Surface Failure Analysis in Semiconductor Packaging

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  - ESCA (Electron spectroscopy of Chemical analysis)
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  - EDS (Electron dispersive X-ray spectroscopy)
  - AES (Auger electron spectroscopy)
  - SIMS (Secondary ion mass spectroscopy)

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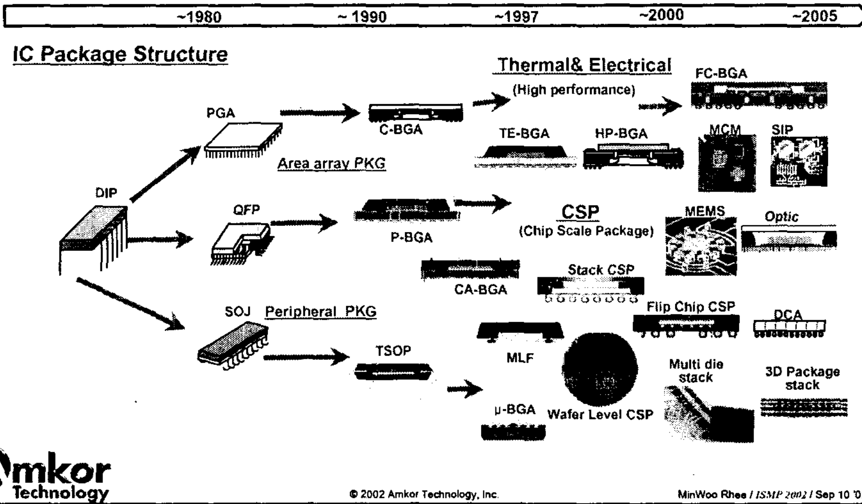
IC packaging evolution

- To meet the trend of miniaturization, light weight, high speed and various function in electronic devices, new packaging technologies have been emerged



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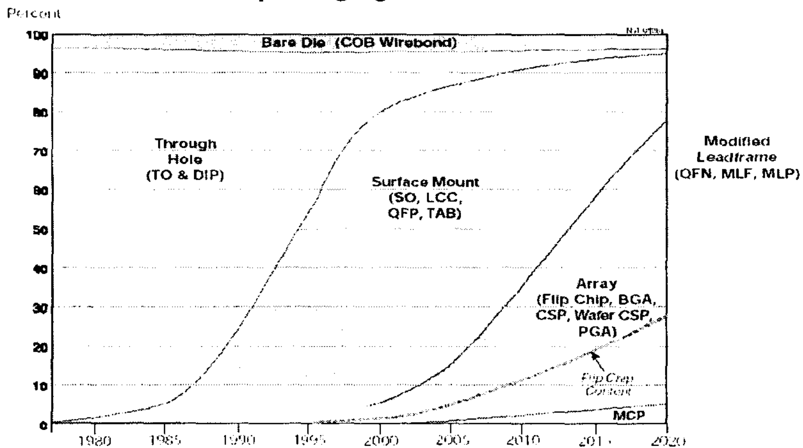
IC packaging evolution

- **Waves of electronic packaging**



PRISMARK

Source: Prismark

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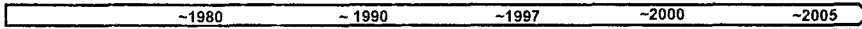
IC packaging Material evolution

• Packaging Material Trends



Packaging Material evolution

- Ceramic substrate
- Metal lead frame
- Sn/Pb plating
- Ag plating

- Organic substrate (2~4 layer)
- Cu heat spreader
- Ni/Au plating
- Eutectic Solder ball, paste
- Liquid encapsulation
- SMT

- Electrical characterization
- Organic substrate (Multi-layer)
- Surface treatment
- Embedded passives
- Environment-friendly material set
- Lead free plating, Solder ball, paste
- Film adhesive
- ACF, underfill
- Wafer bumping / UBM process
- Wafer thinning
- Low K material set
- Materials for 3D packages
- High accuracy alignment system

Increasing Thermal & Electrical consideration
for High Frequency application

Complicated Packaging layer structures
and material option

Package Miniaturization
while increasing I/O Count and functionality

Basic understanding
of Material Surface
characteristics
is essential

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Role of Surface analysis in IC Packaging

• Why Surface Analysis is important?

The understanding of the outer most layers of packaging material plays a critical roles in IC package's quality, process yield and reliability.

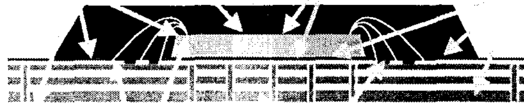
Surface analysis provides information for the surface of Package's organic & inorganic interfacial layers

Electrostatic behavior

Contaminants Foreign materials

Chemical activity adhesion

Corrosion phenomena



inter-metallic diffusion behavior

Process residues and impurities

inter-metallic wettability

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Role of Surface analysis in IC Packaging

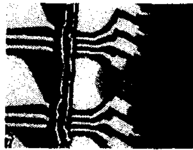
• **Surface defect Failure analysis**

The ability to analyze sub-micron defects or particulate contaminants is of critical importance to increasing product yield in IC Packaging industry as follows

