Electronics and
Electrical Engineering

AIMS Electronics and Electrical Engineering, 3(4): 397–414.
DOI: 10.3934/ElectrEng.2019.4.397
Received: 27 August 2019
Accepted: 15 November 2019
Published: 26 November 2019

http://www.aimspress.com/journal/ElectrEng

Review

A critique of the approach to controlling electrostatic risk in semiconductor production and identification of a potential risk from the use of equipotential bonding

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Abstract: Equipotential bonding, whereby objects are connected to a common electrical potential (usually ground) to prevent electrostatic discharges during material handling, has been shown to increase the risk of field-induced reticle damage. It is explained how the presence of an electric field can cause electrostatic damage in a reticle without a discharge event taking place. A comparison is drawn between the damage mechanisms that can take place in reticles and in semiconductor devices. The use of equipotential bonding during the manufacture of electrically sensitive semiconductor and micro-electro-mechanical systems is discussed. It is concluded that while equipotential bonding eliminates the risk of ESD during material handling, it simultaneously creates other risks for the devices being manufactured, which has the potential to introduce latent defects. An alternative methodology for dealing with electrostatic risk in semiconductor manufacturing is proposed, which would eliminate the undesirable enhancement of field-induction effects that is a consequence of using equipotential bonding.

Keywords: ESD; EFM; ESDS; EES; field induction; device damage; equipotential bonding; grounding

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Abbreviations: ACLV: Across Chip Linewidth Variation (in the lithography process); CD: Critical Dimension (of features in a reticle); CDM: Charged Device Model (of electrostatic discharge); EES: Extremely Electrostatic Sensitive; EFM: Electric Field induced Migration; EMI: Electro Magnetic Interference; ESD: Electrostatic Discharge; ESDS: ESD Sensitive (of devices); HBM: Human Body Model (of electrostatic discharge); IRDS: International Roadmap for Devices and Systems; ITRS:

International Technology Roadmap for Semiconductors; SEMI: Global semiconductor industry association (previously Semiconductor Equipment and Materials International)

1. Introduction

ESD damage to semiconductor devices and the disruption caused by electromagnetic interference emanating from spark discharges have been perennial problems for the semiconductor industry. In the 1990s as device geometries became smaller following Moore's Law the problems grew in both frequency and severity, with electrostatic damage to the reticles being used to print the devices also becoming a major problem. Reticle damage had a severe impact on yield, since every device printed using a damaged reticle could fail. Therefore, the industry invested a great deal of effort in developing ways to control the problem.

The control of static electricity in manufacturing and material handling is not a new requirement, however. For example, it was realised even before electrostatics were fully understood that certain materials and handling practices had to be used for the safe handling of gunpowder. Ways of controlling the risk were also continually being developed as electrostatic problems were experienced in other industrial situations. So, by the time electrostatic damage became a critical problem for the semiconductor industry there was already a wealth of knowledge and a community of electrostatics experts available to help.

The standard principles that were adopted for controlling ESD are now familiar to most people working in the semiconductor industry:

a) Eliminate all non-essential insulators (because they can accumulate static electricity)
b) Neutralize all essential insulators, using methods such as air ionization
c) Connect all conductive objects to a common electrical potential, normally ground (which is known as "equipotential bonding"). Personnel working within a factory are also required to wear conductive clothing and to be connected to ground, either through conductive footwear or by a special grounding strap at a workstation.

Since material being processed in a factory needs to be moved from one processing point to the next, it is essential to ensure that the material being transported is at the same electrical potential as its destination, to eliminate the possibility of an electrostatic discharge at hand-off. So, it has become standard practice to ground any object that is being moved within the factory, and to avoid any risk of a high-power discharge taking place on connection to ground, resistive contact materials (otherwise referred to as "static dissipative") are used.

If one regards the objects being handled as homogeneous entities having a single electrical potential, and the objective is purely to prevent electrostatic discharges when the objects contact one another, then this approach is perfectly logical. However, the reticles used to produce semiconductor devices are not homogeneous entities having a single electrical potential – "bright field" reticles actually consist of an array of isolated conductive features distributed on the surface of an insulating substrate. Connecting one part of this array to ground potential does not fix the potential of the other isolated conductive features so, in the presence of an electric field, potential differences can be induced between different parts of the reticle pattern.

Ironically, rather than being protective, grounding a reticle through equipotential bonding has been shown through computer simulation to increase these induced potential differences [1] which increases the likelihood and severity of any damage that may be caused.

Semiconductor devices are not homogeneous entities having a single electrical potential either; they contain electrically isolated circuitry that requires different parts to be held at different potentials for them to work. So, during manufacturing and handling of the device different parts of the circuitry are able to be driven to different electrical potentials, even when a part of the device is grounded. If the potential differences induced within the circuit by exposure to electrostatic stress during handling were to exceed the normal operating parameters of the design, the device could be damaged.

The focus in the design of automated handling equipment has logically been to reduce the generation of static charge within the equipment anywhere near the handling path of the sensitive devices being manufactured. The presence of static charge is revealed by detecting the electric field it produces.

