Arc Detection and Mitigation In RF Systems

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INTRODUCTION

Radiofrequency (RF) plasma generation and application is a critically important technology that is broadly applied throughout semiconductor device manufacturing. Processes that employ RF excitation include physical vapor deposition (PVD), plasma etch and clean and plasma-enhanced chemical vapor deposition (PECVD). Arc events within a plasma chamber can occur during device manufacturing and such events may damage both the devices under construction and the plasma-based fabrication tools. As well, arc events can initiate undesirable chemistry in the process gas that can produce contaminants that impair device yields. Arcing events are especially a hazard for semiconductor memory device manufacturing processes.

Arc disturbances in an RF plasma are typically short transients with a duration of a few microseconds; they occur as discharges between the plasma and the electrode, the plasma and the chamber sidewall, or discharges within the plasma that are induced by the build-up of polymer structures. A reliable means for detecting these occurrences and for intercepting the RF power delivery to mitigate the arc event is thus of critical importance to minimize arc-induced damage in these systems. Signals and sensors that have been employed for arc detection include measurements of the forward and reverse power from a directional coupler, measurements of the voltage and current from a VI sensor and the corresponding harmonic information. These methods employ signals *(s)* from the sensors for comparison against some threshold value (τ). When the signal exceeds the threshold there is a high probability that an arc event (E_{arc}) has occurred:

$$P\left(E_{arc} \mid s_1 > \tau_1, s_2 > \tau_2\right)$$

Later detection methods improved on this approach by applying the derivatives of the measured signals to determine the presence of an arc:

$$P\left(E_{arc} \mid s_1 > \tau_1, \dot{s}_1 > \tau_2\right)$$

These methods suffer from the fact that they are heuristic and non-quantitative. While they can be used to detect the occurrence of something unusual in the system, they cannot characterize the event in any quantitative fashion.

In this paper we describe a novel solution for arc detection that supersedes conventional heuristic methods. This solution uses tools from a communications equivalent paradigm to provide quantitative arc detection that measures the relative RF energy of the plasma arc transient. When an arc event is detected, arc mitigation based on suppressing the RF power with duration proportional to the measured RF energy can be deployed. The rapid and, if necessary, repeated control of the RF source results in a reduction in the plasma potential to extinguish the arc source and alleviate subsequent damage. Results from PECVD and PVD tools corroborate the impact of this new scheme to ameliorate the occurrence of arcs in thin-film manufacturing.

THEORY OF OPERATION

Figure 1 shows a schematic of an RF power delivery system for an RF plasma source. A matching network is located between the RF power supply and the RF plasma discharge. An RF sensor is coupled to the output of the matching network to measure the voltage and current signals representative of the broadband electro-magnetic fields from the RF power supply and the emissions from the plasma source. In an impedance-tuned condition, the transmission line between the power supply and the match contains an RF power wave in the forward direction. In this operating condition, only the voltage and current traverses from the power supply to the matching network. With a nominal loss of the power through the matching network, the RF power is coupled from the match to the plasma chamber. Rarely is the output of the match tuned to the transmission line impedance and plasma chamber impedance. In this portion of the RF circuit, a forward and reflected power wave traverses at the frequency of the RF generator. Due to the non-linear characteristics of the plasma chamber, the RF spectrum contains an additional set of frequencies from the emission of the plasma source. Both the voltage and current signals are indicated in the figure to represent the frequencies corresponding to the RF generator and the N frequencies emitted from the plasma source. Two options for sensor placement are clear: insertion of the RF probe ahead of the matching network (pre-match); or, as shown in the figure, insertion of the probe between the matching network and the plasma chamber (post-match). The first option provides an attenuated version of the RF spectrum.

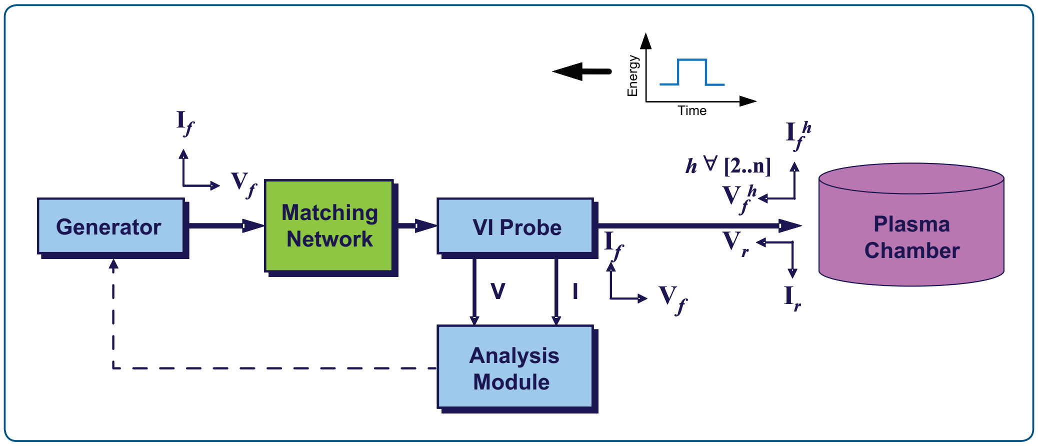


Figure 1: - System model for an RF plasma enhanced semiconductor process tool

If, however the sensor is placed between the matching network and the plasma chamber (post-match), as in the second option, the information content is significantly richer since harmonic and intermodulation distortion signals emitted from the plasma source are combined with the forward and reflected voltage and current waves. While the matching network applies a level of attenuation to the broadband spectrum, we will show that arc detection with a pre-match sensor using our detection method provides analogous detection with respect to the post-match sensor. This is achieved with our wide sensitivity, broadband and quantitative detection scheme.

