Detecting Power Shorts from Front and Backside of IC Packages Using Scanning SQUID Microscopy

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Abstract

As process technologies of integrated circuits become more complex and the industry moves toward flip-chip packaging, present tools and techniques are having increasing difficulty in meeting failure analysis needs. One of the most common failures in these types of ICs and packages is power shorts, both during fabrication and in the field. Many techniques such as Emission Microscopy and Liquid Crystal are either not able to locate power shorts or are inhibited in their effectiveness by multiple layers of metal and flip-chip type packaging.

A scanning SQUID microscope can overcome some of these difficulties. A SQUID (Superconducting Quantum Interference Device) is a very sensitive magnetic sensor that can image magnetic fields generated by magnetic materials or currents (such as those in an integrated circuit). The current density distribution in the sample can then be calculated from the magnetic field image, and resolutions approaching 5 times the near field limit can be obtained.

We present here the application of a SQUID microscope to physical failure analysis and compare it with other techniques to detect shorted current paths in flip-chip mounted ICs and packages.

Introduction

In the late 1960s, Gordon Moore of Intel Corporation suggested that integrated circuits will *double* in complexity roughly every 18 months. This exponential increase in circuit complexity continues to tax our ability to debug and analyze failures in integrated circuits. Further complicating failure analysis is the industry's recent trend toward flip-chip packaging. This requires that nondestructive measurements be made through the silicon substrate. As noted by Larry Wagner of Texas Instruments, "The tools we've become accustomed to using are in some jeopardy of not being able to meet our needs in the very foreseeable future." [1].

Of greatest interest to the failure analyst is the ability to see how the circuit is actually functioning, i.e. what currents and voltages are occurring in the circuit during operation. Although techniques such as voltage contrast electron microscopy have some ability to detect circuit operation, they also have limitations. Voltage contrast microscopy can detect voltage differences, not actual voltage or current, and only in conductors near the surface of the chip. Modern ICs now have as many as four to seven layers of metal interconnects above the transistors. The top layer of metallization is often a large area power or ground plane which may shield out all electric fields of the lower level conductors through the Faraday effect. Thus it is very difficult to do non-destructive evaluation of the lower level conductors, and impossible in a flip-chip configuration. Furthermore, currents are not detected directly by voltage contrast, so failures such as a short circuit can only be detected indirectly.

The SQUID (Superconducting Quantum Interference Device) microscope overcomes many of these problems. It enables backside or through-the-package imaging of current. These current paths can be compared to CAD layouts for short localization.

Scanning SQUID Microscope

A Scanning SQUID Microscope is a sensitive near-field imaging system for the measurement of weak

magnetic fields. This unique microscope can map out buried current-carrying wires by measuring the magnetic fields produced by the currents, or can be used to image fields produced by magnetic materials. By mapping out the current in an integrated circuit or a package, short circuits can be localized and designs can be verified to see that current is flowing where expected.

For the present experiments, we used Neocera's SQUID microscope, MAGMA-C1, which is shown in Figure 1. This instrument is capable of measuring magnetic fields as small as 20 pT (about 2 million times weaker than the earth's magnetic field).

Figure 1 Photograph of the commercial scanning SQUID microscope, MAGMA-C1, with electronics rack and probe station.

The SQUID sensor is sensitive enough that it can detect a wire even if it is carrying only 10 nA of current at a distance of 100 µm from the SQUID sensor with 1 second averaging. The microscope uses a patented design to allow *the sample under investigation to be at room temperature and in air* while the SQUID sensor is in vacuum and cooled to less than 80°K [2]. 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, whichever is larger. To best locate a wire 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 [3,4]. 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 magnitude (after processing) versus position on the sample. After processing to obtain current magnitude, this microscope has been successful at locating shorts in conductors to within ±16 µm at a sensor – current distance of 150 µm. The physics of SQUIDs and SQUID microscopy is described in more detail elsewhere [5-7].

