Copper Metallization
Can we trust it?

Electronic Parts And Packaging For Space And Aeronautic Applications Advanced Technology Workshop (ATW)

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Metallization

• Requirements
  Low resistivity
  • Process Compatibility
  Low resistivity
  • Reliability
  Low resistivity
  • Availability
  Low resistivity
## Periodic Table of the Elements

In the periodic table, the elements are arranged in order of increasing atomic number. Vertical columns, headed by Arabic numerals, are called Groups. A horizontal sequence of elements is called a Period. The most active elements are at the bottom left of Group 1 and the top right of Group 17. The staggered line (Groups 13-17) roughly separates metallic from non-metallic elements.

**Groups**—Elements within a Group have similar properties and contain the same number of electrons in their outside energy shell.

- The first Group (1) contains hydrogen and the alkali metals.
- The last (18) contains the noble gases.
- Group (17) contains the halogens.
- The elements interverting between Groups 2 and 13 are called transition elements.

**Periods**—in a given Period, the properties of the elements gradually pass from a metallic to a non-metallic nature, with the last member of a period being a noble gas.

### Key

<table>
<thead>
<tr>
<th>Name of Element</th>
<th>Color</th>
<th>Atomic Weight</th>
<th>Atomic Symbol</th>
<th>Atomic Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thorium</td>
<td>Tan</td>
<td>232</td>
<td>Th</td>
<td>90</td>
</tr>
<tr>
<td>Protactinium</td>
<td>Red</td>
<td>231</td>
<td>Pa</td>
<td>91</td>
</tr>
<tr>
<td>Uranium</td>
<td>Yellow</td>
<td>238</td>
<td>U</td>
<td>92</td>
</tr>
<tr>
<td>Neptunium</td>
<td>Green</td>
<td>237</td>
<td>Pu</td>
<td>93</td>
</tr>
<tr>
<td>Americium</td>
<td>Black</td>
<td>241</td>
<td>Am</td>
<td>95</td>
</tr>
<tr>
<td>Bikridium</td>
<td>Green</td>
<td>249</td>
<td>Bk</td>
<td>97</td>
</tr>
<tr>
<td>Californium</td>
<td>Black</td>
<td>257</td>
<td>Cf</td>
<td>98</td>
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<tr>
<td>Einsteinium</td>
<td>Yellow</td>
<td>255</td>
<td>Es</td>
<td>99</td>
</tr>
<tr>
<td>Fermium</td>
<td>Green</td>
<td>257</td>
<td>Fm</td>
<td>100</td>
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<td>Mendelevium</td>
<td>Black</td>
<td>258</td>
<td>Md</td>
<td>101</td>
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<tr>
<td>Nobelium</td>
<td>Green</td>
<td>259</td>
<td>No</td>
<td>102</td>
</tr>
<tr>
<td>Lawrencium</td>
<td>Black</td>
<td>263</td>
<td>Lr</td>
<td>103</td>
</tr>
</tbody>
</table>

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Top Ten Metals

Resistivity in \( \mu\Omega\text{-cm} \)
at 20°C
The Noble Metals

Copper
Cu
63.546
29

Silver
Ag
107.87
47

Gold
Au
196.97
79

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The Noble Metals

- Silver
  - Best Conductor
  - Diffuses incredibly rapidly through glass
    - forms dendrites in “real time”
  - Very susceptible to corrosion
    - especially in the presence of an electric field
  - Difficult to process
    Just Too Much Trouble
The Noble Metals

- The “most noble” of the metals
- will not corrode
- Fast diffuser though glass
- Serious poison to Si devices
- Just as much trouble as Cu
- resistivity not much better than Al

Not enough advantage over Al

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Noble Metals

• Copper
  – Second best Conductivity
    • almost as good as Ag
  – Poison for Si devices
  – Diffuses Rapidly through glass
    • Not as bad as Ag
  – Adheres Poorly

  If we have to put up with Noble metal hassles
  Cu is the best compromise
Suitable Metallization

In the absence of high $T_c$
high critical current superconductors
All we have is

Aluminum
Copper
and their alloys

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Aluminum

• Very Good Conductivity
  – Not as good as Noble Metals but close

• Easy to Process
  – Forms thin oxide that makes Al forgiving

• Adheres and does not diffuse through glass

• Does not affect Si too badly
  – Does not diffuse rapidly into Si

Very Poor Electromigration Resistance
Al Alloys

- Pure Al was not able to withstand high current densities necessary for use in Integrated Circuits
- Al alloys used instead
  - Al/Cu best choice/compromise
  - higher resistivity
  - processing more difficult
    - corrosion
  - Solved reliability problem

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Aluminum

• Good Conductor
  – Pure Al
    • 2.7 μm - cm
  – Al/Cu
    • Al/4%Cu = 3.5 μm - cm
    • Al/0.5%Cu = ~3.0 μm - cm
    • Other alloys not as good
Al and Alloy Electromigration

• Al
  - $\Delta H = 0.5$ eV
  - $t_{50} = 1$

• Al/Cu
  - $\Delta H = 0.7$ eV
  - $t_{50} = 100$

• Al/Cu sub-micron
  - $\Delta H = 0.9$ eV
  - $t_{50} = 1000+$

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Electromigration in sub-micron Al alloy conductors

