EVALUATION OF SOLDER BONDS IN A SILICON FLIP CHIP DEVICE

Edward L. Ginzton Laboratory
W. W. Hansen Laboratories of Physics
Stanford University
Stanford, California 94305

INTRODUCTION

Recently we adapted two nondestructive testing techniques for the evaluation of electrical connections between a silicon device wafer and an inverted silicon interconnect chip. We used a focused acoustic microscope to check the mechanical quality of the connections, and a photothermal probe to measure their electrical conductivity. With the combination of these two techniques, we can differentiate between good bonds, partial disbonds, and complete open circuits. We can also determine the type of disbond.

THE DEVICE

The device is shown in Fig. 1. The wafer and the four interconnect chips are bonded together by hundreds of 100 µm diameter solder bumps. The bumps are connected electrically by a stitchwork pattern of conducting films. These particular devices are used to test the manufacturing process which consists of depositing matching sets of bumps on both top and bottom wafers, aligning the wafers, pressing, and heating. After construction, a means is needed for locating the regions of poor contact. It is also desirable to know whether a disbond is due to the two halves of the bump making poor contact to each other or to one of the bumps being pulled away from the substrate.

The small size and high density of the solder joints, as well as the thick wafers of silicon that obscure them, make this a particularly difficult sample to image. Any imaging system must be able to penetrate the silicon and retain adequate resolution at the solder bump interface. This requirement is especially critical in the case of thermal imaging where effects from the various bumps would be overlapping and severely attenuated at the outer surfaces of the device.

ACOUSTIC MICROSCOPY

The mechanical properties of the solder bumps were evaluated acoustically. We used a 50 MHz focused acoustic microscope operating in
Fig. 1. Schematic of the device. (a) Top view with one interconnect chip removed showing the solder bump pattern. (b) Side view.

water to image the interface between the silicon and the solder bumps. Basically, the technique consists of driving a planar transducer at one end of a buffer rod and focusing with a spherical lens formed in the other end of the rod. In order to go through the thickness of the silicon (500 μm), it is necessary to have a lens with a focal distance of at least 3.0 mm in water, since the longitudinal velocity of the acoustic wave is six times greater in silicon than in water. Also, in order to get the maximum signal into the silicon, the lens has to have a large F-number so that none of the incident energy exceeds the critical angle for total internal reflection.

In a standard acoustic microscope, the signal from the plane of interest, the silicon-solder interface, is mixed with the signal from the silicon-water interface. We found that for this problem, it was possible to time gate the silicon-water interface signal from the silicon-solder interface signal. Consequently, only the signal from the solder bump interface was detected, and its amplitude was used to modulate the intensity of the display. Thus, the microscope is used more like a focused C-scan imaging system, but with an rf tone burst excitation instead of a broadband pulse excitation.

With the silicon samples being accessible from the back side only, it was necessary to deal with the problem of the surface roughness on the back side of the wafers. If the microscope is used in the mode where
the outer surface signal is mixed with the signal of interest, the roughness problem would be severe enough to prevent us from getting any meaningful data. Because we use the instrument in a modified focused C-scan mode, however, it is possible to obtain images without any special data processing. Still, our images were much clearer when the silicon wafer's back side was polished to accommodate the thermal probe measurement.

Figure 2 shows the result of a test of the two sides of a flip chip. The rows of solder bumps are very clear in this test pattern. On one side (Fig. 2a), all the solder bumps are clearly visible as small dark circles where the acoustic reflectivity is low. On the opposite side (Fig. 2b), however, it is clear that a large number of bumps are

Fig. 2. Acoustic images of the solder–silicon interfaces.
completely disbonded. In this image, we see that only the outer row of solder bumps makes good contact. The results are very conclusive and very promising as to the potential of this method for detecting disbons at the solder-silicon interfaces. We expect that an amplitude and phase measuring microscope at twice the frequency (100 MHz) would be capable of giving higher resolution pictures of the solder bumps and the location of the disbons. We estimate that the location of the disbons can be detected in the phase portion of the images.

PHOTOTHERMAL MEASUREMENTS

While the acoustic microscope can locate complete disbons, it cannot differentiate between good bonds and partial disbons. These types of flaws are likely to develop into short circuits at a later time. However, poor bonds can be identified by their low electrical conductivity. We measured the conductivity by measuring the heat generated by an AC current passing through the bumps.

The temperature was measured with a recently-developed photothermal probe. The probe senses periodic changes in the optical path of a laser beam caused by periodic heating. A schematic of the probe is shown in Fig. 3. The light from a semiconductor diode laser is split into two components by a birefringent Wollaston prism oriented at 45° to the direction of polarization. These beams emerge angularly, separated by 0.5°, and are focused to two spots on the sample. One beam is focused onto an unheated region of the sample to serve as the reference while the other is phase modulated by the periodic thermal expansion and contraction of the heated material. The reflected beams retrace their paths and interfere on the photodiode, yielding a current of the form

\[ I = \eta P_0 [1 + \cos(k\Delta L) + \sin(k\Delta L)2\phi \cos \omega_s t] \]  

where \( P_0 \) is the optical power in each arm, \( \eta \) is the conversion efficiency of the detector, \( k \) is the optical wave number, \( \Delta L \) is the static path length difference between the two beams, and \( \Delta \phi \) and \( \omega_s \) are the magnitude and frequency of the phase modulation.

