Nondestructive void size determination in copper metallization under passivation

Gan, Zhenghao; Tan, Cher Ming; Zhang, Guan

2003

Gan, Z., Tan, C. M., & Zhang, G. (2003). Nondestructive void size determination in copper metallization under passivation. IEEE Transactions on Device and Materials Reliability, (3)3, 69-78.

<https://hdl.handle.net/10356/79913>

<https://doi.org/10.1109/TDMR.2003.815285>

© 2003 IEEE. Personal use of this material is permitted. However, permission to reprint/republish this material for advertising or promotional purposes or for creating new collective works for resale or redistribution to servers or lists, or to reuse any copyrighted component of this work in other works must be obtained from the IEEE. This material is presented to ensure timely dissemination of scholarly and technical work. Copyright and all rights therein are retained by authors or by other copyright holders. All persons copying this information are expected to adhere to the terms and constraints invoked by each author's copyright. In most cases, these works may not be reposted without the explicit permission of the copyright holder.

Downloaded on 26 Apr 2023 09:12:37 SGT

Nondestructive Void Size Determination in Copper Metallization Under Passivation

Zhenghao Gan, Cher Ming Tan, *Senior Member, IEEE*, and Guan Zhang

Abstract—A novel nondestructive failure analysis technique to rapidly locate tiny voids in narrow metallization line covered with passivation is proposed, based on the simulation results. In this technique, the current alteration in a metal line under study is recorded continuously when it is subjected to electron beam shining and biased by a small external voltage. Finite-element analysis is performed to simulate the temperature distribution and current alteration in the metal line. The electron-beam heating is demonstrated as the most important factor contributing to the current alteration. Reconstruction of voids with any shape (such as wedge or slit) is possible on the basis of the gradient of the current alteration. It is found that the minimum detectable void size can be as low as 50 nm. Experimental verification of the technique is underway.

Index Terms—Electromigration, electron-beam heating, finite-element analysis, metallization, nondestructive technique, void detection.

I. INTRODUCTION

METAL interconnection in ULSI generally contains voids [1]–[3]. These voids can be due to processing [4] or stress migration [5]. This is particularly significant when the metal line width becomes less than 1 μm due to stress relief [6]. Voids can also be formed due to electromigration [7] when the device is operating for some time or under reliability test.

Although the void sizes can be very small, they can act as precursors for larger successors. For example, the presence of voids could enhance electromigration, making the device less reliable [8]. Hence, it is necessary to detect tiny voids on metal lines even before shipment, and scanning electron microanalysis to detect voids is becoming common in wafer fabrication plants.

The present method to detect voids on Al metal lines is through manual inspection under scanning electron microscopy (SEM), and it is inefficient if the metal line is long. Also, the manual inspection method cannot be applied to Cu metal lines because the passivation layer on top of the Cu metal lines is about 700 nm, thus, no secondary or backscattering electron image can be formed for the metal line. The passivation layer cannot be removed as Cu is easily oxidized.

Much research has been done to effectively detect voids on metal interconnects. Table I [9]–[23] provides a summary of the various methods used on for void detection. While some methods are effective in detection, the smallest void detectable

is too large to be appropriate when the metal line width can go below 0.25 μm [15]. Some methods can provide good detectivity, but may cause damage or defects in the scanned sample [10], [11]. As we enter into the deep-submicron era, a nondestructive technique to detect very small voids (as small as 50 nm) is necessary.

In order to meet the need, we have developed a method based on the principle of electron-beam heating. The concept of using spot heating to detect voids was originally proposed by Nikawa *et al.* [14]. In their method, called optical-beam induced resistance change (OBIRCH), a laser beam with specific wavelength is used to spot heat a metal line. Heat transmission is supposed to be impeded when it encounters voids, as compared with its free transmission in void-free regions. Hence, when the laser beam is incident on regions with and without voids underneath, a difference in the increase in temperature of the metal line will be observed. This difference can be reflected as a difference in the change of resistance for the two regions, which can be used to modulate the CRT display in the form of brightness changes.

However, the laser beam can only heat the surface of the passivated metal line. It is expected that a void could be detected when the void is below the surface. When the voids are at the surface, as is usually the case for Cu metallization [24], the detectability will be low because the effect of heat blocking caused by the void no longer exists. Furthermore, the resolution of the OBIRCH is limited to half the wavelength of the laser light frequency.

Besides the above-mentioned limitation of the laser-beam method, the radiation damage on copper due to the laser could be serious if the laser-beam intensity is too high. It was found that the measured damage threshold values for polished copper range from 10.1 J/cm² for a pulse duration of 1.7 ns to 67 J/cm² for a pulse duration of 58 ns [25]. The corresponding laser intensity thresholds are 6 GW/cm² and 1.1 GW/cm² for pulse durations of 1.7 and 58 ns, respectively. A lower damage threshold will result if the pulse duration is prolonged [26]. For good void detectability using laser-beam heating, longer pulse duration and higher laser beam intensity will be necessary, and this could cause damage to the metal line under investigation.

To overcome the limitations of OBIRCH, we used an electron beam (EB) instead of a laser beam as the heating source. The diameter of the EB is small and controllable with the electromagnetic lens in the SEM column. The accelerating voltage of a conventional JEOL SEM is up to 30 kV [27]. With this accelerating voltage, the EB has sufficient energy to penetrate through the passivation layer and reach the covered metal line, as shown by the Monte Carlo simulation.

Also, as the EB energy is much lower than 120 keV, which was employed by high-energy electron-beam method [10], [11],

Manuscript received January 13, 2003; revised March 19, 2003. This work was supported by the A*Star/MOE Research Funding under ARC1/00.

The authors are with the Division of Microelectronics, School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore 639798 (e-mail: ecmtan@ntu.edu.sg).

