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LITHOGRAPHY: RETICLE MANAGEMENT

Estimation of the Field-Induced Damage Thresholds in Reticles

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ABSTRACT

It has been reported previously that three separate processes cause damage when an electric field interacts with a reticle: electrostatic discharge (ESD) and two different types of electric field-induced metal migration (EFM). This paper presents some further data analysis allowing a first-order calibration of the thresholds for these different forms of field-induced reticle damage. EFM is shown to take place with gap voltages within the reticle pattern that are more than an order of magnitude below that which results in ESD damage. The effect of reticle layout on the predicted sensitivity to different types of field-induced damage is also explored.

The cost implications of having a large quantity of unidentified faulty inventory in the production pipeline could be much more serious than anything that has been caused by reticle ESD in the past.

INTRODUCTION

The complex nature of the interaction between photomasks and electric fields has recently been described through the use of computer simulation [1]. The presence of a continuous chrome border (guard ring) surrounding the image area was shown to concentrate the largest induced potential differences in the region at the edge of the die, creating a characteristic reticle damage pattern that is known as the "ring of fire." The damage produced in this area of a reticle is generally the first to be noticed during routine reticle inspections since it is the most severe, resulting from powerful electrostatic discharges (ESD) that can blast off the antireflection coating and either melt or vaporize the edges of chrome lines. It was shown in a second paper [2] that there are two further reticle damage mechanisms, both attributed to the electric field induced migration (EFM) of chrome onto the surface of the quartz between the image lines. These two migration mechanisms take place at lower induced voltages than give rise to ESD events, hence they can be seen in the central regions of reticles, away from the ring of fire. Such an effect was reported by Rudack et al, who investigated the sensitivity of different types of production reticles to electric field induced damage [3].

As awareness increases within the semiconductor industry about the dangers posed by electric fields around reticles, there is a probability that the main risk factors will come under better control. The adoption of measures to control static electricity, such as the replacement of insulating materials with static dissipative ones and the installation of air ionizers in critical locations, will reduce the magnitude of electric fields wherever reticles are handled in accordance with the guidelines published in the ITRS [4]. Such precautions are likely to reduce the frequency of ESD damage to reticles, which might lead some observers to believe that the risk to reticles has been adequately controlled. That would be a dangerous conclusion because EFM damage, which is more difficult to detect yet which is no less harmful to a reticle, could still occur.

Since EFM is a gradually-operating cumulative damage mechanism, it can cause reticle degradation over an extended time. Such reticle degradation during use has the potential to cause drifting parametric performance that will eventually result in yield loss with no warnings having been raised by EMI detectors or similar ESD event monitoring. Furthermore, the CD degradation caused by EFM is localized between certain features so it is unlikely to be detected by in-line process control techniques such as wafer scatterometry. A great deal of work-in-progress in the fab could be processed with a degrading reticle before detection of any problem. The cost implications of having a large quantity of unidentified faulty inventory in the production pipeline could be much more serious than anything that has been caused by reticle ESD in the past.

Different types of reticles are known empirically to have a different sensitivity to ESD, depending upon the length, spacing and density of the chrome lines within them. Typically, metallization (interconnect) layer masks are the most sensitive to electric fields as they have the longest chrome traces on them. However, reticles with pattern types that until now have not

exhibited sensitivity to ESD may, as feature dimensions continue to be reduced, start to exhibit sensitivity to EFM damage. Hence, rather than focusing attention elsewhere when reticle ESD seems to have been brought under control, yield managers and photo-area managers need to be even more vigilant to ensure that these more subtle and difficult-to-detect reticle damage mechanisms do not begin to wreak havoc in production. A paradigm shift in reticle protection is needed.

