Copper Plating in Via Arrays

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SAND2010-6242P

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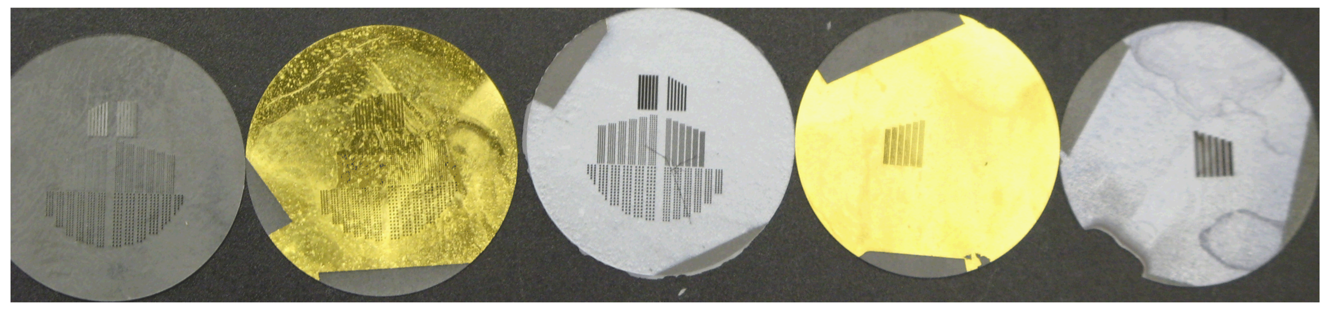
Background

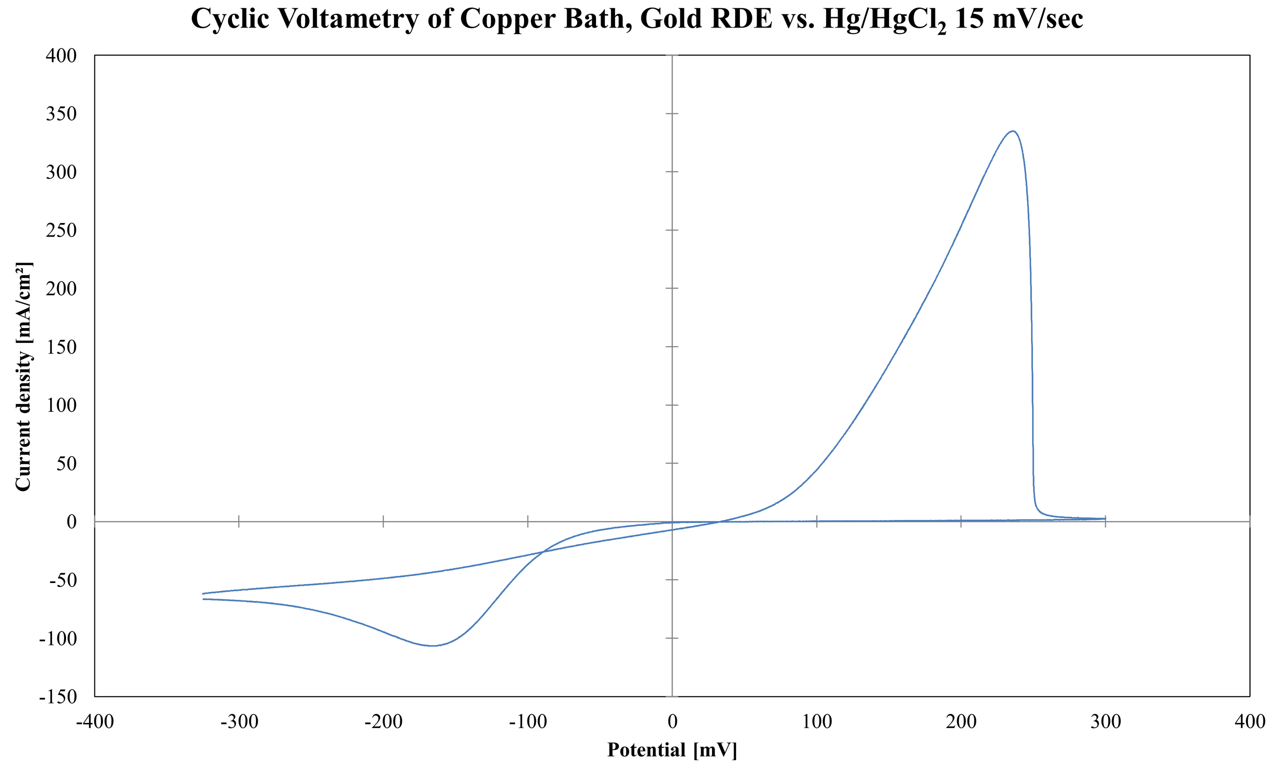
- Via plating is ideal for electronic equipment and medical device implants
- Vias can range from10-100 microns in diameter with 75-225 micron thick substrates, aspect ratios >5.5:1
- Substrate wafers can be up to 6 in. diameter with 100,000's of vias
- It is difficult to achieve uniform depositions throughout each via and across the area of the substrate
- Strategies include reverse pulse plating, altering bath chemistries using organic additives, and using an electroless bath to deposit a seed layer
- The Working Electrode setup and geometry have proven to be crucial to achieving uniform via plugs

