Vibration-induced Fatigue Failures in Bonding Wires Used in Stacked Chip Modules

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Abstract

An instrument recently constructed for Goddard Space Flight Center involved stacked chip memory modules having about six thousand 1 mil gold wires, each between 4.6 mm and 6.1 mm long. Four of these bond wires fractured during the final box-level random vibration test which had spectral power to 850 Hz. Investigation determined that these wires have fundamental resonant frequencies in the range from 1.4 kHz to 2.3 kHz, with quality factors up to 300, when the bonds at each end are rigid. However, a nearly severed top bond decreases the lead's fundamental frequency to the range 600 Hz to 750 Hz. The lowered mode is strongly excited by the box-level vibration test, leading to fatigue-fracture of that already weakened bond during the several minutes of the vibration test. However, such a lowered mode would not be excited by previous shock and vibration tests, since these happened to have no spectral power in the region from 600 Hz to 750 Hz. An unfractured 1 mil gold wire was still intact after 12 days (1.4 billion oscillations) at 1.4 kHz at a root-strain of 0.2%, while several (deliberately) nearly fractured wires failed after less than a minute (less than 41,000 oscillations) at 680 Hz at the same drive stress.

Key words: resonance, fatigue, fracture, wire bond.

Introduction

Goddard Space Flight Center is developing solid state recorders to augment and possibly replace tape recorders used in spacecraft. A solid state recorder is a computer with 10 or more gigabits (Gbit) of random-access memory, interfaced to the spacecraft's data-collection, transmission, and command centers. DRAM of good commercial heritage is used, and special attention is given to ensuring radiation-tolerant behavior; this includes robust error sensing and correcting circuits. The DRAM is a commercial stacked chip design that has steadily evolved in complexity as experience has given increased confidence in the basic design. The units chosen for a recently developed solid state recorder (hence called SSR) achieve 320 megabits (Mbit) per module; this involved increasing the height of each of the two die stacks per module to 12 die. The memory chips used in the modules are each 16 Mbit, giving 384 Mbit per module; this allows defective elements (if any) to be masked out and still attain the specified 320 Mbit, increasing the yield. Higher density chips are available, but their radiation resistance is lower at this time. There are 72 modules in the SSR, for a total of 23 Gbit.

The modules passed space flight quality screens, including an acceleration of 5,000 G's. The SSR passed a box-level sine burst test: 20 G's at 20 Hz for 1.6 seconds. However, the SSR no longer functioned after a random vibration test of 6.0 G(rms) with spectral power extending to 850 Hz. This random vibration test is an accurate predictor of some of the stresses that are imposed on the SSR during launch; thus, it was necessary to identify the root cause of the failure, and to fix it.

Investigation

The failure was traced to four of the seventy-two DRAM modules: three had failed with an electrical signature pointing to an open bond wire that is supposed to connect a pad at the top of the stack to the substrate bonding platform of the module. The fourth demonstrated an intermittent during random vibration only. De-lidding the modules confirmed that each had a stack wire that was ruptured at the top bond: the stack wire was electrically disconnected at the top end. The intermediate behavior was caused by sporadic shorting of a stack wire against a neighbor; the local geometry around the other three broken stack wires precluded shorting.

Each module contains 80 stack wires (40 per stack) of 25.4 μm (=1 mil) gold wire, bonded to gold pads on a tungsten subpad. While there are other wire bonds within the module, they were all flaw-free and will not be discussed; in the following, "wire" refers to the stack wire only. There are a total of 5760 wires in the SSR modules. The wires used in these modules are unusual in two respects. Most crescent bonds used in microcircuit applications are located at the package- (or substrate bonding platform-, if a platform is used) end of the wire, and the ball bond is located at the chip. However, the conventional bonding order was reversed in order to provide extra clearance at the package lid for these memory module stack wires: the ball bond is at the package and the crescent is at the top of the die stack. In addition, because of the height of the stack, the wires are much longer than in typical microcircuit applications -- approximately 5.0 mm here, versus the typical 1.0 to 1.5 mm. Thus, the ratio of length to diameter is approximately 200 here, versus the typical 40 to 60. This breaks the usual rule that the ratio of the length to the diameter should not exceed 100. This extreme length happened incrementally as a result of gradually extending a successful design by adding additional die to the stack.

