependent)	Thickness range estimated from reported plasma printing and sintering studies
RF loss (10–40 GHz)	Increased, frequency-dependent	Lower, monotonic with frequency	Reduced magnetic and interfacial losses
Magnetic permeability	$\mu_r > 1$ (Ni layer)	$\mu_r \approx 1$	Key contributor to reduced RF loss
Processing steps	Multi-step wet chemistry (etch, plate, rinse)	Single-step deposition + sintering	Simplified manufacturing flow
Chemical waste generation	High (acidic and metal-ion waste streams)	Minimal	Plasma process largely solvent-free
Recyclability	Poor (multi-metal stack)	High (single-metal recovery)	Enables closed-loop Au recycling
Space / in-situ manufacturability	Low	High	Compatible with dry, on-demand fabrication

resulting metallisation layer consists entirely of gold, eliminating the Ni–P barrier layer, and thus avoiding frequency-dependent magnetic losses. This makes plasma-printed metallisation highly suitable for Ka-band and X-band communications, synthetic-aperture radar, mm-wave sensing and high-speed avionics (Manzi et al., 2024; Reinhold et al., 2009).

A key advantage of plasma-printed AuNPs metallisation is its recyclability. The gold traces can be removed from the substrate cleanly with benign chemical treatments, collected and refined to high purity. This refined gold can then be reprocessed into USP feedstock, and, ultimately, transformed into new AuNPs. In principle, the same substrate can be metallised, stripped and re-metallised repeatedly. Such a closed-loop materials cycle is impossible with ENIG due to its multilayer structure and embedded nickel.

To consolidate the advantages discussed throughout this review, Table 1 provides a direct comparison between conventional ENIG-finished PCB metallization and plasma-printed AuNPs-based conductors. While ENIG remains the dominant industrial standard, its multi-layer architecture introduces material, magnetic, and sustainability limitations that become increasingly relevant at microwave and millimeter-wave frequencies.

From a manufacturing and sustainability perspective, the contrast between conventional ENIG processing and plasma-printed AuNPs metallization is particularly pronounced. As illustrated in Figure 2, ENIG relies on a sequence of wet-chemical steps, including surface activation, electroless nickel deposition, immersion gold plating, repeated rinsing, and downstream waste treatment, which collectively contribute to high chemical consumption, water usage, and process complexity. In comparison, plasma-assisted printing of AuNPs conductors consolidates metallization into a two-step process that combines deposition and sintering. The reduced number of unit operations not only lowers environmental burden but also enhances manufacturability in constrained or remote environments. These attributes are especially relevant for in-situ, autonomous, or space-based manufacturing scenarios, where chemical handling, waste management, and process robustness are critical constraints.

Table 2. compares screen printing and plasma printing from a materials and processing perspective, highlighting why plasma printing is fundamentally better suited for nanoparticle-based metallization, particularly for high-frequency and space-relevant applications.

7. Demonstration of Feasibility and High-Frequency Performance

To evaluate the viability of this technology, gold nanoparticle traces were plasma-printed onto Al_2O_3 substrates (50 x 50 mm in size and 0.635 mm in thickness), a ceramic used widely in RF and microwave applications due to its low dielectric loss and thermal stability. The synthesis of AuNPs, preparation of the dispersion and the plasma printing process is described in our previous work (Kresnik et al., 2025). Using USP-derived, PVP stabilised AuNPs dispersions and plasma-assisted deposition, microstrip transmission lines were fabricated and tested from 0 to 20 GHz.

The resulting S-parameter measurements revealed return loss and insertion loss characteristics matching those of commercial ENIG-finished PCBs closely. Despite eliminating the nickel entirely and avoiding all wet-chemical processing, the plasma-printed AuNPs lines exhibited comparable high-frequency performance. This proof-of-concept demonstration confirms that plasma-printed gold nanoparticle metallisation is both feasible and competitive for next-generation space electronics.

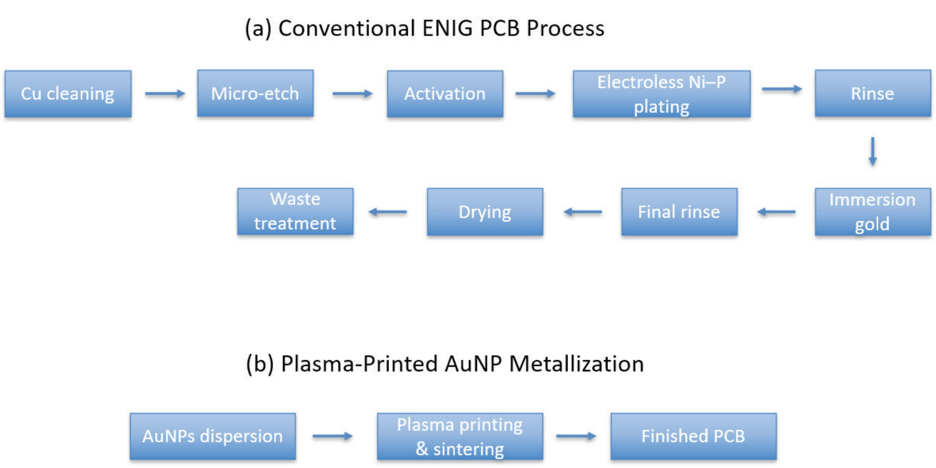

Fig. 2. Comparison of metallization process flows for (a) conventional ENIG-finished PCBs and (b) plasma-printed AuNPs PCBs