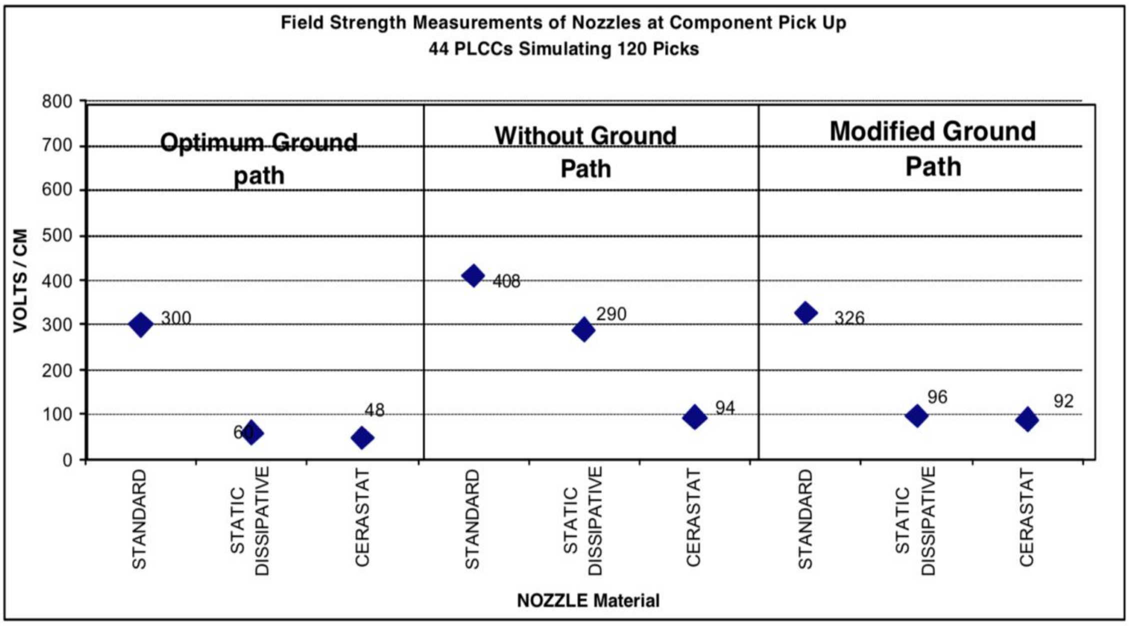


Figure 1. Reduction in the level of electric field generated within a piece of automated material handling equipment by optimizing the design of the ground path and changing the material of the vacuum nozzle used to pick and place the components. Reproduced from [2].

Figure 1 presents the results of a study of electrostatic risk reduction in automated handling equipment [2] and it shows that electric fields can be reduced through suitable equipment design and material choices, but they are generally not eliminated completely. This means that some electric field is always likely to be present in the handling environment of sensitive devices during their manufacture and handling. Furthermore, as the author states in his observations;

> *"the typical end user of components in their assembly work, whether Contract Electronic Manufacturing or Original Equipment Manufacturers, do not or cannot obtain accurate sensitivities of the components they are trying to handle with automated equipment".*

This means that a risk from field induction is always likely to be present, but the degree of susceptibility to that risk of the devices being handled is unknown.

Since equipotential bonding is known to enhance field induction the question needs to be asked; does its use during material handling help to keep sensitive electronic devices within their normal design parameters or, as is now known in the case of reticles, actually increase risk?

2. An historical overview of field induction as it affects reticles

When electrostatic damage to reticles became a critical problem for the semiconductor industry at the end of the 1990s, it was initially believed that damage was being caused by the direct transfer of static charge to or from the reticle via a spark during handling, which is known as "conductive ESD". Hence, it was decided that protection of the reticle would best be achieved through equipotential bonding. Guidance was published stating that reticles should always be handled using grounded conductive tools fitted with static dissipative contact materials [3]. This concept was also extended to the design of reticle pods, most of which now incorporate reticle grounding as a claimed protective measure. It is mentioned in the SEMI Standards for Reticle Handling [4] that:

> *"The end user may require a continuous path to ground from the reticle to the carrier registration and handling features. The purchaser needs to specify whether electrostatic dissipation is required".*

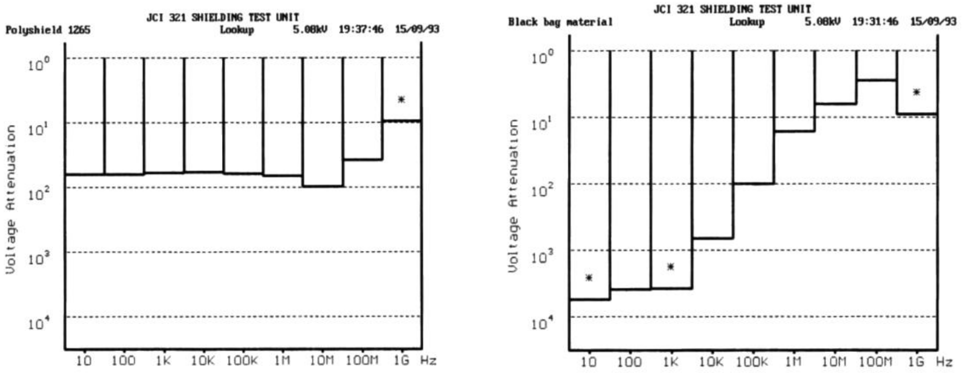
Research into reticle electrostatic damage conducted at International Sematech and other commercial facilities identified that reticles are susceptible to damage through exposure to electric fields [5]. Damage can be induced within the reticle pattern by an externally generated electric field, without any charge transfer taking place to or from the reticle and without the reticle even being touched. Measurements of the strength of electric field that would cause ESD damage in typical production reticles led to guidance being published through the SEMI Standards program and through the ITRS (now replaced by the IRDS) to limit the level of electric field to which reticles might be exposed. It also prompted the development of static dissipative plastic reticle pods and boxes, which were considered less likely to generate an electric field than those made from insulating plastic, as mentioned in the SEMI Standards.

However, shortly after the introduction of static dissipative plastic reticle pods and boxes it was proven experimentally that they are not able to fully protect a reticle, because electric field can penetrate static dissipative materials. Levit and Weil [6] measured the penetration of electric field from an electrode positioned outside a pod, representing the charged hand of an operator carrying the pod, to the position where a reticle would be stored. They showed that as well as incompletely shielding the reticle from the electric field, the shielding effectiveness of the static dissipative plastic material rapidly diminished as the frequency of the applied field was increased. It typically took almost a second for the pod to screen out the external field, so any field that changed more rapidly than this would not be effectively screened.

This characteristic of static dissipative materials was studied more extensively by Chubb [7], who used specially-designed apparatus to measure the field transmission properties at frequencies up to 1 GHz of various materials used for packaging in electronic component handling. Figure 2 shows his measurement of field transmission through a metallized plastic "shielding bag" and also through a static dissipative bag. In both cases the conductivity of the material was insufficient to fully screen the bag's contents from electric field, and the shielding efficiency dropped rapidly as the frequency of the field was increased. The behaviour as a function of frequency shown in b) is a characteristic of all static dissipative plastic materials.

