1 Introduction

The extensive use in semiconductor fabs of plastics and ceramics for their chemical resistance, low humidity for corrosion control, and the continual movement of inventory, machinery, and human operators combine to make a potent recipe for disaster. The motion of one material against another can result in a charge being transferred between them in a process called tribocharging. If the materials are electrically insulating and in a low-humidity environment, the charge can remain trapped on their surfaces for very long periods. This is referred to as "static electricity" because it is immobile.

In its most obvious manifestation, static electricity in the fab results in sparks (electrostatic discharge; ESD). The electromagnetic interference from a spark can cause robotic systems to lose control or data in computers and other process-control electronics to become corrupted. When machinery starts to malfunction and warning lights are triggered on instrument control panels, the phenomenon is highly visible and understandably receives a lot of attention.

A slightly less obvious but no less important form of ESD can cause direct damage to semiconductor devices while they are being manufactured. Wafers can become charged during processing, and moving these charged wafers inside machinery or into wafer carriers can result in discharges. In such cases, the die in certain parts of the wafer may be damaged and this will lead to partial yield loss, depending on the number of die on the wafers that are affected. Wafer maps showing which die have been damaged can serve as useful diagnostics to help identify and correct the cause of the damage.

Then, perhaps in its most subtle form, ESD causes tiny amounts of damage to the edges of the pattern features on reticles (the photomask "negatives" that are used to print the dozens of separate layers that make up a complete integrated circuit). In magnitude, the damage is tiny, but the potential impact of such minuscule damage is nevertheless huge because every device printed with a reticle that is damaged in this way can be defective. When reticle ESD strikes, a production line can go from full productivity to zero yield with no warning. The problem then involves trying to identify where in its handling path the reticle has been damaged. This can be extremely difficult and time consuming, but production usually cannot be halted while the investigation is underway, so it is often decided to simply replace a damaged reticle and resume production before the cause has been identified and corrected. The problem then can—and often does—repeat itself.

This kind of repeating reticle-damage event became increasingly common by the turn of this century, with the problem becoming so significant that some devices could not even progress beyond the prototyping stage before the reticles were damaged. The economic impact of this was huge, so the semiconductor industry invested a great deal of time and effort toward finding ways to solve the problem. This intense focus on the reticle electrostatic-damage problem is illustrated by a graph showing the number of applications each year for patents describing reticles

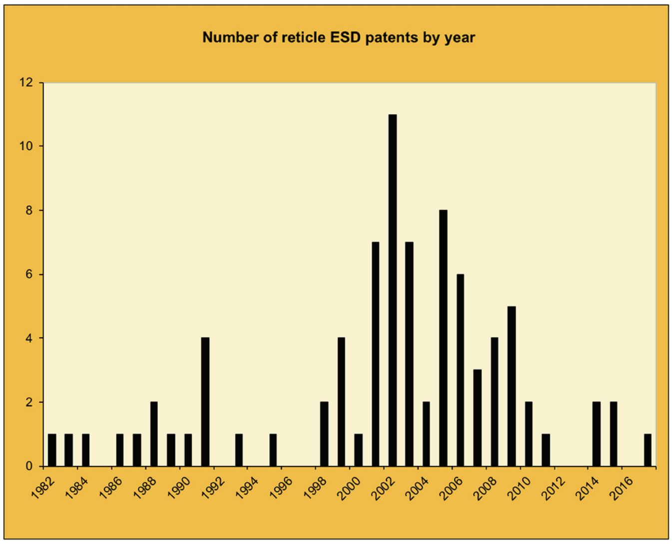

Figure 1 Graph showing the number of patent applications describing reticles that are resistant to ESD damage by year. 75 have been identified by a manual search of the world patents database—but some may have been missed.

that are resistant to ESD, as shown in Fig. 1. At the time of writing, the total number of such patent applications identified was 75, with 11 being submitted in 2002 alone. The semiconductor industry consortium International Sematech, located in Austin, Texas, was tasked with studying the problem and finding suitable solutions. Researchers there spent several years studying the subject and finding ways to address the problem. By 2003, it was felt that the problem was sufficiently understood and could be adequately controlled in semiconductor production, so the project was ended.

Ironically, later that same year, I gave a seminar at Sematech to present the results of my own “back to basics” study of reticle electrostatic damage.[1] The study revealed that ESD was not the only type of damage taking place; a previously unknown phenomenon had been identified that results in chrome migration on the surface of the reticle. This gradually distorts the features in certain parts of the pattern and ultimately leads to opaque bridges being formed between adjacent features, a reticle-damage characteristic that had previously been attributed to multiple low-intensity ESD events.[2]

I gave this new damage mechanism the acronym EFM (for electric field-induced migration) to distinguish it from ESD because at the time, everyone was talking about reticle ESD, and it was important to recognize that they are different damage processes. The cause of EFM is the same as that which causes ESD—field induction—but the physics of the two are very different. Of greatest concern to me was the fact that this newly identified damage mechanism appeared to have a much lower onset threshold than ESD and was cumulative in nature, which meant that it could cause progressive damage to reticles under field exposure conditions that might be perfectly safe against ESD.

