ROBUST “RIBBED” NANOPOROUS MEMBRANES FOR IMPLANTABLE BIO-ARTIFICIAL KIDNEYS

B.W. Chui, P. Taheri-Tehrani, N. Wright, J. Ly, and S. Roy
University of California, San Francisco, California, USA

ABSTRACT

We have designed, fabricated, and tested nanoporous membranes with improved robustness and performance for the implantable bio-artificial kidney (iBAK). By superimposing a network of thicker “ribs” onto a thin membrane, we have shown that it is possible to achieve mechanically robust membranes and high filtration rates at the same time.

BACKGROUND

The “implantable bio-artificial kidney” is a national research effort headquartered at UCSF [1] and aimed at eliminating the need for dialysis or kidney transplants for end-stage renal disease (i.e. kidney failure), which affects more than 650,000 patients in the US alone with treatment costs exceeding \$35 billion per year.

INTRODUCTION

One critical MEMS component of the iBAK is the filter unit, in which polysilicon membranes with nanoscale slit pores are used to mimic the kidney's filtering function in extracting creatinine, urea, and other harmful substances from blood [1]. The pore width (typically 5-30 nm wide) is set such that “useful” components (e.g. red and white blood cells) remain in the blood while “unwanted” components pass through into the ultrafiltrate due to the difference in pressure between the two sides.

We have previously developed a reliable process for fabricating such membranes with highly uniform and precisely tuned pore sizes [2]. But to match the mass-transfer throughput required for dialysis, another order-of-magnitude improvement is required: for example, by (i) implementing parallelism on the system level (e.g. multiple chips); (ii) increasing pore density at the chip level (advanced lithography or nano-imprint); and (iii) reducing flow-path resistance of the pores (e.g. thinner membranes). This abstract focuses on option (iii): making membranes thinner without sacrificing mechanical integrity.

DETAILED DISCUSSION

While one can imagine thinning a membrane *ad infinitum* to minimize flow-path resistance, eventually it becomes too fragile to withstand typical blood pressures. This is clearly unacceptable in implantable medical devices, where long-term reliability is key.

Figure 1: Conceptual diagram of (a) flat, (b) ribbed membrane. Fig.(c) shows 3D rendition of orthogonal backside rib network.

Therefore, we have designed a variable-thickness membrane consisting of a “thin” active porous area reinforced by a scaffolding of “thick” ribs to give it extra rigidity (Fig. 1). Ideally, the reinforcing elements should not take up too much active filter area. Also, the rib protrusions should be on the *back* side (filtrate side) of the chip to avoid disrupting blood flow. This precludes “post-depositing” the rib material on top of an existing membrane.

Given these constraints, in this work we adapted a thin-film plate-stiffening technique [3,4] for use in our membrane process flow as follows: a grid of 1.5 μm -wide grooves (the “rib molds”) is etched 2.5-5.0 μm deep into the surface of a silicon substrate (Fig. 2a). A 0.5 μm thermal oxidation followed by a 0.8 μm polysilicon deposition effectively fills up the grooves (forming the eventual ribs on the *bottom* of the membrane) and re-planarizes the surface. We then revert to the original process flow detailed in [5] (Figs. 2c-2f). The finished device is shown in Fig. 3.

To find a rib configuration that combines robustness with ease of fabrication, we performed finite-element analysis on membrane deflection and maximum stress vs. rib height. We found that membrane strength (maximum principal stress) increased quickly even with modest increases in rib height (Fig. 4). Accordingly, we made nanoporous membranes with 0 μm (flat), 2.5 μm and 5 μm -tall ribs and compared their hydraulic rupture thresholds. Table 1 shows that the ribbed membranes performed 50-85% better than their flat counterparts, well worth the slight loss (13%) in active pore area. Both types of membranes also underwent bio-filtration clearance tests and demonstrated favorable performance (Fig. 5).

Figure 2: Fabrication process flow for ribbed nanoporous polysilicon membranes

Figure 3: (a) Optical image of ribbed membranes, (b) Top-view scanning electron micrograph (SEM) (inset shows close-up of nanopores), (c) Bottom-view SEM (inset shows details of ribs).

Table 1: Measured hydraulic rupture pressure for various designs

($\times 1000$ mmHg)	Flat (no ribs)	2.5 μm ribs	5 μm ribs
Sample 1	1.03	2.22	2.69
Sample 2	1.40	2.22	2.74
Sample 3	1.91	--	--
Average	1.45	2.22	2.72

CONCLUSION

We have proven a design and fabrication method that enables significantly thinner nanoporous membranes while preserving device robustness, thereby improving filtration efficiency on our way towards the ultimate goal of a fully implantable bio-artificial kidney—the “silicon kidney.”

ACKNOWLEDGEMENTS

We would like to acknowledge the support of the Stanford Nanofabrication Facility, the Berkeley Marvell Nanolab, and NIH Quantum Grant U01EB021214.

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Figure 4: Simulated membrane deflection and peak stress vs. rib height for 300 mm Hg pressure. (A logarithmic color scale is used to resolve the range of all five cases.) It can be seen that membrane deflection (solid line) and peak stress (dotted line) both decrease rapidly with rib height.

Figure 5: Measured cumulative creatinine clearance for ribbed vs. flat membranes. The lower clearance for the ribbed membranes is partly due to a 13% reduction in active pore area taken up by the ribs.

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