Bonding pad resistance. A combined approach.

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ABSTRACT

Introducing new intermetal materials, with improved electrical properties but lowered mechanical resistance, requires in terms of reliability to design new structures for pads. The test structures under fabrication have been simulated to try and evaluate the state of stress under various loads in the structures: the analysis of the results aims at supporting the choice of a specific type of structure and optimizing the parameters of this structure. The present work will help analyze further experimental data under compressive stress.

Keywords: bonding pad, mechanical stress, simulation, reliability, compression test

1 INTRODUCTION

Pads are multilayers as the rest of the circuit and introduction of new dielectric material has to be studied in terms of reliability. Mechanical behavior of large metal plates may not be compatible with low-k materials in the pads. Reducing the size of the pads tends to lower their mechanical resistance whereas the loads they have to bear are not necessarily lowered. Pads must resist to compressive stress during the wiring and then to possible tensile and shear stress. Failure can occur by peeling of the last level or by cratering deep into the pad (Figure 1). New design proposals have been made and test structures are being processed. Meanwhile, a simulation of mechanical stress state of the various pad structures under various loads is started using Ansys® [1] to complement the experimental results.
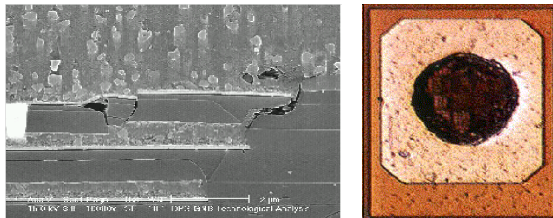

Figure 1: Analysis of failure mechanisms.
   a) SEM cut view of last levels metallization: Peeling.
   b) Optical top view of the sample after reliability test.

The structures under study are first briefly described. The main design parameters are extracted. Then applied loads and boundary conditions are exposed. The numerous assumptions required to proceed to the simulation are given, along with the material properties. Finally results under compressive loads are given for each pad and a first analysis is made, with the prospect of enriching it as soon as more experimental results are available.

2 DESCRIPTION OF SIMULATED PADS

Design of pads obeys to design rules:
• avoid the need for any special mask or process step.
• respect the density rule imposed by CMP for planarity.
• adapt dimensionally the pads pitch to the technology.
The pads have a connecting function and must bear external loads. Classical design has been challenged and new architectures envisioned. One of them is presented in Figure 2. Sixteen variations (A to P that can not be detailed here) were made based according to:
• density of metal: dense/less dense (I(F)/J) (K/N)
• metal superimposition: alternate/stack (F/K) (J/N)
• number of levels: levels 5 and 6 only/all levels (B/A) (G/F) (P/O)
• via stiffening: via/no via (A/C) (F/H) (K/L)
• metal reinforcement (depending on spacing within aluminium layer Cx, Dx, Ex, (Figure 2)): with/without (I/F) (M/K).
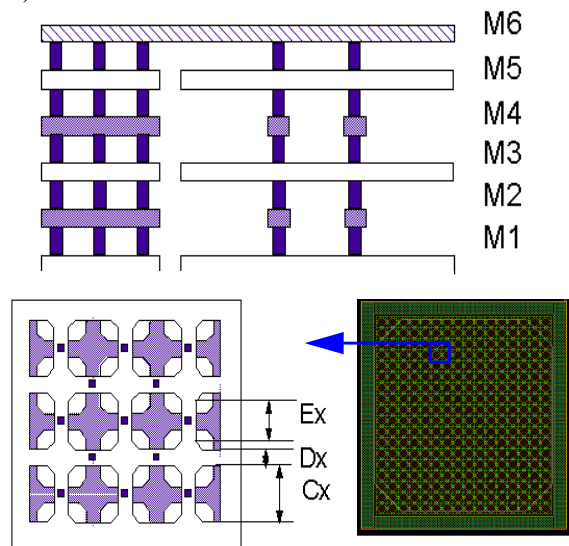

Figure 2: design F under investigation.
Only one motive is represented here, dimension 8x8 μm^2.
Cx = 3 μm, Dx = 1 μm, Ex = 3 μm.