INDUCED VOLTAGE RANGES FOR FIELD INDUCED RETICLE DAMAGE

When a reticle is exposed to an electric field, different types of damage are caused as a function of the induced voltage or local field strength between the reticle features. The characteristic appearance of each type of damage is shown in Figure 1. This is a compilation of atomic force microscope images of damaged features on canary test reticles, which have been described previously [2]. These defect types replicate those seen in production reticles, with the benefit that they are generated at known locations on a reticle under known conditions, making systematic study with techniques such as AFM possible. As far as can be determined from the reviewed data (AFM images from several canary test reticles, damaged to different extents by exposure to different levels of electric field for different durations) each type of damage has a different onset voltage (or field strength) as depicted by the horizontal axis in Figure 1. Each type of damage can be seen together with the others on any reticle feature depending on the duration and severity of the field exposure, but for clarity the images shown in Figure 1 have been selected to illustrate predominantly only one type of damage per image.

EFM type 1 and EFM type 2 are cumulative damage mechanisms, whereas ESD occurs as a discrete event once the air breakdown threshold is reached. Thus the presence of different amounts of each type of damage in a reticle will give an indication of how severe the field induction has been and for how long it has been present. For example, extended or repeated exposures to low level electric fields are likely to produce more of EFM type 1 than EFM type 2 (as illustrated by the first two images in Figure 1) and short exposures to high levels of electric field produce ESD damage without any EFM being seen at all (as illustrated by the sixth image in Figure 1).

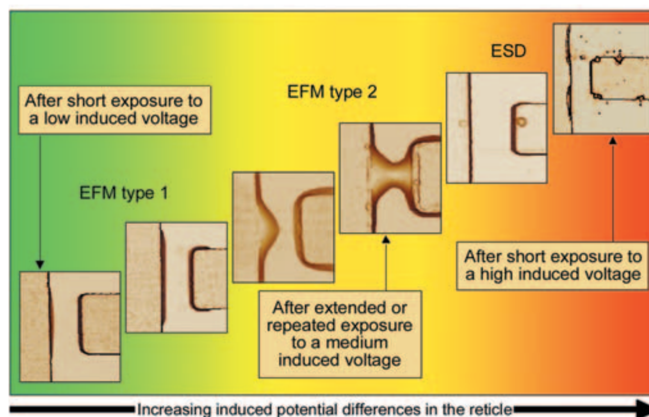
It would be useful to know how large the induced potentials (or local field strengths) were that caused each example of damage in Figure 1. Unfortunately, it is not possible to obtain a direct measurement of the voltages induced in a reticle by an electric field, since any attempt to do so would modify the field coupling and change the result. To try and better quantify the voltages that gave rise to the damage in the illustrated examples, results from other reticle tests have been examined.

I-V CHARACTERISTICS OF MICRON-SIZED GAPS

In a study conducted by Wallash and Levit [5], voltage was applied directly to the chrome features in a canary ESD test reticle. The voltage was increased at a fixed rate of 5 V per second and the current passing between the features was measured to determine the point at which a spark occurred. For a 0.9 micron gap on a previously undamaged reticle, a spark occurred at around 150 V. During the preliminary work while setting up their experiment, Wallash and Levit recorded current-voltage (I-V) data from several gaps on previously-used Canary reticles to help refine their experimental technique. These gaps had already sustained an unknown amount of damage before the recording of the I-V traces so the data were not useful for determining the spark threshold for a production reticle, which was the objective of their experiment. However, the data are extremely valuable because they add important information to the previous study of EFM and help to quantify the damage spectrum of Figure 1.

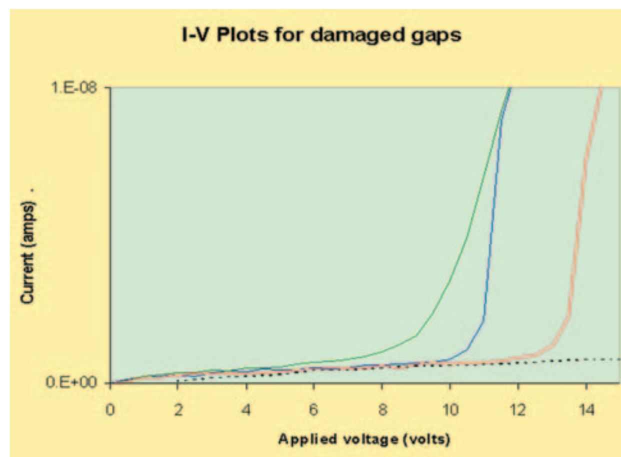
Figure 2 is a chart showing three of the I-V plots recorded from damaged canary reticle gaps. The dashed line is the leakage current in the measuring system, as recorded with the

FIGURE 1



Relative field induced damage regimes in reticles.