- *Semiconductor device fabrication*
- Microelectronic packaging process
- Substrate manufacturing
- Packaging Material manufacturing

surface contamination

Dendrite growth


Substrate contamination

Foreign material

Inter-metallic diffusion

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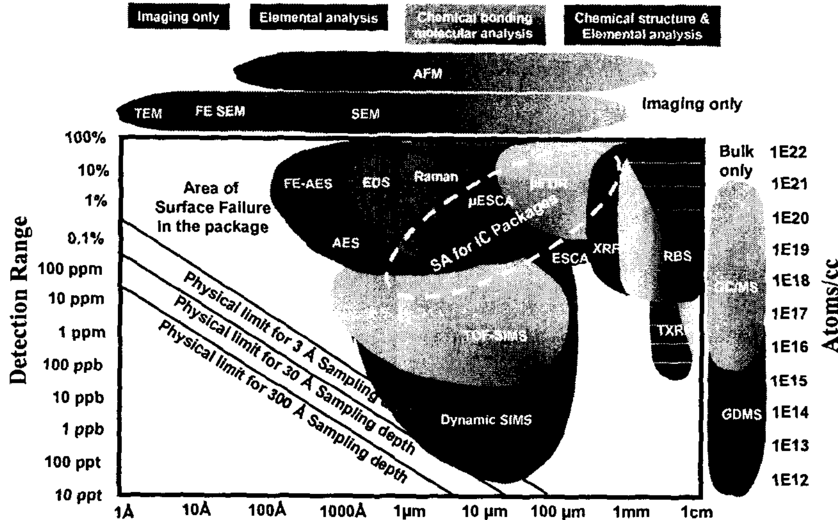
Surface Analysis detection range



reference : Charles Evans & Associates

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Surface Analysis detection range

Analytical technique	Typical application	Signal detected	Elements detected	Organic structure information	detection limit	depth resolution	Imaging mapping	Lateral resolution
AES	Elemental surface analysis high resolution depth profiling	Auger electrons from near surface atoms	Li – U	N/A	0.1~1 atomic%	2~6 nm	Yes	100nm
micro FTIR	identification of polymers Plastics, Contaminants, Organics films, fibers and liquid	infrared absorption		Molecular Group	0.1~100 ppm		No	5um
Raman	identification of organics and inorganics	Raman scattering	Molecular chemical identification from vibrational spectra		~0.1wt%	confocal mode 1~2um	Yes	1um
XPS/ESCA	Surface analysis of organic and inorganic molecules	Photoelectrons	Li-U	Chemical bonding	0.01~1 atomic%	1~10nm	Yes	10um ~ 2mm
XRF	Thin film Thickness composition	X-rays	Na-U		10 ppm		No	100um
EDS (SEM)	imaging and elemental microanalysis	Secondary ion and backscattered electrons and X-rays	B-U		0.1~1 atomic%	1~5um (EDS)	Yes	4.5nm(SEM) 1um (EDS)
SIMS	Dopant and impurity depth profiling, surface and microanalysis	Secondary ions	H-U		1E12~1E16 atoms/cc	5~30nm	Yes	<1um(imaging) 30um (depth profiling)
Quad-SIMS	Dopant and impurity depth profiling, surface and microanalysis insulators	Secondary ions	H-U	--	1E14~1E17 atoms/cc (ppm~ppb)	< 5nm	Yes	<5um(imaging) 30um (depth profiling)
TOF-SIMS	Surface microanalysis of polymers, plastics and organics	Secondary ions, atoms, molecules	H-U	Molecular ions to Mass 10,000	<1ppm ~1E8 atoms/cc	1 monolayer	Yes	0.10 um

reference : Charles Evans & Associates

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Surface Failure Analysis Case Studies

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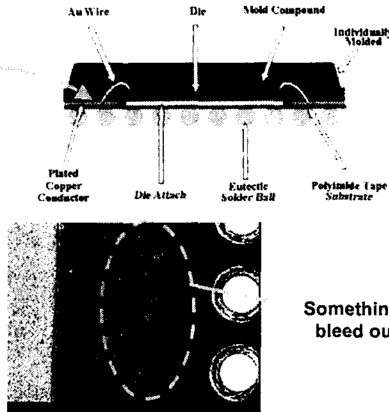
FTIR –Microscope

Case (1) : Organic contamination on Bond finger

- **Bond finger contamination**
  - Polyimide Tape substrates have a contamination problem near the bond finger during Wire bonding process
  - This kind of contamination cause the wire bonding quality problem and yield loss.

Figure : contamination on lead finger



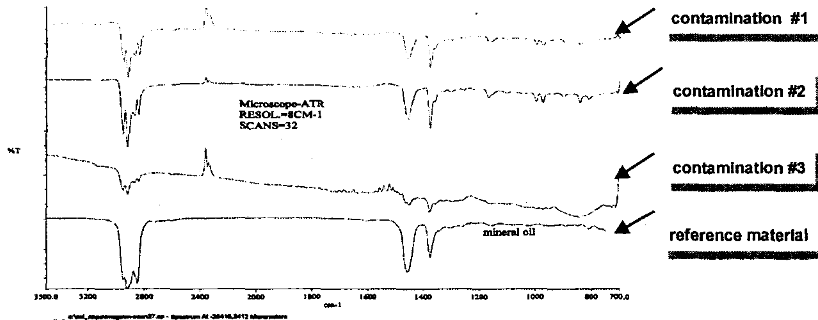
Something is bleed out ?

