Additive Manufacturing Methods for Embedded Resistors

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Abstract

Embedded resistors can reduce component count, routing complexity, and assembly requirements in high density printed circuit boards (PCBs); however, conventional subtractive manufacturing of patterned resistive foils requires multiple steps and generates large amounts of hazardous waste and CO_2 emissions. In this work, we investigate direct-write additive manufacturing of resistive films onto patterned copper terminations as a potential replacement for lithographically patterned foil resistors. Carbon-based resistive inks were deposited using a Voltera Nova dispensing platform and characterized to determine the effects of substrate fixturing, deposited geometry, process calibration, and copper–resistor interface resistance. Substrate fixturing was identified as a critical source of variability because the contact-based surface probing routine can deform thin PCB substrates and produce an inaccurate height map. Direct measurements on substrates confirmed that vacuum-bed fixturing limited out-of-plane displacement to 0.01 mm to 0.02 mm while corner clamping produced deformation of 0.72 mm. Replacing clamping with vacuum-bed fixturing reduced the maximum resistance variation from 150% to 6%. Variable length resistance calibration coupons were used to determine copper termination spacings for target values for 25, 50 and 100 Ω resistors. Results demonstrate batch resistance tolerances within ±5%, successfully remaining within the 20% tolerance threshold for foil resistors. Resistance vs. length measurements also indicated an apparent interface resistance contribution of approximately 4–8 Ω. Passivation of the copper surface with a layer of gold supported the hypothesis that the interface chemistry contributes to device resistance; however, the interface contribution is not sufficiently stable over time to be treated as a fixed calibration parameter. Preliminary life-cycle assessment indicated that the printed resistor approach can reduce panel-level CO_2 emissions relative to conventional NiCr embedded resistor foil technologies. The results demonstrate that substrate planarity, surface height measurement, and interface control are key requirements for repeatable direct-write fabrication of printed embedded resistors.

Key words

Additive manufacturing, direct-write printing, embedded resistors, polymer thick film resistors, printed electronics, semi-additive PCB fabrication.

I. Introduction

Embedded passive components have become increasingly important as electronic systems continue to demand greater functionality, higher packaging density, and reduced size, weight, and power (SWaP). Embedding resistors within a printed circuit board (PCB) can reduce surface component count, simplify assembly, and preserve active area for surface devices. Embedded resistors are commonly fabricated using either polymer thick-film screen-printing processes or laminated resistive foil materials. While both technologies are well established, each introduces manufacturing constraints that can limit design flexibility and increase process complexity.

Embedded resistor foils are typically laminated into the PCB stack and then patterned using imaging, developing and etching steps. These subtractive processes are energy-intensive and generate large quantities of hazardous waste

and leave a significant fraction of the laminated resistor material unused after processing. Replacing resistor foils with screen-printing processes requires dedicated screens for each design iteration, increasing cost and lead time.

Direct-write additive manufacturing dispensing systems provide digital manufacturing flexibility. Toolpaths can be modified without physical tooling enabling rapid prototyping, materials screening, design optimization, and applications requiring multiple resistor geometries on one substrate. Direct-write deposition may also reduce material waste and eliminate some resistor-specific lithographic and wet-chemical operations; however, electrical performance is sensitive to deposited length, width, thickness, and cross-sectional uniformity. Small changes in tip-to-substrate offset, substrate planarity, or ink deposition rate can therefore produce significant changes in the final resistance.

Achieving repeatable resistor performance requires control over deposition parameters and the electrical interface between the ink and the copper termination. During the pressure dispensing process, the ink is a liquid bridge between the dispensing tip and the substrate. The stability of this capillary bridge is governed by fluid dynamics, surface tension, and rheology, therefore excessively high printing speed or a tip–substrate gap that destabilizes the bridge can lead to discontinuous lines or print defects. Contact-based height mapping can compensate for substrate topography, but inadequate substrate fixturing or deformation during surface probing can result in variations in ink deposition thickness. In addition, oxidation at the ink–copper interface may introduce additional resistance that is independent of resistor length. Both of these effects must be quantified before direct-write resistors can be designed for specific nominal values or evaluated against established foil resistor technologies.