FIGURE 2



I-V plots for three previously-damaged canary reticle gaps, showing significant current rise above background at very low applied voltage. The dotted curve is the leakage current measured with the probes not in contact with the reticle.

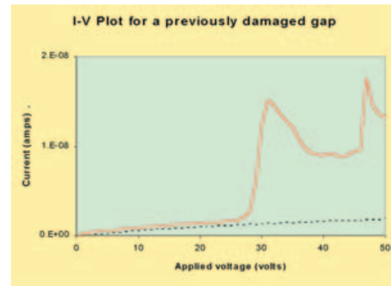
probes in air and no reticle present. Any current above this value was therefore flowing between the features on the reticle. Each curve showed a significant current rise above 10 V that indicates more than simple ohmic conduction across the gap.

Other I-V scans continued to over 100 V, revealing more of the characteristics of these current rises. Figure 3a shows a scan from a damaged gap in which two broad current peaks were recorded at quite low voltages. The current rise in each peak is moderate and gradual, spanning almost one second, followed by a more gradual decrease taking 1 to 2 seconds. After the first current peak, the current level above background is more than 10 times the current that flowed before the peak, showing a significant reduction of the electrical resistance across the gap. Figure 3b is a scan from another previously damaged gap in which two broad peaks are seen at low voltage, followed at higher voltage by a single sharp peak. In Figure 3c, which was recorded from a previously undamaged canary reticle, a broad peak is seen at about 80 V (16 seconds into the scan) followed by two sharp peaks at 129 V and 136 V. After the broad peak there is an elevated current flowing between the electrodes, but after the first sharp peak the current is reduced.

The possibility that these fluctuations were caused by unreliable connections rather than changes within the reticle itself was explored. It was concluded that this was not the case because the current is always stable and the data are noise-free. Unreliable electrical contact would be more likely to cause noisy data and a reduction of the current flowing (some data sets like this were seen). Hence, the broad current peaks at low voltage in these scans are not spurious and are all thought to result from the formation of a conductive surface track on the quartz, which would eventually lead to a bridge between the features. Continued application of voltage once a surface track has formed would add more material to the track and would also heat it by Joule heating. A point would be reached where the heating effect would dominate, melting the bridge or track and causing the chrome atoms on the quartz surface to coalesce under surface tension forces. This could be the origin of the surface "beading" reported in [2]. Continued application of voltage would cause the chrome to migrate on the quartz again and a further rise in current would be expected at a later time. ➡

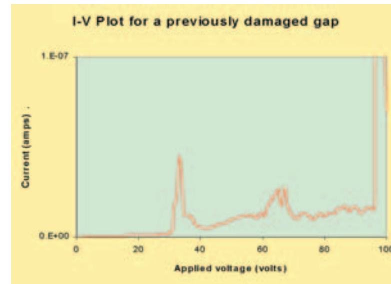
FIGURE 3

I-V plots from canary reticle gaps (5V/s voltage scans):



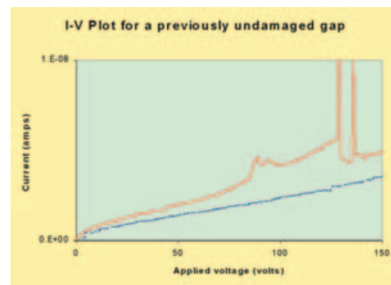
A

I-V plots from canary reticle gaps (5 V/s voltage scans):
A) I-V plot from a damaged gap, interpreted as formation of a surface track that is subsequently melted and then reformed later in the voltage scan.