Digital Object Identifier 10.1109/TDMR.2003.815285

TABLE I
SUMMARY OF EXISTING TECHNIQUES FOR LOCATING VOIDS IN METAL LINES

Techniques	Characteristics	Advantages	Limitations
Conventional scanning electron beam	Surface morphology is obtained based on secondary electrons (SE) or backscattering electrons (BE).	Convenient and most widely used.	Deprocessing is needed to allow direct access to the layers of interest embedded in the passivation layers [9].
High energy electron beam [10,11]	High-energy electrons (120keV) penetrate through a dielectric layer and reach the interconnect line.	Resolution of the instrument is as low as 50 nm.	May cause damage or defects to the device-under-test during examination process.
Thermal wave imaging [12,13]	Propagation of thermal wave stimulated by external heat flux is differentiated between defect and non-defect regions.	Surface technique and convenient.	Resolution for subsurface flaws is highly degraded due to instrumentation noise and limited by optical wavelength.
Optical beam induced current change (OBIRCH) [14]	Laser beam is used to heat the specimen. Current alteration in the metal line caused by the heat is detected.	Laser can penetrate through passivation layer (SiO_2) and Si substrate and then heat the embedded metal line surface directly.	Only the surface of the embedded metal line is heated.
Infrared (IR) or liquid crystal (LC) imaging [15]	Applying a current across a test section of the metallization pattern to generate hot spots which are detected by IR or LC.	Generally unaffected by feature size and integration level.	The spatial resolution is restricted by IR and LC [16].
Magnetic (SQUID) techniques [9,17]	Using a SQUID sensor to detect magnetic field produced by the current in an IC.	Non-electrical-contact and non-destructive; imaging is up to many layers of metal or packaging materials.	The system could be complicated because the SQUID needs to be cooled to less than 90K for correct operation [9].
Voltage alteration [18] and photon emission techniques [19]	Take advantage of the p-n junction phenomena caused by external energy source,	Effective to detect defaults in ICs with p-n junction character.	Not efficient to detect void in metal line.
Spectral density related techniques such as S-parameter [20] and noise measurement [21]	Utilizing noise or magnitude & frequency of non-periodic low frequency voltages induced by direct current flow in test structures	Sensitive to the amount of voiding damage in the metal line.	Sensitive to undesirable noise; database is needed; no information on void geometry and location.
Resistive contrast imaging (RCI) [22,23]	A SEM technique to generate a relative resistance image of the conductor path between two test nodes.	Non-destructive; image is not affected by surface charging; effective to detect open and short paths.	Hard to provide void information since no abrupt resistance changes.

the possibility of radiation damage or defects in the testing structure during examination is much less. It has been reported [28] that the threshold electron energy for causing displacements in metals is of the order of a few hundred keV, depending on atomic number and the orientation of the specimen with respect to the EB. In copper, for example, this threshold is about 400 keV

at the $\langle 111 \rangle$ orientation. In our case, the primary electrons are 30 keV, which is much lower than the threshold voltage, hence, the radiation damage due to the EB in our case can be ignored.

When the EB is incident on a specimen, electrons will penetrate into the specimen and interact with the solid. Due to inelastic scattering of the incident electrons in the solid, they will

lose their energy, which will be converted into heat. This amount of energy is expected to be about 40%–80% of the incident electron energy [29]. Therefore, energy absorption takes place within the solid-beam interaction volume (SBIV), not just at the surface of the metal line, as in the case of OBIRCH. If a void in the metal line is within the SBIV, the energy absorption will be less. Such information could be utilized to detect the void.

Various investigations, including experimental [30], [31] and numerical [32] analyses, show that an increase in specimen temperature indeed occurs when an EB is focused on a specimen during transmission electron microscopy analysis. The resultant temperature rise was found to be directly proportional to the EB flux and the density of the specimen and inversely proportional to the thermal conductivity of the specimen. Beam current is demonstrated experimentally as the major factor controlling the temperature rise [33]. Therefore, the EB can indeed be used as the spot heating source.

In Section II, a detailed description of the principle of the technique is given. Section III describes the model formulation for the simulation. A square void was used to illustrate the physics and simulation. In Section IV, the numerical results on a metal line with a square void are given. The proposed methodology is then applied to the wedge and slit voids as they are usually observed in electromigration failures. Finally, the conclusion is given in Section V.

II. PRINCIPLE OF THE TECHNIQUE

When an EB is incident on a metal line, some incident electrons will be absorbed by the metal line, and they constitute a current flow through the metal line [22]; some will be converted into heat through inelastic collision in the material [29].

The additional current flow due to the incident EB was utilized by Smith *et al.* [22] for the detection of open- and short-circuited paths, where abrupt resistance changes are present. This detection method is called resistive contrast imaging (RCI). However, it is not suitable for void detection because no abrupt resistance change exists.

When a void is present at the spot where the EB is incident, the heating effect by the EB will be altered due to uneven heat absorption and the impedance to thermal transmission. The amount of additional current flow due to incident EB will also be altered when there is a void. Hence, if the information of the additional current flow and the temperature rise due to EB heating can be extracted, the detection of a void can be obtained.

To extract this information, a constant voltage is applied across the metal line, and the current through the metal line is measured. Due to the alternation of the additional current flow and EB heating, the current will be different if a void is present. Hence, if the measured current can be used to form an image, the presence of a void can be observed. However, when a current flows through the metal line, joule heating will also heat up the metal line, which will cause the resistance of the metal line to change as well, and this must be taken into account.

To provide a detailed qualitative analysis on this principle, we assume a rectangular void in a metal line. Fig. 1 illustrates schematically the scanning of an EB across the void with size d from the left (A) to the right (F) in the x direction. The cor-

Fig. 1. Schematic illustration showing EB scanning across a void with size d . The dotted, rectangular, and blank circles represent void and SBIV, respectively. The EB, perpendicular to the paper and located at the centers of the circles, is scanning from the left to the right in x direction. Phase 1: SBIV far away from the void → its right edge (RE) touches the left edge (LE) of the void (for EB: A → B). Phase 2: SBIV's RE touches void's LE → SBIV's RE touches void's RE (for EB: B → C). Phase 3: SBIV's RE touches void's RE → SBIV's LE touches void's LE (for EB: C → D). Phase 4: SBIV's LE touches void's LE → SBIV's LE touches void's RE (for EB: D → E). Phase 5: SBIV's LE touches void's RE → SBIV far away from the void (for EB: E → F).

responding SBIV is represented by open circles. Although the SBIV will be altered depending on the proximity of the EB to a void, such information cannot be obtained from the present Monte Carlo simulation. Hence, for simplicity, the SBIV is assumed to be constant in this paper. The effect of the changing SBIV on the void reconstruction will be presented in future work.