Outline

- Determine the electrochemical surface area and use this to determine the diffusion and reaction rates for the Copper (II) ion in the electroplating bath
- Use the Copper (II) diffusion and reaction rates to develop and tailor direct current and reverse pulse plating regimes for electroforming in via arrays
- Experiment with electroless Copper as a seed layer for electroplating in via arrays
- Experiment with various setup methods to achieve a hermetic seal and uniform via filling across the sample

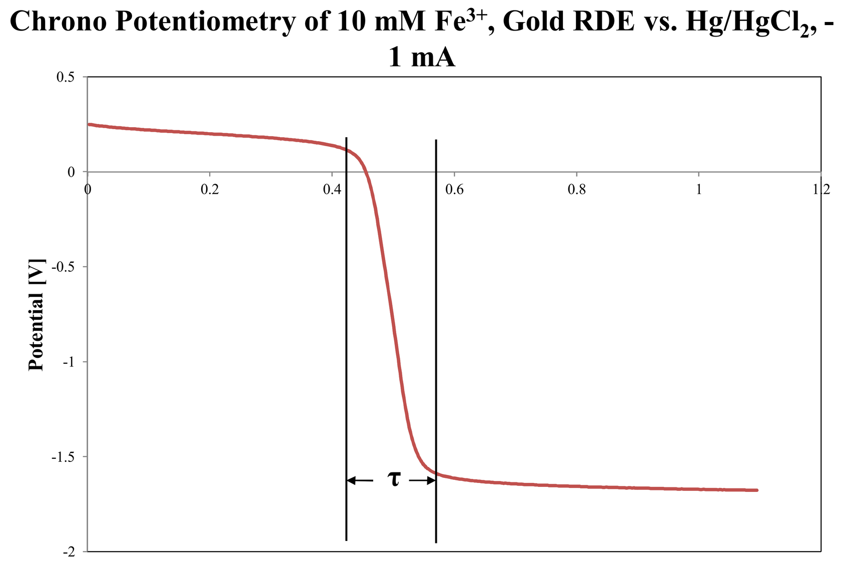


Cyclic Voltammetry of Copper Bath, Gold RDE vs. Hg/HgCl$_2$ 15 mV/sec

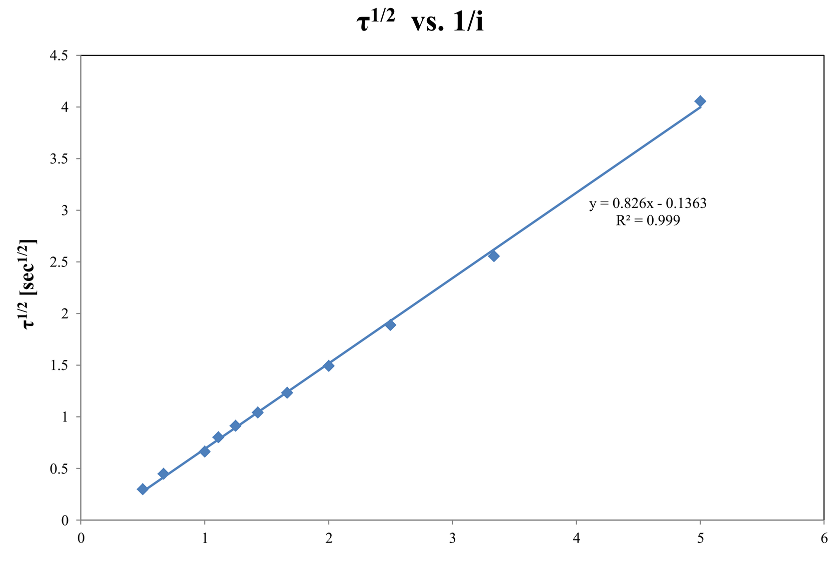


Surface Area

Chrono Potentiometry of 10 mM Fe^{3+}, Gold RDE vs. Hg/HgCl$_2$, -1 mA



$\tau^{1/2}$ vs. 1/i



Sand's Equation:

$$\sqrt{\tau} = \frac{85.5 n A C_b \sqrt{D}}{i}$$

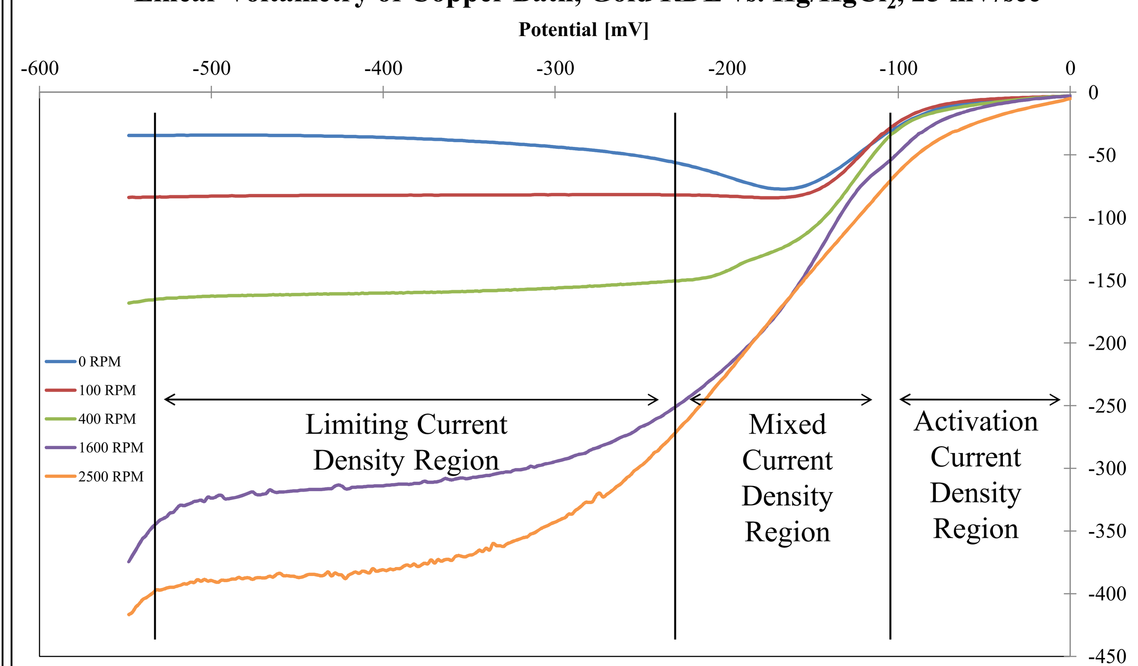
τ = Transition Time [sec]
n = # of e⁻ transferred, 1 e⁻
D = Diffusion Coefficient [cm^2/sec]
A = Electrochemical Surface Area [cm^2]
C_b = Bulk Concentration, 1E-5 mol/mL Fe^{3+}
i = Current [mA]

- By applying a constant current and determining the transition time τ Sand's Equation can be used to determine the electrochemical surface area of a electrode