Principle of Arc Detection

In our approach, a wideband correlation function collectively processes the signals that are sampled by the RF sensor, analogous to a digital communication system deploying a correlation receiver. The voltage and current signals from the RF sensor are digitally sampled and the power between these signals is derived from the cross correlation function. For arc detection, the signal processing is wideband to include the broader set of information signals contained in the RF spectrum. The detection scheme is linear for varying signal phase and magnitude range.

As noted above, the RF probe with post-match placement samples the forward and reflected power, the harmonic power, and the intermodulation distortion signals. The cross correlation derived from these signals is sensitive to variations in both duration and signal-to-noise (SNR) to permit the sensor to distinguish arc events from other system changes.

Figure 2 shows the differing character of the cross correlation function to differentiate a contrived arc from a step change in RF power. The uniform steps, step rate, and bandwidth provide distinguishing features from the cross correlation function to differentiate an arc event from one typical of RF operating condition, such as an RF power level change.

Arc detection is based on the cross correlation function performed for blocks of samples of the voltage and current signals with frequency f_{RF}, sampled at the rate f_s. Blocks contain k periods for $k \frac{f_s}{f_{RF}}$ total samples and duration $\Delta t = k\, f_s$.

Cross correlation of the sampled voltage and current signals is computed as:

$$r_{vi}(m) = \sum_{\forall n} v[n]\, i[n-m]$$

In our implementation, the cross correlation is performed for blocks of 22 samples of the sampled voltage and current signals with a sampling period of 10 ns.

When the log index $m = 0$, the power of the signals is obtained and the discrete correlation function reduces to a dot product, *<vi>*. The mean of each sampled sequence is subtracted since the sampling is not coherent to the signal's frequencies and other offsets are present.

$$r_{vi}(m := 0) = \sum_{\forall n} (v[n] - E[v[n]])(i[n] - E[i[n]]) = p$$

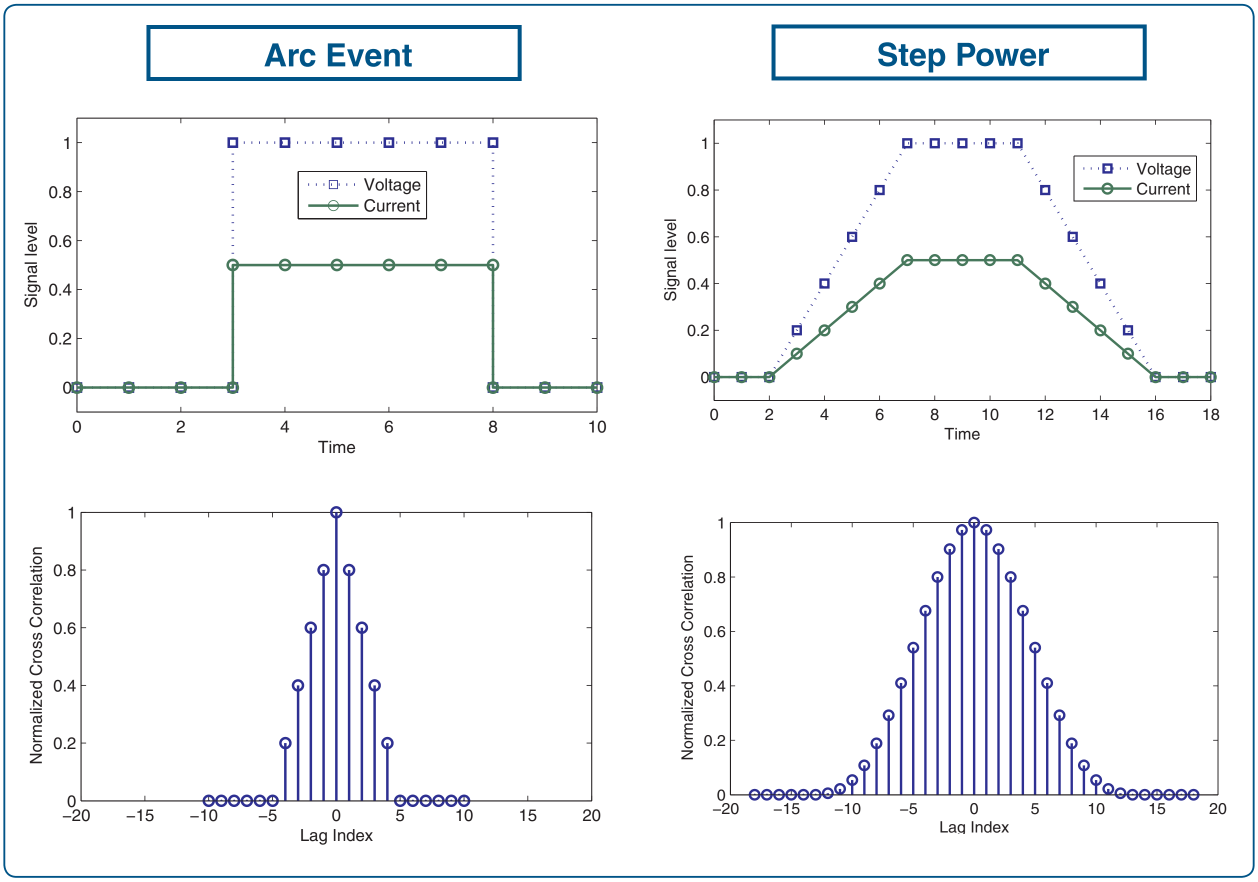


Figure 2 - The variable character of the normalized cross correlation for an arc event vs. a step change in the power

With the change in power that occurs during an arc event, it is possible to quantitatively determine the change in RF energy, $E = \Delta p \Delta t$, resulting from the arc transient.

