Micro filtration Membrane Sieve with Silicon Micro Machining for Industrial and Biomedical Applications

Cees J.M. van Rijn* and Miko C. Elwenspoek

University of Twente, MESA Research Institute,
Micromechanical Transducers, Electrical Engineering Department
P.O. Box 217, 7500 AE Enschede (The Netherlands)

*Aquamarijn Microfiltration B.V.,
G. Doustraat 10, 1072 VP Amsterdam (The Netherlands)

Abstract
With the use of silicon micromachining an inorganic membrane sieve for microfiltration is constructed, having a siliconnitride membrane layer with thickness typically 1 μm and perforations typically between 0.5 μm and 10 μm in diameter. As a support a <100>-silicon wafer with openings of 1000 μm in diameter is used. The thin siliconnitride layer is deposited on an initial dense support by means of a suitable Chemical Vapour Deposition method (LPCVD). Perforations in the membrane layer are obtained through the use of standard microlithography and reactive ion etching (RIE).
The flow rate behaviour and the pressure strength of the membrane sieve are calculated in a first approximation. A process for manufacturing is presented and some industrial and biomedical applications are discussed.

Introduction Sieve Filters
Sieve filters are characterized by thin membrane layers with uniformly sized pores and for most applications the membrane layer is sustained by a support. Until now lithographic techniques have not been used for the construction of micro filtration membrane layers made of inorganic materials as siliconnitride and silicon1.
Inorganic membrane and in particular ceramic membranes2 have a number of advantages above polymeric membranes like high temperature stability, relative inert to chemicals, applicable at high pressures, easy to sterilize and recyclable. However they have not been used extensively because of their high costs and relatively poor control in pore size distribution. Also the effective membrane layer is very thick in comparison to the mean pore size (typically 50 -1000 times), which results in a reduced flow rate.

A composite filtration membrane having a relatively thin filtration or sieving layer with a high pore density and a narrow pore size distribution on a macroporous support will show good separation behaviour and a high flow rate. The support contributes to the mechanical strength of the total composite membrane. The openings in the support should be made as large and numerous as possible in order to maintain the flow rate of the membrane layer and to reduce the interaction of the support with the fluid. An established use of inorganic membranes with very thin membrane layers, in particular microsieves with high flow rates, will result in an energy- and cost-saving separation technology for present and future innovative applications, like micro liquid handling, modular fluidic systems or micro total analysis systems3.

Figure 1, Pore size distribution of various membrane filters.

1 Handbook of Industrial Membrane Technology, L.Porter, C.Mark and H.Strathmann, 1990
Construction

Figures 2 to 5 show cross-section subsequent stages of a process for the production of the membrane consisting of a support and a membrane layer. On a surface of the support 1, a single crystalline 3" <100>-silicon wafer with thickness of 380 pm a layer 2 of siliconnitride with thickness 1 pm is deposited by means of 'Chemical Vapour Deposition'. The layer 2 is formed by reaction of dichloresilane (SiH2Cl2) and ammonia (NH3) at elevated temperature 850° C and low pressure (LPCVD). On the siliconnitride layer 2 a photosensitive lacquer layer 3 is formed by spincoating at 4000 r.p.m., figure 2, in this example Shipley Europe Resist S 1818 with a thickness of 1.8 pm. The lacquer layer 3 is then being exposed to a mask pattern with the use of a suitable UV source, here with a Karl Süss projection system using proximity projection. The mask pattern is made of a square field of 10 x 10 membrane areas of 1000 pm by 1000 pm. The membrane areas are separated at spacings of 200 pm. Each membrane area has 100 x 100 circular perforations with diameter 4 pm. The mutual distance between the centre of the perforations is 10 pm. After exposure the lacquer layer 3 is developed for 45 seconds in a diluted NaOH solution giving a mask pattern in the lacquer layer 4 on the siliconnitride layer 2, figure 3. In the siliconnitride layer 2 then the mask pattern is etched by means of CHF3/O2 reactive ion-etching at 10 mTorr and 75 Watt for 15 minutes forming the perforations 5 in the membrane layer, figure 4. Next perforations 6 of 1000 pm x 1000 pm are etched using the backside siliconnitride layer 2 as an etch mack in the silicon support 1 with an anisotropic etch along the <111>-planes with a 10 % KOH solution at 70 ° C until the membrane layer is reached, figure 5.

