

# Advancing On-Chip Micromotor Fabrication Through Electrochemical Micromachining of Silicon

*Farbod Abazar<sup>1</sup>, Salvatore Surdo<sup>1</sup>, Chiara Cozzi<sup>1</sup>, Giovanni Polito<sup>1</sup>, Giuseppe Barillaro<sup>1\*</sup>*

<sup>1</sup> *Department of Information Engineering, University of Pisa, via G. Caruso 16, 56122, Pisa, Italy*

*\*Corresponding Author's e-mail address: giuseppe.barillaro@unipi.it*

## Summary:

This paper presents the first fabrication of interlocked microgears etched in silicon chips using electrochemical micromachining (ECM). These microgears represent a major step toward the development of fully integrated silicon-based micromotors. The ability to fabricate freestanding rotors around stationary stators with sub-micrometric precision with a single-step etching surpasses the capabilities of existing micromachining technologies. As proof of concept, we demonstrate the integration these microgears within a microfluidic channel designed for transduction of flow motion into rotational speed.

**Keywords:** MEMS, Electrochemical micromachining (ECM), Silicon micromachining, Microgears, Micromotors

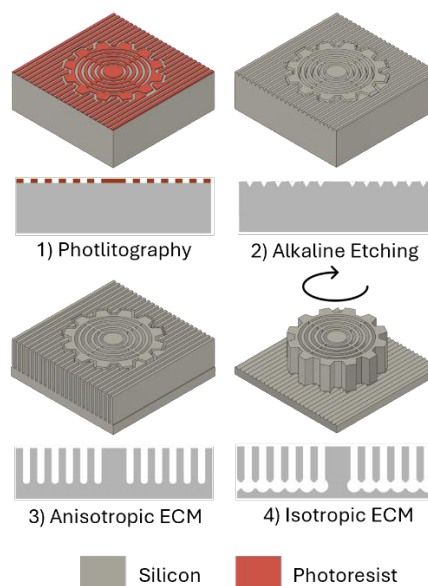
## Introduction

Silicon micromachining tools have enabled disruptive technologies like micro-accelerometers, pressure sensors, and inkjet heads. However, deep etching of silicon has yet to demonstrate rotating structures like microgears. The most advanced fabrication method remains the LIGA process [1], which relies on metal electrodeposition within patterned polymers. Meanwhile, micromotors powered by chemical reactions hold promise for power-free lab-on-chip devices [2].

ECM has recently demonstrated its capability for etching complex, freestanding microstructures at high aspect ratios ( $AR > 100$ ) and ultra-smooth surfaces (roughness  $< 10$  nm) [3,4]. Here, we extend ECM to the fabrication of free-standing silicon microgears (rotors) around anchored shafts (stators) for integrated micromotors. As a case study, we integrate interlocked microgears with involute teeth into a microfluidic channel, suitable for future fluidic-to-mechanical energy conversion.

## Results and discussion

The fabrication process involves three main steps (Figure 1): (1) surface patterning of a silicon substrate, (2) nucleation seed formation for ECM, (3) anisotropic ECM phase to define deep features, and (4) isotropic ECM phase to release the freestanding microgear. By dynamically switching between anisotropic and isotropic etching phases, ECM allows achieving movable Si micro-rotors, using sacrificial support structures for precise large-area fabrication.



*Fig. 1. Schematic of the fabrication steps used for silicon microgear electrochemical machining*

Figures 2A and 2B present a representative example of an array of two interlocked freestanding microgears etched in silicon. Each gear is  $\sim 50$   $\mu\text{m}$  tall and is free to rotate around a cylindrical shaft anchored to the Si substrate. The gear structure consists of periodic parallel circular silicon walls ( $\sim 1$   $\mu\text{m}$  thick,  $AR \sim 50$ ) acting as distributed Bragg reflectors, enabling optical monitoring of rotation speed. The smaller gear,  $68$   $\mu\text{m}$  in diameter with 20 teeth, interlocks with a larger  $136$   $\mu\text{m}$  gear with 40 teeth, providing a 1:2 gear ratio. This ensures that one gear rotates at twice the speed of the other, demonstrating precise mechanical transmission.

A major advantage of ECM is the superior surface quality and precision achieved. The gear teeth exhibit a smooth surface roughness ( $\sim 10$  nm) and an involute profile, critical for smooth rotational power transmission. Unlike conventional deep silicon etching (e.g., DRIE), which suffers from scalloping effects and requires additional post-processing, ECM directly yields high-aspect-ratio structures with ultra-smooth surfaces. This advantage minimizes speed or torque variations during gear interlocking, improving efficiency and durability.