This work focuses on two main objectives related to direct-write printed resistors including improving dimensional repeatability through substrate fixturing and dispensing process control and evaluating the contribution of the ink–copper interface via gold passivation. Resistors targeting 25, 50, and 100 Ω were fabricated and characterized across multiple coupons and print sessions. The results are considered together with preliminary life cycle and manufacturing analysis to assess the potential of direct-write printing as a flexible and more resource-efficient alternative to NiCr resistor foils. Figure 1 compares the conventional foil-patterning manufacturing process with the proposed direct-write process.

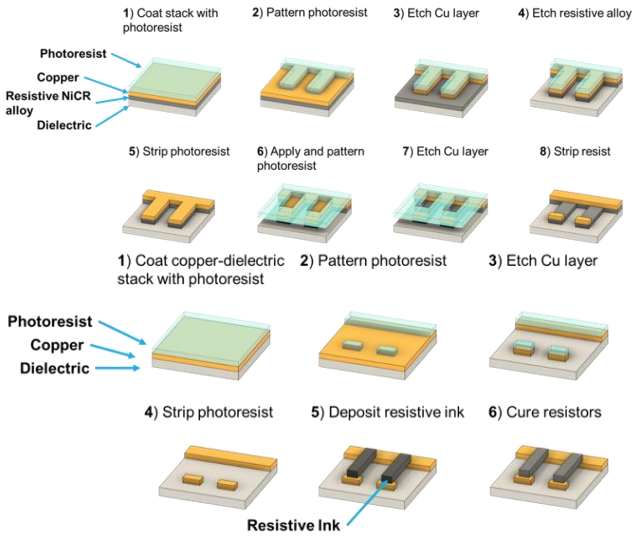


Fig. 1. Comparison of conventional embedded resistor foil processing (top) and proposed direct-write printed resistor process flow(bottom).

II. Experimental Methods

A. Materials

Micromax HT602 carbon-based resistive ink was selected for initial testing because of its stable particle dispersion, ease of handling, room-temperature dispensing capability, and low hazard profile. Test coupons were fabricated from Isola 370HR and MT40 substrates with double clad half-ounce Cu foil.

B. Equipment

Test coupons and termination patterns were fabricated using an LPKF PCB Prototyping system, consisting of a Protomat CNC mill and ProtoLaser laser patterning system. For coupons with gold passivation layers, the gold was deposited using a Leica SCD500 sputter coater. Resistors were fabricated using a Voltera Nova direct-write dispensing platform.

Resistance measurements were performed using Fluke handheld digital multimeters and four-point probe multimeters. Ink resistivity was obtained using a Signatone 4-point probe and a KLA-Tencor D-500 profilometer. Printed resistor dimensions were obtained using a Keyence VHX microscope. Figure 2 demonstrates a summary of the main process flow used in this work.

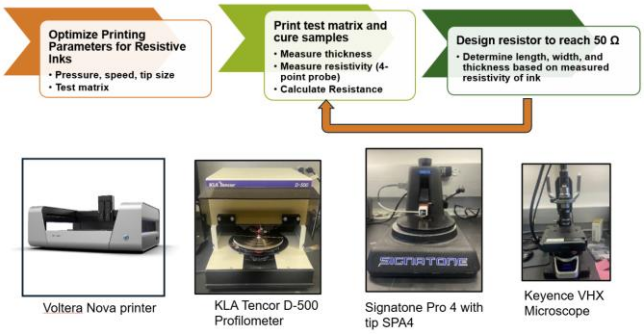


Fig. 2. Experimental equipment used for resistor fabrication and characterization, including the Voltera Nova printer, profilometer, four-point probe station, and optical microscope.

III. Process Development and Optimization

A. Process calibration

Batch-to-batch testing identified printed resistor thickness as a major contributor to resistance variability. Measured deviations exceeding 20% were primarily associated with differences between predicted and actual deposited thickness, highlighting the need for improved process control and height prediction models. The printing process was optimized through a three-step calibration procedure: (1) ink characterization and dispensing parameter optimization; (2) toolpath and print geometry optimization; and (3) electrical calibration through resistance-versus-dimension measurements.

The resulting calibration procedure established design rules that relate resistor geometry to final electrical resistance, as shown by Figure 3.