FTIR –Microscope

Case (1) : Organic contamination on Bond finger

- **FTIR-microscope spectrum of contaminated area**

By using FTIR-microscopy (ATR) analysis, the contaminating material in discolored position was found to be the hydrocarbon based material which had the alkyl group



FTIR-microscope spectrum shows peak in wave number of :

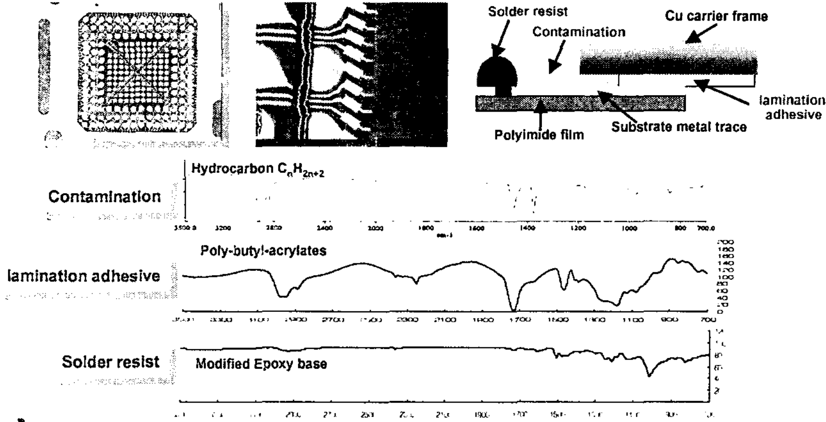
- 2800~2900 cm-1 : which represents $-CH_3$, $-CH_2$ of stretching
- 1500 cm-1 : which represents $-CH_2$ of bending
- 1380 cm-1 : which represents $-CH_3$ of bending

FTIR –Microscope

Case (1) : Organic contamination on Bond finger

- **FTIR-microscope spectrum of Suspected Materials**

Suspected lamination adhesive and Solder resist material showed different spectrum from the contaminating material detected by FTIR-microscope



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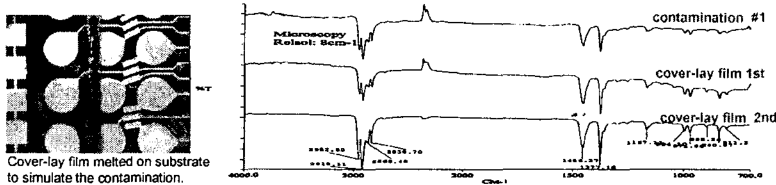
FTIR –Microscope

Case (1) : Organic contamination on Bond finger

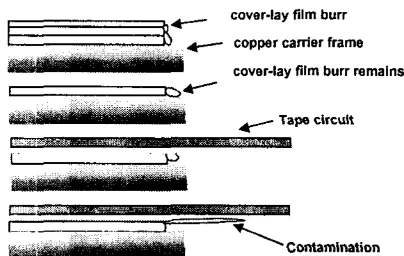
- **Root cause finding : lamination adhesive cover film burr**

FTIR spectrum of adhesive cover-lay film (Poly ethylene based) is exactly same with contaminated material.



Cover-lay film melted on substrate to simulate the contamination.

- **Contamination process**
  1) Punched lamination adhesive is attached to carrier frame
  2) cover-lay film & back paper is detached
  3) Tape substrate is attached to carrier frame
  4) Cover-lay film is melt out to bond finger at 180'C heater block



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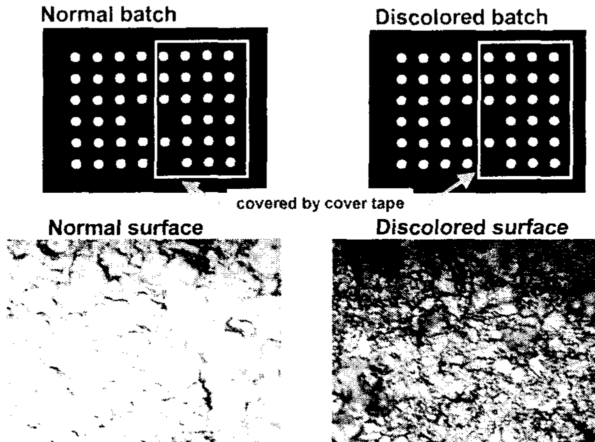
FTIR –Microscope

Case (2) : Ball land discoloration

- **Ball land discolor during elastomer curing process**

Half of the circuit ball pads in the unit were covered by cover-lay tape to check elastomer *fume effects during* cure process. In the old batch, sample shows severe discoloration except covered area. But new batch shows no discolor at the same condition



