Gold wire bonding on Low-k Material

A new challenge for interconnection technology

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1. Introduction

The gold wire bond technology is still widely used in back end assembly. Even for conventional devices the wire bond technology applies mechanical stress on the bond pad and substrate layers, which leads to known damages like cratering and oxide cracks. The parameter combination of ultrasonic power and impact force may cause serious mechanical damage on the device. The wire bond technology is a trade off between proper interconnection on gold and aluminum and prevention of any mechanical damage on the stacks under the aluminum pad. Therefore it is crucial to control these parameters precisely in a defined and tight range.

In terms of mechanical response on stress factors, low-k material is very sensitive. Wire bonding equipment needs to address this issue and must be designed for such a challenge.

2. Low-k material consideration

The present sub-0.25µm technology nodes or interconnect delays respectively are comparable to transistor delays. This delay is a function of the product of the total resistance and capacitance of the whole interconnects structure. To further reduce this interconnect delays (in effect increasing the device speed and performance), the need to narrow the spacing between the circuit lines have become inevitable. The transition from aluminum to copper wires would reduce the resistance component of the total delay, while reducing the dielectric constant (K) would reduce its capacitive effect.

In any present device, thin aluminum (Al) lines (often described in sub micron nodes) are isolated from each other using an insulating material commonly known as silicon dioxide (SiO2), which has a dielectric constant value of 4.0. As the Al circuit lines approached the sub-0.18µm nodes level, copper (Cu) line was introduced to address the interconnect resistance delay caused by the Al lines.

Further reducing the Cu circuit lines at sub-0.13µm nodes, the need to reduce the dielectric constant has become inevitable. Lowering the dielectric constant would improve the signal integrity by reducing the cross talk effect between adjacent conductive lines (see illustration below).

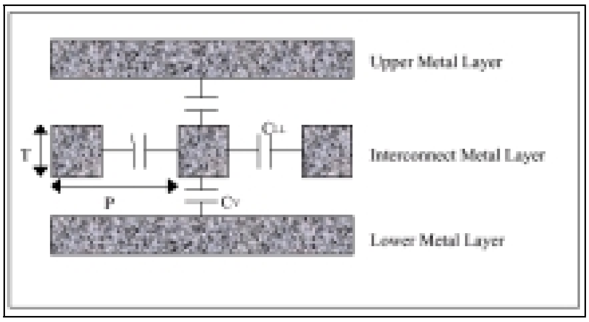

Figure 1: Electrical schematic

SiO2 is the perfect material for interconnects except for its dielectric constant characteristics as previously mentioned. Replacing it with low-k material will generally weaken the mechanical properties and reduced thermal conductivity. When electronic packaging engineers discuss about low-k dielectrics, they refer to materials with dielectric constants of less than 3.0.

Actually, the use of low-k material terminology in today's evolving technology is not aptly precise. Any k values less than 4.0 have been used to describe as low-k. It comes in different class of materials and there are many variations within each class. For example, the simplest dielectric, fluorine-doped SiO2, is usually described as FSG (fluorosilicate glass, a proven compatible with existing process) with a dielectric constant of 3.5 (compared with SiO2 of 4.0). All are referred to as low-k material.

Material	k
CVD-SiO2	4.2-4.5
FSG	3.6-3.9
OSG	2.8-3.3
SiLK	2.6
Porous SiLK	2.1

Table 1: Low-k dielectric material

The ultimate target of the industry is to reduce the k value to 2.5 or less. The disadvantage of having lower dielectric constant value is the increased degree of porosity of the material. Further reducing the dielectric constants of less than 2, the researchers have envisioned a possibility of using freestanding metal lines, with air replacing the dielectric. However, this technology is still at the infant stage as major issues still needs to be addressed for K values of <=3.0.

3. Effects of Low-k material on wire bonding process

The characteristics of low-k materials are summarized as follows:

- Poor mechanical characteristics: Lower mechanical structure stability
- Low mechanical strength; Lower Young's Modulus
- Low adhesive strength: Low aspect ratio

Problems associated with wire bonding are as follows (typical failure reject criteria):

- Non-sticking on bond pad
- Metal peeling / de-lamination
- Damaged / fractured bond pad
- Effects of probe marks
- Poor bond shear strength

3.1 Wire bond equipment related issues

The key parameters for a gold wire bond process, apart from temperature, are bond force (divided into static and dynamic / impact force) and ultrasonic power. The precise controlling of these parameters is an essential factor for a high yield interconnection process. An important factor is the bond head design and motion principal; another major factor is the ultrasonic transducer design.