Another serious concern was raised during the seminar because computer simulation had shown that a key element of the methodology being adopted by the industry to counter the reticle ESD risk—equipotential bonding through static dissipative contacts—actually has the opposite effect to that intended when it is applied to reticles. Rather than helping to reduce the risk of electrostatic damage, grounding actually increases the severity of field induction that a reticle experiences (see Section 3.1).

Initially, these findings were met with a high level of skepticism because dozens of electrostatics experts had been working on this problem for many years. Many lifetimes' worth of their collective learning and experience had been pooled in coming to the conclusions that had been reached. It seemed highly implausible that someone working alone without the resources of the major semiconductor companies at their disposal had discovered something that nobody else had noticed. The skepticism was further heightened because the study's conclusions about the negative effect on reticles of equipotential bonding directly contradicted the "established wisdom" on the subject.

Fortunately, some of the researchers who had been involved with the reticle ESD research project at Sematech decided to test the findings experimentally, and they were confirmed. Since that first publication describing the discovery of EFM and the negative effect on reticles of equipotential bonding, several independent groups have looked more closely at the subject. All of the main findings from the 2003 seminar have been supported, and later studies have even shown that the 2003 estimate of reticle sensitivity to electric field had been somewhat conservative, underestimating the risk from electric field exposure.

With design rules for semiconductor devices continually shrinking, the features on the reticles used to print them are becoming smaller, closer together, and ever more susceptible to electrostatic influence. Furthermore, the printing process is becoming increasingly sensitive to small variations in line quality on the reticle, meaning that even the smallest reticle defects can affect the process window and potentially even change the operation of the final device. Hence, even though this problem has been addressed in semiconductor fabs for many years, its potential impact on production is still present.

Semiconductor manufacturing is not an academic subject, however, and producing working microelectronic devices does not require everything in the factory to be technically perfect; it only needs to be good enough for the task being undertaken. This means that factories are tolerant of many imperfections in what they do. If something is not quite right but is not significantly affecting production, it will often be ignored. That is the situation at present with the electrostatic protection of reticles.

But although the present flawed reticle protection regime seems to have been adequate for some fabs, it does not mean that things will always be that way. Field induction in a reticle is very complex, nonlinear, and significantly affected by the reticle's environment, so it is practically impossible to determine how susceptible any production reticle is likely to be to electrostatic damage. It is also impossible to quantify all the electrostatic risks that a reticle will face during its operational life in the fab. All one can do is measure what is measurable, calculate what is not directly measurable, and estimate the level of risk from what is known about past reticle damage cases. That is the rationale behind this review.

At present, we have an indeterminate sensitivity of typical production reticles to electric field, and we have an indeterminate level of electrostatic risk in the reticle-handling environment. We also have reticle-handling practices that can be objectively tested to gauge their effectiveness at countering any electrostatic risk that may be present—and we find that they are not as good as they are believed by many to be. The findings are that the reticle electrostatic damage risk is still significant, and some of the things that are being done in the belief that they protect reticles are actually putting those reticles at greater risk of damage.

Effectively, the semiconductor industry has been taken down a "blind alley" on a path that does not offer adequate electrostatic protection for reticles and which, in certain circumstances (as will be described), makes the risk of reticle damage worse. The avoidance of significant amounts of reticle electrostatic damage in semiconductor production at present is, therefore, more likely to be due to other moderating factors and good luck rather than a result of sound preventive design. But since the actual level of risk is not directly measurable, the risk factors themselves are invisible and constantly changing, and each new device generation increases the probable risk—nobody can know for certain how close they are to the tipping point or when that point may be reached.

To respond to this situation in a proactive manner, rather than waiting for disaster to strike before reacting to it, the industry must reverse out of the blind alley it has been taken down and take a new route forward by adopting practices that are known to be effective at reducing or even eliminating some of the electrostatic risks that are currently present and could cause yield loss to strike at any time, without warning. The new path is described in SEMI Standard E163,[3] and this Spotlight hopefully provides enough evidence to show why taking the new path is advisable.

2 Some Basic Elements of Electrostatics

When a static charge builds up on a sensitive product, work surface, equipment, or person, the result can be destructive. Products may be damaged, and processes may become degraded. Because the relative humidity in most cleanrooms is around only