Final Report on Wireless Wafer Proof-of-Principle

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Summary

Our experiments demonstrated that a wireless connection, capable of transmitting important wafer-processing information, could be used to communicate outside the chamber without the need for new penetrations. This represents the first step toward a fully integrated wireless network, capable of supporting multiple wafer-based sensors, established inside the processing chamber. Follow-on work would migrate toward a spread spectrum RF transmitter capable of operating inside the chamber and providing wafer-processing data in real-time rather than the current technique that requires off-line processing of the test wafers to determine critical process parameters.

After evaluating a number of alternatives, we settled on a miniature, 390 MHz transmitter sealed inside a wafer-size pillbox. Transmission through the existing RF coupling window (during plasma generation) resulted in the detection of the signal at a level consistent with our expectations for data transmission. Migration to 2.4 GHz, spread spectrum RF transmission is expected to result in even more noise immunity and overall robustness. The next step in our development plan is to test a prototype 900 MHz device recently built in Oak Ridge for our wireless research program.

Introduction

Several promising options for wireless data transmission from an in-process wafer have been investigated during the course of this study. All of the examined options appear to have sufficient potential to merit further consideration for selective applications. However, we have focused on identifying and developing those options with the greatest potential for widespread general application on present day plasma processing tools. Although the feasibility of using an optical link was investigated briefly initially, the RF/microwave wireless options have been emphasized because the environment of the plasma processing chamber is more favorable to that approach.

The plasma source presents a very low-noise RF/microwave environment for a data communication link. It is found that at frequencies above the 20th harmonic of the RF source frequency (i.e. above 300 MHz), the sensitivity of the receiver is limited only by preamplifier noise, which is typically less than -112 dbm per MHz of bandwidth. When combined with a transmitter capable of transmitting at least +10 dbm of power, this results

in a highly favorable situation where up to 120 db of transmission loss can be tolerated. Given that situation, there are several routes available for coupling the RF/microwave signal out of the processing chamber. Of these, the RF coupling vacuum window, common to all plasma processing tools, is the primary subject of this study. Other potential pathways offering attractive alternatives (including the RF bias transmission line and the vacuum pumping duct) are also discussed. Choice of the transmission frequency will depend on details of constraints associated with each signal path, but generally are well served by using the FCC approved license-free ISM (industry, science, and medicine) bands at 915, 2450, and 5800 MHz.

Optical Wireless Link

A plasma processing chamber is a hostile (extremely photon-rich) environment in which to establish an optical link. The basic problem is that a large fraction of the RF plasma-heating power is eventually radiated by the plasma through atomic and molecular processes, primarily in the ultraviolet and vacuum ultraviolet range, but also extending throughout the visible and infra-red regions of the spectrum. For many gas mixtures, closely spaced emission lines from the plasma can be expected to exceed the light output of an LED source by as much as an order of magnitude, or more. Limited testing at SEMATECH confirmed that the light coupled from a super-high brightness LED source through two line-of-sight optical ports on a plasma chamber to the fiber optic input of a visible spectrometer was weak compared with the light intensity typically produced by a plasma etch tool. Optical links might nevertheless prove to be feasible for specialized applications where one or more of the following favorable circumstances exist:

1) The plasma line emission spectra for a specific working gas has an exploitable gap in the emission lines, with a minimum of continuum (molecular) radiation.
2) An array of optical sources at different wavelengths can be used to provide frequency diversity (via frequency hopping spread spectrum), enhancing the probability that at least one source will provide a viable link.
3) A highly-directional direct line-of-sight link between the on-wafer light source and the receiving optics can be assured.
4) A narrow-line source such as a solid-state laser can be used in place of an LED.

A narrow-line filter (or spectrometer) in front of the detector will be required to reject the bulk of the plasma emission spectra, enabling the detector to sense milliwatts of received optical signal within a narrow spectral band from a plasma environment that is generating 100’s of watts of photons.

