Electromigration and Electrochemical Migration in Electronic Package

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Electromigration and Electrochemical Migration in Electronic Package

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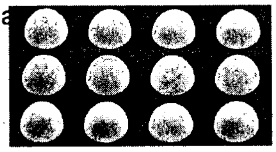
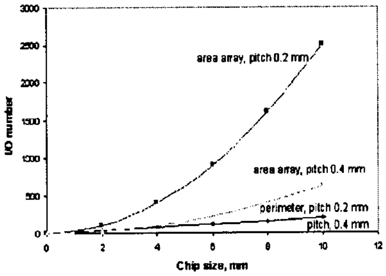
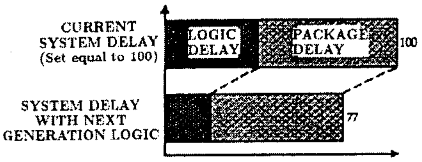
Introduction

Application to flip chip

- ☐ Smaller size : Increased I/O #(area array) enables more signal and functionality
- ☐ Improved performance : Low electrical dela
- ☐ Improved reliability
- ☐ Low cost : regardless # of I/O



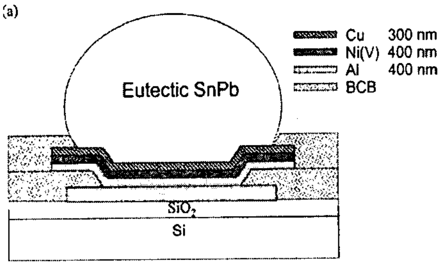


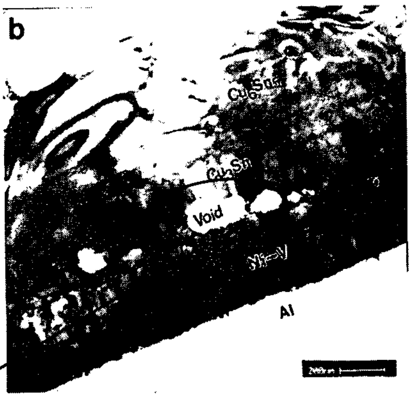


50% IMPROVEMENT IN LOGIC PERFORMANCE FOR A SYSTEM RESULTS IN MUCH SMALLER OVERALL GAINS, UNLESS PACKAGE DELAY IS ADDRESSED

Introduction

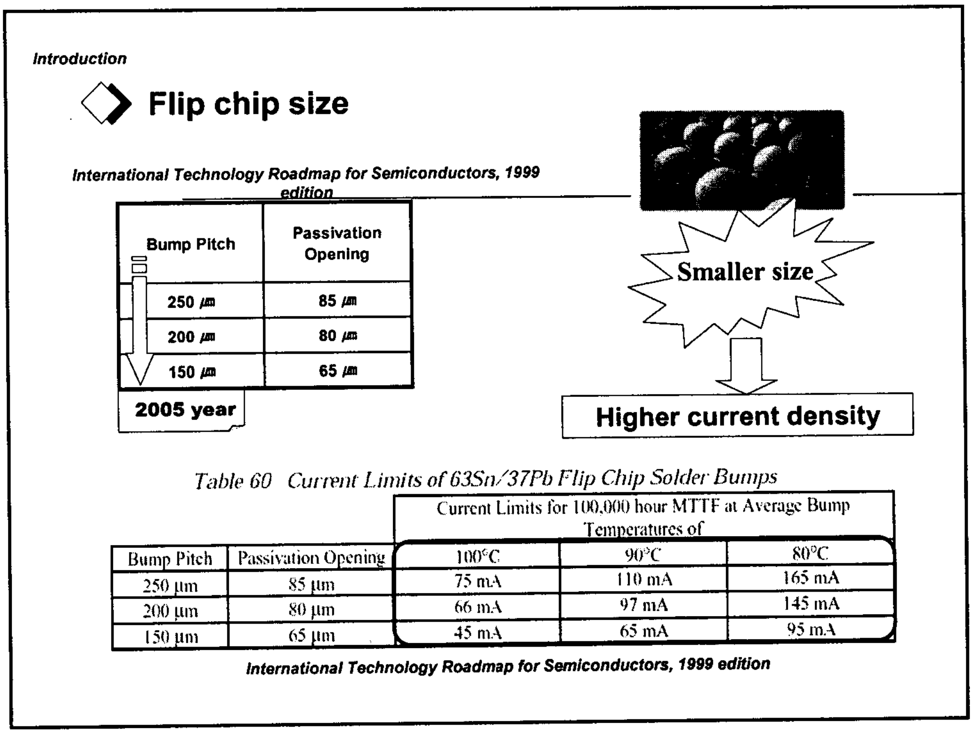
Void formation of flip chip solder bump





Kirkendal voids

Liu, et al., JAP (2000)



Introduction

Flip chip size

International Technology Roadmap for Semiconductors, 1999 edition

Bump Pitch	Passivation Opening
250 μm	85 μm
200 μm	80 μm
150 μm	65 μm

2005 year

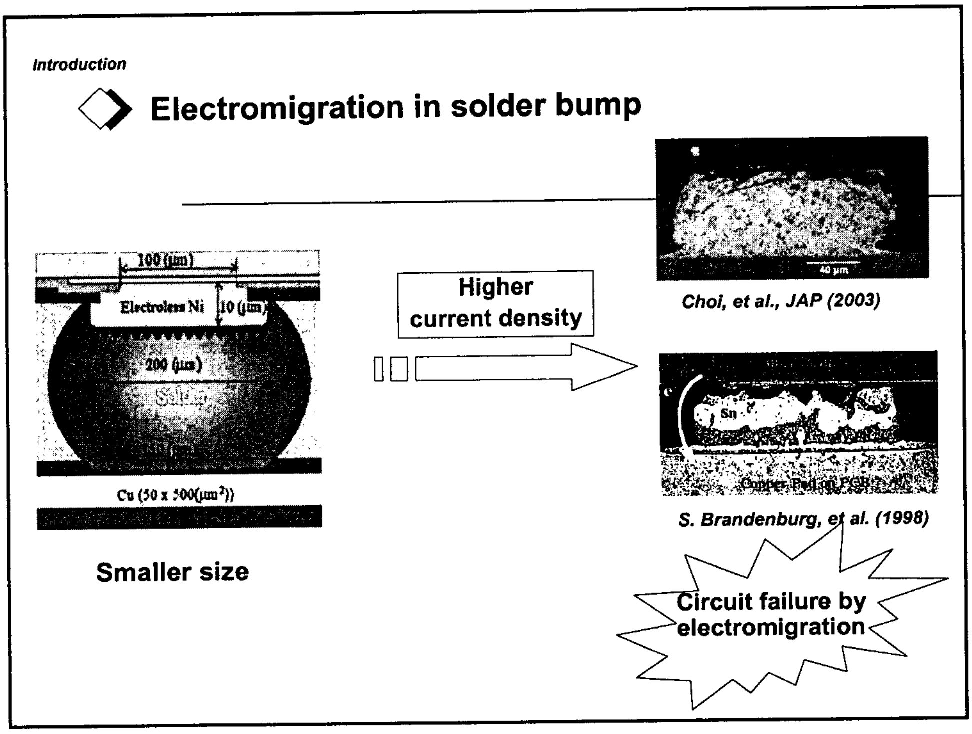
Smaller size

Higher current density

Table 60 Current Limits of 63Sn/37Pb Flip Chip Solder Bumps

Bump Pitch	Passivation Opening	Current Limits for 100,000 hour MTTF at Average Bump Temperatures of 100°C	90°C	80°C
250 μm	85 μm	75 mA	110 mA	165 mA
200 μm	80 μm	66 mA	97 mA	145 mA
150 μm	65 μm	45 mA	65 mA	95 mA

International Technology Roadmap for Semiconductors, 1999 edition



Introduction

Electromigration in solder bump

Smaller size

Higher current density

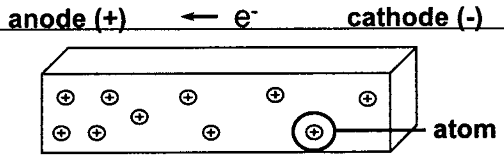
Choi, et al., JAP (2003)

S. Brandenburg, et al. (1998)

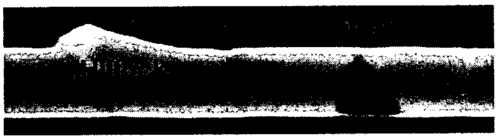
Circuit failure by electromigration

Introduction

What is electromigration?