Deflection and Pressure Strength of a Clamped Rectangular Membrane

The deflection curve \( w(x) \) of a rectangular plate with dimension \( l \times b \times h \) clamped at two edges \( x = 0, l \) stretched by an axial distributed force \( S \) and uniformly loaded under a pressure \( q \) is given by the well known differential equation

\[
D \frac{d^4w(x)}{dx^4} - S \frac{d^2w(x)}{dx^2} = q
\]

with flexural rigidity \( D = \frac{Eh^3}{12(1 - \nu^2)} \) (\( \nu \) = Poisson's ratio, \( E \) = Young's modulus).
The general solution symmetrical in $x = 1/2$ following Timoshenko\textsuperscript{4} is given by

$$w(x) = \frac{q t}{16 u^2 D \tanh u} \left( \cosh \left( \frac{1 - 2x}{l} \right) \right) - \frac{q t^2 (1 - x) x}{8 u^2 D}$$

with definition $u^2 = SI^2 / 4D$.

The points of inflection ($d^2 w / dx^2 = 0$) of the deflection curve are determined by the dimensionless parameter $u$. For small values $u << 1$ the inflection points are almost independent of $u$ and given by $x = 1/2 \pm \sqrt{1/2} S$. At a large axial force $S$ the points of inflection will move toward the edges. For $u >> 1$ these points are located at $x = 1/2 \pm \sqrt{1/2} S$. For very thin plates or membranes $u$ will be already large at moderately values of the axial force $S$.

The general solution is fully determined by the constants $D$, $S$ and $q$. For large deflections the axial force $S$ will increase due to elastic extension $\Delta l$ of the plate clamped between the edges. We will show that $S$ may be expressed as a simple function of $D$, $q$, $l$ and $v$ in the limit for large values of $u$. In this limit $S$ is still a constant (dependent only on other constants) and is independent on $x$, so the deflection curve $w(x)$ is still a solution of the differential equation. The increment $\Delta S$ is related to the increment $\Delta l$.

$$\Delta l = \Delta l = \frac{\Delta S(1 - v^2) l}{h E} = \int_0^l \Delta l = \int_0^l \sqrt{dx^2 + dw(x)^2}$$

It can be shown that the latter term is almost independent on $w(x)$ for all deflections under the condition $dw(x)/dx << 1$, or $w_{\text{max}} << l$. $\Delta l$ scales then with $w_{\text{max}}^2 / l$. For a parabolic deflection curve is valid $\Delta l = (8/3) u_{\text{max}}^2 / l$. Using $u^2 = (S + \Delta S) l^2 / 4D$, one obtains

$$\Delta l = \frac{u^2 - u_0^2}{4D^2 h E} = \frac{8 w_{\text{max}}^2}{3}$$

Alternatively $w_{\text{max}}$ is determined by the deflection curve, for $u >> 1$ at $x = 1/2$, $w_{\text{max}} = q l^2 / 32 u^2 D$. For large deflections the inflection parameter $u_0$ related to the initial axial force density $S$ may be neglected, i.e. $u >> u_0$, hence the following relation is found for $u$

$$u^6 = \frac{9(1 - v^2) q l^6}{8E^2 h^8}$$

The maximum deflection $w_{\text{max}}$ at $x = l/2$ is given by

$$w_{\text{max}} \approx \frac{q l^4}{32 Du^4} = 0.34 \sqrt{\frac{q l}{E h}}$$

The constant tensile stress in the plate is then estimated for large values of $u >> 1$

$$\sigma_{\text{tensile}} = \frac{N}{h} = 4u^2 D l^2 = \frac{E \left( \frac{q l^2}{3(1 - v^2)} \right)}{h} = 0.37 \sqrt{\frac{q E l^2}{h^3}}$$

and the maximum bending stress at the edge of the membrane is estimated by

$$\sigma_{\text{bend}} = \frac{E}{1 - v^2} \frac{d^2 w}{dx^2} = \frac{3q}{2 au \tanh u} \left( \frac{l}{h} \right)^3 = 1.47 \sqrt{\frac{q E l^2}{h^3}}$$

The above expressions are valid for a rectangular plate clamped at two edges, and may be valid for a thin membrane plate under a substantial load at large deflections $w_{\text{max}} / h > 1$.

