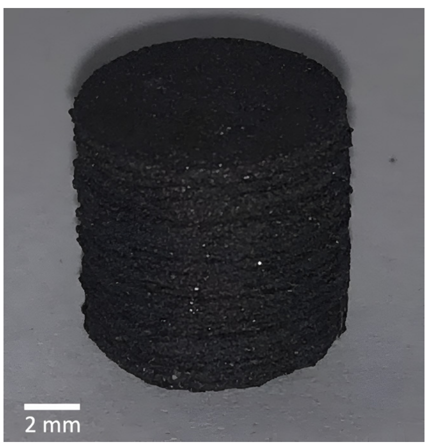
3DHI & Additive Manufacturing

Additively Manufactured Permanent Magnets

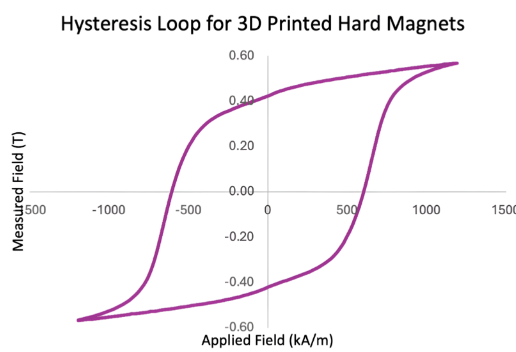
Z. Bigelow, L. F. Velásquez-García
Sponsorship: Empiriko Corporation

Hard magnets are extensively used in numerous industries, including electronics, automotive, renewable energy, healthcare, and consumer goods. However, conventional methods for producing these magnets are limited to simple shapes and require assembly, leading to increased production costs and constrained geometries and devices.

We present a novel three-dimensional (3D) printing process capable of producing hard magnets using micro- and nano-reinforced materials, thereby expanding the scope of their practical applications. Our research focuses on the fabrication of isotropic magnets at a miniature scale, typically ranging in size from a few millimeters. The material composition utilized in our printing process consists of a blend comprising 75% NdFeB and 25% Nylon 12 by volume. Our 3D-printed hard magnets exhibit a measured remanence of 0.423 T, coercivity of 606.7 kA/m, and energy product of 29.5 kJ/m^3. These results illustrate the feasibility of 3D printing hard magnets and underscore the potential for fine-tuning magnetic properties through additive manufacturing techniques. These advancements offer precise control over magnet geometry and performance, presenting significant opportunities for industries seeking tailored magnetic solutions.



▲ Figure 1: 3D printed 75% NdFeB magnet.



▲ Figure 2: Hysteresis loop analysis of a 3D printed 75% NdFeB magnet.

FURTHER READING

- A. P. Taylor, J. Izquierdo-Reyes and L. F. Velásquez-García, "Compact, Magnetically Actuated, Additively Manufactured Pumps for Liquids and Gases," *J. of Physics D–Applied Physics*, vol. 53, no. 35, 355002, Aug. 2020. doi: 10.1088/1361-6463/ab8de8
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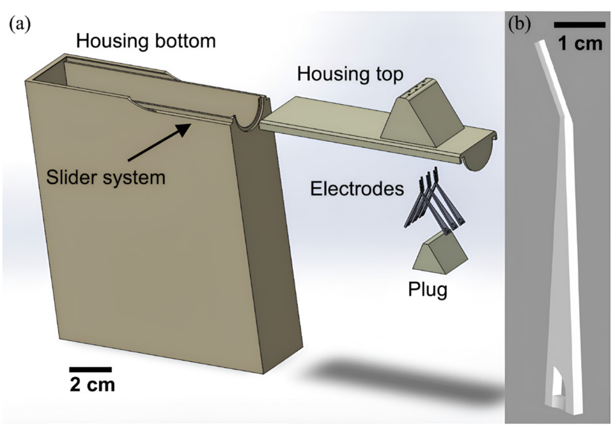
3D-Printed CubeSat Plasma Sensors

