Calibration Techniques for Precision Power Measurement in Semiconductor Process Applications

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Introduction

Radio frequency power measurement has been an important component of semiconductor processing since the time that plasma was first used for wafer processing. Power measurement was, and continues to be important, as radio frequency energy is used to excite the plasma, and the plasma characteristics are in large part determined by the excitation energy. In this article, we will discuss various means of measuring radio frequency power, along with their limitations. In addition, we will present the best calibration methods for radio frequency power measuring instruments.

Beginnings

As the need for RF power measurement developed in the semiconductor industry, the first instruments used were high power RF wattmeters that had originally been developed for use in communications applications.

MCS Standard

For the most part, these products were comprised of a section of precision air transmission line, with a lumped element directional coupler / detector system for sampling the energy in the transmission line. The

directional characteristics of this instrument could be used to provide a crude indication of the load impedance relative to the characteristic impedance of the transmission line, (usually 50 ohms) the detector used in these power meters was of a single diode design, with the detector operating in square law, transition, and linear regions of its dynamic characteristic curve. The fact that the diode was operated over both square law and linear regions of its characteristic curve led to accuracy specifications as a percentage of the full-scale capability of the instrument. In most cases, the accuracy was specified as +/-5% of full scale. The majority of the error with instruments of this type is related to diode-to-diode changes in dynamic characteristics, and the use of a single analog meter scale for all diode detectors.

Bird Directional Power Meter

Standards used for the calibration of these power meters were either directional coupler/ power meter combinations, or a similar combination involving the use of an attenuator in place of the directional coupler. In many cases, standards were based upon instruments of the same type as those being calibrated, except that these standards included temperature stabilization elements to improve the stability of the reference, as well as mirrored scale analog meters with improved linearity to reduce errors due to parallax and dynamic linearity. These standards were more than sufficient for the calibration of these first generation devices, considering their overall accuracy limitations.

As mentioned above, dynamic characteristics of diode detectors comprised a major source of error for these power meters. In addition to dynamic error, another significant error source was the frequency response error associated with the directional coupler circuits used to provide a sample of the transmission line power.
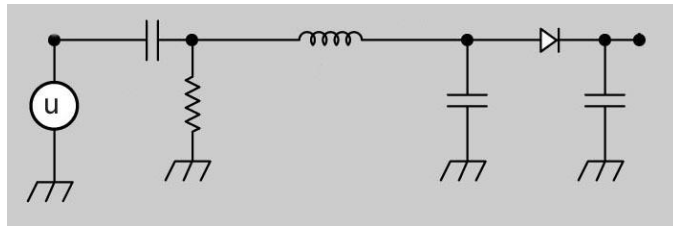
Lumped Element Directional Coupler

As with any directional coupler, passive frequency compensation networks are difficult to realize in forms that will provide compensation over a very wide frequency range, without affecting other important directional coupler performance parameters such as directivity. An attempt to deal with these two significant power measurement error sources resulted in the development of the 4421 Precision Power Meter, and the associated 4020 series directional power sensors.


4421 Power Meter w/ 4027 Precision Sensor

4421 / 4020 Series Precision Power Meter

The 4421 family of power measurement instruments was introduced as a general purpose laboratory power meter product, for use in applications where a directional power measurement was required, as compared to traditional terminated measurements.

The main advantages of the 4421 are

• Superior accuracy in applications requiring a directional measurement. This is driven by the power sensor design approach, which integrates the directional coupler, detector, analog gain stages and signal conditioning, and A/D functions, and then *calibrates these functions as a system.* The interface between the 4421 and its associated 4020 series power sensor is a differential serial communications link. Completed power measurement numbers are transferred from the power sensor to the 4421 display, and require no further processing before display.

• The detector system used in the 4020 series system is a diode scheme that provides inherent temperature correction, and an extremely linear dynamic response of over 30 dB.

• Automatic correction for directional coupler frequency response characteristics. The sensor measures the operating frequency, and then corrects the power reading according to a value stored in memory.

• The instrument is extremely easy to use, especially when compared to traditional terminating type laboratory power meters.