Figure 3a shows representative VI signal traces collected in an arc detection experiment. The signals were sampled using a wideband A/D converter with a sample rate of 100 MSPS. The arc event is visually apparent in these traces. Figure 3b shows the cross correlation function calculated from this VI data.

A plot of the first differences of the VI cross correlation function presented in Figure 4 clearly shows the arc duration of 23 µsec. As noted, when $m = 0$, the cross correlation function reduces to the power. Figure 5 shows the power measurement in the presence of the arc transient. The corresponding arc RF energy is determined from the accumulated fixed, non-overlapping correlation block functions. By measuring the amount of RF energy change at the moment of detection, an arc counter measure can be initiated that uses the RF power supply to reduce the plasma potential and suppress the arc source.

Figure 8 presents a synchronized comparison of the Langmuir probe signal against the VI data contained in Figure 7 at various levels of processing (See Figure 6) in the arc detector. Processing the raw VI data to produce a power curve as shown in Figure 8a gives a somewhat clearer indication of the presence of the arc event, albeit at relatively low SNR of the arc transient. When the power data is processed through a 3-tap filter, this indication becomes substantially distinct (Figure 8b). Rate of change data for the power and RF energy (Figure 8c) are also included in the sequence of plots. When these signals are further processed through the arc detection (Figure 8d) and arc energy (Figure 8e) functions, clear, strong signals that indicate the arc occurrence and the arc energy are generated. The sensitivity of the arc detector is shown in Figure 9 with an approximate resolution of 86 µW.

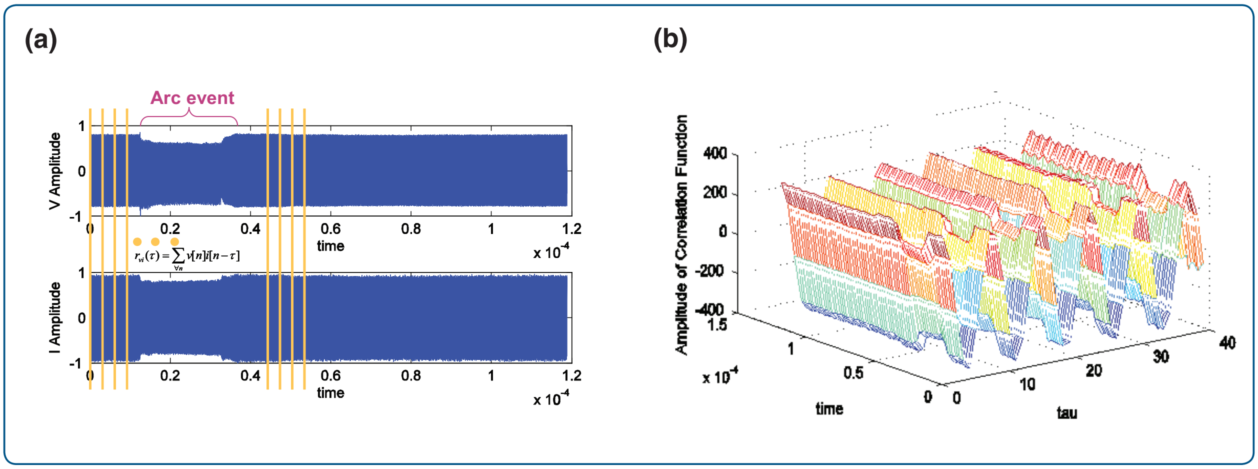


Figure 3 - An arc event example: (a) Sampled voltage and current signals with a visually noticeable arc event; (b) Correlation function for arc event in (a)

QUALIFICATION OF THE ARC DETECTION METHOD

Arc Detection and Sensor Placement

Laboratory experiments were performed to demonstrate the efficacy of our arc detection and a comparative assessment of the sensor location. The evaluation was analytically summarized in a Receiver Operating Characteristic (ROC) curve to show low false-positive occurrences. ROC curves are conventionally used in communications, RADAR, and pattern recognition systems. They provide a quantitative means to verify the ability to accurately discriminate between events or patterns. In our tests, the ROC curve demonstrates the robust detection of arc transients relative to a ground truth source and yields insightful information contrasting the detection of arc disturbances in different RF sensing locations in the RF power delivery system.