The traditional concept of wire bond equipment has remained unchanged for decades and has limited potential for improvements. The current z-axis pivoting systems mounted on a x/y orthogonal x/y – stage show a clear dependency between high speed bonding and bond quality in terms of position accuracy, settle time and wearing effects over the time. Therefore such a concept is not sufficient to provide a required controlled process parameter window under production condition for a sensitive low-k process.

A. Force system / Force generation

The WB3100 bondhead system is based on a new kinematics principle, a rotational motion bondhead based on air bearing technology. The bondhead has a lightweight z- axis with frictionless bearings. The design principle leads to an extreme high speed under low vibration, hence resulting in low settle time with very high position accuracy. The mechanical design is associated with a "closed loop force control" system and " closed loop position control " system with DSP, both systems enable the bonder to control the dynamic force in a way that is not conceivable with conventional orthogonal system.

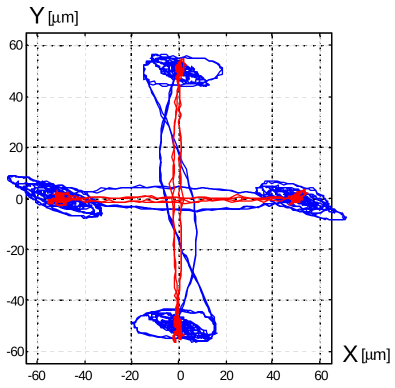

Figure 2: Comparing movements of an conventional x/y-stage (blue line) with a y/theta-stage (red line). The measurement shows the capillary movement.

Summary of major advantages of the new bond head concept is:

- Lightweight z – axis / high stiffness
- Closed loop position control with DSP
- Closed loop force control
- High accuracy position measuring
- Frictionless air bearing technology

B. Ultrasonic system

Another essential part of the bond head is the ultrasonic system. The ultrasonic transducer transforms electrical energy into mechanical energy. The ultrasonic energy contributes the major part of the required inter-diffusion energy for the Al/Au contact system; therefore it is crucial to control the ultrasonic power precisely.

It is a common understanding today to use US- frequencies above 100 kHz, known as high frequency US-systems but the frequency of the system is not the only quality determination factor. The new US system is consequently designed to reduce the mass (titanium transducer), to move away parasitic modes (x and z oscillation and torsion) and reduce variations to different capillary types. Apart from the frequency, all these criteria are important to provide a stable US system and maintain a portable and reproducible process window.

Summary of advantages of new US-system:

- Reduced influence of parasitic modes (x/z/torsion-mode)
- Reduced variations from transducer to transducer (improved portability)
- Reduced variations with different capillary designs and geometry
- Improved capillary clamping, more robust and reproducible
- Design is less sensitive to piezo property
- Variations (frequency drift)
- Reduced y-shift/ higher stiffness
- Maintain the sensitivity of the Tsunami force sensor

C. Bond process

For the following process studies on low-k-material, an ESEC Wire Bonder Tsunami 3100 was used. The enhanced concept allows monitoring of all relevant parameters and adjusting of key parameters like impact-force, bond-force and US power for each bond segmenting separately.

4. Experimental Design

The low-k material used for the investigation was a test wafer that contains 8 different low-k structures. The bond pad structure was a 4 layer Al-metal.

For the properties, refer to table 2. In addition, 3 different capillary types have been evaluated (Table 3).

The process itself was based on a 40um fine pitch process (specification refer to Table 4).

A DOE study was done with 3 Factors on 3 levels with 3 Replication with 81 runs per capillary. (Refer to Table 5)

Test Chip Area	M1	M2	M3	M4
1	SLM	SLM	NOM	SM
2	SLM	SLM	SLM	SM
3	SLM	SLM	CH	SM
4	SLM	SLM	CH	SM
5	SLM	SLM	CH	SM
6	SLM	SLM	SLM	SM
7	SLM	SLM	SLM	SM
8	SLM	SLM	SLM	SM

Table 2: Integration schemes of low-k material

Legend:		
	SLM -	slotted metal
	M -	solid metal
	CH -	cross hatch
	NOM-	no metal under POR

Capillary type	**A**	**B**	**C**
Hole [µm]	**20**	**20**	**20**
Tip [µm]	**51**	**51**	**51**
CA [°]	**90**	**70**	**50**
CD [µm]	**23**	**23**	**23**
FA [°]	**11**	**11**	**11**
OR [µm]	**8**	**8**	**8**

Table 3: Capillary dimensions

The capillary type was a typical 40um pitch capillary. The difference was only the chamfer angle of 90, 70, and 50deg. The SPT capillaries used in this study have satisfied the condition of having high compliance (e.g. higher amplitude displacement and high amplification factor).