- ☐ Atom transport due to momentum exchange between conduction electrons and metal ions
- ☐ Atoms migrated toward electron flow direction

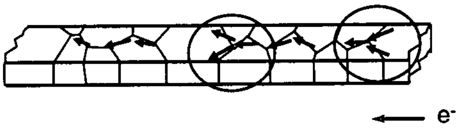


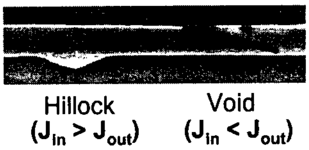
Introduction

EM site – flux divergence in interconnects

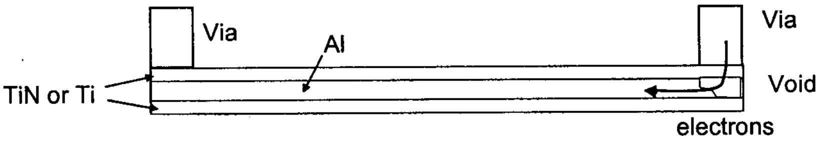
- ☐ Electromigration-Induced Failures
  - EM damage occurs at the site of flux divergence ($J_{In} \neq J_{out}$)
  - Sites of flux divergences in lines :

  1) Local grain structure variation (grain boundary triple points, grain clusters - bamboo grains)





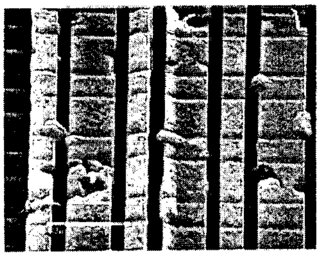
  2) At the vias (materials are discontinuous due to W via or barrier layer (TiN, Ta)) => Most dominant failure site

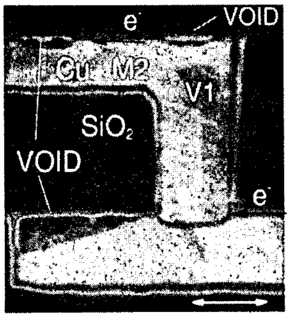


Introduction

◇ EM failure in chip interconnect

AlCu/TiW





0.3 μm

C. K. Hu, et al., APL(2001)

☐ **EM failure is critical problems in chip interconnects**

Introduction

◇ Electromigration of eutectic SnPb in flip-chip

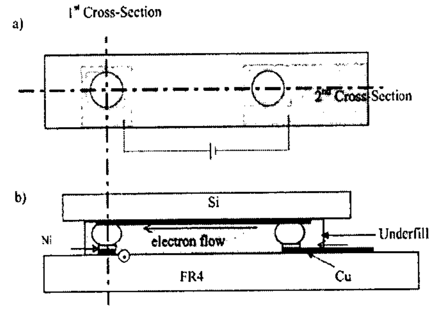


FIG. 1. Schematic diagram of the electromigration test sample (a) plane view and (b) side view.

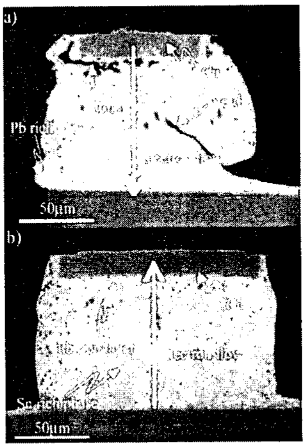


FIG. 6. SEM micrographs of (a) second cross section of cross sectioned solder ball and (b) Cross section of the entire solder ball in the underfill.

K. N. Tu, et al., JAP(2001)

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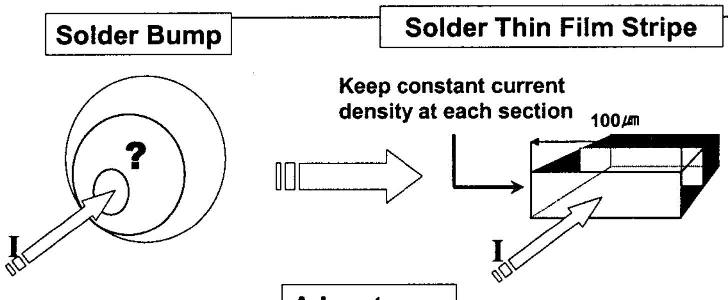
Electromigration of solder

Reason for making stripe specimen

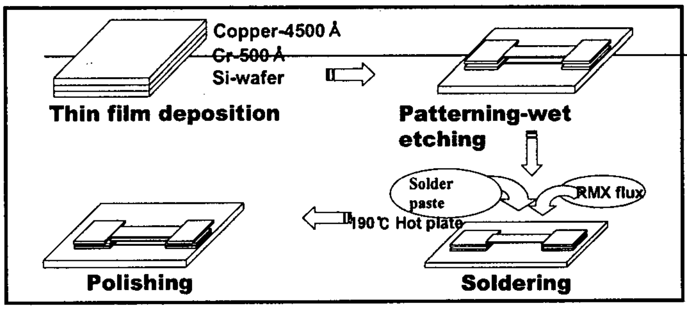


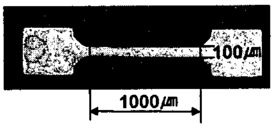
Advantage

- Easy to observe the microstructure change
- Keep constant density & joule heating at each section
- Easy to fabricate

Electromigration of solder

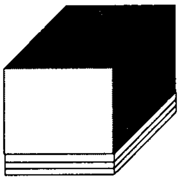
◇ Fabrication of the stripe specimen





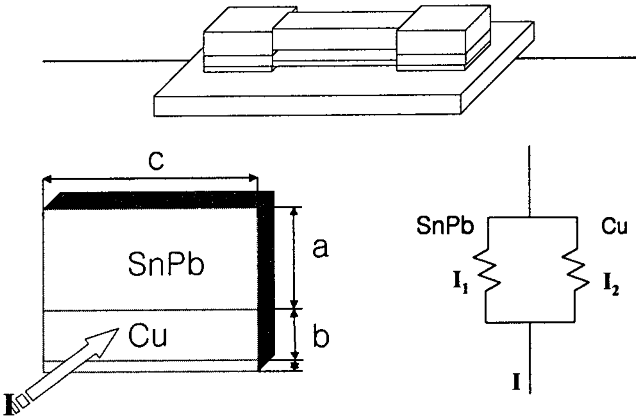
SEM picture of the specimen

Cross section



Electromigration of solder

◇ Current density calculation

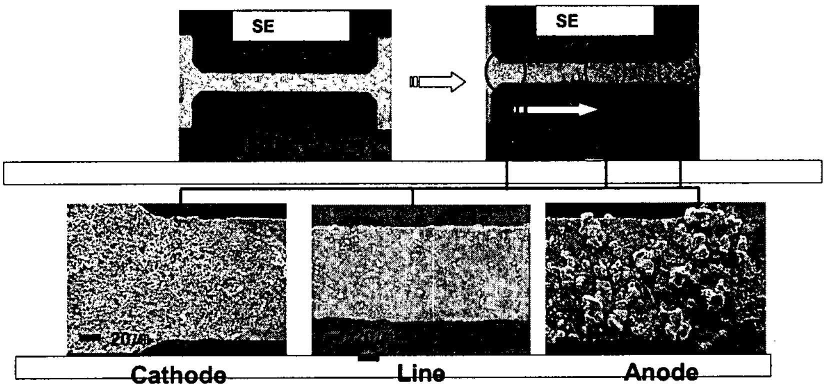


The copper has 1/10 of resistivity in comparison to SnPb + Consider the thickness of each film + Calculate the resistance of each line & Current density of the SnPb line

