New Approach of Laser-SQUID Microscopy to LSI Failure Analysis

Kiyoshi NIKAWA††††, Shouji INOUE††, Nonmembers, Tatsuoki NAGAISHI†††, Member, Toru MATSUMOTO†††, Nonmember, Katsuyoshi MIURA††††, and Koji NAKAMAE††††, Members

SUMMARY We have proposed and successfully demonstrated a two-step method for localizing defects on an LSI chip. The first step is the same as a conventional laser-SQUID (L-SQUID) imaging where a SQUID and a laser beam are fixed during LSI chip scanning. The second step is a new L-SQUID imaging where a laser beam is stayed at the point, located in the first step results, during SQUID scanning. In the second step, a SQUID size ($A_{ef}$) and the distance between the SQUID and the LSI chip ($AZ$) are key factors limiting spatial resolution. In order to improve the spatial resolution, we have developed a micro-SQUID and the vacuum chamber housing both the micro-SQUID and the LSI chip. The $A_{ef}$ of the micro-SQUID is a thousand of that of a conventional SQUID. The minimum value of $AZ$ was successfully reduced to 25 $\mu$m by setting both the micro-SQUID and an LSI chip in the same vacuum chamber. The spatial resolution in the second step was shown to be 53 $\mu$m. Demonstration of actual complicated defects localization was succeeded, and this result suggests that the two-step localization method is useful for LSI failure analysis.

key words: SQUID, laser, LSI chip, failure analysis, defect localization

1. Introduction

The concept of a scanning laser-SQUID microscope (L-SQUID) which uses the combination of laser beam and SQUID (superconducting quantum interference device) magnetometer was proposed first by Beyer et al. [1]. They applied the L-SQUID to inspect uniformity of impurity in Si wafers. We have proposed to apply the L-SQUID for inspection, monitoring and failure analysis of LSI-chip-defects, and demonstrated inspection and failure analysis of actual LSI chips [2]–[5]. In demonstration of failure analysis, we found that we can localize a single site open defect using L-SQUID without any help of other tools such as CAD-navigation [4],[5]. Other defects, however, such as short defects, multiple site open defects or more complicated defects, could not be localized using L-SQUID.

In this paper, we propose and demonstrate a new approach where we can localize not only open defects but also short defects or more complicated defects.

2. Laser-SQUID Microscope with SQUID-Scanning Capability

L-SQUID described in [4] and [5] has not SQUID scanning capability. We have added a SQUID scanning capability to our L-SQUID system this time. The effective area ($A_{ef}$) of the micro-SQUID for scanning which we have developed this time is a thousandth of a conventional SQUID (cf. Appendix A).

2.1 Basic Concept of Conventional L-SQUID and New L-SQUID

Figure 1 shows basic concept of a conventional L-SQUID (a) and a new L-SQUID (b). In the scheme of the conventional L-SQUID, a SQUID magnetometer and a laser beam are fixed during sample scanning. As a consequence, the laser beam scans on the sample. In the scheme of the new L-SQUID, on the other hand, the laser beam stays at a certain point on a sample during SQUID scanning.

The spatial resolution in the conventional L-SQUID scheme is limited by the laser beam diameter. The spatial resolution in the new L-SQUID scheme, on the other hand, is limited by the SQUID size ($A_{ef}$) and the distance between the SQUID and a sample ($AZ$). The SQUID size and the $AZ$ are therefore important factors in the new L-SQUID scheme. In order to achieve high spatial resolution, we have developed a micro-SQUID and a vacuum chamber housing both the micro-SQUID and an LSI chip.

2.2 System Setup

The essence of our L-SQUID system is shown in Fig. 2.
When a laser beam is focused at a p-n junction on an LSI chip, a photocurrent is induced and the photocurrent induces a very weak magnetic field. The magnetic field is detectable by a DC-SQUID magnetic sensor. The whole system is magnetically and electromagnetically shielded (the shield room is not shown in Fig. 2). In the conventional L-SQUID scheme, a ceramic stage scans when a wide area is scanned, and a laser beam scans when a narrow area is scanned. The SQUID chip in the SQUID sensor module is cooled down to about 77 K using a liquid nitrogen (L.N.) cryostat. The $\Delta Z$ ($\Delta Z_1 + \Delta Z_2 + \Delta Z_3$ in Fig. 3(a)) is usually set to about 0.4 mm in the conventional L-SQUID scheme. The $\Delta Z$ in the new L-SQUID scheme ($\Delta Z_4$ in Fig. 3(b)), on the other hand, can be set down to 25 $\mu$m because a sample is set in vacuum as shown in Fig. 3(b). Figure 4 shows the side view of the SQUID chip and an LSI chip when the $\Delta Z$ is 50 $\mu$m. The side view can be imaged by telemicroscopes set at two perpendicular positions each other (only one is shown in Fig. 2). The effective area ($A_{eff}$) of the conventional SQUID chip used in the conventional L-SQUID scheme is 0.2 mm$^2$. That of the micro-SQUID chip used in the new L-SQUID scheme, on the other hand, is 0.0002 mm$^2$. The detail of the two types of SQUID chips is described in Appendix A.

