ROBUST "RIBBED" NANOPOROUS MEMBRANES FOR IMPLANTABLE BIO-ARTIFICIAL KIDNEYS

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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 long-term project at UCSF [1] 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 and other harmful substances from blood [1]. The pore width (typically 5-30 nm wide) is set such that "useful" components (e.g. red/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 tunable pore size [2]. To match the mass-transfer throughput of dialysis, however, 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.

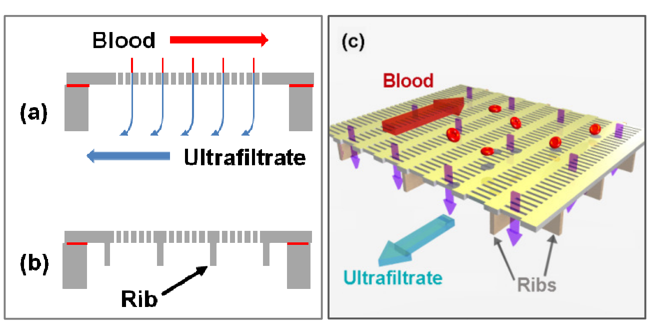

Fig. 1: Conceptual diagram of (a) flat and (b) ribbed membrane. (c) 3D rendition of orthogonal network of backside ribs.

DETAILED DISCUSSION

While one can imagine thinning a membrane *ad infinitum* to minimize flow-path resistance, eventually the membrane becomes too fragile to withstand typical blood pressures. This is clearly unacceptable in implantable medical devices where long-term reliability is paramount. Therefore, we have designed a variable-thickness membrane consisting of a "thin" active porous area reinforced by a scaffolding of "thick" ribs criss-crossing its surface to give it extra rigidity (Fig. 1).

Ideally, the reinforcing elements should not take up too much active filter area. In addition, the rib protrusions should be on the *back* (filtrate) side of the chip to avoid impeding blood flow. This precludes "post-depositing" the rib material on the membrane.

Accordingly, in this work we adapted a thin-film plate-stiffening technique [3,4] to our porous membranes in which a grid of 1.5 µm-wide grooves (the "rib molds") are etched 2.5-5.0 µm deep into the surface of a Si 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* side of the membrane) and re-planarizes the surface. We then revert to the original process detailed in [5] (Figs. 2c-2f). The finished device is shown in Fig. 3.

