Liquid Sheet Nozzles Manufactured from Isotropically Etched Glass

Supplementary Information

NOZZLE EXIT APERTURES

Separation of the nozzles from the wafer left rough edges around the nozzle exit. This didn't have an observable effect on the sheet dimensions but did affect the liquid sheet roughness. The nozzle exit surface was polished on a lapping machine using 3 micron grit lapping paper. Nozzles would be occasionally cleaned and inspected during the lapping process. Glass particulates would clog the aperture during polishing but were easily removed with compressed air. Polishing the nozzle exit face would also increase the width of the nozzle exit. The nozzle would be polished until a satisfactory surface quality was achieved and the nozzle width would be measured by optical microscopy. All nozzles used in the main test of this manuscript were polished and exits area measured in this manner.

A subset of the nozzles was examined with a three-dimensional optical profiler to quantify the defects in the exit surface. A typical image is shown in figure S1. Peaks and valleys in the glass surface are of order 10µm. The nozzle shown here is the same for which before-and-after sheet images are shown in figure 9 of the main text.

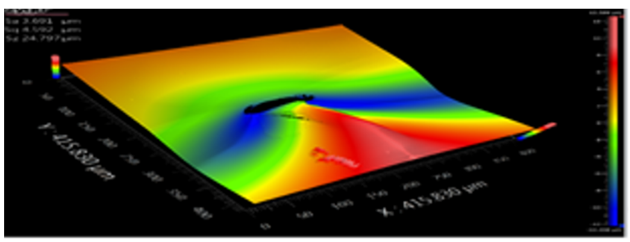

FIG. S1. Initially some of the nozzles produced irregular patterns. Further investigation revealed that the process of separating the glass nozzles from the wafer produced an uneven surface with peaks and valleys on the order of 10µm as shown in the profilometry data of figure S1. This was improved upon after polishing the nozzle exit face with 3 micron lapping film.

SHEET THICKNESS

Sheet thickness was previously studied for rectangular aperture nozzles by Ha. et al. In that work, the sheet thickness was shown to be a function of nozzle geometry only as follows [10].

$$\frac{h}{w_o} = 0.36\frac{d}{x}(1 + 1.5\alpha^2)\beta^{-1} \quad \textbf{Eq S1}$$

Here h is sheet thickness, w_o is nozzle exit width, d is nozzle exit depth, α is the aspect ratio defined as $\frac{d}{w_o}$, and β is the ratio of spanwise to streamwise momentum flux. It was previously shown [10] that beta is dependant only on the converging angle of the nozzle, more specifically, $\beta = 1 + \cot(0.67\theta)$. As we have only one angle, beta was replaced by a constant. The above equation and other second order polynomial expansions in alpha were compared to the data with best fit order zero. The geometry used here differs from the rectangular geometry used to find Eq S1. Isotopically etched glass produces a shape that is closer to an oval, the intersection of a plane and a converging channel with semicircle shaped edges. This causes an error when approximating the cross sectional area by dw_o, and this error is largest for large aspect ratio. This may in itself account for some of the aspect ratio correction term in Eq S1

Figure S2 shows the fit of Eq S1 to the thickness data collected for 11 nozzles. All nozzles have the same depth. The disagreement with the fit is therefore aspect ratio dependant.