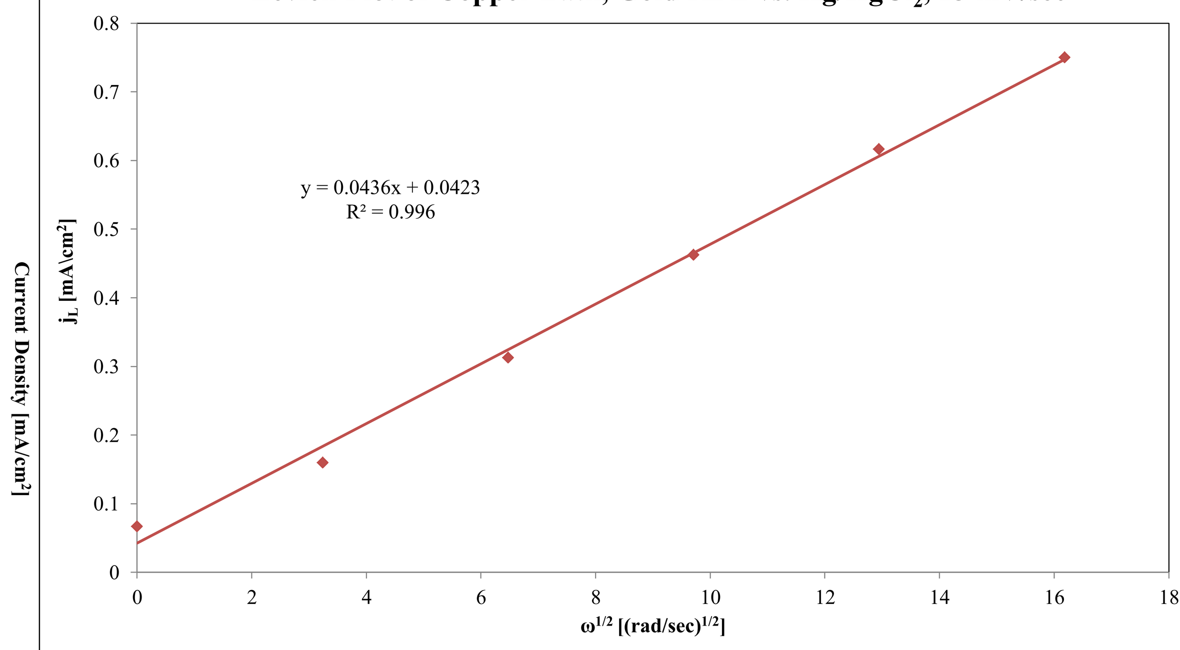
Geometric Surface Area: 0.03142 cm^2
Electrochemical Surface Area: 0.3504 cm^2

Diffusion & Reaction Rate

Linear Voltammetry of Copper Bath, Gold RDE vs. Hg/HgCl$_2$, 25 mV/sec



Levich Plot of Copper Bath, Gold RDE vs. Hg/HgCl$_2$, 15 mV/sec



Levich Equation:

$$j_L = \frac{.62 n F C_b D^{2/3} \omega^{1/2}}{\upsilon^{1/6}}$$

j_L = Limiting Current Density [mA/cm^2]
F = Faraday's Constant, 96,485 J/C
n = # of e⁻ Transferred, 2 e⁻
υ = Kinematic Viscosity, 9.43E-3 cm^2/sec
ω = Rotational velocity [rad/sec]

- Using the Levich Equation the diffusion coefficient can be determined by plotting j_L vs. $\omega^{1/2}$
- The diffusion coefficient can be used to determine the time needed for Cu^{2+} to diffuse across the diffusion layer

Diffusion coefficient = 4.74E-6 cm^2/sec

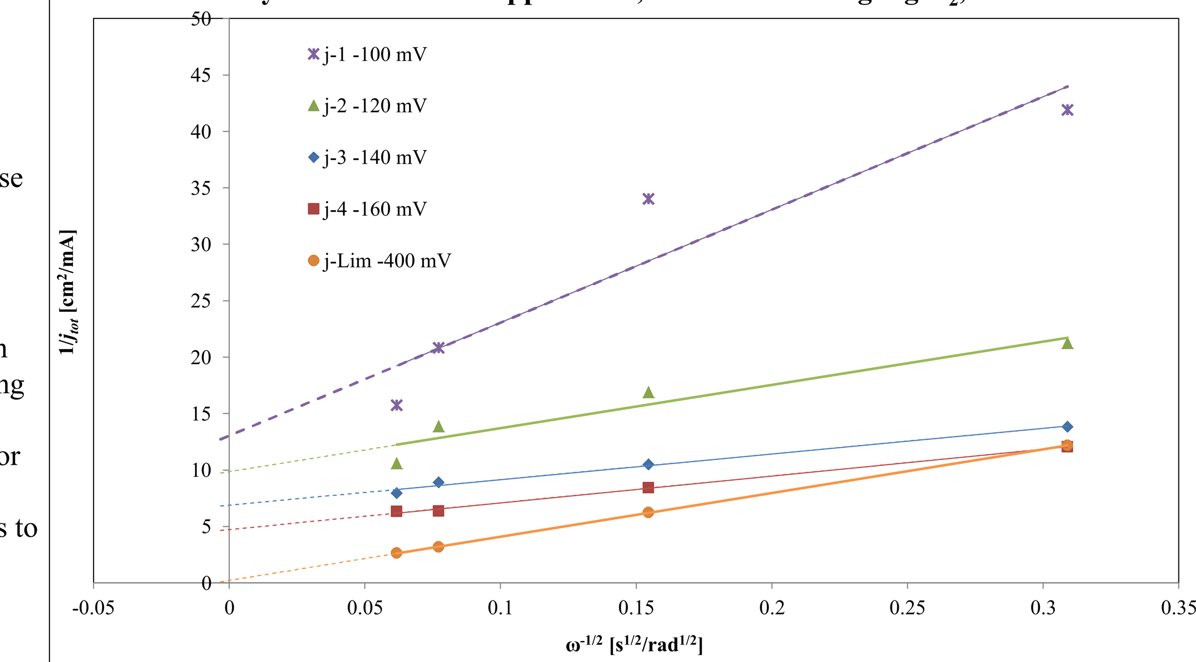
Diffusion Layer Thickness:

$$\delta = \frac{nFDC_b}{j_L} \qquad \delta = (\pi D t)^{1/2}$$

δ = Diffusion Layer Thickness [cm]
t = Plating Time [sec]

- The Diffusion Layer Thickness is the length that the concentration gradient at the working electrode extends out into the solution
- Applying a current density of 20 mA/cm^2 for 100 ms yields a diffusion layer of 137 microns, requiring 12.6 seconds for the ions to diffuse across to the working electrode

Koutecky-Levich Plot of Copper Bath, Gold RDE vs. Hg/HgCl$_2$, 15 mV/sec



Koutecky-Levich Equation:

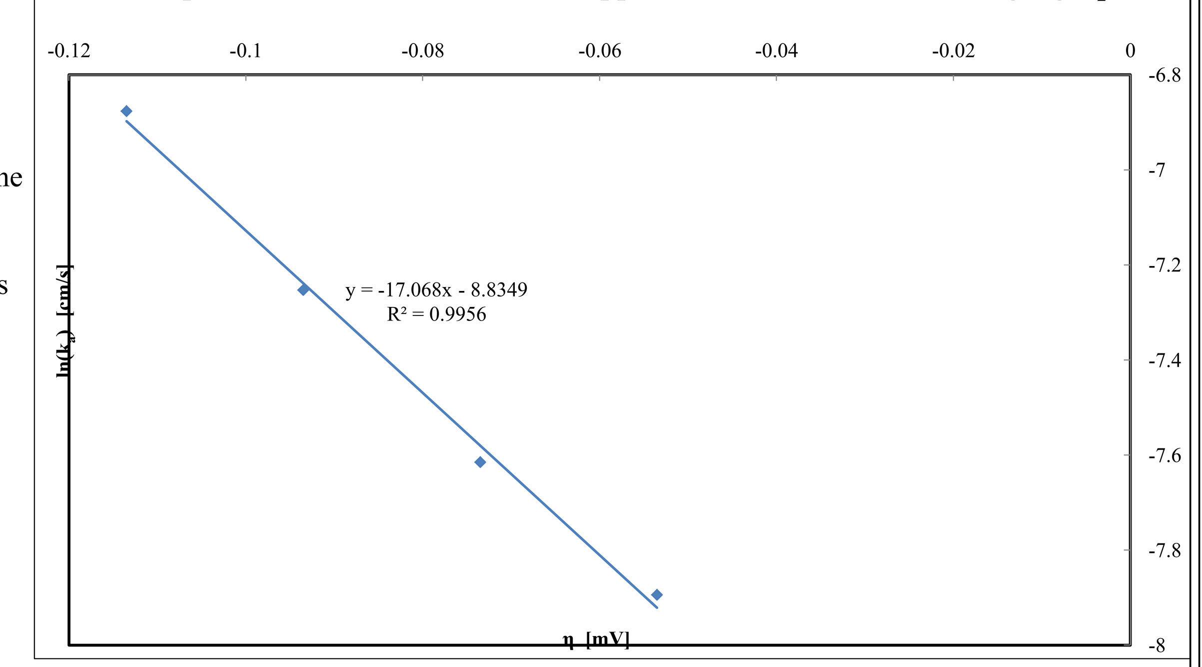
$$\frac{1}{j_{tot}} = \frac{1}{j_k} - \frac{1}{j_L} = \frac{1}{j_k} - \frac{1}{B\omega^{1/2}}$$

j_{tot} = Total Current density [mA/cm^2]
B = Slope of Levich Plot
j_k = Kinetic Current Density [mA/cm^2]
j_L = Limiting Current Density [mA/cm^2]