Our experimental system for the comparison of accurate pre- and post-match arc detection is shown schematically in Figure 10. RF sensors are located at the input and output of the matching network. The output voltage and current signals of each sensor are coupled to an analysis module that contains an FPGA to perform the signal processing for the arc detection we described in the previous section. A computer is connected to the analysis modules to collect arc detection results. Each analysis module compares its detected arc with respect to an input trigger and produces a digital output to flag an arc event was detected. This input and output allows statistics to be developed to compare performance at pre- and post-matching network locations. The input trigger of the pre-match arc processing unit is connected to our ground truth source; a Langmuir probe and digital oscilloscope. For each arc detected by the pre-match system, a signal triggering the detection of the arc is sent to the input of the post-match arc processing unit. In this way, the pre-match arc processing unit compares the arc it detects with the arc detected by the ground truth source. The post-match arc processing unit compares the arc it detects with the pre-match arc processing unit. The RF power supply was configured with a power set point such that arcs were continuously produced in the RF plasma source and detected by the ground truth source and the two arc processing units.

Figure 11 shows a summary of data collected by the computer from the arc processing units. The summaries are labeled pre-match and post-match detection. Each summary contains a histogram of the detected RF energy of the arc transients. Visual comparison shows that the distribution of the energies of the post-match has a tighter distribution than that for arcs detected by the pre-match arc processing unit. Most important, the ROC, shown as a pie-chart, of the pre-match arc processing unit detected 98.8% of the arcs and missed only 1.2% or 30 arc events detected by the ground truth source. The ROC chart for the post-match arc processing module indicates better than 92% agreement with the pre-match detection system.

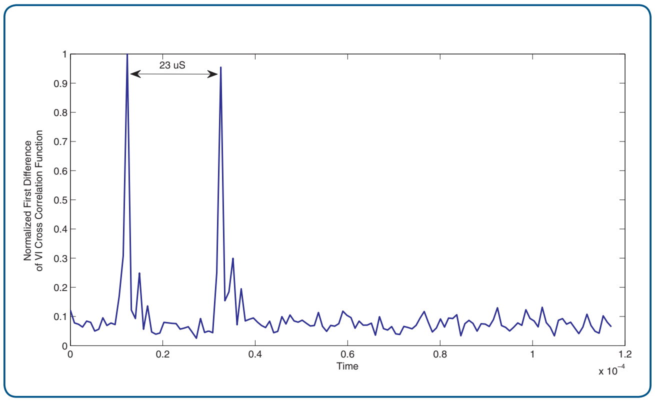


Figure 4 - Arc transient period detected

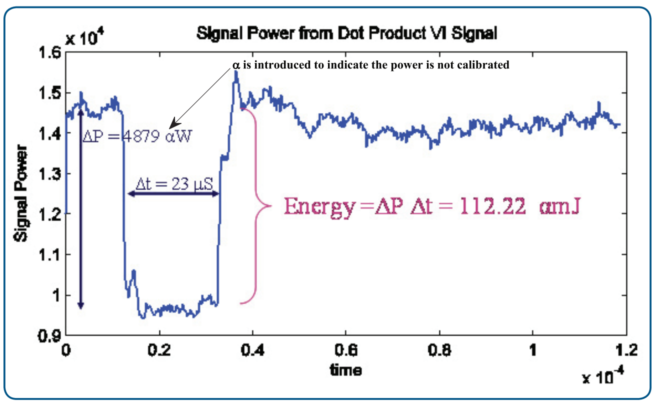


Figure 5 - Energy results from the computation of the cross correlation over fixed, non-overlapping blocks

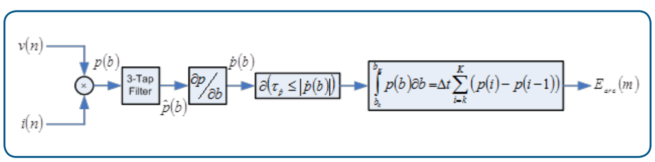


Figure 6 - Signal processing in the arc detector

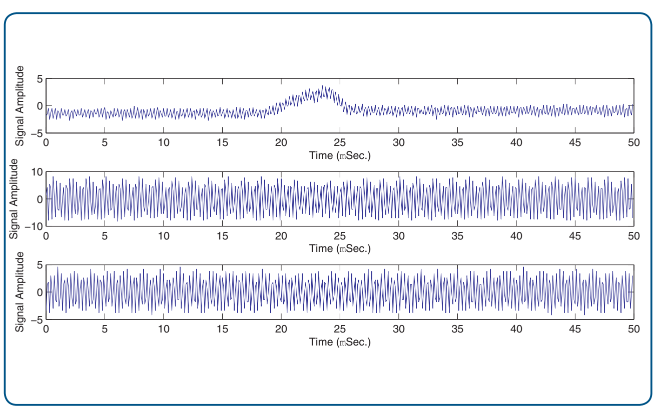


Figure 7 - Langmuir probe signal and raw VI traces for the arc detection test

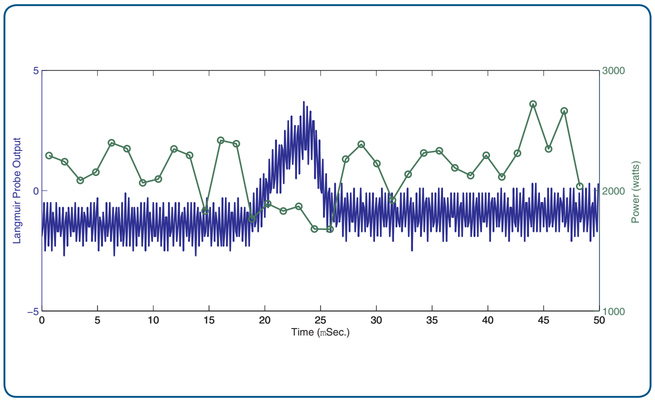
Using the Arc Detection for Arc Suppression

The ability to detect arcs with substantial performance parity between pre-match and post-match enables a control protocol for arc suppression. Coupling the arc detector, which detects the arc and measures the relative RF energy of the disturbance, with a countermeasure response from the RF power supply proportional to the measured arc energy can provide an effective approach to suppressing the arc source, alleviating damage to manufacturing process yields. Figure 12 illustrates the effectiveness with an arc suppression protocol implemented. In response to the detected arc, the RF power is suppressed for a period allowing the arc source potential to decrease.