	Average	Range	Stdev
Ball diameter [µm]	28	+/-1	< 0.8
Ball height [µm]	8	+/-1	< 0.6
Min. Shear strength [g/mil²]	5.5		
FAB [µm]	22		< 0.5
Wire diameter [µm]	15 um		

Table 4: 40 µm bond specifications

The start point was determined by the lowest shear strength specification, it means the lowest parameter set up (- - -) has to meet the 5.5 g/mil^2 criteria. The upper limit was determined by the geometrical dimension of the bonded ball (max diameter < 32 µm).

	-1	0	+1
Parameter	Low	medium	high
Bond force [mN] BS1	80	100	120
US power [%] BS1	8	10	12
Velocity [mm/s] BS1	8	10	12

Table 5: DOE Parameter set up (3 Factors /3 Levels)

Parameter	Impact segment 1	Impact segment 2	Bond segment 1
US power[%]	8	8	8/10/12
Force end[mN]	100	100	80/100/120
Duration [ms]	4	4	5
Shift[um]	0	0	0
US rise time[ms]	0.3		
Search time[mN]	12.5	12.5	
Search distance[um]	100	100	
Search velocity[mm/s]	8	8	8/10/12
TD ign delay[ms]	3		
TD level [mN]	80		

Table 6: Bond parameter ESEC 3100 Wire Bonder (First bond/ball)

5. Results

In general, the bond results show a clear response to the parameters. The bond-ability of the low-k material can distinguished in 3 major groups:

1. Good bond-ability was given, clear response to the parameters (comparable to a normal 40um process) on test chip area 5, 6, 7, and 8.

2. Bond-ability was hard to achieve, some ball non-sticks appeared (lower parameter level), but on the higher side metal peeling was already observed on test chip area 3, and 4.

3. Not bondable at all, regardless which parameter set up was chosen (even on the lowest side), metal peeling appeared in more than 80% of the cases on test chip areas 1, and 2.

The reject criteria was metal peeling (1) and low shear readings (3).

The trade off was to determine a process window in order to get a stable bond process in terms of good interconnection (meet shear criteria) and no mechanical defects, like oxide damages or metal de-lamination.

The following SEM pictures show the failure rejects under different parameter configurations in different bond sectors.
Figure 4 shows that even under "high set up" the bond-ability in this specific test chip area was given.

Run	X1	X2	X3	peeling
1	-	-	-	0
2	0	-	-	0
3	+	-	-	0
4	-	+	-	3
5	0	+	-	2
6	+	+	-	2
7	-	0	-	0
8	0	0	-	0
9	+	0	-	0
10	-	-	0	1
11	0	-	0	0
12	+	-	0	0
13	-	+	0	3
14	0	+	0	4
15	+	+	0	3
16	-	0	0	0
17	0	0	0	0
18	+	0	0	0
19	-	-	+	1
20	0	-	+	0
21	+	-	+	1
22	-	+	+	5
23	0	+	+	4
24	+	+	+	4
25	-	0	+	1
26	0	0	+	2
27	+	0	+	2

Table 7: Peeling rejects test chip area 6

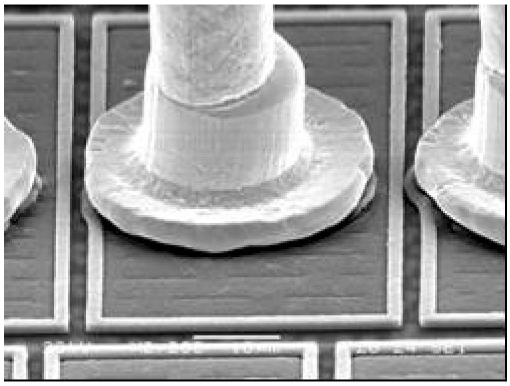

Figure 4: Ball bond / high parameter set up on test chip area 6

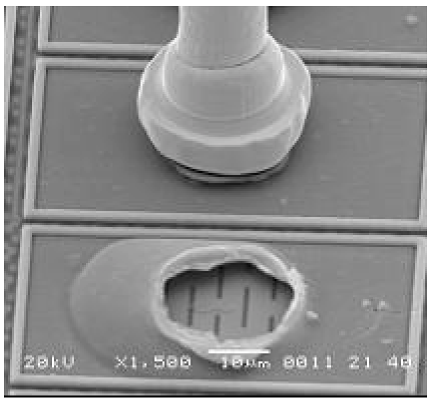

Figure 5: Metal peeling / low parameter set up (group 3 reject)

