PARTICLE CONTAMINATION CONTROL IN PLASMA PROCESSING: BUILDING-IN RELIABILITY FOR SEMICONDUCTOR FABRICATION

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Particulate Contamination Control in Plasma Processing: Building-In Reliability for Semiconductor Fabrication

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ABSTRACT

Plasma processing is used for ~ 35% of the process steps required for semiconductor manufacturing. Recent studies have shown that plasma processes create the greatest amount of contaminant dust of all the manufacturing steps required for device fabrication. Often, the level of dust in a plasma process tool exceeds the cleanroom by several orders of magnitude. Particulate contamination generated in a plasma tool can result in reliability problems as well as device failure. Inter-level wiring shorts different levels of metallization on a device is a common result of plasma particulate contamination.

We have conducted a thorough study of the physics and chemistry involved in particulate formation and transport in plasma tools. In-situ laser light scattering (LLS) is used for real-time detection of the contaminant dust. The results of this work are highly surprising: all plasmas create dust; the dust can be formed by homogeneous as well as heterogeneous chemistry; this dust is charged and suspended in the plasma; additionally, it is transported to favored regions of the plasma, such as those regions immediately above wafers. Fortunately, this work has also led to a novel means of controlling and eliminating these unwanted contaminants: electrostatic "drainpipes" engineered into the electrode by means of specially designed grooves. These channel the suspended particles out of the plasma and into the pump port before they can fall onto the wafer.

INTRODUCTION

I'd like to thank the conference organizers for inviting me to come out to this lovely location in the Sierras and for the opportunity to breathe the thick air here at 6000 feet. Los Alamos is at 7300 feet.

I'd also particularly like to thank Harry Schafft for fostering the connection between contamination control, an area I've been involved in for about eight years now, with Building-In Reliability. Certainly the connection has been there for yield and contamination control activities for some time, but I think there's also an important application in this area for reliability concerns.

I'll start with a very general slide, "Why Contamination Control?". This is what comes to mind first and foremost. You're all familiar with the clean room. This is often thought to be the "front line" of contamination control. However, today, with modern cleanrooms, improvements aimed at the clean room do not have a great deal of influence either on yield or contamination control. The reason is the best clean rooms today are pretty good. Modern cleanrooms are advanced to the point at which they already have controlled the contamination that used to end up on the wafer, so there is very limited additional benefit to derived from further advances in this facility. Some of the older clean rooms weren't quite as good.

That's what I'm showing here, a pie chart from Sematech showing the source of particles on a typical wafer for 1990 and 1995.

![Particle Contamination in MFG: Source](chart)

Fig. 1: Breakdown of particle contamination on wafers, by source for 1990 and 1995. Source: Sematech.

Overwhelmingly, most of the contamination results from exposure to tools and processes required for device fabrication. Let's also put that in perspective with a hospital operating room, in perspective with New York City air, and with the inside of your plasma tool. Today 90% of the particles that end up on a wafer come about from the process tools [1]. But the emphasis shouldn't be to get rid of these tools because they are "dirty". They are needed for device fabrication. The emphasis should be to make them clean.

Similarly, the emphasis shouldn't be just to measure particles in tools. That's been the approach in the past. We measure, we measure, we measure, because the previous control technique was strictly limited to preventive maintenance. For the purposes of this discussion, we'll call this "the something happens" school-of-thought. We didn't know exactly what happened, but by measuring the contamination, we were able to at least limit the impact of the problem. In other words, contamination was thought to be a random event, generally beyond control, therefore we must measure it and that's how we correct it. We have no other means of control. The problem is that measurements consume time and resources, limit production and often aren't terribly meaningful.
What I’d like to propose instead is an approach by which we build in reliability, not only for the product, but also for the process. I think its fairly obvious to most people here that some or most of the variation in device product is due to variations in the product fabrication process. Better control of the fabrication process, should also mean better control over product reliability, especially for reliability problems caused by particle contamination. To do that we have to understand what happens, what causes particles to form, to be transported, and be deposited onto wafers. Particles in a plasma process are much different from particles in other device fabrication processes, say, furnaces.

Most of the people involved in particle control in fabs have their background in aerosol science. Plasmas are very different from the non-ionized ambient usually studied by aerosol scientists, so the peculiarities of particles in plasmas was generally overlooked by contamination control specialists for the last 20 or 30 years. First, we must recognize that a plasma is an ionized environment containing electrons and ions. When a particle is present in a plasma, electrons will attach to it because electrons have very high mobility, much more so than ions. Electron collisions with the particle will occur faster than the positive ion collisions. The electrons attach to the particles just like the electrons attach to a probe or a wire that you put in a plasma. The result is that the particles become negatively charged [2,3]. This is illustrated in Fig. 2.