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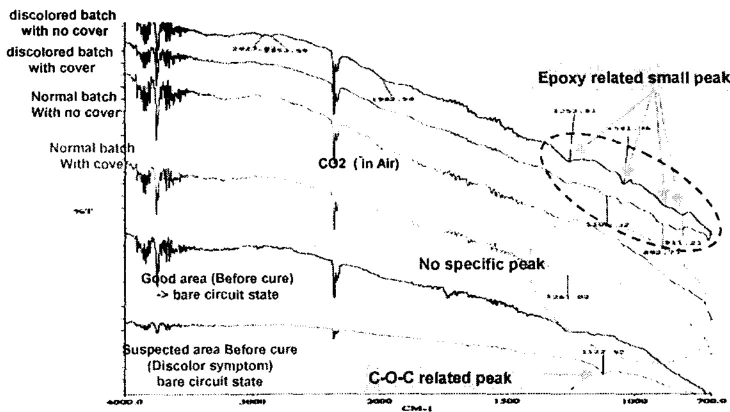
FTIR –Microscope

Case (2) : Ball land discoloration

- **Root cause finding : Epoxy resin**

In the defected sample, both covered area and exposed area shows Epoxy related peak →possible component is elastomer or tape adhesive.



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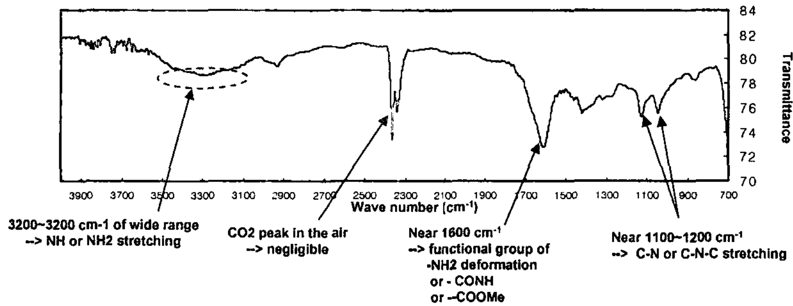
FTIR –Microscope

Case (3) : Substrate surface discoloration

- FTIR-microscope spectrum of contaminated area

Checked area spot size 10um using ATR (attenuated total reflectance) option



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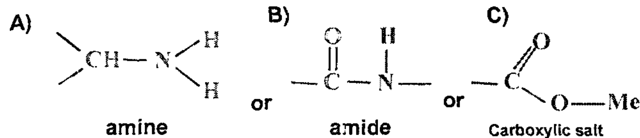
FTIR –Microscope

Case (3) : Substrate surface discoloration

- Root cause identification

Basic functional group and Typical Structure



- Root cause

The root cause were defined as bacteria in Au plating bath in substrate – amide chemical compound (bacteria's protein)

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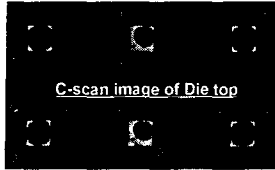
FTIR-microscope

Case (4) : incompletely cured PI passivation layer

- **Die top surface delamination during process**

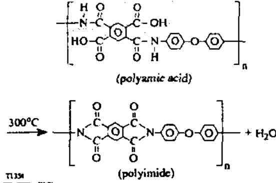


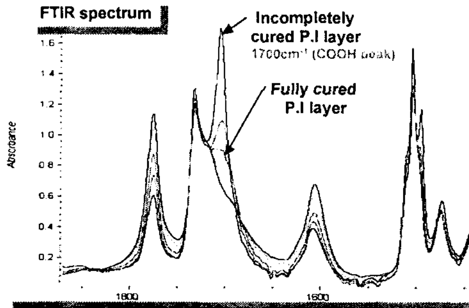
Delaminated die top surface

•From FTIR spectrum, delaminated Die passivation area shows incompletely cured PI structure (- COOH, 1700cm^{-1})

•Peak disappears when the damaged P.I undergoes annealing process over 300'C

Cure process





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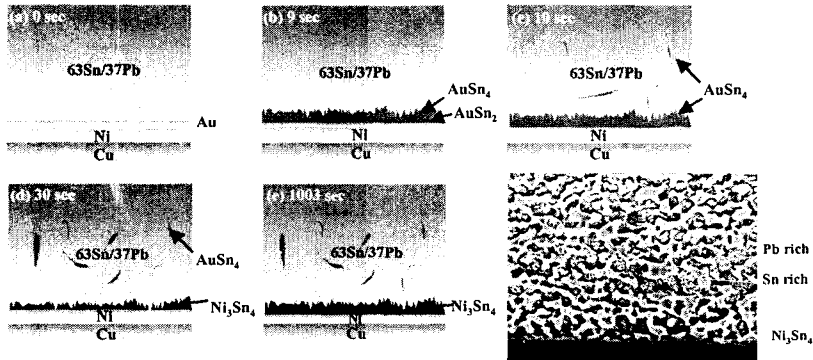
EPMA

Solder Ball inter-metallic image mapping

- **Solder ball reaction kinetics**

The illustration the Eutectic 63Sn/37Pb's reaction kinetics when 220'C reflow is as follows

Reaction kinetics of Eutectic 63Sn/37Pb Solder ball on Ni/Au pad



Reference :C.E.Ho and el, "Reaction Kinetics of Solder –Balls with Pads in BGA Packages during reflow soldering" JEM vol. 28 No 11 November 1999 pp1231-1237