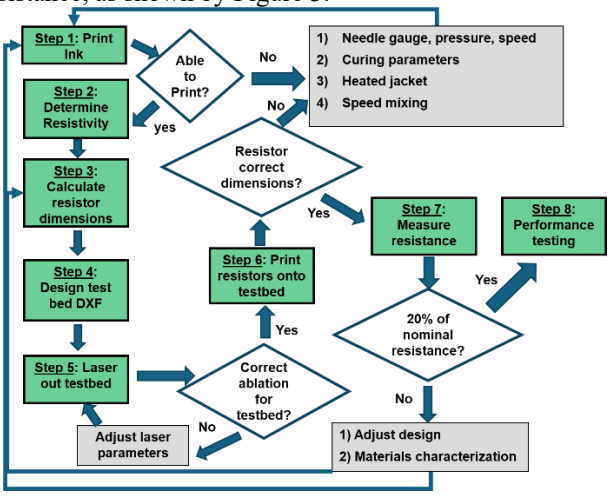


Fig. 3. Workflow used for characterization of resistive inks and calibration of printed resistor dimensions.

B. Effect of Fixturing on Resistance Repeatability

The Voltera Nova direct-write printing platform employs a contact-based probing routine to generate a surface height map of the substrate prior to deposition. This surface-height map is subsequently used to maintain a constant nozzle standoff distance during printing, enabling uniform material deposition across surfaces exhibiting local height variations, such as the copper termination features present on the test coupons. Maintaining a consistent nozzle-to-substrate distance is particularly important for printed resistors because the deposited film thickness directly influences the cross-sectional area of the resistive path and, consequently, the resulting resistance.

Initial fabrication trials exhibited substantial resistance variability despite the use of identical printing parameters. Root-cause analysis revealed that substrate deformation during the probing routine introduced errors into the measured surface height map. The original fixturing approach utilized corner clamps and localized support features that allowed the PCB substrate to deflect under the probing force. As a result, the recorded surface profile did not accurately represent the substrate geometry during printing, leading to variations in nozzle standoff distance, deposited resistor thickness, and measured resistance.

To mitigate this effect, the clamping-based fixturing approach was replaced with a vacuum-bed fixture, as shown in Figure 4. The vacuum fixture constrained the entire substrate against a rigid reference plane, minimizing local deformation during probing and providing a more accurate surface height map. This approach improved dimensional consistency by reducing variations in deposited film thickness across the coupon.

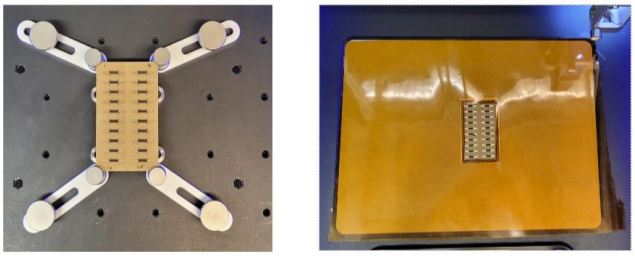


Fig. 4. Comparison of original clamp-based fixturing (left) and vacuum-bed fixturing (right) used during Voltera Nova printing.

To confirm that probe-based deformation was the cause, substrates with no patterned terminations were probed under both fixturing methods. Two substrates were tested, one 0.3mm thick, the other 0.6mm thick. The substrates were held taut and clamped at the corners, leading to an unsupported span of roughly 35 x 60 mm for clamping. Substrates were laid on the vacuum-bed and a Kapton mask was used to ensure the vacuum-bed had enough suction to hold the coupons down during vacuum-bed testing. Coupons underwent the probing routine, and then probe data was extracted from the Voltera Nova and analyzed. Out-of-plane displacement was measured as the maximum and minimum height compared to the corners of the substrate. For the vacuum-bed coupons, the height displacement was only

above the corners and was 0.02 mm for the 0.6 mm thick coupon, and 0.01 mm for the 0.3mm thick coupon. For the clamped coupons, the height deviation was 0.0 5mm above and below the corners for the 0.6 mm coupon, and 0.72 mm below the corners for the 0.3 mm coupon.

