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Couple Passive Voltage Contrast with Scanning Probe Microscope to Identify Invisible Implant Issue

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Introduction

As rapid development of semiconductor process technology has led to rapidly decreasing feature size on integrated circuits, analysis techniques, which are used to look for the root causes of failure, are increasingly challenged to maintain their applicability in localizing exact fault position or catching sight of the defect mode. Especially in advanced ULSI technologies, PFA (physical failure analysis) frequently fails to identify the defect because the type of defect may be invisible even by SEM and TEM observation, or too tiny to be localized.

Among most applications, PVC (passive voltage contrast) is a popular technology to determine opens or shorts after deprocessing. The difference in secondary electron emission, which is a function of surface work function, topography, and local surface potential, assists us in revealing the abnormal phenomenon at a failure site. That is to say, as a sample is exposed to the electron beam, floating and grounded structures acquire different surface potentials, which generate different amounts of secondary electron emission, resulting in variations in SEM contrast between structures.

Recently, SPM (scanning probe microscopy) offers another solution for deep-submicron technologies because the piezoelectric scanner of the SPM has very high resolution of spatial dimensions, even in the nanometer range. Thus it is able to probe deep-submicron or nanometer features accurately. Furthermore, it can also provide current mapping with high sensitivity and I-V (current–voltage) characterization of targets.

In this paper, our objective was to organize a judicious reasoning method by coupling PVC with SPM for revealing particular invisible defect modes, which were imperceptible to observe and very difficult to identify by means of traditional PFA techniques. In order to certify this compound method, it is applied to an implant issue as a case study. Through solving this particular defect mode, whose exact failure position could not be determined even with the most sensitive PVC or high-resolution SPM current mapping, the procedures and contentions are illustrated further.

Methods and Results

As most of us know, PVC is a popular failure analysis technique to determine open or short issues [1]. SPM is another powerful technique for measuring, characterization of dielectric or judging gate-oxide integrity [2].

The purpose of our experiment was to establish a novel failure analysis methodology that coupled passive voltage contrast with scanning probe microscopy to reveal some particular invisible defects. Because of different imaging mechanisms of PVC and SPM, more diagnostic information is provided for reasoning out failure mechanisms.

Generally, the reasoning method can be itemized as the following steps concisely.

First, PVC is used for isolating the suspected AA (transistor active area) around a localized position. Next, in order to lessen questionable targets, SPM should be utilized to obtain a current mapping around the region that had been detected as abnormal by PVC. Sometimes even the highest resolution of current mapping is unable to identify the failure In such cases, differential analysis must be utilized. One by one the I-V curves of all contacts on the suspected and matching AA should be measured by SPM to form a comprehensive data set.

Following measurement and comparison, every contact with an abnormal I-V curve is carefully checked based on its attributes to expose the relationship between neighbors. Thereupon, a conceivable failure mechanism is proposed according to the electrical information obtained by SPM and theory of semiconductor physics. Simultaneously, the exact defect site could be pointed out by matching the layout and deductions from electrostatics. Finally, the proposed failure mechanism should be reviewed for conformity with the observed PVC.

In the following experiment, a sample of interest with 0.1um process had BIST (built-in self test) failure around the edge of wafer. Because emission microscopy could not detect a solid hot spot, the failure site was located by using the test datalog and fault diagnosis method. After deprocessing to the contact layer and utilizing SEM PVC, all N+/PW contacts around the suspected position and on the same active area were brighter than normal (Fig. 1).

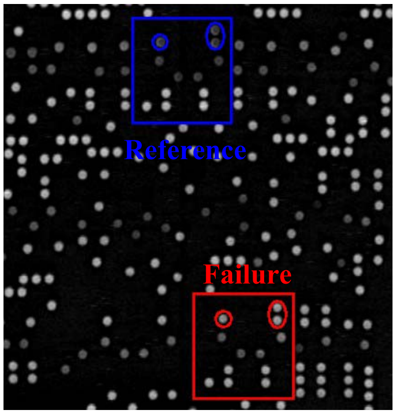

Figure 1: From 1kV SEM PVC, all N+/PW contacts on the same active area showed brighter than reference.

