TECHNICAL PAPER

Meeting ITRS Roadmap Guidelines for Particle Measurements in Ultrapure Water

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Meeting the ITRS Roadmap Guidelines for Particle Measurements in Ultrapure Water

Lighthouse Worldwide Solutions

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Introduction

DI water is used throughout electronics manufacturing. In semiconductor manufacturing it is used for multiple processes including the cleaning and etching of wafers. DI water is also used in other critical semiconductor processes such as CMP and immersion lithography. Over one thousand gallons of water is needed to process a single 300mm wafer. Because DI water is used pervasively and because it directly contacts the wafer, controlling its contaminants is critical to maintaining high yields in the semiconductor industry. On line monitoring of particle levels is a standard method of controlling contamination in DI water systems.

While these water systems do a great job of treating and filtering the water, the output needs to be monitored in the unlikely event there is a problem with the system. Particles can occur due to issues with the piping, ion exchange beds, pumps and or filters.

Particle concentrations in semiconductor DI water systems are extremely low. The International Technology Roadmap for Semiconductor's (ITRS) future goal specifies particle levels of less than 200 particles per Liter at 50 nanometers size. Because the particle levels are so low, making a precise measurement of particle levels with optical particle counters becomes a significant design challenge. This article will discuss the precision of particle measurements in DI water applications, the precision requirements for measurements at today's ITRS target particle levels, and some design approaches to improve the measurement precision of optical particle counters.

Optical Particle Counter Precision

Optical particle counters measure particles one at a time. When trying to determine the concentration of particles, the measurement precision is influenced by the time of arrival of the particles which is governed by a Poisson statistical process. At the same time optical particle counters can experience false count measurement errors that are infrequent random discrete events that are also described by Poisson statistics. These measurement errors also influence the precision and accuracy of the measurement. Therefore it is useful to review Poisson statistics and apply them in modeling the performance of the instrument in certain applications.

Poisson statistics or specifically the Poisson distribution is used to express the probability of a number of events occurring in a given period of time. If the expected number of events is λ, then the probability that there are exactly k events is given by:

$$F(k; \lambda) = \frac{\lambda^k e^{-\lambda}}{k!}$$

Where

- e is the base of the natural log
- k is the number of events given by the equation
- k! is the factorial of k
- λ is the expected number of events

It is straightforward to model the data produced by an optical particle counter with a given sample rate utilizing the Poisson distribution if the sample time and expected concentration are known.

In semiconductor DI water monitoring the target particle level is below 200 particles per Liter. Typical sample rates of optical particle counters are a few milliliters per minute. If the sample time is also known, then we can model the expected results from the optical particle counter. Figure 1 is an example of particle counter data given the following typical conditions:

- Water System Particle Levels = 66 particles per Liter
- Measurement Sample Time = 40 minutes
- Optical Particle Counter Sample Rate = 3.75 ml/min

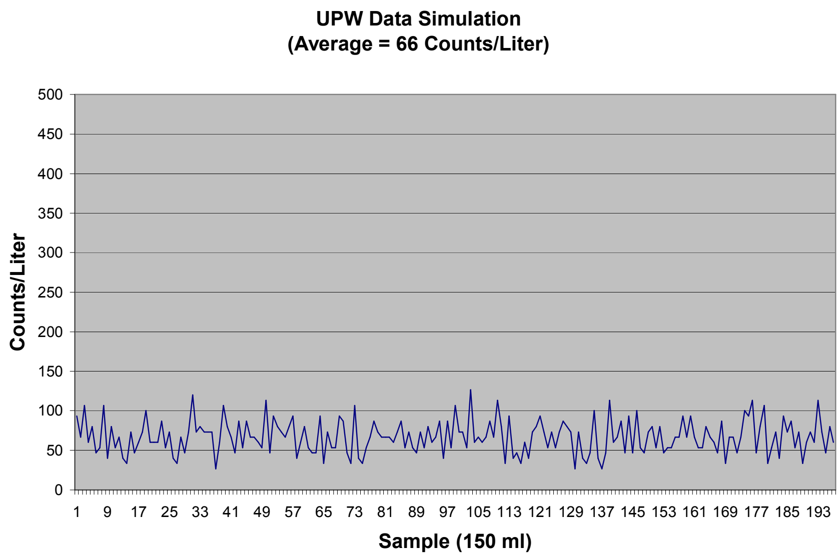

Figure 1

These models are useful to visually understand the precision of these types of measurements made with optical particle counters. They can help to estimate the improvements in precision by changing sample volumes or improving the sample rate of the instrument. For example, figure 2 is an example of particle counter data given the following conditions:

- Water System Particle Levels = 66 Counts Per Liter
- Measurement Sample Time = 40 minutes
- Optical Particle Counter Sample Rate = 0.375 ml/min

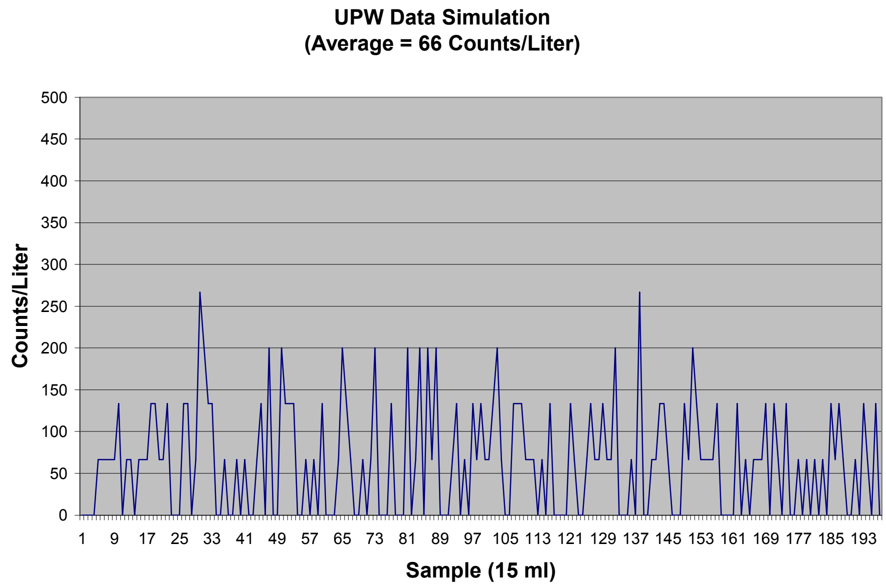

Figure 2

Since the number of events in each sample is reduced by a factor of ten (the reduction in sample rate of the optical particle counter) the precision of the measurement is also reduced significantly. The number of events directly impacts the precision of the measurement and so the sample time and sample rate must be such that the desired precision of the measurement is achieved.

Since the number of particle events influences the precision of measurements with optical particle counters, the instrument's sample rate and sensitivity play a role in its precision. The number of particle events in a given sample time is proportional to the sample rate of the sensor. In addition, because ambient particle distributions on DI Water systems are such that there are more particles at smaller sizes, the sensitivity of the instrument can also impact the precision of the instrument in these applications. Clearly these instruments must be designed with adequate sample rates and sensitivities so that the desired measurement precision can be achieved with acceptable sample times.

Background False Count Errors and the Impact on Accuracy and Precision

Optical particle counters are susceptible to cosmic rays. Cosmic rays are actually energetic particles in the atmosphere. They cause discrete random false count events in particle counters which can also be modeled using a Poisson process. Figure 3 is an example of optical particle counter cosmic ray false count errors under the following conditions:

- Average Cosmic Ray False Count Rate = 1 count every minute
- Measurement Sample Time = 40 minutes