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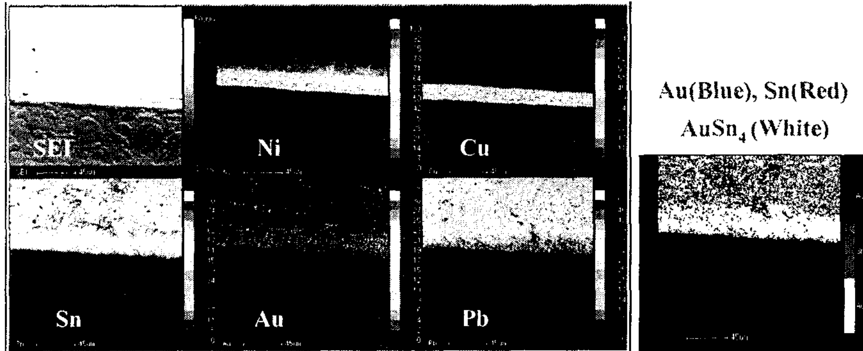
EPMA

Solder Ball inter-metallic image mapping

- 63Sn/37Pb Solder ball inter-metallic image mapping by EPMA (reflow condition 240°C)



- Au plating is diffused to Solder during reflow and forms brittle inter-metallic with Sn

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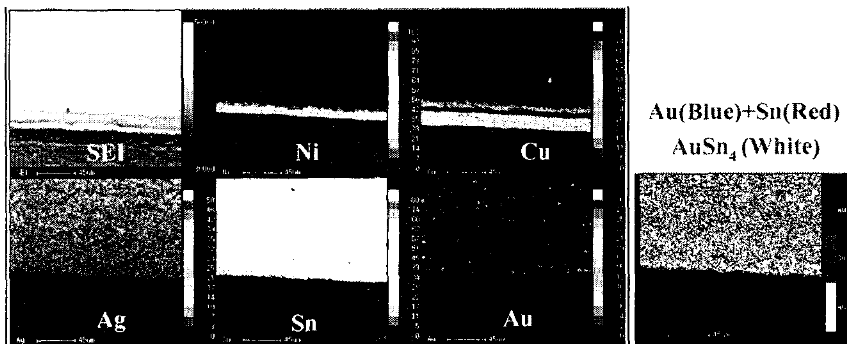
EPMA

Solder Ball inter-metallic image mapping

- Lead free Solder ball (Sn-3.5Ag-0.75Cu) inter-metallic image mapping by EPMA (reflow condition 240°C)



- Both Au and Ag plating is diffused to Solder during reflow
- The copper inside the 3.5Ag/0.75Cu balls gather at the interface of the Ni plated and the solder ball (To form stable Eutectic inter-metallic composition near Ni layer)

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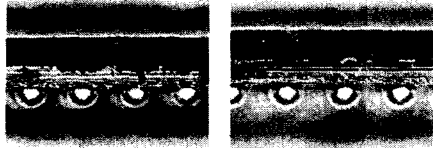
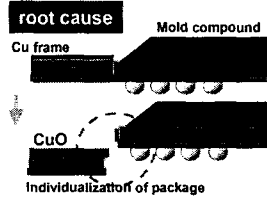
ESCA

Foreign materials on Package edge

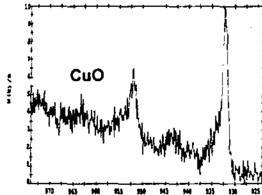
- **Foreign Material determination**

ESCA analysis spectrum showed that the foreign material adhered at package edge is Copper oxide rather than Cu. The root cause of this adhered material is oxidation of copper carrier frame during packaging process

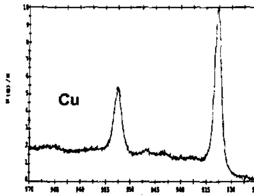




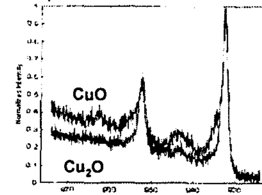
- **ESCA analysis**



(a) Tested sample



(b) Cu - reference



(c) CuO and Cu_2O- reference

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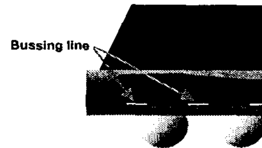
ESCA

Foreign materials on Package edge

- **Resistance of copper oxide film**



CuO/Cu_2O layer near the Bussing line for Ni/Au plating – electrically short ?

Resistivity of Copper Oxide film (Ohm m)

material	Cu	Cu_2O	CuO
resistivity	1.694×10^{-8}	10-50	6000

--> Resistivty of CuO and Cu_2O is as 10^9~10^{11} times higher than Cu

Calculation of Resistance of CuO (or Cu_2O) film

Sheet resistivity : The resistance of a conductor or resistor in sheet form is according to following equation

$$R = \frac{r\,l}{d\,b}$$

r : electrical resistivity
l: length of the material
d: thickness
b: width

Oxidation layer thickness and its color

color	reference	CuxO thickness
copper		~25nm
red		~40nm
violet		~60nm
gray		~80nm
yellow		~120nm
red		120nm ~

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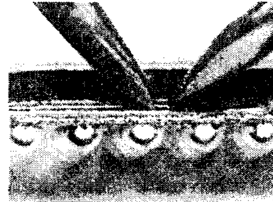
ESCA