Then the SPM tool was applied to obtain the current mapping and measure I-V curves (Fig. 2 and 3). According to the electrical information, both larger reverse saturation current and larger drift current of forward bias showed there was an abnormal P-N junction involved with the failure. The shift of cut-in voltage implied insufficient N+ doping concentration in the target area. Moreover, considering the features observed by PVC, a poor N+ implant was highly suspected.

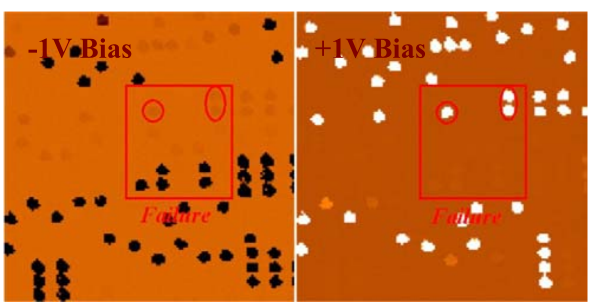

Figure 2: After current mapping of SPM, no abnormal contact could be identified, although there were obviously abnormal PVC on targets.

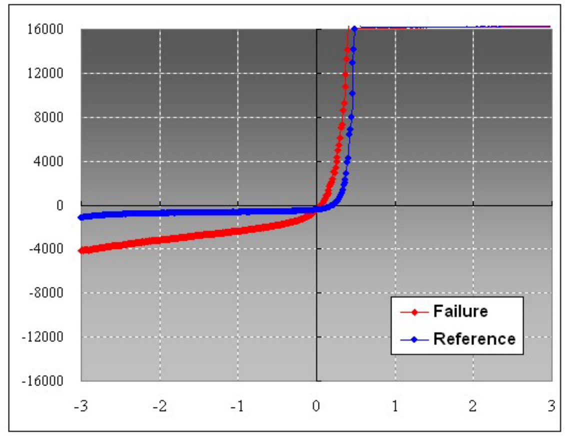

Figure 3: According to SPM I-V curve, both larger reverse saturation current and drift current showed an abnormal P-N junction. The forward cut-in voltage shift implied insufficient N+ dopant in the located region.

Because the failure was induced not by full blocked, but only partial, implant issue, chemical staining was not suited to the occasion. So TEM was used successfully to substantiate the indirect inference that a poor implant caused poor salicide formation (Fig. 4). Subsequently, feedback from the KLA team confirmed our inference.

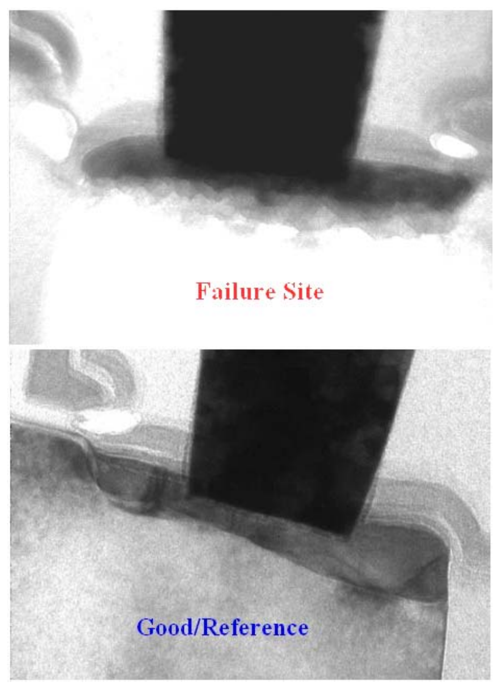

Figure 4: Comparing rough shape at failure site to smooth shape of reference, poor Co-salicide was revealed to be the indirect inference. This was induced by prior poor N+ implant process.

For further study, two more specific samples that suffered the same failure type were selected for PFA. One had been diagnosed and located to a fault buffer, and the other had an irregular block SRAM failure.

Following the previous steps, the PVC of the first sample was found to be abnormal with graded brightness along the located N+/PW region (Fig. 5). SPM measurements showed different levels of reverse saturation current that corresponded to the voltage contrast variations (Fig. 6).