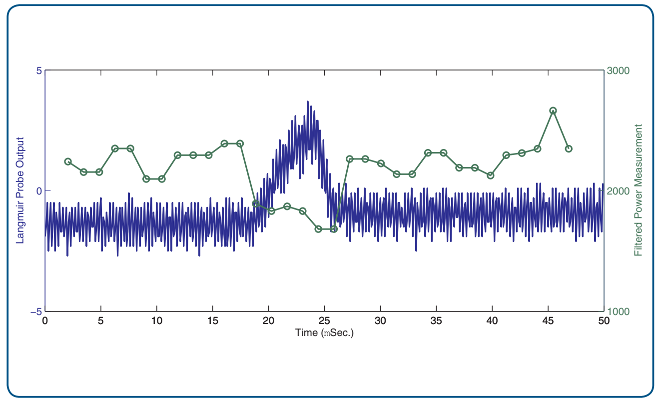
FIELD EVALUATION

Field trials of the arc detection system were performed on PVD and PECVD tools that are employed in photovoltaic (PV) device fabrication. The device structure and the corresponding areas of PVD and PECVD application are shown in Figure 13. These field trials outline the broad utility of the MKS arc detection and arc mitigation method for all RF processes associated with this and other semiconductor device fabrication processes.

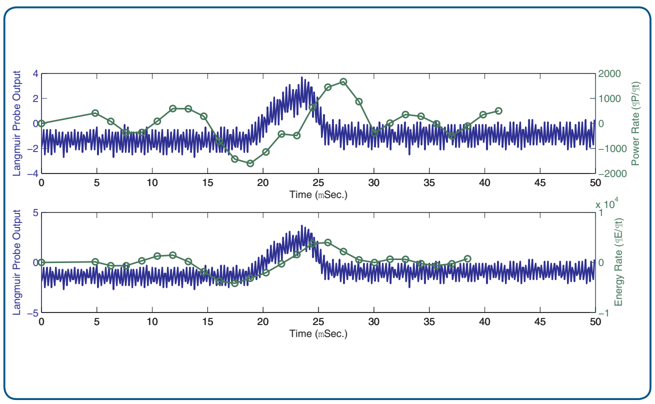
The test for a PVD process was performed in a system that employed an MKS SurePower 13.56 MHz, 10.5 kW RF generator for aluminum and zinc deposition. The system was first tested using an Al cathode; after passing the customer's acceptance criteria in this application, testing with the Zn cathode proceeded. The test with the Zn cathode, inherently more difficult than with the Al cathode, was deliberately stressed even further to demonstrate the MKS system under the harshest possible process conditions. The target surface was roughened using steel wool and poisoned by long term exposure to oxygen. The test was performed in an oxygen-rich process to further enhance the surface reactions that occur with arcing and cathode burning. The arc detector/mitigation system parameters for these tests included a 1.7 µsec countermeasure to suppress the RF power in response to a detected arc event. The configuration required no customer intervention with the auto-threshold functionality to alleviate manual adjustments and fine tuning of the arc detector. Figure 14 shows the results for the PVD test using the Zn cathode. Figure 14a shows the condition of the Zn cathode after a short period of normal tool operation without the MKS arc detection/mitigation method. Obvious "burn" spots on the



