Wafer Charging Bulletin

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From the Editor ...

- **Approaches and guidelines:** In this issue, we discuss approaches our customers employed to eliminate charging damage using CHARM-2 monitors. We also provide guidelines for interpreting CHARM-2 data to make engineering decisions.

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Wanted: Source of 300 mm wafers

We are still trying to locate a manufacturer for 300mm CHARM-2 wafers. The CHARM-2 wafers may be built on an EEPROM or FLASH technology. If you know of a potential candidate, please contact us.

New and exciting ...

CHARM-2 improves 300 mm tools!

We are pleased to see that WCM customers are now successfully using 200 mm CHARM-2 wafers in 300 mm tools, by placing CHARM-2 wafers on top of oxidized 300 mm wafers.

Placing a CHARM-2 wafer off-center in a center-charging plasma resulted in an un-distorted bulls-eye pattern that is offset from the center of the wafer, as illustrated in Figure 1. The 200 mm CHARM-2 wafer captured the essential features of the 300 mm pattern. Using this approach, a process optimization experiment yielded the significantly improved results shown in Figure 2.

Although some may question whether the charging levels measured in this manner are the same as the values that would be obtained using a 300 mm CHARM-2 wafer, practical applications have confirmed that this method works and produces valuable results. For example, process optimization efforts aimed at reducing the CHARM-2 signal in magnetic read head processing tools resulted in reported GMR read heads yield improvement [1]. In this case, the CHARM-2 wafer was placed on top of the GMR head substrate.

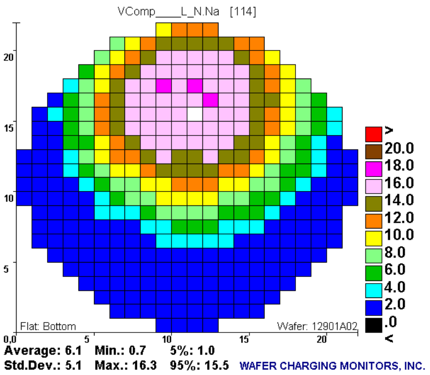

Figure 1. Positive potentials in a center-charging 300 mm tool recorded with off-centered CHARM-2 wafer.

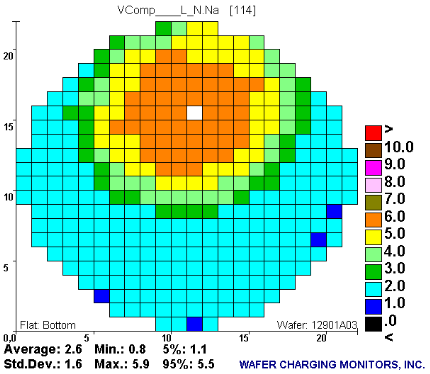

Figure 2. Positive potentials are significantly reduced during first process optimization experiment.

Approaches and guidelines …

During the last seven years, our customers have used CHARM-2 monitors in many different applications with the goal of eliminating charging damage during wafer manufacturing. In the following, we summarize the different approaches used in each of these applications and provide guidelines on how CHARM-2 data can be interpreted to make engineering decisions.

What others have done …

The easiest way to eliminate charging damage in IC manufacturing is to use non-damaging process tools. Consequently, some of our customers have used CHARM-2 monitors to identify and select the most benign equipment. This is a trivial task for CHARM-2 monitors: the best tool is the one which shows the lowest response (ideally, no response) on CHARM-2 charge-flux sensors, potential sensors, and UV sensors.

However, even the best tool may not be properly installed or properly set up. To ensure this does not happen, some of our customers used CHARM-2 monitors to verify the charging characteristics of their tools before shipment from the manufacturer, and again after installation in their facility. This is an excellent way to confirm proper installation and, thereby, to avoid start-up problems.

When new tools are added to existing process lines, split-lot evaluations are typically required to qualify the new tools for production. Some of our customers avoided the long delays associated with split-lot evaluations by using CHARM-2 monitors to compare their new tools to their existing tools. If the new tools showed equal or less charging on CHARM-2 monitors, the new tools were immediately qualified for production [2].

Sometimes it is possible to decrease process time and increase wafer throughput by changing the process recipe. Whether this can be done safely or not can be easily evaluated using CHARM-2 monitors. If the charging characteristics of the more aggressive process are no worse that the old process, the new process may be safely implemented. Some of our customers have used this procedure to increase ion implanter beam current, thereby increasing implanter capacity [3].

