SAND99-0710J
RECEIVED
APR 07 1999
OSTI

What is Scanning Probe Microscopy? And How Can it be Used in Failure Analysis?

by

Paiboon Tangyunyong and Ann Campbell
Failure Analysis Department, Sandia National Laboratories
Albuquerque, NM 87185

Introduction

Scanning probe microscopy (SPM) refers to a suite of techniques that measure the interaction between a fine probe or tip (diameters from < nm to μm) and sample at a small probe-sample separation (from contact to μm distances). These measurements of interactions allow the study of properties such as topology, magnetic field, electrical field, capacitance, temperature, work function, and friction. This information obtained from SPM can be useful in supporting IC failure analysis, as we will describe in this article.

Scanning tunneling microscopy (STM) [1] was the first SPM technique and was invented in the early 1980s. STM measures the tunneling current between the tip and the sample surface at a tip-sample separation of several angstroms. The usefulness of STM is limited particularly for analyzing microelectronics since both tips and samples need to be conductive and a high vacuum environment is normally required. In 1985, scanning force microscopy (SFM) [2], commonly known as atomic force microscopy (AFM), was developed. An important advantage of SFM over STM is that tips and samples need not to be conductive. SFM can also operate in ambient environments with no vacuum requirement. SFM measures the local forces or force gradients between the tip and the sample. These local forces include contact force, frictional force, van der Waals force, magnetic and electrostatic forces. SFM uses a tip that is attached to a flexible cantilever. The local force or force gradient is detected by measuring the deflection of the cantilever. To date, SFM is the most widely used SPM technique.

Recently, other SPM techniques such as scanning thermal microscopy (SThM) [3], scanning capacitance microscopy (SCM) [4] and tunneling AFM [5] have been developed. This class of SPM techniques combines contact-mode AFM with a second measurement technique (e.g. a thermocouple attached to the tip) to obtain information such as semiconductor doping, temperature, or Fowler-Nordheim tunneling current distributions.

SPM as a Failure Analysis Tool: Strengths and Limitations

The use of SPM has not become widespread in the failure analysis community mainly due to its limited scan range, nominally 100 x 100 μm maximum. With this limited range, it would take weeks and perhaps months to completely examine a whole die. In essence, SPM is not useful for defect localization. SPM is also not useful as a backside analysis tool. From the backside, the SPM probe is at least 30-50 μm from the active area. Since all SPM interactions drop off significantly as the tip-sample separation increases, signals from the active areas are extremely weak and not observable. Another disadvantage of SPM is that its probe assembly must be custom-designed to fit into packaged ICs. Data interpretation may be difficult in SPM, particularly if the signals come from different levels of metals in an IC.

SPM, however, offers excellent spatial resolution, nominally in nanometer range. This unparalleled spatial resolution may offer a distinct advantage over other techniques for resolving sub-micron features. In addition, some SPM techniques have high detection sensitivity. For example, scanning kelvin probe microscopy can detect mV potential variations [6] and magnetic force microscopy (MFM) can detect AC current in the μA range [7].

This article focuses only on SFM techniques. We will highlight several areas where SFM may be used for failure analysis of ICs. We will also show examples with unique and interesting SPM information.

Topology

Typically, SFM is used to obtain topology images on ICs. There are three modes for topology imaging: contact, intermittent-contact (tapping) or non-contact. Tapping-mode imaging yields an image with the best spatial resolution and minimal damage to both tips and samples. All the topology images in this article were obtained using the tapping mode. Fig. 1 shows the top and surface views of the memory areas of a CMOS SRAM. The image was acquired in about ten minutes. SFM topology images provide 3-D information (length, width and height), in contrast to optical and SEM images where only 2-D information (length and width) is obtained. The height information can be used to calculate surface roughness.