To evaluate the scanning SQUID microscope as a failure analysis tool, we investigated shorts at both the die level and package level.

Experimental Results: C4 Flip-Chip Devices

To compare the advantages of scanning SQUID microscopy over other failure analysis tools, three C4 flip-chip devices with five layers of metallization were selected. A photograph of this device is shown in Figure 2. These devices were yield rejects and the failure mode was established to be power shorts or Vcc-Vss shorts. A good device was selected as a control unit.

Backside Sample Preparation

For thinning the samples a polishing wheel with a Micro Adjustable Tool [8] was selected. Since the thickness of the die's substrate can affect the results on certain backside failure analysis tools and techniques, the substrates of the C4 die were thinned and polished to 80 µm for maximum efficiency [9].

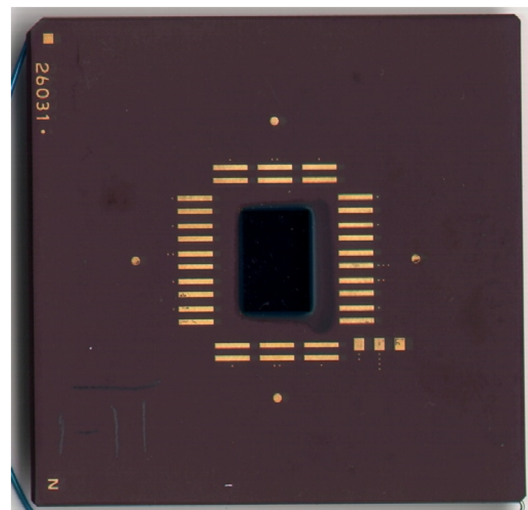


Figure 2 Photograph of a C4 flip-chip device.

In order to keep the physical conditions of the samples the same through out the experiment, all the devices including the control sample were thinned.

Emission Microscope Analysis

Emission microscopes can detect metal-metal shorts due to thermal radiation [10]. This also requires hundreds of milliamps of current. Even at a very high current, the filament which caused the short may vaporize and change the failure mode/mechanism. Also, at high current, some transistors may go to saturation and misguide the analyst. In our case, the failed devices did not show any emission even at higher current (~2 mA), but the control unit showed several emission points which are characteristic of a good device.

Hot Spot Detection Technique

Ferrier in 1997 proved that liquid crystal techniques for very thick ICs (more than four layers of metallization) are impossible especially if the leakage current is low [11]. In the case of a C4 flip-chip, the thickness of the substrate is about 80 μm thick, therefore Ferrier's technique will not work. Another hot spot detection technique is the "poor man's technique" in which the surface of the substrate is cooled by Freon gas. The device is then powered up and consequently the hotter spots on the die melt the thin layer of ice. When trying this approach on our samples, no hot spots were detected. The substrate was too thick, and the current was too low (~2 mA).

Scanning SQUID Microscope Analysis

The SQUID microscope was used to investigate the three C4 flip-chip devices. The samples were imaged nondestructively at a SQUID – current separation of ~350 μm (measured at the corner of the package) using currents as low as 170 μA at 2 kHz. Figure 3 shows the raw magnetic field image of the control sample overlaid on an optical photograph. The image corresponds to the z component of the magnetic field (perpendicular to the plane of the sample). The red and blue correspond to oppositely directed fields and the white corresponds to zero field in the z direction (in the simplest case, white corresponds to where current is flowing). In the majority of shorts, the location of the fault can be identified by the presence of a very intense localized magnetic field. This sample shows a complex distribution of magnetic fields resulting from the current as it follows a distributed path through the package and die. On the die there is a strong magnetic field in the lower left corner which indicates the presence of concentrated current. This is the result of normally higher levels of current in the buffer region of the die. This region