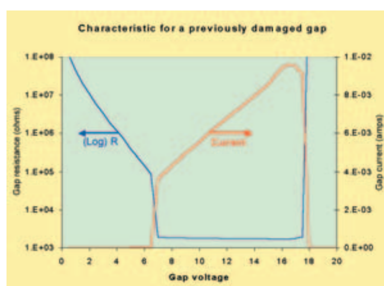
B

B) I-V plot interpreted as the formation of two surface tracks across a damaged gap, followed by a spark.



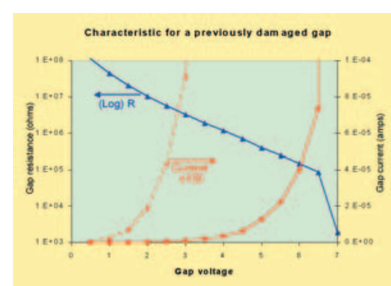
C

C) I-V plot recorded from a previously undamaged gap, interpreted as the formation of a surface track that was melted, shortly followed by two sparks.



D

D) I-V and resistance characteristic of a severely damaged gap, interpreted as the surface track forming phase followed by ohmic conduction through a fully conductive bridge, then bridge evaporation. (Note the much higher current that flows when a fully conductive bridge is formed.)



E

E) Detail of gap current during track forming phase from D.

This type of characteristic was present in almost all of the I-V data sets.

One badly damaged gap produced a very distinctive I-V characteristic, as shown in Figures 3d and 3e, where the gap resistance (calculated from R = V/I) has also been plotted (note the logarithmic scale). From the very first application of voltage across this gap the current is seen to rise exponentially. At 7 V there is a sharp transition to ohmic conduction, after which the resistance of the gap has a fairly stable value of ~2×10^3 ohms and the current flowing is seen to be proportional to the applied voltage (I = V/R). At 18 V the current falls sharply to zero and the resistance increases to a very high value, indicating that the connection between the reticle features has either melted or vaporized, like a fuse blowing. This result is included here because it shows that there is a marked difference between the conduction characteristics at different stages of the gap bridging process and suggests that:

a) The gap resistance changes (due to EFM) with extremely low applied voltage, or
b) The current flowing before a fully conductive bridge forms has an exponential dependency on the field strength, or probably
c) Both of the above are true.

The sharp peaks at high voltage in the I-V traces of Figure 3 involve a very fast rise to maximum current within one data channel, so this type of current peak is different from the broad peaks described above. They are attributed to air discharges, which have a current rise-time of only nanoseconds. All types of air discharge have such short current rise times, with streamer propagation acting as the precursor for air breakdown, which does not always occur. Streamers are ionized tracks through the air that are created when free electrons accelerated by the electric field ionize air molecules, eventually leading to a charge cascade called a Townsend avalanche. The propagation velocity of a streamer through air at atmospheric pressure is $>10^5$ m/s [6], so charge takes only picoseconds to cross the gap in air discharges between electrodes at sub-micron separation. Thus, the low voltage broad current peaks are unlikely be due to any form of air discharge, so they probably do reflect changes in the condition of the reticle surface.

QUANTIFYING THE DAMAGE REGIMES

Air discharge: The "high" induced-voltage range that results in air discharge has been shown to start somewhere around 100 V for reticle gaps of about 1 micron that have previously suffered some EFM damage (Figure 3b), whereas a previously undamaged gap showing no evidence of surface track formation in the I-V scan has a discharge voltage of around 150 V [5]. These values are fairly consistent with those found in studies of electrical breakdown in MEMS (micro electro-mechanical systems) by various workers [7, 8, 9, 10].