Electromigration of solder

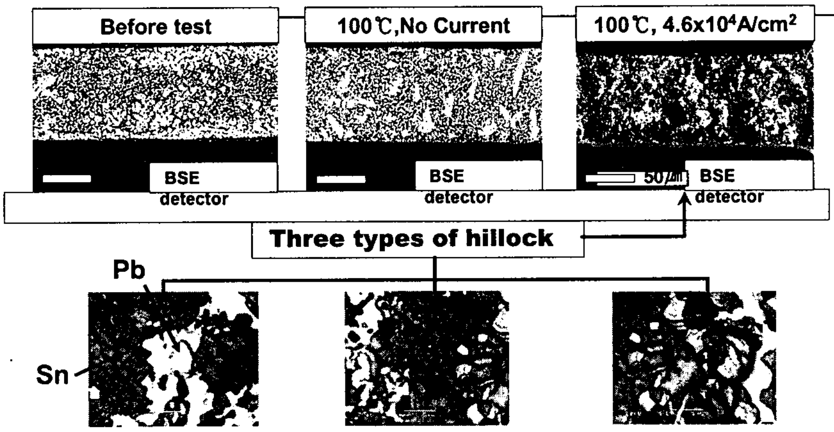
◇ Hillocks and voids formation

(100℃, 8.7 X10^{4}A/cm^2 for 5 days)



Electromigration of solder

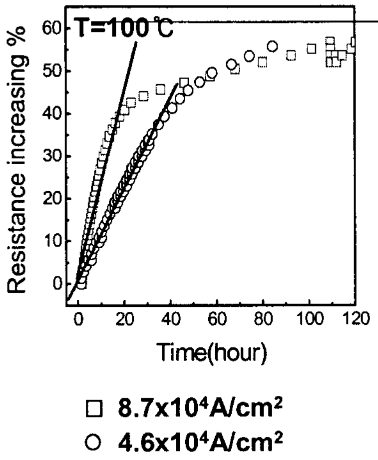
◇ Microstructure change



Pb-rich hillock Sn-rich hillock Lump hillock

Electromigration of solder

◇ Different current density of EM in eutectic SnPb



- ☐ Resistance increasing % = $\dfrac{\Delta R}{R_{initial}} \times 100$

- ☐ **Flux equation of electromigration**

$$J_{flux} = C\left(\frac{D}{kT}\right)Z^{*}q\rho j = C\left(\frac{D_o}{kT}\right)\exp\left(-\frac{E_a}{kT}\right)Z^{*}q\rho j$$

Assumption ⇨ **Slope** $\propto J_{flux}$

(Resistance increasing %/hour)

(Hummel R. international Materials Reviews (1999))

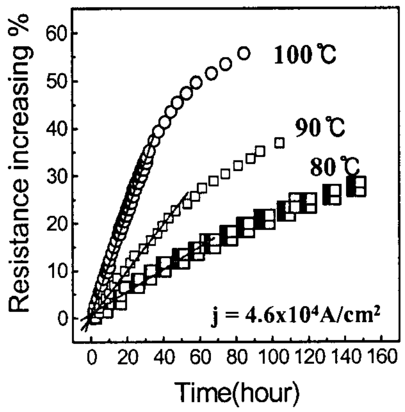
If constant temperature

$$\frac{J_1}{J_2} = \frac{j_1}{j_2} \approx \frac{Slope_1}{Slope_2} = \frac{2.3}{1.1} \cong 2.1$$

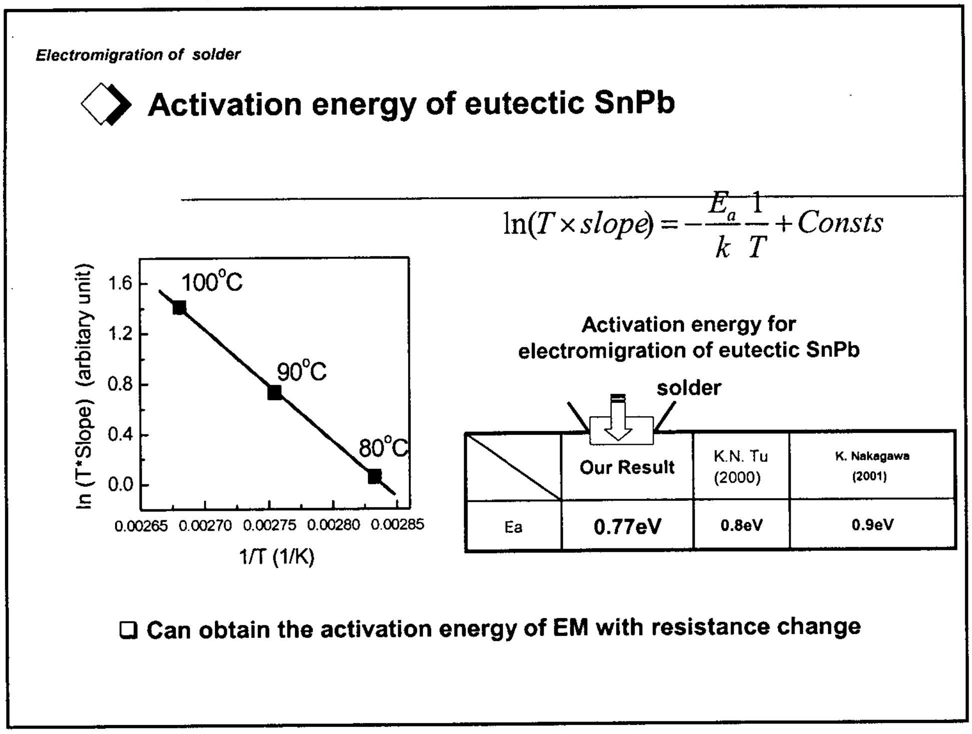
Electromigration of solder

◇ Different temperature of EM in eutectic SnPb

Temperature T - variation



$$\boxed{\ln(T \times slope)} = -\frac{E_a}{k}\boxed{\left(\frac{1}{T}\right)} + Consts$$



