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Robust Electromigration reliability through engineering optimization

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ABSTRACT

With complex process integration approach and severe fabrication limitations caused by introduction of new materials and diminishing process margins, there are mounting concerns with the increased failure rate at the early life cycle (e.g.<1 year operation) of product application known as infant mortality failures. A paradigm change in reliability qualification methodology aim at understanding the impact of variation on reliability is required to ensure reliability robustness. Using Electromigration (EM) as an example, this paper described a methodology where the impact of process variation on reliability is studied. A model that predicts the impact of process variation on EM sigma is also proposed which enables variation and its impact on reliability to be quantified. Using this methodology, the critical process parameters impacting reliability could be identified and controlled to ensure reliability robustness.

1. Introduction

To sustain Moore's Law, the continuous scaling of integrated circuitry has resulted in very stringent requirements in the manufacturability and variation control capability of the fabrication tools. In advance technology, manufacturers have been working below a robust manufacturing level resulting in severe process and reliability marginality issue especially during mass production phase. To ensure robust reliability for high volume manufacturing, a paradigm change in reliability qualification methodology aim to establish a good linkage process variation is required [1,2]. An innovative Design-For-Reliability (DFR) methodology was previously proposed [3], using engineering optimization.

2. Methodology & test structure

In order to study process variation and its impact on reliability in the early stage of technology development, test structures with build-in variation are tested using fast Wafer Level Reliability (fWLR) methods [4–6]. The DFR test structures are designed with the objective of simulating process variation and its impact on the reliability margin, as described in [3].

3. Experimental results

Results collected from the DFR test structures are analyzed with reference to the nominal test structure for both the downstream and upstream Electromigration (EM) reliability degradation mechanism.

3.1. Build-in variation on via

For the study of the impact of build-in variation on via, via misalignment and via critical dimension (CD) variation are investigated. A via misalignment in the *X*-direction reduces the cross section area that the via makes with the lower metal thus increasing the current crowding effect at the bottom of the via as shown in the following Fig. 1 [7,8]. For the modeling of the downstream EM performance due to via misalignment, we use the effective cross section area that the via is making with the lower metal after the via misalignment and found that a power law model as described by Eq. (1) fits the data as shown in Fig. 2

$$\frac{TTF_{\mathrm{Variation}}}{TTF_{\mathrm{Nominal}}} = \left(\frac{MCD_{\mathrm{Nominal}} - V_{\mathrm{Misalignment.X}}}{MCD_{\mathrm{Nominal}}}\right)^{0.98} \quad (1)$$

Where $TTF_{\mathrm{Variation}}$ is the EM Time-To-Fail for structure with build-in variation, TTF_{Nominal} is the EM Time-To-Fail for nominal structure without build-in variation, MCD_{Nominal} is the nominal Metal1

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0026-2714/

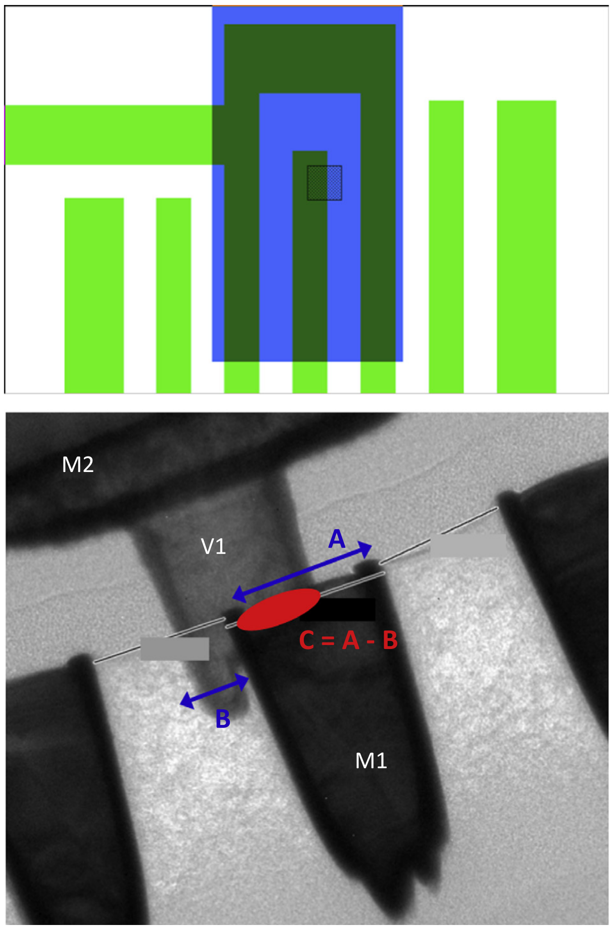

Fig. 1. Effective cross section area denoted by "C" at the via bottom which modulates the current crowding effect. "C" can be calculated by subtracting the via misalignment as denoted by "B" from the metal CD which is denoted by "A".