In the case of a metal line without EB heating (EBH), let I be the current flows through the metal line and R be the resistance of the metal line. Then we have the voltage across the metal line $U = IR$. In the case with EBH, we have $U = (I + \Delta I)(R + \Delta R)$. As the interconnection is usually long, and only a small portion of it is heated up by EBH, we can assume $\Delta R \ll R$. With some mathematical manipulation, we have

$$\Delta I = -I \cdot \frac{\Delta R}{R + \Delta R} = -\frac{U}{R} \cdot \frac{\Delta R}{R + \Delta R} \approx -\frac{U}{R^2} \cdot \Delta R. \quad (1)$$

Therefore, one can see that ΔI is proportional to the resistance change ΔR .

But

$$\Delta R = \Delta \rho \cdot a_1 \quad (2)$$

where $\Delta \rho$ is resistivity change caused by temperature change (i.e., EBH)

$$a_1 = \frac{L}{S}$$

where L and S are length and cross-section area of the affected volume, respectively. The electrical resistivity of Cu could be estimated as a linear function of temperature [34] as follows:

$$\Delta \rho = \Delta T \cdot a_2 \quad (3)$$

where a_2 is a positive constant which can be obtained from Schuster *et al.* [34]. Hence, we have

$$\Delta R = a_1 a_2 \Delta T. \quad (4)$$

The temperature change ΔT due to EBH around a void is attributed to two factors, namely, the amount of energy absorption and the impedance of heat transmission. If the ΔT due to

Fig. 2. Schematic illustration of intersection area A between SBIV and void.

the former is denoted as ΔT_a , and that due to the latter is denoted as ΔT_i , then the total change in temperature is given by

$$\Delta T = \Delta T_a + \Delta T_i. \quad (5)$$

For the case of ΔT_a , consider Phase 2 in Fig. 1. As the SBIV continuously enters into a void region, the intersection area A between the SBIV and void, as shown in Fig. 2, can be expressed as

$$A = \alpha \cdot r^2 - r \cdot (r - x) \cdot \sin \alpha \quad (6)$$

where

$$\alpha = \arccos \frac{r - x}{r}. \quad (7)$$

If (6) is plotted as A/r^2 in terms of x/r , it can be seen that for a given r the area A could be approximated as a linear function of x . Hence, (6) can be written as

$$A = a \cdot x + b \quad (8)$$

with $a > 0$.

As the SBIV continuously enters into the void region, the intersection area A will increase, thus, the absorbed energy will decrease continuously. To simplify the qualitative analysis, the absorbed energy Q_a can be considered to be proportional to the area A , thus, Q_a can be estimated as a linear function of EB location x as follows:

$$Q_a = x \cdot a_{3a} + b_{3a} \quad (9)$$

where a_{3a} and b_{3a} are constant. Note that $a_{3a} < 0$ since the absorbed energy Q_a decreases with an increase in x .

According to thermodynamic theory

$$Q_a = c \cdot \Delta T_a \quad (10)$$

where c is the specific heat of the metal line. Hence, combining (9) and (10), we have

$$\Delta T_a = \frac{1}{c} (x \cdot a_{3a} + b_{3a}). \quad (11)$$

Combining (1)–(4) and (11), we get the current change ΔI_a due to ΔT_a as follows:

$$\Delta I_a = -\frac{a_1 a_2 U}{c R^2} (x \cdot a_{3a} + b_{3a}). \quad (12)$$

The gradient of ΔI_a with respect to x is then

$$\text{grad}(\Delta I_a) = -\frac{a_1 a_2 a_{3a} U}{c R^2}. \quad (13)$$

It is clear that $\text{grad}(\Delta I_a) > 0$ since $a_{3a} < 0$ and the other constants are positive. This means that the current change due to energy absorption will increase linearly as SBIV continuously enters into a void.

Fig. 3. Schematic diagram of the multilayer structure used for simulation.

On the other hand, the heat dissipation around a void will be slower due to the low thermal conductivity of a void, as it is assumed to be vacuum within. It is expected that such heat transmission impedance will be higher when the EB is approaching the void. Following the approach in heat absorption, we can assume that the temperature change due to the impedance of heat transmission ΔT_i as a linear function of beam location as

$$\Delta T_i = x \cdot a_{3i} + b_{3i} \quad (14)$$

where a_{3i} and b_{3i} are constants. In this case, $a_{3i} > 0$ since ΔT_i increases as x increases.

Similarly, we can obtain the current change ΔI_i due to ΔT_i

$$\Delta I_i = -\frac{a_1 a_2 U}{R^2} (x \cdot a_{3i} + b_{3i}) \quad (15)$$

and its gradient with respect to x is

$$\text{grad}(\Delta I_i) = -\frac{a_1 a_2 a_{3i} U}{R^2}. \quad (16)$$

In this equation, since $a_{3i} > 0$, it is interesting to find that $\text{grad}(\Delta I_i) < 0$. Hence, the current change due to heat transmission impedance will decrease linearly when the EB is approaching the void.

Since there is a change in gradient of ΔI as the beam is scanning across the voids, one could use the information to locate the void using the principle of EBH. In order to verify the principle, simulation is performed using finite element analysis (ANSYS, version 5.6). The additional current flow and amount of EB heating is determined by the EB trajectory, which is obtained from Monte Carlo simulation. The formulation of the simulation will be discussed in Section III.