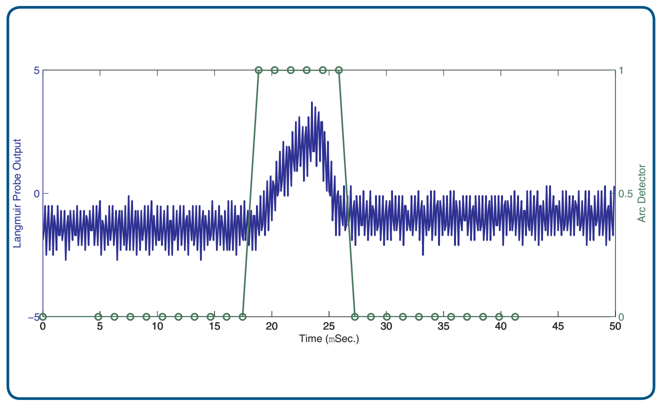
(a) Raw power trace



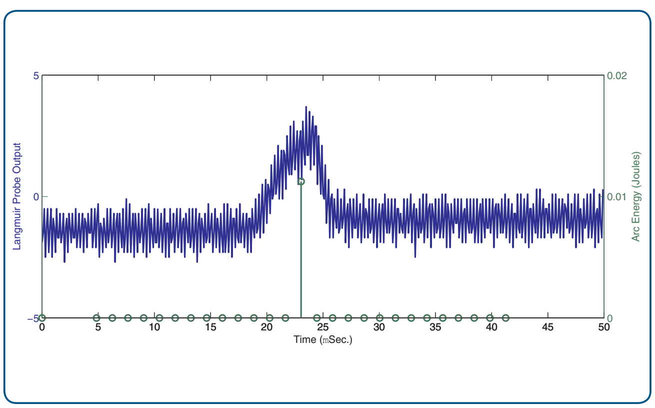
(b) Filtered power trace



(c) Rate of change curves for power and RF energy



(d) Cross correlation arc detection function



(e) Arc energy determination

Figure 8 - The arc detector signal at various stages of processing

cathode surface attest to the presence and severity of arc events during operation. Figure 14b shows the condition of the Zn cathode with the MKS arc detection and mitigation system for a considerable period of operation that ceased shortly before the Zn cathode material was depleted. Clearly, arc damage was eliminated through the use of the MKS system. As well, bursty arc disturbances are mitigated using the MKS arc detection/mitigation system (Figure 15).

The MKS arc detection system was evaluated in a PECVD tool using two different carrier trays, designated Rev B (notorious for arcing) and Rev C (an improved design). Normal chamber conditions of cleaning and seasoning were employed in all tests. The process utilized relatively harsh conditions with a power of 12kW. The detector monitor mode employed an auto-threshold functionality. The process employed 20 cycles for 10 tray runs and the number of arcs was recorded. Figure 16 shows the results of the PECVD tests.

The MKS arc detection system clearly differentiated the higher arc count in Rev B as compared with Rev C and demonstrated again a reliable tool in evaluating the probability for arcing issues for hardware status in these thin-film processing systems.

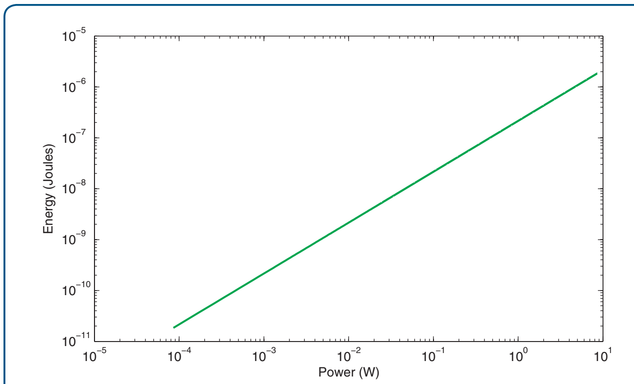


Figure 9 - The arc detector sensitivity curve

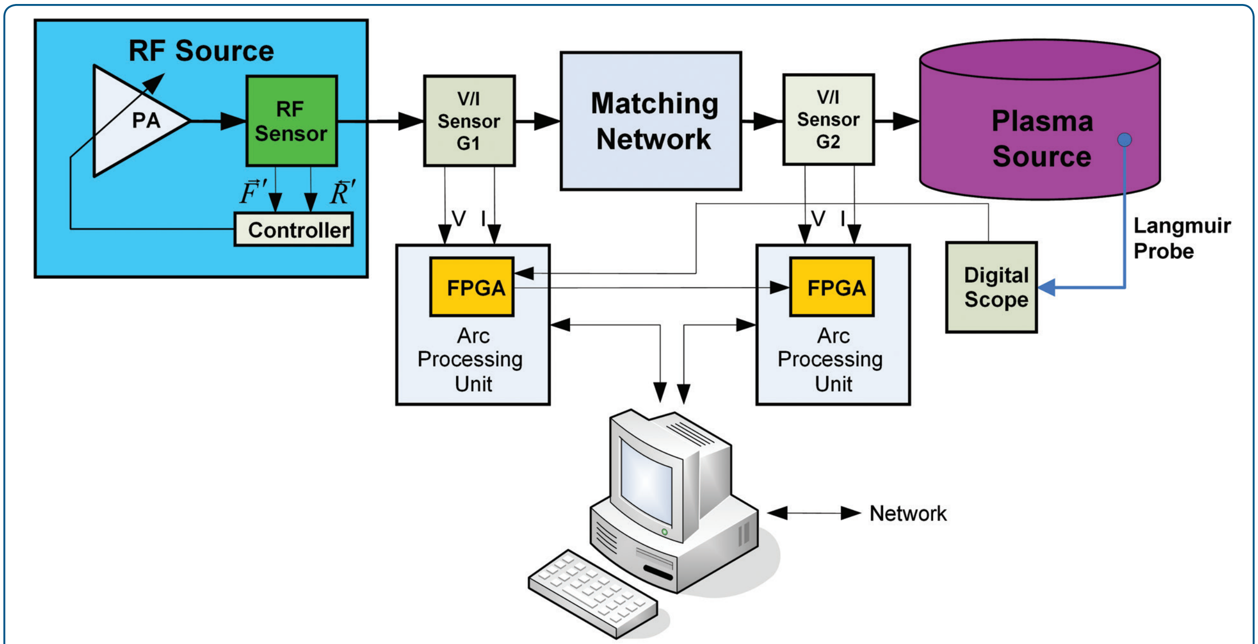


Figure 10 - Laboratory configuration for the demonstration of the ability to detect arcs using energy disturbances with pre- and post-matching network arc processing

