ICIRES 2026
23th International Conference on Innovation and Research in Engineering Sciences
(ICIRES 2026)
13 March 2026 -TBILISI GEORGIA
www.icires.ir
info@icires.ir

Two-dimensional relief metal forming for the fabrication of micron-scale patterns on flat substrates

Amir Hossein Nabi

Affiliation: Advanced Micro and Nano devices Lab., Department of MEMS and NEMS, School of Intelligent Systems, University of Tehran

Javad Koohsorkhi

Affiliation: Advanced Micro and Nano devices Lab., Department of MEMS and NEMS, School of Intelligent Systems, University of Tehran

Email: koohsorkhi@ut.ac.ir *

Abstract

This paper introduces a comprehensive metal microforming system based on 2D relief printing, designed to address the limitations of conventional microelectromechanical systems (MEMS) fabrication methods. Suspending thin wires in thermal flow sensors enhances measurement accuracy due to the low thermal conductivity of air, while semicircular microfluidic channels improve fluidic performance by reducing turbulent flow. Conventional techniques such as photolithography and hot embossing face challenges in fabricating suspended structures, semicircular microchannels, and in processing low-cost, rigid substrates.The proposed integrated system, comprising mechanical and electronic subsystems and a dedicated nozzle, is controlled using optimized G-code commands and enables direct printing of resistive and capacitive sensors with significantly reduced fabrication steps. Experimental results demonstrate successful printing of linear patterns and suspended electrodes with diameters ranging from 10 to 100 µm on plastic and glass substrates.

Keywords: Microfluidics; Flowmeter; Metal Microforming; Photolithography; Microelectromechanical Systems (MEMS)

1. Introduction

While microelectromechanical systems (MEMS) technology continues to face challenges such as complex fabrication processes and high production costs, a novel metal-forming-based printing platform offers a significant reduction in manufacturing steps and overall cost. This platform is demonstrated through 3 key applications: a hot-wire flow sensor with suspended electrodes, the fabrication of microfluidic channels with circular cross-sections, and the direct printing of resistive and capacitive sensors.

The field of microelectronics began in 1948, and in the 1980s, the development of microelectromechanical systems emerged with the introduction of microsystem technology (MST). This technology enabled the fabrication of integrated chips capable of both sensing and actuation. Over the past decades, this advancement in microelectronics has driven major progress in the development of microsensors and microactuators [1].

MEMS devices are now widely used in industries such as automotive, medical, wireless communications, electronics, and sensing. These systems benefit from small size, low weight, high performance, low cost, and compatibility with mass production. Common sensing mechanisms are based on capacitive, electromagnetic, and piezoelectric principles. MEMS are commonly used to measure mechanical variables including motion (displacement, velocity, and acceleration), force and torque, deformation, stress, and strain [2].

MEMS fabrication methods are generally divided into 2 categories: lithography-based and non-lithography-based techniques. Over the past 2 decades, several non-lithographic fabrication approaches have been developed, including electrical discharge machining, micromechanical cutting, micro cutting and drilling, laser micromachining, embossing, and micro molding. Although lithography-based processes can achieve smaller feature sizes, micromachining offers greater flexibility in material selection and enables the fabrication of more complex geometries. As shown in Fig. 1, this technology has strong potential to bridge the gap between macro- and nanoscale fabrication. While micromachining techniques are conceptually similar to conventional machining, size effects prevent simple downscaling. In MEMS, sensors serve as the system’s input units, providing data to the processor, which then generates the required control signals for the actuators.

There is a critical need for flow rate and direction sensors in various medical, industrial, and environmental applications. Flow sensors are essential for measuring the rate and direction of liquid and gas flows in a wide range of applications, including the determination of flow patterns, wall shear stress, viscosity, and density [4]. One key approach to simplify sensor fabrication and reduce costs is the use of direct metal electrode printing, which eliminates the need for complex photolithography steps. However, conventional direct printing methods still face significant operational challenges. Major limitations include the inability to produce mechanically stable raised patterns and the difficulty of freely suspending electrodes without relying on sacrificial layers.