• Extensive field testing, as well as laboratory testing has indicated a system measurement to measurement repeatability of better than 0.3%

4421 Mainframe
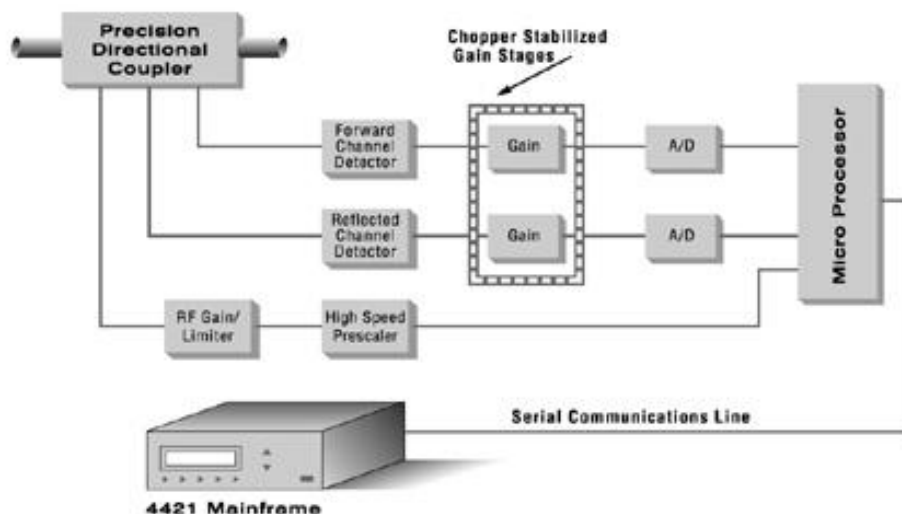
Considering these characteristics and advantages, the 4421 system has become the instrument of choice in semiconductor process applications. In recent years, improvements have continued with the 4421/4020 series family, with the introduction of the 4027 family of power sensors. The 4027 power sensor operates in much the same manner as previous generation sensors, with the added benefit of better accuracy +/- 1%, (1σ) at calibration points). This is accomplished by limiting the frequency range of the 4027 to a narrow band of frequencies including and adjacent to specific semiconductor processing points. In addition, the 4027 family is calibrated using direct calorimetric techniques, which we will describe below.

Direct Calorimetric Calibration

As mentioned, the 4020 series power sensors are available in two varieties, based upon accuracy. The table below outlines the various 4020 series power sensors, and their related accuracy:

Power Sensor Model	Frequency Range	Accuracy (1σ)
4021	1.8-32 MHz	+/-3%
4022	25-1000 MHz	+/-3%
4024	1.5-32 MHz	+/-3%
4025	100-2500 kHz	+/-3%
4027A12M	10-15 MHz	+/-1%
4027A250K	250-400 kHz	+/-1%
4027A400K	400-550 kHz	+/-1%
4027A800K	800-950 kHz	+/-1%
4027A2M	1.5-2.5 MHz	+/-1%
4027A4M	3-5 MHz	+/-1%
4027A10M	10-15 MHz	+/-1%
4027A25M	25-30 MHz	+/-1%
4027A35M	35-45 MHz	+/-1%
4027A60M	45-65 MHz	+/-1%
4027A100M	95-105MHz	+/-1%
4027A150M	145-165MHz	+/-1%

It can be seen from the table, that the 4021 through 4025 models are wideband sensors, where the 4027 family of sensors is designed to operate over a narrow frequency band. The improved accuracy performance of the 4027 sensors is made possible by narrowing the frequency coverage of the sensor, and through the calibration of the power sensor directly to a *calorimetric power standard.*