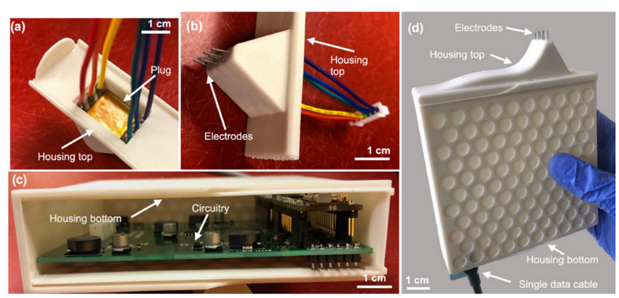
Z. Bigelow, L. F. Velásquez-García
Sponsorship: MIT Portugal

The ionosphere, a critical layer of Earth's atmosphere, is composed of plasma, a qua-si-neutral, superheated state of matter consisting of neutral molecules, ions, and elec-trons. The thermosphere, a region within the ionosphere (ranging 80–600 km above Earth's surface) plays a significant role in global warming. Obtaining accurate plasma measurements in this region has proven challenging since the most reliable data is gathered by satellites orbiting within the thermosphere itself. Given the high cost associated with launching hardware into space, the use of miniaturized satellites, e.g., CubeSats, is an ideal solution to collect ionospheric plasma data. Thus, a strong demand exists for low-cost and compact plasma sensors that can be directly integrated into CubeSats.

We report the design, fabrication, and characterization of a novel, compact, and fully additively manufactured multi-Langmuir probe (MLP) for CubeSat ionospheric plasma diagnostics (Figure 1). The MLP incorporates three different Langmuir probe (LP) arrangements (single, dual, and triple LPs) to accurately measure a wide range of plasma properties with redundancy. The reported MLP has integrated low-power, compact electronics and is manufactured via 3D-printing; consequently, it is a plasma sensing solution compatible with CubeSats that aligns with in-space manufacturing. The dielectric parts of the MLP are made via vat photopolymerization of vitrolite; the conductive parts are made via binder jetting of SS 316L. The electronics of the MLP were verified using calibrated equipment. Experimental characterization of MLP prototypes was conducted using a laboratory helicon plasma chamber and showed good agreement across different LP configurations. The first of its kind, the MLP (Figure 2) enables superior and more affordable CubeSat plasma sensors and aims at providing crucial data to improve understanding of ionospheric plasma and its implications for climate change.



▲Figure 1: (a) Computer-aided design (CAD) exploded view of MLP. Driving electronics are inside housing bottom. Housing top and bottom are assembled using slider mechanism. (b) CAD close-up of LP electrode used in MLP.



▲Figure 2: Selected images of MLP during assembly. (a) Underside of housing top showing plug holding electrodes in place. (b) Top side of housing top showing array of electrodes protruding. (c) Housing bottom with driving circuit inside. (d) Fully assembled device.

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Fully 3D-printed, Three-dimensional Cored Solenoids

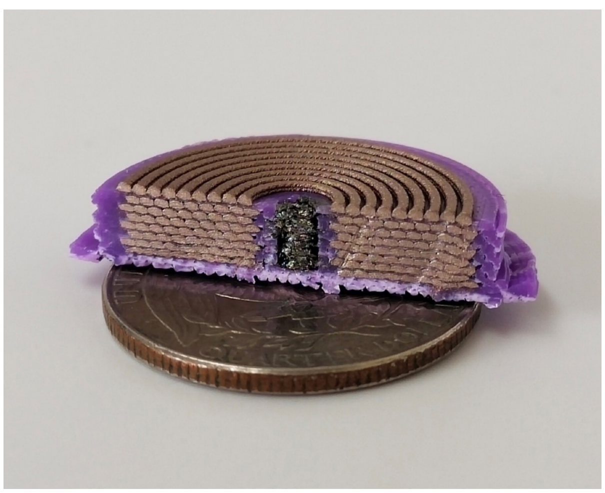
J. Cañada, L. F. Velásquez-García
Sponsorship: Empiriko Corporation, "la Caixa" Foundation