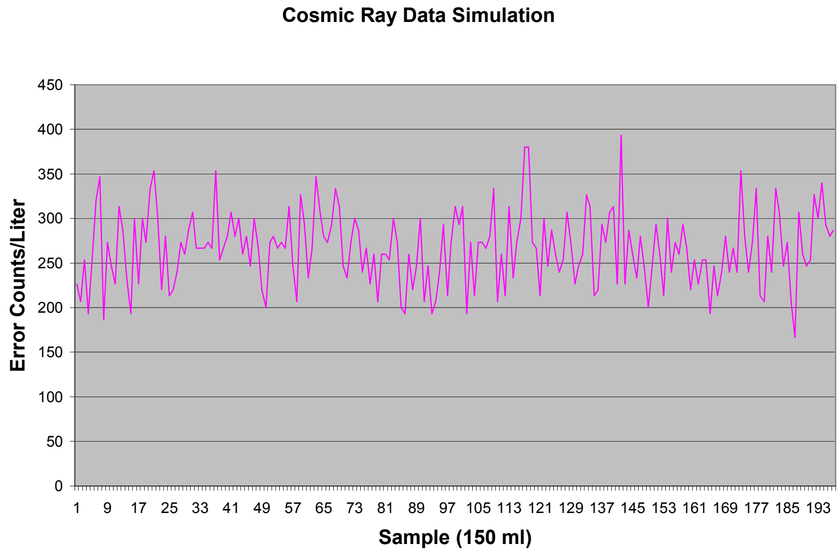

Figure 3

Clearly the cosmic ray errors from an instrument with this false count rate are significant at the particle levels being measured on today's water systems.

To more accurately model optical particle counter data we can include these measurement errors in our previous particle count model. Figure 4 is an example of optical particle counter data with and without cosmic ray errors given the following conditions:

- Water System Particle Levels = 66 Counts Per Liter
- Measurement Sample Time = 40 minutes
- Optical Particle Counter Sample Rate = 3.75ml/min
- Average Cosmic Ray False Count Rate = 1 count per minute

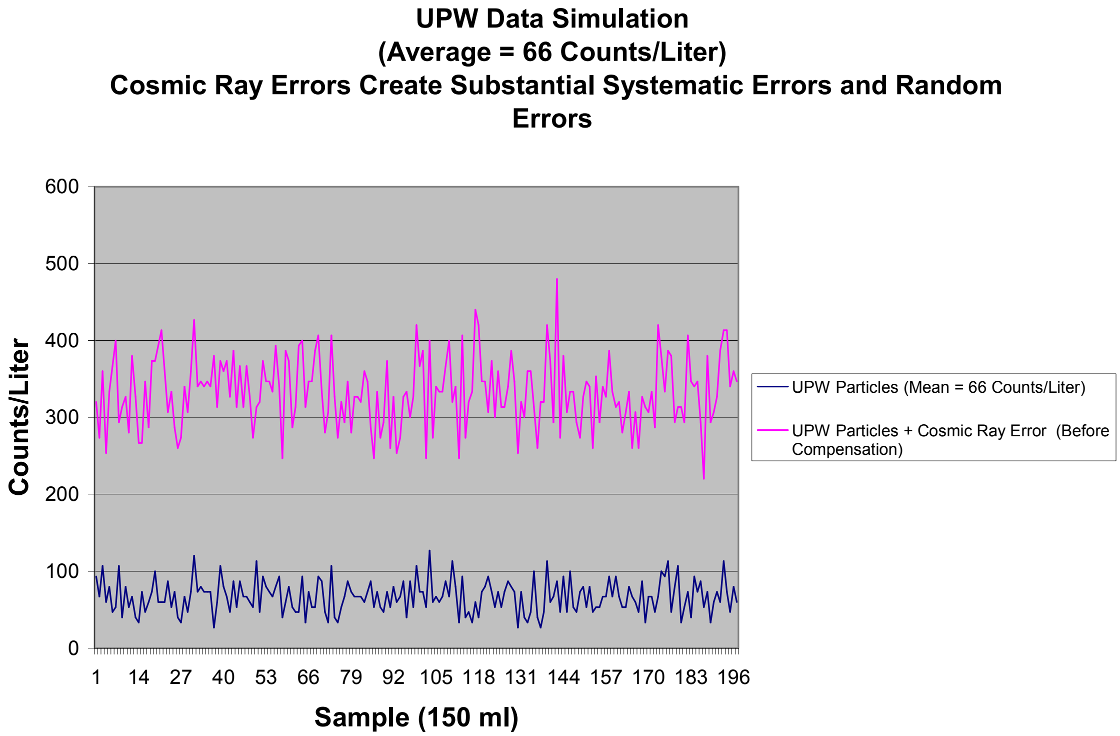

Figure 4

The cosmic ray false count errors introduce a systematic and random error in the measurement. The systematic error component causes a long term offset in the reading equal to the long term average rate of false count events. Since this error is somewhat constant over long time intervals, it may be possible to compensate for it to some degree. However, the underlying assumption is that this average cosmic ray error rate does not change appreciably over a period of days or months. It may be better to assume some amount of long term drift in this average level given the uncertain nature of the process.