Figures 5 and 6 show metal peeling behavior in test chip areas 1 and 2. These chip areas were considered “unbondable” because it is apparent that the peeling phenomenon is not bond parameter related. A metal de-lamination is already observed without any bond stress. Figure 7 shows clearly that no parameter window exists between “non stick” and metal de-lamination.

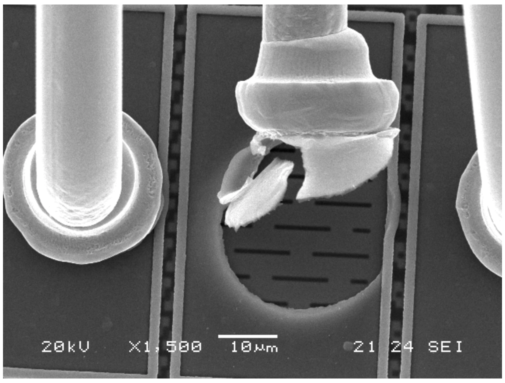

Figure 6: Metal peeling in test chip area 2

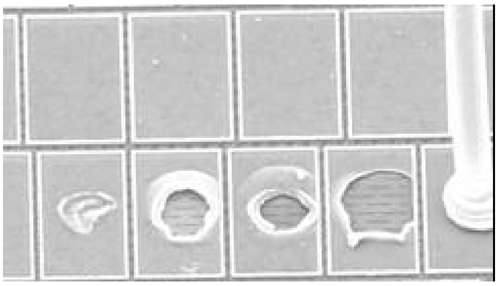

Figure 7: Metal peeling in chip area 2

As mentioned, the only difference in the SPT capillary design for 40µm BPP (PI-20051-23XF-ZP34S) is the chamfer angle. The following observations were made based on the results taken from test chip area 6:

1. The chamfer angles 90deg and 70deg design met the ball shear stress readings of 5.5gms/mil2-minimum criterion set.
2. The chamfer angle 50deg showed variation in meeting the minimum criterion for ball shear stress readings at different DOE runs.

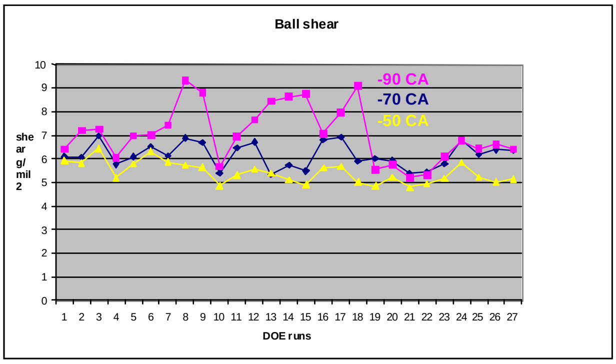

Figure 8: Ball shear of test chip are a 6” with 3 different capillaries

6. Conclusion and Outlook

The study clearly demonstrated that different low-k materials require different parameter setups. Some materials have to be considered as “unbondable” as the mere drag force of the capillary is sufficient to cause metal peeling.

It is identified that the impact force is the significant factor involved in peeling. It is also noted that the process window on these low-k materials is generally smaller. In addition, it was found that even though the types of capillary used are not a major influence, the 70deg chamfer angle capillary is the best compromise. However, further investigations and studies will be conducted to improve the capillary design in providing consistent response for low-K materials.

These findings clearly show the challenges for Wire Bond equipments to bond low-k materials. Low-k material is generally bondable but precise controlling of impact force (search velocity) and US power is imperative. Hence new revolutionary bond head concept is required for high precision control of bond force and US power in order to maintain a stable and reliable production process for high sensitive low-k material. The hardware solution has to be associated with software and process features which allow setting up the process for several types of material.

This investigation gave a first attempt to bond low-k material. Additional tests have to be carried out in order to study the effects of stress behavior, oxide cracks and the also the influence of the bond parameter regarding different pad metal structures and low–k materials.

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