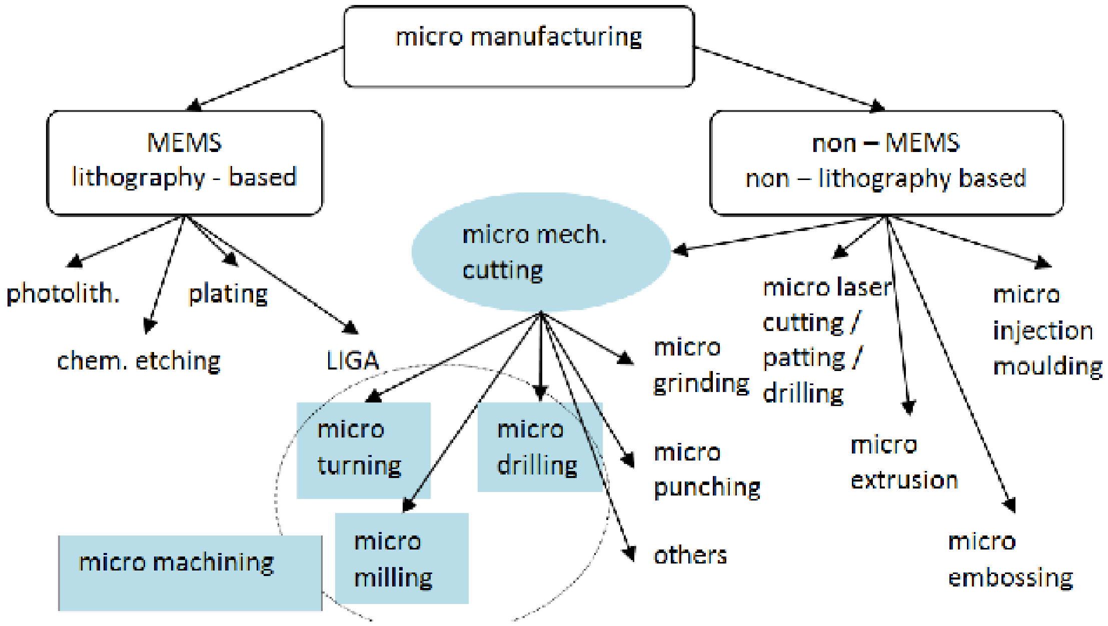

Figure 1. Classification of micro-scale fabrication methods [3]

In this paper, a metal-forming-based approach for fabricating microelectromechanical systems (MEMS) is presented, offering several advantages: reducing fabrication steps, overcoming certain limitations of lithography-based methods, addressing challenges in hot-embossing techniques, facilitating microfluidic processes, and enabling the direct printing of resistive, capacitive, and RF MEMS devices.

2. Materials and Methods

To perform the forming process, a comprehensive metal-forming system with micron-level precision is required, designed to ensure process repeatability and adaptability (Fig. 2). The core of this technology consists of a four-axis mechanical subsystem (three linear axes and one rotational axis) responsible for precise movement of the tool head in three-dimensional space. In this setup, a combination of linear rails and a ball screw is employed to convert rotational motion, serving as the system's control backbone. For ease of troubleshooting and future upgrades, the hardware is designed in a modular configuration.