Chubb noted:

> *"Electrostatic spark discharges involve current rise times and voltage collapse times down to below 1ns. Lower voltages shorter times. Transport packaging hence needs to provide >200:1 attenuation for frequencies to 1 GHz."*



a) *Shielding performance of metallised shielding bag* b) *Shielding performance of carbon loaded 'black bag'*

Figure 2. Chubb's measurement of the field penetration characteristics of different materials used to make static protective bags: a) Field attenuation by a metallised plastic bag; b) Superior field attenuation at low frequency by carbon loaded (static dissipative) plastic bag, but inferior shielding at higher frequency.

It is important to appreciate that Chubb's specification related to the protection of packaged semiconductor devices. Reticles, which from the Sematech research had been shown to be far more sensitive to field-induced damage than semiconductor devices, were clearly not going to be adequately protected by static dissipative plastic reticle pods. Nevertheless, when the newly-recommended reticle handling practice and static dissipative reticle pods were introduced alongside all the other static-reduction measures being taken in semiconductor factories at the time, the rate of reticle ESD damage was significantly reduced. So, with reticle ESD considered to be under control, attention within the industry shifted to other pressing concerns such as 193nm lithography's rapidly developing reticle haze problem. The Sematech project to study reticle electrostatic damage was terminated.

However, later in that same year (2003) new research findings were published that challenged the wisdom of the decision to end the Sematech project [8,9]. Not only was it shown through this research that the grounding of reticles during handling made the risk of field-induced damage worse rather than reducing it, a newly-identified form of field-induced reticle damage called EFM had been identified. Unlike ESD, which instantaneously causes very obvious visible damage to a reticle, EFM is a gradual degradation process that does not generate easily detectable damage until it is well advanced. It progresses cumulatively, under levels of field-induction at least two orders of magnitude weaker than would be necessary to induce ESD in a typical production reticle in use at that time.

There was a great deal of scepticism expressed by ESD experts in response to the assertion that equipotential bonding increases the electrostatic risk to a reticle rather than reducing it. This had been revealed through computer simulation, and it was believed by many industry experts that the simulations were incorrect, because the indications were not in accord with their practical experience of ESD prevention in the semiconductor industry. However, the findings were independently confirmed by experimentation with production reticles and special test reticles [10], amply demonstrating that field induction is a complex subject that can confound even those who specialise in electrostatic protection.

Later research [11] has shown that attempts to improve the electrostatic protection offered by static dissipative reticle pods, by making the plastic "conductive" rather than merely static dissipative, are not fully effective. It was shown that ESD could be induced in a reticle inside a "conductive plastic" reticle pod, proving that electric fields can penetrate even a "conductive plastic" pod shell. If field penetration into a "conductive plastic" reticle pod can be sufficiently strong to induce ESD in the reticle inside it, such a pod would certainly not offer adequate protection against field-induced degradation that takes place under much lower levels of field exposure. The research also confirmed that because such reticle pods have conductive paths connecting the reticle to the grounded load port, as mentioned in the SEMI Standards, field induction inside such reticle pods is enhanced and the risk of reticle damage is actually increased by this supposedly protective design.

So, the classical methodology for ESD prevention during handling had clearly been proven to be incapable of fully protecting reticles against electrostatic damage. One of the pieces of expert advice about reticle ESD prevention (i.e. equipotential bonding through dissipative contacts) had very quickly been shown to make the electrostatic risk to a reticle worse rather than being protective, and the newly-developed static dissipative reticle pods were repeatedly being proven through detailed testing to offer inadequate protection against electrostatic damage.

Yet despite these research findings being published, unequivocally showing the lack of effectiveness – and even the contrary effect – of these supposedly protective measures, the semiconductor industry has continued to use equipotential bonding for reticle handling and static dissipative reticle pods have become the de facto standard for use in semiconductor production.

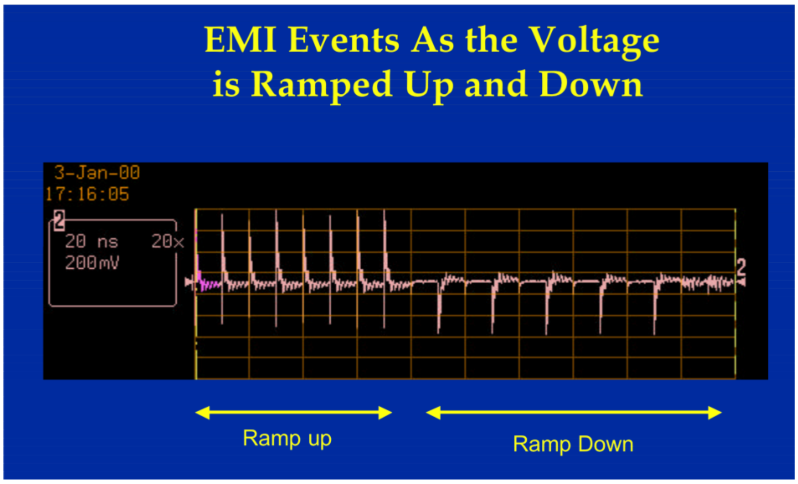
In 2008 further research into EFM was published [12,13] confirming the initial interpretation of the reticle damage mechanism as the field-induced migration of chrome and fully quantifying the effect. This showed that reticles were even more sensitive to electric field than had been estimated five years earlier. Other research being conducted around the same time into reticle degradation in semiconductor production revealed that as well as directly distorting the reticle features through chrome migration, EFM could also cause ACLV in the printed pattern by reducing the light transmission of the clear areas of the mask [14]. Device yield had been impacted by this subtle form of reticle degradation, even though the reticle had passed regular inspections with no defects being detected. It required the use of highly specialised surface analysis and destructive failure analysis techniques, which were far more advanced than those normally used in the semiconductor industry, to unambiguously identify the cause of the yield loss as chrome migration [15]. This difficulty in detecting and diagnosing it perhaps explains why, over fifteen years since its discovery, EFM is rarely identified as a reticle damage mechanism in modern semiconductor production fabs.