Ono et al [7] have used a microscope equipped with video integration facilities to record images of the light emitted by

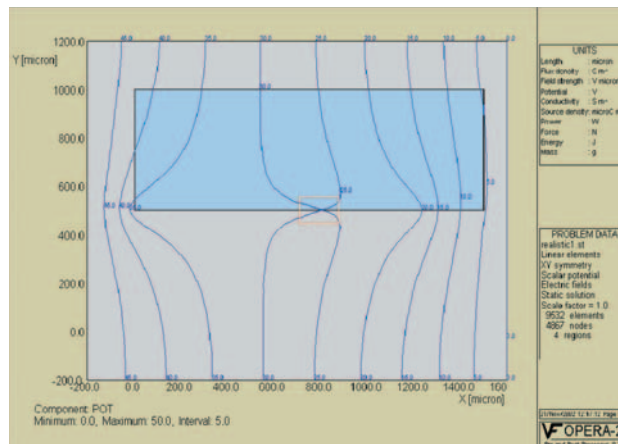
FIGURE 4

Damage Type	Induced Voltage Between Features	Damage Characteristics
EFM Type 1	<5V	Edges of chrome lines spread outwards across the quartz, degrading reticle CD
EFM Type 2	5-10V	Chrome (oxide?) film migrates onto the quartz between adjacent features, eventually building into a conductive bridge; continued exposure to fields causes current flow through the bridge that heats the chrome lines resulting in localized oxidation ("chrome foam"). In high fields the bridge may vaporize.
ESD	>100V	Line edges and line ends develop notches ("mouse bites"); the antireflection layer is lost from points along line edges. In severe cases, particulate debris can be deposited onto the quartz around damage sites.

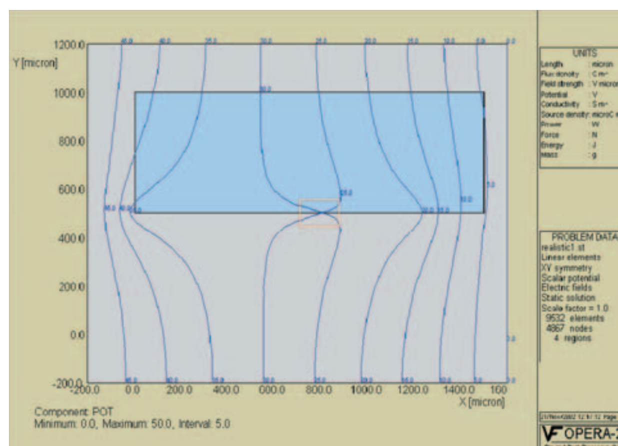
Tabulation of the induced voltage regimes for different types of field induced reticle damage in a canary reticle with ~1 micron gaps.

FIGURE 5

Finite element simulation of the interaction between an electric field of 250 V/cm and reticle features 1 micron apart, equivalent to the maximum ITRS recommendation for reticles at the 250 nm node. The field is amplified between the features by a factor of >200x.



A) Sectional view showing how the reticle features distort the field.



B) Detail of the gap showing the compression of the voltage contours.

electrical discharge in air between micro-machined structures having separations from 2 microns to 10 microns. The onset voltage for light emission by air discharge across a 10-micron gap was 40 V and as the electrode spacing was reduced the

threshold voltage for optical emission increased, qualitatively following Paschen's Law. Light emission was always observed below the breakdown voltage for the gap. It is possible that this light emission signifies the onset of streamer formation, which is a precursor for (but does not always result in) air breakdown. This could indicate that air discharge in a reticle occurs in two separate stages – a low voltage/low power one that does not result in air breakdown, plus a higher voltage/high power one that leads to a spark. If so, this could account for the two different damage signatures for air discharges shown in images 5 and 6 in Figure 1 and as reported earlier [2].

EFM type 2 (surface track and bridge formation): Bridge formation in the canary reticle was shown previously [2] to be a function of both voltage and time, as are the I-V scans shown in Figures 2 and 3. Owing to the presence of an unknown amount of previous damage in the gaps, the voltage at which a broad current peak is seen in these I-V scans has no particular relevance except as confirmation that material migration has started at some lower voltage. The "medium" induced-voltage range for EFM type 2 certainly seems to have started by around 5 to 10 V, as depicted in Figure 2. Figure 3e suggests that changes on the reticle surface could even be happening at a lower voltage than this. Further experiments are required to provide better quantification for the threshold, but 5 to 10 V is a conservative estimate for lines with the geometry of a canary reticle gap. The threshold voltage is likely to reduce with future reticle generations, as explained later.