Additive manufacturing can readily produce freeform, mechanically functional parts, including complex systems, e.g., pumps. However, the three-dimensional (3D) printing of electronic components that could enable the monolithic manufacture of integrated electromechanical devices is lagging. Material extrusion, also known as fused filament fabrication (FFF), is an accessible additive manufacturing technique. FFF allows the monolithic fabrication of parts comprising multiple materials, e.g., dielectric and conductive. Reports of 3D-printed resistors, capacitors, and inductors demonstrate the feasibility of 3D-printing electronic components via dielectric- conductive material extrusion. However, the 3D-printed inductors reported in the literature are limited to two-dimensional designs. This work aims to improve the versatility and performance of 3D-printed solenoids by expanding them to truly 3D designs and adding soft magnetic cores.

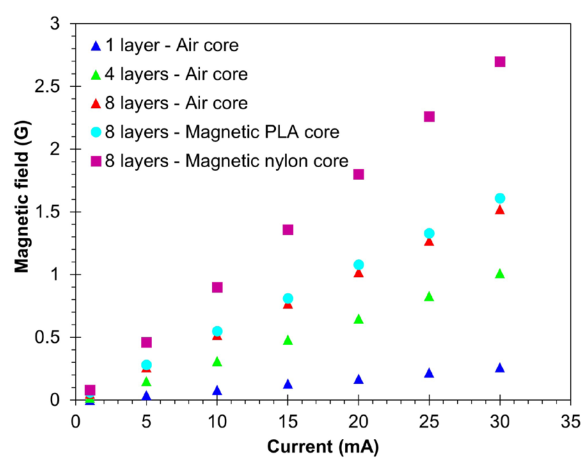
The 3D-printed solenoids have been fabricated through material extrusion using polylactic acid (PLA)- and nylon-based materials: we used dielectric PLA to produce insulation films and structural support features, copper microparticle-doped PLA to create a spiraling conductive trace, and iron-doped PLA and FeSiAl-doped nylon to fabricate soft magnetic cores to be embedded at the center of the structures. By stacking conductive spirals and insulation films, we created truly 3D solenoids (Figure 1).

Magnetic field measurements reveal that 3D-printed solenoids can generate Gauss-level magnetic fields while drawing tens-of-mA currents. The magnitude of the magnetic fields that the solenoids can generate strongly correlates to the number of stacked conductive layers and to the presence of a soft magnetic core. Moreover, an increase in the magnetic permeability of the material used to produce the cores can boost the generated magnetic fields (Figure 2).

This technology is of particular interest for low-cost, low-waste manufacturing of integrated devices and highly customized hardware in remote areas with limited access to resources and manufacturing equipment (e.g., in-space manufacturing).



▲ Figure 1: Three-dimensional, monolithically 3D-printed FeSiAl nylon-cored solenoid cut in half, on top of a U.S. quarter.



▲ Figure 2: Measured magnetic field vs. current for various 3D-printed solenoids.

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- I. A. Perales and L. F. Velásquez-García, "Fully 3D-Printed Carbon Nanotube Field Emission Electron Sources with In-Plane Gate Electrode," *Nanotechnology*, vol. 30, no. 49, p. 495302, Dec. 2019. doi: 10.1088/1361-6528/ab3d17