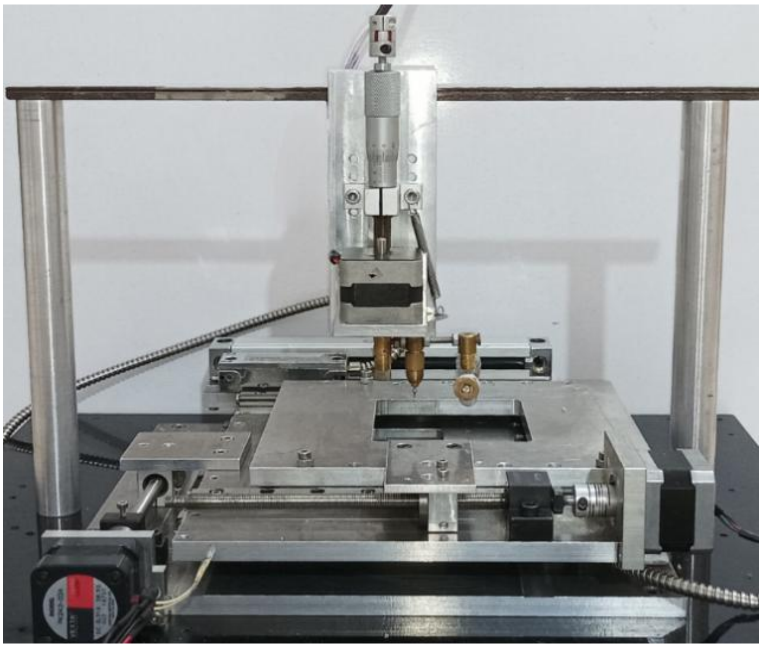

Figure 2. View of the mechanical subsystem

Stepper motors are used for linear movement, complemented by software configurations and microstepping settings in the drivers, the electronic control unit, and a customized tool head. The electronic subsystem is responsible for executing G-code commands, managing electrical current, and monitoring overall system performance. In contrast, the tool head, as the operational unit, handles the supply of raw material, precise height adjustment at the micrometer scale, and geometric metal forming on the substrate.

The coordinated interaction of these three components provides a flexible and stable platform for the direct printing of various micron-scale patterns, with rotational capability and high mechanical stability. The electronic subsystem serves as the interface between the user and the mechanical components, processing instructions and precisely controlling system movements (Fig. 3).

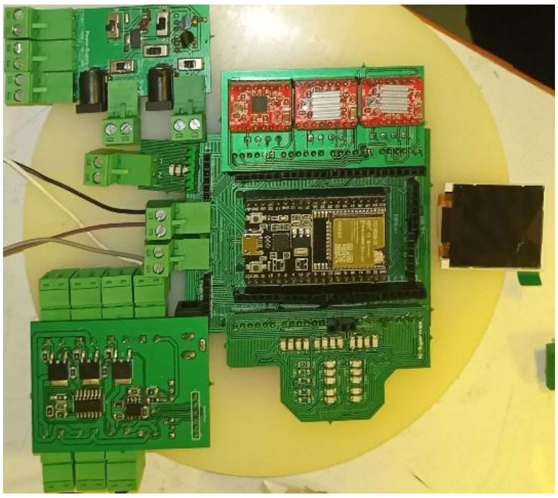

Figure 3. View of the electronic subsystem

The system software, developed in the Arduino environment, is responsible for interpreting standard G-code commands and converting them into motion and operational instructions. In addition to executing linear (G0, G1) and relative (G91) movement commands, the program incorporates trigonometric algorithms for real-time calculation of rotational axis angles. Figure 4 illustrates the patterns used in this study.

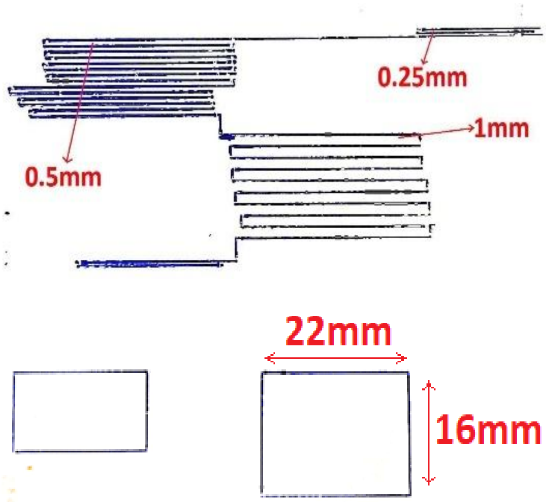

Figure 4. Drawing geometric shapes using a pen

After analyzing the mechanical and electronic subsystems, the tool head emerges as the main distinguishing feature and technical challenge of this study in implementing a metal-forming system for 2D relief printing. The primary challenge in this process is achieving a stable wire-to-substrate connection. After evaluating various bonding methods, thermal bonding was selected as the optimal approach. In this process, the tool head locally heats the material to soften it and simultaneously applies pressure to create a strong mechanical connection.

3. Results and Discussion

In this section, the experimental results and practical performance of the system in fabricating microelectromechanical devices are evaluated. The main goal is to assess the coordination among components, the functionality of the user interface, and to validate the device's capabilities through the practical printing of diverse patterns on different substrates with varying wire diameters. A particular focus of this stage is on the fabrication of a prototype flow sensor on a glass substrate with suspended wire structures, aimed at minimizing thermal exchange, thereby demonstrating the system's ability to produce precise outputs that meet technical expectations.