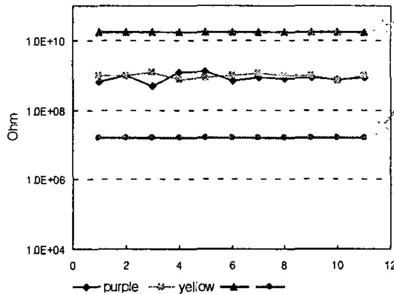
Foreign materials on Package edge

- **Resistance from Measured data**



- **Measuring method**
  Mega Ohm meter (0.1M~1G Ohm)
  with fine needle electrodes

- **Measured resistance (Ohm)**



From the calculation and experimental measuring data, resistance of CuO (or Cu_2O) film could be safe from trace short problem.

Galvanostat

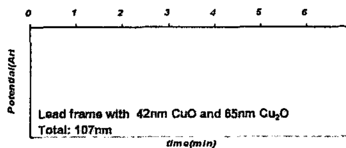
Average oxidation layer thickness on Cu

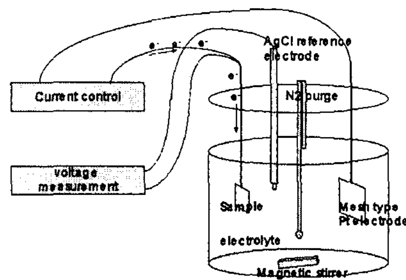
- **Basic principle of reduction method**
  - By the electrochemical reducton method , the amount of Cu_2O, CuO on Cu can be measured. and also it can be applied to Cu_2S, CuCl on CU, SnO, SnO_2 on Sn and Ag_2O , AgO , Ag_2S on Ag
  - if we know the amount of charge which was participated to reduce oxide, we can calculate the amount of oxide and this amount can be interpreted into thickness easily.

Faraday's law : Thickness of oxide

$$\delta = \frac{it}{2F}V$$

Where
I : Current density (mA/cm²)
t : Reduction time(sec)
V : Molar volume of the oxide phase. (CuO:12.4cm³/mole,Cu_2O:23.9cm³/mole)
F : Faraday's constant





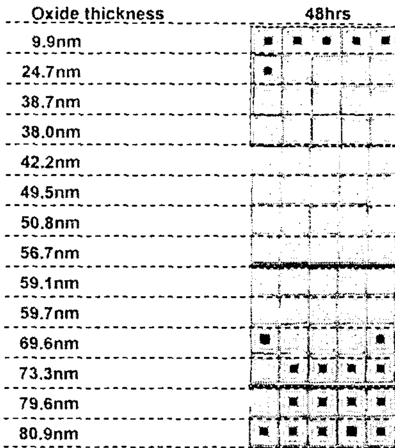
Galvanostat

Average oxidation layer thickness on Cu

• **Package delamination vs Cu Oxide thickness on lead frame**

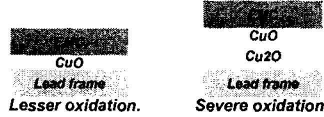
T -scan image : Moisture soak(85'C/85%) / VPS 3X

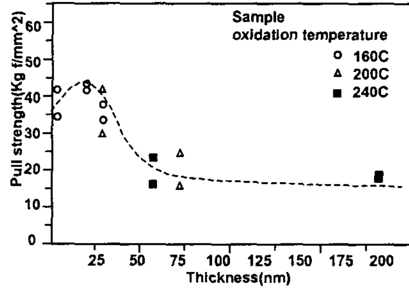
Oxide thickness	48hrs
9.9nm	
24.7nm	
38.7nm	
38.0nm	
42.2nm	
49.5nm	
50.8nm	
56.7nm	
59.1nm	
59.7nm	
69.6nm	
73.3nm	
79.6nm	
80.9nm	



❑ *Oxide structure*

CuO/Cu_2O/Copper Lead frame





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EDS

Case (1) Foreign materials on Substrate metal trace

• **Foreign Material on the Substrate metal trace**

Rounded small particles are inspected on the metal trace The size of particles on the traces are below 10um.

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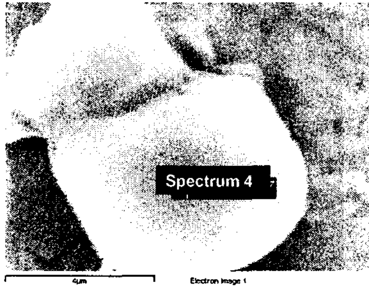
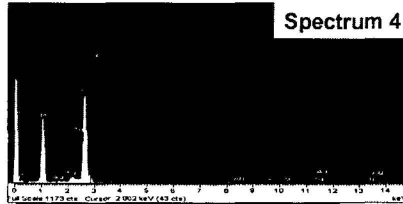
EDS

Case (1) Foreign materials on Substrate metal trace

• **EDX analysis of Foreign Particle**





Element	App Conc.	Weight%	Atomic%
C K	0.77	21.41	39.46
Na K	12.91	33.88	32.63
Cl M	11.49	44.71	27.92
Totals		100.00	100.00

•Detected elements : Carbon(C), Sodium(Na), Chloride(Cl).