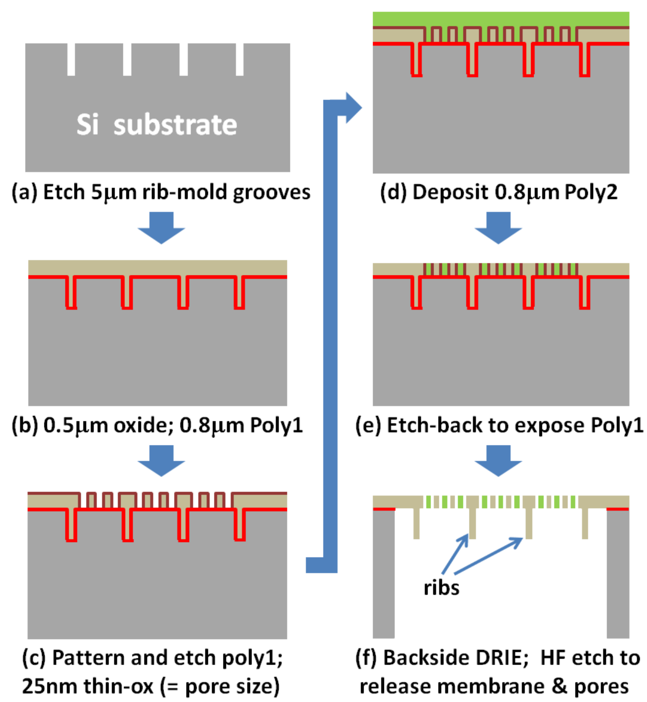

Fig. 2: Fabrication process flow for ribbed nanoporous poly-silicon membranes

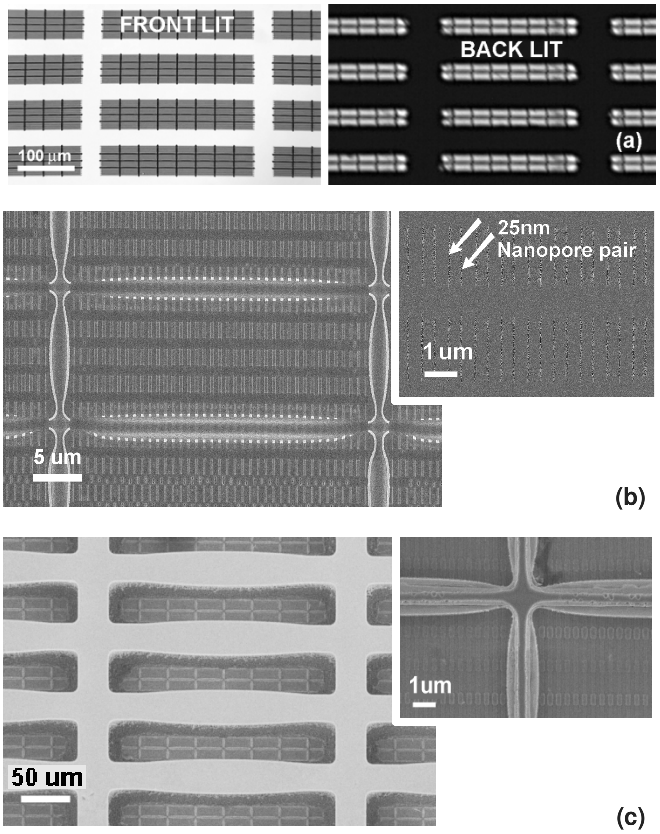

Fig. 3: (a) Optical image of ribbed membrane, (b) Top-view SEM (Inset shows details of the nanopore slits), and (c) Bottom-view SEM (Inset shows details of the ribs).

To find a rib design that combines robustness with ease of fabrication, we performed finite-element modeling of membrane deflection and maximum stress vs. rib height *h*. We found that membrane strength increased quickly even with modest increases in *h* (Fig. 4). Accordingly, we made nanoporous membranes with 0 µm (i.e. flat), 2.5 µm and 5 µm-tall ribs and measured their hydraulic rupture threshold. 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. (Design efforts are under way to further reduce this loss.) Both types of membranes were also subject to bio-filtration cleanrance tests (Fig. 5).

Table 1: Measured hydraulic rupture pressure for various designs

(×1000 mmHg)	**Flat (no ribs)**	**2.5µm ribs**	**5µm 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

In 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."

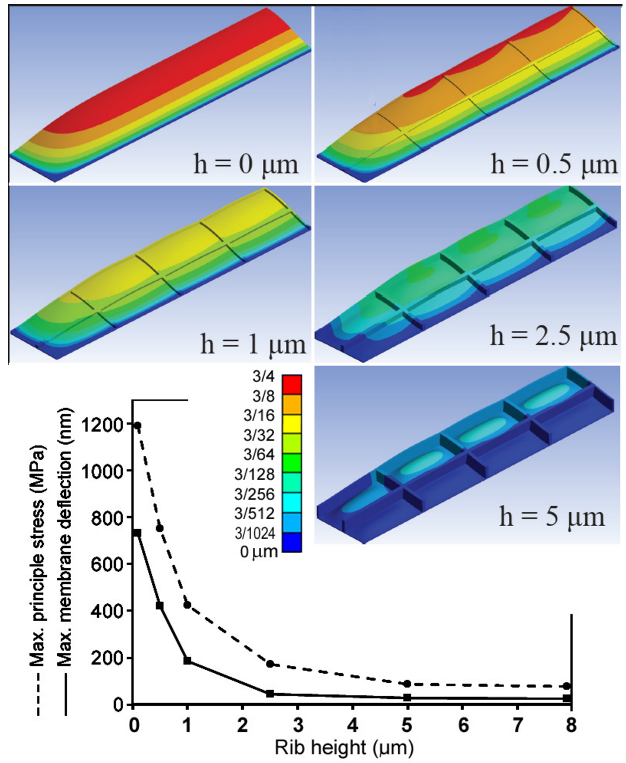

*Fig. 4: Simulated membrane deflection and peak stress vs. rib height **h** for 300 mmHg pressure. A logarithmic color scale is used to span the range of all five cases. Note that membrane deflection (solid line) and peak stress (dotted) both decrease rapidly with **h**.*

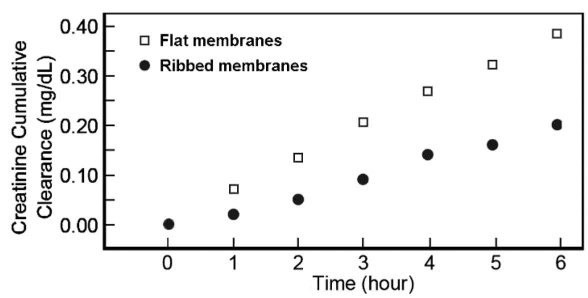

Fig. 5: Measured cumulative creatinine clearance for ribbed vs. flat membranes. The lower clearance for the former is partly due to a 13% reduction in active pore area taken up by the ribs.

REFERENCES

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