The random component has the effect of reducing the measurement precision by introducing random errors. At the levels in the above example, the effect is substantial and is the equivalent of reducing the sample rate of the instrument by a significant amount. In fact, occasional peak readings above the ITRS target control limit result with the given set of measurement conditions, even if the data is properly compensated for the systematic long term average error component. Figure 5 is a comparison of the ideal water system data to the data after compensation for the systematic error component from the cosmic rays.

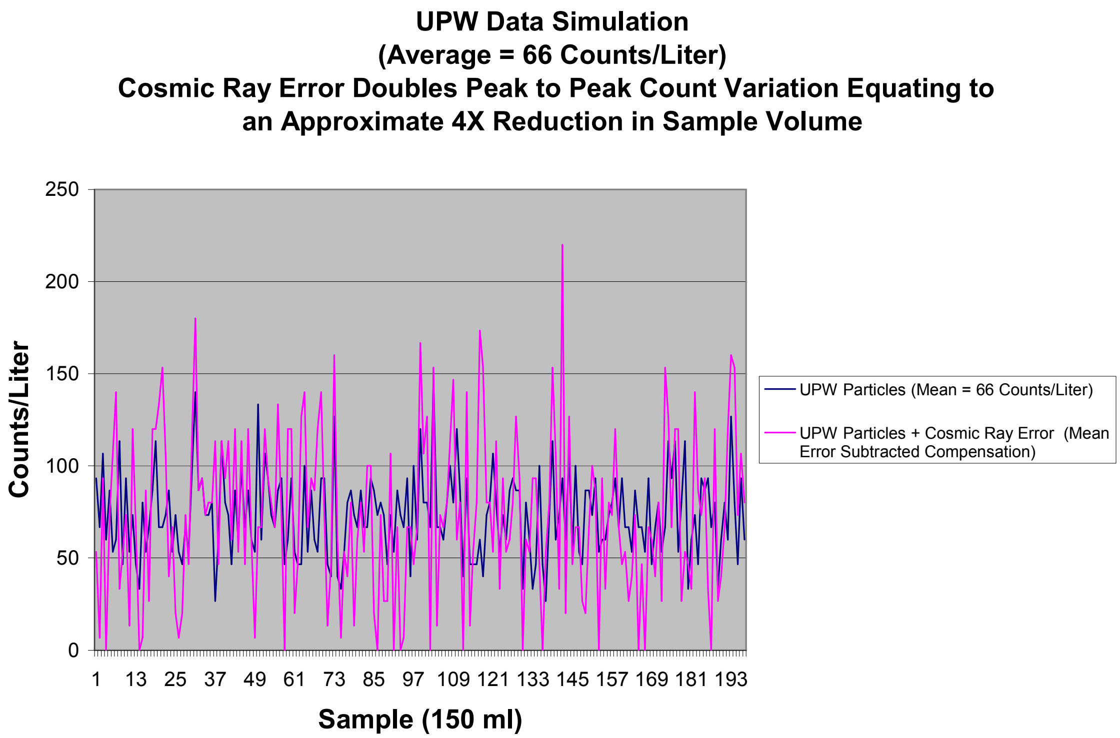

Figure 5

Designs for Today's Measurements

Today's water systems have a target control limit of 200 Particles/Liter. Their actual particle levels are well below this limit. Figure 1 is representative of data from such a system. Now assuming we design a particle counter to have one false count in 30 minutes, the blue trace in Figure 6 is example data that would result from the instrument under the following conditions:

- Water System Particle Levels = 66 Counts Per Liter
- Measurement Sample Time = 30 minutes
- Optical Particle Counter Sample Rate = 5ml/min
- Average Cosmic Ray False Count Rate = 1 false count per 30 minutes