Electromigration of solder

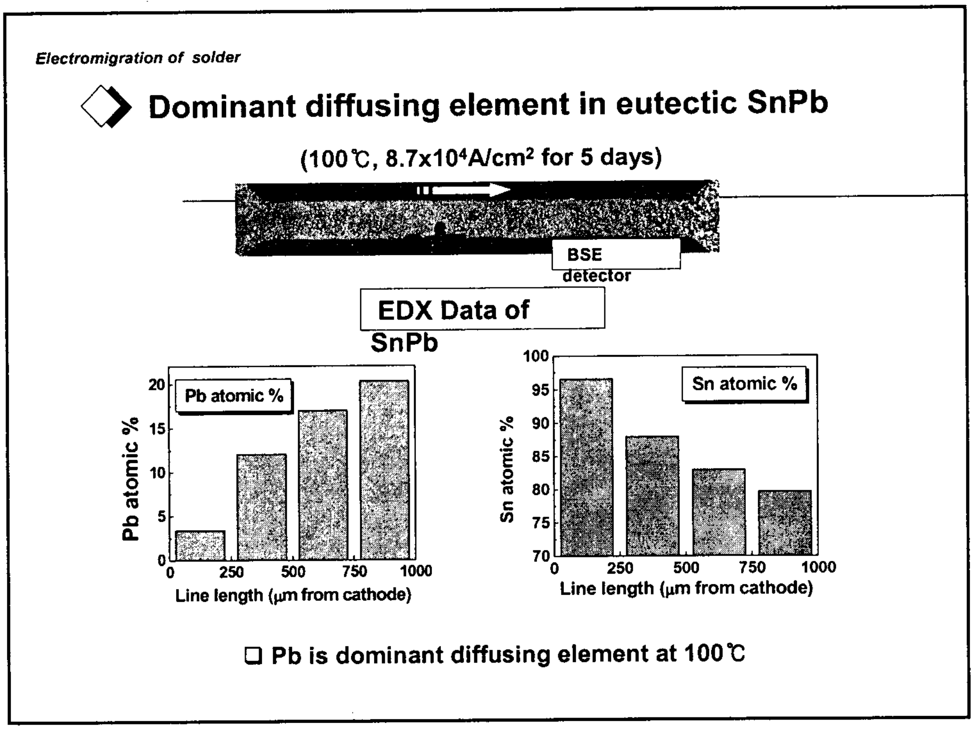
Activation energy of eutectic SnPb

$$\ln(T\times slope) = -\frac{E_a}{k}\frac{1}{T} + Consts$$

Activation energy for electromigration of eutectic SnPb solder

	Our Result	K.N. Tu (2000)	K. Nakagawa (2001)
Ea	**0.77eV**	0.8eV	0.9eV

❑ **Can obtain the activation energy of EM with resistance change**



Electromigration of solder

Dominant diffusing element in eutectic SnPb

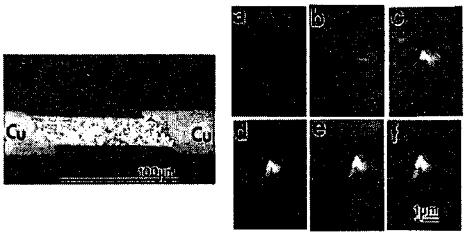
(100℃, 8.7x10^{4}A/cm^2 for 5 days)

EDX Data of SnPb

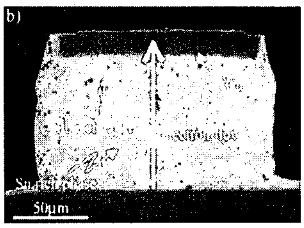
❑ **Pb is dominant diffusing element at 100℃**

Electromigration of solder

◇ Dominant diffusing element compared to previous results



K. N. Tu, et al., APL(1999)



K. N. Tu, et al., JAP(2001)

Stripe specimen

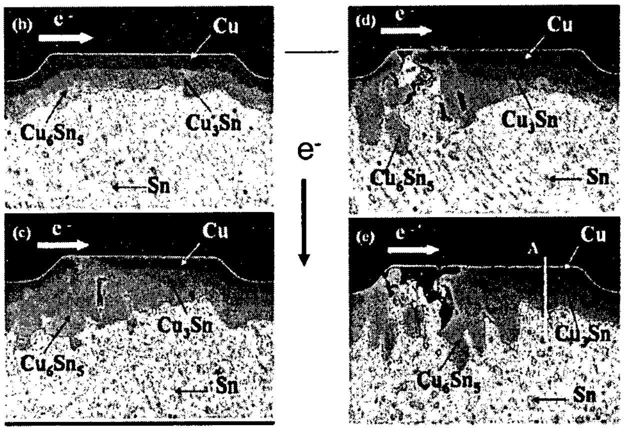
	Our results	K.N. Tu
Test temperature	100℃	R.T
Dominant diffusing element	Pb	Sn

Flip chip specimen

	S. Brandenburg	K.N. Tu
Test temperature	150℃	100~120 ℃
Dominant diffusing element	Pb	Pb

Electromigration of solder

◇ Dissolution of Cu between Cu UBM and SnPb solder

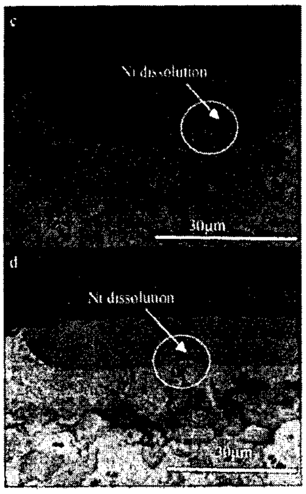


J. W. Nah, et al., JAP(2003)

- ☐ **Failure due to Cu dissolution into SnPb solder**
- ☐ **Occurrence at the cathode significantly**

Electromigration of solder

◇ Dissolution of Ni between Ni UBM and SnPb solder



(T. Y. Lee, et al., JAP (2001))

☐ Ni dissolution into SnPb solder as well as Cu dissolution

Electromigration of solder

◇ Lead free solder

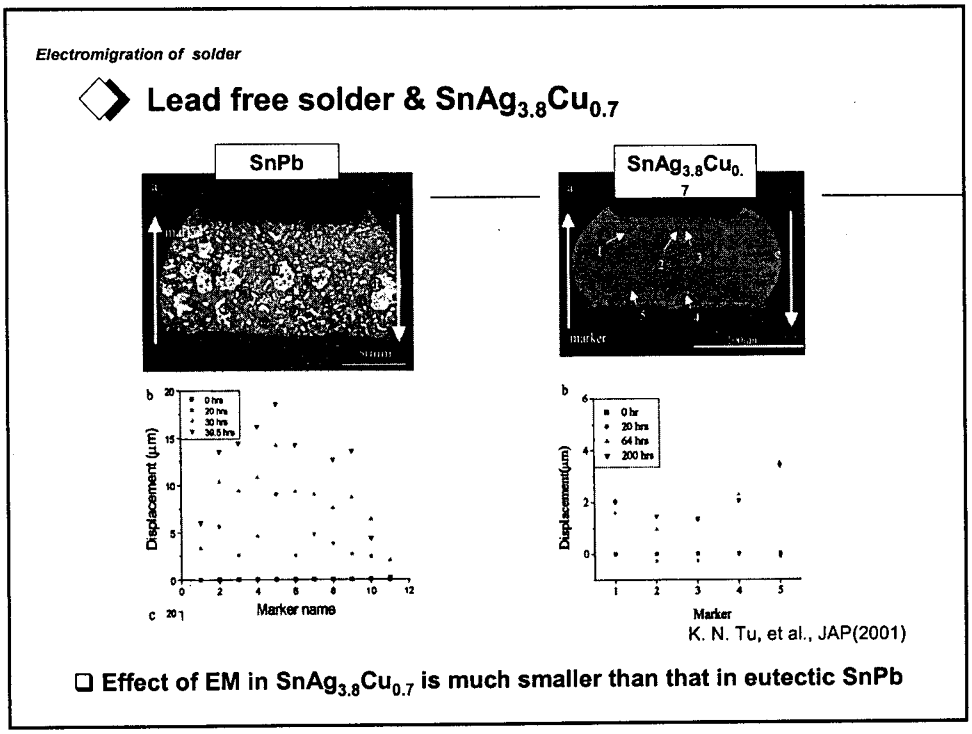
Eutectic SnPb solder ⇨ **Lead free solder**