RF/microwave Wireless Link Through the RF Coupling Window

Virtually all RF plasma sources utilize a dielectric vacuum window to allow an external RF antenna (or coil) to couple RF power to the plasma. Since the vacuum window also supports the propagation of higher frequency RF & microwave signals, it provides a potential path for a wireless link between the wafer and an external receiver, a pathway that is common to all present-day plasma processing tools.

During the course of this study, two types of experimental activities were performed in a plasma processing chamber to explore the feasibility of using this signal path. The first involved a proof-of-principle measurement to demonstrate that a reliable RF wireless link can in fact be established using this pathway, and that such a link can be used to transmit encoded signals. The second activity included detailed measurements of the transmission losses associated with this path, leading to a criteria for choosing the optimum frequency for this wireless link.

It is well known that the high-density plasma region located immediately in front of the RF window is non-propagating at all frequencies below the electron plasma frequency. For a plasma source with a density of 1.0×10^{12} cm^{-3}, the electron plasma frequency is 8.9 GHz, for example. An obvious (but perhaps unnecessarily expensive) solution is to specify the use of a transmission frequency above 10 GHz. However, it is further understood that the electron density is not entirely uniform over the entire surface of the RF window, and can be significantly lower at the edge, with characteristic density profiles dependent on the RF design of a particular source. Even when a high-density plasma uniformly blankets the entire surface of the RF window, transmission through the window can still occur at a small but finite level because RF signal can still propagate through the electron depleted plasma sheath region located at the wall of the processing chamber. As a result, wireless links through the RF coupling window should be feasible at frequencies well below the peak electron plasma frequency. Unfortunately it is difficult to estimate from first principles the window transmission-loss factors that should be expected at frequencies below the electron plasma frequency for a specific chamber design. But based on the measurements detailed below, we provide experimental evidence that wireless transmission links are in fact feasible at frequencies well below the peak electron plasma frequency.

For the initial test measurements, a miniature battery-powered transmitter operating at a frequency of 390 MHz was enclosed in a wafer-size vacuum-tight pillbox. The pillbox features a quartz window through which the transmitted signal is radiated. To protect the transmitter electronics from the deleterious effects of extremely large electric fields at the RF driving frequency (13.56 MHz), an electrostatic Faraday screen was provided. The Faraday screen was carefully configured so as not to inhibit radiation from the magnetically-coupled resonant-loop transmitting antenna. Testing was performed in an ICP (Inductively Couple Plasma) source that uses a 6-inch diameter flat spiral antenna. The received signal was picked up using the capacitively coupled voltage probe that is normally used to monitor the RF antenna/coil voltage at 13.56 MHz. This probe is located in a

coaxial section between the RF spiral antenna and the matching network. Although this arrangement did not provide optimal sensitivity for a receiving antenna at 390 MHz, the resulting performance was found to be acceptable. A frequency multiplexer with 50 db rejection at 13.56 MHz was used to reduce the amplitude of the signal component at the RF driving frequency to a safe level. The conditioned signal was then amplified with a low-noise amplifier to maximize the dynamic range of the receiver and/or spectrum analyzer

Using this test setup, a wireless communication link between the wafer chuck and an external receiver was successfully demonstrated. An encoded transmission was successfully communicated from a battery powered transmitter, operating at a frequency of 390 MHz, to an external receiver. Tests were performed in an ICP source using low density argon plasma, operated at a pressure of about 10 mTorr. A reliable wireless communication link was maintained for RF power levels up to about 100 watts. When the coupled RF power was further increased, the increased plasma electron density resulted in increased blockage of propagation through the RF coupling window, exceeding the dynamic range of the receiver.