- Line width is less than the grain size
- No continuous grain boundary diffusion pathway
- Diffusion is along Interfaces (more difficult path)
- Reliability is far superior to earlier wide line conductors

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Aluminum

• Very Reactive
  – Rocket Fuel
  – Very Difficult to Separate from Ore
    • Napoleon’s Dinnerware
    • Washington Monument
  – Reduces SiO₂
    • Forms Al₂O₃ at Al/glass interface
    • Acts as diffusion barrier
    • Promotes good adhesion
Cu Reliability

Electromigration

Leakage

Stress Voiding

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Electromigration

- The activation energy for diffusion tracks closely with the melting point for metals with similar structures
- All are FCC

\[ t_{50} = A j^{-n} \exp \left( \frac{\Delta H}{kT} \right) \]

- Therefore it is expected that EM lifetime for Cu should be much greater than for Al alloys

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Electromigration

- Copper has the highest melting temperature of the best four conductors
  - Al 660C 933K
  - Ag 962C 1235K
  - Au 1064C 1337K
  - Cu 1084C 1357K
- Gives rise to great expectations
Activation Energy for Cu Diffusion

- Lattice
  - 2.3 eV
- Grain Boundary
  - 1.2 eV
- Surface
  - ~0.8 eV
Activation Energy for Cu Electromigration

- Measured activation energies vary considerably

$$\Delta H = 0.28 \text{ to } 1.26 \text{ eV}$$

Much lower than expected
Activation Energy for Electromigration

- Recent narrow line Al/Cu data activation energies have been observed in the range

0.9 to 1.0 eV

Higher than Cu values
Cu Electromigration

- Poor performance can be attributed to the nature of the Copper surface
  - Does not form adherent oxide
  - Adhesion of Cu to most materials quite poor
  - Narrow lines have large surface to volume ratio
  - Cu electromigration is critically dependent on the “quality” of the interface

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Cu and Al Electromigration

- Al/oxide surfaces are not diffusion paths
- Cu interfaces are major diffusion pathways
- Al reacts with and adheres to just about everything
- Cu does not adhere well to most materials
- Al electromigration is very microstructure dependent
- Cu electromigration is relatively insensitive to microstructure

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Cu Electromigration

• If the interface is well passivated, the electromigration behavior is adequate.
• Condition of the interface may be very process dependent
  – Interface reactions critical to performance
• Lot to lot variation will be serious
  – variation may be orders of magnitude
Electrochemical Migration

- Noble metal ions diffuse readily

\[ J = \frac{DFC}{kT} \]

\[ F = \nabla \mu = ZeE = \frac{kT}{C} \nabla C \]

\( \mu = \) chemical potential
Cu Diffusion

• Challenge
  – Make liner material as thin as possible
    • To preserve low $\rho$
    • Achieve low contact resistance
    • Must be continuous
    • Must be stable over time
  – High Temperature Stability
    • Processing
Reliability Issues
Diffusion Of Cu

• Interlevel and Intralevel leakage paths
  – Not an issue with Al alloys
    • Oxide formation precludes diffusion
  – Big issue with noble metals
    • especially Ag and Cu
  – Process variation dependent
  – Depends critically on barrier integrity

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Cu Diffusion

- Cu and Ag act differently in an electric field than in an unbiased environment
  - Diffusion coefficient is significantly higher
- SiO$_2$ biased
  - $D$ at 260$^\circ$C = $\sim 10^{-14}$ cm$^2$/s
- SiO$_2$ unbiased
  - $D$ at 260$^\circ$C = $\sim 10^{-16}$ cm$^2$/s
- Presumably Cu ionization is the reason
Cu Diffusion

• Noble metals are unlike Al
• Al forms Al$_2$O$_3$ that stops diffusion through SiO$_2$
• Al will reduce SiO$_2$ and other dielectrics and form barriers
• Noble metals diffuse readily through dielectrics, especially SiO$_2$
Cu Reliability

What you saw ain’t what you got!!!

- Cu structure is not stable.
  - There is considerable Cu grain growth at room temperature

- May be a function of the as deposited texture

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Stress Voiding

• Thermal Coefficient of Expansion
  – Si 3x10^{-6}/C
  – Al 23.6x10^{-6}/C
  – Cu 16.6x10^{-6}/C

• Biaxial Modulus
  – Al 112 GPa
  – Cu 191 GPa
Stress Voiding

\[ \varepsilon_{th} = \Delta \alpha \Delta T \]

- For same temperature excursion as compared to Al
  - Cu has greater stress
  - Cu has less strain
Stress Voiding in Cu

Driving Force for voiding greater than in Al

Ultimate void size smaller

More but smaller voids

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-Bottom Line

When she's good,
She's very very good,
but when she's bad,
She's horrid

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In Space

- Copper Process is **MUCH** more variable than Al based metallization
- Cannot depend on large scale production to ensure consistency of product
- A bad Al day is a minor event, a bad Cu day is a disaster
- COTS without lot traceability cannot be used

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In Space

• Cooperation with vendor/designers will have to be instituted to ensure reliable operation

• Normal industry supplied information is not adequate
  – Based on average probabilities of failure
    • Many parts gives low numbers
    • MTBF is not applicable!!
In Space

- A program of frequent testing and analysis will have to be implemented
- Each lot will have to be qualified
- Al/Cu will have to be specified if lot specific data cannot be obtained.