Fully 3D-printed, Semiconductor-free Logic Devices

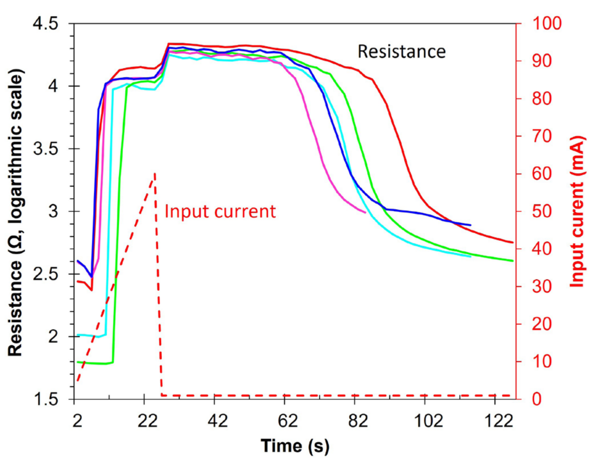
J. Cañada, L. F. Velásquez-García
Sponsorship: Empiriko Corporation, "la Caixa" Foundation

Additive manufacturing technologies can readily produce complex, structurally functional parts, including complex microfluidics. There are also reports of three-dimensional (3D)-printed, passive electronic components (e.g., resistors, capacitors, inductors) and electromechanical devices, including sensors and actuators. However, the 3D printing of active electronics with control and processing capabilities remains a challenge. As a result, the integration of additively manufactured electromechanical devices necessarily relies on off-the-shelf components and integrated circuits to produce functional, controllable systems.

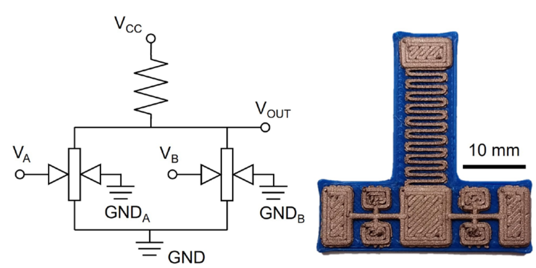
This work reports the first proof-of-concept demonstration of fully 3D-printed, semiconductor-free active electronic devices. The devices are fabricated via material extrusion—one of the most accessible 3D printing technologies. Material extrusion creates parts by heating up feedstock and pushing it through a nozzle, constructing parts layer by layer; it is one of the few additive manufacturing technologies that allows monolithic multi-material fabrication.

The active electronic devices have been fabricated combining dielectric polylactic acid (PLA) (as substrate) and copper-reinforced PLA. The devices take advantage of a newly discovered reversible fuse-like behavior exhibited by narrow 3D-printed traces of copper-reinforced PLA: when a high-enough current is applied to a trace, its resistance spikes by orders of magnitude; after it cools down, its resistance drops to its original range (Figure 1). Harnessing this phenomenon, we created a switching device qualitatively comparable to a p-channel metal-oxide semiconductor transistor to use as a building block to implement fully 3D-printed, semiconductor-free logic gates (Figure 2).

This technology allows the monolithic fabrication of electromechanical devices integrating simple control and data processing functions and can enable the additive manufacture of fully functional, intelligent devices, right off the printer bed. The technology holds particular interest for low-cost, low-waste manufacturing of integrated devices and highly customized hardware in remote areas with limited access to resources and manufacturing equipment (e.g., in-space manufacturing).



▲ Figure 1: Resistance of narrow 3D-printed traces of copper-reinforced PLA (solid lines) when subjected to ramp up current (dashed line) and then allowed to cool down. Voltage limited to 30 V.



V_{CC} (V)	V_A (V)	V_B (V)	V_{OUT} (V)
6	0	0	0.03
	0	20	0.08
	20	0	0.73
	20	20	5.3

▲ Figure 2: Fully 3D-printed AND gate: schematic (top left), picture of fabricated device (top right), and input/output signals (bottom).