☐ Lead free alloy candidate

Alloy	Melting Range (C)	Metal Cost/Lb (as of 2/3/99)	Density at 25C (lbs/cubic in)	Metal Cost per in³	Patent (Yes/No)
63Sn/37Pb	183	$2.37	0.318	$0.75	No
42Sn/58Bi	139	$3.44	0.316	$1.09	No
77.2Sn/20In/2.8Ag	179-189	$30.06	0.267	$8.02	Yes
91Sn/9Zn	199	$3.23	0.263	$0.85	No
91.8Sn/3.4Ag/4.8Bi	208-215	$6.24	0.272	$1.70	Yes
90Sn/7.5Bi/2Ag/0.5Cu	186-212	$5.09	0.273	$1.39	No
96.2Sn/2.5Ag/0.8Cu/0.5Sb	213-219	$5.48	0.267	$1.46	Yes
95.5Sn/4Ag/0.5Cu*	217-218	$6.55	0.269	$1.76	No*
95Sn/3.5Ag/1.5In	218	$8.15	0.268	$2.18	No
93.5Sn/3.5Ag/3Bi	216-220	$5.92	0.269	$1.59	No
96.5Sn/3.5Ag	221	$6.32	0.368	$2.33	No
99.3Sn/0.7Cu	227	$3.48	0.264	$0.92	No
95Sn/5Sb	232-240	$3.37	0.263	$0.88	No

* Some SnAg/Cu alloy compositions are covered by patents, however, this composition can generally be considered free and clear.

A Bench mark process for the lead free assembly of mixed technology PCB's (α-metal Chris basteki 1999)

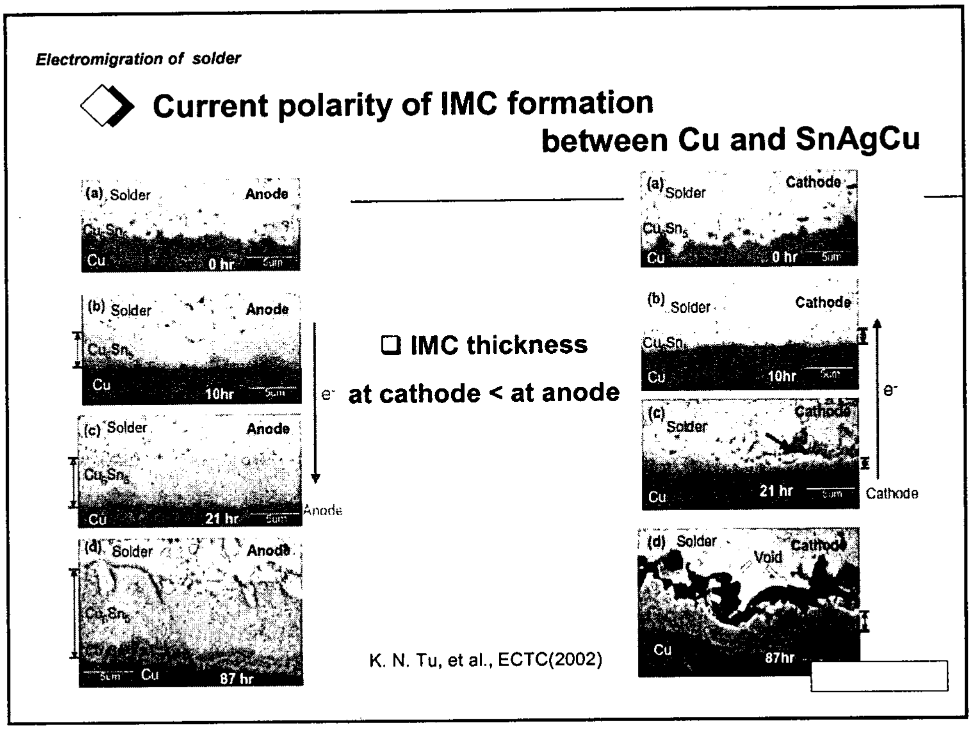


Electromigration of solder

◇ Lead free solder & $SnAg_{3.8}Cu_{0.7}$

K. N. Tu, et al., JAP(2001)

❑ **Effect of EM in $SnAg_{3.8}Cu_{0.7}$ is much smaller than that in eutectic SnPb**



Electromigration of solder

◇ Current polarity of IMC formation between Cu and SnAgCu

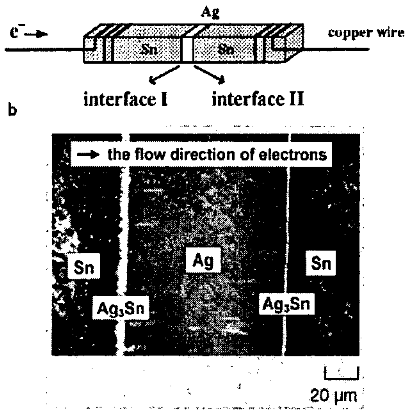
❑ **IMC thickness at cathode < at anode**

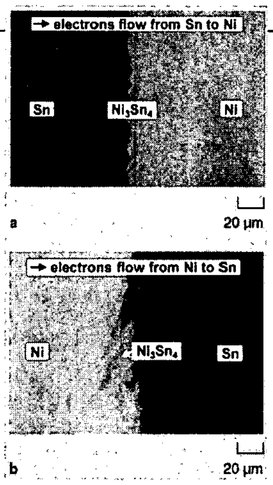
K. N. Tu, et al., ECTC(2002)

Electromigration of solder

◇ Current polarity of IMC formation between Ag or Ni and Sn

1 mm X 1mm X 40 mm, Ag : 0.5 mm





S. –W. Chen and C. –M. Chen, JOM (2003)

- ☐ **Different thickness of IMC formation at cathode and anode**

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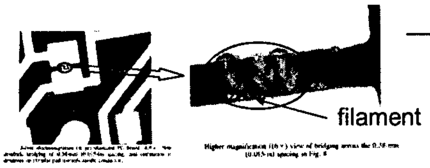
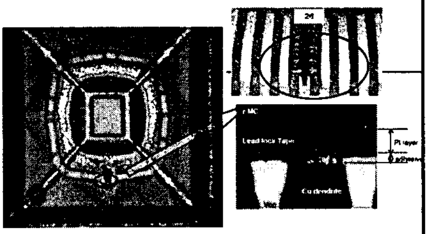
Electrochemical migration (ECM)



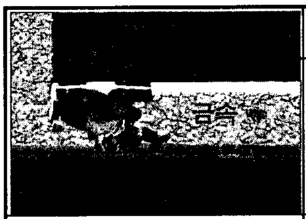
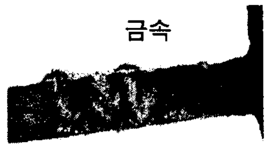
Krumbein, Trans. Comp., Hybrids, and Manuf. Tech., IEEE(1988).



