Advances in scanning magnetic microscopy for die-level, stacked die and package-level fault isolation

J. O. Gaudestad, S. I. Woods, A. Orozco, L. A. Knauss
Neocera Inc., 10000 Virginia Manor Rd.
Beltsville, MD 20705

Abstract

Recent advances have enabled magnetic field imaging to localize high resistance (HR) defects in packages to within 20 µm. This is done in a non-contact, non-destructive way for several packages including stacked die. For die-level applications submicron resolution can be achieved. Two types of magnetic microscopes have been used in high resolution current mapping. The scanning fiber/SQUID microscope uses a SQUID sensor coupled to a nanoscale ferromagnetic probe, and the second approach uses a magnetoresistive (MR) sensor.

Introduction

In recent years, current imaging through magnetic field detection has become a main-stream approach for short localization in the package [1] and is also heavily utilized for die level applications [2]. Current imaging is based on the measurement of the magnetic field generated by current carried in the structures of the device under test (DUT). The magnetic fields are typically measured with a SQUID (Superconducting Quantum Interference Device) which is a very sensitive magnetic field sensor.

A new approach to isolating high resistance defects (HR) has been recently developed using SQUID based current imaging. High resistance defect describes any damage in a current path that results in an increase in resistance of that path. Some physical defects include cracked traces, non wet or cracked C4 bumps, delaminated vias, etc.

Integrated-circuit process technologies become more complex as the industry moves to 90 nm line widths and beyond, requiring higher resolution failure analsysis techniques. Magnetic imaging can help meet this need and enable designers and failure analysts to see current paths in a nano-scale regime.

Two approaches have been developed for nano-scale imaging using magnetic fields. One approach involves coupling a magnetic fiber to a SQUID. This fiber can be etched to a tip that is as small as 10 nm and used as a probe to deliver high spatial resolution.

The other approach involves a magneto-resistive (MR) sensor, which is intrinsically less sensitive to magnetic fields than the SQUID, but is readily miniaturized to the nano-scale. If this sensor is brought within about 1 µm of currents to be measured, it has the magnetic sensitivity to map out submicron current lines carrying less than 500 µA of current.

In recent years the semiconductor industry has been forced to shrink their devices to accommodate the handheld consumer electronics industry, which again has led the industry to move towards complex packaging structures including stacked die of two, three and even four ICs. The magnetic field microscope can detect fields through all these packaging structures even when multiple die are involved. Since there is no shielding by the packaging material, current can be imaged as low as 100s of nano amps.

Magnetic-Field Imaging System

The source currents in electronic devices can be calculated from their magnetic field images providing the failure analyst the ability to see a map of current in the device. By mapping the current in an integrated circuit, stacked die or a package, short circuit defects can be localized and designs can be verified to see that electricity is flowing where expected. Also, HR defects can be found by recognizing differences in the magnetic field. The strength of using a magnetic field detection technique is that unlike thermal, optical, ion, or electron beam techniques, magnetic fields are not affected by the materials in an integrated circuit (IC) or package, therefore imaging can be performed from both the front and backside of a device through many layers of metal, die or packaging materials. The only difficulty is that the strength of the magnetic field decreases with current magnitude and increasing separation between the sensor and source currents. The rate of decrease depends on the nature of the current source, but for ICs the magnetic-field strength is typically inversely proportional to the distance between the sensor and the source.

Magma C20, a commercial magnetic field imaging instrument designed for failure analysis of ICs, stacked die, packages, and boards has been developed using a high-temperature SQUID with a sensitivity of 20 picotesla (two million times smaller than the Earth's magnetic field). By using a high-temperature SQUID, the microscope (SSM) has been designed to keep the SQUID cold and in vacuum, while the DUT is at room temperature and in air. The unique design of the magnetic field microscope also facilitates positioning the SQUID as close as 70 µm from the DUT. The system can run samples requiring high resolution current images (die and wafers) as well as samples requiring high sensitivity (low current and HR) in the same system. Sensitivity is high enough to detect currents as small as 10 nA at a 100 µm working distance with 1 second averaging, but low enough to enable the instrument to function in an unshielded environment.

Resolution, when using a high resolution sensor approach, is good enough to resolve 0.3 µm (300 nm) features with a potential to reach 0.01 µm (10 nm) resolution. The sensor is held stationary while the DUT is raster scanned under the magnetic sensor to acquire the magnetic field image. The current supplied to the DUT is typically alternating at a frequency less than 100 kHz. By using a lock-in technique, an image of just the applied current can be acquired while magnetic fields generated by currents at other frequencies or static background fields are ignored.