The actual case to be considered here is a rectangular membrane clamped at all four edges. With the principle of virtual work Timoshenko\textsuperscript{5} has calculated the deflection $w_0$ of the center of a square membrane clamped at four edges

$$w_0 = 0.802 a^3 \sqrt{\frac{q d}{E h}} \approx 0.318 a^3 \sqrt{\frac{q l}{E h}}$$


and corresponding tensile stress $\sigma_0$ in the middle of the membrane

$$\sigma_0 = \frac{E}{1-\nu} \frac{0.462 \text{h}^3}{d_{\text{eff}}} = 0.39 \sqrt{\frac{q^2 E^2}{h^2}} = 0.29 \sqrt{\frac{q^2 E^2}{h^2}}$$

The values for $w_0$ and $\sigma_0$ are reasonably well corresponding with the values found for $w_{\text{max}}$ and $\sigma_{\text{tensile}}$ for the two clamped case. The value for the maximum deflection $w_{\text{max}}$ in the two edge clamped case is slightly larger than in the four clamped edge case due to the extra constraint and thus limiting the value of the deflection in the middle of the membrane.

A fortiori it is assumed that the ratio between $\sigma_{\text{bend}}$ and $\sigma_{\text{tensile}}$ remains unchanged for the two clamped and four clamped case, because both stresses scale identical near the edge of the membrane. Moreover in the four clamped case the maximum stress $\sigma_{\text{max}}$ is found near the middle of the edges. The deflection curve will resemble there the most the two clamped case. The total tensile stress near the edge is the addition of the constant tensile stress due to stretching and the bending stress near the edge:

$$\sigma_{\text{total}} = \sigma_{\text{tensile}} + \sigma_{\text{bend}}$$

From recent data the intrinsic tensile stress $\sigma_0$ in a siliconnitride membrane with thickness 1 μm ranges from 0.8 to 1.6 x 10^8 Pa. The maximum tensile stress $\sigma_{\text{yield}}$ before fracture occurs is for siliconnitride about 1.4 x 10^10 Pa. The intrinsic tensile stress may according to the above safely be neglected in calculating the maximum pressure $\sigma_{\text{max}}$ before fracture occurs ($\sigma_{\text{max}} > \sigma_0$). Using Young's modulus $E$ for siliconnitride 3.85 x 10^11 Pa and $\nu$ = 0.25 we find $\sigma_{\text{max}}$ = 15 bar for a dense square siliconnitride membrane with length $l$ = 1000 μm. The inflection parameter then is $u = 160$. The inflection points of the membrane are then located at 16 μm from the edge.

For a perforated membrane above equations may be used choosing a different value for $E$ and $\sigma_0$. In a first order approximation both $E$ and $\sigma_0$ are smaller and proportional with the unperforated fraction of the membrane. This will result in a smaller pressure strength also proportional to the unperforated fraction as can be obtained from above scaling equation for $\sigma_{\text{total}}$.