III. FINITE-ELEMENT MODELING

A. Model Description

Fig. 3 shows schematically the cross-sectional view of the model to be used in the simulation. Although in actual Cu metallization system, a cap layer of silicon nitride (Si_3N_4) exists on top of the Cu line, we do not include this layer because the EB penetration through silicon oxide and nitride are similar, as shown in Fig. 4, and the computation can be simplified if we consider only a single passivation material.

The width of the embedded metal line is $1 \mu\text{m}$ and its thickness is $0.5 \mu\text{m}$. The primary EB is assumed to be scanning over the top surface of the structure.

As the purpose of the simulation is to study the EB and joule heating effects for metal lines with and without voids, computation time can be reduced if only a portion of the structure is simulated. However, the portion must be large enough that the

Fig. 4. EB penetration depth in SiO_2 and Si_3N_4 in terms of the energy of the primary EB.

thermal field will not be affected by the boundary of the structure. Following Beaudoin *et al.* [35], the portion of the structure for simulation in this work is set at $10\text{ }\mu\text{m}$ wide by $60\text{ }\mu\text{m}$ long.

Electrical circuit analysis is performed using the three-dimensional eight-node element type SOLID5 [36]. Fig. 5 shows the finite element mesh for the case where void is present in the metal line. The void size is assumed to be $0.4\ \mu\text{m} \times 0.4\ \mu\text{m} \times 0.5\ \mu\text{m}$. A fine mesh was adapted around the void so as to obtain detailed temperature distribution there. However, the other location was meshed coarser to reduce computational time. The fine mesh is chosen so that no appreciable changes in the contours of temperature distribution around the void will result if further refinements in mesh resolution are taken.

A reduction of element size by half of that shown in Fig. 5 leads to the difference in temperature distribution of less than 0.1% and that for the current distribution of less than 0.03%. On the other hand, the computational time is increased by more than 6 times with the reduction of the mesh size. Hence, the mesh size shown in Fig. 5 is used in this work.

The scanning speed of the EB assumed in the modeling is about 0.1 m/s. This scanning speed corresponds to a 1024×768 pixels frame (17-in monitor) scanning time of 2 s when the magnification is 1500. The accelerating voltage of the incident EB is 30 keV. It is noted that the fastest scanning speed of the JEOL JSM-5900LV SEM is 0.19 s/frame and the slowest one is 160 s/frame [37].

According to (1), it is desirable to apply higher biasing voltage U to the metal line so as to improve the current signal ΔI . However, in order to ensure that the current density in the metal line is not so high as to cause damage, 0.09-V biasing voltage is applied on the metal line in the modeling. This will result in a current density of about 9×10^6 A/cm² through the copper metal line with a resistance of $1.7 \mu\Omega\cdot\text{cm}$ [38]. It has been proven that the application of such current density over a short period is not destructive at room temperature [14].

During the scanning process, the EB is perpendicular to the length-width (x - y) plane of the metal line (Fig. 6). To assist the description of the beam movement, a dashed-line grid is added around the void in Fig. 6. Each element of the grid is a $0.1\text{ }\mu\text{m} \times 0.1\text{ }\mu\text{m}$ square. The EB is assumed to move along the grid from the starting point [node $(-1.0, 0)$] to the successive nodes, horizontally, as indicated by the block arrows. After the EB reaches

Fig. 5. Finite-element mesh for a metal line with void (the top SiO₂ layer is not included).

Fig. 6. Schematic illustration of the grid for EB scanning. The EB is scanned perpendicular to the x - y plane. The EB moves from the starting point to the successive nodes as indicated by the block arrows (units in μm). The void shown here is $0.4\ \mu\text{m} \times 0.4\ \mu\text{m}$ in square shape.

node (1.0, 0), it moves to node (-1.0, 0.1) and shifts horizontally again. The process repeats until the EB reaches the ending point [node (1.0, 0.5)]. It takes 1 μ s for the EB to move from one node to the successive one, which is calculated from the scanning speed of the EB (0.1 m/s) as mentioned earlier. Considering the symmetrical geometry of the metal line, only the region from $y = 0$ to $y = 0.5 \mu\text{m}$ is simulated.

In the modeling, the dynamic temperature change in the metal line is included. The change of temperature of the spot of the metal line where the EB is incident on is shown in Fig. 7. This temperature profile will be used in the calculation of the ΔT and ΔI in this paper.

B. Temperature-Dependent Material Properties

Temperature-dependent thermal conductivities of the thin layers (SiO₂ and Cu) and Si substrate are extracted from the Material Property Database [39]. The temperature-dependent electrical resistivity ρ of bulk copper [34] is used for the thin copper lines. This approximation is justifiable because the copper thickness of 500 nm is much greater than the mean free path of the conduction electrons in this simulation. The mean

Fig. 7. Rise in temperature due to EBH as a function of the EBH time.

Fig. 8. (a) Typical Monte Carlo calculation of the electron trajectory in the multilayer specimen using CASINO. (b) Approximation of the energy transfer volume in the multilayer structure.

free path is generally of the order of several hundred angstroms at room temperature [40].

C. Spatial and Depth Distribution of Energy Dissipation of the Incident Electrons

To estimate the spatial and depth distribution of energy dissipation of an incident EB, a freeware of the Monte Carlo simulation program CASINO [41] was used to simulate the electron trajectory in the multilayer structure. In the simulations, the accelerating voltage of the primary EB was 30 keV and its beam diameter was 5 nm. Fig. 8(a) shows a typical Monte Carlo calculation of the electron trajectory in the multilayer specimen by using CASINO. Based on this electron–solid interaction volume, the energy transfer volume in the specimen may be approximated as a cone, as shown in Fig. 8(b).

