SPIN-COATING

Introduction

Spin coating is a process of coatings a flat surface by a thin liquid film facilitated by a fast rotation of the surface. This process is widely used in semiconductor industry for depositing layers of photoresist (i.e., polymers sensitive to light) on silicon wafers. The photoresist layers are then used in photolithographic patterning of integrated circuits.

Spin-coater is essentially a turntable maintained under vacuum conditions. To perform spin coating, a substrate is placed on the turntable and then a liquid is deposited at the center of the substrate. This is followed by a very fast (thousands of RPMs) rotation of the turntable. The liquid spreads outwards to the edge of the substrate and forms a thin film of a relatively uniform thickness. It is important to understand effect of various control variables on the film thickness and uniformity since manufacturing of semiconductor devices requires smooth and uniform photoresist films of predictable and reproducible thickness.

Theory

The thickness $h$ of the coating layer depends on the fluid viscosity $\mu$, the fluid density $\rho$, the angular velocity $\omega$ of the turntable, and the total time $t$ that the sample is rotated. To determine this dependence, it is necessary to solve equations for fluid dynamics during the spin coating process. We will use the model for the spin coating developed by Emslie et al. [1]. This model assumes that the fluid is Newtonian, which is a reasonable assumption for silicon oils considered in this lab. However, this may be a poor assumption for liquids used in industrial applications (e.g., polymer solutions).

This model of Emslie et al. also assumes that the fluid flow is unidirectional in the radial direction, i.e. only the radial component of the fluid velocity, $v_r$, is not zero. The fluid is assumed to rotate together with the substrate, i.e. the angular velocity of the fluid is

$$v_\phi = \omega r.$$  \hspace{1cm} (1)

Then the continuity equation for the fluid velocity (in the cylindrical coordinates) becomes

$$\frac{1}{r} \frac{\partial}{\partial r} (rv_r) = 0$$  \hspace{1cm} (2)

and the Navier-Stokes equations are

$$\rho \left( v_r \frac{\partial v_r}{\partial r} - r \omega^2 \right) = -\frac{\partial p}{\partial r} + \mu \left[ \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial v_r}{\partial r} \right) + \frac{\partial v_r^2}{\partial z^2} - \frac{v_r}{r^2} \right]$$  \hspace{1cm} (3)
Unit Operations Lab

Spin-Coating

2ρν_ρω = \frac{1}{r} \frac{∂p}{∂φ} \tag{4}

0 = \frac{∂p}{∂z} \tag{5}

Assuming that the height of the liquid layer is much smaller than its radius, we can introduce a rescaled coordinate r* = εr. Then Eq. (3) becomes:

\rho \left( εν_ρ \frac{∂ν_ρ}{∂r^*} - ε^{-1} r^* \omega^2 \right) = -ε \frac{∂p}{∂r^*} + μ \left[ ε^2 \frac{1}{r^*} \frac{∂}{∂r^*} \left( r^* \frac{∂ν_ρ}{∂r^*} \right) + \frac{∂ν_ρ^2}{∂z^2} - ε^2 \left( r^* \right)^2 \right] \tag{6}

Neglecting terms of order ε and higher, we obtain:

-ρrω^2 = μ \frac{∂ν_ρ^2}{∂z^2} \tag{7}

In Eq. (7), we returned to the original coordinate in the radial direction, r = ε^{-1} r*.

The boundary conditions for the fluid velocity are: (i) the no-slip condition at the substrate surface,

v_ρ(r, z) = 0 \text{ at } z = 0, \tag{8}

and (ii) the free surface condition at the interface between the fluid and the vacuum,

\frac{∂v_ρ(r, z)}{∂z} = 0 \text{ at } z = h(r, t), \tag{9}

where h(r, t) is the height of the liquid layer. Integrating Eq. (7) twice and using the boundary conditions (8), (9), we obtain:

v_ρ(r, z) = \frac{ρrω^2h(r, t)^2}{μ} \left[ \frac{z}{h} - \frac{z^2}{2h^2} \right] \tag{10}

Equation (10) describes the radial velocity corresponding to an instantaneous film height h(r, t).

The film height is much smaller than its radius. Moreover, it is expected to vary smoothly. This allows us to neglect the dependence of the height on the position r and determine h(t) from the mass balance in the radial direction,

\frac{dh}{dt} + \frac{1}{r} \frac{∂}{∂r} (rq) = 0 \tag{11}

where

q = \int_0^h v_ρ \, dz = \frac{ρrω^2h^3}{3μ} \tag{12}

is the radial flow of fluid per unit length of circumference. Substituting Eq. (12) into the mass balance equation (11), we obtain
\[
\frac{dh}{dt} + K h^3 = 0 \tag{13}
\]

where

\[
K = \frac{2 \rho \omega^2}{3 \mu} \tag{14}
\]

Solving equation (13), we obtain

\[
h = h_0 \left[ \frac{1}{2 K h_0^2 t + 1} \right]^{1/2} \tag{15}
\]

where \(h_0 = h(t=0)\). Assuming that

\[K h_0^2 t \gg 1,\tag{16}\]

Eq. (15) yields the following scaling relationship for the film thickness:

\[
h \sim \left( \frac{\mu}{\varepsilon \omega^2} \right)^{1/2} \tag{17}
\]

References