The most recent assessment of all the effects produced by field induction in reticles concludes that very short-duration field transients and rapidly changing electric fields to gigahertz frequencies and beyond are capable of causing cumulative damage [16]. Rapidly varying electric fields, especially field transients of the kind that are produced by the tribocharging of static dissipative plastics, are potentially more damaging to a reticle than an equivalent strength of constant electric field, because hazardous charge displacement occurs within the reticle pattern whenever the field conditions within the reticle change.

This characteristic was demonstrated during the field induction experiments conducted by Montoya et al [5,17]. Spark discharges induced within the reticle pattern by a high potential applied to an electrode held just above the reticle were detected using an RF loop antenna connected to a storage oscilloscope, as shown in Figure 3 which is from their presentation at the Sematech ESD Symposium of 2000. As the voltage on the electrode was increased, sequential discharges were detected within the reticle. Then, as the voltage was removed, discharges of opposite polarity were observed as the displaced charge within the reticle returned to its original location.

The movement of charge that contributes to the reticle damage is induced entirely within the reticle pattern; the reticle remains electrically neutral throughout the process. In addition to the field induction of ESD within the reticle, other forms of field-induced damage that do not involve discharges can also occur as a result of exposure to electric fields.

The reticle inherently amplifies any electric field that is present in its environment by up to several orders of magnitude, the degree of amplification depending on the arrangement of the isolated conductors in the image. Since this field amplification results from the movement of electrons within the reticle's conductive structures it happens almost instantaneously. This field amplification characteristic is illustrated by the computer simulation of Figure 4.


EMI Events As the Voltage
is Ramped Up and Down

Ramp up

Ramp Down

Figure 3. Measurement of multiple sequential ESD events induced within an electrically isolated reticle as the voltage on a nearby electrode is first increased and then decreased, from [17]. The opposite polarity of the signals as the field is removed indicates that the displaced charge that caused the initial series of ESD events as the field was applied is returning to its original location within the reticle and causing further ESD damage.

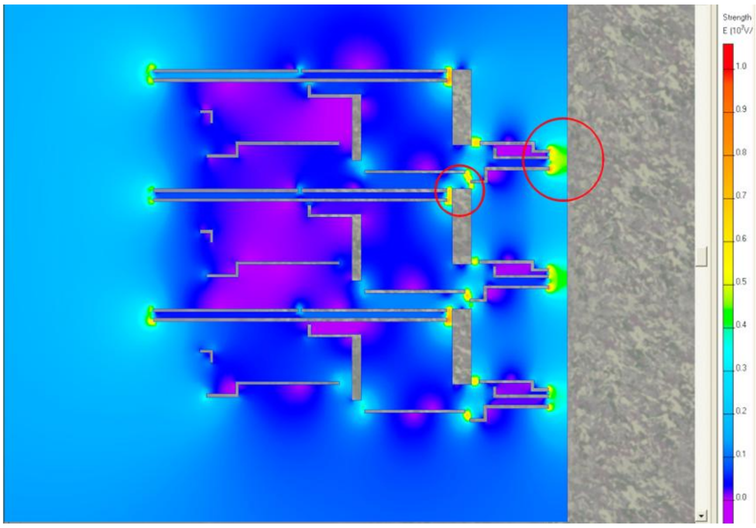


Figure 4. Two-dimensional finite element simulation of the interaction of an electric field with a reticle. The grey structures represent isolated conductive lines, with the large grey block on the right representing the border around the image area. A uniform electric field with a strength represented by the mid-blue tone at the left of the image is applied from left to right. The conductive features making up the reticle pattern cause the field strength to be reduced in some areas and amplified at the ends of long lines, particularly between closely adjacent features near the edge of the image (circled).

The field amplification is also a function of the orientation of the reticle pattern relative to the electric field. So simply moving the reticle – without changing the electric field it is exposed to – will change the field conditions within the reticle pattern, with a corresponding risk of the reticle being damaged. A similar situation occurs if conductive objects such as robotic arms are moved within the vicinity of a reticle in the presence of an electric field, because such objects perturb the electric field around and within the reticle. The perturbation of electric field by conductive robotic arms is revealed by the recording in Figure 5, which was made using a specially designed field-sensing reticle that measures and records the electric field which a normal reticle would be exposed to in the same situation [18].

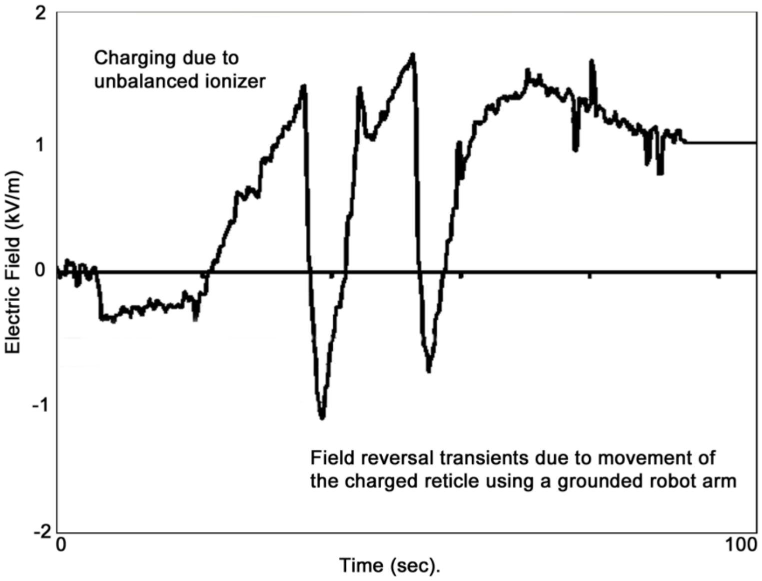


Figure 5. Electric field recorded by a sensor reticle introduced to a piece of handling equipment fitted with an unbalanced ionizer and a grounded robot arm with static dissipative reticle contacts. The electric field generated by the charge on the reticle is strongly perturbed each time the robot arm approaches to move the reticle. Note that grounding the reticle through static dissipative contacts does not remove the charge.