The stopping energies of the electrons at the interfaces are shown in Fig. 8(b). This stopping energy is the minimal electron

energy at which a trajectory is terminated. Hence, the estimated energy absorption by the various layers can be obtained as the difference of these stopping energies at the respective interfaces. The estimated energy absorption by the first SiO₂ layer, the Cu layer, and the second SiO₂ layer is 1.33, 3.17, and 1.90 keV, respectively. Note that the void in the specimen was assumed to be a vacuum, which will not absorb energy when an EB is heating the specimen.

In the modeling, 10% of the incident EB is assumed to flow through the Cu metal line. This 10% is estimated from the solid–beam interaction volume within the metal line, and hence, it represents the maximum amount of absorbed current in metal line. In fact, the exact amount of absorbed current is not important, because its effect on ΔI is insignificant compared with that due to EHB, as can be obtained from the simulation. The ratio of the current change ΔI due to the absorbed current to that due to EB heating is only about 0.1% when the absorbed current is assumed as 10% of the primary EB. For a lower percentage of the absorbed current, the ratio will be even smaller.

IV. SIMULATION RESULTS AND DISCUSSION

A. Temperature Contour in Cu Line

Temperature contours of the Cu line, with and without voids, are compared in Fig. 9(a) and (b) when the EB is incident at node (0, 0.5) in Fig. 6 assuming the ambient temperature of the metal line is 298 K. One can see that the maximum temperature in the line with void (319.188 K) is about 7 K lower than that in the void-free case (326.068 K). The difference in temperature between these two cases is mainly attributed to the lesser energy absorption in the line with void.

B. Maximum Temperature and Current During EB Scanning

Fig. 10 shows the maximum temperature in the line with void with respect to the location of the incident EB. It can be seen that the curves in Fig. 10 are symmetrical about $x = 0 \mu\text{m}$. The closer the EB to the center of the void, the lower the temperature of the metal line, hence, higher current is expected due to the lower resistance, as shown in Fig. 11. The highest current could be detected when the EB reaches the center of the void.

C. Void Reconstruction

Let us now apply the theoretical consideration in Section II to analyze the current change in Fig. 11. Fig. 12 illustrates the current change in terms of the phases for the square void when the EB is scanning along x direction at $y = 0.5 \mu\text{m}$. In Phase 1, ΔI_a equals zero because there is no interaction between SBIV and void. Therefore, the current change is solely caused by impedance of heat transmission and its gradient is negative (16). As the SBIV begins to enter into the void region in Phase 2, ΔI_a is no longer zero, making the gradient become positive.

In Phase 3, the void volume covered by the SBIV is unchanged, thus ΔI_a is a constant and $\text{grad}(\Delta I) = 0$. For the case of Phases 4 and 5, due to the symmetry of the structure and the antisymmetry of the EB scanning action, the $\text{grad}(\Delta I)$ in these two phases will be opposite to that in phases 2 and 3, respectively.

(a)

(b)

Fig. 9. Temperature profiles of the Cu line. (a) Void-free case. (b) Void case.

Fig. 10. Maximum temperature in the metal line with void as a function of the EB locations.

If we look at Fig. 1 in more detail, the distance that the EB travels in Phase 2 (from B to C) is equal to the void size d . Therefore, the void size could be identified from Fig. 12 exactly by analyzing $\text{grad}(\Delta I)$.

The square void studied above assumes full penetration of the void through the thickness of the metal line. In practice, it is

Fig. 11. Current through the left face in the metal line with void as a function of the EB locations.

Fig. 12. Detailed illustration of the current change at difference Phases depicted in Fig. 1 for square void when the EB is scanning at $y = 0.5 \mu\text{m}$. The simulation results (shown as solid dots) are replotted from Fig. 11. Fig. 13. Simulation results for square-shaped void of $400 \text{ nm} \times 400 \text{ nm}$ in size with 1/3, 2/3, and full penetration through the thickness of the metal line.

common that a void extends only partially through the thickness of a line. It is reasonable to expect that both the void size and void depth may affect the pattern and magnitude of the $\Delta I-X$ curve. Fig. 13 shows the simulation results for square void of $400 \text{ nm} \times 400 \text{ nm}$ in size with 1/3, 2/3, and full penetration through the thickness of the metal line. It can be seen that the magnitude of the maximum current change is proportional to the void depth, and hence, the void volume. This is easily understood because a deeper void (i.e., larger void volume) leads to less energy absorbed by the metal line during EBH around the void, as compared with the EBH of a perfect metal line. Higher temperature variation is thus achieved during EBH around the void.

Fig. 14. (a) ΔI image. (b) $\text{grad}(\Delta I)$ image. (c) Final image for the metal line with a square void.

Further investigation has shown that the void volume, void size, and equivalent void depth could be extracted, as is elaborated elsewhere [42]. Hence, a three-dimensional void in passivated metal interconnects could be reconstructed in principle using this method [43].

To obtain the void shape from the raw data of ΔI in Fig. 11, a basic image processing procedure is employed. The image of ΔI for the square void (shown in Fig. 6) is plotted in Fig. 14(a). The white zebra lines are deliberately added in the image to show the void shape and location. It is found that there is much difference between the ΔI image and the square void.

If, on the other hand, the image of $\text{grad}(\Delta I)$ for the square void is plotted instead, we have Fig. 14(b). A coupled square-like shape, similar to the centered zebra-lined square void is observed. The symmetrical images of the squares are a reflection of the symmetrical characteristic of $\text{grad}(\Delta I)$, where Phases 4 and 5 are mirror symmetry to Phases 2 and 1, respectively. With some image processing, the image of $\text{grad}(\Delta I)$ can be made to be close to the zebra-lined shape, as shown in Fig. 14(c). Therefore, both the void shape and location could be identified. The blur image along the y direction is due to the finite size of the SBIV. For example, when the EB is scanning at $y = 0.1 \mu\text{m}$, there will be overlapping of the SBIV with the void. Hence, partial void information will be contained in the ΔI at $y = 0.1 \mu\text{m}$ even though the void does not extend to $y = 0.1 \mu\text{m}$. Further refinement is underway.