Recently, we have used SFM to analyze the effect of focused ion beam (FIB) exposures on ICs. Fig. 2a shows a top view of a planarized *n*-channel transistor that was given an initial low-dose FIB exposure (0.1 nC/μm^2) without charge neutralization. The image shows areas that resemble small "bumps" in the passivation layer with the height of 5 -10 nm. These "bumps" were not seen with either optical inspection or SEM imaging. The same *n*-channel transistor received an additional 0.5 nC/μm^2 dose. The additional FIB exposure converted some of the "bumps" into the "pits" (Fig. 2b). These "pits" may be the result of an ESD discharge during the FIB exposure. Subsequent electrical measurements confirmed that the transistor had indeed been damaged and there were gate oxide shorts in this transistor. The SFM

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, make any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

results suggest that the "bumps" may be the precursors of the "pits".

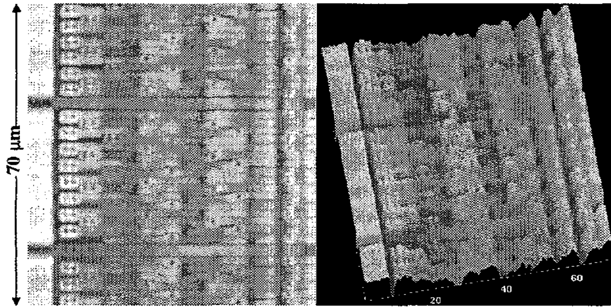

Fig. 1 : Top view (left) and surface view (right) of memory areas in a CMOS SRAM

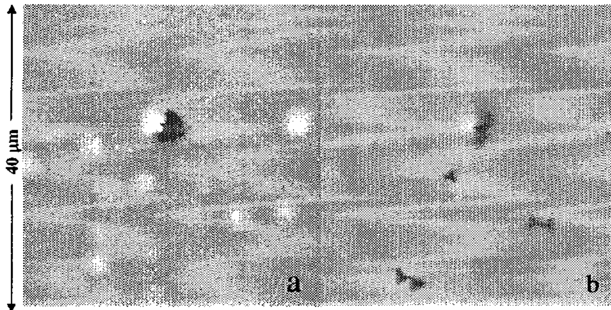

Fig. 2 : Topology images of a planarized *n*-channel transistor after exposed to (a) an initial light-dose and (b) a subsequent higher-dose of FIB irradiation .

SURFACE POTENTIAL MEASUREMENT USING SCANNING KELVIN PROBE MICROSCOPY (SKPM)

Scanning kelvin probe microscopy (SKPM) is an offshoot of electrostatic force microscopy (EFM). EFM is a subset of SFM that measures the electrostatic force between tips and samples. Both EFM and SKPM require tips to be conductive. SKPM is performed in non-contact mode with the tip positioned tens to hundreds of nanometers above the sample surface. An AC voltage at the resonant frequency (ω) of the cantilever is first applied to either the tip or the sample. A DC nulling voltage is then applied to the tip so that the ω component of the electric force between the tip and the sample vanishes. When this happens, the vibration amplitude of the cantilever at ω frequency is zero and the nulling voltage equals the surface potential.

Variations of surface potential have several sources such as changes in work function or accumulation of charge on the surface. Changes in work function result from several factors such as changes in dopant concentration or materials on the surface. Surface adsorbates and contaminants can also alter the work function. We have recently used this technique to look for residual surface charging after FIB exposure (without charge neutralization) on an *n*-channel transistor (the same transistor described in previous section). Fig. 3a shows slight or no variation in surface potential over the FIB-irradiated area after the initial low-dose exposure. Some residual charge was observed after the subsequent higher-dose exposure (Fig. 3b). The most dominant area is indicated by an arrow in Fig. 3b that happened to be where one of the "bumps" was located (Fig 2). Three more areas with smaller residual charge were observed and these areas coincided with the "pit" locations in Fig. 2b. The existence of large residual charge on one of the "bumps" suggests that there is a charge build up on the "bump" prior to an ESD event.

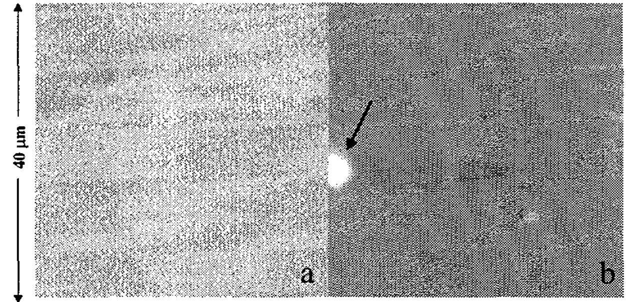

Fig. 3: Corresponding potential images of the planarized *n*-channel transistor shown in Fig. 2.

