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Abstract
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RELIABILITY OF THE 3-D COMPUTER UNDER STRESS OF MECHANICAL VIBRATION AND THERMAL CYCLING

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ABSTRACT

This paper describes an assessment of the mechanical reliability of the 3-D Computer being developed at the Hughes Research Laboratories. The purpose of this reliability assessment was to gain confidence in the feasibility of this unique stacked wafer approach for space based applications. The investigation addressed via analyses and experiments, both the mechanical and thermal reliability.

INTRODUCTION

Recognizing the tremendous potential impact of high throughput signal and image processing computers, Hughes Aircraft Company has developed a new, special-purpose data processing concept — the 3-D (microelectronic) Computer (Figure 1a). This new idea in digital computing reorganizes the physical structure and the approach to parallel computing. The 3-D Computer concept consists of a large number of parallel processors ($10^4$ to $10^6$) in a cellular array configuration. A wide variety of computationally intensive applications can be performed by this processor with substantial system level advantages. Efficiently structuring a massively parallel processor requires interconnecting a large number of microelectronic chips containing densely packed circuits. Because of the enormous number of data lines ($10^4$ to $10^6$), a natural solution is the stacked wafer approach, with interconnections made in one-to-one topological correspondence. This is the approach taken by the 3-D Computer program at Hughes. The subject mechanical reliability assessment was undertaken to evaluate the feasibility of the stacked wafer approach for space applications. (Details on the architecture, technologies and the circuits of the 3-D Computer can be found in other papers at this conference.)

The 3-D Computer consists of an assembly of stacked wafers, as shown in Figure 1. Electrical signals pass through each wafer by means of specially processed feedthroughs, shown in Figure 2. The wafers are interconnected by means of microbridges, shown in Figure 3. A laboratory version of the 3-D Computer has been assembled and operated to conclusively demonstrate the feasibility of this approach.

Because mechanical failure of the assembly or its elements is likely to lead to electrical failure, the reliability of the 3-D Computer depends on its mechanical integrity. From a mechanical standpoint, the interwafer electrical connections of the 3-D Computer represent the largest departure from conventional microelectronic systems. (The intrawaffer communication channels are heavily doped regions in the silicon wafer and from a mechanical point of view do not represent anything different from conventional ICs.)
ARRAY OF PROCESSING CELLS ON EACH CHIP

1 - 2 MILS

-10 MILS

FEEDTHROUGH

SILICON CHIPS

INTERCONNECT

(a) Concept of the 3-D Computer

(b) 3-D wafer assembly

Figure 1. Hughes Research Laboratories 3-D Computer
MECHANICAL AND THERMAL ANALYSES

The finite element method of structural mechanics was employed to analytically evaluate the response of the 3-D Computer to environmental stressing. The finite element method is a well-proven tool for the thermal and vibration analysis of complicated structures. In order to control the complexity of the analyses, separate models of the test fixtures, wafer stacks, and microbridges were developed. These models were combined as necessary to achieve the desired objectives while minimizing computing costs. The analyses included natural frequencies of vibration, mode shapes, deflections, and stresses within the assemblies due to vibration and temperature variation. The structural analyses provided detailed dynamic and stress information that augmented the data obtained from the environmental testing.

Mechanical

Finite-element models (FEMs) of the 2- and 4-inch diameter wafer stack test fixtures were developed. The models included the top and bottom plates and the fixture spacers. The purpose of the analyses was to verify that the test fixtures were adequately designed for the proposed vibration testing and that they would support the wafer stacks without inadvertently damaging the stacks due to excessive flexibility. The analyses indicated that the fixtures were sufficiently...
rigid below the 2000 Hz upper frequency limit of the vibration tests, which was verified by the tests.

A finite-element model of a microbridge spring was developed in order to determine its load and deflection characteristics. These characteristics were used to develop simplified spring elements for incorporation into the wafer stack FEMs. Due to the large number of microbridges (4096), it would have been impractical and too costly to include each spring assembly in detail. Instead, one-dimensional spring elements were incorporated into the wafer stack models. Each spring element was assigned a stiffness equal to the combined stiffness of the microbridge assemblies which they replaced.