- Using the Koutecky-Levich Equation the diffusion coefficient can be determined by plotting $1/j_{tot}$ vs. $1/\omega^{1/2}$

Diffusion coefficient = 8.41E-6 cm^2/sec

Overpotential vs. Reaction Rate of Copper Bath with Gold RDE vs. Hg/HgCl$_2$



Overpotential:

$$\eta = E - E_{Eq}$$

η = Overpotential [mV]
E = Measured Potential [mV]
E_{Eq} = Equilibrium potential, 46.5 mV

- The Kinetic Current Density can be determined by looking at the y-intercept of the Koutecky-Levich plots at various overpotentials
- The Reaction Rate increases exponentially as a function of overpotential and can be determined by taking the natural log to get a linear plot

Kinetics Equation:

$$\ln k = \ln k_0 + \frac{\alpha F \eta}{RT}$$

k = Reaction Rate [cm/sec]
α = Transfer Coefficient
η = Overpotential [mV]
R = Gas Constant, 8.314 J/mol K
T = Room temperature= 296.15 K

j_k (A/cm^2)	k_a (cm/sec^1)	$\ln(k_a)$
0.0069	3.34E-05	-10.31
0.0091	4.42E-05	-10.03
0.0131	6.35E-05	-9.66
0.0190	9.25E-05	-9.29

Reaction Rate = 1.46E-4 cm/sec
Transfer Coefficient = 0.44

Sidewall and Plug Plating Results

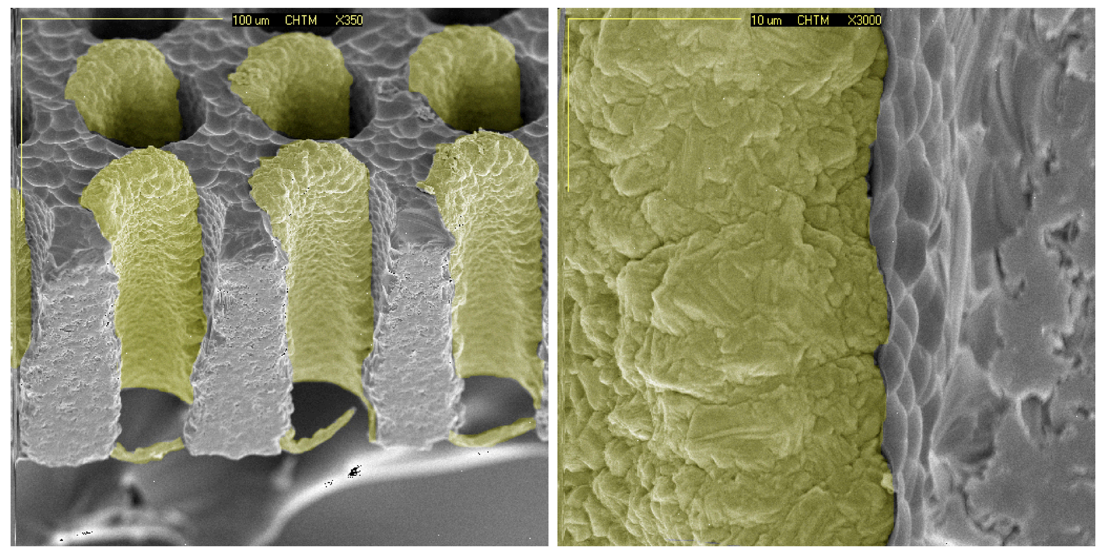


Figure 1- Galvanostatic pulse: forward current -0.4 mA for 0.5 seconds, reverse current 0.4 mA for 0.1 seconds, 67.5 minutes of forward operating time.