3.1 Formation of Straight Wires on Different Substrates

3.1.1 On Plastic Substrates

Figure 5 shows a pattern printed with a 60 µm wire on a plastic substrate using simultaneous heating and electrical bonding. This approach results in smoother printing and reduced wire deviation. However, the electrical bonding may cause slight oxidation of the wire. By carefully adjusting the tool head height to achieve partial penetration of the wire's cross-section into the substrate, precise molds can be produced, which are useful for hot-embossing processes in fabricating microfluidic channels on low-cost plastic substrates.

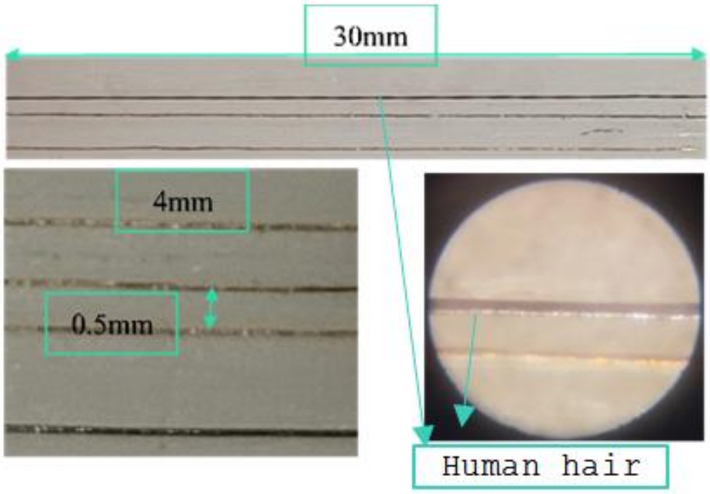

Figure 5. Printed pattern with a diameter ranging from 20 to 60 micrometers on plastic substret.

3.1.2 Glass Substrate

This substrate requires a preparation process consisting of multiple coatings of cyanoacrylate adhesive on a laboratory glass slide using the doctor-blade deposition technique, followed by a drying stage. Printing a 100-micrometer wire on the adhesive-coated glass substrate provides a smoother process and higher-quality output compared to plastic substrates.The main challenge in this method is the non-uniformity of the adhesive layer and the surface roughness it creates. This issue can be improved by using adhesives with lower viscosity and by precisely controlling pressure and temperature to minimize residual irregularities.Figure 6 illustrates the metallic wire pattern formed on the glass substrate.

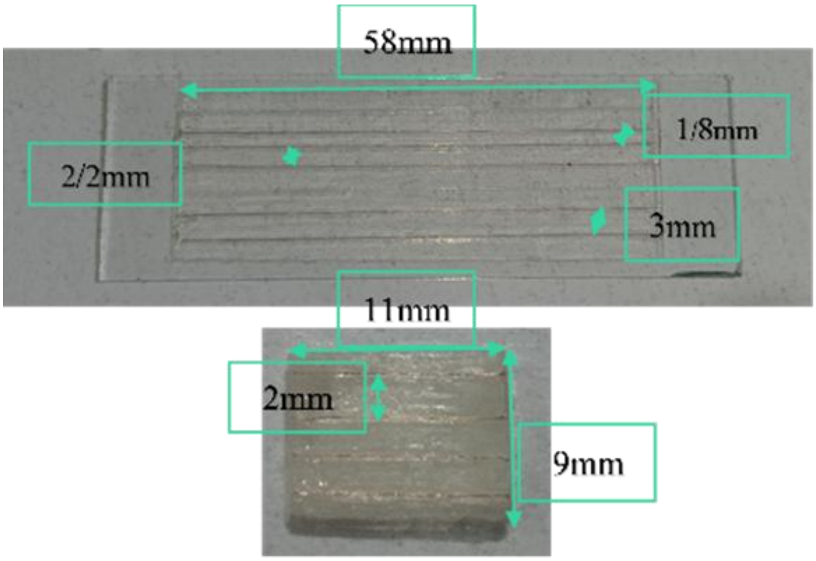

Figure 6. Printed pattern with a diameter of 100 micrometers on glass with varying spacing.