![Dust Charging in a Plasma](image)

**Fig. 2**: The charging of particles in a plasma by electron collisions. Note that low energy electrons are deflected after particle charging, whereas positively-charged ions are attracted to the particle. This results in zero net current flow, but an average negative charge [2,3].

Eventually, each negatively-charged particle builds up a sheath around itself. Very quickly, the flux of negative charge and positive charge to the particle is zero. Low energy electrons are repelled. Positive ions are attracted, but the particle remains negatively charged. Also, it doesn’t matter whether the particle comes off a wall, whether it’s one nucleated by the chemistry of the plasma, or whether it’s one that’s produced in an etching plasma, a deposition plasma, or even an ion beam. It’s negative. And the negative charge is what dominates. Typically, a one micron particle has $10^4$ negative charges [4]. That’s what makes particles in plasmas different. The charge of the particle affects the growth, transport and deposition onto a wafer.

Because the particle is negatively charged, there’s a unique force that occurs only in plasmas. We call that the ion drag force [5]. Positive ions are attracted to the particle, but many will not collide with the particle. Instead, their trajectory is deflected by the sheath field. This results in a loss of momentum to the ion, which is transferred to the particle. Since the sheath field surrounding the electrodes in a plasma tool results in a directed flux of ions, particles also acquire some of the directed drift of the ions due to the ion drag force. Accordingly, particles formed in the plasma or those that flake off of tooling walls drift in the direction of the ion flow, which is towards the wafer. Eventually, the particles migrate towards what we call the sheath boundary of the plasma. This is the high field region surrounding the electrode and the wafer. Once they reach the sheath boundary, the negatively-charged particles are then repelled by the strong, time-averaged repulsive field in this region. The result is that the particles balance, or suspend, at this point. That has a great deal of influence on where the particles go and how particles contaminate wafers in a plasma tool. The result of this force balance is that the particles will be suspended. Clearly, this is contradiction to the behavior of particles in non-ionized environments, such as cleanrooms [6].

### Other Forces on Particles

**Neutral Drag Force (Stokes Force)**

\[
F_{\text{drag}} = 6\pi \eta D \frac{v}{v_{\text{mean}}}
\]

**Gravitational Force**

\[
F_g = m g
\]

**Thermophoretic Force**

\[
F_T = -3\pi \eta v^2 \frac{T_h - T_c}{T_h}
\]

![Other Forces on Particles](image)

**Fig. 3**: The ion drag force results from momentum transfer from ions deflected by the negative charge surrounding a particle. This force is then counter-balanced at the electrode sheath boundary.

Let’s examine the effect further. With $10^4$ charges on a one micron particle, the electric field necessary to suspend the particle is simply a tenth of a volt per centimeter [7]. That’s a very small field, about three orders magnitude smaller than a typical sheath field surrounding the wafer in a plasma tool. Even a 10 micron particle could be easily suspended. The result of particle charging in a plasma is that unlike other cases in semiconductor fabrication, in plasmas, particles suspend at the sheath boundary. The particle is suspended in the plane of the sheath boundary, and its transport along that plane is something like a puck in air hockey. It is nearly frictionless.

There are some other effects. Here, we show the neutral drag force, also known as the Stokes force. This force results from gas molecules banging into particles, transferring momentum to the particles. The Stokes force tends to push the particles along the direction of the gas flow.

Gravity has a very minor effect in most plasma tools and processes because of the more dominant electrical forces at play.

Another force of importance if there is a temperature gradient is the thermophoretic force [8]. Hot molecules hit the particles faster than cold molecules do. So, in a temperature gradient, more momentum is applied to the particles on the hot side of the thermal gradient. The result is that particles migrate toward the colder surface. In plasma processes there are often thermal gradients because there are regions of power application and power removal by cooling.
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**Experimental**

Our work is in the detection and control of these particles. We use a specialized particle detection method to monitor particles right inside the tool. This also connects with the building-in reliability aspect of this work because particle detection is not merely a means of monitoring to signal for preventative maintenance, but rather a means of understanding for particle elimination and control. Let me stress that further. The goal is *not to count* the particles, but rather to *eliminate* them. If you eliminate the particles, you also eliminate the need for counting. That is our goal. To do this we use light scattering, actually a laser-induced form of Mie scattering. As it turns out, Mie scattering works for particles larger than about 0.3 microns, which are generally also the particles of interest.