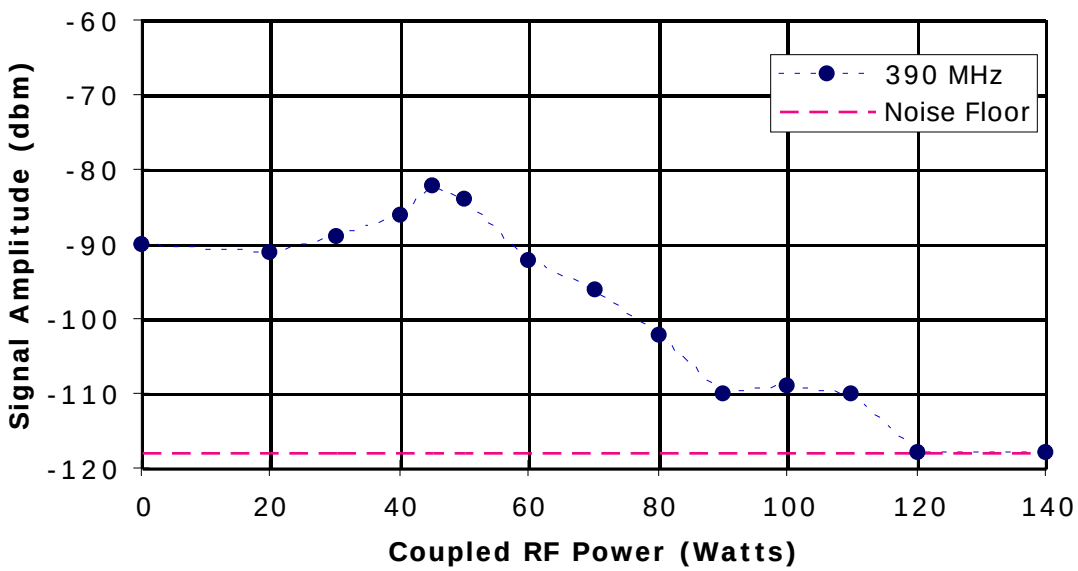

Fig. 1 Amplitude of the encoded 390 MHz signal measured at the receiving antenna as a function of the coupled RF power at 13.56 MHz. The noise level referenced to the preamplifier input is -118 dbm in a 100 kHz bandwidth.

To document the variation in transmission loss with increasing RF power, the received signal amplitude was measured using a spectrum analyzer. An example of the resulting data is shown in Fig. 1, where the amplitude of the received signal is plotted as a function of the plasma-coupled RF power. With no plasma present, the coupling between the transmitter (located on the wafer chuck) and the receiver probe (located in the RF coupling system outside the vacuum chamber) is not optimal, so that the coupling initially improves with increasing RF power. It was latter found that this behavior is attributable to cavity

resonances in the chamber, as will be discussed in greater detail below. The important trend is the reduction in the received signal amplitude from -80 dbm to less than -120 dbm as the RF power is increased from 40 to 120 watts. When the coupled RF power exceeds 120 watts, the plasma density is not only sufficient to completely block propagation at the center of the window, but also allows very little leakage at the periphery of the window where the electron density is much lower. For these measurements the noise level of the receiver system corresponds to -118 dbm in a 100 kHz signal bandwidth, referenced to the preamplifier input. The plotted data values represent the signal amplitudes at the receiving antenna location, prior to amplification by the preamplifier.

To further explore the feasibility of a wireless link through the RF coupling window, a loop probe was installed in a lower side port of the ICP chamber to serve as a broadband transmitting antenna, enabling transmission measurements to be performed over a range of frequencies extending up to 2.4 GHz. Although this bypasses the signal path from the wafer chuck to the outer wall of the chamber, it is clear that the only significant propagation barrier is the high density plasma located immediately in front of the RF vacuum window. What is of particular interest is to measure the shielding effectiveness of that high-density plasma (for blocking propagation through the window) under circumstances where the transmitter frequency is a factor of 2 or more below the peak plasma frequency, in which case the plasma is expected to provide a substantial, but imperfect, barrier for propagation through the RF window.