Simulation is also performed on a square void as small as 50 nm. Fig. 15 shows that measurable current alteration can be achieved even with such a small void size.

Fig. 15. Estimated ΔI versus conductor length for 50-nm square void (full penetration).

D. Thermal Void Growth During EB Heating

As the technique relies on EBH, possible void growth due to this heating could distort the void shape and size. In order to demonstrate the effect of heating on void growth, thermomigration in copper line during EB inspection is analyzed. The temperature distribution and its gradient, extracted from the finite-element modeling, are used to estimate the thermomigration.

The thermomigration can be expressed as [44]

$$\begin{aligned} \frac{\partial C}{\partial t} &= -\nabla (J_{\text{thermal}}) \\ &= -\nabla \left(-\frac{Q^* DC \nabla T}{KT^2} \right) \\ &= \frac{Q^* D}{KT^2} \frac{dC}{dx} \cdot \frac{dT}{dx} + \frac{Q^* DC}{K} \frac{d}{dx} \left(\frac{1}{T^2} \frac{dT}{dx} \right) \end{aligned} \quad (17)$$

where

- Q^* quantity of heat flow needed to maintain steady-state conditions with unit mass transport [44] (for copper, it is equal to $2.77\text{e-}8 \text{ pJ}$ [45]);
- T absolute temperature of the metal line;
- C copper atom concentration, equal to $8.44\text{e}28 \text{ m}^{-3}$;
- K Boltzmann's constant;
- D diffusivity of copper atoms in copper polycrystalline line.

D is given by

$$D = D_0 \exp \left(-\frac{E_a}{KT} \right) \quad (18)$$

where D_0 is the apparent value of D at infinite temperature, which is equal to $0.84\text{e-}5 \text{ m}^2/\text{s}$ for copper [46] and E_a is the activation energy for copper thermomigration, which is equal to 1 eV [47].

The first term on the right-hand side of (17) can be ignored because copper atomic concentration in the line can be assumed as uniform. Thus, (17) reduces to

$$\frac{dC}{C} \frac{1}{dt} \approx \frac{Q^* D}{K} \left(\frac{-2}{T^3} \left(\frac{dT}{dx} \right)^2 + \frac{1}{T^2} \frac{d^2 T}{dx^2} \right). \quad (19)$$

Fig. 16 shows a typical temperature T , its gradient dT/dx , and the second derivative $d^2 T/dx^2$ along the metal line. Their respective maximum values are 25 K , $30 \text{ K}/\mu\text{m}$, and $150 \text{ K}/\mu\text{m}^2$. With these values, the maximum value of $(dC/C)(1/dt)$, as

Fig. 16. Typical temperature T and its gradient dT/dx and second derivative (d^2T/dx^2) along the metal line.

Fig. 17. Final images of the voids. (a) Wedge-shaped void. (b) Slit-shaped void.

computed using (19), is found to be about $6.46 \times 10^{-9} \text{ s}^{-1}$. Since the EB remains on a spot for about $1 \mu\text{s}$, the percentage change in the copper atomic concentration due to this induced thermomigration is only about $6.46 \times 10^{-13}\%$, a value that can be neglected. Thus, the void growth caused by electron heating during beam scanning can be ignored.

E. Application of the Methodology to Real Voids

The above results were based on a square void. However, wedge and slit voids are the most frequently observed morphology in metal lines with polycrystalline [48] and bamboo structures [49], respectively, during electromigration tests. Therefore, simulation was also performed to study the possibility of identifying such void shapes based on our technique.

Following the procedures described above for the square void, the final images for wedge and slit voids are shown in Fig. 17(a) and (b), respectively. The void boundary is clearly visualized. In fact, since the gradient contrast across the void interfaces is expected despite the geometrical sophistication of the voids, the method is expected to enable visualization of void of any shape.

V. CONCLUSION

A method was proposed to rapidly locate small voids for deep-submicron metal lines. In this method, the embedded metal line was connected to an external circuit. The metal line was also biased by a small external voltage. The current flow in the metal line was monitored during EB scanning of the specimen surface. The void information (location and shape) could be obtained from the gradient of the current perturbation. Simulation demonstrated the applicability of the technique, which is universal to detect void with any shape. Experimental validation of this simulation and refinement of the resulting void image is being undertaken.

ACKNOWLEDGMENT

The authors would like to thank Prof. D. Drouin from the Université de Sherbrooke, Quebec, in providing assistance in the Monte Carlo simulation of the electron-beam-solid interaction. They also thank Dr. C. Y. Li, Prof. K. Prasad, and Prof. D. H. Zhang for their assistance with this project.