As shown in Fig. 2, the laser beam is introduced from the bottom side. We use a 1065 nm wavelength fiber laser which can penetrate a Si substrate and generate photocurrents at p-n junctions near the surface of the Si substrate. The intensity of the laser beam is modulated with an acousto-optic modulator and the resulting modulated SQUID output signal is introduced into a lock-in amplifier. The output signal of the lock-in amplifier is used for imaging intensity and phase. The combination of magnetic shielding and “laser modulation/lock-in” approach makes pico-Tesla-order magnetic signals detectable in micro-Tesla-order magnetic noises in our laboratory.

3. Application to LSI Failure Analysis

3.1 Defective Part Localization by Sample-Scanning (Conventional Approach)

Figure 5 shows a result of a conventional approach where Vdd-open-site is localized by the conventional L-SQUID scheme. The maximum magnetic field (the brightest point) in the intensity images is about $3 \times 10^{-10}$ T. The sample is designed (layout design) and manufactured using the system of VDEC (VLSI Design & Education Center, the University of Tokyo) based on C7552 circuit of ISCAS’85 benchmark circuits [6]. In Fig. 5, you can see a layout, an optical image, and L-SQUID images. The field of view (FOV) of each image is 1 mm x 1 mm. In the optical image, the Vdd-open site, which is designed in a no good chip, is shown. By comparing L-SQUID images of good and no good chips, you can clearly find out the differences in both intensity images and phase images. In the intensity image of a no good chip, open site is localized as a dark part between two bright parts. In the phase image of a no good chip, open site is localized as the interface of inverted phases.

We have localized many single-site-open defects using the conventional L-SQUID scheme as shown in Fig. 5 and in [4] and [5]. Other defects such as short or more complicated defects, however, have not been localized by the conventional L-SQUID scheme. In the next section, we would like to propose and demonstrate the new idea of two step localization in order to localize not only open defects but also short defects or more complicated defects.
3.2 Defective Part Localization by Sample-Scanning Followed by SQUID-Scanning (New Approach: Two Step Localization)

Figure 6 shows a main concept of two step localization. In the first step, L-SQUID images of both good and no good chips are taken in the conventional L-SQUID scheme. Then a contrast-different part between good and no good chip images is selected as the laser-beam stay point in the second step. In the second step, the laser beam is stayed at the point, determined in the first step, during SQUID scanning. The scanning SQUID images of both good and no good chips are converted into current images using Fourier Transform (see Appendix B). If there are any different parts between two current images, at least two cases are possible. In one case, a short defect must exist at the image different part. In another case, an open defect must exist at the image different part. In the former case, a part of current paths appears in a no good chip image (Fig. 6). In the later case, on the other hand, a part of current paths disappears in a no good chip image: this case is not shown in Fig. 6.

The key factors of the spatial resolution in the second step are \( \Delta Z \) and \( A_{\text{eff}} \) as described above. In order to confirm the spatial resolution in the second step, we used a test structure shown in Fig. 7. The test structure made on a Si substrate consists of a p-n junction and a rectangular metal loop. The linewidth of the loop is 2 \( \mu \)m. A scanning SQUID image when a laser beam is stayed at the p-n junction is shown in Fig. 8(a). The maximum magnetic field (the brightest point) in the intensity images is about \( 5 \times 10^{-8} \) T. The line profile of the magnetic field intensity along a line shown in the right image of (a) is shown in (b). In this scanning, we used the micro-SQUID (\( A_{\text{eff}} = 0.0002 \) mm\(^2\)) described in Appendix A and set \( \Delta Z \) to 25 \( \mu \)m. Figure 8(b) shows that the spatial resolution is 53 \( \mu \)m (FWHM, full width at half maximum).

In order to demonstrate the two step localization method, we selected the 256MDRAM chip which had been tested electrically by conventional probing and had found out to be stand-by-current failure. Figure 9 shows conventional L-SQUID images of good and no good chips. The maximum magnetic field (the brightest point) in the intensity images is about \( 1 \times 10^{-9} \) T. You can clearly see the contrast differences between good and no good chip images. We selected two points indicated by arrows as “1” and “2” in
Fig. 9 Conventional L-SQUID images of 256MDRAMs in the first step: The maximum value of the magnetic field (the brightest point) in the intensity images is about $1 \times 10^{-9}$ T.

Fig. 10 Scanning SQUID images and converted current image in the second step when a laser beam was stayed at the point “1”: The maximum value (the brightest point) in the intensity images is about $7 \times 10^{-8}$ T, and that in the current images is about $2 \times 10^{-5}$ A.