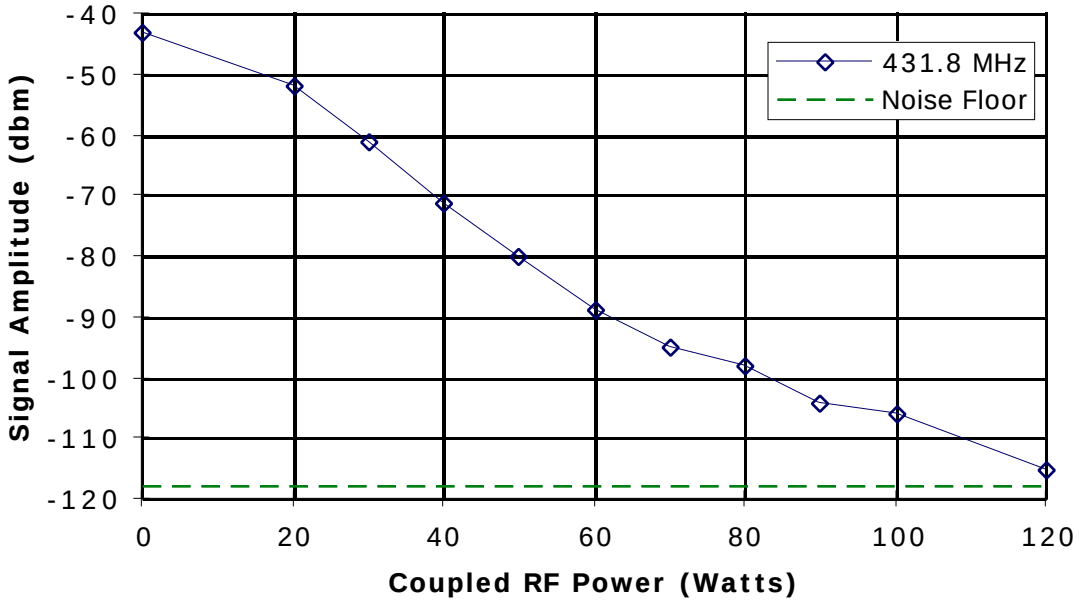

Fig. 2 Received signal amplitude at 432 MHz as a function of the coupled RF power level. Using a detection bandwidth of 100 kHz, the noise level is -118 dbm at the preamplifier input.

Using a swept frequency source to power the loop antenna, a more complete picture emerges detailing the circumstances that existed for the 390 MHz proof-of-principle demonstration. Sweeping the frequency over the range from 100 to 1000 MHz reveals that in the absence of plasma, signal coupling across the chamber and out through the RF window is strongly influenced by cavity modes in the vacuum chamber. This is particularly true in the low frequency range where cavity modes are widely spaced, and less true at progressively higher frequencies. The amplitude of the received signal varies by up to 3 orders of magnitude, or more. It is largest at frequencies corresponding to cavity resonances having a mode structure that is compatible with the desired signal path, and the transmitter polarization. In the absence of plasma, 390 MHz is not an optimal choice of frequency for good signal coupling. However, that situation changes significantly when plasma is introduced. With the ICP source turned on (Ar at 10 mTorr), the resonant frequencies of the cavity are shifted in frequency, as expected, resulting in optimal coupling at a different set of frequencies, depending on the plasma density. In addition, the large variation in the amplitude of the coupled signals with frequency is reduced, presumably due to plasma loading of the cavity resonances.

When the plasma density is increased by increasing the RF power up to 120 watts and beyond, the transmitted signal amplitude is progressively attenuated. A example of how the transmission loss increases with RF plasma heating power is detailed by the data shown in Fig. 2. This measurement was performed at a frequency of 432 MHz, a frequency selected on the basis of good signal coupling in the absence of plasma. By driving the transmitter loop antenna with +15 dbm of power and utilizing a low noise amplifier in front of the spectrum analyzer, it proved possible to document the variation in the received signal amplitude over a dynamic range of nearly 80 db. It should be noted that the data in figures 1 and 2 reveal remarkably similar behavior for the RF power range between 40 and 120 watts. The only significant difference between these two measurements is that 390 MHz is not an optimal choice of frequency for signal coupling in the absence of plasma, as evidenced by reduced signal amplitude in the RF power range between 0 and 40 watts (see fig. 1). For either data set, it is evident that at RF power levels above 120 watts the observed transmission losses are simply too great to be compatible with reliable operation of a 400 MHz wireless link.

