Additive Manufacturing of Electronic Circuits for Novel Applications

Daniel R. Hines

The next generation of electronic circuits will most likely not be flat, rectangular printed circuit boards (PCBs) as we are familiar with inside many of our computers and electronic gadgets. Such a form factor may be acceptable for controlling big, boxy electronics but not for sensors fitting within, say, a football players mouth guard or helmet, or on the skin of a premature infant in a neonatal unit. What if electronic sensors could be fabricated to be flexible, stretchable, or even built right into the gadget that they are designed to work with [1, 2]? For example, it takes a lot of time and effort to take an airplane out of service for a few days in order to inspect the air frame for wear-and-tear, material fatigue, microcracks, and other lifetime aging. What if strain sensors could be fabricated right into the airplane's fuselage or wings and monitored in real-time over the life of the airplane? With such a data set, recording the history of a specific plane (or any mechanical system for that matter) could provide a very advanced understanding of the need for maintenance or for an assessment of a safe, functional lifetime of the plane. Couple this with artificial intelligence (AI) and machine learning, and an industry could create a very powerful and much safer means of understanding the integrity and lifetime of many mechanical systems, not just airplanes.

Additive manufacturing printing methods

So, how can the fabrication of such next-generation sensors and electronic circuits be achieved? Let's consider the advancements that are being made in the area of additive manufacturing. We are all familiar with three-dimensional (3D) printers, where a filament passes through a heated nozzle and is printed layer-by-layer to fabricate some mechanical part of interest. Actually, such 3D printers come in many varieties which can typically print parts out of plastic and metal materials [3, 4, 5]. There is also a subcategory of 3D printers referred to as direct-write printers which encompass syringe, inkjet, and aerosol-jet (AJ) printing [6, 7]. An example of syringe printing could be the use of a piping bag for cake decorating, while an example of inkjet printing could be an inkjet printer used to print black and white or color copies of a paper document, and then an example of AJ printing could be a spray paint system or an artist's airbrush used to paint car bodies. For additive manufacturing, utilizing such direct-write printing methods, the passive (only conveying color or optical contrast) inks in the examples above would be replaced with active materials such as metal nanoparticle inks for printing conducting features or polymer inks for printing dielectric/insulating features [8]. Equipped with such functional inks, a direct-write printer could be used to print alternating layers of patterned conducting features separated by printed dielectric layers to fabricate circuitization (i.e., wiring) layers onto a given surface that would function in a manner equivalent to the copper/flame retardant 4 (FR4) layers in a PCB. Furthermore, other functional inks having resistive, magnetic, ceramic, etc. properties could also be used in such direct-write printers to print sensor elements.

While all three direct-write printing methods can and have been used to fabricate electronic components [9, 10], there are application-specific advantages to one method over another. For example, syringe printing typically requires the end of the printing tip to track the print surface within a distance equal to half the tip diameter. For fine feature printing, this could mean tracking a non-flat surface within 10–25 micrometers (μm). This can be a daunting task for non-ideal, non-flat surfaces. Inkjet printers are typically equipped with an array of microprint nozzles configured in a straight line. This multinozzle print head typically needs to track the surface at a distance of 2 millimeters (mm) above the print surface. Therefore, printing onto non-flat surfaces can be problematic with such a print system. When dealing with non-flat, 3D surfaces, AJ printing can offer a specific advantage over these two other printing methods in that an AJ print nozzle is set to track 3–5 mm above the print surface and therefore is rather insensitive to surface roughness and can be easily manipulated to print onto a 3D surface. For these reasons, the main body of work related to the application of additive manufacturing methods to the fabrication of high-quality electronic circuits and sensors presented below will focus on AJ printing.

Aerosol-jet printing

Currently available AJ printing tools come in two types, one where the aerosol is created using ultrasonic energy and one where the aerosol is created pneumatically. For the ultrasonic method, ultrasonic energy is transferred into an ink container such that a surface wave is created at the top surface of the ink, causing small droplets of ink to be "ripped off" the ink surface, thus creating an aerosol mist above the ink. This aerosol is then transported by a gas flow that carries this aerosol mist into a mist tube, thus creating an ink stream [11]. For the pneumatic method, much like in a stray paint can, ink is sucked up into a tube and forced through a pin hole by a gas flow stream. This Venturi effect creates an aerosol mist in the ink jar that is carried into the mist tube by the gas flow. Unlike the spray paint can, however, some of the gas flow needed to create the aerosol must be removed in order to establish a controllable ink stream, and the ink stream needs to be collimated so that it is confined to a diameter somewhere, typically, in the range of 10–200 μm. This can be accomplished by adding an aerodynamic-focusing insert and an exhaust in order to both collimate and reduce the gas flow rate of the ink stream as it enters the mist tube. A schematic drawing showing the details of an AJ print nozzle and a picture of a commercially available AJ printer printing a silver (Ag) nanoparticle ink onto a 4-inch hemisphere is shown in figure 1.