Ultimately, all equipment drifts, and requires maintenance. Some of our customers used CHARM-2 monitors to quantify equipment drift to determine optimum maintenance schedules, and optimum maintenance procedures [4].

Another popular application is the use of CHARM-2 monitors to re-qualify equipment after maintenance. This is an excellent way to avoid potential problems, and is easily performed by comparing CHARM-2 results after maintenance to results obtained when the equipment was performing properly [5].

However, the most frequent application of CHARM-2 monitors is identifying tools responsible for charging damage problems. Typically, tools used in back-end processes (such as sputter cleans, metal deposition and etching, oxide deposition and etching) are implicated in charging damage since high temperature anneals cannot be used to remove the damage. Identifying which tools are the most likely offenders is a very simple task for CHARM-2 monitors: the tool that generates the largest response on CHARM-2 charge-flux sensors, potential sensors, and UV sensors is the most likely offender[1].

Once the offending tool is identified, the problem must be eliminated. Since CHARM-2 monitors provide a direct measure of UV intensity, surface-substrate potentials, charge-fluxes, and duration of charging events, they provide more direct diagnostic information than any other charging monitor. If the tool is malfunctioning, the effect of changing components is very apparent in the CHARM-2 data. Since on-site turn-around for evaluation of CHARM-2 results is very short[2], rapid and fool-proof equipment repair may be achieved.

Sometimes, however, the equipment may exhibit charging problems because the design is faulty or the process is not optimized. In this case, an extensive DOE optimization may have to be undertaken to establish the best operating point. Due to the large number of variables that may be involved, high resolution is required to correctly identify the relevant variables and possible interactions between them. Due to their high resolution, CHARM-2 monitors are the tool of choice, and thus are popular with process equipment manufacturers.

How to compare tools/processes …

Most of the above applications require quantitative comparison between two sets of CHARM-2 results. In the following, we describe how CHARM-2 data should be interpreted to make meaningful comparisons, and how to draw valid conclusions.

The most important information about the charging characteristics of a process tool comes from the J-V plots, obtained at each die location on the CHARM-2 wafers. These plots show the positive and negative charging current densities generated by the charging source (and CHARM-2 is the only monitor that provides them). (The importance of J-V plots was discussed in WCM Wafer Charging Bulletin, vol. 1, no. 1, available from the WCM web-site[3]: www.charm-2.com.) To learn how to deal with J-V data, let's examine the positive J-V plots obtained in two different processes (in the same tool, or two different tools) shown in Figure 3.

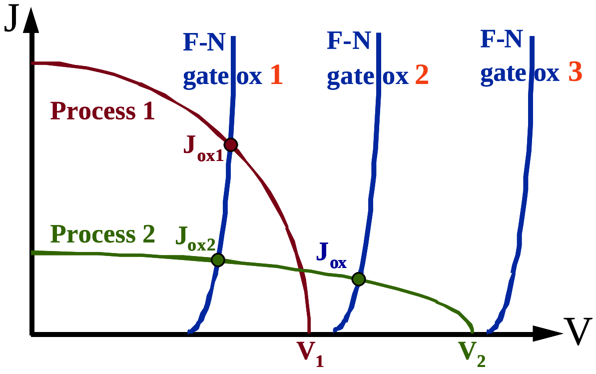

Figure 3. Positive J-V plots for two different processes, and gate oxide current-voltage (F-N) plots for three different gate oxide thicknesses (gate ox 3 > gate ox 2 > gate ox 1).

The typical question asked by every customer is: How can I tell which process is "better"? The answer depends on the product gate oxide thickness, and the presence or absence of "electron shading" and other patterning effects which elevate the charging potentials and current densities.

Let's first consider the simpler case where "electron shading" and other patterning effects are negligible. In this case, if the product uses *gate ox 3*, both processes are equally "safe",

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[1] Product layout and design rules also play a major role.

[2] It can be less than 30 minutes.

[3] The web-site also contains previous bulletins, publications, and other useful information.

since neither J-V plot intersects the *gate ox 3* F-N plot[4]. If the product uses *gate ox 2*, Process 1 is better than Process 2 since the J-V plot of Process 1 does not intersect the F-N plot of *gate ox 2*. Since Process 1 will not force current into the gate oxide, it will not cause damage. On the other hand, Process 2 will force current into *gate ox 2* and cause damage, because its J-V plot intersects the F-N plot of *gate ox 2.* It is interesting to note that V_2, the peak potential of Process 2, is greater than V_1, the peak potential of Process 1. So, in this case, the process which develops lower peak potential is the better process.