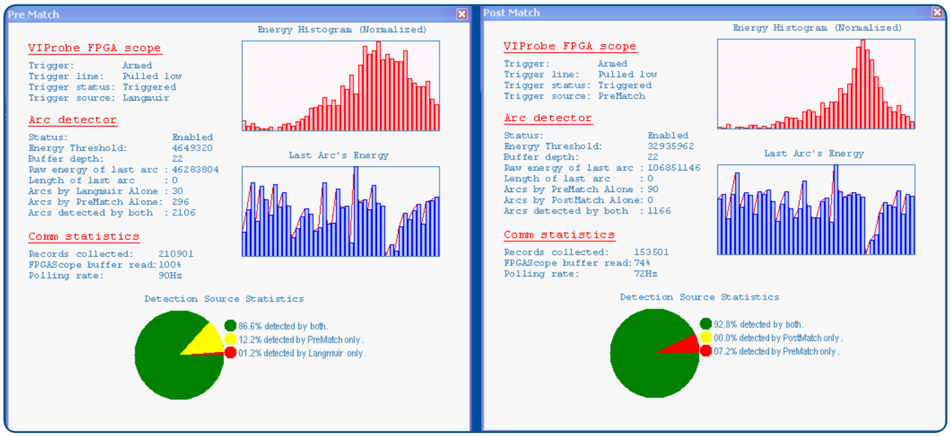


Figure 11 - ROC curves for pre- and post-matching network sensor locations showing the detector's ability to discriminate arc events

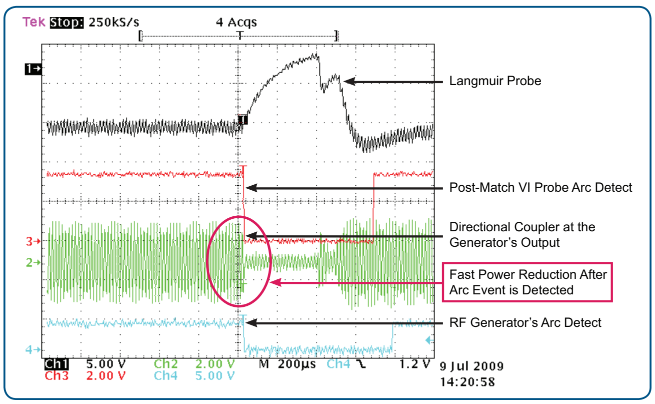


Figure 12 - Timing diagram of arc detection and arc mitigation

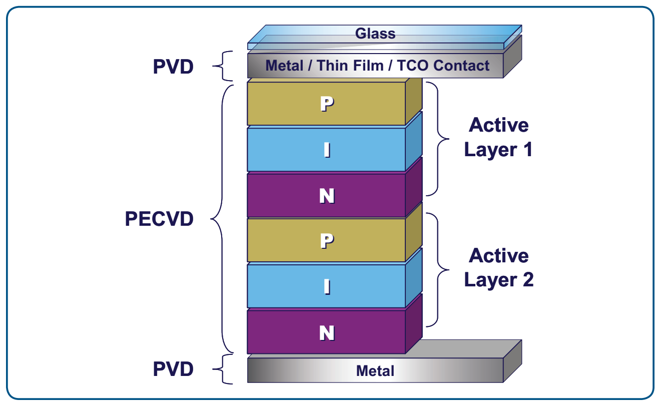


Figure 13 - The device structure used in MKS arc detector field trials

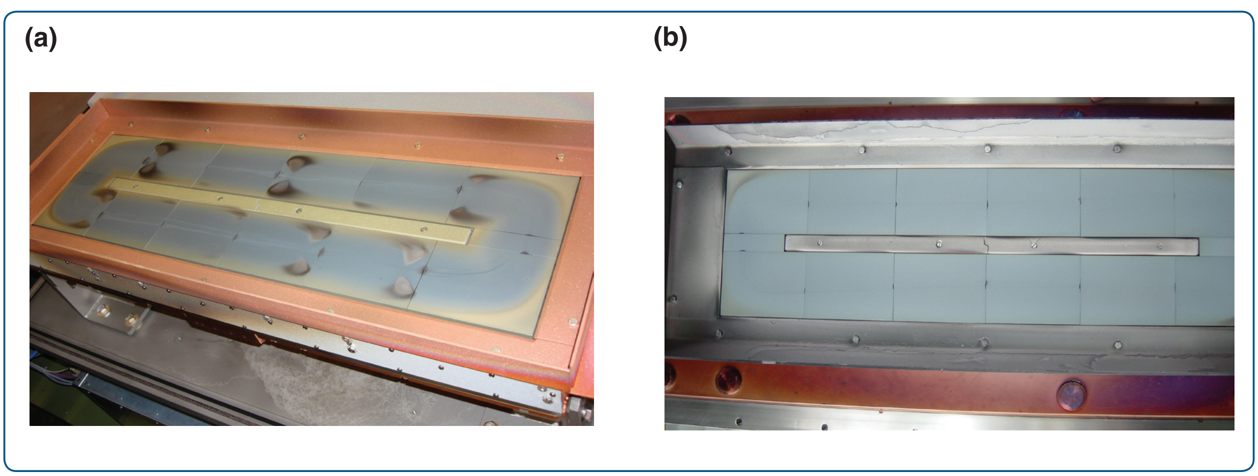


Figure 14 - PVD Field Trial Results: (a) typical Zn cathode after normal operation; (b) Zn cathode results using MKS' arc detection/ arc mitigation scheme