Fig. 11 Overlay of a layout and two current images when a laser beam was stayed at the point “1.”

Fig. 12 Optical microscope images of a defective area localized when a laser beam was stayed at the point “1.”

Fig. 13 Scanning SQUID images and converted current images in the second step when a laser beam was stayed at the point “2”: The maximum value (the brightest point) in the intensity images is about $1 \times 10^{-7}$ T, and that in the current images is about $4 \times 10^{-5}$ A. In Fig. 15, you can see a few-tens-μm size defect in no good chip images.

Concerning the stay point “2,” we have also succeeded to localize a defect. Scanning-SQUID images with converted current images, overlay of current images and a layout, and optical images are shown in Figs. 13, 14, and 15 respectively. The maximum magnetic field (the brightest point) in the intensity images in Fig. 13 is about $1 \times 10^{-7}$ T, and that in the current images is about $4 \times 10^{-5}$ A. In Fig. 15, you can see a few-tens-μm size defect in no good chip images.

These results suggest that the two step localization method is useful for localization of complicated defective sites on an LSI chip.
4. Summary and Conclusion

We have proposed and successfully demonstrated the two-step localization method. In order to improve the spatial resolution in the second step, we have developed the micro-SQUID and the vacuum chamber housing both the micro-SQUID and an LSI chip. The spatial resolution was shown to be about 50 μm. Several μm-sized and a few-tens-μm size defects have been localized on a 256MDRAM chip by applying the proposed method. These results suggest that the two-step localization method proposed in this paper is useful for localization of complicated defective sites on an LSI chip.

Acknowledgments

A part of this research and development was supported by JST (Japanese Science and Technology Agency). A part of the VLSI chips in this study has been fabricated in the chip fabrication program of VLSI Design and Education Center (VDEC), the University of Tokyo.

References


Appendix A: Two Types of SQUID Chips: Conventional SQUID and Micro-SQUID

Two types of SQUID chips shown in Fig. A-1 are used in this study. Both are the square washer type with different sizes and shapes. The conventional type SQUID has millimeter order washer size. The other is the small SQUID with 20 μm square washer size: a micro-SQUID [7], [8].

The details of the SQUID designs are shown in Fig. A-2. The main portion of the conventional type SQUID is given in Fig. A-2(a). It has 4 μm wide and 250 μm length slit which focuses the magnetic fluxes. The other slits to make junctions with 2 μm wide are elongated to one side of the washer. Full picture of the micro-SQUID is given in Fig. A-2(b). The micro-SQUID has 10 μm by 10 μm hole with 20 μm by 20 μm washer and the slits located opposed position to make 2 μm wide junctions. Superconducting thin films are HoBa2Cu3O7-x on SrTiO3 substrates and the junctions are the step-edge type. The differences of the parameters and the characteristics are given in Table A-1.

Appendix B: Conversion of Magnetic Field to Electric Current

In this appendix, we show a method to calculate the electric...
current density vector from the measured magnetic field. It is based on the method proposed in [9], [10] and sensitivity distribution of a SQUID is introduced in it.

When it is assumed that the current is flowing only in a very thin sheet of thickness \( d \) that exists in the \( x-y \) plane, two-dimensional (2D) Fourier transformation of current density \( j_x(k_x, k_y) \) and \( j_y(k_x, k_y) \) can be calculated by the following equations [8], [9]:

\[
j_x(k_x, k_y) = \frac{i 2}{\mu_0 d} e^{k_x k_x} b_z(k_x, k_y, z) \cdot f(k), \quad (A \cdot 1)
\]

\[
j_y(k_x, k_y) = \frac{i 2}{\mu_0 d} e^{k_y k_y} b_z(k_x, k_y, z) \cdot f(k). \quad (A \cdot 2)
\]

where \( k_x \) and \( k_y \) are the \( x \) and \( y \) components of the spatial angular frequency, \( k = \sqrt{k_x^2 + k_y^2} \), \( i \) is the imaginary unit (\( i = \sqrt{-1} \)), \( \mu_0 \) is the magnetic permeability of free space, \( z \) is a distance from the sheet to the SQUID, \( b_z(k_x, k_y, z) \) is 2D Fourier transformation of the measured magnetic field, and \( f(k) \) is a low-pass filter function to suppress high-frequency noise. Therefore, the current density vector \( J(x, y) \) can be obtained by applying inverse 2D Fourier transformation to Eqs. (A·1) and (A·2).