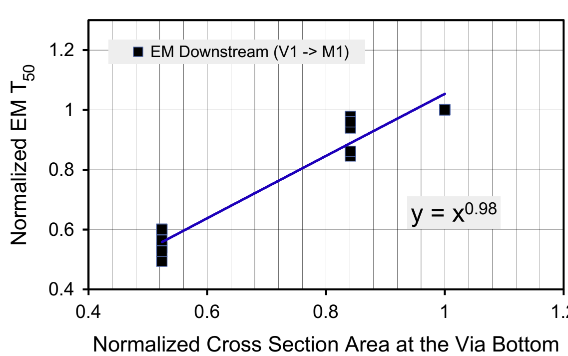

Fig. 2. Modeling the downstream EM performance due to via misalignment by considering the effective cross section area at the via bottom.

Critical Dimension (CD) and $V_{\mathrm{Misalignment,X}}$ is the via misalignment in the *X*-direction

For via misalignment in the *Y*-direction, the modulation of the EM performance is due to the line end extension effect [9,10]. Moving the via in the positive (negative) *Y*-direction reduces (increases) the line end extension as shown in the following Fig. 3. Different EM performances were observed when we reduce or increase the line end extension as shown in Fig. 4. The modelling of the downstream EM performance due to via misalignment in the positive or negative *Y*-direction is therefore carried out separately. Eq. (2) models the performance for positive *Y*-direction while Eq. (3) models the performance for negative *Y*-direction.

Positive *Y*-direction:

$$\frac{TTF_{\mathrm{Variation}}}{TTF_{\mathrm{Nominal}}} = \exp\left(-0.55 \times \frac{V_{\mathrm{Misalignment,Y}}}{MCD_{\mathrm{Nominal}}}\right) \tag{2}$$

Negative *Y*-direction:

$$\frac{TTF_{\mathrm{Variation}}}{TTF_{\mathrm{Nominal}}} = \exp\left(-1.51 \times \frac{V_{\mathrm{Misalignment,Y}}}{MCD_{\mathrm{Nominal}}}\right) \tag{3}$$

where MCD_{Nominal} is the nominal Metal1 Critical Dimension (CD) and $V_{\mathrm{Misalignment,Y}}$ is the via misalignment in the *Y*-direction

The observed effect of via CD variation and its impact on EM performance was ascribed to modulation of the current crowding effect at the via bottom and the void nucleation rate at the bottom of the via. To model the impact of via CD variation on EM downstream performance the normalized cross section area that the via is making to the metal below is used as described by Eq. (4) and Fig. 5

$$\frac{TTF_{\mathrm{Variation}}}{TTF_{\mathrm{Nominal}}} = \left(\frac{VCD_{\mathrm{Variation}}}{VCD_{\mathrm{Nominal}}}\right)^{2.72} \tag{4}$$

where VCD_{Nominal} is the nominal via Critical Dimension (CD) and $VCD_{\mathrm{Variation}}$ is the via CD with build-in variation

3.2. Build-in variation on metal alignment

Using a similar method used in the study of via variation, the impact of variation in metal CD and trench depth is investigated. The impact of metal CD variation on the downstream EM performance may be contributed to be due to the modulation of the current density in the metal line where a smaller metal CD result in higher current density in the metal line which degrades the EM performance, as a consequence. To model this mechanism, the normalized metal CD is used as described by Eq. (5) and following Fig. 6.

$$\frac{TTF_{\mathrm{Variation}}}{TTF_{\mathrm{Nominal}}} = \left(\frac{MCD_{\mathrm{Variation}}}{MCD_{\mathrm{Nominal}}}\right)^{2.72} \tag{5}$$

where MCD_{Nominal} is the nominal metal Critical Dimension (CD) and $MCD_{\mathrm{Variation}}$ is the metal CD with build-in variation.

As the metal width variation, also the variation of metal trench height modulates the current density in the metal line where a shallower metal trench results in higher current density in the metal line which degrades the EM performance. To model this mechanism, the normalized metal trench depth is used as described by Eq. (6) and following Fig. 7.

$$\frac{TTF_{\mathrm{Variation}}}{TTF_{\mathrm{Nominal}}} = \left(\frac{MTD_{\mathrm{Variation}}}{MTD_{\mathrm{Nominal}}}\right)^{1.68} \tag{6}$$

where MTD_{Nominal} is the nominal metal trench depth and $MTD_{\mathrm{Variation}}$ is the metal trench depth with build-in variation

4. Process variation EM model

Using the method correlating the impact of via and metal variation to the normalized EM downstream performance, the EM downstream lifetime distribution sigma due to process variation can be derived as illustrated in Eq. (7). *A*, *B*, *C*, *D* and *E* are the coefficients obtain from the modelling of the EM performance against the build-in variation as discussed in the earlier section.

$$\frac{TTF_{\mathrm{Variation}}}{TTF_{\mathrm{Nominal}}} = \left(\frac{MCD_{\mathrm{Nominal}} - V_{\mathrm{Misalignment,X}}}{MCD_{\mathrm{Nominal}}}\right)^{A} \cdot \exp\left(B \times \frac{V_{\mathrm{Misalignment,Y}}}{MCD_{\mathrm{Nominal}}}\right) \cdot \left(\frac{VCD_{\mathrm{Variation}}}{VCD_{\mathrm{Nominal}}}\right)^{C} \cdot \left(\frac{MCD_{\mathrm{Variation}}}{MCD_{\mathrm{Nominal}}}\right)^{D} \cdot \left(\frac{MTD_{\mathrm{Variation}}}{MTD_{\mathrm{Nominal}}}\right)^{E} \tag{7}$$