The light scattering will occur mostly in the forward direction with a very weak component in the reverse or perpendicular directions as shown in Fig. 8. This work was first started while I was at IBM. As shown in Fig. 9, we use a continuous wave laser, such as an ion laser, reflect its beam into the plasma tool while the wafers are being etched and deposited. We then raster the laser beam very rapidly so that to the video camera it looks continuous. This same technology is used for laser light shows and for supermarket scanners. In this technique, particles that intersect the laser beam will scatter light in the forward direction which is then picked up by the video camera. This also provides a means of recording the signal. In this way, we can view the particles in slow motion and we get a record of the process. Most importantly, we can see what happens as we turn the knobs and change the tooling conditions.

**Directionality of LLS**

**MIE Scattering**

*Particle Size > Wavelength*

**Parameters:**

D = 1.091 microns  
Wavelength = 633 nm  
N = 1.5  
Spherical nonabsorbing particle

**Reference:**


Fig. 8: Directionality of Mie light scattering for a 1 micron particle and 633 nm light.
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Laser Light Scattering Particle Detection

Fig. 9: Schematic diagram of the laser light scattering particle detection system.

RESULTS

I'm going to show you a series of photos showing some of our laser light scattering results [10]. First, the perspective: we're looking into the forward direction of the laser beam, in fact at a shallow angle to the beam so that the scanner is in the background. This is the electrode of the plasma tool. At this shallow angle, the wafers appear elliptical as seen in Fig. 10. The deflection limit of the scanner is between these two points. Also, the direction of the gas flow is from the wall to the center, where the pump port is.

WAFFER ORIENTATION IN TOOL

Fig. 10: Orientation of the laser raster plane, the electrode, viewport and 3 wafers placed on the electrode during laser light scattering measurements.

Here, we see the clouds of dust suspended in the plasma. These particles are suspended about eight millimeters over the wafer at the edge of the sheath boundary. This entire structure consisting of a dust cloud we call a “trap”. Traps are basically a plasma nonuniformity, characterized by a localized increase in the plasma potential by a few volts. Particles, being negatively charged, migrate to those spots.

Fig. 11: Dust clouds trapped over 3 wafers on the electrode during plasma processing.

Traps are largely what determine the nature and extent of contamination in plasma tools. Traps locally confine the particles and prevent their elimination to the pump port. Then, because the particles are suspended, they grow. Because they are trapped, they are confined in this region during the process, all the while growing during the process. Then when the plasma turns off, they fall down, many of them landing on the wafer.

Fig. 12: Another view of trapped dust clouds over 3 wafers during plasma processing.

So how do we make this process more reliable so that the product is more reliable? We can use these traps to control the particles. More on that soon. Here is another view. About two years ago we made connection with astrophysicists for obvious reasons, because the same phenomena occurs in comets and planetary rings. Astrophysicists were long aware of the unique properties of dust in plasmas. They call their traps comets and planetary rings.

Fig. 13: Dust clouds containing lower particle density still show trapping.

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Now we’re viewing the laser raster plane above the outermost particle trap. We’re illuminating the trap in the center of the wafer, which we call a dome. This particular photograph was done using 3 different lasers, each operating at different wavelengths. The different colors in this photo correlate with different sizes of particles. Another view. This is a non-random distribution of particles. Clouds of dust. The density of these particles is about $10^8$/cm$^2$.

Now it’s clear why I say the dominant effect of contamination is in the process tool. When you try to correlate reliability with contamination a lot of people try to use contamination measurements from the clean room. Clearly this is a minor problem. Unfortunately, even the contamination measurements made inside plasma tools are invalid for the most part, because in most cases measurements are made without the plasma on. All of the physics I just showed regarding particle nucleation, growth and transport is overlooked.

Of course, that’s not always the case. However, lower levels of contamination, such as we have here in this view, measured with a krypton ion laser, show similar trends. Here, we can see individual particles present, rather than clouds of dust. But even under these conditions, the particles go first to their favorite location, where the trap is strongest. Trapping is the dominant effect, even if the particle density is very low. I’ll finish up with these pictures. If you like these photos you can get your own off the Web site. You may pull these images off our web site and print them out. We just ask that you don’t publish them without our permission.