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Additively Manufactured Quadrupole Mass Filter with Unity Mass Resolution

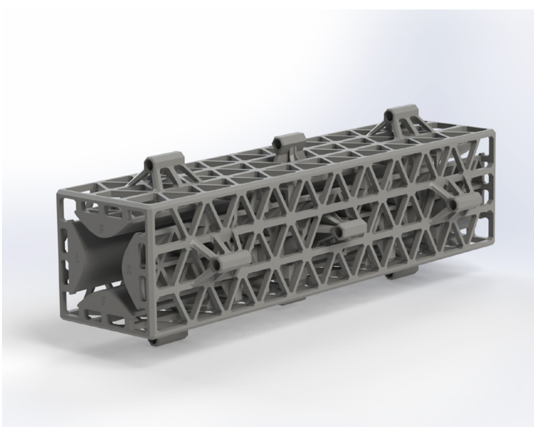
C. Eckhoff, L. F. Velásquez-García
Sponsorship: Empiriko Corporation

Mass spectrometry is a crucial analytical technique in any field that works with chemistry. The heart of a mass spectrometer is the mass filter, a structure that sorts species based on their mass-to-charge ratio. There have been numerous efforts to miniaturize and reduce the cost of mass filters to broaden the range of applications of mass spectrometry.

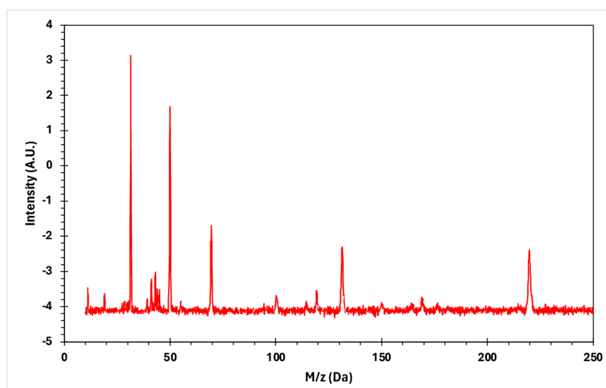
A quadrupole mass filter (QMF) is a popular choice for a mass filter due to its sturdiness, mass range, resolution, and sensitivity. Unfortunately, miniaturizing QMFs usually significantly compromises their performance because high-quality QMFs require high relative manufacturing precision. We have successfully approached this problem by employing advanced additive manufacturing to make a lower-cost, lighter-weight QMF that still boasts exceptional performance for practical mass spectrometry.

Our devices feature a monolithic and skeletonized design, integrating all four electrode rods into a single piece for precise alignment and reduced assembly needs. This design not only cuts production costs, but also creates lightweight components. Utilizing digital light processing (DLP) of glass ceramics, we printed the QMF geometry, which is then selectively metallized with electroless nickel-boron plating. To ensure electrode isolation, a lacquer-based maskant was applied at specially designated points—imperative for monolithic designs. One of our QMFs requires 10s of U.S. dollars in materials and takes about a day to manufacture.

Mass spectra experiments showcase well-resolved peaks with full width at half maximum (FWHM) of 0.7 Da or less at 69 m/z (the threshold of unity mass resolution). These exciting results bolster the potential of additive manufacturing to create portable mass spectrometers and other next-generation scientific instruments. Our primary focus now falls on further enhancing the device's performance to be compatible with isotope detection and increased mass range.



▲Figure 1: Rendering of device, showcasing monolithic fabrication and skeletonized architecture.



▲Figure 2: Scan of PFTBA with unity mass resolution at 69 m/z.