- Uniform copper deposition throughout the length of the via and across the area of the substrate
- Non-uniform deposition around the circumference of the via
- Good copper adhesion

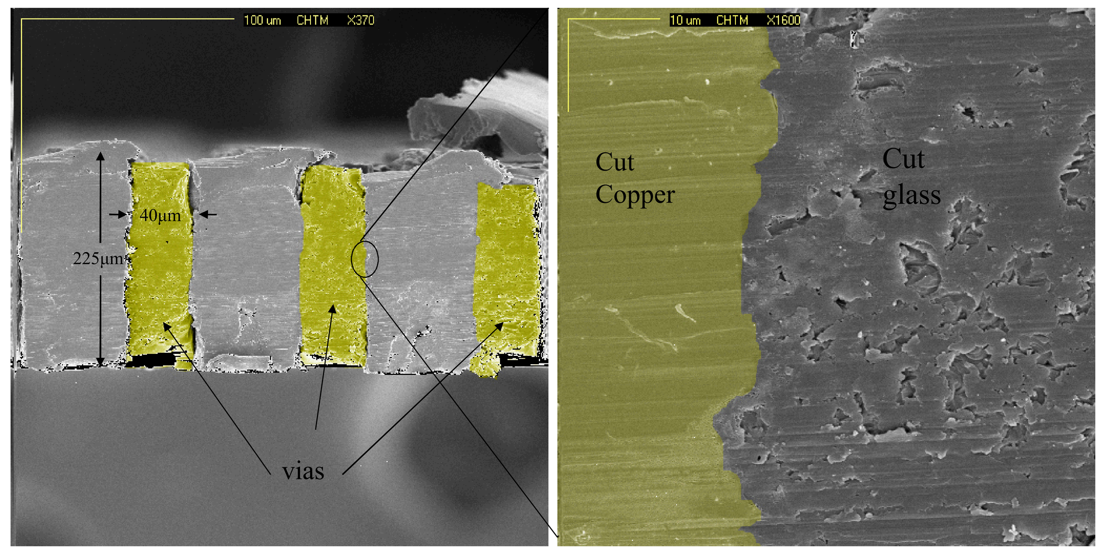
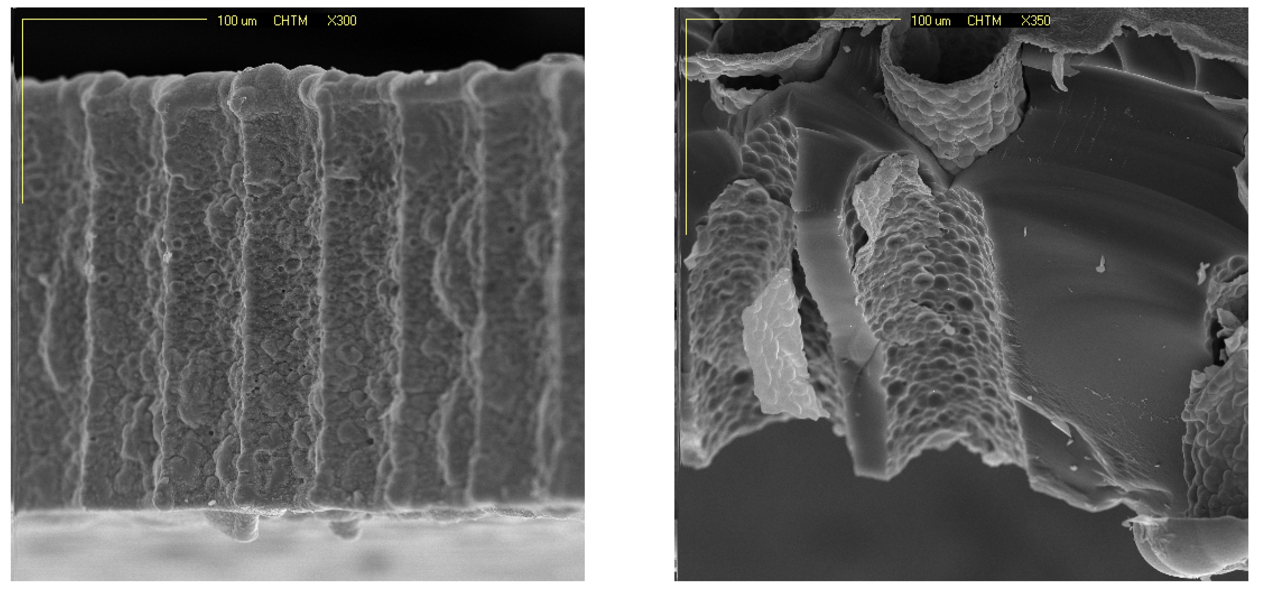


Figure 2- Galvanostatic pulse: seed current -5 mA, 10 seconds; forward current -0.35 mA, 0.5 seconds; reverse current 0.4 mA; 67.5 minutes of forward operating time.