When an electric field is present between reticle features, several things can happen:

a) Electrons can move across the insulating surface of the reticle, with the current being inversely proportional to the surface resistance of the substrate. Since reticles are kept extremely clean and are often stored in very dry atmospheres, surface conductivity is low and electron “leakage currents” will consequently also be small and unlikely to cause any damage.

b) Polarizable or ionizable adsorbates present on the reticle surface can be induced to move by the electric field, and their otherwise random thermal diffusion on the surface can become directed along the field lines. If these adsorbates react together to form opaque compounds, which is the mechanism for haze crystal formation, the distribution of the deposits will show a correlation with the pattern and strength of the electric field. This has been observed in the formation of haze on a MoSi reticle [19].

c) In chrome-on-glass reticles, chrome atoms can be liberated from the reticle structures and diffuse thermally on the surface, in a process referred to as EFM type 1. This is due to the distortion of the “potential well” that binds the surface chrome atoms into the metal matrix, making it easier for them to escape from the matrix and diffuse randomly. (This process, whereby the presence of an electric field enhances surface atom diffusion, can be used to promote the formation of smoother surfaces during molecular beam epitaxy [20]. Fields are observed to promote smoothing of metal surfaces [21] and are seen to affect the chrome surface in reticles, resulting in a loss of anti-reflective quality [5,13]). The natural vibration frequency of metal surface atoms at room temperature is several terahertz [22], so the electric field that distorts the potential well only needs to be present for one atomic vibration cycle to be able to affect the probability of surface diffusion; even a gigahertz-frequency electric field or a similarly fast field transient will appear to be a constant electric field to a vibrating surface atom. It is energetically favourable for chromium atoms to be present on a quartz surface, so once they are liberated from the matrix by the electric field, chromium atoms will diffuse onto the glass as well as diffusing on the metal surface.

d) At slightly higher levels of field induction than in c), or following the creation of a sharp meniscus at the base of the reticle feature by EFM type 1, the electric field at the edge of the reticle feature can become strong enough to ionize a surface atom. The ion thus produced is immediately repelled from the reticle feature by electrostatic force and rapidly moves across the glass surface, driven by the electric field. Thus, positive metal ions become a significant charge carrier for conduction across reticle surfaces under field-induction [12]. This directional movement of chrome ions through field-induction generates protrusions on certain reticle features in the pattern, ultimately forming opaque bridges between lines. The printed pattern at wafer level becomes defective long before this point is reached [23].

e) At even higher levels of field induction the electric field at the sharp outer edges of the reticle features can become sufficient to cause the field emission of electrons into the air. This process can lead to an air discharge (ESD event) between reticle features. This is often a catastrophic event that vaporizes the edges of the reticle features, immediately causing printing defects [24].

The progression of metal migration under the influence of an electric field has been measured experimentally, with the damage caused by different levels of field exposure revealed by atomic force microscope edge profile scans of the test reticle features [12]. With the electric field in the gap generated using a power supply, the rate of CD degradation of the gap was over 6nm per second at 100V potential difference. It can be easy for such high voltages to be induced within a reticle by an electric field – for example, the sparks recorded in Figure 3 would have required the induction of at least 150V across the reticle gaps to trigger each discharge [24].

The chrome migration produced in EFM type 1 (at the lowest level of field induction, for example in Figure 6b) generates a sharp meniscus at the base of the chrome line, with a very low contact angle of approximately 10 °at the point where the chrome film joins the glass substrate. This point in the reticle already experiences some field enhancement due to the polarizability of the glass substrate, in the same way that a dielectric film in a capacitor increases the capacitance. The generation of a meniscus through EFM further amplifies the local field strength at this point, as shown in the computer simulation of Figure 7.

Thus, EFM is not only a cumulative damage mechanism, it is self-enhancing. Once a reticle starts to degrade by EFM, the rate of reticle degradation and its susceptibility to electric field-induced damage will increase, and the level of electric field exposure needed to cause further degradation will decrease.

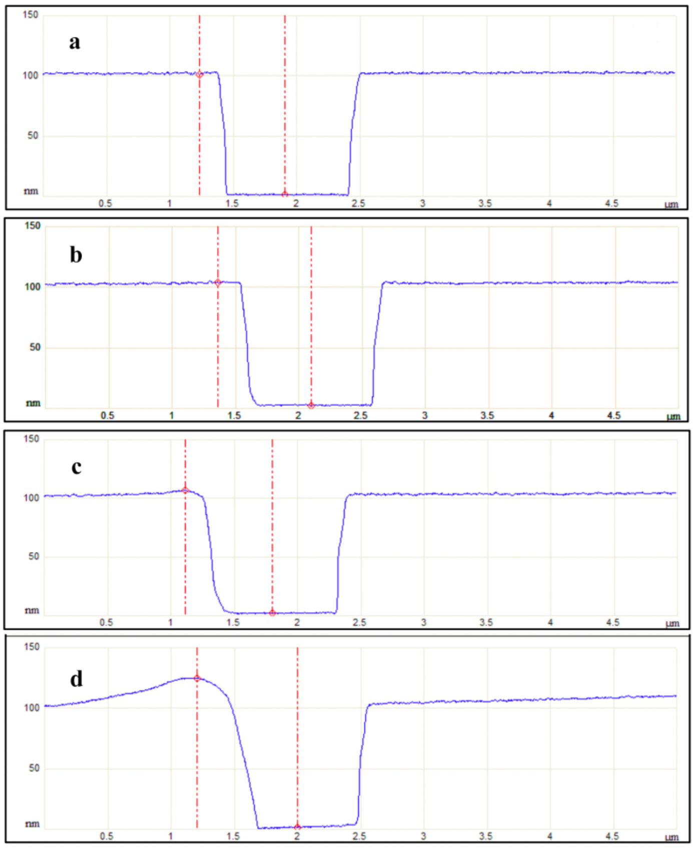
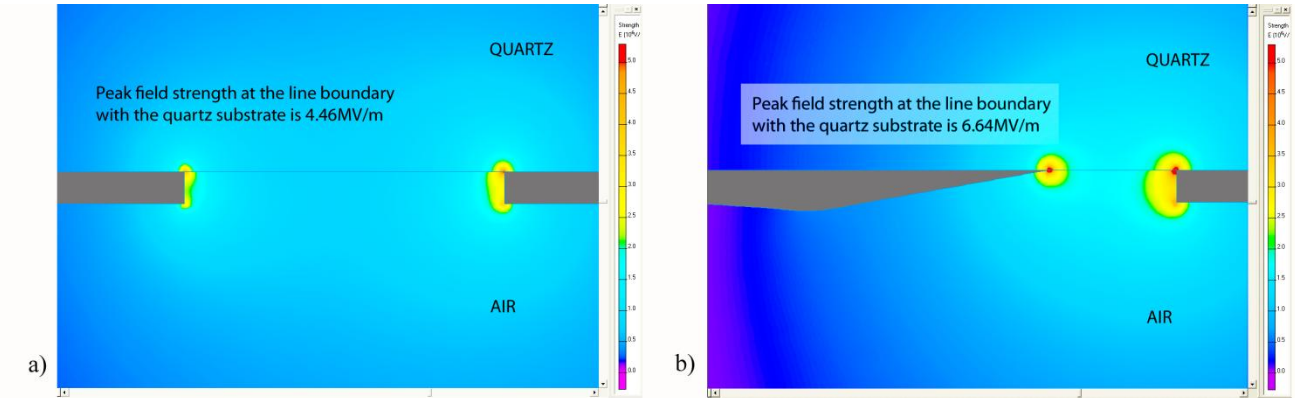