Very similar behavior was observed at all other frequencies throughout the frequency range up to 1 GHz. For example, data obtained at 900 MHz are very similar to those at 400 MHz, with a only a modest 50% shift toward higher RF power. Therefore, in order to establish a reliable wireless data link through the RF coupling window under conditions with 1-2 kW of RF power, it is clear that higher transmission frequencies will be required.

Propagation through the RF coupling window improves significantly when the transmitter frequency is increased above 1 GHz. At frequencies above 1.8 GHz, complete blockage of signal path through the vacuum window is not observed even when the RF power is increased to 500 watts. In figure 3, transmitted signal amplitudes measured at

frequencies of 1.808 and 1.875 GHz are plotted as a function of the coupled RF power. To obtain this data, a B-dot loop that normally serves to monitor the RF antenna current at 13.56 MHz was used as the receiving antenna. The noise floor for the measurement, -115 dbm, was determined by the noise figure of the 2-8 GHz microwave preamplifier.

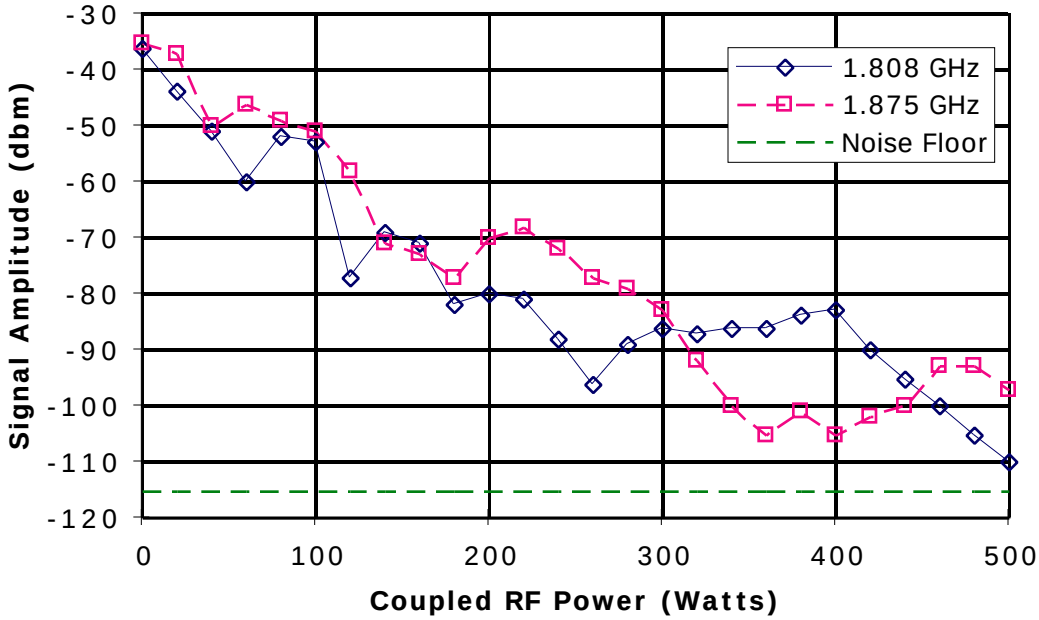

Fig. 3 Received signal amplitudes at 1.808 and 1.875 GHz measured as a function of the coupled RF power. The 13.56 MHz current monitor probe located between the RF antenna and the match box was used as the receiving antenna. Preamplifier noise limited the noise floor of the measurement to -115 dbm.

For this particular plasma source, the electron density profile is peaked at the center of the RF window, decreasing nearly parabolically to the edge. In all likelihood, the electron plasma frequency at the center of the window probably already exceeds the transmitter frequency when the RF power is 100 watts, accounting for the nominal 20 db blockage of the window at that point. When the RF power is further increased to 500 watts, the electron density increases nearly linearly with the power, resulting in an expansion of the non-propagating plasma region until it nearly fills the window. But because of the available dynamic range at these frequencies, it is relatively easy to continue to maintain a reliable communication link, even though the peak electron plasma frequency substantially exceeds the transmission frequency.