4020 series power sensors with +/-3%, (1σ) accuracy specifications are calibrated using wideband RF power sources, which develop very stable, spectrally pure calibration signals. The reference power meter system used for the calibration is comprised of a precision directional coupler, with a calibrated terminating type power meter connected to the coupler sidearm. (See diagram)
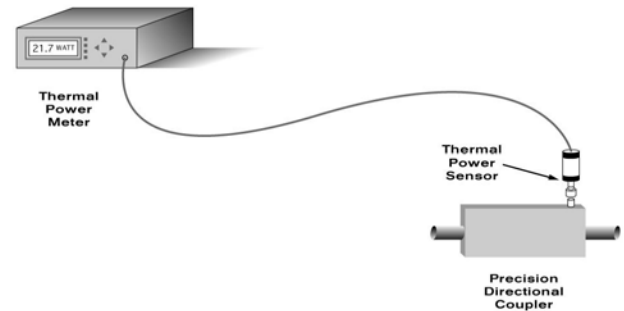
A power reference of this type was chosen for its inherent wide dynamic range, and wide frequency range, established by the directional coupler frequency response, as well as the terminating power meter response characteristics. The power reference standard is calibrated by first determining the coupling value associated with the directional coupler very precisely, using a precision measuring receiver. When the coupling value has been determined, the main and coupled arm return loss characteristics are determined using a calibrated network analyzer. The network analyzer is also used to determine the input return loss characteristics of the power sensor. These measurements are then used together to determine the mismatch uncertainty associated with the combination of the directional coupler and the power sensor.

Calometric Power Measurement Systems

Calorimetric Calibration

The best RF calibration method that is currently available involves the use of calorimetric techniques for the measurement of RF energy. Through this technique, it is possible to make very precise measurements of the total power in a signal, including the effects of any harmonic or non-harmonically related frequency components. In effect, the calorimeter provides a measurement, which for all practical purposes represents the true heating power of a particular waveform. Adding to the attractiveness of this approach is that precision measurements may be made directly, at very high power levels.

Calorimetric power meters designed for the measurement of RF energy are configured according to the block diagram next page.
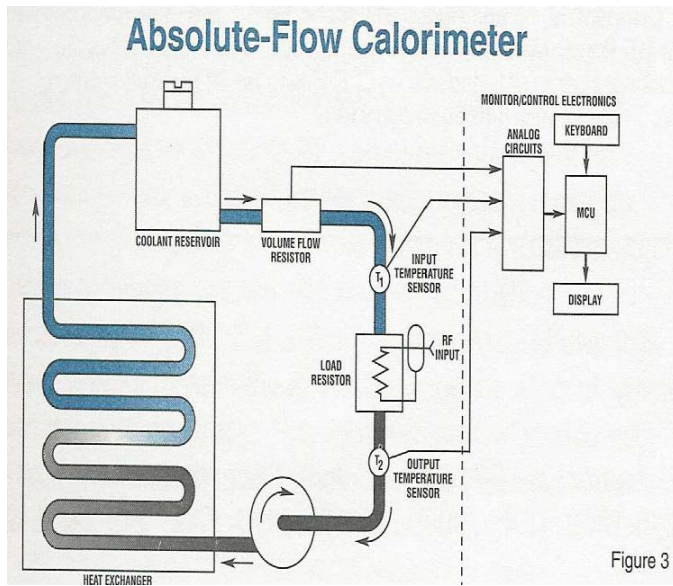

**Absolute-Flow Calorimeter**

Figure 3

Calometric Power Measurement Systems

The heart of the calorimetric power measurement system is a water cooled RF load resistor, which not only provides a high return loss termination for the transmission system under test, but also provides for the highly efficient conversion of radio frequency energy to heat. Located in close proximity to the coolant inlet and outlet ports of the RF load are precise temperature measurement sensors and these are used to determine the differential temperature across the load. Also in the coolant path is a precise liquid flow measurement sensor, which is used to determine the mass flow rate of the coolant in the system. These three parameters, input temperature, output temperature, and coolant flow rate, may then be used to determine the energy dissipated in the RF load.

