Integration of 3D Additively Manufactured High-Aspect-Ratio Polymer & Copper Pillars with 2D Microelectronic Devices

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Additive manufacturing offers freedom of 3D design, rapid prototyping, and manufacturability unprecedented by traditional 2D microfabrication methods alone. For instance, processes such as multi-photon polymerization [1], and metal electrodeposition [2] have enabled the realization of complex and high-aspect-ratio (HAR) geometries [3][4] that would otherwise require multi-step processing such as DRIE and/or electroplating [5].

To build truly high-capability MEMS, however, 3D microprinting, particularly polymer-based, needs to be integrated with sensing/actuating active microelectronics. One bottleneck in achieving this integration is getting good ($< \pm 1\mu m$) alignment of the 3D-printed structure on top of $< 3\mu m$ features of the micro/nanoscale device since most 3D printing tools have large working distances, hence lower-resolution optics. Another challenge is compatibility of active devices with 3D printing processes.

This work presents integration of microelectronic piezoresistive devices, fabricated using mostly 2D CMOS techniques (detailed in [6]), with two separate additive manufacturing technologies, to form highly sensitive MEMS F_x sensors. The 3D-printed HAR pillars act as structural components transferring stress from any applied force F_x to the underlying piezoresistors. By having vertical, out-of-plane beams, the sensor achieves a minimal on-substrate footprint of few μm^2. First, two-photon polymerization (TPP) on the Nanoscribe is used to form low spring constant, cylindrical pillars on top of the resistors (see Fig. 1). We accomplish $\pm$ 0.3μm alignment between pillar and the sub-μm width of resistors by tracking the laser in manual mode. Second variation of sensors integrate ultra-HAR (> 100) electrodeposited copper pillars on top of the piezoresistors, where the higher pillar aspect ratio helps increase sensor F_x sensitivity. To the best of our knowledge, this work is the first of its kind to demonstrate successful 3D printing of HAR metal beams on microelectronics using local electrodeposition. We outline the design, material modifications and packaging, required to make silicon devices compatible with electrodeposition and the required acidic electrolyte (dilute H_2SO_4+HCL). As shown in Fig. 2, we achieve $\pm$ 0.6μm XY alignment between the copper HAR pillars and devices using 3D markers and device surface height mapping. To demonstrate working devices post-printing, the sensors are tested for F_x sensitivity and exhibit $\Delta R/R$ of up to 0.25 % per μN F_x applied.

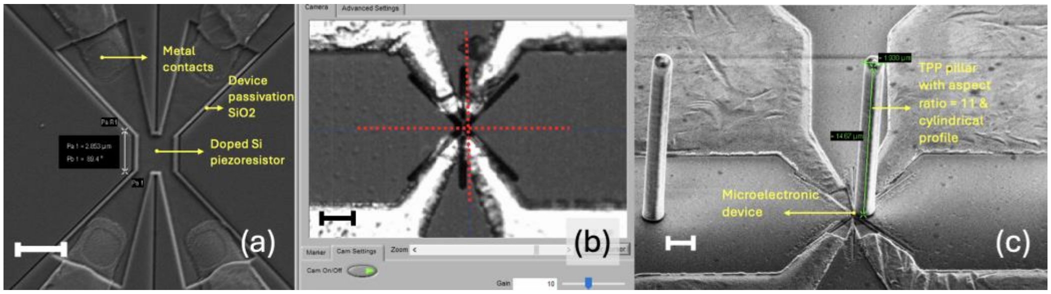

Figure 1: The Nanoscribe two-photon polymerization (TPP) printing and alignment method. (a) Top-down SEM of a CMOS-fabricated piezoresistor [6]. (b) Snippet of the Nanoscribe camera vision screen before a pillar print. The location of the printing laser is 'marked' with the cursor lines (highlighted in red). (c) TPP-printed pillar aligned off-center to the piezoresistor showing the complete MEMS F_x force sensor with 3D printed pillar aligned to microelectronic device [6]. (Imaged at 45° tilt). *All scale bars are 3μm.*

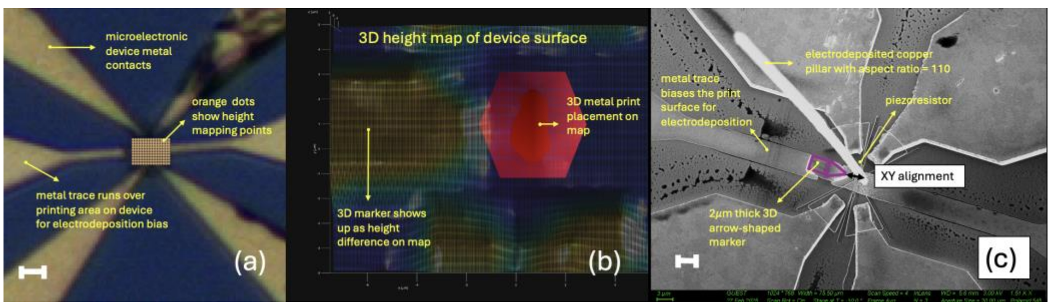

Figure 2: Summarized alignment process for the 3D metal printing (Exaddon Ceres). (a) Snippet of the system top camera view showing device immersed in electrodeposition chamber (2X lens with ~2μm resolution). Orange dots indicate points on the device surface that will be 'tapped' by the printing cantilever to obtain height variation over the XY area specified. (b) Color plot of the height variation across the mapped device surface. Blue color represents the flat, lowest points on mapped area, while orange represents highest points on the surface. (c) SEM image of a silicon piezoresistive device with a ~110-aspect-ratio copper pillar (1.8μm diameter, imaged at 20° tilt). The metal arrow-shaped 3D alignment mark artificially outlined in purple is 2μm thick and shows up pronounced on the height map. *All scale bars are 5μm.*

REFERENCES:

1. F. Lux, C. Aybuke, and A. Çağlar Ataman, "Monolithically 3D nano-printed…", 2025. preprint arXiv:2501.10254.
2. G. Sotto-Valle et al., "Additively Manufactured RF Interconnects…" IEEE 74th Electronic Components and Technology Conf. (ECTC), 2024.
3. DG Kim et al., "Magnetically actuated micro-scale…", Int. Conf. on Manipulation, Automation and Robotics at Small Scales (MARSS), 2020.
4. R. Acevedo et al., "3D Nanoprinted External Microfluidic…" IEEE 34th Int. Conf. on MEMS, 2021.
5. Y. Tang and K. Najafi, "A two-gap capacitive…," IEEE International Electron Devices Meeting (IEDM), 2015.
6. I. Lodhi et al., "Piezoresistive Micropillar Sensors…," Journal of Microelectromechanical Systems JMEMS), 2024.