Their qualities in terms of mechanical resistance have to be compared. Given the complexity of the actual problem, the aim of the study is not to simulate the reality (real geometry, adherence variability or defects can not be mod-

eled at this time) but to simplify it using hypothesis and identify the most resistant pad architecture. Simulation by itself may not be sufficient. The results obtained still will be of use for the interpretation of experimental tests to failure.

Mechanical resistance can not be addressed itself since failure criteria are missing. This work aims at estimating the state of stress under load for the various structures and to isolate potential stress concentration points that have to be avoided in a design.

2.1 Loads and boundary conditions

Compressive, tensile and shear stress must be studied corresponding to the actual loads that pads may have to stand. Experimental tests are usually practiced to qualify the pads. Corresponding loads are reproduced in our simulations. Compressive state is simulated applying a surfacic load (pressure of 80 N/mm^2) on the top of the pad. Pressure is applied on the vertical direction (z) upon the level 6 layer. This simulation work is restricted to an analysis in elasticity. Tensile and compressive behavior are similar (with a reversed sign for principal stress and same sign - always positive- for Von Mises stress).

Methodology and results concerning shear stress solicitation can not be fully exposed here and constitute the topic of a second paper [2].

A boundary condition precluding displacement in every direction is set at the base of the structure. No substrate elasticity is taken into account. Experimentally, a pad is set on the substrate. We consider the substrate as a stiff surface. Strain is equal to 0 at the z=0 boundary. The side boundaries are more difficult to model. We chose to let the boundary free and allow this way displacement of nodes and elements that compound the boundary.

2.2 Assumptions and mechanical data

Only a primitive motive of section 8x8 or 9x9 μm^2 is modeled for each pad. The influence of pad pitch (50, 65, 80 μm^2) can not be addressed here. (One motive is modeled instead of 72 for the pad under study due to the considerable amount of finite elements already required).
- the ring around the pad is not modeled
- the partially capping nitride is not modeled
- microstructure heterogeneity is not reproduced
- adherence problem or voids can not be addressed
- material properties used may be unaccurate
- no plasticity is modeled.
- a boundary condition precluding displacement in every direction is set at the base of the structure.
- no residual stress is taken into account prior to loading.
- metal lines (composite in practice) are considered as monolayers of aluminum. Diffusion barriers are intentionally not taken into account.

Mechanical characteristics corresponding to the materials of the pads are listed in Table 1.

Material	ν (Poisson)	E [GPa]
W	0.28	350
Al	0.3	76
SiO$_2$ TEOS	0.2	60

Table 1: Mechanical properties

Model	σ_{mises}max in W [MPa]	σ_{mises}max in Al [MPa]	σ_{mises}max in TEOS [MPa]
A	(365) 365	(128) 177	(173) 189
B	(321) 321	(215) 232	(114) 130
C	-	(98) 98	(180) 196
D	(357) 357	(145) 195	(170) 188
E	(371) 371	(125) 190	(175) 194
F	(502) 510	(217) 244	(107) 119
G	(525) 555	(189) 224	(111) 119
H	-	(68) 69	(70) 74
I	(515) 531	(150) 181	(119) 141
J	607 (651)	(180) 226	(130) 138
K	(475) 487	(170) 175	(184) 202
L	-	(125) 147	(184) 202
M	(468) 488	(220) 245	(111) 126
N	(446) 446	(182) 216	(183) 203
O	(360) 360	(220) 269	(100) 128
P	(378) 378	(165) 184	(146) 167

Table 2: Simulation results summary (nodal) / element

2.3 Results under compressive load

Results for the 16 structures are summarized in Table 2. Nodal (average results) are given under brackets, when element results represent the value without averaging. We chose to extract maximum Von Mises stress to compare the level of stress in the different architectures, and detect concentration of stress.

3. ANALYSIS OF THE RESULTS

The choice was made to start with the analysis of the simulation parameters and a discussion of the options that were chosen for the modeling of the designed pads.

3.1 Parameters influence, choices and remarks

• The choice was made to work on Von Mises equivalent stress and evaluate the maximum in each material for each pad under load. This enables to attain possible critical point, since the equivalent Von Mises stress can be compared to a value of plastic threshold when available.