Figure 6. Atomic force microscope line-edge profiles of reticle test cells with a 1 micron gap, with increasing levels of stress: a) No stress; b) 50 V for 15 seconds; c) 100 V for 15 seconds; d) 100 V for 300 seconds (Vertical scale x10 for improved clarity).


a)

Peak field strength at the line boundary with the quartz substrate is 4.46MV/m

b)

Peak field strength at the line boundary with the quartz substrate is 6.64MV/m

Figure 7. Finite element analysis of the field strength induced between adjacent reticle features by a constant applied electric field at different stages of reticle degradation by EFM. a) shows the maximum induced field strength in the "as manufactured" reticle with nominally vertical side walls, as in Figure 6a, b) shows the local field strength after the reticle feature has been damaged by EFM.

The latest generations of reticles are being produced using other absorber materials than chrome, for a variety of technical reasons. This changes the level of risk of some of the damage mechanisms that are observed in chrome-on-glass reticles. However, it is not safe to assume that because field-induced absorber migration effects have not yet been observed in these other reticles they are immune to field-induced degradation. The physics of the diffusion mechanisms that cause reticle degradation will be the same for all absorber and substrate materials, it is only the activation energies and the rates of degradation that will be different from one material to the next. Furthermore, empirical evidence indicates that haze formation in MoSi reticles is enhanced by an electric field [16]. So just as EFM had already been damaging reticles for several years before it was identified and characterized, there may well be field-induced degradation mechanisms affecting these latest generations of reticles that are yet to be observed.

Thus, for absolute security, no amount of exposure to electric field should be considered safe for any transmission reticle. Since equipotential bonding increases the deleterious effect of any field exposure, it should not be used for reticle handling.

3. Implications for the safe handling of electrostatic sensitive devices

When material handling “best practice” was being defined for the semiconductor industry decades ago, the problem was addressed in a logical but arguably over-simplistic way. It was apparent that semiconductor devices were being damaged by conductive ESD during handling. As attention was focused on the harmful effect of such ESD events on devices, and because any ESD happening within a factory also has other negative consequences, comprehensive action was taken in the production environment to prevent electrostatic discharges.

This has led to the adoption of equipotential bonding as a core element of most fabs’ ESD prevention strategies as described previously. But while reducing ESD events through the use of equipotential bonding undoubtedly has achieved an improvement in device yields, and reduced equipment downtime caused by EMI, it does not necessarily prevent all forms of electrostatic damage. Just as has been observed with reticles, there are damage mechanisms driven by electric field that can potentially cause devices to malfunction without an external (or even an internal) ESD event taking place [25]. So, these types of damage might not be prevented by ESD countermeasures such as equipotential bonding that are targeted specifically at preventing external ESD events.

It is well known that a semiconductor device can be damaged by an ESD event if it becomes electrically charged (for example by friction during handling) and it is subsequently brought close to or into contact with a grounded conductive surface. This is referred to as CDM damage, and the damage caused is a consequence of the power delivered by the current surge into the device. To prevent such power surges from happening, devices are normally contacted using resistive materials, which limits the current that flows between the device and ground when contact is made. The slowing down of charge transfer in this way reduces the peak current and hence the power dissipated during the charge transfer, but the total amount of charge transferred depends only on the amount of static charge held on the device.

It is believed by many people that the spark between a grounded handling tool and a charged device results in the device literally becoming “discharged”, meaning neutralized. When a device that has experienced such an ESD event is measured using a Faraday cup it is found to carry little or no net static charge, so this reinforces the impression that the device has been neutralized by the discharge. However, the static charge on the device will probably be present on an external insulating surface, and the spark that jumps between the handling tool and the device generally strikes one of the device’s connector pins, which is why it damages the internal circuitry. So, what actually happens during such a static discharge event is that an opposite charge to that held on the encapsulation enters the device circuitry from ground, attracted by the electric field emanating from the static charge. This results in the device being in an energized state, just like a charged capacitor. The same final energized state will be achieved whether the “balancing charge” flows into the device rapidly through a spark or slowly as a reduced current through a resistive contact, as either way the total amount of charge flowing into the device is the same.

The presence of static charge on the external insulating surface of the device and an equal and opposite balancing charge in the internal circuitry results in the device having an overall net charge of zero, but it is certainly not in the electrically neutral condition that many people believe it to be. It contains electrostatic potential energy, just as a charged capacitor does, stored within the internal electric field. Such an internal electric field could be harmful to a sensitive electronic device, even though it has not been accompanied by a current surge from a high-power discharge.