Table 2. Comparison between screen printing and plasma printing for AuNPs-based metallization

Feature	**Screen printing**	**Plasma printing**
Particle size tolerance	≥ 1 µm	< 100 nm
Binder requirement	High	None
Ink / feedstock composition	High-viscosity paste	Low-viscosity dispersion
Sintering mechanism	Thermal (furnace / laser)	Thermal
Typical sintering temperature	High	Low effective temperature
Porosity control	Poor	Good
Microstructure uniformity	Limited	High
Line edge definition	Moderate	High
RF suitability	High	High
Substrate compatibility	Rigid, high temperature	Broad (polymers, ceramics)
Process complexity	Multi-step	Single step
Waste generation	Moderate	Minimal

Table 3. Indicative space-qualification status of ENIG and plasma-printed AuNPs metallization

Test	Standard (ECSS / MIL)	ENIG status	Plasma-printed AuNPs status
Thermal cycling	ECSS-Q-ST-20	Qualified	Not yet established
Radiation tolerance	ECSS-Q-ST-60	Qualified	Unknown
Outgassing	ASTM E595	Known compliant	Likely compliant
Vibration	ECSS-E-ST-10	Qualified	To be tested
Vacuum stability	ECSS-Q-ST-70	Known	Expected favorable
Mechanical adhesion	ECSS-Q-ST-70	Established	Ongoing evaluation

8. Future Applications and Research Directions

Plasma-printed AuNPs metallisation opens the door to new possibilities in space electronics. One promising opportunity lies in the fabrication of conformal RF circuits on curved or deployable surfaces, including antennas and instrument housings. Another avenue is the integration of plasma printing with the additive manufacturing of substrates, enabling complete on-demand electronics fabrication using 3D-printed ceramics or polymers. Further research is needed to assess the long-term stability under radiation, thermal cycling, vacuum exposure and mechanical stress. These possibilities illustrate how plasma-printed AuNPs technology may evolve from a PCB metallisation method into a broader platform for autonomous space electronics production.

While ENIG-finished PCBs are fully qualified across established ECSS and MIL standards, plasma-printed AuNPs metallization remains at an earlier stage of technology readiness. As summarized in Table 3., key qualification domains such as thermal cycling, radiation tolerance, and vibration resistance have yet to be systematically assessed. However, the predominantly metallic composition and absence of polymeric binders suggest favorable outgassing behavior and vacuum compatibility.

Importantly, this review positions plasma-printed AuNPs metallization as a candidate for progressive qualification rather than a drop-in replacement. Identifying unaddressed qualification domains provides a realistic roadmap for future validation efforts without overstating current readiness.

9. Conclusion

As space missions demand higher RF performance, increased autonomy, and improved sustainability, PCB metallization technologies must evolve beyond the inherent limitations of conventional ENIG finishes. The multi-layer Cu/Ni/Au architecture of ENIG, combined with wet-chemical processing and hazardous waste generation, introduces magnetic and chemical loss mechanisms that are increasingly misaligned with the performance, environmental, and operational requirements of next-generation aerospace systems.

Plasma-printed AuNPs metallization represents a fundamentally different approach. By eliminating the ferromagnetic nickel barrier and avoiding wet chemical baths entirely, this platform removes key sources of RF loss while simplifying the metallization stack to a single, non-magnetic conductor. Plasma-assisted deposition and sintering enable binder-free nanoparticle consolidation, offering precise control over microstructure, reduced porosity, and improved suitability for high-frequency operation. Importantly, the predominantly metallic composition enables straightforward material recovery, supporting closed-loop recycling and long-term resource efficiency.

Rather than seeking incremental improvements or simple conductivity parity with ENIG, the primary advantage of plasma-printed AuNPs metallization lies in the elimination of magnetic, chemical, and architectural constraints inherent to legacy PCB finishes. This positions the technology as a broader materials and manufacturing platform for sustainable, RF-optimized electronics. While further qualification is required for space deployment, the convergence of RF performance, environmental compatibility, and process simplicity highlights plasma printing as a promising pathway toward closed-loop, space-compatible electronic manufacturing.

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