•The atomic contents of Na and Cl are almost same : 32.63% Na / 27.92% Cl refer to the results, the particles are NaCl.

•Possible root cause : human sweat by handling problem
: Salt remnant in plating bath in substrate process line.

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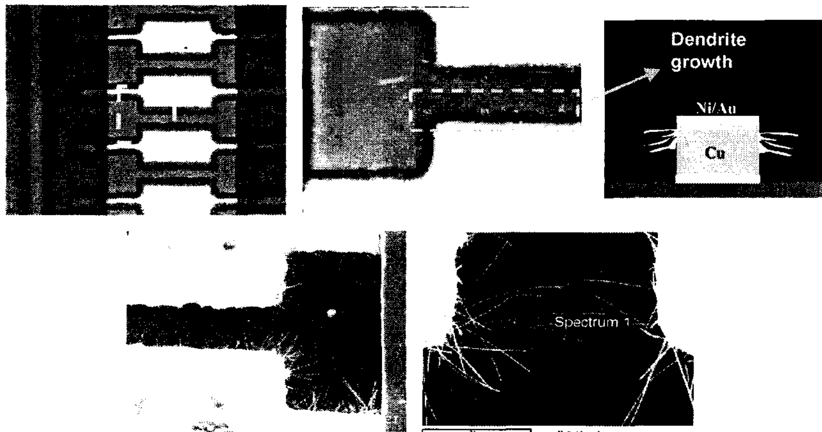
EDS

Case (2) Dendrite growth during Non-Biased HAST

• **Dendrite on additive build-up organic substrate**

Dendrite is detected on the metal trace of organic substrate (additive build-up process) after the non-bias HAST test (130°C/85%R.H./72hrs)



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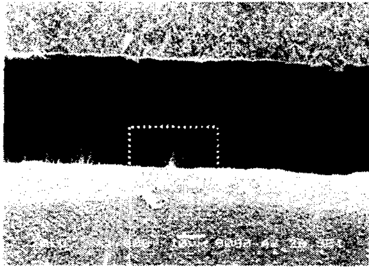
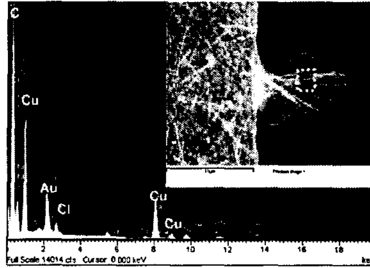
EDS

Case (2) Dendrite growth during Non-Biased HAST

• **SEM & EDX analysis of dendrite**





• **EDX test shows that major component of the dendrite is Cu.**

•**C and O are detected from base material (organic components)**

Element	App Conc.	Intensity Corrn.	Weight%	Weight% Sigma	Atomic%
Cl K	1.38	0.8050	0.60	0.07	0.25
Cr K	1.68	0.8542	0.69	0.12	0.19
Ni K	0.98	0.8139	0.42	0.18	0.10
Cu K	33.81	0.7713	15.31	0.58	3.54
C K	150.63	0.8137	64.63	1.11	79.05
O K	19.41	0.3691	18.36	1.27	16.86
Totals			100.00		

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EDS

Case (1) Dendrite growth during Non-Biased HAST

• **Root cause – ionic impurities on substrates**

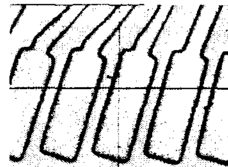
Ionic impurities level of defected substrate sample

- Analytical instrument : Ion Chromatograph, Dionex - DX 100
- *Test condition* : 4 hrs extraction with D.I. water at 125'C (ng/cm²)

Substrate ion content		Sample 1	Sample 2	Sample 3
Anion	F (-)	650.53	732.99	763.02
	Cl (-)	91.98	63.33	94.75
	Br (-)	0.00	0.00	0.00
	NO2 (-)	0.00	0.00	0.00
	NO3 (-)	14.20	12.76	7.16
	PO4 (3-)	0.00	0.00	0.00
	SO4 (2-)	365.86	872.30	313.76
	Total	1122.57	1681.38	1178.69
Cation	Na(+)	1161.00	2522.41	1534.73
	NH4 (+)	361.01	352.62	475.67
	K (+)	35.26	3.61	0.46
	Mg (2+)	57.85	1.80	8.85
	Ca (2+)	403.14	1.52	39.77
	Total	2018.25	2881.95	2059.47
Ion total		3140.82	4563.33	3238.16

• **Ionic impurity controlled sample**

-- **Passed HAST test**
-- **No dendrite detected**
-- **total ionic impurity : average 530.36 ng/sqm**



- Ionic chromatography test results with raw circuit show higher impurity level. This phenomena represent substrate manufacturing & cleaning process should control the ionic impurity level.

