Task ID: 425.014
Task Title: Environmentally Benign Electrochemically-Assisted Chemical-Mechanical Polishing
Deliverable: Report on the conducting pad designs capable of E-CMP removal of copper and barrier films on patterned wafers

GOAL: **Electrochemical and Geometric Tool/Pad Modeling for Alternative Conductive Pads in Electrochemical-Mechanical Polishing (ECMP)**

Electrochemical-mechanical polishing (ECMP) is of substantial interest as an additional option or component in the polishing and planarization of copper and barrier materials in advanced interconnect technologies. The use of independently biased cathode zones in a typical ECMP tool enables control of removal rates across the wafer to account for variations in the incoming copper thickness profile and to compensate for tool and process effects, enabling excellent wafer level uniformity. In these configurations, the cathode is a metallic plate, separated from the wafer anode by a conventional CMP polishing pad with access holes cut in it through which the electrolyte comes in contact with the cathode. Our goal in this deliverable item is to model and investigate alternative pad properties, as well as pad and tool geometries, that can enable the E-CMP removal of both copper films, and potentially of the underlying barrier films. This will help enable the application of ECMP beyond the bulk copper removal step, with potential environmental, waste, cost, and time savings by full removal of copper/barrier using ECMP (potentially followed by a conventional oxide CMP step for surface quality improvement).

SUMMARY:

Our approach is to investigate the E-CMP process, including pad properties and pad/tool geometry effects, using a combination of simulation and experimental work. The initial focus has been on building the modeling infrastructure. Accomplishments to date include:

- Construction of a 2D numerical model, considering the spatial distribution of electrical current through multiple cathode zones, through the electrolyte, and through the surface copper film on the wafer to an edge contact zone. This initial work is with a conventional (non-conductive) polishing pad, and focused on the current spreading through the electrolyte and thin metal films.
- Extension of the purely ohmic model (above) to capture the electrochemical effects at the anode (wafer). These effects are nonlinear with respect to voltage; an equivalent resistor-diode model was defined to capture this dependency. Improved uniformity
- Current work is extending the electrochemical model to include effects at *both* the anode and cathode. This is crucial to being able to study the effect of localized voltage applied through a conducting pad serving as the cathode, near to the wafer serving as the anode.

In this report, the non-ohmic model is summarized, as it serves as the baseline for comparison with conducting pads in our future simulation studies. In addition, preliminary extensions to the two-diode model are described; these models are currently being implemented and tested against experimental data. Finally, plans for further studies on conducting pad designs using the extended model will be summarized.

NON-OHMIC MODEL FOR CATHODE/ANODE/PAD EFFECTS IN ECMP

A previous physical model [1], [2] attempted to predict the spatial dependence of the copper removal rate across the wafer during ECMP, based on the spatial distribution of electrical current flow through the electrolyte and the thin copper surface film as a function of applied voltages in different radial zones. In this section, we review the mathematical formulation of an improved version of this model. During polishing, an electrical potential is applied between the cathode platen and anode as shown in Figure 1. The copper contact points in the wafer contact zone provide a conductive path from the copper surface of the wafer to the anode. The conductivity of the contact points is 7 orders of magnitude higher than electrolyte; therefore, the whole wafer surface is assumed to be grounded. Current flows from the biased cathode through the electrolyte; this current can be solved given the cathode bias conditions, conductivity of the electrolyte, and the geometry of the system. Electrical current oxidizes the copper atoms on the wafer surface, and copper ions dissolve in the electrolyte. The copper removal rate is proportional to the current density, with a proportionality defined by a constant from Faraday's law of electrolysis.

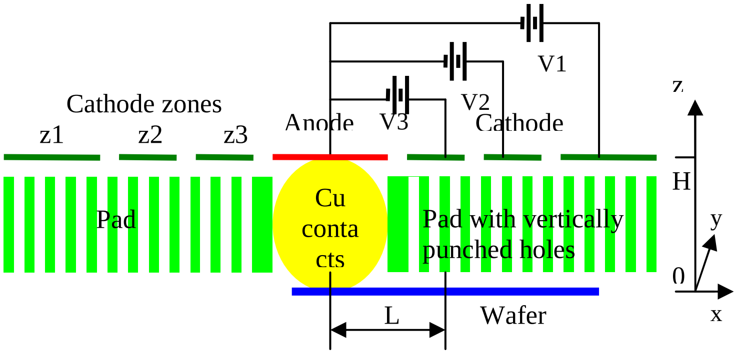

Figure 1: The ECMP system (not to scale) with conventional polishing pad, having vertically punched holes. A side view along *x*-*y* horizontal plane.

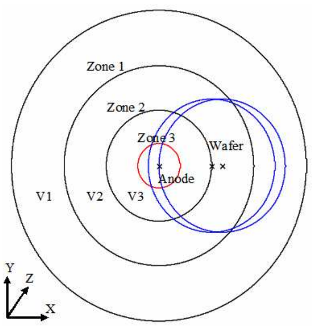

Figure 2: Schematic view of the relative position of wafer and cathode zones. The wafer center is typically swept sinusoidally 5-6 in. from platen center.