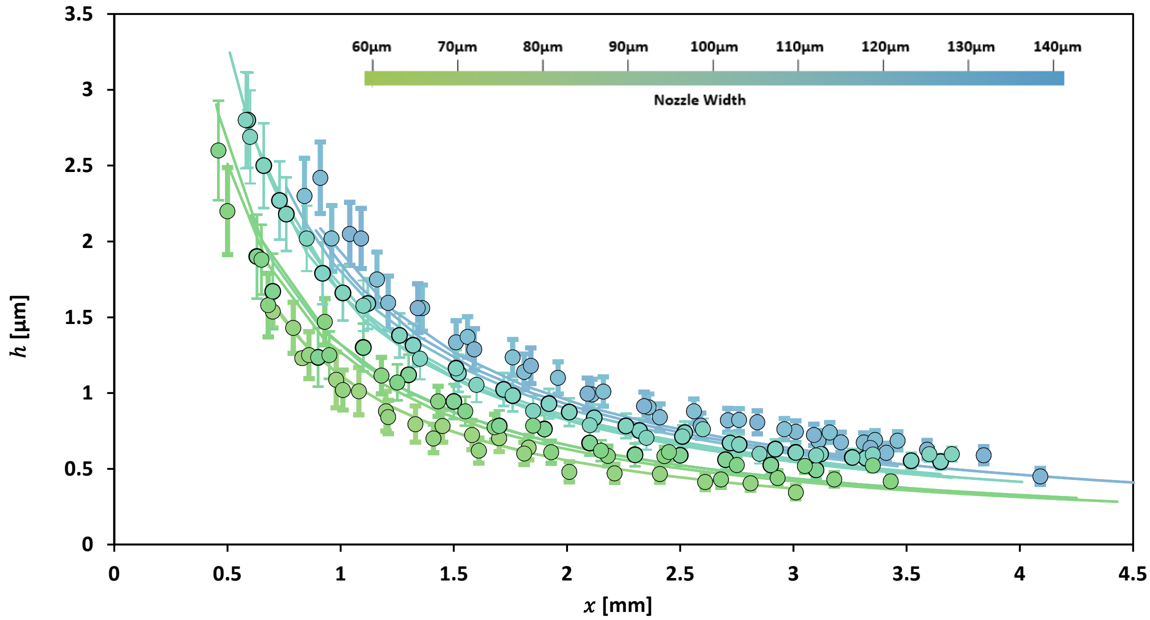

FIG. S2. The results of the measured sheet thickness for nine nozzles, together with the calculation results based on Eq S1.

The smallest of the nozzles fabricated for this test had a width of 45µm but either due to the nozzles position during breakout from the wafer or due to polishing, the nozzles widths used were always larger. The expected minimum sheet thickness for a 40µm x 20µm nozzle exit with a 60 degree converging angle should be about 160 nm check this against corrected Eq S1. As a result of the increased width, sheet thickness were also larger. The minimum measured sheet thickness was also dependent on the focus of the reflectometer; if the illumination spot, approximately 150µm overlaps the sheet edges "rims", data could not be collected. Figure S3 shows data collected for a nozzle that had not been polished and with a slightly better illumination focus demonstrating that thinner sheets are possible. The sheet used is the same as in figure 4. Sheet thickness was recorded at 2 flow rates, 3.0 ml/min and 3.5ml/min. The higher flow rate extends the length of the sheet allowing for data to be collected at thinner regions.

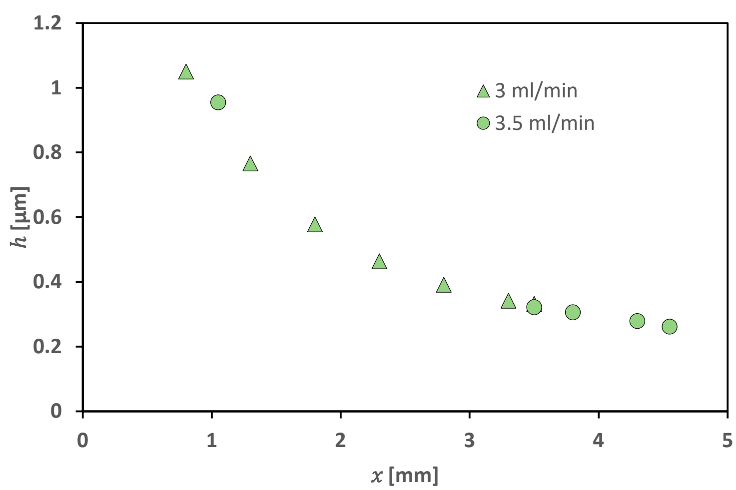

FIG. S3. Shows the sheet thickness as measured for the sheet in figure S1. Data were recorded at 2 different flow rates 3.0ml/min and 3.5ml/min.

Error estimation

This section describes the estimation of the sheet thickness uncertainty as a function of error in chip fabrication, measurement location, and thermophysical constants. As shown in Eq 1, the measured sheet thickness $h = h(x, d, w_0)$, where x is the streamwise location, d is the nozzle depth, w_0 is the nozzle width. We assume here that each of the errors in x, d, and w_0 (i.e. Δx, Δd, and Δw_0) is statistically independent and that each random error has a Gaussian distribution with zero mean. These assumptions allow the use of propagation of error theory to analytically estimate the uncertainty of each experimental sheet thickness measurement Δh. This Δh is given by

$$\Delta h = \sqrt{\left(\frac{\partial h}{\partial x}\Delta x\right)^2 + \left(\frac{\partial h}{\partial d}\Delta d\right)^2 + \left(\frac{\partial h}{\partial w_0}\Delta w_0\right)^2}, \tag{1}$$

Where

$$\frac{\partial h}{\partial x} = -0.84\frac{dw_0}{x^2}, \tag{2}$$

$$\frac{\partial h}{\partial d} = 0.84\frac{w_0}{x}, \text{ and} \tag{3}$$

$$\frac{\partial h}{\partial w_0} = 0.84\frac{d}{x} \tag{4}$$

Note that Δx, Δd, and Δw_0 were here assumed to be constant (Table S1). Further, the above expression indicates we are 95% confident that the true value of the sheet thickness h_{true} is $h \pm \Delta h$.