To summarize, particles are ubiquitous to plasma processing. We have seen particles in every plasma process we’ve looked at and we’ve looked at a great number of them [11]. The particles behave similarly regardless of their composition or origin. That provides a means of controlling them because we don’t need to develop different technologies for each type and composition of particle. That’s a great advantage. Instead, we can generate a generic particle control technology. As you’ll see in the video tape. the walls, the chemistry, the pressure, the temperature, all influence the generation and growth of particles. The transport of particles is primarily influenced by electrostatic forces. This is giving us a means for controlling them and eliminating them. If we eliminate the particles, we also eliminate the need to count them. I’d be very interested to correlate this with reliability results.

**ANSWER:**

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**QUESTION:** Which is worse, plasma etch or deposition?

**ANSWER:** It varies by tool. There’s a different in process designs and hardware designs, even for different plasma tools running the same process. The process chemistry influences the formation of the particles. The tool design influences the transport of the particles. So which is worse? Considering only what ends up on the wafer, probably deposition is worse. We’ve measured almost all the various tools. Shortly, I’ll show you a complete characterization of one tool on video tape.

The electrostatic particle traps that shape the outline and intensity of these dust clouds, come about due to changes in the electrode topography and design. This happens because traps create a localized plasma non-uniformity by locally increasing the plasma potential. And by the way, this not only affects particles, but it affects the quality of that process as well. We found that the localized ion flux to the wafer changes because of traps. As a result, traps influence more than particle contamination on a wafer; they also affect device critical dimensions, and feature slope and uniformity of the etch rate [12]. This has been verified by Langmuir probe measurements and by optical emission measurements [13,14]. To summarize, we find that negatively charged particles move to the traps and therefore the traps strongly influence particle transport. We also believe that we can’t completely stop particle formation. This is because particle formation is due to the process chemistry and the process chemistry is necessary to make the product. The important question then becomes, can we use traps to minimize particle deposition onto the wafer. How do we do that?

One approach we found is by cutting a groove into the electrode of the plasma tool [15]. By doing this we intentionally create a trap, by increasing the plasma potential over the groove. This acts to draw particles to this region. We essentially getter particles from various other traps in the plasma and collect them over the groove. Then by continuing that groove to the pump port — and there’s a whole range of variations for this — tools with clamp rings, tools with electrostatic chucks, it is even possible to do this right on the wafer. By this approach, we can drain the particles out of the plasma and into the pump port. There are two steps here. First, the particles are electrostatically attracted to the groove and then we use the gas flow, or Stokes force, to channel the particles through this equipotential pathway and into the pump port. We simply purge the particles out of the plasma. This is one form of building-in reliability.

**ELECTROSTATIC PARTICLE TRAPS**

(Grooved Electrode)

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**ELECTROSTATIC PARTICLE TRAPS**

(Grooved Electrode)
**QUESTION:** How big are the grooves?

**ANSWER:** That varies with the plasma. Sometimes the grooves are a few microns in size and sometimes fractions of an inch.

Here’s a photograph of the groove in operation. The groove is purging the particles out of the plasma making this process cleaner and reducing the amount of particle deposition onto the wafer. So what we’re getting at here is a means of controlling the process to make it cleaner and thereby we are building-in reliability.

**VIDEO TAPE 1**

So let’s move on to the video tape. As seen here, we’re moving the laser plane up and down over the electrode in this plasma tool. This is why I can’t show you in still pictures. You can see the particles suspended at the sheath boundary within a range of a couple millimeters. Also, there’s a size difference in the particles within this narrow suspension region. Larger particles are suspended lower, closer to the wafer. Now, you’re going to see what happens during pump down. What we’re getting at is all of the factors that influence particles. This sequence shows a tool during pump down from atmospheric pressure. The swirling spots of light you see are droplets of water with condensation nuclei inside them, all inside the plasma tool.

Here’s a record. We see a 5 millimeter suspended particle right here. Watch this one and see how it gets so big. Agglomeration. Now we see the result of laser heating of particles suspended in a trap. Heating, caused by the laser, drives some of the particles out of the trap. Note also, that there two wafers juxtaposed on the electrode just past the trap fill of particles.

Now you see the groove operation in real time during plasma processing. Here, particles are moving in single file to the pump port exactly following the path of the curved groove. The particles are suspended around 6 mm over the groove; they don’t actually go inside the groove. The purpose of the groove is to create a disturbance that traps the particles, and confines them within the outline of the groove. Then, the drag force carries the particles along the groove and drops them into the pump port.