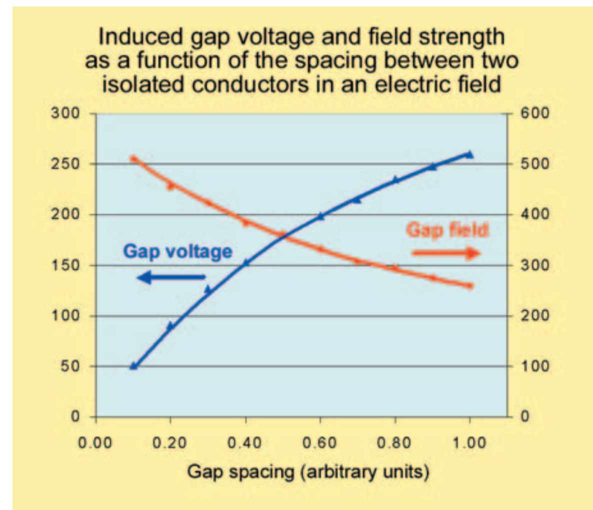
EFM type 1 (CD degradation, line spreading): The "low" induced-voltage range that results in EFM type 1 was seen in [2] to begin somewhere below the onset of EFM type 2, and it appeared to have an onset threshold defined by the field strength at the edge of the chrome line. The rate of CD degradation by EFM type 1 appears to be constant once a threshold field at the line edge is reached. This means that reducing the field strength around reticles will not reduce the rate of CD degradation unless the local field strength at the line edges is kept below a safe limit. This will be highly dependent upon the detailed reticle structure, not just the external field strength, as explained later. It is not possible to estimate the threshold for this damage mechanism without further experimentation. From the present evaluation it is only possible to state that the induced voltage that causes this kind of reticle damage is below that which causes EFM type 2 and is very low indeed by comparison with ESD.

These conclusions are summarised in Figure 4.

THE EFFECT OF RETICLE LAYOUT ON FIELD INDUCED DAMAGE

The average field strength between the reticle features in the I-V tests at the onset of EFM type 2 (~5V) would have been around 50 kV/cm. It is difficult to visualise how such high electric fields could be created in a reticle during normal handling, so some field simulation was undertaken to demonstrate this.

FIGURE 6



Variation of the induced voltage and field strength across a gap between isolated conductors in an electric field as a function of their separation. (Values taken from 2D finite element simulation).

Figure 5 shows the result of computer simulation of two isolated conductors held in a 250 V/cm electric field, which is the ITRS recommended maximum for reticles with micron gaps (250 nm technology node). The simulated features are an 800-micron long chrome line facing a 400-micron long line across a 1-micron gap. The voltage contours cannot pass through the chrome lines because they are conductors, each of which must be at a single potential when at equilibrium. Hence the voltage contours are squeezed through the gap between the chrome lines, as shown in Figure 5b. A reticle can thus be thought of as an electric field amplifier, where the gain is a function of the feature size, line spacing and orientation relative to the external field. In the simulated scenario of Figure 5 the field strength is amplified from 250 V/cm in the ambient to over 50 kV/cm in the gap.

Production reticles containing long chrome lines (such as metallization layer masks) are known from experience of reticle ESD in fabs to be very sensitive to electric fields. This is because rows of long features aligned in the direction of the field will have high potential differences induced between them, just as in the canary reticle experiments and the simulation of Figure 5. However, this is an overly simplistic interpretation of the factors that make a reticle sensitive to electric fields. As the spacing between isolated conductive features in an electric field is changed, the potential induced between them changes in a non-linear way, as illustrated in Figure 6. This chart shows that the average field strength in the gap also changes in a non-linear manner.