A scanning electron microscope was used to examine a total of about 100 crescent bonds, some from each of the four modules. The bonding pads were oval in shape, with a very rough granular surface; the valley-to-peak distances were roughly a quarter to a half of the diameter of the wire. Near the center of each pad was a cavity created by incomplete filling of the via between the top layer and the inner layers. Every examined bond showed a bond tool impression on the pad adjacent to the crescent bond, which is evidence of overcompression. Further, many of the crescents were wider and thinner than those regarded as ideal. This thinning was localized to the inside edge of the #2 chip stack in each module. Consultation with the company that carried out the bonding established that the wire bonding machine had been slightly out of alignment at the time, and did not apply the same pressure to all pads. Inspection of the alignment is now part of their daily procedure.

There were seven crescent bonds (7% of those examined) that were either partly lifted from the bonding pad, or both lifted and torn for about a quarter to a third of the width of the crescent. Tearing happened when three situations coincided: (a) the crescent bond happened to be placed directly over the via-cavity, (b) the roughened surface also placed an irregularity at one edge of the crescent, and (c) the bonder's pressure was higher than usual. Thus, there is a degree of randomness to the extent of a tear in the crescent bond.

Computing the resonant frequencies requires mapping the shapes of a number of these jumpers: see FIGURE (shapes of the wires). We used a 200X microscope with a 3-axis micrometer stage. The bonding pads on the top die caps alternate in position: the first is near the edge and the second is more distant (etc.). This results in alternating long and short wires. Further, some of the short wires have a low loop, barely clearing the edge of the die stack, while the rest of the short wires have a high loop. Thus, there are three classes of wires, based on length and shape. There is no analytic treatment possible for the shapes of these wires, but there is a complete analytic treatment for the n th resonant mode of a straight beam, under various end conditions. For example, the n th modal frequency is $f_n = [(k_n L)^2][d/L^2][Y/\rho]^{1/2}$, where d is the diameter of the wire, L is its length, Y is the Young's modulus, ρ is the density, and $(k_n L)$ is a dimensionless number that depends on the mode number n=1,2,3,…, and especially on the end conditions. We are only interested in the case of a rigid bottom bond rigid: this is called a "clamped end" in beam theory. We consider the case in which the top bond was also rigid; then $(k_1 L)$=4.73. And we consider the case in which a fracture is so nearly complete that it acts as a hinge: this called a "fixed end" or a "hinged end"; then, $(k_1 L)$=3.93. Hence, the frequency of the lowest mode of a straight beam with a hinged top is 69% that of the beam with a rigid top bond. (The decrease is larger for the shapes of the bond wires.) This equation acts as a guide, even when the beam is bent. For example, it illustrates that the modal frequency is proportional to the wire's diameter, and, thus, will vary over a family of bonds in the same way that the wire's diameter does, some ± 5%, using a typical specification. On the other hand, a 5% increase in the length will decrease the modal frequency by 10%. Since there is no analytic treatment possible for shapes like the ones of FIGURE, we used finite element analysis (FEA) which allowed computation of the frequencies and shapes of the lowest several modes within a few seconds; the most time consuming part was detailing the shapes.

We made direct measurements of the resonant frequencies of a number of the wires. A particular wire was selected and a small magnet was positioned directly in front of it. Microprobes were placed onto the top and bottom pads, and connected to an audio oscillator, to pass a current $I=I_0 \sin(2\pi f t)$ through the wire. This imposed the force $F = L \times B \times I(t)$ on it. The direction of the force is perpendicular to the wire and to the magnetic field, and so was parallel to the long axis of the stacked chip array. This bends the wire sideways, and will excite its fundamental mode when the frequency is correctly adjusted. In effect, this turns the wire jumper into a linear electric motor, a kind of miniature loudspeaker. The magnet provided a field of about 500 gauss at the wire, while the current ranged from 1 mA to 50 mA: these produced forces comparable with the weight of the wire. The wire was observed using a 40× microscope, and the frequency of the oscillator was adjusted until the wire was seen to oscillate. The agreement between the computed and measured frequencies was within 15%, which is within the expected margins, given the variability of wire diameters and especially the uncertainty of measurements of wire shapes. The longest wires resonated at 1.4 kHz, the high-looped short wires at 1.9 kHz, and the low-looped short wires at 2.3 kHz.