Clearly, the real test is how well this all works in manufacturing. I can show you some of these results. This is actual manufacturing data. The process that we worked on was at the time the dirtiest process in the fab, giving us not only a yield hit but a reliability hit as well. Over time, by implementing some of this technology, we were able to reduce the averaged particle contamination level by a factor of 20.

**Fig. 17:** By extending the groove from around the wafer to the pump port, the particles will be continuously purged from the plasma.

**Fig. 18:** Still photograph of particles being purged out of a plasma fitted with a grooved electrode.

**Fig. 19:** Contamination reduction results from a sputtered quartz deposition process, actual manufacturing data.
In another approach, we can set up a “microwave broom” to channel the particles out [16]. Here, you see a plasma with two opposing microwave antennae at opposite ends. At first, the microwave power is off, then turn the microwave power on and it causes the trap to dissipate. This is an example of process control techniques, designed to eliminate particles. The strategy is to build particle elimination technology into the fabrication process so that we don’t have to monitor the particles. Instead, we eliminate them.

This next view is of a new approach to cleaning wafers in a plasma tool. As you can see, particles “puff” out from between the two electrodes. This is one of the lab programs that we have currently going - development of a method for dry cleaning of wafers using a plasma. See the particles in this plasma: some are trapped. Now, when the plasma turns off, the field dissipates and the particles are pushed out instead of ending up on the wafer. This can be seen better in this slow motion video. Quite a burst of particles!

**VIDEO TAPE 2**

This is a complete characterization of a tool, using laser light scattering [17]. We use the results of this video to improve the tooling design to make it cleaner. A high density tool, the one shown in this video has many of the latest features, very desirable for 0.25 and 0.35 micron geometries. Not only does the tool have a high density source, but it also uses an electrostatic chuck. As we see, the electrostatic chuck has influence on particles. In this view you can see the front of the tool from inside the clean room. Here are the load locks.

The control touch screen is up here. This is the process chamber. The source, shown here is a Helicon source design. This is the laser light scattering setup mounted on the equipment rack. Note that we use a wafer as a 5 inch mirror. Here are the wafers during processing. We’re actually looking at surface particles on the wafer during the process. Very soon you’ll see the beam focused down right on the wafer and we can see it’s fairly clean. This plasma tool, however, doesn’t drop its particles on the wafer during the process, instead it drops particles at the end of the process. There, as you can see.

This is the electrostatic chuck, holding the wafer. We can turn the bias voltage on or off to see the influence of this on particle deposition. First, however, here’s a wafer coming in with some particles. Next, the plasma turns on and the etch begins. Use the laser light scattering technique, we find that the electrode bias provides a protective field against particle deposition onto the wafer. Now we see that this protective field, the wafer bias, is turned off so when the plasma stops, particles are deposited on the wafer. To correct this problem and to reduce particles and improve the reliability of the process, all we have to do in this tool is switch the shut-down sequence of this process. Some engineers might look at this and say “Let’s use this to monitor.” But we don’t think that’s necessary. We think we could build contamination control directly into the process to make it cleaner. This work is an example of that.

To demonstrate that, we now intentionally inject particles into the plasma by tapping on the side. The color change you just saw, was due to a slight air leak that resulted when the flange is tapped. When the electrode bias is on, the sheath protects the wafer from particle deposition even following injection of particles. As shown, fairly simple changes in the design can have a dramatic effect on particles. With the electrostatic chuck off, in slow motion, we’re going to inject particles in the same way. As we shall see, the electrostatic chuck actually affects particle contamination. When the chuck is on, particles stick. By doing this, we identify all the sources of contamination and correct them. So, we build-in a cleaner process.

Watch this pump down sequence. Those swirling dots are all particles. This was done right after a clean, called a wet clean. In this technique, the tool interior surfaces are wiped down with solvent or water-based cleaning solution. All the moisture coming off the walls at pump down causes the flakes to form. We eliminate particles and eliminate the need to count them and reduce the need for tool cleaning.

Now we can see a dirty incoming wafer and the effect of a tool vent. This would be missed by other detection techniques. To correct this we move the injectors for the nitrogen vent to a different spot. Down here is the only spot on this tool we can find traps, down at the bottom. Note that the wafer is way up here. This screw, for whatever reason, is creating a sufficient disturbance to the plasma that it’s trapping particles. The particles move only between these two screws.