REFERENCES

- [1] A. S. Oates, "Electromigration transport mechanisms in Al thin-film conductors," *J. Appl. Phys.*, vol. 79, no. 1, pp. 163–169, 1996.
- [2] W. L. Smith, C. G. Welles, and A. Bivas, "Evaluating voids and microcracks in Al metallization," *Semiconductor Int.*, vol. 13, no. 1, pp. 92–95, 1990.
- [3] S.-H. Lee, J. C. Bravman, J. C. Doan, S. Lee, P. A. Flinn, and T. N. Marieb, "Stress-induced and electromigration voiding in aluminum interconnects passivated with silicon nitride," *J. Appl. Phys.*, vol. 91, no. 6, pp. 3653–3657, 2002.
- [4] A. Zitzelsberger and M. Lehr, "Reliability aspects of stress-induced voiding in $0.25 \mu\text{m}$ metallization," in *Proc. IEEE Int. Integrated Reliability Workshop*, 1999, pp. 10–13.
- [5] H. Okabayashi, "Stress-induced void formation in metallization for integrated circuits," *Materials Sci. Eng. R: Reports*, vol. 11, no. 5, pp. 191–241, 1993.
- [6] T. D. Sullivan, J. G. Ryan, J. R. Riendeau, and D. P. Bouldin, "Stress-induced voiding in aluminum alloy metallizations," in *Proc. SPIE—Metallization: Performance and Reliability Issues for VLSI and ULSI*, vol. 1596, 1991, pp. 83–95.
- [7] R. Frankovic and G. H. Bernstein, "In situ observations of electromigration-induced void dynamics," in *MRS Symp. Proc.: In Situ Electron and Tunneling Microscopy of Dynamic Processes*, vol. 404, 1996, pp. 163–169.
- [8] S. A. Lytle and A. S. Oates, "The effect of stress-induced voiding on electromigration," *J. Appl. Phys.*, vol. 71, no. 1, pp. 174–178, 1992.
- [9] L. A. Knauss, A. B. Cawthorne, N. Lettsome, S. Kelly, S. Chatrathorn, E. F. Fleet, F. C. Wellstood, and W. E. Vanderlinde, "Scanning SQUID microscopy for current imaging," *Microelectron. Reliab.*, vol. 41, pp. 1211–1229, 2001.
- [10] T. Marieb, J. C. Bravman, P. Flinn, and M. Madden, "In situ observations of voiding in metal lines under passivation," in *MRS Symp. Proc.*, vol. 338, 1994, pp. 409–413.
- [11] J. C. Doan, J. C. Bravman, P. A. Flinn, and T. N. Marieb, "A quantitative study of void nucleation times in passivated aluminum interconnects," in *MRS Symp. Proc.*, vol. 516, 1998, pp. 83–88.
- [12] W. L. Smith, C. G. Wells, and A. Rosencwaig, "Apparatus for evaluating thermal and electrical characteristics in a sample," U.S. Patent 5 228 776, July 20, 1993.
- [13] J. C. Murphy, J. W. MacLachlan, and L. C. Aamodt, "Image contrast processes in thermal and thermoacoustic imaging," *IEEE Trans. Ultrason., Ferroelect., Freq. Contr.*, vol. UFFC-33, pp. 529–541, Sept. 1986.
- [14] K. Nikawa, C. Matsumoto, and S. Inoue, "Novel method for defect detection in Al stripes by means of laser beam heating and detection of changes in electrical resistance," *Jpn. J. Appl. Phys.*, vol. 31, pp. 2260–2265, 1995.
- [15] J. T. Yue and S. Pramanick, "Void detection in metallization patterns," U.S. Patent 5 504 017, Apr. 2, 1996.