Figure 5 compares the measured resistor height profiles and resulting resistance distributions obtained using the two fixturing methods. The improved fixturing reduced within-coupon resistance variation from values exceeding 150% in the worst-case condition to approximately 6%. The substantial reduction in resistance spread indicates that substrate planarity and accurate surface-height characterization are critical factors governing repeatability in direct-write fabricated resistors. These results further indicate that dimensional process control is the major contributor to resistor-to-resistor resistance variation under the investigated process conditions. The results demonstrate that accurate substrate fixturing and height-map generation are prerequisites for achieving resistance tolerances comparable to those required for embedded passive applications.

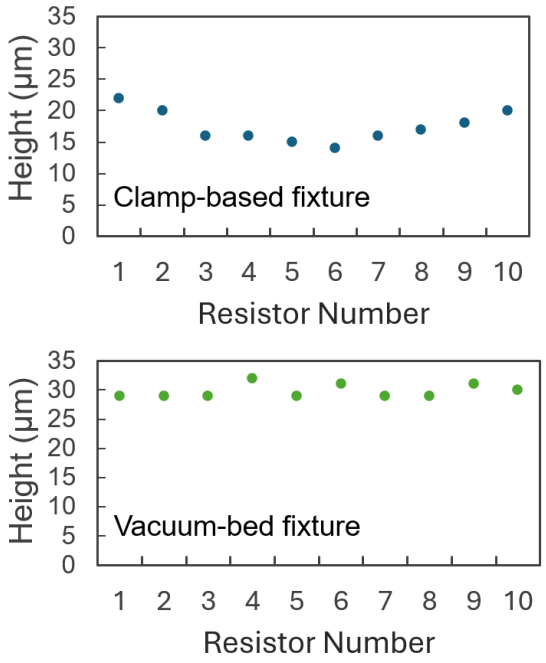


Fig. 5. Measured resistor height profiles using clamp-based (left) and vacuum-bed (right) fixturing.

C. Target Resistance Methodology

A calibration coupon containing resistors of varying lengths was fabricated and measured (Figure 6, left). Resistance values were plotted against resistor length and fitted using linear regression, as shown in Figure 7.

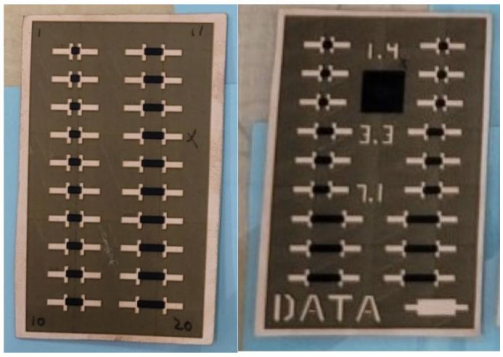


Fig. 6. Varying length test coupon (left) used to determine the lengths to achieve desired resistance values for test coupon (right).

The resulting empirical model was then used to predict the geometry required to achieve desired resistance values, and a test coupon was printed as shown in Figure 6 (right).

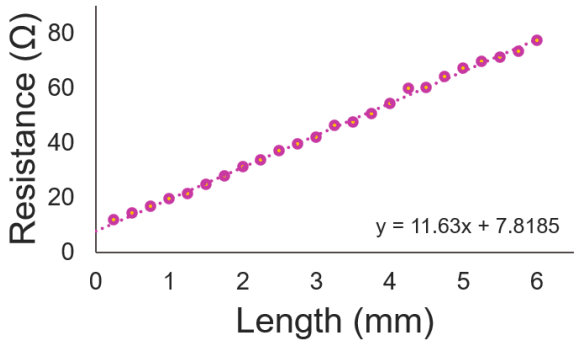


Fig. 7. Measured resistance as a function of resistor length for HT602 printed resistors.

Using this calibration approach, resistor structures designed for nominal values of 25 Ω, 50 Ω, and 100 Ω yielded average measured resistances of 27 Ω, 56.5 Ω, and 111.5 Ω, respectively. Although a systematic offset was observed between predicted and measured resistance values, the fabrication process exhibited high repeatability, with coupon-to-coupon and resistor-to-resistor variation remaining below ±5%. The largest observed deviation from the target resistance was +16%, remaining within the project's ±20% tolerance requirement for embedded resistors.