Filament formation under an applied DC voltage bias in small pattern design & harsh environments of temperature & humidity

Failure of electronic component

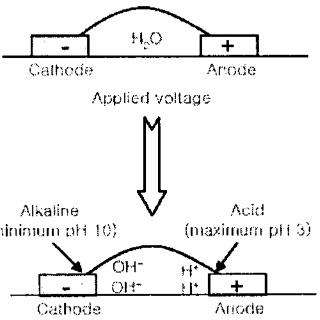
Electromigration vs. Electrochemical migration

		
	손상 형상	
금속 내부	**손상 경로**	금속 사이 절연체
전류, 온도	**발생 인자**	전압, 온도, 습도
반도체내 금속배선 패키지 솔더 조인트	**발생 전자부품**	인쇄회로기판 표면 및 내부

Electrochemical migration

Mechanism of ECM

1. **Water absorption on board from the humidity in the air.**



When applied voltage = minimum 2 V DC

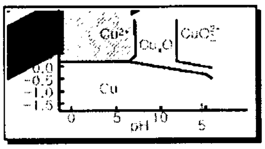
2. **Changes in pH in the vicinity of the electronics.**

Cathode (alkaline): $4H_2O + 4e^- \rightarrow 2H_2 + 4OH^-$

Anode (acid) : $2H_2O \rightarrow 4H^+ + O_2 + 4e^-$

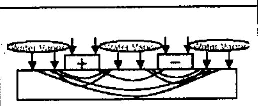
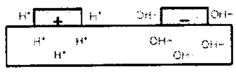
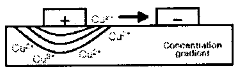
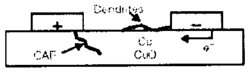
3. **Metal ion formation at anode**

Potential–pH equilibrium diagram (Pourbaix diagram)



Electrochemical migration

Mechanism of ECM

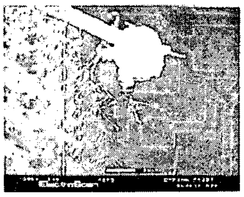
Reaction	Mechanism diagram	Acceleration factors
1. Water adsorption and diffusion		• Amount of vapor • Temperature • Material quality
2. Changes in pH due to the electrolysis of water (acidization)		• Voltage • Amount of water vapor • Temperature
3. Copper elution and copper ion diffusion (diffusion)		• Voltage, water vapor • Material quality • pH, impurity ions • Amount of dissolved oxygen
4. Electron transfer and ionic migration occurrence (reduction)		• Voltage • Material quality • ph, impurity ions

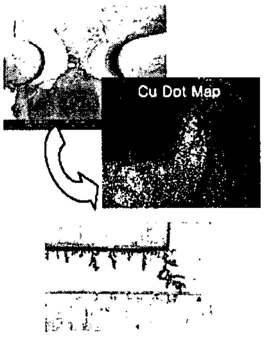
Electrochemical migration

Migration metal – Sn, Ag, Cu, etc.

- **Significant growth potential-metals with loosely bond oxides**
  - Silver, tin
- **Lesser growth potential**
  - Copper, gold, zinc, cadmium


Sn – Migration


Ag – Migration



Cu – Migration

Electrochemical migration

Metallic electromigration

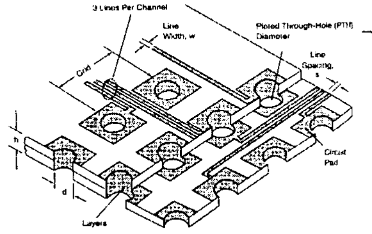
☐ **Not only silver, but also gold, copper, nickel, tin, lead**

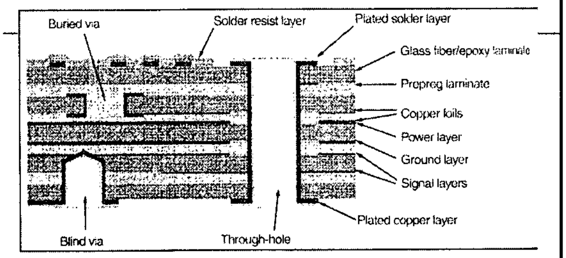
☐ **Migrated gold resistive shorts**
- **Failure due to bridging of narrow circuit spacing by dendritic filaments of gold in IC devices and hybrid microcircuit systems**

☐ **The copper migration in PWB**
- **Emanating from the positively biased conductors (anode)**
- **Growing along the reinforcing glass fibers**
- **Filament formation**

Electrochemical migration

A typical printed circuit board configuration





- **Line Width & Line spacing**

  : 한 layer 위에서 pattern를 이룬 전도체의 선폭과 선 간격
- **Plated Through- Hole**

  : layer와 layer 사이의 electrical contact 형성을 위해 drilling 후 도금처리
- **Micro Via**

  : 상,하 두 layer 간의 electrical contact을 위해 Via 형성

Electrochemical migration

PCB parameters status

Current technology 2002/2003

Attributes	Conventional	Leading Edge	State of the Art
Conductor Width and Conductor Space (min) μm	125	75	
Plated Hole Diameter (min) μm	250	200	
Microvia Diameter (min) μm	N/A	100	

IPC National Technology Roadmap Electronic Interconnections 2002/2003

Electrochemical migration

◇ Failure mechanism in PCB

PCB site

CAF (Conductive anodic filament)

Dendritic growth

Connector corrosion

Trace corrosion

Lead Pad corrosion

Intermetallic formation

PTH barrel fatigue

Fiber/Resin debonding

Tg limitation

Delamination

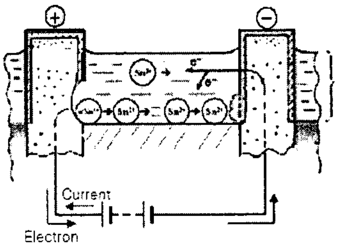
Laminate Plasticization

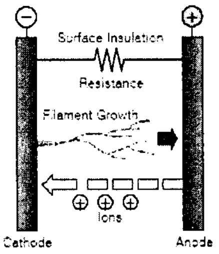
Electrochemical migration

◇ Dendrite Growth Migration

- Migration occurs when moisture adheres between electrodes made of materials such as copper, solder, or silver. As voltage is applied, the electrons carrying the Coulomb charge created by the ionization of the positive electrode flow towards the negative electrode. The charged electrons is reduced at the negative electrode and extends back toward the positive electrode.

◇ Pattern of Ion migration





Electrochemical migration

Conductive anodic filament (CAF)

•**CAF**

-A type of electrochemical migration

-Consist primarily of metallic conductive salt

-Being transported across a nonmetallic substrate under the influence of an applied electric field

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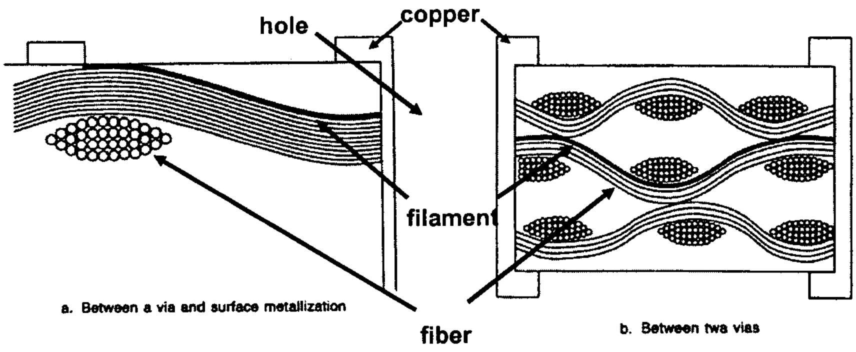
Electrochemical migration

Mechanism of filament formation

1. Electrochemical reaction leading to loss insulation resistance



a. Between a via and surface metallization

b. Between twa vias

Electrochemical migration

Mechanism of filament formation

2. Electrochemical reaction leading to loss insulation resistance

- **Cu ion**

At anode

$Cu \rightarrow Cu^{n+} + ne^-$

$H_2O \rightarrow \frac{1}{2}O_2\uparrow + 2H^+ + 2e^-$

At cathode

$H_2O + e^- \rightarrow \frac{1}{2}H_2\uparrow + 2OH^-$

***Filament : copper salt (containing chloride or bromide) & copper ion**

※ **Water-soluble flux** (WSF- glycols, polyglycols, glycol esters, poly glycol surfactants, polyols, glycerine등) 가 PWB제조 공정중에 resin과 fiber 사이에 스며들어 Salt 형성

Electrochemical migration

Mechanism of filament formation

1.Delamination at the glass fiber-epoxy resin interface (path creation)

- Epoxy resin 과 glass fiber의 TCE Mismatch
- Epoxy resin (thermal coefficient of expansion : 60ppM/ ℃)
  Glass fiber (thermal coefficient of expansion : 5ppM/ ℃)