A similar risk from the generation of internal electric fields could also be present when a silicon wafer becomes charged during processing. If the partially-completed devices on the wafer contain conductive layers separated by dielectric barrier layers, an electric field can be generated between the isolated layers. If a balancing charge is introduced to the substrate during handling, attracted by static charge on an outer (insulated) layer of the partially-completed devices, the balancing charge will distribute itself within the wafer until it is as close as possible to the static charge, after which further movement (and ultimately, static charge neutralisation) will be prevented by the interposed insulating layer(s).

One example of the risk that could be caused by an internal electric field within a device is that an electric field can damage the structure of dielectric material, resulting in the rearrangement of the atomic bonds, which degrades its insulating strength [26]. It has been shown that this mechanism and the degradation it produces are independent of the dielectric composition [27] and the dielectrics being used in latest-generation devices have been shown to exhibit degradation characteristics that are dependent on the field strength within the dielectric [28].

A device containing field-degraded dielectric layers may operate as it was designed to, but the robustness of the dielectric to electrical overstress or time dependent dielectric breakdown (which is a life-limiting aspect of many semiconductor devices) will be reduced. Such material degradation that has the capability to cause premature failure is classified as a “latent defect”, and it is evident that the practice of equipotential bonding has the capability – at least, theoretically – to introduce such defects into devices, by enhancing field induction effects.

Another field-induced damage process in semiconductor devices involves the diffusion of dopants and contaminants [29]. This can alter the electronic properties of devices that rely on a particular dopant profile within their active features, or create conduction barriers at interfaces. So, it is conceivable that enhanced electric fields produced within the device during its manufacture, as a consequence of using equipotential bonding, could result in such dopant and contaminant diffusion – with negative consequences for device operational performance.

The importance of any such material degradation and the impact it might have would be dependent on the nature of the device and how it was subsequently handled or operated. When failure eventually happened, it would not be apparent that the use of equipotential bonding during the manufacture of the device could have contributed to its demise. It would be practically impossible to identify the root cause of such a delayed failure.

4. Discussion

The implications described in section 3 are, in the absence of any experimental research into field-induced degradation effects in modern devices, only speculative extrapolations that follow directly from what has been learned about reticle damage and the enhancing effect that equipotential bonding has on field induction. It is reasonable to make such extrapolations, however, because it is not possible to directly observe such effects in a semiconductor manufacturing environment; hence there is currently no empirical evidence available to analyse. Such effects could only be observed and measured if controlled and targeted experimentation were carried out, in much the same way as reticle electrostatic damage was studied at Sematech. That experimentation ultimately led to the completely unexpected discovery of both EFM and the detrimental effect of equipotential bonding, so similar studies could potentially reveal previously unidentified field-induced degradation effects in semiconductor devices.

The importance of understanding and controlling all forms of device degradation, going beyond those typically caused by ESD, has been emphasised by Sonnenfeld et al [30] who state:

> *"…it is not widely known how degradation mechanisms propagate as a function of environmental conditions and various stressors. The attainment of such knowledge is critical for advancements in the field of power electronics health management and prognostics. The ability to perform large scale experiments and characterize the degradation signatures of such semiconductor devices under various scenarios is of great interest…*
>
> *The assumption of new functionality will also increase the number of electronics faults with perhaps unanticipated fault modes. In addition, the move toward lead-free electronics and microelectromechanical devices (MEMS) will further result in unknown behaviors."*

The study of field induction in reticles and the computer simulations performed to help the understanding of field induction on a nanometer scale, which cannot be directly measured, have demonstrated that measurements of charge and voltage on a macroscopic scale during typical ESD audits in a factory environment tell only a partial – and often misleading – story. It is necessary to consider the physics that operate on the scale of the device structures themselves, or even at an atomic level, to fully appreciate the varied detrimental effects that may be caused by electrostatic imbalance. This requires shifting the focus of attention from the traditional approach of voltage control on a macroscopic scale to field management on a microscopic scale.

One might wonder why focusing on electric field management might lead to a different treatment of electrostatic risk than other approaches, such as those designed to control electrical potential. After all, electric field is measured in volts per meter, so if voltage is controlled, electric field will be controlled too. Intuitively the two approaches might seem to be the same. However, the reason for the fundamental difference should become clear by looking at a graph of field induction between conductive structures on the scale of the features found in reticles and semiconductor devices.

Figure 8 is a computer simulation of the electric field and voltage that would be induced between two isolated conductors by a constant electric field as a function of their separation. It was produced to help explain the effects of field induction in reticles. The simulation shows that as the separation of conductors is reduced (as reticle patterns and the structures in semiconductor devices become further miniaturised following Moore's Law) the voltage that is induced between adjacent features by an externally applied electric field rapidly falls, while the electric field concentrated in the gap between them rapidly rises. The effect is highly nonlinear.

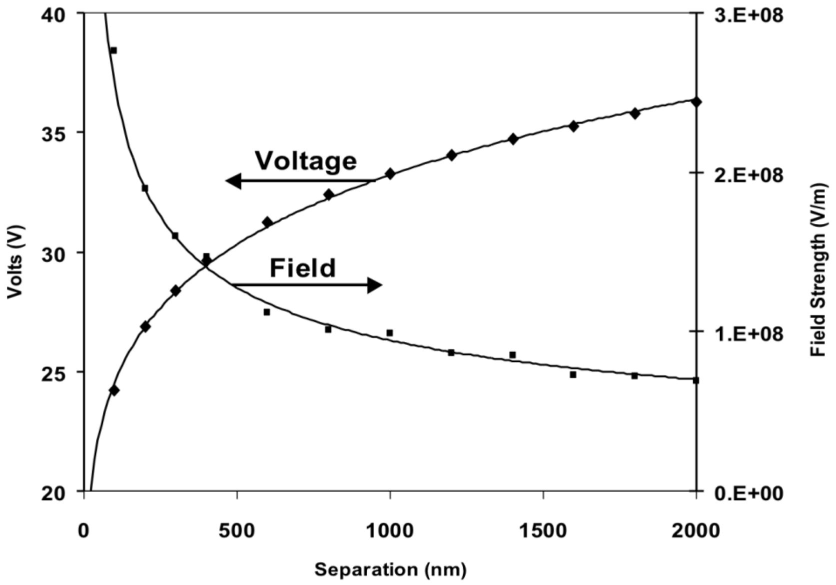


Figure 8. Two-dimensional finite element analysis simulation of the induced potential difference and field strength between two isolated conductive lines as a function of their separation in a constant external electric field.