- Uniform deposition throughout via with no voids
- High Aspect Ratio >5.5:1
- Good Copper adhesion

Electroless Copper

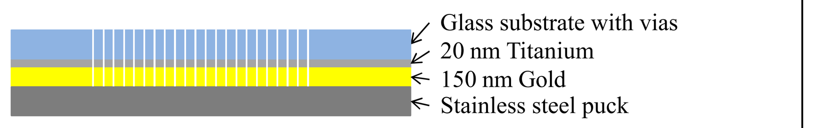
$$Cu^{2+} + 2HCHO + 4OH^- \rightarrow Cu + 2HCOO^- + 2H_2O + H_2$$



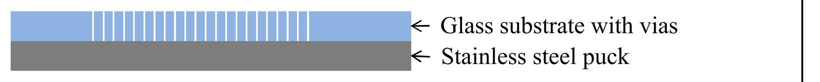
- Electroless Copper provides a thin seed layer with variable adhesion

Approaches for Uniform Plug Plating

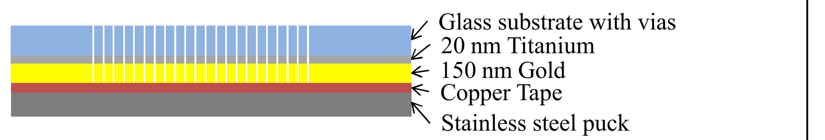
Setup 1- Growing copper from a Ti-Gold seed layer



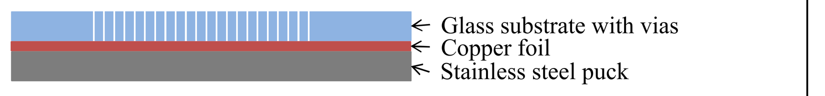
Setup 2- Using passivated stainless steel for backside plating



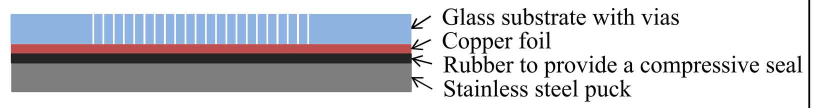
Setup 3- Using conductive copper tape to seal the back side



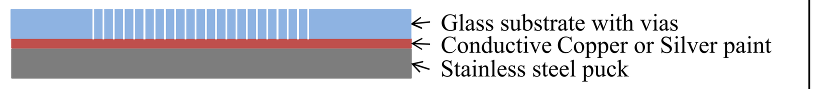
Setup 4- Using thin copper foil for backside plating



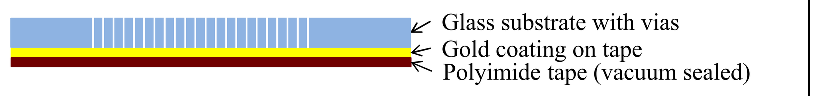
Setup 5- Using rubber in conjunction with copper foil to provide a compressive seal for backside plating



Setup 6- Using conductive copper or silver paint to seal the back side



Setup 7- Vacuum sealing Gold coated polyimide tape to the back of the via substrate



Conclusions

- Sidewall plating ,with good adhesion, was achieved using direct current and a reverse pulse plating regime using galvanostatic and potentiostatic plating modes
- Sidewall plating was achieved using an electroless copper bath
- Copper tape and copper foil yielded uniform sidewall plating, but it was difficult to achieve plug plating
- Copper and Silver paints worked well for achieving copper plugs but the plating was non-uniform
- It was difficult to get the copper to adhere to and plate into the vias without the Ti-Gold coating on the substrate

Future Work

- Continue to experiment with new or different ideas to improve the fixture to get a better backside seal and improve plating uniformity
- Develop a fixture for plating larger area via arrays
- Experiment with higher aspect ratio vias

Acknowledgements

- Carrie Schmidt, SEM Pictures
- Funding: New Mexico Small Business Association
- Facilities: Sandia National Laboratories and Life BioSciences
- Sandia National Laboratories Student Internship Program

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