Measuring ink stream dynamics

With an ink stream having been created for a given ink on an AJ printer, the volume of ink printed must be set and/or measured in order to print a feature of a specified geometry [12, 13]. This can be done by mounting an inkwell array, similar to what is shown

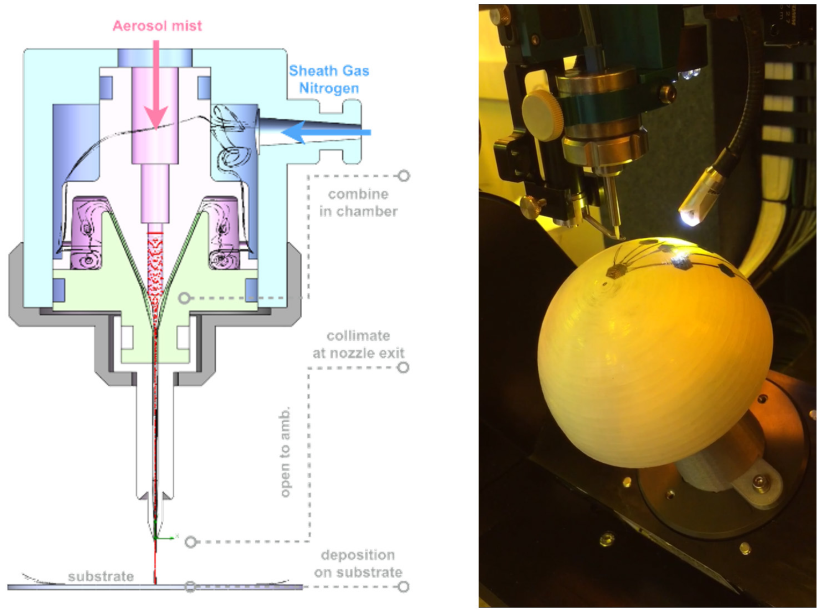

FIGURE 1. The cutaway drawing (left) highlights the ink stream dynamics within an aerosol jet (AJ) printer nozzle [11]. In the photograph (right), an AJ printer nozzle is being used to print a silver (Ag) nanoparticle ink onto the surface of a 4-inch hemisphere.

exact gas flow rates, changes in the ink over time, room temperature, and humidity, etc. Currently, there is no good way to track these changes in the ink stream, and so it is an interesting area for further research efforts [16]. Currently, the best method is to set a specific R_{ink} and then print a test trace. After post-processing, a post-processing deposition rate R_{pp} can be calculated by measuring the cross-sectional area (CS) of the test trace and multiplying that by the print speed (s) used to print the trace, such that $R_{\mathrm{pp}} = CS * s$. At this point, the solids fraction of the ink stream used to print the test trace can be represented as a scale factor (f) where $f = R_{\mathrm{pp}}/R_{\mathrm{ink}}$. Using these AJ printing techniques, it is possible to fabricate high-quality electronic components within an acceptable tolerance [17].

in figure 2, onto the build plate of the printer and sequentially printing into individual inkwells of a known volume (V_{inkwell}) for a specified time interval (t_{inkwell}) and adjusting the gas flow rates until each inkwell is just filled [14].

With this inkwell method, a specific ink stream deposition rate can be established where $R_{\mathrm{ink}} = V_{\mathrm{inkwell}}/\ t_{\mathrm{inkwell}}$. Knowing the exact deposition rate then allows for a specific volume of ink to be printed as required to print a feature with a specific designed volume, V_{design}. However, depending on the properties of a given ink, R_{ink} may not be the deposition rate that corresponds to the volume of a designed feature. This is because an ink can contain solvents, binders, etc. that are removed from the printed feature during post processing (e.g., curing, sintering), leaving only the "solids" as part of the final printed feature. Therefore, the "solids fraction" of an ink stream needs to be measured for a given ink on a given AJ printer [15]. Furthermore, depending on the dynamics of the ink stream, the solids fraction can vary depending on the

Printed hybrid electronics

What does it mean to additively fabricate an electronic sensor or circuit [18, 19, 20, 21]? Electronic circuits typically contain passive components (such as resistors, capacitors, and inductors) and active components [such as integrated circuits (ICs) wire-bonded into packages] soldered onto a PCB. Examples of printed resistors, capacitors, and inductors are

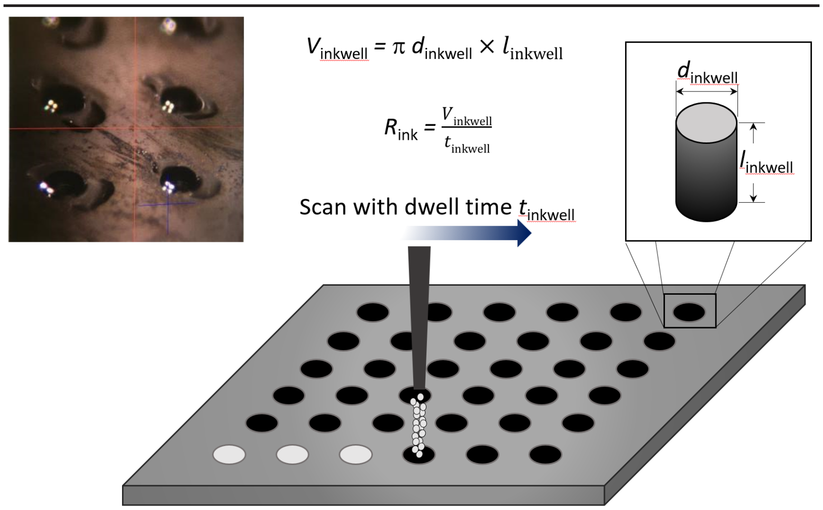

FIGURE 2. The inkwell method depicted here allows for the determination of an ink stream deposition rate R_{ink} [14].

