A Novel Approach to Identifying and Validating Electrical Leakage in Printed Circuit Boards through Magnetic Current Imaging

Craig Hillman

Originality and Novel aspects of this paper
(for reviewer's benefit only, this will be removed in the final manuscript)
This paper describes the use of magnetic current imaging to isolate a plane-to-plane short in a printed circuit board. The sensor used for the magnetic current imaging is a SQUID. This technique is realtively new, but the real novel application here is the use of the tool for validating the presence of current in the defect ***after*** *cross-sectioning. In this example, the electrical connection of the defect was not able to be proved after coss-sectioning without the use of the SQUID to show that current was present in the defect. This is a completely new approach to the use of magnetic current imaging, which has previously been used solely for fault isolation before physical failure analysis.*

Introduction

While failures due to electrical opens in printed circuit boards can require innovative techniques to determine their root-cause, it is relatively unproblematic to locate the failure site through a series of electrical measurements. Electrical shorts are much more problematic. In addition to being more difficult to pinpoint because they can be located over a much wider area, their intermittent behavior can result in halting progress.

Magnetic current imaging using a superconducting quantum interferance device (SQUID) is a radically new technique that uses detection of magnetic fields to image current paths within electronic devices. This technique has been successful in non-destructively identifying the location of low leakage currents, even when the failure site was between a power and ground plane (roughly equivalent to finding a needle in a haystack). The use of low voltage and low current is vastly superior to thermal imaging, which often results in irreplaceable damage to the failure site and masking of the true root cause of failure.

In this case study, the customer was experiencing ignition of a 20-layer printed circuit board after approximately 1000 to 4000 operating hours in an indoor-controlled environment. High currents on the board resulted in extensive damage, effectively preventing initial identification of the failure site, failure mechanism, or root-cause.

Failure Mechanism Identification

A thorough approach to failure analysis, involving the identification of the failure mode, failure site, and failure mechanism, was used to isolate the root-cause of the ignition. The failure modes identified with burning are an electrical short or excessive heating.

All field failures originally occurred in fully-populated assemblies. While this implied that the original failure site could have been at the component level, accelerated tests on bare boards demonstrated shorting between power and ground. Assuming that the accelerated tests are triggering the same failure mechanisms seen in the field, the results suggested that the root-cause that was internal to the board and was not function of component failure. This narrowed further examination to electrical overstress (EOS), electrochemical migration (ECM), and conductive filament formation (CFF)

Based upon a methodical review of potential failure mechanisms, construction analysis, and accelerated testing, traditional failure mechanisms and root-causes did not seem to provide adequate explanation for the observed failure behavior.

Failure Analysis

Resolution required actual physical identification of a failure site. Unfortunately, this was hindered by the large area covered by the power and ground planes, which made identification of the failure site using functional or parametric testing virtually impossible. Visual inspection was also difficult due to the absence of a controlled burn area. The high glass transition temperature (Tg) of the dielectric material, 180^{o}C, made it relatively resistant to high temperatures. The temperatures necessary to ignite the material were so high as to result in thermal runaway. The effect was binary: failed boards had either no visible charring or had large areas of the board severely burned, with any evidence of root-cause destroyed. Either case tended to hide the physical object causing the electrical short.

This behavior also prevented use of thermal imaging, because the energy required to dissipate sufficient heat also tended to result in damage to the failure site. The initial solution was to modify a procedure used to identify very small voids that bridge multilayer ceramic capacitors (MLCCs) and cause current leakage. The resistance between a power and ground pin were monitored as the board was sectioned. Using a binary approach, the potential failure site was narrowed to a relatively small area. This area was very slowly ground and polished until a change in resistance was observed. At this point, large angular particles were observed in the cross-section.

There were two problems with this initial approach. First, considering the size of the board and the corresponding internal power and ground planes, the time required to find the short was time consuming. In addition, visual observation could not conclusively determine if these particles were the cause of the conductive path between power and ground, especially given the absence of a detectable conductive filament. More rapid and conclusive identification of the shorting path required the use of magnetic current imaging with a SQUID sensor.

Magnetic Current Imaging

Magnetic current imaging with a SQUID sensor is a sensitive near-field imaging technique. This technique can image buried current-carrying wires by measuring the magnetic fields produced by the currents, or it can be used to image fields produced by magnetic materials. By mapping the current in an integrated circuit or a package, short circuits can be localized and designs can be verified to ensure that charge is flowing where expected. The system used for this work was a Neocera MAGMA-C10, which uses a high temperature SQUID with a sensitivity of 20 picotesla or two million times smaller than the Earth's magnetic field. The sensitivity is high enough to image currents as small as 600 nA at a 100 µm working distance with 30 ms averaging.

During non-contact imaging of room temperature samples in air, the system achieves a raw, unprocessed spatial resolution equal to the distance separating the sensor from the current, or the effective size of the sensor (~30 microns for a standard SQUID tip), whichever is larger. To best locate a short in a buried layer, however, a Fast Fourier Transform (FFT) back-evolution technique can be used to transform the magnetic field image into an equivalent map of the current in an integrated circuit or printed wiring board. The resulting current map can then be compared to a circuit diagram to determine the fault location. With this post-processing of a magnetic image and the low noise present in SQUID images, it is possible to enhance the spatial resolution by factors of 5 or more over the near-field limited magnetic image. This enhanced resolution describes how well a scanning SQUID microscope can resolve current paths in a sample. The system's output is displayed as a false-color image of magnetic field strength or current density (after processing) versus position on the sample.