3-2. Fabrication of Suspended Wire Structures as Flow-Sensor Elements on Glass Substrate

The capability of depositing thin wires over a micro-channel in this system enables the realization of flow-rate sensors, overcoming the limitations of photolithography in producing suspended structures. Experimental observations indicate that for wires of 100 μm and larger, the electrical bonding method results in superior adhesion, although controlling the printing speed is critical to prevent oxidation, and accurate height calibration is required to avoid arching in the bridges. Figure 7 presents a schematic of suspended wires over a channel, utilized as a hot-wire flow sensor. Thermal flow sensors determine flow velocity based on the rate of heat transfer [5], providing high sensitivity and accuracy along with minimal output-signal drift.

To reduce heat loss between the hot wire and the substrate, these wires are typically fabricated in suspended form. As illustrated, the suspension process of such thin wires remains one of the key challenges in this technology. In this paper, a direct fabrication method is introduced that allows realizing hot wires of various dimensions without the need for conventional suspension processes.

Figure 7: Schematic of a calorimetric hot-wire sensor structure.

The substrate preparation steps for the glass substrate at this stage involve two fundamental procedures: first, the precise creation of the “bridge” structure on the glass is achieved using hydrofluoric acid solution via the wet etching method. Subsequently, to prepare the substrate for wire attachment, several layers of cyanoacrylate adhesive are applied onto the laboratory glass slide using the blade coating technique and processed until complete drying and stabilization of the intermediate layer. Figure 8 illustrates images of parallel wires with varying thicknesses. Furthermore, Figure 8 displays parallel wires bridged over a circular cavity.

(a) (b)

Figure 8: (a) Overview of the printed pattern with different diameters on a: glass and b: over the cavity.

The performance of the system in bridging over glass substrates with a 100 μm100 μm wire was evaluated as favorable; however, success in this process necessitates precise control over the wire attachment at the bridge edges to prevent deviation and misalignment. Results indicated that the smaller the bridge width, the better the stability and tension of the wire; conversely, at larger widths, especially at 20 μm dimensions, the phenomenon of slackness and sample quality degradation was observed.

4. Conclusion:

The designed system, by demonstrating accuracy and finesse in micron-scale printing, holds significant potential for manufacturing various resistive, current, and voltage sensors, including temperature, acoustic, rain, electrochemical sensors, and especially thermal flowmeters. Achieving the capability of wire suspension and array printing with very small spacing enables the production of precise current sensors for the medical, oil, and gas industries.The ability to print electrodes with a diameter of 10 μm10 μm demonstrates the high capability and precision of the system. This capability affords us the possibility of printing patterns with extremely small dimensions. It is worth noting that the printing of electrodes with a minimum diameter of 10 μm10 μm does not represent the maximum precision of this system, but rather the minimum thickness available commercially, which is 10 μm; it is possible to print even smaller diameters by obtaining wires with lesser thickness and implementing minor adjustments in the groove. Precise temperature regulation, achieved through the fine-tuning of the current passing through the wire and also the heating element, has a very significant impact on the quality of the print. The accurate adjustment of the printing height, much like the current magnitude, is the primary factor in determining the quality of the printed pattern. Similar to the current, fine adjustment of the height also requires extensive empirical observation following practical experiments.

References

- **Gardner, J. W. (1994).** Microsensors, actuators, systems, and application. *IEEE Proceedings - Circuits, Devices and Systems*, *141*(1), 1–10.
- **Khoshnoud, F., & de Silva, C. W. (2012).** Recent advances in MEMS sensor technology—mechanical applications. *IEEE Instrumentation & Measurement Magazine*, *15*(2), 14–24.
- **Piljek, P., Keran, Z., & Math, M. (2014).** Micromachining. *Interdisciplinary Description of Complex Systems*, *12*, 1–27.
- **Ejeian, F., et al. (2019).** Design and applications of MEMS flow sensors: A review. *Sensors and Actuators A: Physical*, *295*, 483–502. doi: 10.1016/j.sna.2019.06.020.
- **Koohsorkhi, J., Madadi Bandan, A. R., & Hamidzadeh, M. H. (2025).** Investigation of the Sensitivity of a Micro-Machined Acoustic MEMS Sensor to Input Sound Wave Intensity. *Journal of Acoustical Society of Iran*, *13*(1), 62–67.