The ohmic model works well when the bias condition for a zone (V_x) is either 3V or 0V. When we have cathode zones biased at different voltages, however, the fit is not as good across the entire wafer. A likely cause is that the system contains important nonlinearities with respect to bias voltage. We verify the presence of nonlinearity by a second set of experiments. Here, we bias zone 1 and zone 3 at 0V, but set zone 2 to five different voltages; we maintain a fixed head position at 6.0 inches, and we keep our other conditions the same. The amount of removal is shown in Figure 3, where a nonlinear relationship between removal amount and bias voltage is indeed observed. Based on electrochemical interactions, the expected nonlinear relationship is between the voltage and current density. Specifically, a non-ohmic component of the system that has been neglected in our basic model is the overpotential, the potential drop at the solid electrode and electrolyte solution interphase. Taking into account the surface overpotential, which is related to current density j by the Butler-Volmer equation [6], the boundary-value problem for the electrical potential Φ in domain Ω has a new boundary condition at the electrodes,

$$-\sigma\nabla\Phi \bullet n = i_0\left(e^{\frac{\alpha_a F}{RT}\Phi} - e^{-\frac{\alpha_c F}{RT}\Phi}\right) \text{ on } \Gamma_A, \qquad (9)$$

where R is the universal gas constant, T is temperature, j_0 is the exchange current density, and α_a and α_c are the apparent transfer coefficients.

Instead of solving this modified boundary-value problem directly, we propose a simple 1-D model as an approximation [3]. The presence of the insulating polishing pad with punched holes largely prevents global ion diffusion, drift, or convection. The effective horizontal conductivity is assumed, to first order, to be much smaller than the vertical conductivity, and thus each hole subsystem is independent from others. Hence, we consider the electrolyte contained in a hole, the cathode surface, and the wafer surface at the two ends of the hole as an isolated subsystem. The electrolyte in the hole is ohmic, and is electrically equivalent to a resistor. The current density and overpotential at electrolyte-electrode interphase obeys the Butler-Volmer equation, which has a high-overpotential approximation, $j = j_0 e^{\frac{\alpha_a F}{RT}\eta_s}$, and this is equivalent to a diode. Therefore, the equivalent circuit for current flow from wafer to cathode in a punched hole on the pad is simply a resistor and a diode, as pictured in Figure 4. Given the voltage V

at the cathode surface at one end of the hole, and with the wafer surface on the other end of hole being grounded, we simply solve the equation pair $j = \sigma_z V_R = j_0 e^{\frac{\alpha_a F}{RT}\eta_s}$ and $V_R + \eta_s = V$ numerically.

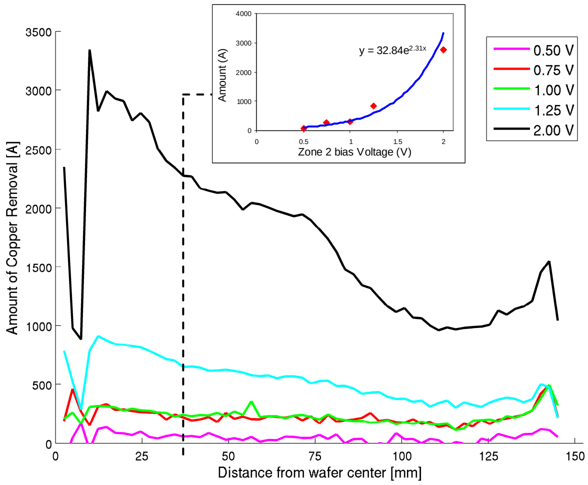

Figure 3: Experimentally measured copper removal in 80 seconds for five different values of V_2 (with V_1 = V_3 = 0V). Figure inset shows the observed nonlinear relationship between V_2 and the removal amount (current density) for one selected wafer radius.

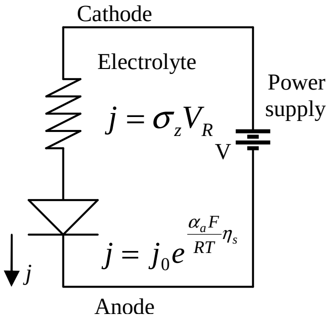

Figure 4: Equivalent circuit for a vertically punched hole in pad.