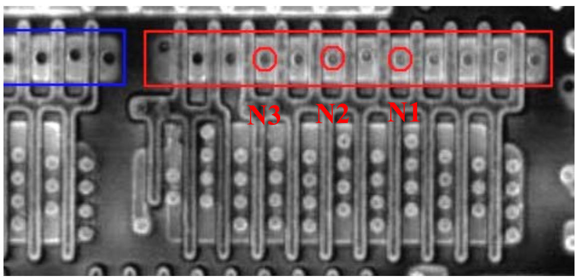

Figure 5: From 1kV SEM PVC, there was graded brightness (i.e. N1>N2>N3) along located N+/PW region of the fault buffer.

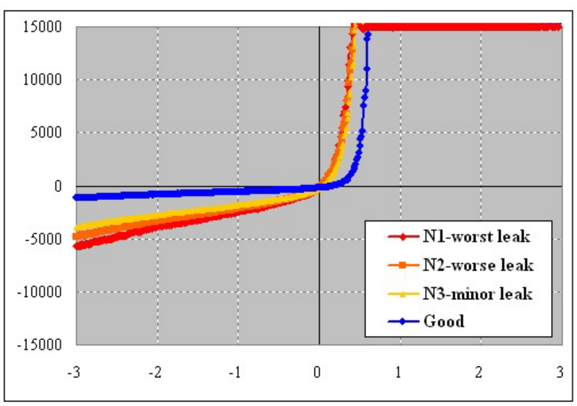

Figure 6: SPM measurements showing that different levels of reverse saturation current (i.e. N1>N2>N3) corresponded to the voltage contras. variations.

In the meanwhile, the other specimen which had block SRAM failure showed similar results both in PVC and SPM after deprocessing and measuring (Fig. 7 and 8).

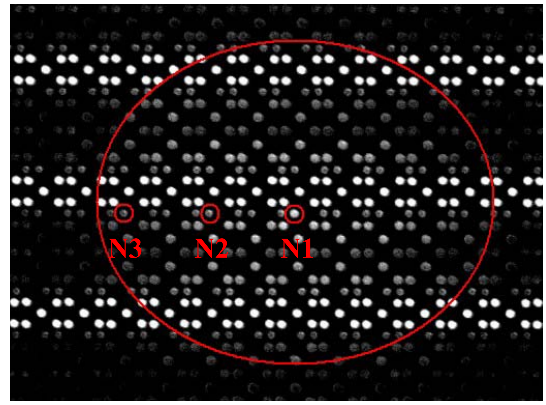

Figure 7: From 1kV SEM PVC, there was graded brightness (i.e. ***N1>N2>N3****) around the NMOS site of the block SRAM failure region.*

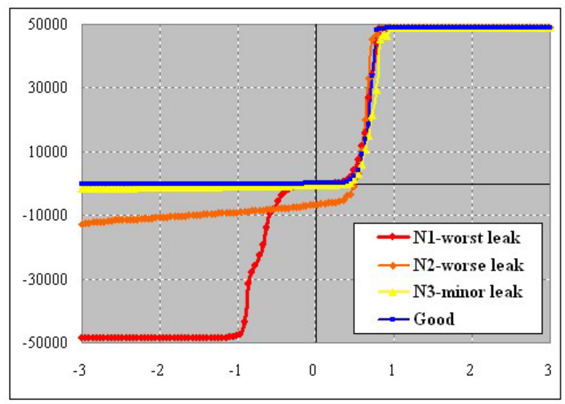

Figure 8: SPM measurement showed that different levels of reverse saturation current (i.e. N1>N2>N3) corresponded to above the voltage contrast variations.

Gathering these results, the abnormal implant issue could be expressed by three different types of I-V curve (Fig. 9).

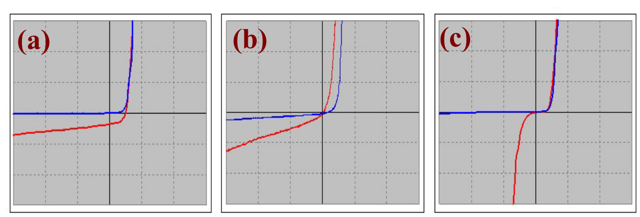

Figure 9: Three different types of I-V curve
- *(a) Partial implantation induced leakage current*
- *(b) Insufficient implantation induced Schottky barrier*
- *(c) Too little implantation induced junction breakdown*

Basically, these I-V curves and unusual P-N junction characteristics could be produced and explained by the "ideal diode equation" and "theory of the junction".