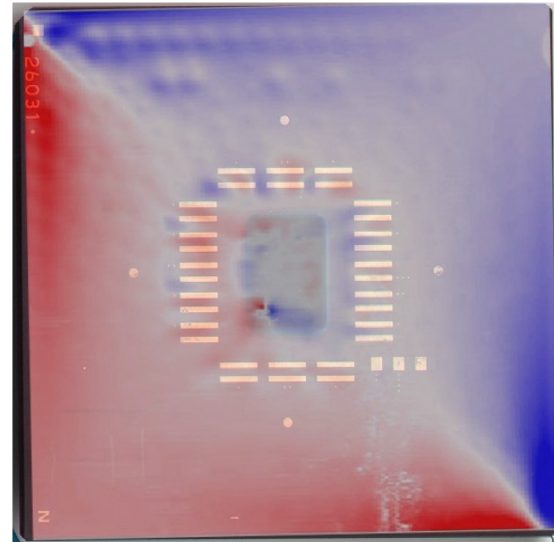
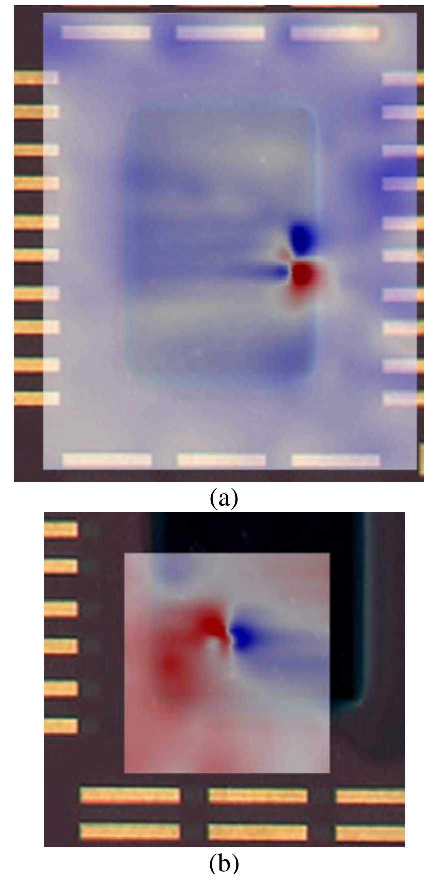


Figure 3 Magnetic field image of the control sample. The gold bars are 3.42 mm long.

corresponds to the location of emission sites observed with the emission microscope.

Figure 4 (a) and (b) show the magnetic fields of the



(a)

(b)

Figure 4 (a) and (b) Magnetic field images of power shorts in two different flip-chip devices. The gold bars are 3.42 mm long.

two samples with power shorts overlaid on an optical image of the die. Figure 4(a) is a scan of a region slightly larger than the die, and Figure 4 (b) is a scan of the lower left quadrant of the second die. In each image, the location of the short is indicated by a large localized magnetic field at different locations.

To more precisely localize the defect region, the magnetic fields can be used to calculate the current path in the die. Figure 5 (a) and (b) show the current images for the shorted samples in the same order as the magnetic fields in Figure 4. These images are overlaid on the optical images of the die. The current images show a maximum corresponding to the most concentrated current and therefore the most probable location of the short. From these images the short can be localized to a region of about 300 μm x 300 μm.