By the time the separation of conductors reduces to the scale of the structures in semiconductor devices it becomes extremely difficult to induce high voltages between them, which many people might believe automatically reduces any risk arising from field induction. However, a high induced voltage is not necessarily the stress factor that causes damage. It can be seen from the graph that on this dimensional scale low induced voltages can be accompanied by very strong electric fields, and this fact is further illustrated by the simulation shown in Figure 9.

This computer simulation was produced to show that the guidance published in the ITRS specifying the maximum electric field to which a reticle should be exposed to control ESD risk was actually unsafe when considering the risk of EFM. It shows that on this scale, even with only a small fraction of a volt induced between the conductors, the local electric field strength can be dangerously high. The ITRS guidance was subsequently updated and the figure for the maximum electric field to which a reticle should be exposed was significantly reduced, in recognition of the newly identified risk of field-induced damage.

The pursuit of Moore's Law, with the consequent reduction of the separation between isolated conductive elements in a circuit, therefore acts to accentuate any electrostatic risk that might be caused to semiconductor devices as a direct result of field induction. Having polarizable dielectrics present between the conductive features, as is the situation in semiconductor devices, would further increase the local electric field strength at any induced voltage, by comparison with the situations modelled in Figure 8 and Figure 9.

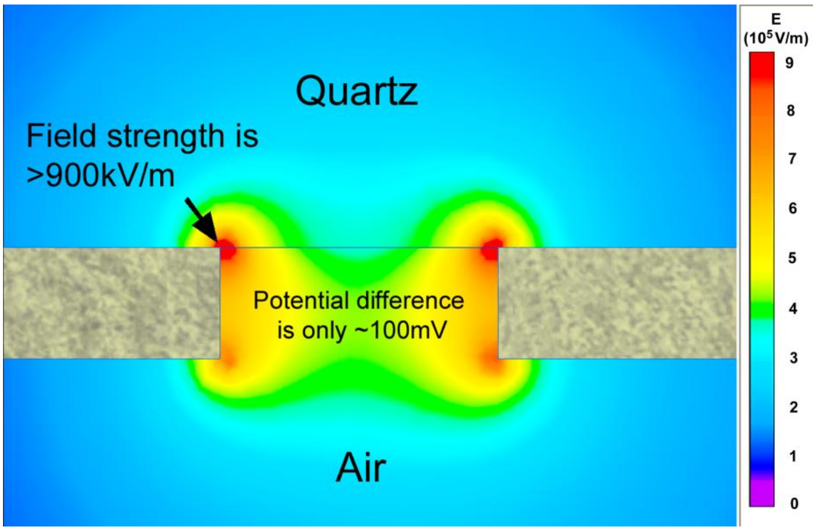


Figure 9. Computer simulation of field induction in a metal-on-glass reticle with a feature separation of 250 nm. The concentration of the field at the edge of the line in contact with the quartz substrate produces field strength above 900 kV.m^{-1} with a potential difference of only around 100 mV induced between the features.

It is impossible to measure the potential differences and local electric fields that are induced between different internal parts of a semiconductor device, so one cannot measure this kind of risk directly. It is also practically impossible to simulate induction effects in such complex three-dimensional structures, so the only way of estimating the risk is to base the risk assessment on what is already known from the study of field induction in reticles. One crucial aspect of this is that grounding through an equipotential bonding program designed to reduce ESD during material handling accentuates any risk that may arise through field induction.

When one becomes aware of this, injecting a balancing charge into a semiconductor device through equipotential bonding, which will inevitably create a strong internal electric field between the device circuitry and the static charge held on an insulating part of the device, does not seem to be a very prudent thing to do.

5. Conclusions

It has been shown theoretically and proven experimentally that using equipotential bonding to prevent ESD during the handling of reticles has negative consequences for the safety of the reticle. Even though equipotential bonding is intended to be protective and it is a recommendation given by many electrostatics consultants, it is definitely not protective for reticles. Detailed investigations of damage effects in reticles have revealed that as well as increasing the risk of ESD within the reticle, rather than reducing it, equipotential bonding enhances other field-driven and field-initiated damage mechanisms that until recently were completely unknown. These cumulative damage processes take place under field exposure conditions orders of magnitude weaker than those that cause ESD.

Extending this understanding to an assessment of the handling of semiconductor devices leads to the conclusion that equipotential bonding could also have negative consequences for their security. Consequently, it is recommended that the extensive experimental research described as being “of interest" by Sonnenfeld et al should urgently be undertaken, to investigate whether electrostatic damage processes are capable of being enhanced in devices by this handling practice that is almost universally presumed to be protective. Even if current semiconductor devices are found to be sufficiently robust to withstand stresses of the kind that have been described herein, it does not mean that creating such stress is advisable; neither is it guaranteed that all future electronic, optoelectronic and micro-electromechanical devices would be able to withstand such treatment.

If it is found that devices are being put at elevated risk of electrostatic damage through the use of equipotential bonding, as has been proven to be the case for reticles, this does not create an insurmountable challenge for the semiconductor industry. A methodology for handling extremely electrostatic sensitive (EES) devices without exposing them to increased risk by grounding them through an equipotential bonding scheme has already been described in SEMI Standard E163 [31], and the technology required to implement such a handling scheme is already available.

What is needed now is further experimental research, and the willingness of the industry to change its way of working if it should be found to be necessary, in order to assure the future electrostatic security of ESDS and EES devices that are yet to be developed.

Conflict of interest

The author declares that there is no conflict of interest in this paper.

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