High Resistance Experimental Results

High Resistance Defects

Typically, a HR defect is the result of a geometrical change in some circuit element such as a delamination process, crack, void, etc. Clearly, the current distribution will be affected by such geometric alterations and correspondingly affect the magnetic field distribution as sketched in Figure 1 for a failing C4 bump.

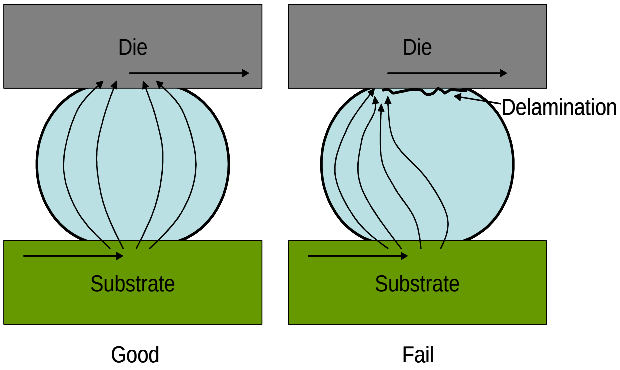

Figure 1: Illustration of current distribution in a good and a delaminated (failing) C4 bump.

In this situation, one expects to see a small change in the magnetic field distribution around the defect as compared with that in a good part, typically in the range of pico tesla to a few nano tesla. A detailed image comparison between the good and failing parts would then be able to detect this difference and subsequently locate the defect region.

The localization of high resistance defects through current imaging is accomplished through a detailed comparison of good and failing parts [3]. The differences in magnetic field explained above are small and therefore require a very careful analysis between the good and failing parts. This requires improvements over conventional technology in two areas. First, the instrumentation for current imaging requires more precise automated control of the sample setup and data acquisition. The scan conditions must be as similar as possible between the good and failing parts, so that an effective comparison can be made. Second, even with careful sample setup and data acquisition, there will still be misalignments between the two images, and potential signal differences due to different working distances, or even part deformations (for example warping). These differences need to be sorted out from the differences due to the high resistance defect. For this, advances have been made in image difference analysis (IDA) to assist in the identification of failing defects. These defects typically show up in IDA images as dipoles where the defect location coincides with the centroid of the dipole.

C4 Bump Failure

One example of a real failure that was tested using the magnetic field microscope is a C4 bump failure [3]. Figure 2 shows the region of interest from the IDA image overlaid on top of the CAD layout for the device.

The 2-D density plot shown in Figure 2 does not adequately present the relative intensity of the magnetic anomaly. A better way of doing that is by using a 3-D representation as shown in the lower left corner of Figure 2, where the z axis is the magnetic field intensity corresponding to the 2-D IDA result. We plot the absolute value of the magnetic field zoomed-in around the anomaly location for the sake of clarity. The two dipole peaks associated with the defect are clearly visible, with the defect located at the center between the two peaks.

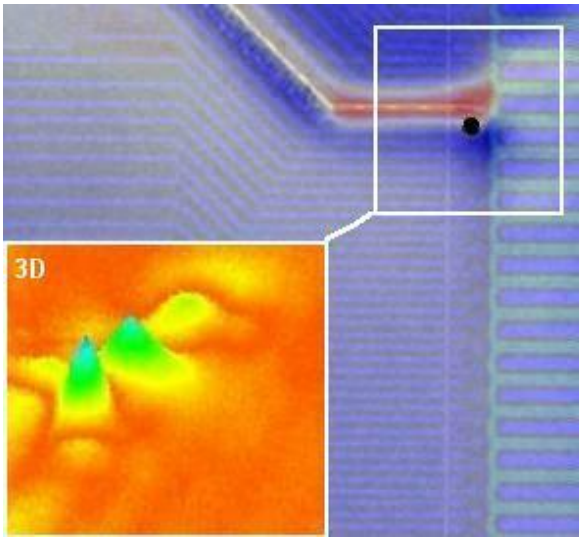

Figure 2: IDA results corresponding to the HR C4 bump damage overlaid on top of the CAD layout. The black dot shows the located faiure location. The white box region is displayed as a 3-D plot in the lower left corner of the image.

In the 2-D image again, the metal trace connecting to the failing bump is marked with the dashed yellow line. The C4 bump is connected at the end of it before the green grid. The centroid for the magnetic anomaly is the black dot, aligning very well with the position of the bump. The defect was located with the SQUID microscope to within 30 µm. Although not shown here, the best localization to date is 20 µm.

High Resolution Experimental Results

Microscope Design

The fiber/SQUID microscope uses a ferromagnetic metal probe 100 µm thick and about 10 mm long, electrochemically etched to a tip with submicron diameter [4]. This probe resides entirely in air, and its end is attached to a window at the bottom of a cone housing a SQUID. The SQUID sensor is isolated at around 77 K in vacuum and the distance between the probe and SQUID can be adjusted to maximize the magnetic response of the microscope. An optical shear force feedback method is used to scan the etched tip over the sample in near-contact (separation distance of less than 100 nm). Use of this feedback method means that topography data can be acquired on the sample at the same time as the magnetic data.