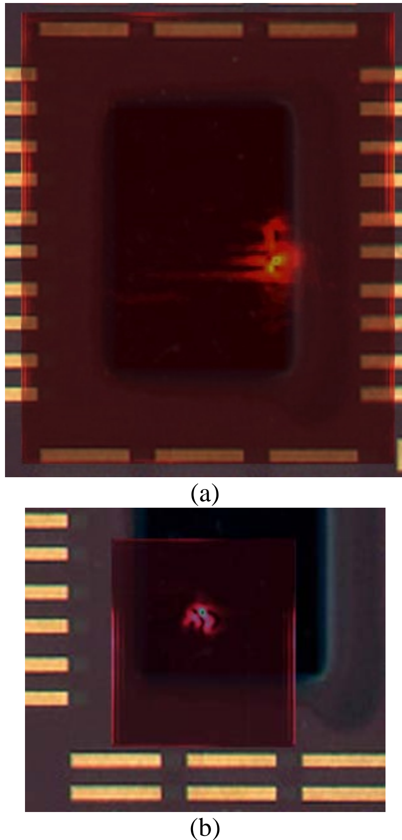


Figure 5 (a) and (b) Current images of power shorts in two different flip-chip devices. The gold bars are 3.42 mm long.

Experimental Results: Package Level

Package level shorts were also investigated with the scanning SQUID microscope on samples received from the Interconnection Technology Research Institute (ITRI). One example of a signal-to-ground short will be given here.

Figure 6 shows an optical photograph of the substrate. This sample had a short between two signal lines and ground. After applying 2 mA at 1 kHz to the appropriate lands on the back of the substrate, the SQUID microscope was used to map out the magnetic fields produced by the current. The magnetic image is shown in Figure 7 (a). The magnetic fields are concentrated where the current is entering and leaving the substrate, but the general distribution of magnetic fields around the whole substrate indicates a general distribution of current as might be expected in the ground plane. Figure 7 (b) shows an overlay of the current image on the schematic of the ground plane. The current can be seen to short from a via to the ground plane where it is distributed through several current paths before converging at another via. The broad distribution of current leading up to the via on the left is in the supply wire attached to the land on the backside of the substrate ~ 1.5 mm away from the SQUID. The distribution of current on the ground plane is interesting, because one can see the current paths on

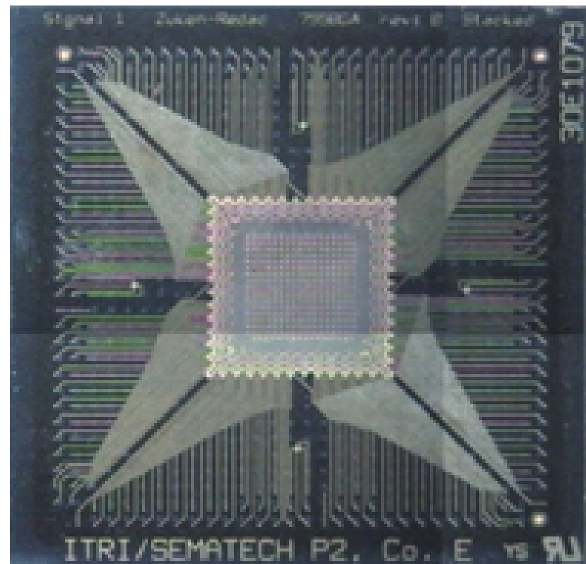
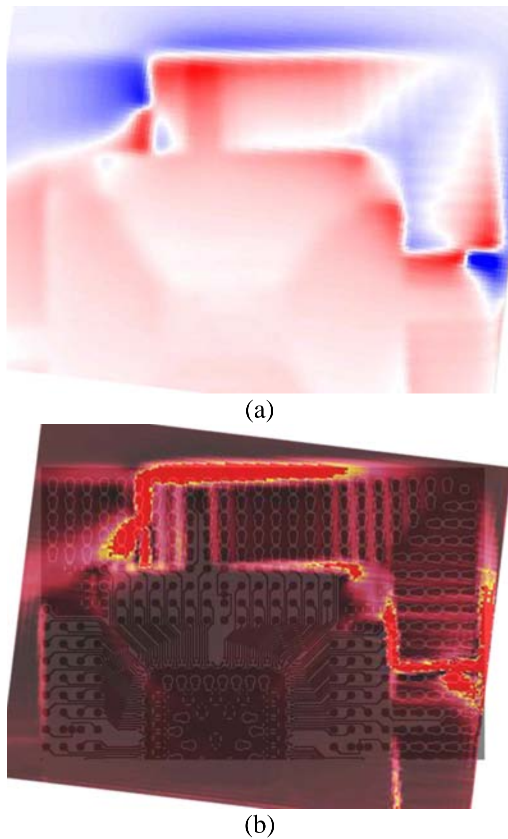