This characteristic has been investigated using simulations of feature dimensions and layouts that might be found in a typical reticle. Figure 7a is a simulation of a 300-micron long line 1 micron from the guard ring on a reticle in an arbitrary electric field. The induced potential difference between the fea-

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tures is 40 V, so the average field strength across the gap is 400 kV/cm. If the gap is increased to 10 microns as in Figure 7b, the induced potential difference across the gap rises to 260 V and the average field strength in the gap is reduced to 260 kV/cm. When several micron-wide features (which could be OPC features or orthogonal lines) are placed in the 10-micron gap as shown in Figure 7c, the induced potential differences and local field strengths are altered in a significant way. The largest potential difference between neighboring features in this configuration is 65 V, giving an average field strength between the features of 650 kV/cm, values that are both more than 50 percent higher than the example of a reticle containing only a long feature with a micron gap to the guard ring as simulated in Figure 7a.

It can be seen that the details of a reticle's layout are influential in determining how sensitive it will be to external electric fields and hence, according to Figure 1, to which types of damage it will be susceptible. It is not only long features aligned with the field direction that can suffer field induced damage. Small isolated features, such as optical proximity correction features or lines running orthogonal to the direction of the external field, can also be at risk depending on their location within the reticle pattern. The example of Figure 7c has shown that even with induced voltages below the threshold for ESD, extremely high local field strength can be present within a reticle. This is likely to result in EFM even if a sufficiently high voltage has not been reached to allow an air discharge to take place.

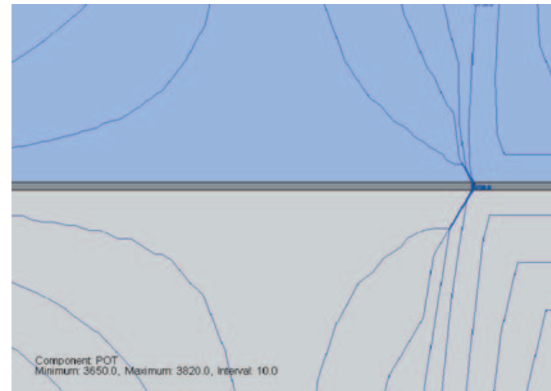
These simulations are only semi-quantitative since they are based on two-dimensional rather than three-dimensional calculations, but they do give good qualitative comparisons and accurately reflect the field-induction characteristics that are seen in real reticles. For example, it was shown in earlier field simulations [1] how the presence of a guard ring on a reticle concentrates fields at the edge of the pattern area and how grounding of the guard ring amplifies this effect, further increasing the risk of field-induced reticle damage. Rudack et al [3] have confirmed these characteristics experimentally by inducing ESD events in different types of production reticles to determine their relative sensitivity to electric fields.

CONCLUSIONS

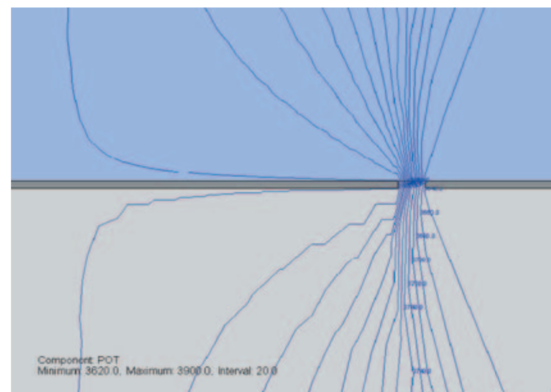
To a first approximation the induced voltage thresholds for field-induced damage mechanisms in reticles have been quantified. It has been shown that reticle damage occurs with induced voltages more than an order of magnitude lower than has previously been identified for reticle ESD. The induction of potential differences and the field compression within a reticle have both been shown to have a non-linear dependency on feature spacing. As reticle gaps continue to shrink in successive generations the tendency will be towards lower induced potential differences and higher localised field strengths. This provides an explanation for the changing characteristics of field induced damage in reticles over recent years, whereby voltage-dependent damage (ESD) is giving way to field-driven damage