Finite element analysis of a microbridge spring yielded a stiffness of 17 lb/in. in the elastic range. Physical experiments conducted at HRL indicated an effective linear stiffness of about 0.4 lb/in. for microbridges having somewhat different geometry. The difference between these evaluations is primarily due to yielding of the springs (plastic flow) at deflections greater than a few microinches. In order to bound the problem, the dynamic analyses of the wafer stacks were performed using both extremes. That is, dynamic responses were predicted for wafer stacks having the smaller of the spring stiffnesses, and also for the case of the larger of the spring stiffnesses. Nonlinear analysis of the stress/deflection characteristics of the microbridges was beyond the scope of this task.

Finite-element models of the 2-inch and 4-inch diameter wafer stacks were developed to evaluate their response to the sinusoidal and random vibration tests. The FEM of the 2-inch stack is shown in Figure 4. The models included two-dimensional plate element simulations of the silicon wafers, and one-dimensional spring element simulations of the kapton spacers and the microbridge arrays. Boundary conditions were imposed that simulated the support provided by the test fixtures. The analyses included static 1-G responses, modal analyses to determine natural frequencies of vibration and their associated mode shapes, random vibration analysis, and sinusoidal vibration analysis.
Natural frequencies of vibration and their associated mode shapes were determined for both the minimum and maximum microbridge spring stiffness limits. It was found that the spring stiffness had little effect on the wafer stack frequencies of vibration. The fundamental mode of the 2-inch diameter stack occurred at 6818 Hz, which is well above the typical 2000-Hz cutoff frequency for environmental vibration testing. The fundamental mode of the 4-inch-diameter stack occurred at 1193 Hz. The significant drop in frequency is due to the larger unsupported area of the 4-inch diameter wafers. The lower natural frequency of the 4-inch diameter stack does not necessarily indicate a potential problem, but the resultant stresses and deflection due to vibration will be larger than those of the 2-inch diameter stack. A higher natural frequency is desirable but not necessary. (It should be noted that these analyses used a modulus of elasticity of 18 Msi for the silicon wafers. Furthermore, the fracture stress of the silicon was assumed to be 9 ksi, based upon references from the literature.)

A random vibration analysis was performed to evaluate the response of the 4-inch diameter stack since the larger wafers are more representative of future 3-D Computer applications. Furthermore, analysis of the 2-inch diameter stack would not have been worth while since the fundamental vibration mode was well above the random vibration input cutoff frequency of 2000 Hz. As such, the 2-inch stack would respond as a rigid body to the random vibration input. The maximum stress in the silicon wafers due to a random vibration input of 10 G rms was predicted to be less than 2 ksi, which would be well below the fracture stress. The maximum relative deflection between the wafers was found to be 1.3x10^-4 inch, which microbridges would tolerate without any damage.

A maximum acceleration response of 840 G was predicted for the 4-inch wafer stack with a 10 G sinusoidal input. This acceleration occurred at a 1193 Hz fundamental frequency of vibration. This acceleration response is reasonable for a distributed mass system having an assumed damping of 1 per cent (Q = 50). The peak silicon wafer stress of 4.2 ksi was below the fracture stress, and the maximum relative deflection between the wafers resulted in a tolerable value, 3.0x10^-4 inch.

**Thermal**

Thermal-stress analyses were performed to determine the effect of the vertical thermal expansion mismatch on the wafer stack, the lateral stress generated on the wafer stack by the materials with different thermal expansion characteristics, and the stress at the microbridge feet due to uniform, bulk temperature changes.

If the difference in the vertical thermal expansion characteristics between the stacked wafers and the fixture screws (Figure 1b) is substantially large, the microbridges between the wafers may separate from one another resulting in failure of wafer-to-wafer electrical connections. The maximum thermal mismatch values were estimated to be 5x10^-5 and 1x10^-4 inches for 2-inch and 4-inch wafer stacks, respectively. These differences can be easily resolved by the use of the spring plungers which can accommodate the thermal expansion differences.