- [16] R. E. Anderson, J. M. Soden, C. L. Henderson, and E. I. Cole, Jr., "Challenges for IC failure analysis—Present and future," in *Proc. 5th IPFA*, Singapore, 1995, pp. 1–8.
- [17] K. Nikawa and S. Inoue, "Novel nondestructive and nonelectrical-contact failure analysis technique—Laser-SQUID microscopy," in *Proc. 39th Annu. Int. Reliability Physics Symp.*, Orlando, FL, 2001, pp. 289–293.
- [18] E. I. Cole, Jr., "Global fault localization using induced voltage alteration," *Microelectron. Reliab.*, vol. 41, pp. 1145–1159, 2001.
- [19] I. De Wolf and M. Rasras, "Spectroscopic photon emission microscopy: a unique tool for failure analysis of microelectronics devices," *Microelectron. Reliab.*, vol. 41, pp. 1161–1169, 2001.
- [20] S. Foley, L. Floyd, and A. Mathewson, "A novel fast technique for detecting voiding damage in IC interconnects," *Microelectron. Reliab.*, vol. 40, pp. 87–97, 2000.
- [21] G. H. Massiha, T. M. Chen, and G. J. Scott, "Detection of hot spots in thin metal films via thermal noise measurements," *IEEE Electron Device Lett.*, vol. 10, pp. 58–60, 1989.
- [22] C. A. Smith, C. R. Bagnell, E. I. Cole, F. A. Dibianca, D. G. Johnson, W. V. Oxford, and R. H. Propst, "Resistive contrast imaging: A new SEM mode for failure analysis," *IEEE Trans. Electron Devices*, vol. ED-33, pp. 282–285, 1986.
- [23] E. I. Cole, Jr., "Resistive contrast imaging applied to multilevel interconnection failure analysis," in *Proc. 6th Int. IEEE VLSI Multilevel Interconnection Conf.*, 1989, pp. 176–182.
- [24] C. L. Gan, F. Wei, C. V. Thompson, K. L. Pey, W. K. Choi, S. P. Hau-Riege, and B. Yu, "Contrasting failure characteristics of different levels of Cu dual-damascene metallization," in *Proc. 9th IPFA*, Singapore, 2002, pp. 124–128.
- [25] J. F. Figueira and S. J. Thomas, "Damage thresholds at metal surfaces for short pulse IR lasers," *IEEE J. Quantum Electron.*, vol. QE-18, pp. 1381–1386, 1982.
- [26] (2003, Mar.) Optical Coating. Seoul Precision Optics, Seoul, Korea. [Online]. Available: http://www.spocc.com/main_coating.htm
- [27] (2002, Oct.) Scanning electron microscopes. JEOL USA, Inc., Peabody, MA. [Online]. Available: <http://www.jeol.com/sem/sem.html>
- [28] M. L. Jenkins and M. A. Kirk, "The role of transmission electron microscopy in characterizing radiation damage," in *Characterization of Radiation Damage by Transmission Electron Microscopy*. Bristol, U.K.: Inst. Phys., 2001, p. 3.
- [29] L. Reimer, "Electron scattering and diffusion," in *Scanning Electron Microscopy: Physics of Image Formation and Microanalysis*. New York: Springer, 1998, pp. 57–134.
- [30] B. Gale and K. F. Hale, "Heating of metallic foils in an electron microscope," *Brit. J. Appl. Phys.*, vol. 12, pp. 115–117, Mar. 1961.
- [31] W. F. Lewis, J. Marti, and D. I. Paul, "New technique for determining the heating effects of the EB on metal foils in an electron microscope," *Rev. Sci. Instrum.*, vol. 46, no. 8, pp. 1092–1094, 1975.
- [32] S. X. Li, G. Yao, Y. D. Tang, L. Z. Sun, and Z. G. Wang, "Heating of metal/ceramic foils in an electron microscope," *Scripta Metallurgica et Materialia*, vol. 30, no. 12, pp. 1547–1552, 1994.
- [33] E. P. Butler and K. F. Hale, "Dynamic experiments in the electron microscope," in *Practical Methods in Electron Microscopy*, A. M. Glauret, Ed. Amsterdam, The Netherlands: North-Holland, 1981, vol. 9, p. 10.
- [34] C. E. Schuster, M. G. Vangel, and H. A. Schafft, "Improved estimation of the resistivity of pure copper and electrical determination of thin copper film dimensions," *Microelectron. Reliab.*, vol. 41, pp. 239–252, 2001.
- [35] F. Beaudoin, X. Chaffleur, J. P. Fradin, P. Perdu, R. Desplats, and D. Lewis, "Modeling thermal laser stimulation," *Microelectron. Reliab.*, vol. 41, pp. 1477–1482, 2001.
- [36] "ANSYS elements reference: ANSYS release 5.6," ANSYS Inc., Canonsburg, PA, 1999.
- [37] "General specifications and composition," in *JSM-5910LV Scanning Electron Microscope Operator's Manual*. Tokyo, Japan: JEOL Ltd., 2001.
- [38] M. Fenn, G. Akutet, and P. E. Donovan, "Electrical resistivity of Cu and Nb thin films," *J. Phys.: Condensed Matter*, vol. 10, pp. 1707–1720, 1998.
- [39] "Material Property Database, v1.58," JAHM Software, North Reading, MA, 1999.
- [40] T. J. Coutts, "Electrical properties and applications of thin metal and alloy films," in *Active and Passive Thin Film Devices*. New York: Academic, 1978, pp. 57–111.
- [41] D. Drouin, A. R. Couture, R. Gauvin, P. Hovington, P. Horny, and H. Demers. (2001, Sept.) CASINO (monte Carlo Simulation of electron trajectory in sOlids), Version 2.41. Université de Sherbrooke, Quebec, Canada. [Online]. Available: <http://www.gel.usherb.ca/casino/>
- [42] C. M. Tan and Z. Gan, "Voids characterization system for metal interconnection," U.S. patent 60 438 920, Jan. 9, 2003.
- [43] C. M. Tan, Z. H. Gan, G. Zhang, K. Prasad, and D. H. Zhang, "A novel technique to re-construct 3D void in passivated metal interconnects," in *Proc. Mater. Res. Soc. Symp.*, vol. 766, 2003, pp. E4.8.1–E4.8.6.
- [44] A. Christou, "Electrothermomigration theory and experiments in aluminum thin film metallizations," in *Electromigration and Electronic Device Degradation*. New York: Wiley, 1994, pp. 291–316.
- [45] R. W. Cahn and P. Hassen, *Physical Metallurgy*. Amsterdam, The Netherlands: North-Holland, 1983, vol. 1, p. 617.
- [46] S. P. Murarka, I. V. Verner, and R. J. Gutmann, *Copper—Fundamental Mechanisms for Microelectronic Applications*. New York: Wiley, 2000, p. 292.
- [47] J. R. Lloyd, J. Clemens, and R. Snede, "Copper metallization reliability," *Microelectron. Reliab.*, vol. 39, no. 11, pp. 1595–1602, 1999.
- [48] P. A. Flinn, M. C. Madden, and T. N. Marieb, "In situ SEM observations of electromigration voids in Al lines under passivation," *MRS Bull.*, pp. 51–55, June 1994.
- [49] E. Arzt, O. Kraft, W. D. Nix, and J. E. Sanchez, Jr., "Electromigration failure by shape change of voids in bamboo lines," *J. Appl. Phys.*, vol. 76, no. 3, pp. 1563–1571, 1994.

Zhenghao Gan received the B.Eng. and M.Eng. degrees in materials science and engineering from Zhejiang University, Hangzhou, China, in 1995 and 1997, respectively, and the Ph.D. degree in mechanical engineering from Nanyang Technological University, Singapore, in 2002.

He is currently a Research Fellow with the School of Electrical and Electronic Engineering, Nanyang Technological University. His research interests include reliability and failure analysis of electronic materials and devices and deposition and

thermal-physical mechanical properties of thin films.

Cher Ming Tan (M'84–SM'00) was born in Singapore in 1959. He received the B.Eng. (Hons.) degree from the National University of Singapore in 1984 and the M.A.Sc. and Ph.D. degrees from the University of Toronto, Toronto, ON, Canada, in 1988 and 1992, respectively, all in electrical engineering.

From 1992 to 1996, he was with LiteOn Power Semiconductor Corporation, Taiwan, R.O.C., as a Quality and Reliability Manager and an Engineering Consultant. In 1996, he joined Chartered Semiconductor Manufacturing, Ltd., Singapore, as a Quality and Reliability Section Manager. In 1997, he joined the School of Electrical and Electronic Engineering, Nanyang Technological University as a Lecturer on IC reliability and failure analysis. His current research areas include reliability data analysis, electromigration reliability physics and test methodology, silicon wafer defects study, quality engineering, and silicon-on-insulator structure fabrication technology.

Dr. Tan is currently listed in *Who's Who in Science and Engineering* as well as *Who's Who in the World*.

Guan Zhang received the B.Eng. degree in measurement and instrument engineering from Xidian University, Xi'an, China, in 1994, and the M.Eng. degree in electrical and electronic engineering from Nanyang Technological University, Singapore, in 2001.

From 1994 to 1998, he was with Shougang NEC Microelectronics Company, Ltd., Beijing, China, as a Senior Equipment Engineer in photolithography process. In 2001, he joined the School of Electrical and Electronic Engineering, Nanyang Technological University as a Research Associate. His current research interests focus on electromigration reliability physics of metal interconnection in VLSI, finite-element analysis of device failure, and reliability data analysis in accelerated lifetime tests.