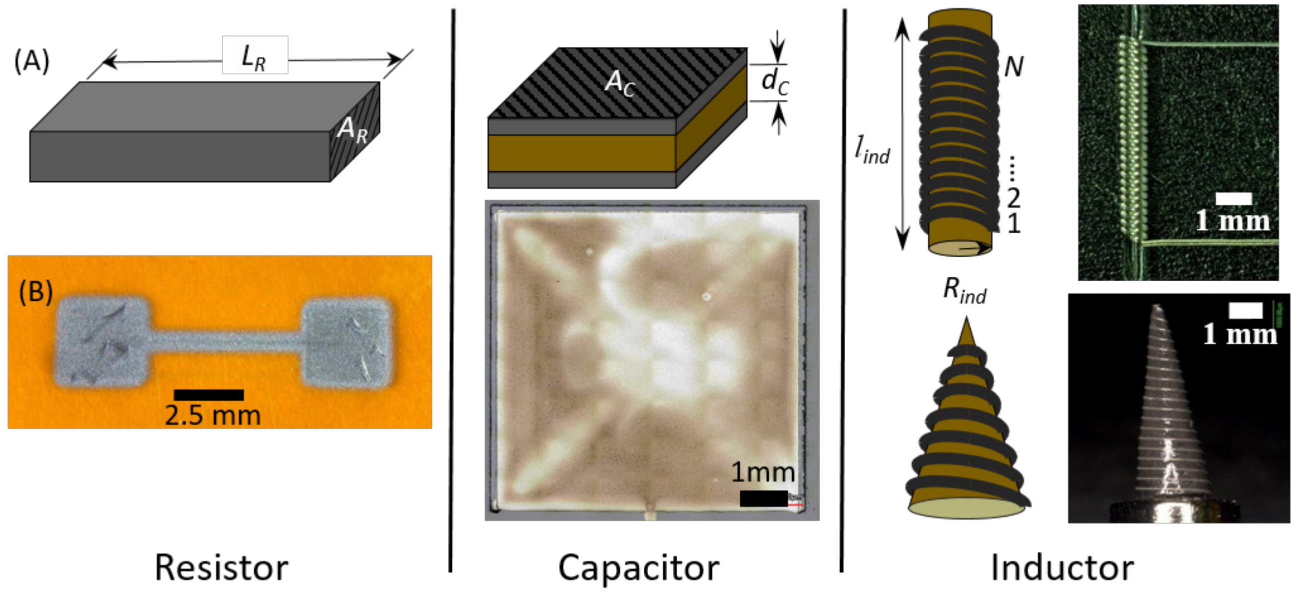

FIGURE 3. Passive components of electronic circuits can be additively fabricated as illustrated here in a printed resistor, a printed capacitor (center), and printed inductors (right).

shown in figure 3; however, most ICs are too complex to be additively fabricated. For example, it is not possible to print an integrated circuit on par with an Intel 16-bit 8088 from the late 1970's, let alone a 32-bit Pentium or 64-bit Core i7 processor from the last two decades.

Nevertheless, such an IC chip can be removed from its package and used stand-alone, where the package and lead frame are eliminated and the wire bonds are replaced by printed interconnects. An example of a packaged IC is compared to a bare die with printed interconnects in figure 4. This allows for a hybrid circuit approach to be developed, where components can be printed where possible and placed as bare die when printed versions are not possible. In addition to the printed and hybrid components, the PCB itself can be replaced with printed circuitization traces. Largely, it is this ability to print a replacement for the PCB that enables a variety of possibilities from rapid prototyping of circuits, to partially printed circuits, to fully printed hybrid electronic (PHE) circuits. Examples of each of these will be presented and discussed in the following section.

From rapid prototyping to PHE circuits

In figure 5, two commercially available circuit boards are shown, the first one is a Mini Circuits, Model ZFL-1000LN+, low noise amplifier (LNA) and the second is an Arduino Mini.