Based on the best available information for this ICP source, the maximum electron density at the center of the RF coupling window is approximately 2-3x10^{11} cm^{-3} when the coupled RF power is 500 watts. Such densities correspond to electron plasma frequencies of 4.0-4.9 GHz. Therefore, the transmission frequencies of 1.8 & 1.88 GHz, correspond to roughly 37 - 47% of the peak electron plasma frequency, demonstrating that it is feasible to establish a reliable wireless link through the RF coupling window by using a transmitter

frequency that is well below the peak electron plasma frequency, by up to a factor of two, or more. The implication for a plasma source with a typical electron density of 10^{12} cm^{-3} is that the transmitter frequency must be in the frequency range of 3.3 - 4.2 GHz, or higher. Conversely, use of the 5.8 GHz ISM wireless band is expected to provide reliable wireless data transmission for plasma densities up to 1.8-3.0x10^{12} cm^{-3}.

RF/Microwave Link Through the Vacuum Pumping Duct

An alternate pathway out of the plasma processing chamber is one utilizing a pickup antenna installed in a section of the vacuum pumping ductwork. Unless the pickup antenna can be located very close to the plasma chamber, the transmitter frequency must be sufficiently high to allow microwave waveguide propagation through the duct. This is only possible when the duct diameter is at least 1.705 times the wavelength. For a 3 inch diameter pipe, for example, this implies a transmitter frequency above 2.3 GHz. While performing transmission loss measurements at frequencies in the range of 2.2-2.4 GHz, substantial microwave leakage out through a 4” diameter viewing port was verified using a pickup antenna located on the outside of the processing chamber.

RF/Microwave Link Utilizing the RF Bias Feedline

For plasma tools with RF wafer bias capability, it is highly recommended that the RF-bias transmission line be considered as a promising transmission path, offering the possibility of using one of the lower-frequency ISM wireless bands (915 MHz or 2.45 GHz) at lower cost. Considering the fraction of plasma process tools that have RF biasing capability, this approach offers considerable potential for widespread applications. In this case, the RF/microwave carrier signal has only to be coupled from the wafer to the wafer chuck. The signal then propagates out of the tool through the RF-bias transmission line, with no adverse impact on the process. The carrier signal is coupled to a receiver using a relatively simple frequency multiplexer, or signal coupler, inserted in the RF-bias transmission line somewhere between the tool and the RF bias supply. This approach bypasses the complications of plasma propagation, requiring only a wireless RF/microwave link between the chuck and the wafer. As with the other RF wireless link options, it is advisable to work at a frequency that is a factor of 10, or more, above the RF source/bias frequency to avoid the harmonics of the RF source frequency. But otherwise, there is no compelling reason to consider higher frequencies, assuming that adequate coupling to the chuck can be obtained with antenna structures of acceptably small size on the wafer. Although we did not have access to an RF bias feedthrough during the course of this study, a commercial RF bias chuck has recently been acquired and will be available for future testing.

Summary and Conclusions

A wireless communication link was successfully demonstrated using a battery powered 390 MHz transmitter located on the wafer chuck to relay an encoded signal to an external receiver. This proof-of-principle demonstration was performed in a plasma environment, utilizing a signal path through the RF-coupling vacuum window, with up to 120 watts of coupled RF power at 13.56 MHz.

Additional RF/microwave transmission measurements were performed to further characterize the transmission losses for the signal path through the RF coupling window, demonstrating the viability of this approach even when the carrier frequency is a factor of two below the peak electron plasma frequency. Based on a simple scaling of these test results, use of the 5.8 GHz ISM wireless band can be expected to provide a reliable wafer data transmission link for ICP processing tools with plasma densities up to $1.8\text{-}3.0 \times 10^{12}$ cm^{-3} at the RF vacuum window.

In addition, other signal pathways have also been considered. For tools with RF wafer biasing capability, it is recommended that the RF-bias transmission line be considered as a highly promising transmission path, offering the possible use of the lower-frequency ISM wireless bands, at 915 MHz or 2.45 GHz, at a lower cost.