The quality factor of a vibrating system is defined in various ways. One definition is a measure of the sharpness of the resonance, $Q = f/\Delta f$, where Δf is the full width between the half power frequencies. Another is a measure of the time τ that the vibration takes to decay to 1/e of its original amplitude when the exciting force vanishes: $\tau = \pi Q/f$. Still another is a measure of the amplification that the amplitude of the oscillation shows at resonance A_{res}, over its value at much lower frequencies A_0: $Q = A_{res}/A_0$. We directly measured the full-width between the half-power points, finding $Q \approx 100$ to 300. This predicts that the wire continues to vibrate for 20 ms to 60 ms, which is consistent with observations: the onset of oscillation when the current is suddenly applied, and its cessation when the current is suddenly terminated, was just noticable. The source of this damping is the viscosity of the air in which the wire moves: these are hermetically sealed parts. If the air were removed, the quality factor would increase dramatically; the next source of energy dissipation is "Zener damping," and is much weaker. The FEA computation shows that the magnetic forces we applied to the wire should cause a displacement of about 0.01 to 0.1 wire diameters when $f << 1$ kHz: this is below our detection limit using the 40× microscope. However, this displacement is expected to increase at resonance by the quality factor (= amplification factor) into the range of 1 to 30 wire diameters. We observed displacements up to 20 wire diameters (single-sided deflection), which is consistent with these estimates.

We set one wire into oscillation with a peak-to-peak amplitude of 10 wire diameters and checked its motion every few minutes for two hours. The initial resonance frequency was 1.40 kHz. This dropped to 1.38 kHz at the end of the two hours, after which we terminated the driving current. We had established that these wires could endure the stresses applied during a vibration test that excited resonance; these 1.0×10^7 oscillations had not induced fracture or even much fatigue. We repeated this study using a different wire, with an initial resonance frequency of 1.41 kHz, and a peak-to-peak amplitude of 10 wire diameters. The resonance frequency dropped to 1.36 kHz over a twelve day period, after which we stopped the observations. The wire had sustained 1.4×10^9 oscillations without fracturing, and without much fatigue. See FIGURE showing top-down view of vibrating wire, and FEA-fit, and root strain. This was repeated using a wire whose crescent bond was deliberately cracked (the width of the crack was 50% of the width of the crescent): the resonant frequency dropped by a few percent, and the wire sustained several hours of vibration without breaking. This was repeated, with the same result. The fatigue lifetime of a cracked crescent is expected to be substantially shorter than that of an uncracked bond. Some 80% to 90% of a given cycling history is spent creating an infant crack, while the remaining 10% to 20% is spent extending that infant crack into a complete rupture. However, a lifetime of even 10% of 2 billion cycles will allow the wire to pass the box-level test. This demonstrated that wires with even half the crescent uncracked would not fracture due to stress, or to fatigue, during a vibration test which lasts for minutes (not hours).

We then deliberately induced a near fracture (90% to 95%) in a crescent bond. This lowered the resonance frequency to 680 Hz, and, with the usual drive current, the fracture developed into a complete rupture within one minute. We repeated this using a second wire and found the same result. Therefore, a nearly severed crescent bond reduces the rigidity of the top bond to the point that it acts as if it were hinged (not clamped); and the lifetime under the imposed vibration stresses is less than a minute, for the stresses we imposed.

We used FEA to compute the fundamental frequency of a wire that had such a large crack that it was effectively not clamped, but hinged. For the longer wires, this was some 600 Hz, in general agreement with the observations. It was up to 750 Hz for the shorter wires. (While the crack will absorb energy from the mechanical vibrations while it is growing, this is a small effect. The main energy loss is controlled by the viscosity of the air, and this loss drops with the frequency; thus, the Q may double.) Such a cracked wire could be driven into resonance during a vibration test with enough spectral power in this range, and the wire would not survive long since it would be nearly cracked through already; rather, the crack would rapidly extend into a complete rupture. This is consistent with our observations of the behavior of the pair of deliberately cracked wires.