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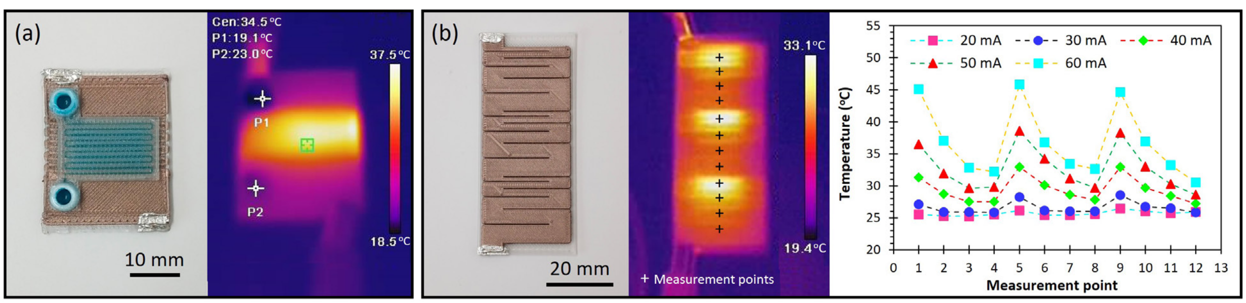
Additively Manufactured, Monolithic, Self-Heating Microfluidic Devices

J. Cañada, L. F. Velásquez-García
Sponsorship: Empiriko Corporation, "la Caixa" Foundation

Temperature regulation is critical in many microfluidic applications, e.g., to sustain living organisms, to trigger specific chemical reactions. Temperature regulation techniques often involve the use of bulky equipment, and integrated cooling-heating systems rely on costly fabrication processes.

We propose the use of multi-material extrusion 3D printing to create monolithic, self-heating microfluidic devices. The proof-of-concept devices are fabricated using two polylactic acid-based materials: one dielectric, used to produce the microfluidic channels; and one conductive, used to fabricate heat-generating resistors. The ability of material extrusion to create custom, intricate patterns enables the fabrication of complex, application-specific designs of both the microfluidic structure and the heating system. This technology can greatly impact the yield of microfluidic research by enabling the fast, inexpensive, in-house fabrication of custom, self-heating microfluidic devices.

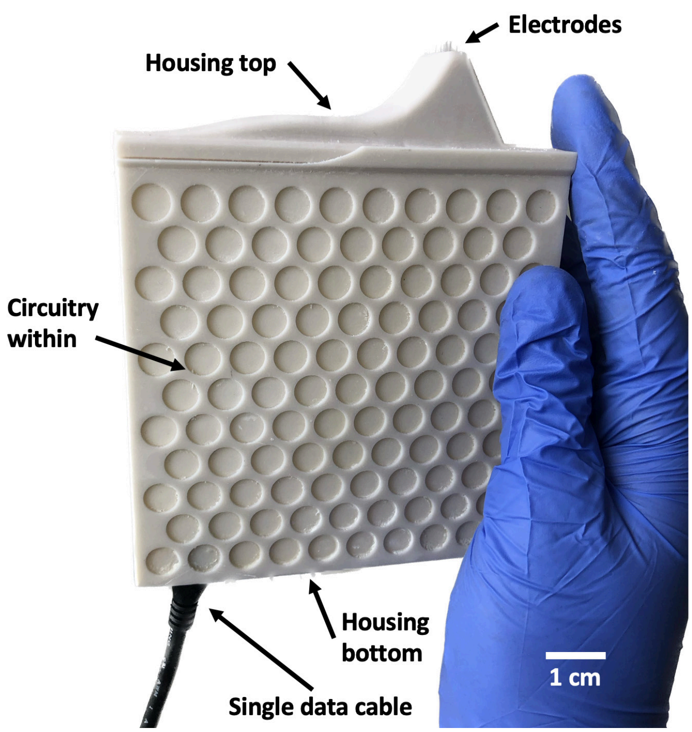


▲ Figure 1: (a) Optical and thermal images of a 3D-printed, self-heating microfluidic device, and (b) Optical and thermal images, and measured temperature profiles of a custom 3D-printed heater.