Here’s the result: you can change the process with some simple fixes so that it’s clean and not a single particle ends up on the wafer. In this view, we’re going into the main etch. No particles are falling on the wafer now. Going into the over-etch. Still no particles. Then the critical moment - turning off the plasma - no particles! Then we let go of electrostatic clamp and remove the wafer. Success. By determining the causes of contamination and correcting them, we build a clean process. We have a clean process, so we don’t have to count particles. Also, you have a more reliable process and a more reliable product.

Summary

To conclude: particle contamination behaves similarly in all plasma tools regardless of the particle source. That provides us an attractive means of control. The sources are many. We can reduce but not eliminate the sources of particles. We can control contamination using this new technology. We also have a clear connection that will improve the reliability of the product, by improving the process and tooling hardware reliability. That provides new opportunities for improved products and tools.

Thank you.

**QUESTIONS AND ANSWERS**

**QUESTION 1:** Will you put your web page address up?

**ANSWER:** Yes.

{http://harry.lanl.gov/bpw/contamination.html}

**QUESTION 2:** Do you have an estimate of the percent reduction in particles?

**ANSWER:** Yes, 80-90% in many cases. Sometimes 95%. To get to 95% level you need a number of techniques. You have to reduce the source, work on the transport, work on your maintenance. Obtaining a 95% particle reduction is hard but it’s do-able. One technique won’t do it, but a combination of these techniques will.

**QUESTION 3:** These particles that you show on the videos. Is this original normal operation machine or intentionally introduced to contamination?

**ANSWER:** We look at both. The sequences I showed you in this last video tape showed wafers being processed with a number of
differen't steps. That was normal operation. We also look at vari-a-
tions on the normal operations. In many cases we intention-ally gen-
erate particles so we can follow the movement of particles and see how they're being made. Because if we can follow the movement of particles under enhanced conditions and control them under the stressed conditions, then we can control particles under normal con-
ditions as well.

**QUESTION 4:** I assume there isn't any equipment like this in the field yet. What are the prospects for it coming out soon and with electrostatics involved, what's the prospects for removing these particles after it comes out of the plasma chamber?

**ANSWER:** There is equipment out there. We're working with some tooling vendors to implement the clean technology into the tools. Wafer cleaning is a current activity we have at the lab. By that we mean techniques to clean particles off wafers. Methods and technology to clean-up plasma processes is an activity that I now have set up with tooling vendors and also chip houses.

**QUESTION 5:** You're working on taking particles off the wafers. Are you planning to share that technology?

**ANSWER:** Yes, in about a year.

**QUESTION 6:** Have you looked at some of the single wafer tools, like the P5000 or Lam etchers? Can you retrofit this easily?

**ANSWER:** Yes, we've done a lot of work on the P5000 and we are going to work on the Lam tools next year. In the P5000 we got a 10x contamination reduction by process changes alone because the customer in that case wanted process modifications only.

**QUESTION 7:** Reliability improvement? How much?

**ANSWER:** No data yet... I'd be happy to work with some of you on that.

**QUESTION 8:** Suppose you have a perfect clean wafer, chamber, everything. What's the origin of the particles?

**ANSWER:** There's been a lot of work done in this field, partic-ularly in the nucleation area. It now appears that negative ions in the plasma undergo various clustering reactions. The negative ions are repelled from all surfaces due to the sheath field just like particles that are negatively charged. So they have a long residence time in the plasma and this enhances the opportunity for them to cluster. Clus-
tering, of course, means growth. Also, cluster reactions are acceler-
ated as the charge on the negative ion becomes enhanced, and the cluster becomes more negative as the particle diameter gets larger. Several researchers have measured growth rates of particles starting at from about 3-5 nanometers right up to fractions of a micron and above. Nucleation, we think, is caused by negative ions that are present in the plasma [9,18]. There are also particles caused by wall flaking, particularly in deposition processes. Deposition processes, by design, put a thickness of film down on a wafer, but they also put a thickness of film down on the walls. The wafer gets removed and a new wafer gets put in, but the wall thickness builds up with each wafer processed.

We believe that thermal stress that acts upon the film on the wall. This is probably due to a thermal mismatch in the expansion between the film and the walls, causing film stress. This stress results gives rise to film fracture and injection of particles into the plasma [19]. Those particles behave just like the ones formed from homogeneous nucleation: we can control these particles, too.

**REFERENCES**


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