Similarly, for Eq S1 the measured sheet thickness $h = h(x, d, w_0, \theta)$, where x is the streamwise location, d is the nozzle depth, w_0 is the nozzle width, and θ is the nozzle convergence angle. We assume here that each of the errors in x, d, w_0, and θ (i.e. Δx, Δd, Δw_0, and $\Delta\theta$) is statistically independent and that each random error has a Gaussian distribution with zero mean. These assumptions allow the use of propagation of error theory to analytically estimate the uncertainty of each experimental sheet thickness measurement Δh. This Δh is given by

$$\Delta h = \sqrt{\left(\frac{\partial h}{\partial x}\Delta x\right)^2 + \left(\frac{\partial h}{\partial d}\Delta d\right)^2 + \left(\frac{\partial h}{\partial w_0}\Delta w_0\right)^2 + \left(\frac{\partial h}{\partial \theta}\Delta \theta\right)^2}, \tag{5}$$

where

$$\frac{\partial h}{\partial x} = -0.36\frac{dw_0}{x^2}[1 + 1.5\alpha^2][1 + \cot(0.67\theta)], \tag{6}$$

$$\frac{\partial h}{\partial d} = \frac{1}{x}\left(0.36w_0 + 1.62\frac{d^2}{w_0}\right)[1 + \cot(0.67\theta)], \tag{7}$$

$$\frac{\partial h}{\partial w_0} = \frac{1}{x}\left(0.36d - 0.54\frac{d^3}{w_0^2}\right)[1 + \cot(0.67\theta)], \text{ and} \tag{8}$$

$$\frac{\partial h}{\partial \theta} = 0.241\frac{dw_0}{x}[1 + 1.5\alpha^2]\csc^2(0.67\theta). \tag{9}$$

Note that Δx, Δd, Δw_0, and $\Delta\theta$ where here assumed to be constant (Table S1). Further, the above expression indicates we are 95% confident that the true value of the sheet thickness h_{true} is $h \pm \Delta h$.

Table S1. List of properties and estimated error.

Property	Variable	Nominal	Error (±)	Units
Water flow rate	Q	1.9 – 4.3	0.19 – 0.43	mL min^{-1}
Nozzle width	w_0	57 – 146.3	5	µm
Nozzle depth	d	16.22 – 18.63	1.587	µm
Nozzle angle	θ	60	0.6	deg.
Water density	ρ	998	19.96	kg m^{-3}
Water dynamic viscosity	μ	1	0.12	mPa s
Water surface tension	σ	72.9	1.46	mN m^{-1}
Streamwise position	x	0.24 – 4.59	0.15	mm

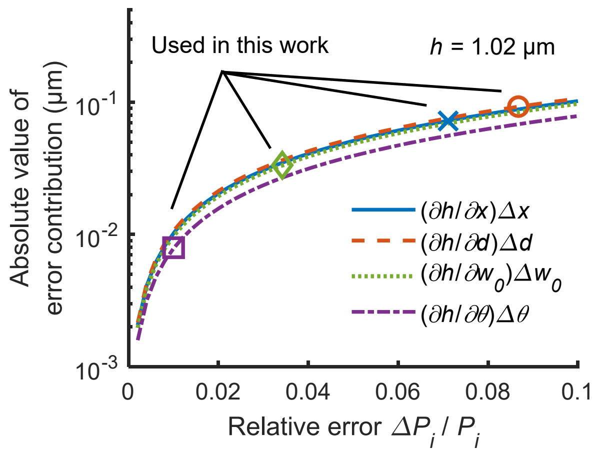

FIG. S4. Example of absolute value of the sheet thickness measurement error versus the relative error of each parameter $\Delta P_i/P_i$. Shown is data for the streamwise position $\Delta x/x$, nozzle depth $\Delta d/d$, nozzle width $\Delta w_0/w_0$, and nozzle convergence angle $\Delta\theta/\theta$. The markers indicate $\Delta P_i/P_i$ for each parameter and the resulting absolute value of its error contribution (calculated via propagation of error technique). The total uncertainty (for 95% confidence) of the sheet thickness is given by a root sum square of each error contribution. Here, the liquid flow rate Q = 3.75 mL min-1, x = 2.11 mm, d = 18.3 µm, w_0 = 146.3, and θ = 60°.