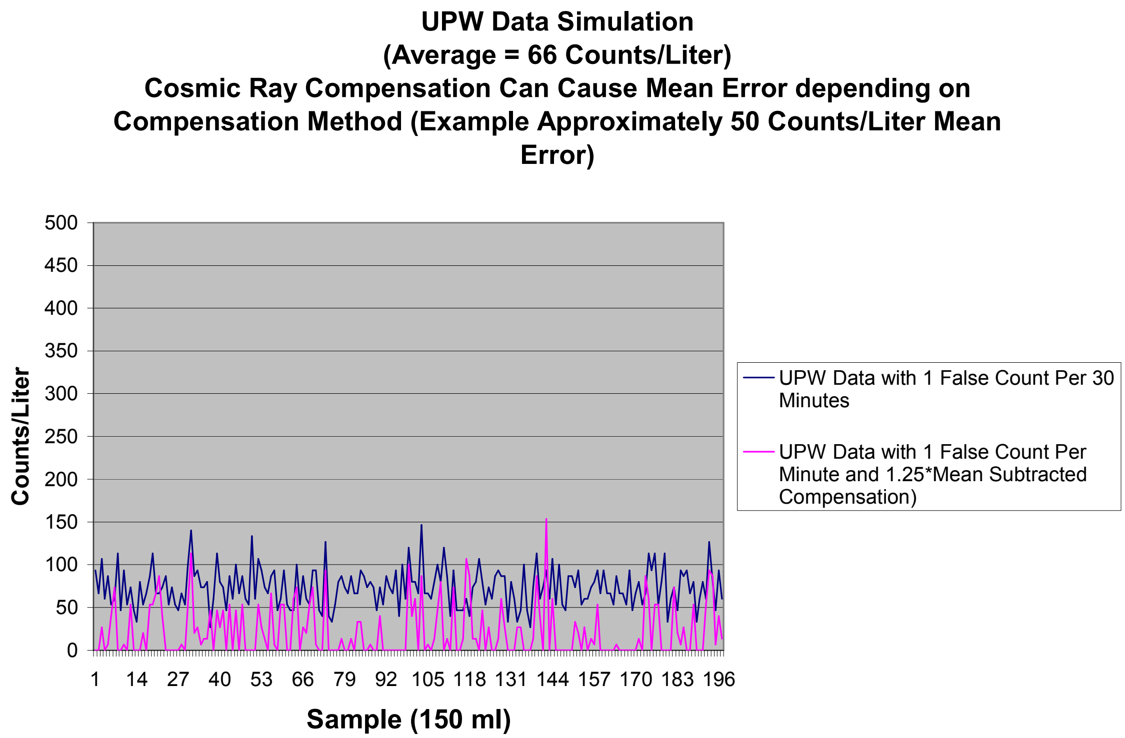

Figure 6

For reference, the pink trace in Figure 6 is data that would result from a particle counter with a false count rate of one false count error per minute with compensation applied so that the peak error values reported are the same level as the peak particle levels output from the more precise instrument. The reduced precision and systematic error present in the instrument with one false count error per minute is readily apparent.

Furthermore, if the optical particle counter is designed to meet the specifications above including one false count error per 30 minutes, then the background count errors have minimal impact on the precision of the measurement if we compare this result to the ideal data in figure 1. Designing a particle counter with these low background false count error rates and 50 nanometer sensitivity starts with a unique approach to the optical design. Specifically, a high numerical aperture, low magnification light collection system is utilized which maximizes the sensitivity of the device by maximizing light gathered while at the same time minimizing the susceptibility to stray light noise in the system. In addition the low magnification permits the use of advanced detector technology which has both high detection sensitivity and very low susceptibility to the cosmic rays that impact the sensor's precision and accuracy at today's particle levels. Figure 7 is a general layout of such an optical system.