• Size of the model: an attempt was made on one case to model a quarter of an actual pad and ring. The number of volumes (and subsequent finite elements) generated becomes critical for the use of FEM code. This aborted attempt confirms that the analysis shall be performed on a simple motive and then hypothesis questioned.

For H architecture (no via) four motives could be calculated. Results show less than 2% a difference between Von Mises maximum stress in Al and W as compared to results obtained from a unique motive.

• With no lateral boundary displacement conditions, stress is maximum at the edge of the base. This is an artefact of modeling, hence a weakness of our simulation due to the necessity to keep restricted to only one motive. This point may be critical for the results, though it is difficult to assess.

• Boundary condition relative to lateral displacement, at the base of the motive and at the lateral boundaries, shall be discussed in terms of the obtained results. Experimentally, the pad is more or less confined laterally. So the simulation should not include free of constraint lateral boundaries. Comparing results between simulations (architecture K, L or M) constraining lateral displacement and letting it free shows more than 20% a difference. Unfortunately, using such a constraint on displacement at the lateral boundaries provokes an artificial stress gradient at the boundary. It is difficult to assess which option enables to stick closer to the reality. Our purpose is not to extract the maximum stress under loading conditions but to compare the structures under test. The choice was made to compare laterally unconstrained models.

3.2 Comparison of the architecture proposals

A general trend observed is that stress is maximum in via. When there is no via, same levels of stress are observed in TEOS and Al (pads C and H) or stress is higher in TEOS (Pad L). The general level of maximum stress is lower in structures with no via. For G-Pads, stress is clearly maximum at the via location. The same trend was observed by He et al. [3] on a deposited metal line on a dielectric; they found the residual stress in the dielectric to be maximum at the vicinity of the edge of the metal line. Experimentally, it has been observed in reliability test that cracks appeared

close to the edge of the base of the via. This tends to prove that shear stress is critical for the structure at the vicinity of the via. In the present study devoted to compression tests, this aspect is not addressed. Still, it is to be noticed that Von Mises stress is generally maximum at the Al / W interface. This is illustrated in Figure 3.
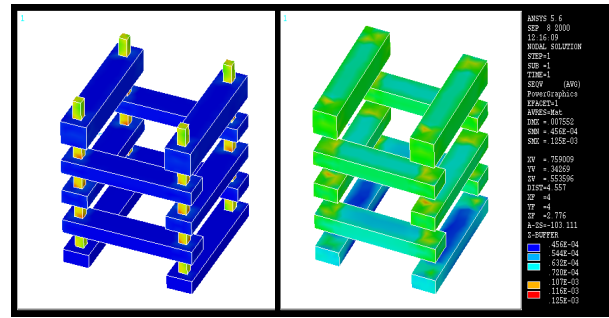

Figure 3: F.E. Modeling of the state of stress.
Result is given under compressive loading. Oxide is not represented. A unique motive ($8x8 \ \mu m^2$) can be modeled.
a) W vias + Al lines. Stress is maximum in the vias, at the interface with aluminium.
b) Al only. Stress concentration located at via interface.

Figure 3a shows the state of Von Mises stress in Al and W in pad F under compression load. Color mapping does not allow to observe the stress gradient in Al due to the difference in level of stress between Al and W. Hence Figure 3b is given, presenting for the same zone the same results for Al only, showing maximum of stress is clearly located under the pad.

Value for σ_{max} in W using nodal results is close to σ_{max} in W using element results. This reveals that gradient of stress in the via is rather smooth. When there are vias in the structure, tungsten being stiffer (elevated Young modulus) than other materials, the force applied (as a pressure) on top of the structure gives birth to high stress in the via. The cumulated sections of the via support a large part of the force and hence large stress appears. Results for I pad stands out of the lot with higher stress in W and Al and reduced stress in TEOS. This means that the metallic 3D grid formed by tungsten and aluminium support more efforts in this design. In terms of reliability, this seems interesting since metal/metal interface should be more resistant than oxide/metal ones. Still, before any experimental test, it is difficult to evaluate the consequence of the level of stress on the reliability. Our purpose consists in producing results that would help shading light on the experimental results and enable to determine potential weaknesses in design that shall be avoided in the final structure.