Both of these circuits can be modified such that rapid prototype and PHE versions can be fabricated using AJ printing methods. Let's first consider the LNA circuit in order to illustrate how additive manufacturing can be used for the rapid prototyping of

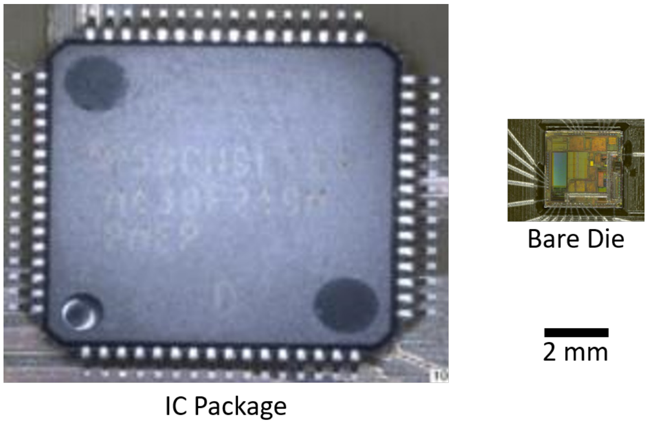

FIGURE 4. Most integrated circuits (ICs) are too complex to be additively fabricated but can be removed from their package and used stand-alone. Here is an example of a packaged IC containing the bare die microcontroller IC chip that is shown (left) as a stand-alone bare die with printed interconnects (right; scale bar related to both images).

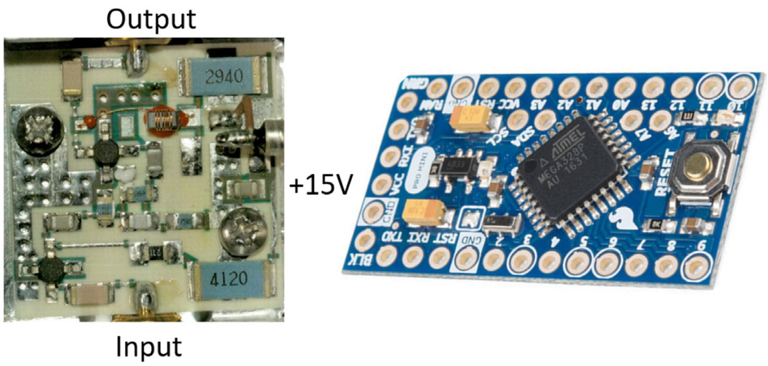

FIGURE 5. Standard commercially available PCBs—(left) Mini Circuits, Model ZFL-1000LN+, low-noise amplifier (LNA) and (right) an Arduino Mini—can be modified such that rapid prototype and PHE versions can be fabricated using AJ printing methods.

an electronic circuit. Suppose we wanted a similar circuit in a different form factor (geometry), that is, not a square geometry but rather a version that is long and skinny. Figure 6(a) shows the commercially available LNA circuit. The circuitization layout can be redesigned for a different form factor and turned into an AJ tool path that can be printed onto basically any surface. In figure 6(b), (c), and (d), versions of this circuit with circuitization are printed in ratios of 1:1 (b), 3:1 (c) and 5:1 (d) are shown [22].

Once a new design layout exists, depending on the complexity of the circuit, a new prototype can be printed in a matter of hours. At this prototype stage, the electronic components are still fully surface mounted. One of the challenges with this is that it is not easy to solder to printed Ag (the standard AJ conduction ink), and as such, the components are typically glued in place with a dot of electronic adhesive and then electrically connected by syringe printing an Ag paste that bridges between the component and the printed trace. This method works reasonably well but is not always as robust, as many of the Ag pastes end up creating a brittle electrical connection. This is an area that provides opportunities for further research into the ability to incorporate soldering methods into additively manufactured circuitization. As additive manufacturing of electronic circuits progresses from the rapid prototype capability to a fully fabricated PHE version of a circuit, it is possible to mix and match standard surface-mounted components, bare die versions of components, and printed components all together in a single circuit. Indeed, there will be many occasions where bare die versions of a packaged component are not available. One workaround to the soldering problem related to integrating such packaged components into an additively fabricated circuit is to use a leadless chip carrier (LCC) version that is mounted upside down in a cavity with printed interconnects. In this same manner, standard passive components can also be used prior to being swapped out for printed versions. Figure 7 shows an LCC packaged accelerometer and standard surface-mounted resistor both mounted in respective cavities.

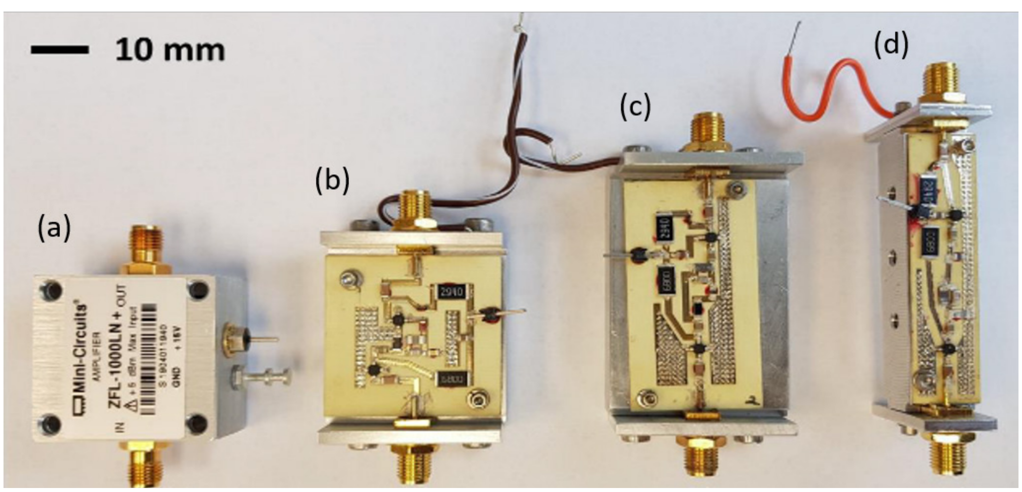

FIGURE 6. (a) For this unaltered LNA circuit, the circuitization layout can be redesigned for different form factors and turned into an AJ tool path that can be printed onto basically any surface, as seen in rapid prototypes **(b)** with a 1:1 ratio, **(c)** with a 3:1 ratio, and (d) with a 5:1 ratio.