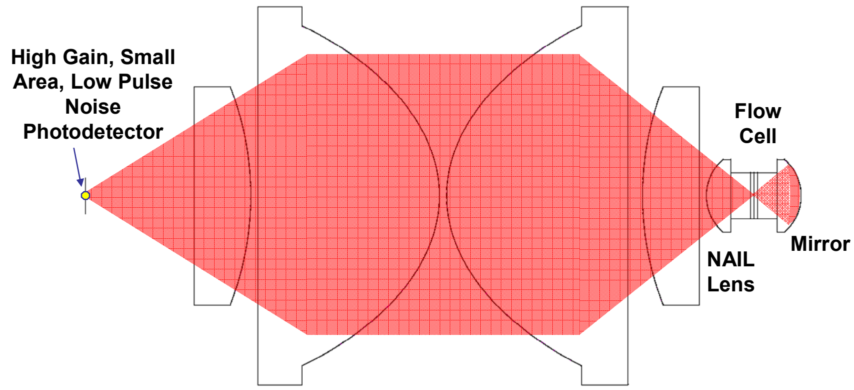

Figure 7

The optical system is comprised of seven optical elements including a flow cell which transports the fluid through the sensor. The flow cell is in direct contact with a reflector mirror and NAIL (Numerical Aperture Increasing Lens) lens. This subsystem allows scattered light to travel in a path with no deviation since all the elements have nearly the same optical index of refraction. The result is scattered light from both sides of the particle up to the corners of the flow cell is collected and exits the NAIL lens with negligible aberration. Four more lenses are used to relay this light onto a photodiode with little additional aberration. The overall system produces excellent signal to noise to permit the detection of 50 nanometer particles.

At the same time the low magnification of the system permits the use of advanced detector technology to address the cosmic ray background design challenges. The detector has an active area that is significantly smaller than detector technologies employed previously thereby dramatically reducing the cosmic ray error rate of the sensor. In addition the detector is fabricated using special materials to further minimize the susceptibility of the element to cosmic rays.

The net result is an instrument capable of 50 nanometer particle measurements with much higher precision and accuracy than was previously available. Figure 8 shows actual water system measurements with such a device. A clear baseline is evident at an average particle level of approximately 100 counts per liter due to the high sensitivity, high sample volume and extremely low background false count level of the instrument.

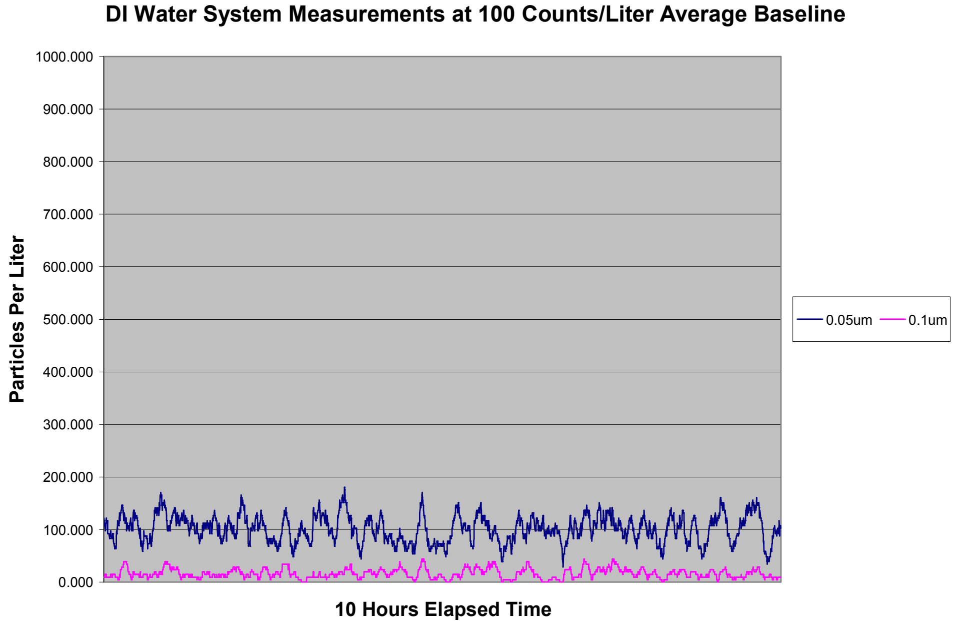

Figure 8

Summary

Future ITRS guidelines for particle levels on DI water systems will continue to challenge optical particle counter technology to provide precise measurements. In addition to having adequate sensitivities and sample rates these instruments must have sufficiently low background false count error rate levels such that these errors do not impact the precision and accuracy of their measurements. With proper design these instruments can meet the sensitivity, sample volume and background false count error rates required for precise measurements on DI Water systems now and in the future.