# Copper Metallization
## Can we trust it?

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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 intervening between Groups 2 and 13 are called *transition elements*.

— Short vertical columns without Arabic numerical headings are called *Subgroups*.

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

s ORBITALS FILLING LIGHT METALS

d ORBITALS FILLING

p ORBITALS FILLING NON-METALS

| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| H | | | | | | | | | | | | | | | | | He |
| Li 3 | Be 4 | | | | | | | | | | | B 5 | C 6 | N 7 | O 8 | F 9 | Ne 10 |
| Na 11 | Mg 12 | | | | | | | | | | | Al 13 | Si 14 | P 15 | S 16 | Cl 17 | Ar 18 |
| K 19 | Ca 20 | Sc 21 | Ti 22 | V 23 | Cr 24 | Mn 25 | Fe 26 | Co 27 | Ni 28 | Cu 29 | Zn 30 | Ga 31 | Ge 32 | As 33 | Se 34 | Br 35 | Kr 36 |
| Rb 37 | Sr 38 | Y 39 | Zr 40 | Nb 41 | Mo 42 | Tc 43 | Ru 44 | Rh 45 | Pd 46 | Ag 47 | Cd 48 | In 49 | Sn 50 | Sb 51 | Te 52 | I 53 | Xe 54 |
| Cs 55 | Ba 56 | La ◆ 57 | Hf 72 | Ta 73 | W 74 | Re 75 | Os 76 | Ir 77 | Pt 78 | Au 79 | Hg 80 | Tl 81 | Pb 82 | Bi 83 | Po 84 | At 85 | Rn 86 |
| Fr 87 | Ra 88 | Ac ▲ 89 | Unq 104 | Unp 105 | Unh 106 | Uns 107 | Uno 108 | Une 109 | Uun 110 | Uuu 111 | Uub 112 | Uut 113 | Uuq 114 | Uup 115 | Uuh 116 | Uus 117 | Uuo 118 |

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ◆ Lanthanide Series | Ce 58 | Pr 59 | Nd 60 | Pm 61 | Sm 62 | Eu 63 | Gd 64 | Tb 65 | Dy 66 | Ho 67 | Er 68 | Tm 69 | Yb 70 | Lu 71 |
| ▲ Actinide Series | Th 90 | Pa 91 | U 92 | Np 93 | Pu 94 | Am 95 | Cm 96 | Bk 97 | Cf 98 | Es 99 | Fm 100 | Md 101 | No 102 | Lr 103 |

**Key**

| Information | Color |
|---|---|
| Name of Element | Red |
| Atomic Weight | Yellow |
| Atomic Symbol | Black |
| Atomic Number | Green |

| | |
|---|---|
| Ag | 1.6 |
| Cu | 1.7 |
| Au | 2.3 |
| | |
| Al | 2.7 |
| | |
| Ca | 4.1 |
| Na | 4.2 |
| Mg | 4.4 |
| Rh | 4.7 |
| Be | 5.0 |
| Ir | 5.3 |

# Top Ten Metals

Resistivity
in $\mu\Omega$–cm
at 20C

# The Noble Metals

Copper
63.546
**Cu**
29

Silver
107.87
**Ag**
47

Gold
196.97
**Au**
79

# 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

# 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

# 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

# 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
  - $t_{50} = 1000+$

# 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

# Aluminum

- Very Reactive
  - Rocket Fuel
  - Very Difficult to Separate from Ore
    - Napoleon's Dinnerware
    - Washington Monument
  - Reduces $SiO_2$
    - Forms $Al_2O_3$ at Al/glass interface
    - Acts as diffusion barrier
    - Promotes good adhesion

# Cu Reliability

# Electromigration
# Leakage
# Stress Voiding

# Electromigration

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

$$t_{50} = Aj^{-n} \exp\left(\frac{\Delta H}{kT}\right)$$

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

# 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

# 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

# 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

# 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 260C = $\sim 10^{-14}$ $cm^2/s$
- $SiO_2$ unbiased
  - D at 260C = $\sim 10^{-16}$ $cm^2/s$
- Presumably Cu ionization is the reason

# Cu Diffusion

- Noble metals are unlike Al
- Al forms $Al_2O_3$ 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

# 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

# opper-Bottom Line

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

# 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

# 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.