Miniature 3D-Printed Super Sensor: Multi-Langmuir Probe Device for CubeSat Ionospheric Plasma Diagnostics

Z. Bigelow, L. F. Velásquez-García
Sponsorship: MIT Portugal, NewSat Flagship Project

The ionosphere is a plasmic part of Earth's atmosphere which affects climate change. Studying it requires satellite based in-situ measurements and the versatility of Langmuir probes make them ideal for this. We report the design, fabrication, and characterization of a compact, fully 3D printed, multi-Langmuir probe (MLP) for use on CubeSats. The MLP has low-power, compact electronics and is fully 3D printed, to be compatible with in-space manufacturing. The MLPs are made via vat photopolymerization of vitrolite for the dielectric parts and binder jetting SS 316L for the conductive parts. The MLP uses three different Langmuir probe arrangements (single, dual, and triple) to measure a wide range of plasma properties with redundancy. The MLP was tested in a helicon plasma chamber, showing good agreement across the different configurations. This MLP enables cheaper CubeSat plasma sensors and aims at improving our understanding of the ionosphere and its effects on climate change.



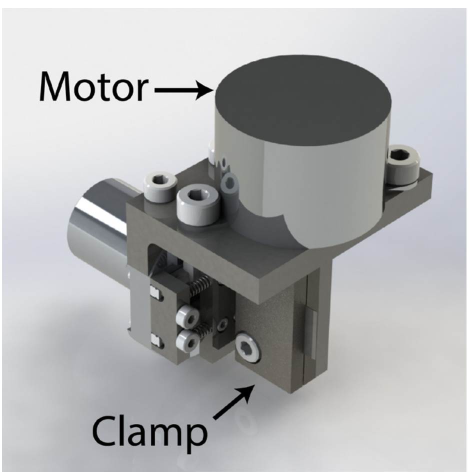
▲ Figure 1: MLP device fully assembled, with relevant parts labelled.

High-precision Adhesion Measurements for Heterogeneous Lintegration

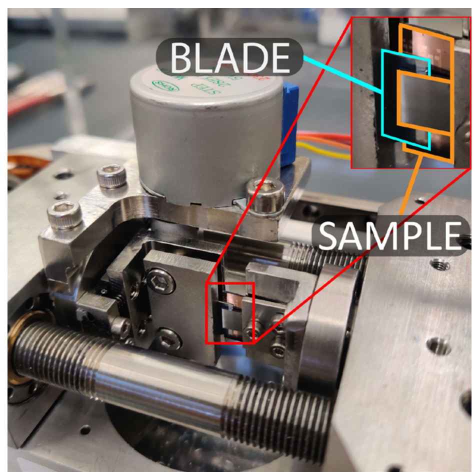
A. T. Wang, C. C. Tasan, C. V. Thompson
Sponsorship: SRC/DARPA, Mitsubishi Materials Corporation

Advances in computing power require rapid development of new materials and processes for heterogeneous integration with two-and-a-half dimensional (2.5D) and three-dimensional (3D) architectures. These architectures require bonding between integrated circuits (ICs) fabricated as separate dies that are interconnected with high densities of electrical interconnects. From a reliability perspective, these bonds may pose an issue since thermomechanical stresses may cause delamination. To assess this risk, adhesion tests must more accurately quantify the strength of the bonds, or more specifically, the work of adhesion. This term represents the energy required to de-bond a sample, which includes any plastic work from permanent deformation and elastic energy released from crack propagation. Ideally, characterization of specific failure mechanisms would be carried out through in situ mechanical testing in scanning electron microscopes (SEMs).

We considered several adhesion measurement tests and selected the wedge test based upon sample size limitations and measurement precision. The wedge test involves inserting a blade between the bonded samples and observing the delamination. The drawback of the wedge test is that it is typically done by hand, which often leads to imprecision. We have resolved this issue by designing and building a setup which can allow the test to be done with a deformation stage. The stage is designed for tensile/compressive testing of small samples and therefore has high force resolution (0.02 to 2000 N) and controlled constant displacement rates (0.1 to 20 μm/s). Furthermore, the deformation stage can be put inside an scanning electron microscope (SEM), which allows for high resolution observations of de-bonding mechanics. The setup also allows for alignment of the blade and the sample within the SEM using a cam-style linear actuator. We performed a proof-of-concept test with the setup. Figure 1 shows a computer model of one side of the designed parts; and Figure 2 shows an SEM micrograph of the proof-of-concept test. GoMoving forward, we plan ton working with university and industry collaborators to begin testing complex bonded structures.