For the magnetoresistive microscope, the sensor has been attached to a cantilever which allows the sensor to be scanned over the sample in soft contact. The cantilever is attached to the SQUID microscope housing by an easily mounted bracket on a piezo stage. In this way, the sensitive SQUID can be used for large area scans to locate regions of interest, and then the MR sensor can be used to perform high resolution scans in these regions.

High Resolution Current Imaging

The fiber/SQUID microscope has been used to image a serpentine structure of micron-scale dimensions. This proof-of-principle scan has demonstrated the feasibility of the approach, but more work is necessary to demonstrate sub-micron capability. The approach is discussed here because of the potential for this technique to achieve 10 nm resolution and to have a form factor capable of scanning in very small cavities.

At present, the MR microscope has been fully developed for sub-micron imaging. The scan shown in Figure 3 was done using a commercial magnetic field microscope with a MR high resolution current scan option. The image is of a die level test structure with 300 nm wide lines 300 nm apart. A current of 500 µA is clearly resolved in this image and overlaid on the optical image of the part.

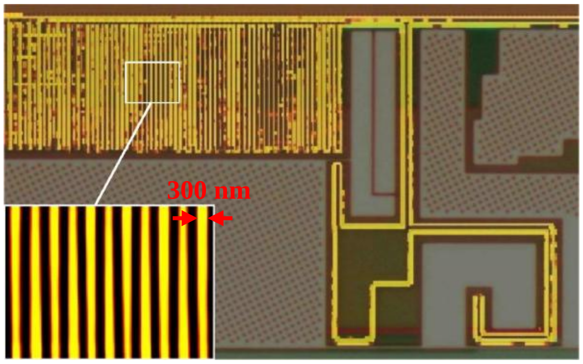

Figure 3: Optical image of the scanned region of a die with 300 nm wide lines each separated by 300 nm. The yellow line current image is overlaid on the optical image.

3-D view of the current

The magnetic sensor detects a stronger field when the current path is closer to the sensor. This means that the different metal layers can be displayed in a 3-D view as long as the current carrying metal line widths are the same for each layer and that no two metal lines from the different layers are directly on top of each other. Figure 4 shows the current image displayed in Figure 3 in a 3-D view. It is clear from the image that all currents in this chip are in the same layer.

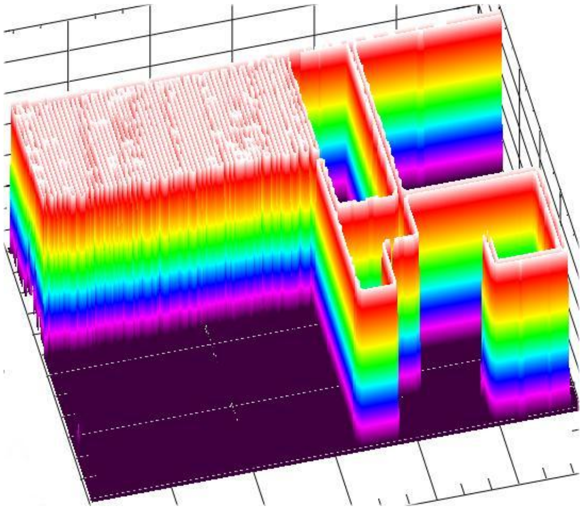

Figure 4: Same current as displayed in Figure 3 in a 3-D view. The currents are flowing in the same layer.

The use of the 3-D view is very helpful when currents are in multiple levels of metal or different die in a stacked die structure. The analyst can see the different layers in the chip or stacked die structure and its related physical coordinates.

Conclusions

Magnetic image difference analysis (IDA) is a new non-contact and nondestructive technique that has been demonstrated to localize high resistance defects in package substrates and interconnections. It has been shown to localize these defects to within 30 microns, which is an order of magnitude improvement over time domain reflectometry (TDR) and without destruction of the sample.

The scans with a MR microscope demonstrate that current lines separated by 300 nm can be resolved. The flux-guide scanning SQUID microscope (SSM) and the MR microscope have excellent potential as tools for locating die level defects and could play a complementary role to standard SSM with a bare SQUID. The standard SSM has unsurpassed current sensitivity and the ability to examine circuits buried 100s of microns, but is limited to applications where spatial features are larger than a micron and for global imaging of current densities. The high resolution microscopes described here can detect submicron anomalies in magnetic fields created by current defects. These microscopes are ideal for wafer level studies or examination of deprocessed samples.

Acknowledgements

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