In this model, the pad effects are assumed to primarily be to apply the mechanical pressure and abrasion to open up the passivation formed on the copper wafer surface, so that the electrochemical dissolution of the exposed copper can proceed. However, removal of the passivation layer by pad abrasion might also be affected by pressure and velocity. A third group of experiments compares results for wafers run with different combinations of rotational speed and pressure. A least-squared fit gives the averaged removal rate $\overline{\mathrm{RR}}$ as a linear combination of pressure and velocity,

$$\overline{\mathrm{RR}} = (1482 \pm 93) + (507 \pm 65)\frac{P}{P_0} + (674 \pm 65)\frac{V}{V_0} \tag{10}$$

where P_0 and V_0 are the nominal pressure and velocity. A 20% change in pressure or velocity results in approximately 5% change in removal rate. The system is non-Prestonian, but the effect of pressure and velocity on removal rate is approximately linear locally. This might imply that the passivation layer cannot be treated as equally instantaneously removed under all of our conditions. A model considering passivation is needed in the future, even for blanket wafers. This effect also motivates placing the electrical contact to the wafer surface much closer to the area undergoing polish, rather than requiring the conduction to take place in the distant wafer contact zone. That is to say, a conducting pad to achieve contact with the wafer could help to make the electrochemical cathode/electrolyte/anode cell much more geometrically compact and local.

In order to analyze conducting pad situations, however, a further extension to our model is required, so that both the anode and cathode electrochemical effects can be included. Preliminary work on this is described next.

EXTENDED CATHODE/ANODE MODEL

The previous non-ohmic model described above only addresses the nonlinear dependence of copper dissolution on the voltage at the anode (wafer). In current work, we are extending the model to include both cathode and anode voltage drops, and the electrochemical effects at both of these electrodes.

The extended model is pictured in Figure 5 and Figure 6. In particular, we see that the extended model must include the voltage drop across or along any conductive polishing pad in future configurations.

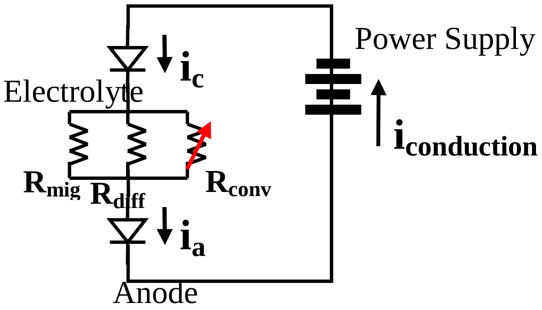

Figure 5: Model with both anode and cathode voltage drops and current components. Butler-Volmer relationships at both electrodes are modeled using equivalent diodes.

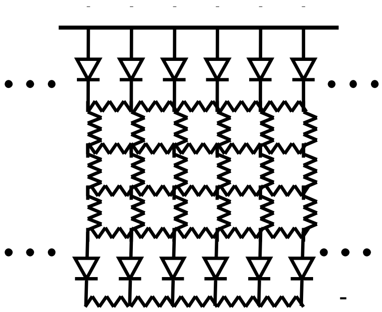

Figure 6: Equivalent circuit for current flow in both the electrolyte (middle resistive network), the cathode (top diodes), and anode (bottom diodes). The resistance of the pad becomes an important component in this model.

PLANS:

The next step is to implement and validate the 2D version of the extended model, encompassing the anode and cathode electrochemical effects, the voltage drops along a conductive pad, as well as current distributions in the electrolyte. Second, we plan to apply the extended model to alternative conductive pad and tool geometries under consideration. For example, the local cell design proposed by XX, shown in Figure YY, will be considered. Here, the polishing "cell" is more spatially local, extending from the underlying cathode plate, through the electrolyte, to the wafer surface as contacted and with voltage as established by a conductive polishing pad. In longer range work, we plan to integrate our pattern dependent models that also incorporate the mechanical properties of the polishing pad and the key effect of local pressure on planarization. This will assist in the modeling, experimentation, and optimization of alternative ECMP pad and processes, to enable the removal of both copper and barrier metal layers.

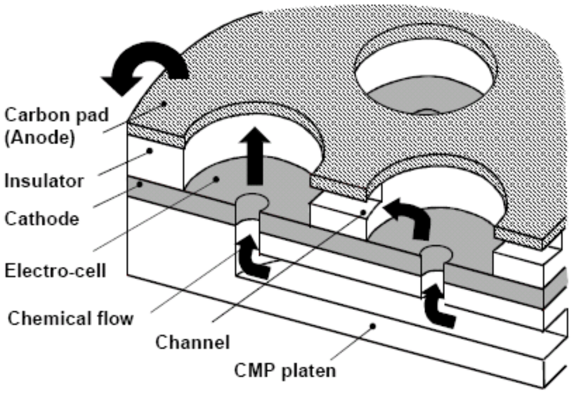

Figure 7: Electro-cell structure fabricated in a conductive carbon pad – Kondo et al. [7].

ACKNOWLEDGEMENTS:

The experimental and modeling discussion on ECMP have been in collaboration with Chris Borst, and Raymond Caramto at Albany Nanotech, SUNY Albany. We also thank Ruitian Lang, MIT, and Srini Raghavan, University of Arizona, for helpful discussion on electrochemistry.

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