Maximizing Buoyancy-Driven Convection in LIGA Development and Electrodeposition

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Abstract

LIGA development and electrodeposition rates are respectively limited by transport of polymer fragments and metal ions within high aspect ratio features, sometimes resulting in process nonuniformities and lengthy processing times. Depending in part upon the wafer orientation, these transport processes may be strongly enhanced by convective motions induced by fluid density differences. In electrodeposition, metal ion depletion at the plating surface produces a lighter fluid that rises out of upward facing features. Conversely in development, dissolved polymer fragments increase the local fluid density causing downflow out of downward facing features. In the present paper, analytical and numerical models are used to explore the dependence of transport rates on feature dimensions and wafer orientation. Attention is focused on three different modes of buoyancy-driven convection in trench-like features. As illustrated in Figs. 1-3, these include two-dimensional motions in either the transverse or longitudinal plane of a trench on a horizontal wafer as well as convection in the longitudinal plane for a vertical wafer. If the wafer has some other inclination to the gravity field, the motion can be estimated from these fundamental modes using gravity components acting along the primary feature axes.

The streamline patterns shown in Figs 1-3 were computed by solving the two-dimensional Navier Stokes equations. For the longitudinal flows in Modes II and III, the equations are supplemented to include an additional shear stress based on the Hele-Shaw approximation of a parabolic velocity variation between the trench side planes. These numerical solutions, available experimental data, and previous results for mathematically analogous flows in porous media were used to guide the development of analytical solutions that apply in the limit of very strong motion. Figs. 1-3 include such expressions for the strength of convective transport relative to diffusion (i.e. the Sherwood number, Sh) as a function of the Rayleigh number, Ra, a measure of the strength of buoyancy forces relative to restraining viscous forces. These expressions for strong convection were blended analytically with newly derived expressions for relatively weak motion to obtain easily applied composite approximations that were used to construct Fig 4.

Figure 4 shows the convective enhancement ratio, Sh, as a function of PMMA thickness, h, for various aspect ratios, h/w, where w is the trench width. The parameters noted in the plot are typical of electrodeposition; Sh will be larger for development because the density contrast, $\Delta\rho$, is similar but the diffusivity, D, is far smaller. As expected, Sh increases with feature depth but is suppressed by high aspect ratios. As also apparent in Fig. 4, there is a threshold feature height required for Mode I convection. This threshold corresponds to a critical Rayleigh number that increases with aspect ratio in accordance with equations given in Figs. 1 and 2 for horizontal

wafers. No such threshold applies to Mode III convection on a vertical wafer. In addition it is seen in Fig. 4 that Mode III convection is stronger than Mode I over the full range of feature geometries. Mode II convection has a lower threshold but is otherwise weaker than Mode I. Thus, it might appear that vertical wafer orientation should be best since it would permit Mode III convection in favorably oriented trenches. However, the gravity vector will probably be orthogonal to the longitudinal plane of some trenches and no gravitational component would act along the axis of circular holes. The problem of trench orientation is remedied by occasional wafer rotation; round holes will benefit from a 45 degree inclination.

It is concluded that convective transport will generally be maximized by inclining the wafer about 45 degrees from the vertical, with features facing upward during electrodeposition but downward during development. F. J. Pantenburg of Forschungszentrum Karlsruhe has for some time been using this approach for development, partly to avoid settling of particulate into features; to release any trapped gas he periodically flips the wafer over within the bath. Occasional rotation of the wafer will also help to promote uniformity across feature orientations.

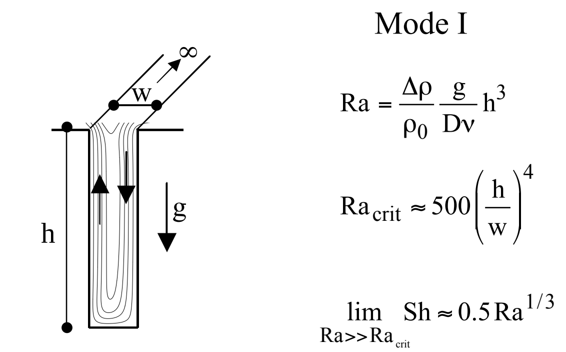

FIGURE 1. Convection in the transverse plane of a trench-like feature on a horizontal wafer.

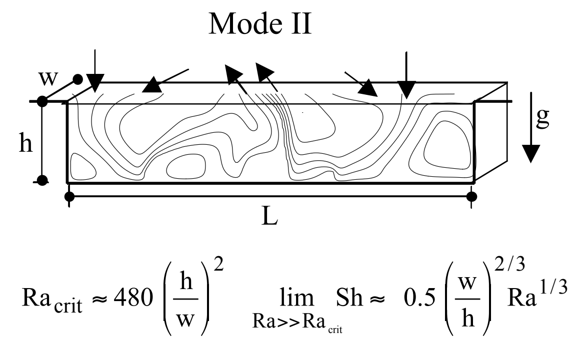

FIGURE 2. Convection in the longitudinal plane of a trench-like feature on a horizontal wafer.

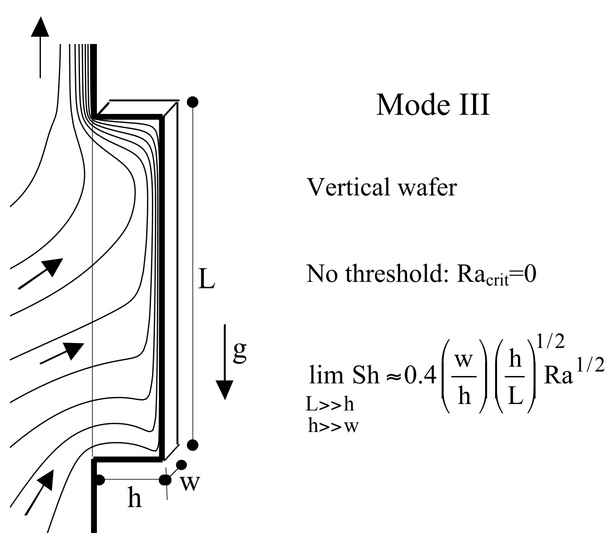

FIGURE 3. Convection in the longitudinal plane of a trench-like feature on a horizontal wafer.

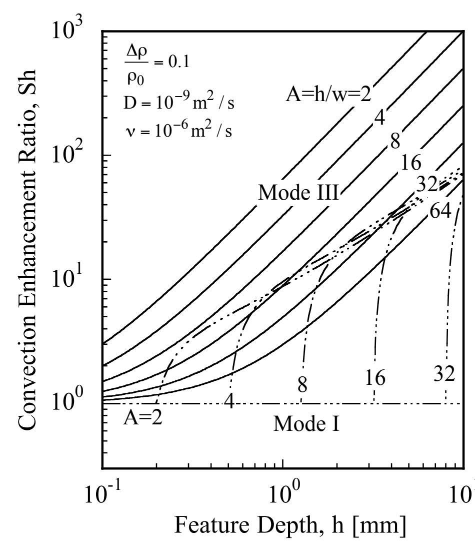

FIGURE 4. Comparison of transport enhancement for Mode I (dotted lines) and Mode III (solid). L/h=10.