Figures 2C and 2D illustrate the integration of these interlocked microgears within a microfluidic system, demonstrating their potential for fluid-to-mechanical actuation. The system consists of two large reservoirs ( $\text{mm}^2$  scale) connected via a microfluidic channel, where one of the microgears partially extends into the channel with paddle-like teeth. This design enables transduction of flow motion into rotational speed, presenting a viable path toward electric-free micromotors.

### Conclusion

Our study successfully extends ECM technology to fabricate interlocked silicon microgears and integrate them into a microfluidic system for transduction of flow motion into rotational speed. The key advantages of ECM include high aspect-ratio etching, sub-micrometric precision, ultra-smooth surface finishing, anisotropic-to-isotropic etching switching. These results open new possibilities for the fabrication of on-chip micromotors, particularly for applications in power-free lab-on-chip devices with microfluidic-driven actuation. Future work will focus on optimizing gear geometries for improved efficiency and demonstrating practical applications in integrated micro-electromechanical systems (MEMS).

### References

- [1] M. S. Huang, C. J. Li, J. C. Yu, Y. M. Huang, L. C. Hsieh, Robust parameter design of micro-injection molded gears using a LIGA-like fabricated mold insert, *J Mater Process Technol*, vol. 209, no. 15–16, pp. 5690–5701, 2009; doi: <https://doi.org/10.1016/j.jmatprotec.2009.05.032>
- [2] G. Vizsnyiczai, G. Frangipane, C. Maggi, F. Sagglimbeni, S. Bianchi, R. Di Leonardo, Light controlled 3D micromotors powered by bacteria, *Nat Commun*, vol. 8, 2017; doi: <https://doi.org/10.1038/ncomms15974>
- [3] M. Bassu, S. Surdo, L. M. Strambini, G. Barillaro, Electrochemical micromachining as an enabling technology for advanced silicon microstructuring, *Adv Funct Mater*, vol. 22, no. 6, pp. 1222–1228, 2012; doi: <https://doi.org/10.1002/adfm.201102124>

- [4] S. Surdo et al., Optofluidic microsystems with integrated vertical one-dimensional photonic crystals for chemical analysis, *Lab Chip*, vol. 12, no. 21, pp. 4403–4415, 2012; doi: <https://doi.org/10.1039/C2LC40613F>

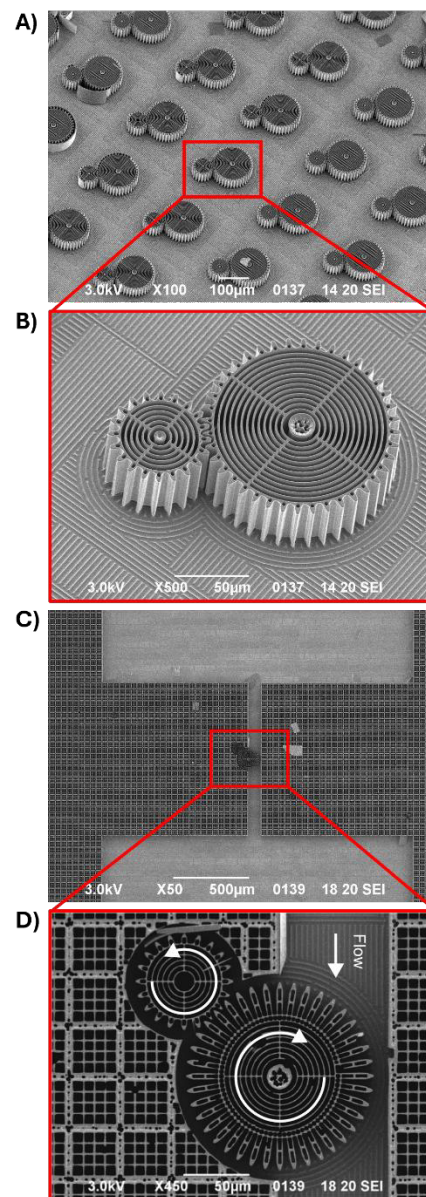


Fig. 2. A) Scanning electron microscopy (SEM) images of an array of interlocked microgears. B) Magnified image of one of the microgear pair in the array. C) SEM (top view) image of a silicon microfluidic system integrating two freestanding interlocked microgears integrated with a microfluidic channel. D) Magnification of the microgears integrated into the microchannel for fluid-mechanical actuation