CURRENT MAPPING USING MAGNETIC FORCE MICROSCOPY (MFM)

Magnetic force microscopy (MFM) is an SFM technique that measures the magnetic force or force gradient between tips and samples. A current through a conductor in an IC produces magnetic fields that are concentric with the conductor. A magnetized tip can detect these magnetic fields. Most commercial magnetic tips are made by coating silicon tips with thin magnetic films such as cobalt, cobalt-chromium alloy or nickel-iron alloy. The magnetic force acting on the tip is the product of the magnetic field gradient generated by the conductor and the magnetic dipole moment of the tip.

MFM is performed in non-contact mode where the tip is positioned tens to hundreds of nanometers above the sample and the cantilever is vibrated at its resonant frequency. Magnetic forces/force gradients acting on the tip change the resonant characteristics (such as amplitude, frequency or phase) of the cantilever. Measuring changes in these characteristics permits detection of the magnetic fields generated by current in the conductors.

Imaging current paths is useful for analysis of failures whose only signature is anomalous high current. High-current defects are routinely detected indirectly using techniques such as liquid crystal and fluorescent microthermal imaging (FMI). MFM, however, combines excellent spatial resolution (50-100 nm) and detection sensitivity (µA for AC current) for direct detection of high-current paths.

Figs. 4a and 4b show the topology and MFM images of an electromigration test structure that was biased with a current of 50 mA at 1.3 V. The arrows indicate the direction of the current. The bright/dark contrast in the MFM image is due to the changing magnetic fields felt by the magnetic tip as it scans across the conductor. Fig. 4b shows that the MFM contrast changes from bright-to-dark to dark-to-bright as the current reverses direction.

Figs. 5a and 5b show the optical and MFM images of an IC with a metal-1 to metal-2 short. This short was created by

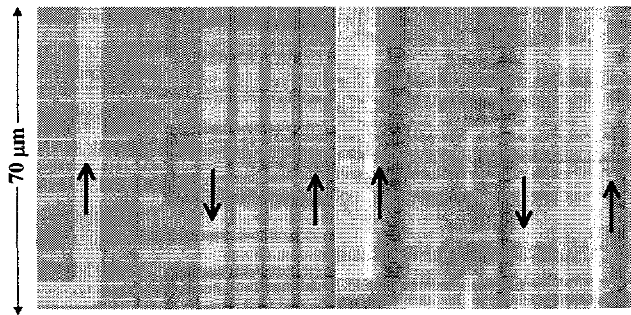

Fig. 4: (a) Topology and (b) MFM images of a electromigration test structure. The arrows show current paths through the test structure.

using a laser to fuse a metal-2 signal conductor to a metal-$1V_{DD}$ power bus. The IC had an I_{DDQ} of 10 mA at 3.3 V (I_{DDQ} was < 50 µA before the short was created). Fig. 5b shows that the current path has the shape of a backward "L". The current path turned 90 degrees at point A even though SEM voltage contrast showed that conductors BC and AD were at the same potential. This example demonstrates that the actual current path can be determined from possible multiple paths using MFM current contrast imaging.

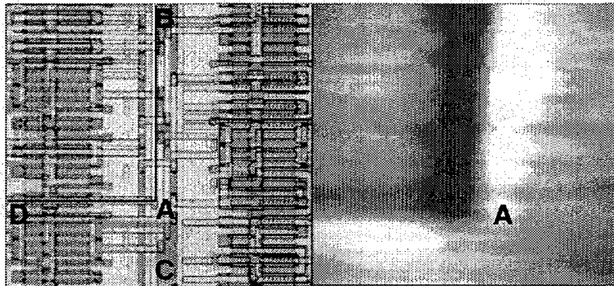

Fig. 5: (a) Optical and (b) MFM images showing the current paths resulting from a metal-1 to metal-2 short on an IC.