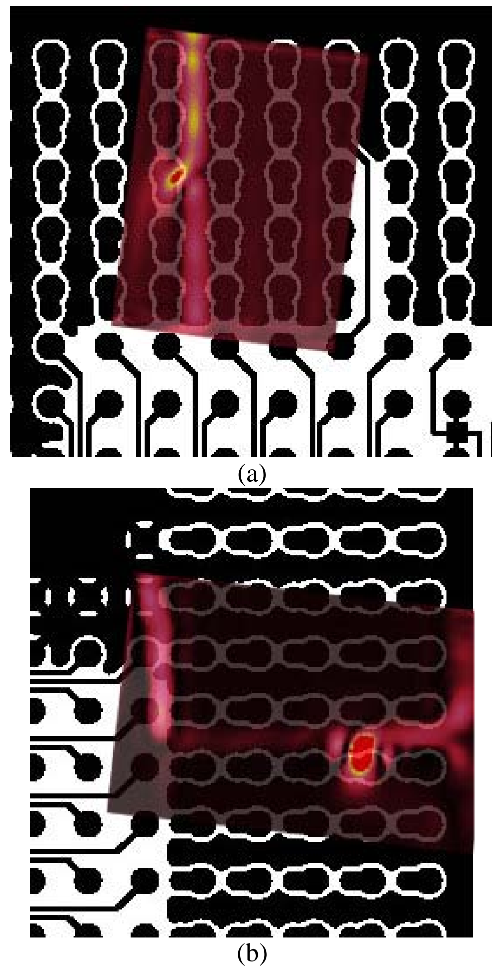
Figure 6 Optical image of substrate from ITRI.



(a)

(b)

Figure 7 (a) Magnetic field image. (b) Current Image overlay on the ground plane schematic (current image has been rotated to match schematic).



(a)

(b)

Figure 8 Current path through short from via to ground metallization at (a) first location and (b) second location. The width of the signal lines in both images is 50 µm. The full width of each image is (a) 4.53 mm and (b) 4.22 mm.

the metallization between the rows of vias. If this were a normally functioning board, one could use that current distribution image to do device verification. From the image, the distribution of current is clearly not uniform possibly indicating a design or processing problem. Additionally, two weak current paths can be observed flowing diagonally toward the center of the substrate. These paths are actually ground lines on the V_{cc} plane in the next layer down indicating the ability to distinguish between current on different layers in the structure. If the intensity of the image is turned down, the location of the shorts can be precisely located. Figure 8 shows a close-up view of the current shorting from each of the vias to ground. In particular, it can be determined which side of the via is shorted and approximately where on that side of the via reducing the area of interest to about 100 µm x 100 µm as compared to the size of the via which is ~ 250 µm x 400 µm. This makes it easy to cross section precisely and determine the cause of the problem.

As one can see from this example, it is possible to use this instrument to do short localization very precisely in a printed wiring board and verify design performance. These measurements can be made through multiple layers of metallization, and information can be obtained to indicate current on different layers. Although the current supplied in this case was > 1mA, high quality images can be obtained at current levels more than an order of magnitude lower.

Conclusions

The scanning SQUID microscope can be used to localize the region of shorts in dies and packages even when other techniques like emission microscopy and liquid crystal are ineffective. The high sensitivity of the SQUID sensor enables these

measurements to be made with currents less than 200 μA with a sample sensor separation of approximately 350 μm. The ability to sense and localize shorts at large distances makes this tool ideally suited for nondestructive evaluation of current paths in buried layers of packages and flip-chip mounted dies.

Acknowledgements

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