Table I. Summary of target versus measured resistance values and resulting tolerances.

Designed value	**25 Ω**	**50 Ω**	**100 Ω**
Measured value*	27	56.5	111.5
Variation	±4%	±3%	±4.5%
Deviation†	2 (+ 8%)	6.5 (+13%)	11.5 (+11.5%)
Max deviation†	28 (+12%)	55 to 58 (+16%)	116 (+16%)

*Average measured value; †Average deviation from target

D. Interface Resistance Effects

Resistance-versus-length analysis consistently exhibited a positive y-intercept ranging from approximately 4 to 8 Ω. For an idealized resistance-vs.-length relationship, extrapolating to zero length would produce a near-zero y-intercept. This offset indicates an additional resistance contribution associated with the ink–copper interface. Copper oxidation is one possible contributor; however, the apparent interface contribution was subsequently observed to vary with time and processing history, indicating that it should not be treated as a fixed interface-related resistance term. Gold passivation layers were added between the copper and ink by sputter deposition to reduce this additional resistance. As shown in Figure 8, the interface-related resistance decreased from approximately +6.4 to a value near zero when the gold passivation layer was introduced into the system. Further investigations into additional passivation layers and their effectiveness are ongoing.

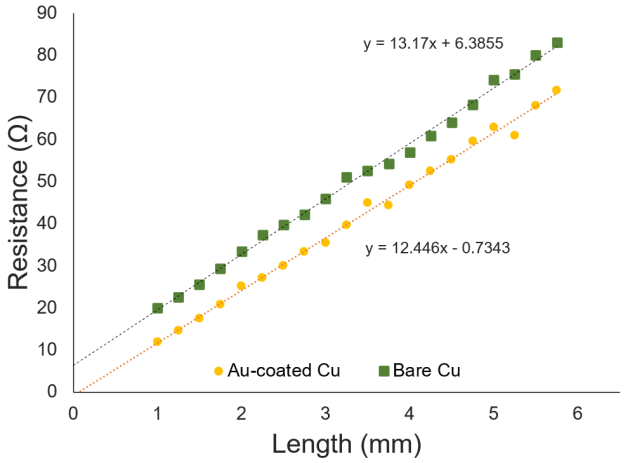


Fig. 8. Comparison of resistance-versus-length behavior before and after application of gold passivation layers.

IV. Electrical Performance

Optimized process conditions produced resistance variation below ±5% for resistors fabricated across multiple coupons and print sessions, as shown in Figure 9. The measured resistance distributions exhibit median values between approximately 65 and 67 Ω, with interquartile ranges of less than 2 Ω and total spreads generally below 5 Ω. The close agreement among the three independently printed coupons indicates high repeatability and limited batch-to-batch variation under the investigated conditions. Only a single high-resistance outlier was observed, while the remaining measurements clustered tightly around the population mean, confirming that the combination of vacuum-bed fixturing, optimized probing procedures, and calibrated deposition parameters substantially reduced process variability, enabling consistent resistor fabrication. These results indicate that substrate fixturing and height-control accuracy are the primary factors governing resistance repeatability in the direct-write printing process.

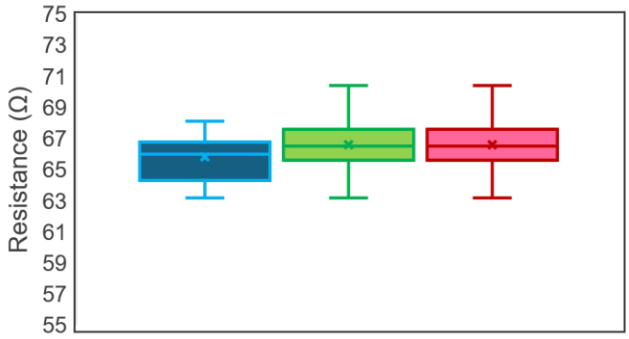


Fig. 9. Distribution of measured resistance values across three coupons, each printed in a different print session.