Note that the cavity always has to be bigger than the component which necessitates a printed moat fill (red adhesive for the resistor and clear polymer for the accelerometer) to create a continuous, smooth surface onto which the interconnects can be printed. Where bare die are available, the bare die itself can be mounted onto a surface and

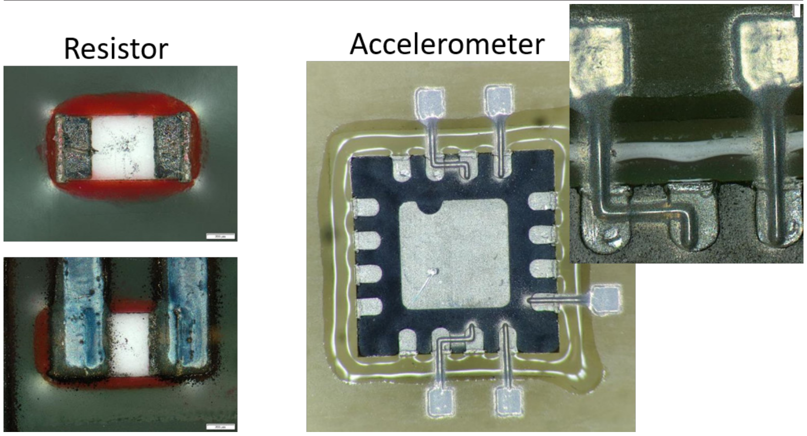

FIGURE 7. On the passive resistor (left) and packaged accelerometer (right), electronic components are mounted in cavities with moat fills printed to create a smooth transition for printed interconnects.

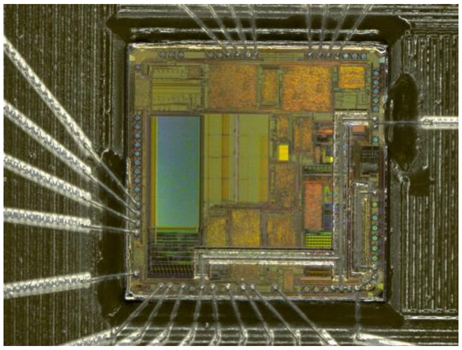

FIGURE 8. In this optical image of a bare die microcontroller chip, printed interconnects are applied over fillets that replace the more standard wire bonds within an IC package.

interconnects printed such that the electrical pads of the die are properly connected to the printed circuitization and thus, as such, properly connected into the electric circuit. Figure 8 shows an example of a bare die with printed interconnects.

Just as with cavity-mounted components, the printed interconnects here also need to have a smooth, continuous surface over which they are printed. A typical bare die can have a thickness of 50–500 μm and so a "ramp" needs to be printed along the edge of the bare die in order to establish the required smooth surface [23]. Such fillets can be seen along the die edges, where needed, in the image shown in figure 8. With the capabilities highlighted in figures 6, 7, and 8, we can redesign the Arduino mini circuit shown in figure 4 so that the circuitization for a similar PHE circuit can be additively fabricated. Figure 9(a) illustrates what is referred to as a three-layer circuit that represents an AJ printable, PHE circuit designed to have similar functionality to an Arduino Mini type circuit.

The red, green, and purple features map out the three circuitization layers, and the magenta features map out the component interconnects. This PHE circuit-level demonstrator contains: 1) a bare die version of an Atmega328P microcontroller (in blue, just below and to the left of center in the circuit layout), 2) an LCC-packaged version of a three-axis accelerometer (in blue to the right of center in the circuit layout), 3) LCC versions of both a 5-volt and a 3.3-volt power regulator, and 4) a variety of cavity-mounted resistors, capacitors, and LEDs; a resistor and LED are highlighted by the red box in the right image). Figure 9(b) shows the corresponding, fully fabricated PHE circuit, printed on a flat, 3D printed substrate. PHE fabrication methods not only enable printing onto flat surfaces, but also allow for the fabrication of circuits onto truly 3D surfaces. The circuit design in figure 10 illustrates an earlier version of the PHE circuit projected onto the surface of a 4-inch hemisphere. In the same way that the PHE circuit shown in figure 9 was fabricated, this hemispherical