The ideal diode equation is:

$$I_S = J_S \times A \times (e^{qV/kT} - 1)$$

$$J_S = [\frac{D_p}{L_p N_D} + \frac{D_n}{L_n N_A}] \times n_i^2 \equiv C_1 \times [\frac{C_2}{N_D} + \frac{C_3}{N_A}]$$

where I_S : *reverse saturation current*

J_S : *reverse saturation current density*

N_D : *N+ donor doping concentration*

N_A : *PW accepter doping concentration*

D_n : *diffusion constant of electron*

D_p : *diffusion constant of hole*

L_n : *diffusion length for electron*

L_p : *diffusion length for hole*

n_i : *intrinsic concentration*

C_1, C_2, C_3 : *constant variable*

First, considering the above equation, since ΔJ_S is inversely proportional to N_D, the corresponding reverse saturation current (i.e. commensurate with leakage current) would increase as the N+ implant concentration decreased simultaneously. The related result was shown in Fig. 9(a).

When the N+ implantation is decreased further the doping of silicon surface is insufficient to form an Ohmic contact. Thus a supplanted Schottky barrier would dominate the P-N junction producing a smaller cut-in voltage and larger drift current. The corresponding diagram is shown in Fig. 9(b).

Further, if the doping concentration of the N+ region is too low, the P-N junction will break down easily. This special phenomenon could be explained by the following formulas.

The depletion layer width is:

$$\chi_n = W \times \frac{N_A}{N_A + N_D}$$

$$W = \sqrt{\frac{2\varepsilon_s (V_{bi} + V_R)}{q}\left[\frac{N_A + N_D}{N_A N_D}\right]}$$

where χ_n : *depletion width of N+ side*

W : *depletion width of P-N junction*

N_A : *PW accepter doping concentration*

N_D : *N+ donor doping concentration*

V_{bi} : *built-in voltage*

V_R : *reverse voltage*

Based on the formulas, the junction breakdown occurred because the depletion layer encroached upon the whole N+ region when reverse biased. The correspondent I-V curve was shown in Fig. 9(c).

For such a worst implantation case, SCM (scanning capacitance microscopy) can help to verify the irregular implant profile at the located site (Fig. 10). And this ability is the extension application of the SPM [3].

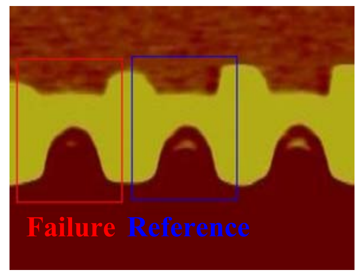

Figure 10: SCM could verify the irregular implant profile when the implant was nearly blocked in process.

Conclusions

The aim of our work was to overcome the difficulty in detecting very tiny or even invisible defects. So a useful method was developed that could infer the failure mechanism and the location of defects before conclusive PFA.

The significance of the reasoning method is based on electrical characterization and differential analysis, unlike earlier methods which placed undue emphasis on sensitive resolution SPM current mapping [4]. By coupling PVC with SPM, the capability to identify tiny defects is not limited to just distinguishing leakage or high-resistance under contacts [5].

In the case studies, PVC could detect abnormal N+ contacts due to improper implanting, and SPM could provide the precise electrical characteristics. Then combining these two types of results, different tactics can be adopted to deal with different states. Thus failure analysis turn-around time would be shortened and yield-improving strategy could be proposed as soon as possible.

The kernel of such an approach was not only the practice that combined with PVC and SPM but also the solid reasoning based on semiconductor physics and theory of electrostatics. So even if there were multiple suspects or no specific bad contact could be found, the electric information still could provide the basis for analysis. Then the failure mechanism could be reasoned, and the specific defect mode or position could be deduced.

References

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