▲ Figure 1: One side of the designed setup consisting of a clamp to hold the blade and a motor connected to a cam twhichat can move the clamp left and right to precisions within one micrometer.



▲ Figure 2: Proof-of-concept of the wedge test with an insert depicting a closer view of the blade being inserted into a bonded sample.

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Development of a GaN/ Si CMOS Stacked-3DIC Platform for W-band Applications

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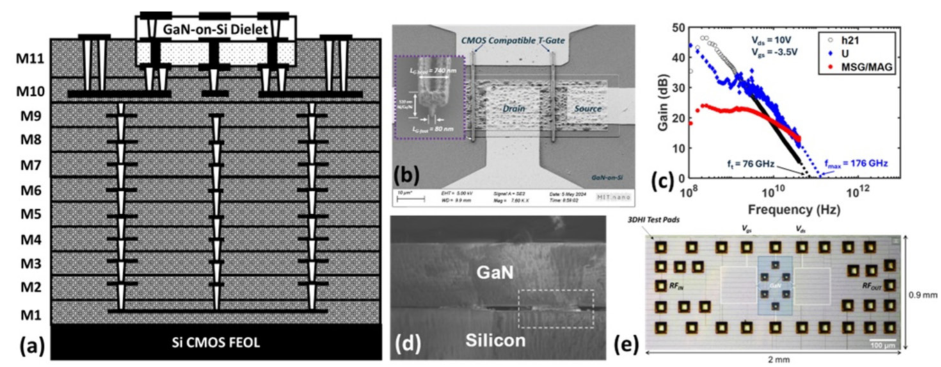
Sponsorship: United States Air Force Office of Scientific Research (Grant No. FA9550-22-1-0367), SRC JUMP 2.0 (Grant No. 2023-JU-3136), Lockheed Martin Corp. (Grant No. 025570-00036), Advanced Research Projects Agency-Department of Energy (Grant No. DE-AR0001591), and National Defense and Science Graduate Fellowship

With data rates pushing into the Tbps for augmented/virtual reality, there is an urgent need for the use of sub-terahertz radio-frequency (RF) front ends and transistors. GaN transistors are an ideal candidate for the front-end-of-line (FEOL) as they push the limits of high-power density, high frequency semiconductor devices. Further, Si is an ideal candidate for the back-end-of-line (BEOL) due to ease of manufacturing and access to complementary logic technology for digital circuits.

In this system, three-dimensional (3D)-stacked GaN dielets, are connected via highly scaled interconnects to the Si BEOL. The dielet is optimally placed to ensure uniform and minimal thermal degradation in the system. This approach will yield a bespoke chip design, tailor-made for the given high-speed application. To design the most efficient high data rate communication systems, we have embraced a design/system-technology co-optimization (DTCO/STCO) approach that combines a highly scaled W-band GaN dielet technology featuring a novel Cu-based gate metallization, with state-of-the-art Intel16 22-nm Si bias and control circuitry, via Cu-Cu 3D-heterogeneous integration.



▲ Figure 1. 3DIC building blocks and key technology nodes. (a) 3DIC integration schematic with GaN dielet leveraging Si complementary metal-oxide semiconductor (CMOS) BEOL (b) 80-nm CMOS-compatible t-gate high-electron-mobility transistorytransistor (HEMT) technology in 200-mm sourced GaN-on-Si (c) W-band RF performance of scaled GaN-on-Si HEMT with CMOS-compatible gate (d) Cross section scanning electron microscopy of GaN/Si CMOS Cu-CU bonding interface. (e) Chip micrograph of Intel16 BEOL circuit.

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