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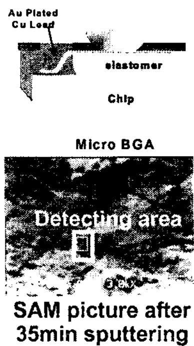
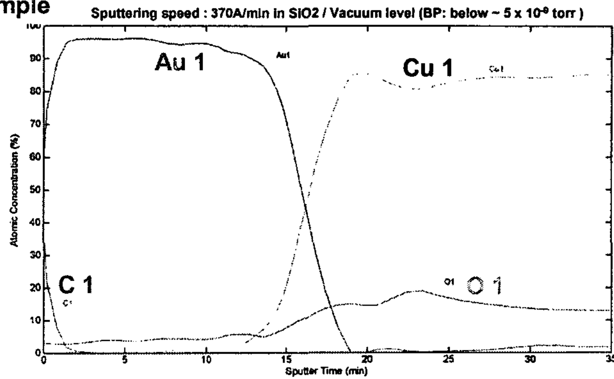
AES

Depth profile of discolored bond lead

- Non discolored sample



SAM picture after 35min sputtering



- ♦ Depth profile for non-discolored sample shows that on the surface, there exist C(carbon) until 3min sputtering.
- ♦ After 15min sputtering, the metallic is changed from Au to Cu
- ♦ Oxygen is exist on the Cu surface which means Cu oxide layer is exist.

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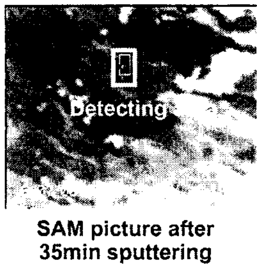
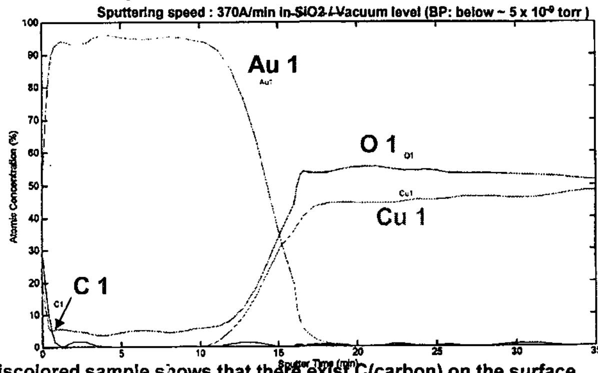
AES

Depth profile of discolored bond lead

- Discolored sample : lead bonding failure



SAM picture after 35min sputtering



- ♦ Depth profile for discolored sample shows that there exist C(carbon) on the surface until 3~4min sputtering .
- ♦ After 15min sputtering, the metallic is changed from Au to Cu
- ♦ Higher content of oxygen is exist in compare with non-discolored sample on the Cu surface which means thick CuO layer is exist.

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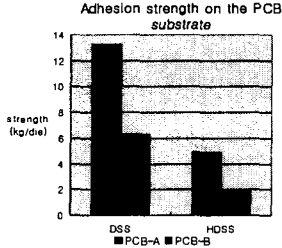
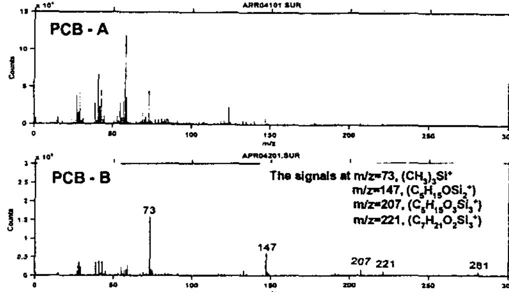
SIMS

PDMS residue on organic substrate

- **SIMS investigation of PCB substrate die attach area**

The SIMS peaks in the survey spectrum show the presence of the organic silicone called polydimethlsiloxane (PDMS) on the PCB-B substrate which has a poor adhesion strength





- **Failure mode**

PCB- A : Solder Resist & substrate Cu

PCB- B : D/A adhesive & Solder Resist surface

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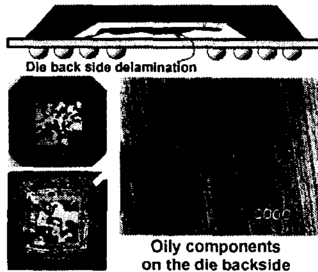
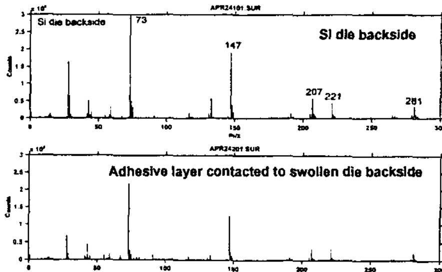
SIMS

PDMS residue on organic substrate

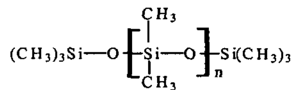
- **SIMS investigation of swollen die backside**

The SIMS peaks in the survey spectrum show the presence of the organic silicone called (PDMS) on the die back side and Adhesive layer contacted to die backside.





- **Root cause : PDMS in Solder resist**
  - A component of solder resist
    Silicone oil such as PDMS used as leveling agent of solder resist.
  - Anti-foaming agent
    PDMS act as anti-foaming agent to reduce the bubble or voids in solder resist developing or stripping process.



$$(CH_3)_3Si-O-\left[\begin{array}{c}CH_3\\ |\\ Si-O\\ |\\ CH_3\end{array}\right]_n-Si(CH_3)_3$$

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