As the low-pass filter \( f(k) \), the Hamming window function expressed by the following equation is used in this study:

\[
f(k) = \begin{cases} 0.54 - 0.46 \cos \left( \frac{2\pi k}{K} \right) & (0 \leq k < K), \\ 0 & (K < k) \end{cases} \quad (A \cdot 3)
\]

where \( K \) is a cut-off frequency. When \( K \) is small, the special resolution of the obtained current density distribution becomes coarse. Contrary, when \( K \) is large, serious artifacts appear in the current density distribution while the special resolution becomes fine. The optimal value of \( K \) is determined depending on the amount of noise in \( b_z(k_x, k_y, z) \).

In the method described above, the size of a SQUID is assumed to be very small and negligible. However, as is described in the Appendix A, the size of a SQUID is in a range from a few tens of micrometers to millimeters. It can not be always ignored. We introduced a sensitivity distribution function \( S(x, y) \) of a SQUID to the conversion method. The measured value \( \tilde{B}_z(x, y, z) \) of the \( z \) component of magnetic field \( B_z(x, y, z) \) is convolution of \( S(x, y) \) and \( B_z(x, y, z) \). From the convolution theory, 2D Fourier transformation of \( B_z(x, y, z) \) is expressed as

\[
\tilde{b}_z(k_x, k_y, z) = s(k_x, k_y) \cdot b_z(k_x, k_y, z) \quad (A \cdot 4)
\]

where \( s(k_x, k_y) \) is 2D Fourier transformation of \( S(x, y) \). From Eqs. (A·1), (A·2), and (A·4), the following equations can be obtained:

\[
j_x(k_x, k_y) = \frac{i 2}{\mu_0 d} e^{k_x k_x} b_z(k_x, k_y, z) \cdot \frac{f(k)}{s(k_x, k_y)}, \quad (A \cdot 5)
\]

\[
j_y(k_x, k_y) = \frac{i 2}{\mu_0 d} e^{k_y k_y} b_z(k_x, k_y, z) \cdot \frac{f(k)}{s(k_x, k_y)}. \quad (A \cdot 6)
\]

As the sensitivity distribution function, the Gaussian distribution is assumed in this study:

\[
S(x, y) = \frac{1}{\sqrt{2\pi} \sigma} \exp \left( -\frac{x^2 + y^2}{2\sigma^2} \right), \quad (A \cdot 7)
\]

and the standard deviation \( \sigma \) is optimized by comparing the measured magnetic field of a simple-structured specimen with calculated one.
Kiyoshi Nikawa received the B.S. and M.S. degrees in material science, and Ph.D. degree from Osaka University, Osaka, Japan. He has been with the NEC group, Japan, where he has been working on reliability engineering for Si integrated circuits, especially, on bipolar devices, electromigration, failure analysis using a focused ion beam, an electron beam, and a laser beam. He is an author or a co-author of more than 200 technical papers and more than twenty books. He was a vice-president of Reliability Engineering Association of Japan (REAJ), and is a council of the REAJ, a committee of the institute of LSI Testing, a member of the Japan Society of Applied Physics (JSAP), IEEE, and Electron Device Failure Analysis Society (EDFAS).

Shouji Inoue received the B.S. degree in telecommunication engineering from Tokai University, Kanagawa, Japan in 1978. In 1979, he joined TDI Co. Ltd. where he worked on the development of the space equipment. Since 1985, he has been working on reliability engineering, especially failure analysis of LSIs.

Tatsuoki Nagaishi received his B.S. degree in Physics from Osaka University in 1985, M.S. degree in Materials Science and Engineering from Stanford University in 1989, and Ph.D. degree from Osaka University in 2005. He joined Sumitomo Electric Industries, Ltd. in 1985. Since 1989, he was engaged in the R&D of high temperature superconducting materials. He developed high quality and large area high Tc thin films using excimer laser deposition. Along with the thin film development, he started the development of high Tc SQUID and commercialized the high Tc SQUID systems in the fields of education, non-destructive evaluation, geophysical exploration and others.

Toru Matsumoto received the B.E. degree in image science from Chiba University, Chiba, Japan in 1988. He joined Hamamatsu Photonics K.K. in 1988 and worked on the development of the inspection system using image sensor. In 2002, he developed the scanning laser SQUID microscope with Dr. Kiyoshi Nikawa. Since 2004, he has been working on the development of the failure analysis system for LSIs using image sensor, SQUID and other sensor.

Katsuyoshi Miura is an associate professor in the Department of Information Systems Engineering, Graduate School of Information Science and Technology, Osaka University, Osaka, Japan. He received the B.E. and M.E. degrees in electronic engineering, and Ph.D. degree in information systems engineering from Osaka University. His research interests include methods and systems of VLSI testing, fault diagnosis and failure analysis.

Koji Nakamae is a professor in the Department of Information Systems Engineering, Osaka University, Osaka, Japan. His current interests lie in LSI fault diagnosis, signal and image processing, and the analysis of the economics of VLSI manufacturing, including test costs. Nakamae received the B.E., M.E., and Ph.D. degrees in electronic engineering from Osaka University.