However, the conclusions are reversed for the case of *gate ox 1*. In this case, both processes can force current into *gate ox 1* since both J-V plots intersect the F-N plot of *gate ox 1*. Consequently, both processes can cause damage. However, the current J_{ox1} forced into *gate ox 1* by Process 1 is greater than current J_{ox2} forced into *gate ox 1* by Process 2. Consequently, Process 1 will cause greater damage than Process 2. So, in this case, the process that develops the higher peak potential is the less damaging process! This shows that we must look at the J-V plots, not the peak potentials, to determine which process will cause greater damage.

In the absence of gate oxide F-N data, the F-N plot can be approximated by a vertical line at the gate oxide breakdown voltage, BV, as shown in Figure 4 for three different thickness oxides, each with its own BV. The J values used to compare different processes are those obtained at the intersection of the BV line with the process J-V plots, as described above.

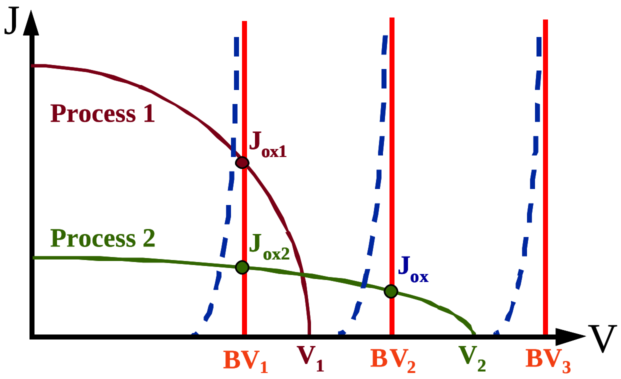

Figure 4. Gate oxide breakdown voltages used instead of F-N plots for comparing processes.

But what can we do when the CHARM-2 charge-flux sensors do not respond and we have no J-V plots to work with? This says that the current density was less than ~ 1 µA/cm^2, which is a good indication that the process is not likely to cause damage if reasonable antenna design rules were used during product design[5]. However, if the potential sensors responded, a low level of charging is still present. The processes may then be compared using the peak voltages: lower is better.

By comparing the J values obtained at the intersection of the J-V plots with a F-N plot, we may: (a) compare different tools/processes to identify the best available equipment; (b) compare tool results before and after installation; (c) qualify new tools by comparing them to existing tools; (d) check equipment drift by comparing results obtained at different times; (e) re-qualify equipment after maintenance by comparing post-maintenance results to base-line results; (f) evaluate processes designed to improve through-put by comparing them to a base-line process; (g) identify equipment responsible for charging damage by looking for tool(s) showing high charging levels; and (h) develop new processes showing lower charging levels.

Is my process safe?

Frequently, our customers want to know if their process is "safe". This is more difficult to answer because it involves not just the process tool, but also the design rules used in product layout. To answer this question with precision typically requires using resist patterns on the surface of CHARM-2 wafers, because the "electron shading" and other effects which elevate charging potentials and current densities exhibit themselves only when a resist pattern is present on the surface of a wafer. Indeed, CHARM-2 wafers covered with resist patterns have been used to quantify these effects [6,7,8,9], and some of our customers used their product resist masks to measure the charging potentials developed on their product wafers[6] [9]. However, resist patterning involves additional steps, so it is more convenient to use un-patterned (bare) CHARM-2 wafers.

Fortunately, yield improvement can be effectively performed with un-patterned CHARM-2 wafers because product designs cannot be changed anyway, and product charging damage is primarily due to charging non-uniformities. (These non-uniformities – easily and accurately recorded with bare CHARM-2 wafers – add to the "electron shading" and other pattern-induced effects, thereby significantly increasing the charging stress on product wafers [10].) Consequently, eliminating charging non-uniformities becomes the overriding goal when dealing with charging damage in wafer manufacturing. This is typically accomplished by changing equipment components and/or process parameters while

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[4] The F-N plot represents the current density which flows through gate oxide as a function of voltage applied across the oxide. It represents the current that the gate oxide can absorb during plasma charging. The plasma J-V plot, on the other hand, represents the current density that the plasma can supply as a function of the gate-to-substrate potential. Consequently, the intersection of the gate oxide F-N plot and the plasma J-V plot represents the current that will flow through the gate oxide during plasma charging. The amount of damage is proportional to this current. This is discussed in more detail in WCM Wafer Charging Bulletin, vol. 1, no. 1.