Fig. 3. Schematic of the photothermal probe.
A number of subtle features of this probe allow us to achieve sensitivities down to the limit of the shot noise of the laser beam. Both beams pass through the same components, making the probe resistant to mechanical vibrations. Further vibration resistance is gained by placing the reference beam on the sample near the sensing beam so that generated acoustic waves, which have much longer wavelengths than the thermal effects, affect both beams in unison. Finally, by using a Wollaston prism as the beam splitter, the two beam paths can be made nearly equal in length, removing phase noise effects of the light source and allowing the use of semiconductor lasers. These types of lasers can deliver light with a very stable intensity, but would normally be inappropriate for interferometry because of their poor coherence.

The shot noise at the detector is given by \( 2q\eta P_0 R_L B \) where \( R_L \) is the load resistor and \( B \) is the bandwidth in Hz. By comparing this expression with the current equation, we see that the minimum detectable phase shift is

\[
\Delta \phi = \sqrt{\frac{qB}{nP_0}}
\]

For a 1 mW probe beam and \( n = 0.55 \text{ mA/mW} \), \( \Delta \phi_{\text{min}} = 1.7 \times 10^{-8} \sqrt{B} \) radians.

When measuring surface temperatures, the optical phase shift is caused by the periodic thermal expansion of the heated sample. However, for reasons mentioned earlier, surface measurements would not be appropriate for this sample. Therefore, we used a 1.3 \( \mu \text{m} \) wavelength probe beam, which passes through silicon, to view the solder bumps directly. In this configuration, the optical phase shift is generated mainly by the change in the refractive index of the heated silicon. This effect is about ten times greater than that of the thermal expansion and very small AC temperatures can be detected. For example, the diffusivity of silicon is 13.3 mm/\( \sqrt{\text{W}} \) and the refractive index changes by \( 1.5 \times 10^{-4}/\text{oC} \) so that with a 20 kHz heating current, the thermal resolution is about 25 \( \mu \text{m} \) and the minimum detectable solder bump temperature is \( 2 \times 10^{-4} \text{oC} \). Hence, excessive currents are not required to generate a detectable signal.

The results of a thermal scan are shown in Fig. 4. This is a view of the outer row of bumps along one side of the device (top row in Fig. 2b). There are 24 bumps in this region, of which the 7 at the left side are not visible because their electrical resistance is too low to generate enough heat. Of the 17 remaining bonds, two in particular stand out, being about ten times hotter than the others. Note that in the acoustic images, all 24 bumps look the same.

Information about the depth of a flaw can be gained by looking at the thermal signal as a function of frequency. As the heating frequency increases, the signals due to disbonds below the silicon-solder interface (for example at the junction of the two halves) will attenuate more rapidly than those due to surface defects. Figure 5 shows two thermal images of the region around the hot bump in the center of the row. The signals from the three bumps located at -300 \( \mu \text{m} \), 0, and +300 \( \mu \text{m} \) vary inversely with frequency, implying a surface defect, while the flaw at the edge of the hot bump, at 100 \( \mu \text{m} \), decays more rapidly, indicating that it is located below the surface. Figure 5a was taken using a 20 kHz heat source and Fig. 5b using 40 kHz. At 80 kHz the side bump is completely gone. These plots also demonstrate the high resolu-
Fig. 4. Thermal image of a single row of bumps heated electrically.

tion of the photothermal probe; the probe spot size is on the order of a few micrometers.

The phase of the thermal signal relative to that of the heat source also carries depth information. If the source of the heat is not coincident with the point of detection, there will be a phase lag between the two associated with the thermal wave travel. Figure 6 shows one example where the phase lag implies that the flaw is 20 μm away from the probe spot (the gap between the two substrates is 40 μm). Through a combination of these two techniques, we were able to determine that the majority of the disbonds were at the solder-silicon interface. This agrees with what we see in the acoustic images.

CONCLUSION

We have demonstrated two nondestructive techniques for evaluating the quality of solder joints in flip chip devices. Both techniques circumvent the major difficulty of imaging these devices, which is the fact that the bonds are obscured by the silicon wafers. The acoustic images clearly show where the bumps have pulled off of the substrates, while the photothermal technique is useful for evaluating bonds that make incomplete contact. We were also able to determine that the major source of disbonds was the solder bumps being pulled from the silicon as opposed to the two halves making poor contact.
Fig. 5. Thermal image of a small region around the hottest solder bump. Adjacent bumps occur at +300 µm and -300 µm.

Fig. 6. Phase of the temperature at the silicon-solder interface relative to that of the heating current.
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REFERENCES