$P \text{ (W)} = .2626 \times \Delta T \text{ (°C)} \times F \text{ (GPM)}$

While this process may sound simple, the application of these principles requires real attention to detail if good results are to be expected. One example of this is in the treatment of the coolant flow rate parameter. While it may seem like a simple matter to measure the flow rate of a liquid, it must also be considered that the coolant physical characteristics, such as specific heat and specific gravity must be taken into account as the temperature of the coolant changes. If a coolant other than pure water is used, then the physical characteristics of the mixture must be accounted for, which means that the mixture must be precisely known. An example of this may be found in the graph below, which outlines the changes in specific heat of pure water versus temperature.
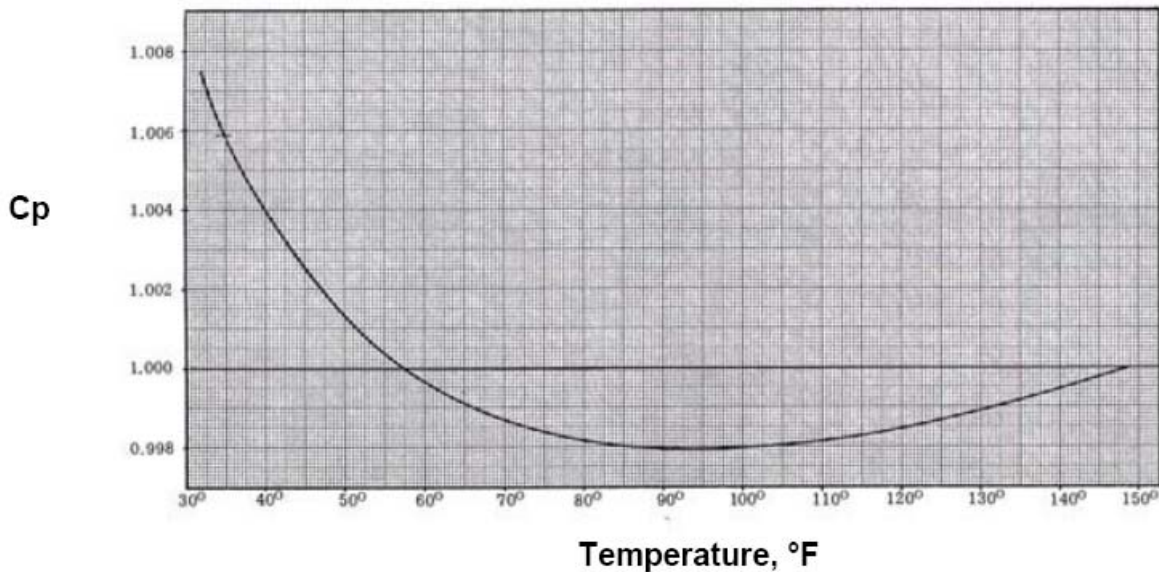