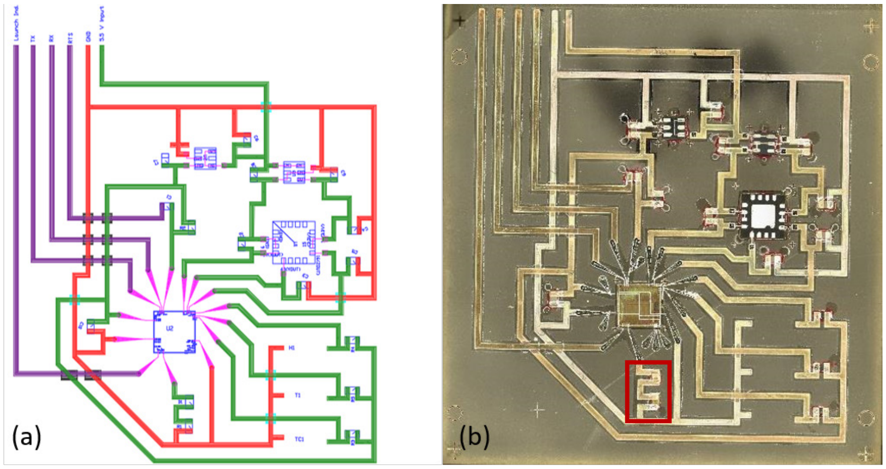

FIGURE 9. The design of a PHE version of an Arduino-type electronic circuit (left) is pictured alongside the fully fabricated AJ printed PHE circuit-level demonstrator (right).

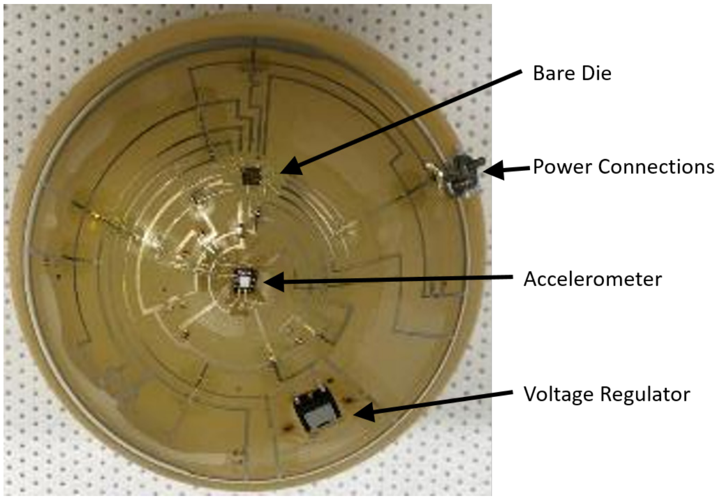

FIGURE 10. Design of a 4-inch hemisphere version of the PHE circuit shown in figure 9 along with the AJ printed, fully fabricated circuit.

circuit was fabricated onto a similarly 3D-printed surface. The only difference in fabrication was that, for the hemispherical circuit shown in figure 10, a five-axis AJ printer was used, while for the flat circuit in figure 9, a three-axis AJ printer was used.

Next steps

As with any new, next-generation technology, proving out reliability and real-world application can be a challenge. This is definitely the case with PHE printing methods used to fabricate 3D, additively fabricated electronic circuits. With this in mind, we are in the process of fabricating some 220 component-level test coupons relevant to the PHE circuit-level demonstrators shown in figure 9 that will go through full reliability testing. Additionally, we are partnering with a number of other government groups, defense industrial base companies, and NextFlex the Manufacturing Innovation Institute (MII) for flexible hybrid electronics (FHE), in order to advance the additive manufacturing ecosystem and prove out the capabilities of this technology. For example, we are collaborating with NASA [Goddard Space Flight Center (GSFC), Marshall Space Flight Center (MSFC), and their Sounding Rocket Operation Center (NSROC)] to fabricate the PHE circuit onto the inside surface of a door panel for