The following paragraphs extract information from the comparison of "neighbor" structures that were intentionally designed to test special aspects.

3.3 Alternate vs. Stack metal layers designs

This element can be assessed considering the results for the couples (F/K) and (J/N). Each couple gathers corresponding designs, F and J presenting alternate layers and K and N formed of stack metal layers.

It is clear that alternate layers tend to provoke a high level of stress in the via and a reduced one in the oxide.

3.4 Density of metal

This element can be assessed considering the results for (I/J) and (K/N). Each couple gathers corresponding designs, I and K presenting denser design than J and N.

Maximum of stress is higher in J as compared to I, maximum of stress is higher in N as compared to K. No influence is found on maximum stress in oxide which is left unchanged. So apparently the denser, the better.

3.5 Number of levels: level 5&6 only/all levels

This element can be assessed considering the results for the couples (B/A) (G/F) and (P/O). Each couple gathers corresponding designs, B, G and P presenting only the metal levels 1, 5 and 6 and the via 5.

Stress in the via is higher in B but stress in Al and TEOS is higher in A. Stress in the via is higher in G but stress in Al is higher in F. Maximum stress in TEOS is similar in F and G.

Stress in the via is higher in P but stress in Al is higher in O. Maximum stress is higher in P. With via at the fifth level only, stress gets higher in the via, but maximum stress is decreased in aluminium. No trend can be extracted for TEOS. This analysis shows that designs with levels of metal 1, 5 and 6 only present a more homogeneous state of stress, which is correlated with previous experimental data showing weaknesses for pads with level 5 and 6 only.

3.6 Via/no via

This element can be assessed considering the results for (A/C) (F/H) and (K/L). Each couple gathers corresponding designs, A, F and K with via and C, H and L without.

The comparison shows that maximum stress is much reduced in aluminium. This could be expected since the maximum of stress in aluminium lies under the via in the structures A, F or K. Nevertheless, in terms of general mechanical resistance, it is doubtful that a design without via to structure a metallic 3D grid may offer such a good resistance and a final judgement on the pad performances can not be pronounced without the analysis under shear stress loading. The density of metal is to be considered here as well: the denser the vias, the lower the stress in the vias.

3.7 Metal reinforcement

This element can be assessed considering the results for the couples (I/F) and (M/K). Each couple gathers corresponding designs, I and M with Al reinforcement and F and K without (e.g. Cx=Ex, see Figure 2). For this last couple, scale is slightly varying as well.

Results show that with reinforcement for I, maximum stress is increased in the via, decreased in aluminium and increased in TEOS. For M, maximum stress is unchanged in the via as compared to K. Results for aluminium and TEOS show that metal reinforcement induces a higher stress in Al, reducing by this mean the stress in TEOS.

Increased level of stress in the via with a reinforced structure of aluminium was expected, since reinforcement tends to raise the stiffness of the aluminium layer and leads to an increased resistance to deformation -and associated level of stress- in tungsten.

Effects of the reinforcement is at this state uncertain.

CONCLUSIONS

Structures with no via tend to present homogeneous state of stress, which means that maximum level of stress is low as compared to what is calculated in other designs. For those, given that tungsten is much stiffer than oxide, high level of stress are reached in the vias, and can be found as well in aluminium at the interface with tungsten. This location could possibly host delamination in tensile condition for instance. On the other hand, the more fragile material is probably the oxide, where it is then interesting to have the lower level of stress possible. In relation to this criterion, I architecture, with alternate layers, and high density of vias is interesting.

This analysis is restricted to results obtained under compressive loading conditions. Complementary results will be gathered in a further paper on a similar analysis realized under shear stress. Shear loading is expected to be more critical, and could then foster other design choices.

The present results have to be taken with caution since the modeling requires to make heavy assumptions. Characterization of materials yield stress is necessary to justify that simulations could be done using elastic laws. Still some trends have been extracted at the moment. When experimental failure analysis is available on those pads, simulation results should be useful to assess for resistance criterion and to optimize the design.

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