When all of the above has been accounted for, there remains the question of how the calorimetric system is to be calibrated, if it is to serve as a precision radio frequency measurement instrument. The best method currently available involves the use of either DC or 60 Hz. substitutions. This technique is based upon the premise that the calorimeter, essentially a device for the measurement of energy in heat, will respond the same to a DC or low frequency waveform, as it will to radio frequency energy. While this is not true in the most exact sense, the differences in calorimeter performance when measuring low frequency energy and radio frequency energy are small enough that they are negligible for the purposes of making an accurate power measurement. The diagram below describes the basics of the substitution technique.
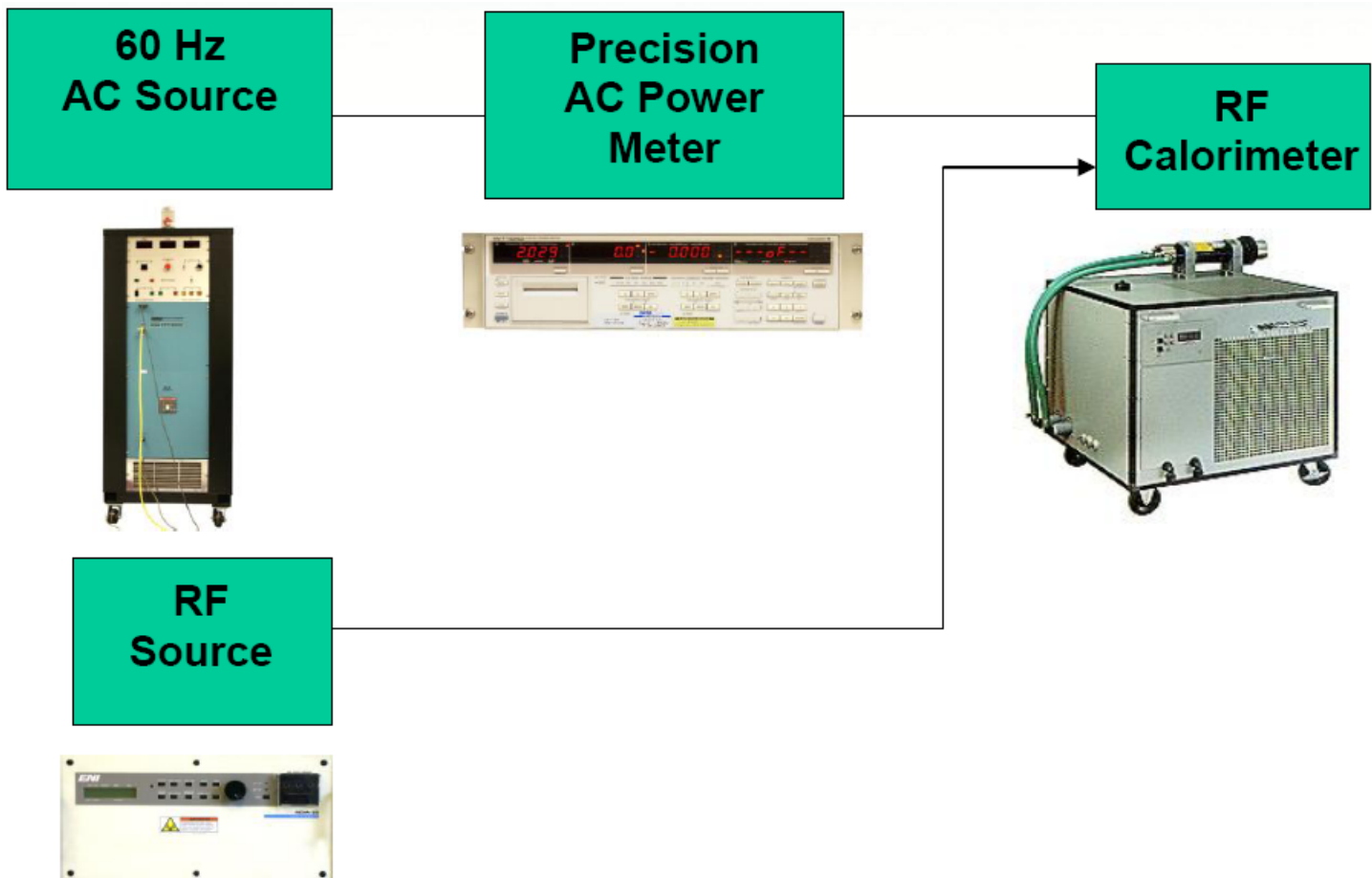
**Block Diagram, 60Hz Substitution Technique**