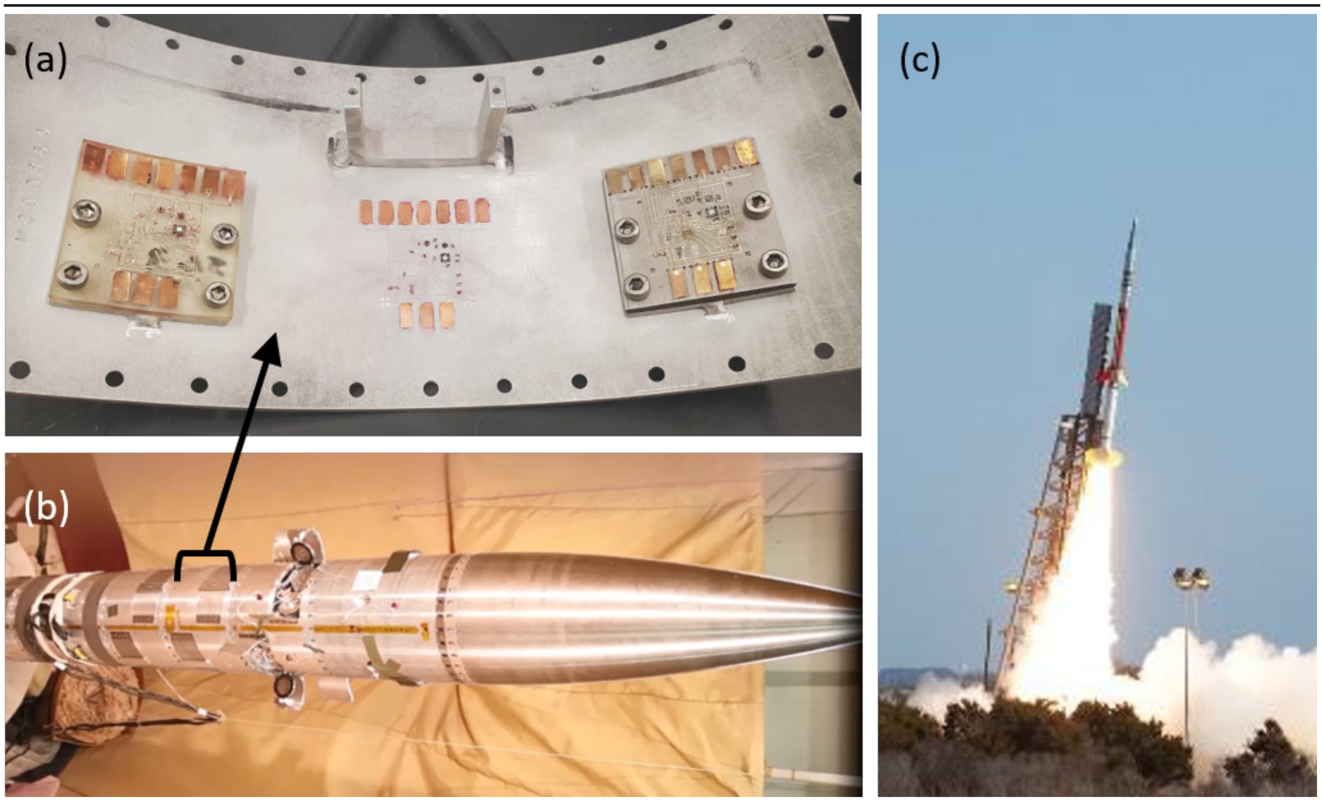

FIGURE 11. (a) The layout of a curved version of the PHE circuit will be fabricated onto the inside surface of a sounding rocket door panel; **(b)** the sounding rocket is pictured during testing and **(c)** launching.

a sounding rocket launch in late 2022. A conceptual mock-up is shown in figure 11 with the actual rocket door panel. Included in the figure is a photo of a rocket in test and at launch.

Conclusion

Additive manufacturing holds great promise as a next-generation method for the fabrication of electronic circuits. For one thing, a stand-alone PCB can now be replaced by printing multilayer circuitization onto non-flat surfaces. This allows for the rapid prototyping of circuits that can take on completely different form factors than has been possible in the past. Additionally, printed and hybrid versions of electronic components are typically thinner and lighter weight as compared to their surface-mounted counterparts. This also eliminates the need for soldering, thus further reducing not only weight but also high thermal stress, processing steps, and the number of different materials involved in the overall fabrication process. All in all, the maturity of additive manufacturing methods applied to the fabrication of electronic circuits has the potential to usher in a new era of electronics integration where the circuitry will become inseparable from the mechanical, geometrical aspect of the physical gadget that it controls.

References

[1] Huang YA, Wu H, Xiao L, Duan Y, Zhu H, Bian J, Ye D, Yin Z. "Assembly and applications of 3D conformal electronics on curvilinear surfaces." *Materials Horizons.* 2019;6(4):642–683. Available at: https://doi.org/10.1039/C8MH01450G.

[2] Wu H, Tian Y, Luo H, Zhu H, Duan Y, Huang Y. "Fabrication techniques for curved electronics on arbitrary surfaces." *Advanced Materials Technologies.* 2020;5(8):2000093. Available at: https://doi.org/10.1002/admt.202000093.

[3] MacDonald E, Wicker R. "Multiprocess 3D printing for increasing component functionality." *Science.* 2016;353(6307). Available at: https://doi.org/10.1126/science.aaf2093.

[4] Gao W, Zhang Y, Ramanujan D, Ramani K, Chen Y, Williams CB, Wang CC, Shin YC, Zhang S, Zavattieri PD. "The status, challenges, and future of additive manufacturing in engineering." *Computer-Aided Design.* 2015;69:65–89. Available at: https://doi.org/10.1016/j.cad.2015.04.001.

[5] Ligon SC, Liska R, Stampfl J, Gurr M, Mulhaupt R. "Polymers for 3D printing and customized additive manufacturing. *Chemical Review.* 2017;117(15):10212–10290. Available at: https://doi.org/10.1021/acs.chemrev.7b00074.

[6] Espalin D, Muse DW, MacDonald E, Wicker RB. "3D Printing multifunctionality: structures with electronics." *The International Journal of Advanced Manufacturing Technology.* 2014;72:963–978. Available at: https://doi.org/10.1007/s00170-014-5717-7.

[7] Li J, Wasley T, Nguyen T, Ta V, Shephard JD, Stringer J, Smith P, Esenturk E, Connaughton C, Kay R. "Hybrid additive manufacturing of 3D electronic systems." *Journal of Micromechanics Microengineering.* 2016;26(10):105005. Available at: https://doi.org/10.1088/0960-1317/26/10/105005.