The lateral thermal expansion mismatch is more serious than the vertical one because of the larger dimensions. However, the overall expansive interaction between the bottom molybdenum fixture plate and silicon wafers was found to be negligible because of the close match of the thermal expansion coefficients and the diamond shaped alignment pin which facilitated the expansive relief (Figure 1b). The thermal expansion mismatch between the wafer unit (silicon wafer and tungsten-steel tab) and the molybdenum plate would produce the maximum differences in expansion of 5x10^-4 and 1x10^-3 inches for 2-inch and 4-inch stacks, respectively. These thermal mismatches would generate maximum stresses of 1.5 and 2.0 ksi. (In this calculation, we assumed both alignment pins were round for simplicity. But in reality, due to the diamond-shaped pin, the actual stresses would be less than the predicted ones.) The preliminary thermal stress experiments showed that the lateral stress was localized in the epoxy between the tungsten and steel tab spacer. Even if all the lateral stress is focused on the
tungsten-steel bonding epoxy, since the shear strength of the epoxy used is 2.6 ksi, no structural failures due to the lateral thermal stress is expected, which is proven later by the experiments.

The microbridge foot was analyzed as first-cut approximations based on strain compatibility through the thickness for rigidly bonded stiff joint materials. The results indicate that stresses in the silicon will be negligible, although there may be some yielding of the ductile deposition materials. These results do not include nonlinear or edge influences which will be present. To obtain a better understanding of the multilayer thermal interactions, solid finite element modeling should be pursued.

VIBRATION AND TEMPERATURE CYCLING TESTS

Two wafer stacks were used in these experiments:

- two 3-wafer stacks of 2-inch diameter wafers consisting of 32x32 arrays of feedthroughs and microbridges, but no circuits. Figure 1b shows the assembly of the 2-inch wafer stack. The housing of the assembly consists of the top molybdenum plate and the bottom molybdenum plate which are connected via bolts and spacers. The spring plungers located in the top plate press the stack with a known force against the bottom plate so that the wafer stacks are captured between the aluminum plate and the bottom plate. The function of the aluminum plate is to distribute the plunger loads over the surface of the top kapton spacer in order to prevent local load concentrations.

The electrical continuity of the microbridge contacts through the stacks were tested before, while, and after the stresses were applied. Each resistance measurement signal passed from the bottom of the bottom wafer to the top shorting layer of the top wafer and back to the bottom wafer including six feedthroughs, eight microbridges, and a shorting layer (Figure 5). This shed light on the mechanical and thermal reliability of the microbridges and the assembly structure.

- a 3-wafer stack of 4-inch diameter wafers that did not include any feedthroughs, microbridges, or circuits. The construction of the 4-inch wafer stack was similar to that of the 2-inch wafer stack without the PC board.

The experiment on this stack revealed the mechanical and thermal properties of the assembly fixtures of a size that would be more realistic as a deployable system.

The assemblies were subject to the thermal cycling test:

- limits of temperature: -55°C to +125°C
- rate of change of temperature: 15°C/min
- dwell time at temperature extremes:
  - 4-inch wafers: 3 min.
  - 2-inch wafers: 8 min.
- number of cycles: 10.

The sinusoidal vibration test involved:

- number of axes: two
  - one perpendicular to the wafer plane
  - one parallel to the wafer plane
- level: 3 steps up tp 10 G (2G, 5G, 10G)
Figure 5. Each resistance measurement path.

Figure 6. Random vibration spectrum curve.
The random vibration test consisted of:

- number of axes: two
  - one perpendicular to the wafer plane
  - one parallel to the wafer plane
- spectrum: per curve in Figure 6
- duration: 1 minute at 3 dB below this level, 1 minute at this level, and 3 minutes at 3 dB above this level.

RESULTS AND DISCUSSION

Post-test visual inspections of the assemblies revealed no mechanical failures of the silicon wafers, the tabs and tab bonds, or the stack assembly support structure. This result agrees with the predictions of the structural analyses. The electrical continuity measurement revealed 1.4% increase in resistance of eight microbridge and six feedthrough system indicating excellent bridge contacts even after the stresses were applied. The pre-test resistance values varied from 132 to 341 ohms, with a mean of 146 ohms. After the environmental stresses, the resistance values ranged from 133 to 298 ohms, with a mean of 147 ohms.

No failures occurred as a result of the applied thermal and vibration environmental stresses. The interpretation of this result requires care, because the 3-D Computer is in an early stage of development and thus cannot yet be expected to be flightworthy. Therefore, any failures would not have proven that the assembly is mechanically unreliable, and the absence of failures does not prove that it is reliable. However, one can conclude that the concept is sufficiently promising to allow its productization to continue.

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