

# Copper Metallization

## Can we trust it?

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# Metallization

- **Requirements**

- Low resistivity

- Process Compatibility

- Low resistivity

- Reliability

- Low resistivity

- Availability

- Low resistivity

s ORBITALS FILLING  
LIGHT METALS

# 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.

p ORBITALS FILLING  
NON-METALS

H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Ac	Unq	Unp	Unh	Uns	Uno	Une	Uun	Uuu	Uub	Uut	Uuq	Uup	Uuh	Uus	Uuo
Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu				
Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr				

**Key**

Information      Color

Name of Element      Red ———

Atomic Weight      Yellow ———

Atomic Symbol      Black ———

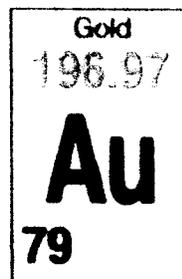
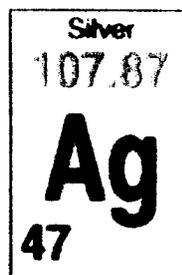
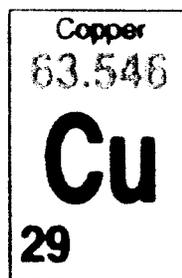
Atomic Number      Green ———

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  $\mu\Omega\text{-cm}$   
at 20C

# The Noble Metals



22 May 2000

# 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 through 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
    - $2.7 \mu\text{m} - \text{cm}$
  - Al/Cu
    - Al/4%Cu =  $3.5 \mu\text{m} - \text{cm}$
    - Al/0.5%Cu =  $\sim 3.0 \mu\text{m} - \text{cm}$
    - Other alloys not as good

# Al and Alloy Electromigration

- Al
  - $\Delta H = 0.5 \text{ eV}$
  - $t_{50} = 1$
- Al/Cu
  - $\Delta H = 0.7 \text{ eV}$
  - $t_{50} = 100$
- Al/Cu sub-micron
  - $\Delta H = 0.9 \text{ eV}$
  - $t_{50} = 1000+$

# 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  $\text{SiO}_2$ 
    - Forms  $\text{Al}_2\text{O}_3$  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<sub>2</sub> biased
  - $D$  at 260C =  $\sim 10^{-14}$  cm<sup>2</sup>/s
- SiO<sub>2</sub> unbiased
  - $D$  at 260C =  $\sim 10^{-16}$  cm<sup>2</sup>/s
- Presumably Cu ionization is the reason

# Cu Diffusion

- Noble metals are unlike Al
- Al forms  $\text{Al}_2\text{O}_3$  that stops diffusion through  $\text{SiO}_2$
- Al will reduce  $\text{SiO}_2$  and other dielectrics and form barriers
- Noble metals diffuse readily through dielectrics, especially  $\text{SiO}_2$

# 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  $3 \times 10^{-6}/\text{C}$
  - Al  $23.6 \times 10^{-6}/\text{C}$
  - Cu  $16.6 \times 10^{-6}/\text{C}$
- **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.