2. Moisture absorption의 차이

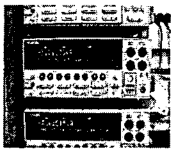
- Glass fibers 와 epoxy resin의(temp, RH) delamination이 심해짐

3. 가공중 발생하는 delamination

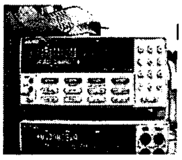
- 가공시 발생하는 물리적 충격에 의한 crack 발생

Electrochemical migration

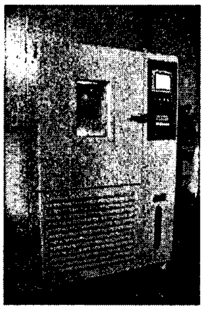
ECM test system



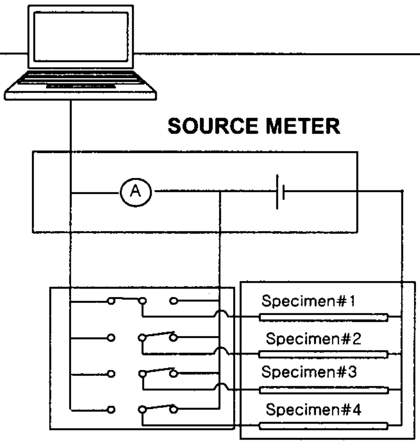
SOURCE METER



SWITCH MODULE



TEMP&HUMID CHAMBER



SOURCE METER

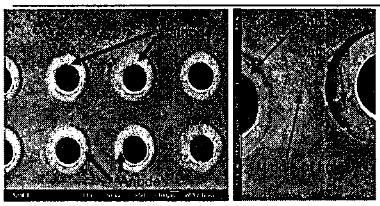
SWITCH MODULE

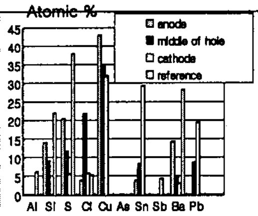
TEMP&HUMID CHAMBER

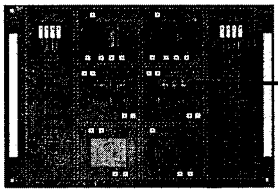
Electrochemical migration

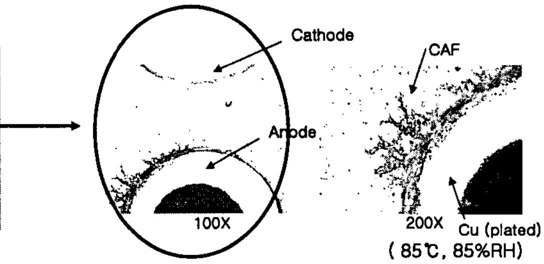
Electrochemical migration in PCB

- **Printed Circuit Board (PCB)**





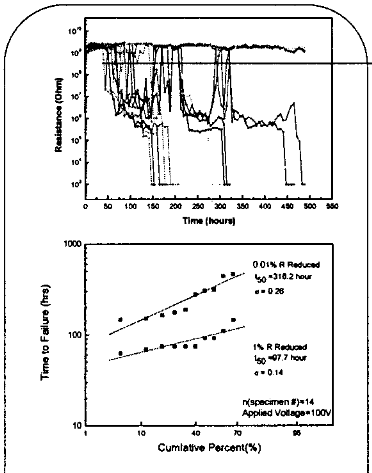




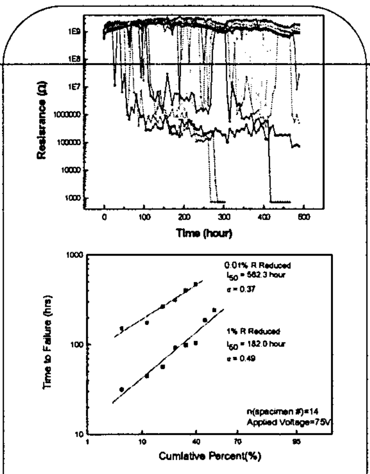
(85℃, 85%RH)

Electrochemical migration

Failure analysis



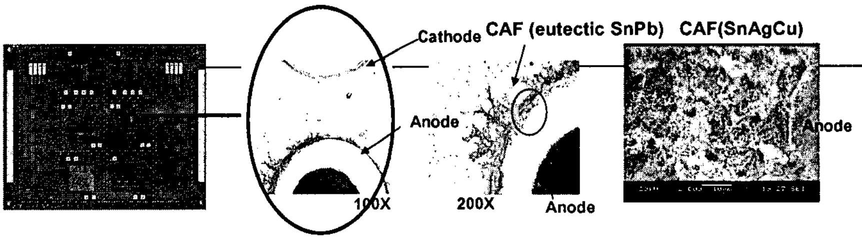
-100V , 85 ℃, 85% test-



-75V, 85 ℃, 85% test-

Electrochemical migration

Corrosion test



ECM에서 CAF가 절연파괴의 주된 원인
Anode에서 Corrosion 특성과 유사한 거동 보임

⇩

Eutectic SnPb / SnAgCu / Pure Pb / Pure Sn 부식 시험

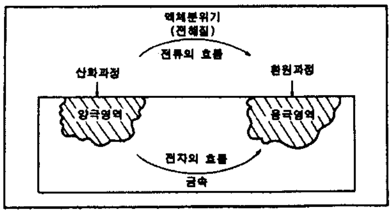
⇒ 분극 곡선 및 부식속도 측정

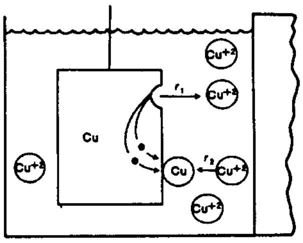
⇩

CAF 발생기구 및 소재별 차이 해석

Electrochemical migration

◇ Corrosion phenomena





- 부식= 산화반응(양극) + 환원반응(음극)

산화반응 : $M = M^+ + e$

환원반응 : $M^+ + e = M$

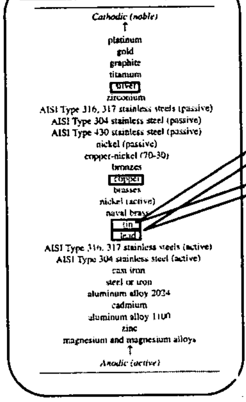
- 부식 발생시 양극과 음극 사이의 전류에 의해 전극전위 변화

  → 전기화학적 분극이 부식속도에 영향

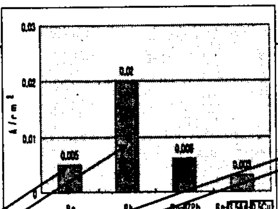
Electrochemical migration

◇ Corrosion resistance : Sn vs. Pb

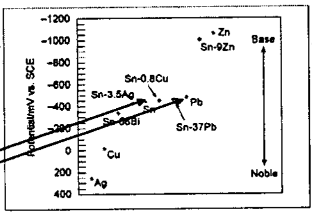
Galvanic series in seawater



Cathodic (noble)
↑
platinum
gold
graphite
titanium
silver
zirconium
AISI Type 316, 317 stainless steels (passive)
AISI Type 304 stainless steel (passive)
AISI Type 430 stainless steel (passive)
nickel (passive)
copper-nickel (70-30)
bronzes
copper
brasses
nickel (active)
naval brass
tin
lead
AISI Type 316, 317 stainless steels (active)
AISI Type 304 stainless steel (active)
cast iron
steel or iron
aluminum alloy 2024
cadmium
aluminum alloy 1100
zinc
magnesium and magnesium alloys
↑
Anodic (active)