V. Sustainability and Manufacturing Implications

One of the primary motivations for this work is the development of a more sustainable embedded resistor manufacturing approach reducing reliance on conventional NiCr resistor foil technologies. Unlike resistor foil fabrication, which relies on multiple lithographic patterning, wet-etching, and chemical processing steps, direct-write additive manufacturing deposits resistive material where required, minimizing material waste and reducing process complexity.

To quantify the environmental benefits of this approach, a comparative life-cycle assessment (LCA) was performed for three resistor integration strategies: (1) conventional PCB fabrication using discrete surface-mount resistors (SMT), (2) embedded NiCr/TCR® resistor foils fabricated using subtractive processing, and (3) carbon-based polymer thick-film (PTF) resistors deposited directly onto PCB substrates using a semi-additive manufacturing process. All scenarios were evaluated using a common functional unit consisting of a six-layer PCB panel providing equivalent resistor functionality.

Preliminary results indicate that the additive manufacturing approach reduces panel-level environmental impact relative to conventional embedded resistor foil processing. The reduction is primarily attributed to the elimination of resistor-specific lithographic operations, reduced chemical consumption, lower material consumption, and decreased process energy requirements. As shown in Figure 10, the additively manufactured resistor approach exhibits lower CO_2 emissions than the embedded NiCr/TCR® foil process. These findings suggest that direct-write fabrication can provide both manufacturing flexibility and measurable sustainability benefits while maintaining electrical performance demonstrated in this study.

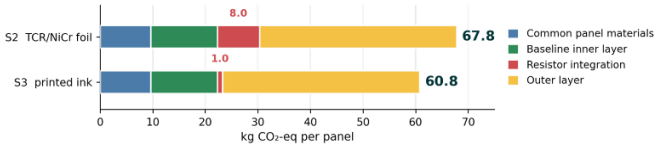


Fig. 10. Preliminary life-cycle assessment comparison between embedded NiCr foil resistors and printed resistor manufacturing approaches.

VI. Discussion

The results indicate that dimensional process control is a primary factor governing the repeatability of direct-write fabricated resistors. In particular, accurate control of deposited resistor thickness was found to have a greater influence on resistance variation. Testing of unpatterned substrates confirmed that corner-clamped thin laminates can deform substantially during the probing process with measured displacement reaching approximately 0.72 mm for a 0.3 mm substrate. By eliminating substrate deformation during the probing and printing processes through the implementation of vacuum-bed fixturing, resistor-to-resistor variation was reduced from greater than 150% to approximately 6%, demonstrating the critical role of substrate planarity and nozzle standoff control in achieving consistent electrical performance. In addition, using the improved printing process along with an empirical resistance-vs.-length calibration, nominal 25, 50, and 100 Ω resistor batches were fabricated with variation generally below ±5%, which is well within the ±20% target.

Preliminary life-cycle assessment results suggest that these performance levels can be achieved while reducing the environmental impact associated with conventional resistor foil fabrication.

Moving forward, several technical challenges remain, including reducing ink–copper interface-related resistance, and establishing robust process-control methodologies suitable for higher-volume manufacturing environments. Although these results indicate that calibration can be applied to reduce tolerance, long-term instability in the interface prevents the application of prediction models. Additional work is also required to evaluate long-term performance stability under manufacturing and operational conditions.

Nevertheless, the results presented in this study demonstrate that direct-write additive manufacturing is a viable alternative to conventional embedded resistor technologies. The approach offers significant advantages in design flexibility, rapid process iteration, reduced material consumption, and simplified manufacturing workflows while maintaining resistance tolerances suitable for embedded passive applications.

VII. Conclusions

Direct-write additive manufacturing was successfully demonstrated as a viable method for fabrication of embedded resistors on PCB-compatible substrates. Our results show that mechanical fixturing, accurate surface-height characterization, deposited geometry, and interface resistance are the principal process-control variables for repeatable direct-write resistor fabrication. Ongoing work includes the exploration of low-hazard, low-cost, scalable Cu passivation methods that generate lower CO_2 emissions. Additional reliability and environmental testing will also be performed on coupons designed to simulate embedded resistors in a manufacturing setting with temperature cycling. Future work will focus on scalable copper-passivation methods, environmental and reliability testing, and refinement of the LCA and TEA to incorporate the final passivation and manufacturing scale-up processes.

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