The process is as follows:

- The calorimeter is connected to a source of DC or 60 Hz. energy, at or near the power level of interest.

- At the same time that the calorimeter is connected, a precision voltage and current meter is also connected to the source.

- With power applied to the calorimeter, read the voltage and current applied to the calorimeter's load. Multiply the voltage and current together to obtain the power applied to the calorimeter. If AC energy is used, (60 Hz.), the phase angle between the voltage and current should be determined, and included in the calculation.

P (W)= (V x I) COS θ

- Calibrate the calorimeter so that it reads the same as the power reading obtained from the voltage and current values.

- The calorimeter is now calibrated, and is ready for RF measurements at the calibrated power level.

Using the above technique, it is possible to perform calibrations with overall uncertainties of less than 1% (2σ). The table below represents long-term data on the performance of a calorimetric power meter, when compared daily to a 60 Hz. reference.
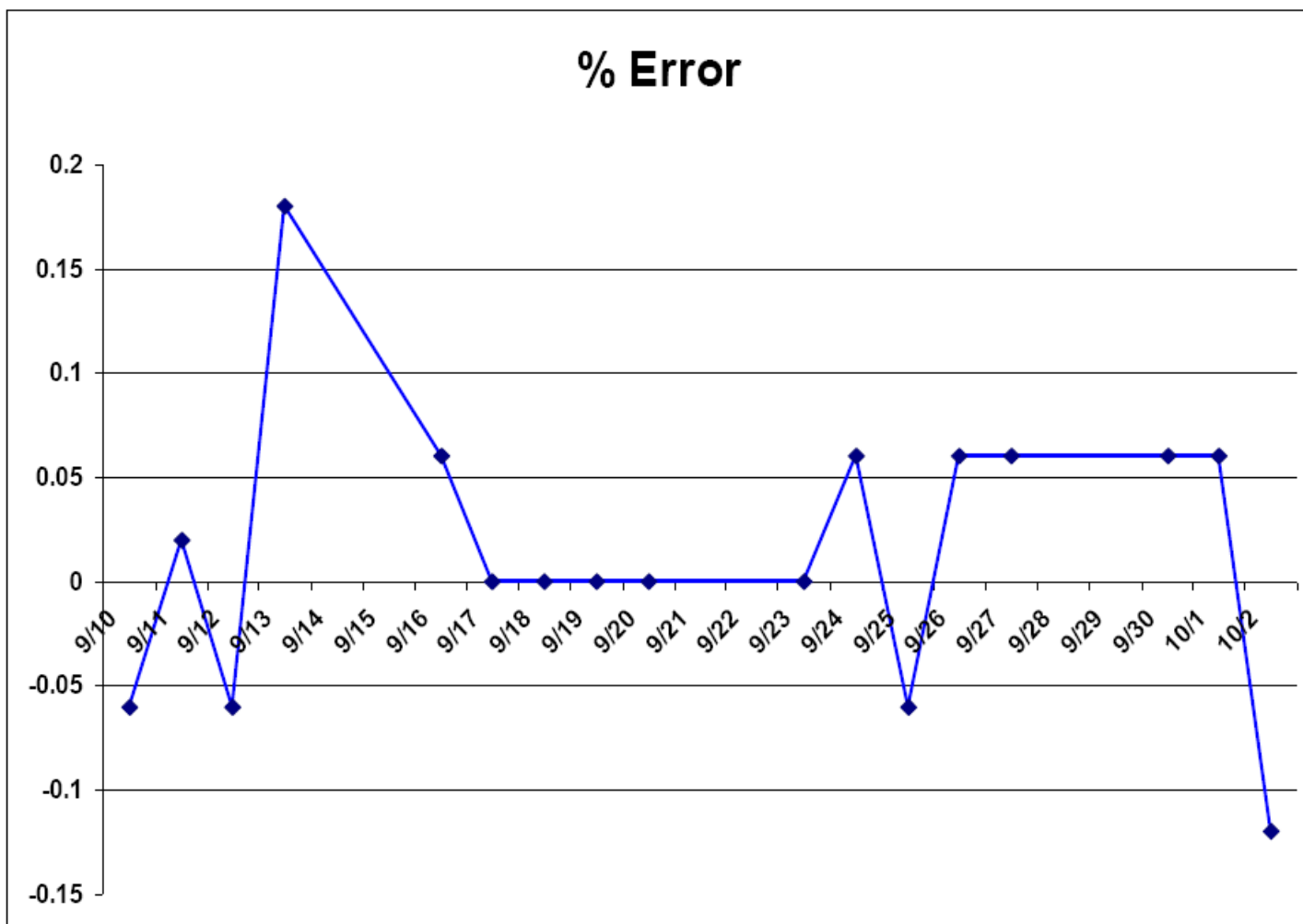
% Error

Calorimeter Error vs Time

It is clear from the above data that properly calibrated and maintained, it is possible to use calorimetric techniques as the cornerstone for very precise, stable RF power calibration.