The results from performing SQUID microscopy on a shorted board are displayed in Figure 1. The bright yellow area on the current map corresponds to the area of highest current density. This is representative of necking down of the conductor path, which is often a strong indication of an electrical short. Cross-sectioning of the board was performed at this location based upon the SQUID image.

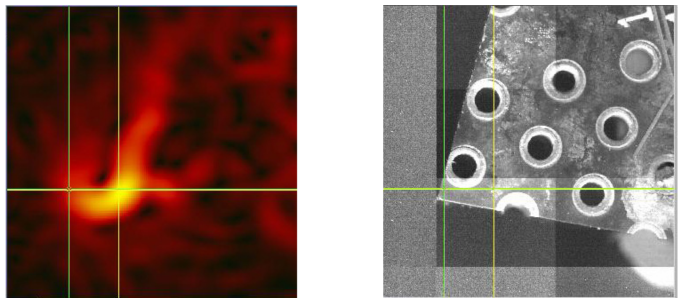

Figure 1: Current map (left) and corresponding photograph (right) of an electrically shorted printed circuit board.

The results of the cross-sectioning are displayed in Figure 2. A large, angular particle is observed bridging the dielectric between the power and ground planes. Tangential evidence, including mounding of copper at the power and ground planes and blackening of the surrounding dielectric material, strongly suggested that the particle was the cause of the drop in internal resistance. Definitive findings were provided through SQUID imaging of the cross-section

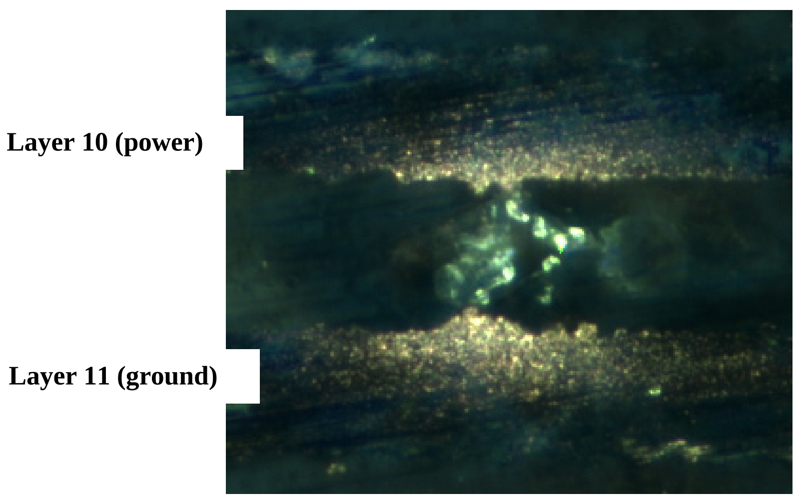

Figure 2 (500x): Particle identified between internal power and ground planes in the approximate area of electrical leakage.

The SQUID images are shown in Figure 3. The results clearly demonstrate that current is flowing through the particle, therefore verifying that the identified particle is the location of the short. However, bridging alone can not explain the electrical failure. This is because the angular nature of the particle suggests that it is electrically insulative. An additional mechanism, known as electrochemical migration (ECM), was most likely required.

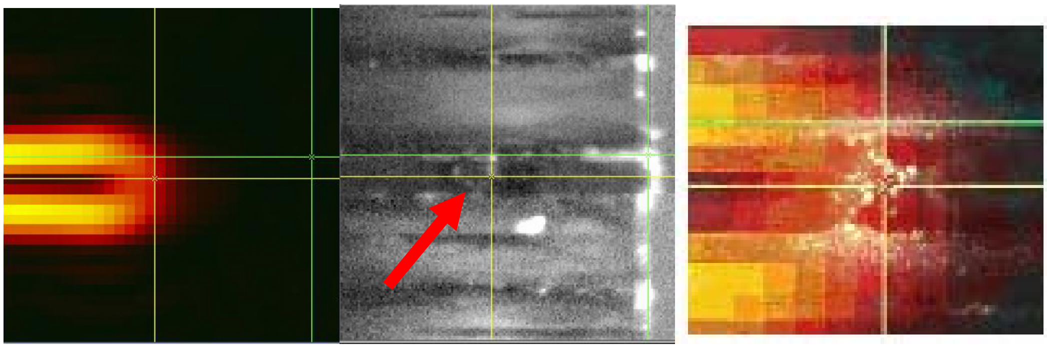

Figure 3: Current map (left) and corresponding optical image (center) of the board cross-section shown in Figure 2. The red arrow identifies the particle sandwiched between layers 10 and 11. A higher resolution overlay is shown on the right.

Conclusion

In conclusion, based on a review of potential failure mechanisms, measurement of relevant parameters, and the results of SQUID microscopy, the process of electrochemical migration around or through the particles was determined to be the most likely root-cause of electrical shorting between power and ground. Actual physical evidence of a conductive path was not observed. This is not surprising. A calculation of the conductor thickness, assuming that the conductor is a copper slab and that the particle is about 2 mils on a side, shows that the conductor is probably 2 to 5 nanometers thick. This calculation explains why the conductor was not seen optically. Even if the resistance prediction, similar to copper, was overly generous, an increase in resistance by three orders of magnitude would still only result in a conductor with a thickness of 2 to 5 microns. In this situation, magnetic current imaging with the SQUID was critical to validate the identified particle as the site of the electrical failure.