Interpretation

We suppose that the four wires (out of 5760) that broke during the box-level random vibration test were initially nearly fractured. Their fundamental resonance was in the range 600 Hz to 750 Hz, their quality factor was larger than 200, and they absorbed sufficient energy during the box-level test to rupture during the duration of that test. The presence of such cracks is suggested by the observation of partial cracks in 7% of the crescent bonds later inspected. We did not see deeper cracks, but we suppose that all the nearly complete cracks were broken by the vibration test. We would have to inspect some 10,000 crescent bonds in unstressed modules in order to be sure of finding between 4 and 8 such fractures.

We now show that such cracks would not have been detected by the tests the modules passed previously.

- We need to ensure there is no conflict between passing all electrical tests before the box-level random vibration test, and having a wire with a deep crack. The resistance increase ΔR of a rectangular conductor, which is a model for the wedge section, with a width a and thickness b, due to a crack of depth c normal to one side, relative to the resistance R of the rest of the wire (of length L and diameter d) is $\Delta R/R = - [(d^2)/(b L)] \ln[\cos(\pi c/2 a)]$. For any wire, 200 diameters long, with a wedge that is 1/4 of a diameter thick, this relative increase remains less than 10% so long as there is 0.4% of the wedge left uncracked. That is, the crack can extend for 99.6% of the width of the wedge bond, and only increase the total resistance of the wire by 10%. This happens because the crack only changes the current flow through the wire within about a diameter's location of the crack, and so only the resistance of that segment is changed, while the resistance of all the rest of the wire is not changed. And these wires are some 200 times longer than their diameter. Thus, the presence of wires with initial cracks extending nearly the entire width of the wedge bond would not interfere with electrical behaviors.
- How large can the crack be and still survive after a steady acceleration of 5000 G's? The force was applied in such a way as to lift an improperly attacked die stack. Thus, most (about 90%) of the force was carried by the bottom ball bond, which were all made correctly. Therefore, each ball bond could sustain 5 to 10 grams of force (= 450 to 1000 dynes), or at least the force developed by 10^5 G’s acting on a 5 mm length of wire. This is twenty times the applied acceleration, and so the ball bonds will carry this load safely. The remaining force (about 10%) is carried by the wedge bond: this force is about 25 dynes at 5000 g's acceleration, or 0.03 grams of force. This can be carried so long as a few percent of the cross section of the wedge bond is intact.
- The SSR operated correctly after a sine burst test in which 20 Hz at 20 g's was applied for several seconds. We do not have proper fatigue lifetime data for the gold wires used for these wire bonds. Therefore we cannot compute the maximum size for a crack that would just survive this test. However, we note that the frequency used in this test is much lower than any resonance, and so it is effectively a static test for the wires. Therefore, the amplification factor was unity for this test. Thus, the sine burst test was at least an order of magnitude less severe than the random vibration test.

We found that essentially identical multichip modules had been created and were being used elsewhere. These modules had identical failures during vibration testing that was similar to ours. The character of the fractures were identical.

Conclusion

The failure of the instrument was caused by two factors, neither of which would have alone produced a failure. The bonding process occasionally (about 7 per 10,000) produced a nearly cracked wedge bond, when pad-features coincided with an especially thinned wedge bond. This dropped the resonant frequency into the range in which box-level random vibration test spectrum excited the fundamental resonance, and thus applied an unusually high stress to the nearly cracked wedge bond, quickly extending it into a complete rupture.

These nearly cracked wedge bonds may not rupture in "normal" practice: this depends on the stresses encountered in that "normal" practice and on the service life. However, such bonds are not as reliable as spaceflight practice calls for, and it is prudent to eliminate any such bonds. The vibration test did this on the original version of the SSR, and we repeated it on the repaired version. We took care to ensure that this test used levels that were distinctly higher than the instrument would see during launch and during service, so that this test would serve as a "proof test," eliminating any nearly cracked wedge bonds, but not leaving an incipient failure. The instrument has been in service since February 1997, and is operating correctly.

Back to Library

Back to TVA Homepage