Common Error Sources in Power Measurements

As outlined above, the 4421 power meters, as well as the 4020 series power sensor have been used to provide highly accurate radio frequency power measurements for many years. While the stated accuracy of the original 4421 and 4020 series sensors is +/-3% (1σ), the typical experience of most users is that the accuracy is much better than this, typically on the order of +/-1.5% (1σ). In most cases, the 4421 power meter is used in an environment where the instrument is measuring a fundamentally continuous wave (CW) signal, with a low harmonic content, and little or no amplitude modulation. In our calibration of all 4020 series products, we maintain our calibration test sources such that the harmonic content of the signal is at least 50 dB below the power level of the fundamental frequency. In addition, the sources are essentially free from amplitude

modulation. (Less than 0.2%) Older generation 4020 series power sensors use a detector scheme, where the detectors are operated over a very wide dynamic range, part of which resides in the square –law region of the diode's operating curve, and the remaining portion of the dynamic range is in the transition and linear region of operation. The main problem with detectors of this type is that they are quite sensitive to the effects of harmonics in the signals that are presented to them. Additional errors are possible with these detector types when the signals that they are measuring are amplitude modulated, as the detectors tend to follow the peak of the modulation envelope. Amplitude modulation is a common characteristic of signals produced by RF generators used in the processing of semiconductor devices, and in most cases, the amplitude modulation is line related, resulting from the use of switching type power supplies.

The potential measurement error sources that are outlined above are important for the following reasons:

RF Generator

4421

4027A

High Power
RF Termination
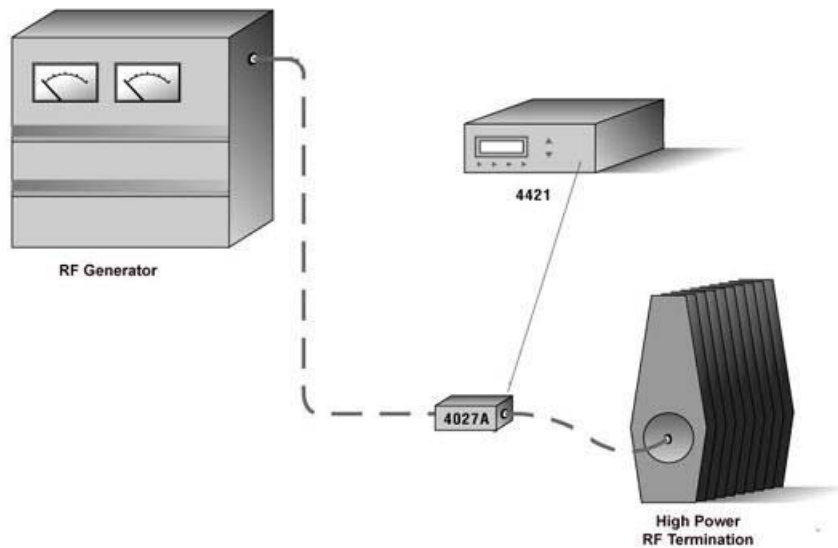
a) In most cases, the 4020 sensors have been used directly on the output of the RF generator, with their output terminated in a high quality 50-ohm load. In these cases, the measurements are quite reliable and accurate, provided that the RF generator has a low harmonic content, and minimal amplitude modulation. In some cases however, the sensor is located at a point in the RF delivery system where it may be exposed to energy reflected from the process reactor, which typically contains much higher harmonic levels, as well as line related amplitude modulation. In these cases significant errors are possible with the sensors.

b) There has been a trend over the past several years, toward making RF generators smaller in size. In many cases, the portion of the generator design that is sacrificed in the effort to make the generator smaller is the low pass filter that is typically located on the output of the generator. Compromising the performance of this low pass filter will result in higher harmonic levels in the generator output.

In an attempt to provide a product with more universal application, and to address the problems outlined above, Bird has developed a new family of 4020 series power sensors. This new product is intended to be used with existing 4421 power meters, and will provide an added benefit of being essentially immune to the effects of high harmonic levels present in the output of RF generators. In addition, the new power sensor incorporates a true

average responding detector scheme, where the entire dynamic range of the power sensor is contained within the square law operating range of the detector. In this manner, the sensor will behave similar to a thermal device, responding to the heating power of the signal being measured. As mentioned above, this new power sensor will afford a more universal application within the RF delivery system, and will be much more forgiving in terms of its ability to provide accurate, reliable power measurement at the output of RF generators, whether or not harmonic energy is present.

Conclusion

It has been the purpose of this note to present a brief background as to some of the more important and common issues associated with radio frequency power measurements in semiconductor process settings. Please contact us with your questions concerning the information presented here, as well as with any other questions that may develop regarding this subject.