[5] An exception to this may occur in old processes employing thick (> 200 Å) gate oxides. Due to their exceptionally small size, "pinholes" in thick gate oxides greatly increase the antenna ratio, making such oxides very vulnerable to charging conditions exhibiting high voltages even if the current densities are very low.

[6] J-V plots are more difficult to obtain when product resist patterns are used on CHARM-2 wafers because the resist coverage over the charge-flux sensors varies, causing irregular looking J-V plots. However, when many such J-V plots are superimposed on the same graph, a J-V envelope becomes apparent [9] which is reasonably close to the J-V plots that are obtained using specially prepared resist masks [8].

looking for the lowest charging conditions on the J-V plots, as described above.

For the purpose of prioritizing yield improvement efforts, as well as answering that inevitable question: Is this process "safe"?, we have developed the following general guidelines from numerous conversations with our customers (and occasional "reading between the lines"). These guidelines assume that typical antenna design rules are used in the product, and that current density is measured using un-patterned (bare) CHARM-2 wafers. The current density value, J, used in the following table, is the value of current density obtained at the gate oxide breakdown voltage, BV.

J @ gate ox BV	Likely level of damage
< 1 uA/cm^2	none
1-10 uA/cm^2	unlikely
10-100 uA/cm^2	possible in sensitive designs
100-1000 uA/cm^2	likely in many designs
1-10 mA/cm^2	very likely in most designs
> 10 mA/cm^2	certain in most designs

We emphasize that the above guidelines are not absolute, and that antenna design rules and layout specifics can exert a large influence on device sensitivity to charging. Ultimately, the only "safe" process is one which does not register a response on CHARM-2 charge-flux sensors or potential sensors, and which does not show high UV levels. All process improvement efforts should have this as their ultimate goal.

What about UV?

By itself, moderate levels of UV do not appear to cause problems. However, in the presence of potentials, UV can be a powerful facilitator. A particularly important case of UV-assisted charging damage occurs during oxide deposition [11]. The UV causes the oxide to conduct current, which is collected during the entire deposition time by conductors (antennas) under the oxide. Since the high deposition temperature greatly lowers the charge-to-breakdown of the gate oxide, this relatively low-level current is sufficient to cause damage even to small antenna-ratio devices. In the absence of UV, the oxide would behave as an insulator and damage, if any, would occur only during the very initial portion of the deposition.

However, even in the absence of potentials, high levels of UV can cause device parameter shifts [12]. Therefore, high levels of UV should be avoided.

Consequently, an absolutely "safe" process exhibits no charge-flux, potential, or UV sensor response on the CHARM-2 monitors. A reasonably "safe" process may show a moderate response on the UV sensors, as long as there is no response on the charge-flux sensors or potential sensors.

Process optimization and DOE …

Due to the stringent, and frequently conflicting, demands placed on contemporary process tools, process optimization is typically a complex task involving several, often interacting, process effects. To identify the optimum settings, design-of-experiments (DOE) techniques are typically used. However, these techniques are effective only if the tools that measure the results possess good resolution. This is where the calibrated CHARM-2 monitors truly excel. Even very small changes in the charging characteristics of a process tool are accurately resolved.

To verify this, we conducted emulation experiments in which a parametric tester was used to apply specific voltages (or currents) to the potential (or charge-flux) sensors. The CHARM-2 wafer was then tested like any other wafer after a charging experiment. The measurement data was then processed like any other charging data to see if the potentials (or currents) applied by the tester could be accurately recovered using our normal data analysis procedures. The voltage data is summarized in the following table.

Applied Voltages	Recovered Voltages #	Standard deviation
16	16.15	0.049
12	12.14	0.048
8	8.14	0.035
4	4.08	0.053
2	2.08	0.021
1	1.38*	0.043

#test algorithm resolution: +/- 0.05V
*detection limit for this experiment

Tester experiments using current-source emulation yielded similarly impressive results.

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[11] K. P. Cheung, Proc. P2ID'00, pp. 161-163.
[12] WCM CHARM-2 UV sensor data.

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