FIGURE 7

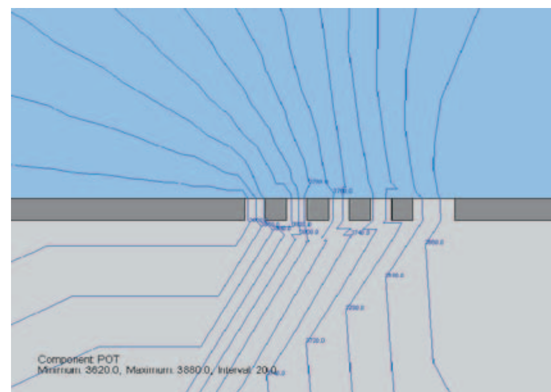
The effect of pattern layout on the induced potential differences and local field strengths between features on a reticle in an electric field (arbitrary external field strength).



A) 300 micron line 1 micron from the guard ring. Induced gap voltage 40 V, average field strength 400 kV/cm.



B) 300 micron line 10 micron from the guard ring. Induced gap voltage 260 V, average field strength 260 V/cm.



C) Four 1 micron wide features in the 10 micron gap of b). Largest gap voltage 65 V; average field strength 650 kV/cm.

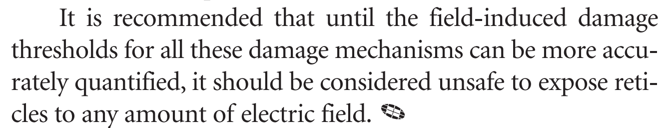
(EFM) that results in CD degradation and gap bridging.

Since EFM has been shown to take place at much lower induced voltages than ESD, reticle types that have not previously shown a tendency to be damaged by ESD could nevertheless be susceptible to damage by EFM. Fabs where the risk to reticles is reasonably well controlled may have avoided ESD problems in the past, but from the evidence already presented EFM is highly likely to have been taking place. This may not have caused process problems in the past because a certain amount of CD degradation may not cause a serious defect in a reticle with large gaps, but in a modern reticle with smaller gaps the same amount of degradation probably would be significant. It is increasingly likely that EFM will impact yield in future reticle generations. This also means that the useful lifetime of a reticle that is exposed to electric fields during its use in a fab will become ever shorter as reticle gaps continue to shrink and EFM becomes more significant.

The sensitivity to field-induced damage of the advanced reticle technologies such as serifs, which are being used in binary reticles to allow optical lithography to keep pace with Moore's Law, and optical proximity correction features may cause EFM to have a much greater impact on semiconductor production in the future than ESD has had in the past. The printability of the type of reticle defect caused by the early stages of EFM has been demonstrated by Rudack et al [10]. This showed how small defects on line edges caused by EFM have a disproportionate impact at wafer level because of the mask error enhancement factor (MEEF). While individual instances of reticle exposure to low-level electric fields may not produce any easily detectable reticle damage, EFM is a continuous and cumulative process that after multiple low-level exposures will eventually cause a printable reticle defect. This characteristic, considered alongside the variable sensitivity of different types of reticle to electric fields, the changing induction characteristics with shrinking gap sizes and the different onset thresholds for the different types of field-induced damage makes it virtually impossible to prescribe a universal guideline for a safe level of electric field near reticles.

The ITRS recommended maximum field strength guideline for reticles at the 250 nm node is thought to be unsafe when considering all types of field-induced reticle damage. This conclusion follows from correlation of field simulations, test reticle damage patterns and current-voltage data for micron-sized gaps. The ITRS maximum electric field guidelines for reticles in subsequent generations are scaled linearly in proportion to the technology node (i.e. feature spacing) but simulation has shown that the risk of damage does not vary linearly with feature spacing, it becomes progressively more severe. Therefore, the validity of all the ITRS guidelines for electric fields near reticles is called into question.

It is recommended that until the field-induced damage thresholds for all these damage mechanisms can be more accurately quantified, it should be considered unsafe to expose reticles to any amount of electric field.



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