Flow Rate

Viscous laminar flow at low Reynolds number (Stokes flow) of a fluid medium through an orifice in a thin wall was first studied analytically by Sampson. For Stokes flows, the mean normal velocity is proportional to the pressure difference across the wall. The volume flow rate $\Phi$ of a fluid with viscosity $\eta$ through a circular opening with radius $R$ is proportional to the pressure difference $\Delta P$:

$$\Phi = \frac{R^3 \Delta P}{3 \eta}$$

Dagan et al. considered the case of a wall with a finite thickness $L$. A good approximate value for the flow rate $\Phi$ is given by them

$$\Phi = \frac{R^3 \Delta P}{3 \eta} \left(1 + \frac{a_1}{3R}\right)^{-1}$$

In a recent paper of Tio and Sadhal the flow behaviour of a microsieve with a very thin sieving layer having a regular pattern of apertures is being described. For a microsieve with a square array of apertures with a fraction $x$ of perforated area the proportionality is given by

$$\Phi = \frac{R^3 \Delta P}{3 \eta} \left[1 - f(x)\right]^{-1}$$

with $f(x) = \sum_{i=1}^{\infty} a_i x^{2i+1/2}$.

The terms $[1 + 8L/3xR]$ and $[1 - f(x)]$ will be viewed here as independent correction terms on the pressure drop due to the geometry of the microsieve. The relation between pressure drop and flowrate for Stokes flow at low Reynolds number then becomes

$$\Phi_{\text{Stokes}} = \frac{R^3 \Delta P}{3 \eta} \left[1 + \frac{8L}{3xR}\right]^{-1} \left[1 - f(x)\right]^{-1}$$

For laminar flow at higher flowrates a significant pressure drop will arise just before the entrance of the orifice, resulting in a velocity distribution of the flow passing the orifices. An estimation of this

---

contribution is given by Michell\textsuperscript{12} and may be explained as an extra pressure $\Delta P$ required to create a velocity distribution just before the inlet of the orifice.

$$\Delta P = \frac{\varrho V^2}{2} \cdot \frac{\varrho V^2}{2} \cdot \frac{\varrho V^2}{4} = \frac{\varrho V^2}{4\pi^2 R^4}$$

with $\varrho$: Mass density fluid
$V_{\text{orifice}}$: Mean velocity of fluid through orifice

The total pressure drop is in approximation the addition of the Stokes flow and the kinetic contribution. The relation between pressure drop and flow rate for Stokes flow with a correction for the kinetic contribution then becomes

$$\sum \Delta P = \frac{3\eta}{R^3} \left[ 1 + \frac{\varrho/\pi R}{1 - f(x)} \right] \Phi + \frac{2.53 \times 10^7}{R^4} \Phi^2$$

in water, with $\eta = 1 \times 10^{-3}$ kg/ms, $\varrho = 1 \times 10^3$ kg/m$^3$

$$\sum \Delta P = \frac{3\eta}{R^3} \left[ 1 + \frac{\varrho/\pi R}{1 - f(x)} \right] \Phi + \frac{2.53 \times 10^7}{R^4} \Phi^2$$

with $\Delta P$ in Pascal, $R$ in $\mu$m and $\Phi$ in $\mu$L/sec.

Industrial and Biomedical Applications

A microsieve with perforations essentially of one size will have potential many interesting applications, like absolute sterile filtration, critical cell-cell separation and cell deformability tests. Depending on the specific application bio or blood compatible materials should be used for the construction of the membrane or at least a suitable coating should be provided on the used membrane surfaces e.g. teflon or titanniumnitride. Interesting applications are possible whenever the membrane layer has a thickness that is smaller than the pore diameter, typically between 0.5 $\mu$m and 5 $\mu$m. This is particularly usefull if stress-sensitive particles or cells with a high flux should be filtered against bigger particles. Some cells, e.g. erythrocytes, will show an enhanced stiffening of their cell-wall whenever they enter narrow perforations, which are longer than their cell diameter, and will stick inside these perforations or release their cell content, e.g. blood platelets. An interesting application may be leukocyte removal from erythrocyt or blood platelet concentrates. A blood compatible microsieve with perforations between 2 and 5 $\mu$m in diameter may retain the remaining leukocytes, while the erythrocytes and/or bloodplatelets will permeate without much hemolysis or bloodplatelet activation, figure 9.

![Figure 8, Leukocytes on microsieve with poresize 4.5 $\mu$m.](image-url)

Acknowledgements

The authors are indebted to Meint de Boer for valuable suggestions for the processing of the microsieves and to Henri Jansen for many stimulating discussions.

---