[8] Hou Z, Lu H, Li Y, Yang L, Gao Y. "Direct ink writing of materials for electronics-related applications: A mini review." *Frontiers in Materials.* 2021;8:647229. Available at: https://doi.org/10.3389/fmats.2021.647229.

[9] Kwon KS, Rahman MK, Phung TH, Hoath SD, Jeong S, Kim JS. "Review of digital printing technologies for electronic materials." *Flexible and Printed Electronics.* 2020;5(4):043003. Available at: https://doi.org/10.1088/2058-8585/abc8ca.

[10] Wilkinson N, Smith M, Kay R, Harris R. "A review of aerosol jet printing—a non-traditional hybrid process for micro-manufacturing." *The International Journal of Advanced Manufacturing Technology.* 2019;105(11):4599–4619. Available at: https://doi.org/10.1007/s00170-019-03438-2.

[11] Chen G, Gu Y, Tsang H, Hines DR, Das S. "The effect of droplet sizes on overspray in aerosol-jet printing." *Advanced Engineering Materials.* 2018;20(8):1701084. Available at: https://doi.org/10.1002/adem.201701084.

[12] Yoo D, Mahoney CM, Deneault JR, Grabowski C, Austin D, Berrigan JD, Glavin N, Buskohl PR. "Mapping drift in morphology and electrical performance in aerosol jet printing." *Progress in Additive Manufacturing.* 2021;6:257–268. Available at: https://doi.org/10.1007/s40964-021-00165-7.

[13] Tafoya RR, Secor EB. "Understanding and mitigating process drift in aerosol jet printing." *Flex. Print. Electron.* 2020;5(1):015009. Available at: https://doi.org/10.1088/2058-8585/ab6e74.

[14] Gu Y, Gutierrez D, Das S, Hines D. "Inkwells for on-demand deposition rate measurement in aerosol-jet based 3D printing." *Journal of Micromechanics Microengineering.* 2017;27(9):097001. doi: 10.1088/1361-6439/aa817f.

[15] Hines DR, Gu Y, Martin AA, Li P, Fleischer J, Clough-Paez A, Stackhouse G, Dasgupta A, Das S. "Considerations of aerosol-jet printing for the fabrication of printed hybrid electronic circuits." *Additive Manufacturing.* 2021;47:102325. Available at: https://doi.org/10.1016/j.addma.2021.102325.

[16] Tafoya RR, Cook AW, Kaehr B, Downing JR, Hersam MC, Secor EB. "Real-time optical process monitoring for structure and property control of aerosol jet printed functional materials." *Advanced Materials Technologies.* 2020;5(12):2000781. Available at: https://doi.org/10.1002/admt.202000781.

[17] Yi C, Fedderwitz R, Park D, Ding C, Lu G-Q, Fleischer J, Li P, Kofinas P, Das S, Hines DR. "Fully printed resonance-free broadband conical inductors using engineered magnetic inks." *Additive Manufacturing.* 2021:44:102034. Available at: https://doi.org/10.1016/j.addma.2021.102034.

[18] Khan Y, Garg M, Gui Q, Schadt M, Gaikwad A, Han D, Yamamoto NA, Hart P, Welte R, Wilson W. "Flexible hybrid electronics: Direct interfacing of soft and hard electronics for wearable health monitoring." *Advanced Functional Materials.* 2016;26(47):8764–8775. Available at: https://doi.org/10.1002/adfm.201603763.

[19] Khan Y, Thielens A, Muin S, Ting J, Baumbauer C, Arias AC. "A new frontier of printed electronics: Flexible hybrid electronics." *Advanced Materials.* 2020;32(15):1905279. Available at: https://doi.org/10.1002/adma.201905279.

[20] Hoerber J, Glasschroeder J, Pfeffer M, Schilp J, Zaeh M, Franke J. "Approaches for additive manufacturing of 3D electronic applications." *Procedia CIRP.* 2014;17:806–811. Available at: https://doi.org/10.1016/j.procir.2014.01.090.

[21] Gupta AA, Bolduc A, Cloutier SG, Izquierdo R. "Aerosol jet printing for printed electronics rapid prototyping." In: *2016 IEEE International Symposium on Circuits and systems (ISCAS);* 2016 May 22-25; Montreal, QC, Canada: pp. 866–869. Available at: https://doi.org/10.1109/ISCAS.2016.7527378.

[22] Clough-Paez A, Yi C, Park D, Ketchum D, Hines DR. "Rapid prototyping of 3D printed, high aspect ratio, low noise amplifier for active hand-held sensor devices." Submitted to *IEEE Transactions on Components, Packaging and Manufacturing Technology* for publication (2022).

[23] Gu Y, Hines DR, Yun V, Antoniak M, Das S. "Aerosol-Jet printed fillets for well-formed electrical connections between different leveled surfaces." *Advanced Materials Technologies.* 2017;2(11):1700178. Available at: https://doi.org/10.1002/admt.201700178.