Two-Dimensional Dopant Profiling using Scanning Capacitance Microscopy (SCM)

Scanning capacitance microscopy (SCM) measures the capacitance variation between conductive tips and samples using a resonant capacitance circuit. SCM is done in contact-mode SFM where both topology and capacitance are measured simultaneously (see the Introduction section). The capacitance variation is generated by applying by an AC voltage (nominally several volts peak to peak in kilohertz range) between the tip and the sample. This AC electric field alternately attracts and repels the free carriers in the semiconductor beneath the tip assuming there is a thin insulating layer (e.g. native oxide) between the tip and the sample. The movement of the carriers can be modeled by an equivalent capacitor plate movement. The dopant concentration is inversely proportional to the measured dC/dV, where dC /dV is the change in capacitance per unit change in the applied voltage. The sign of dC/dV indicates the dopant type such that *n*-type dopants have a positive dC/dV and *p*-type dopants have a negative dC/dV.

The main application of SCM is to provide a two-dimensional dopant profiling, particularly 2-D cross-sectional profiling. Cross-sectional profiling (Fig. 6) provides information such as the depth profiles of the dopants. This technique can qualitatively identify anomalous distributions of dopants. It can also be used semi-quantitatively by calibrating the capacitance signals with those from other techniques such as secondary ion mass spectroscopy (SIMS) and spreading resistance profiling (SRP).

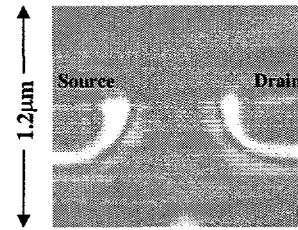

Fig. 6: Capacitance image of a cross section of a 0.5 µm, *n*-channel transistor. The contrast in the image is such that bright areas are areas of lower dopant concentration.

Conclusion

SPM techniques are not suitable as global defect-localization tools. They can, however, pinpoint the exact location of the defects once the approximate locations of the defects have been identified by other failure analysis techniques. SPM techniques also provide information such as 3-D topology, current, surface potential, and 2-D dopant profile that may not readily obtainable with other techniques. This information, coupled with the unparalleled spatial resolution and high detection sensitivity can be used by failure analysts for root cause analysis.

Acknowledgments

The authors would like to thank Rich Anderson, Ed Cole and Chuck Hawkins for reviewing this manuscript. We are also grateful to Craig Nakakura for providing the SCM image. This work was performed at Sandia National Laboratories and is supported by the U.S. Department of Energy under contract DE-AC04-94AL85000.

References

1. J. A. Stroscio and W. J. Kaiser, **Scanning Tunneling Microscopy** (Academic Press, 1993).
2. D. Sarid, **Scanning Force Microscopy, with Application to Electric, Magnetic and Atomic Forces** (Oxford University Press, 1994).
3. A. Majumdar, J.P.Carrejo, and J. Lai, "Thermal Imaging using AFM,"*Appl. Phys. Lett.* **62**, p.2501, 1993.
4. G. Neubauer, et al., "Two-Dimensional Scanning Capacitance Measurements of Cross-Sectioned Very Large Scale Integration Test Structures," *J. Vac. Sci. Technol. B*, **14**(1), p. 426, 1996.
5. B. Ebersberger, C. Boit, H. Benzinger and E. Gunther, "Thickness Mapping of Thin Dielectrics with Emission Microscopy and Conductive Atomic Force Microscopy for Assessment of Dielectric Reliability," *34th Annual Proc. Rel. Phys.*, p.126, 1996.
6. M. Nonnenmacher, M. P. O'Boyle, H. K. Wickramasinghe, "Kelvin Probe Force Microscopy," *Appl. Phys. Lett.* **58**, p. 2921, 1991.
7. A. N. Campbell, E. I Cole Jr., B. A. Dodd, and R. E. Anderson, "Internal Current Probing of Integrated Circuits Using Magnetic Force Microscopy," *31st Annual Proc. Rel. Phys.*, p. 168, 1993.

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under contract DE-AC04-94AL85000.