-400mV(SCE)에서의 부식전류밀도



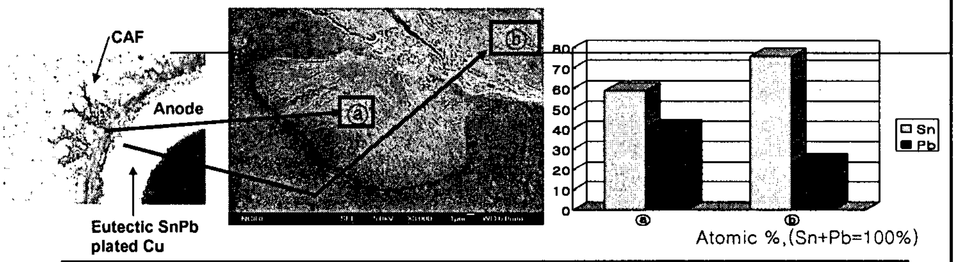
Rest Potencial of each type of solder (0.1mole sodium surfate solution) by ESPEC

※ Corrosion resistance

: Pb < Sn-Pb < Sn < Sn-Ag-Cu

Electrochemical migration

◇ Sn vs. Pb (eutectic SnPb in PCB)



Atomic %,(Sn+Pb=100%)

	ⓐ:CAF	ⓑ:near eutectic solder
Sn	59 ⇦	76
Pb	41 ⇦	24

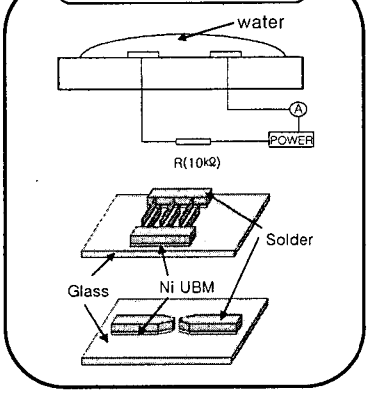
eutectic solder Sn:Pb=74:26 (atomic%)

Pb is more susceptible to CAF than Sn
⇒ Corrosion characteristics !

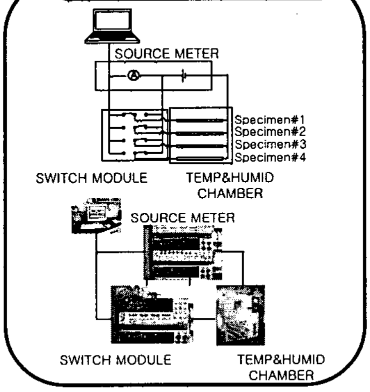
Electrochemical migration

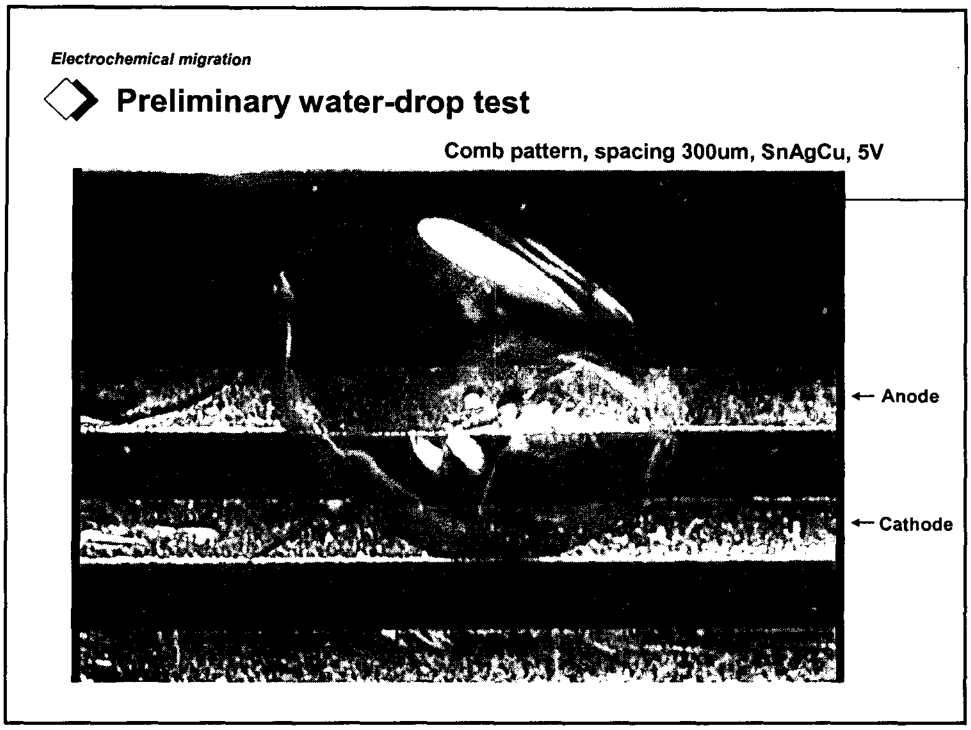
◇ Modeling test with simple structure sample

Water-drop test (in-situ test)



Multi Specimen test (Lifetime test)

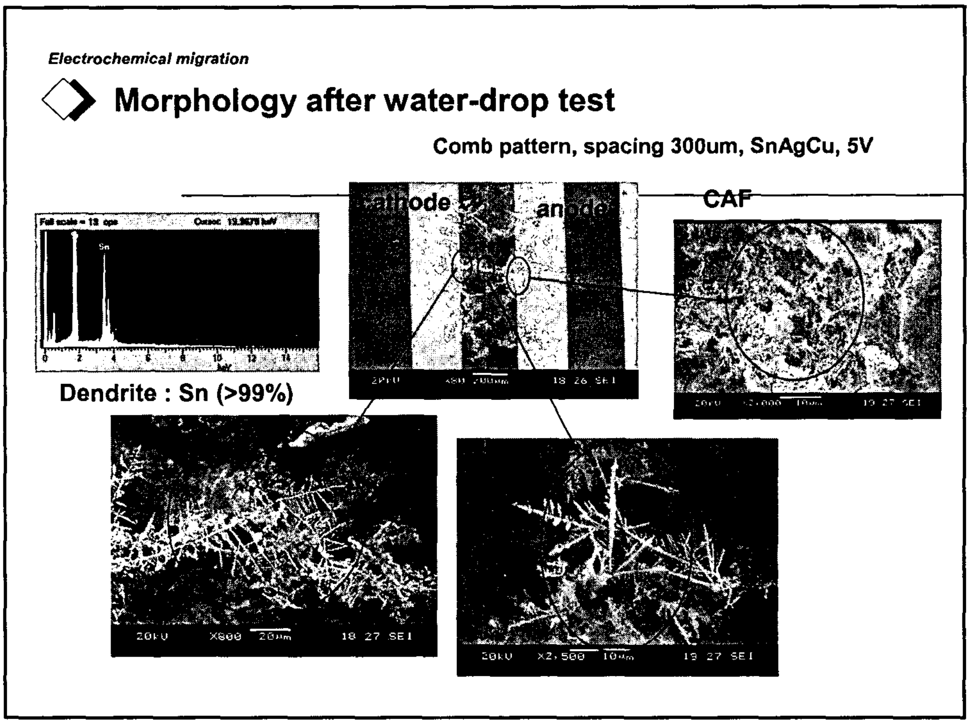




Electrochemical migration

Preliminary water-drop test

Comb pattern, spacing 300um, SnAgCu, 5V



Electrochemical migration

Morphology after water-drop test

Comb pattern, spacing 300um, SnAgCu, 5V

Dendrite : Sn (>99%)

Summary

Smaller size,
Large voltage/current,
high humidity

cause a new reliability threat in microelectronic packaging

Electromigration and Electrochemical Migration