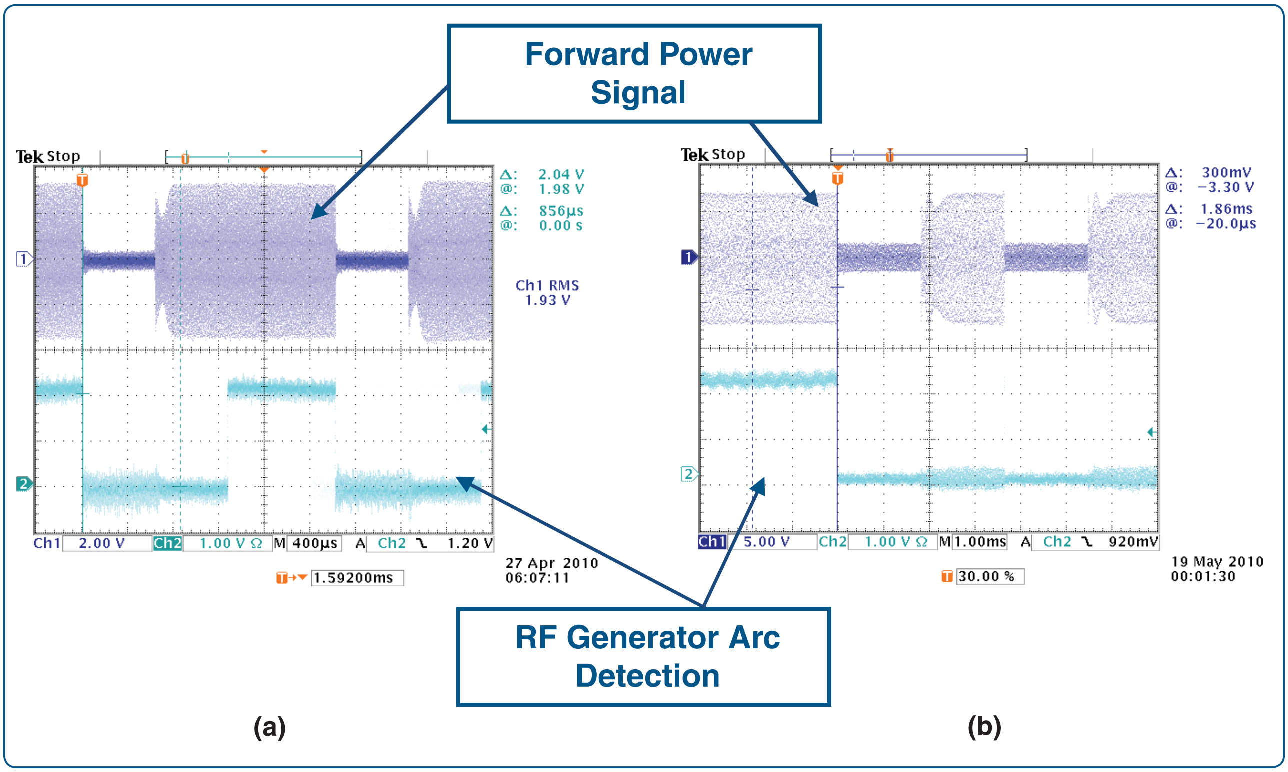


Figure 15 - Arc detection (cyan trace) and sequential countermeasure by RF generator (blue trace) to burst disturbances for aluminum-oxide deposition: (a) first example of consecutive arc events with repeated arc counter response separated by 800 µsec; (b) second example of the countermeasure being repeated a second time

CONCLUSION

We demonstrated a highly reliable and robust method of arc detection and arc mitigation. Our quantitative method of measuring the RF energy of the arc disturbance to the RF power system yielded a strong degree of agreement between the ground truth source, the Langmuir probe, and the MKS arc processing system. Our experimental setup yielded an evaluation platform to contrast the detection performance between pre- and post-match locations. The results produced from the setup showed no degradation for the ability to detect arc events and motivated the integration of the arc detection from a standalone processing system into the RF power supply. Field trials of the MKS arc detection/mitigation system demonstrated effective arc detection and arc mitigation under harsh thin-film processing conditions. The MKS approach enables effective detection and mitigation performance over a broad operating range through the implementation of an auto-threshold method that produces real-time statistical analysis during normal operations. This is invaluable for responding to a succession of arc events and its utility was demonstrated in the detection and suppression of bursty arc scenarios.

CONCLUSION (CONT)

The MKS arc detector is the only available arc detection system for quantitative evaluations, with the RF energy of the arc transient computed for each arc event. This permits tailoring of a suitable arc mitigation strategy that corresponds to the detected arc energy. The MKS arc detection system is contained in the RF power supply and permits end-user control over a small set of relevant parameters of the detection and mitigation algorithm, permitting a simple optimization process of the arc detection solution most appropriate for their operating environment. The tool integration of our arc detection and arc mitigation does not require any additional hardware or modification of the transmission lines with an in-line sensor that may lead to subtle process variation and adversely impact a customer's warranty with the tool supplier.

This study shows that The MKS arc detection/mitigation system has proven an effective tool for the detection, quantification and suppression of arcing events in the various RF plasma tools employed for semiconductor and photovoltaic device manufacturing.

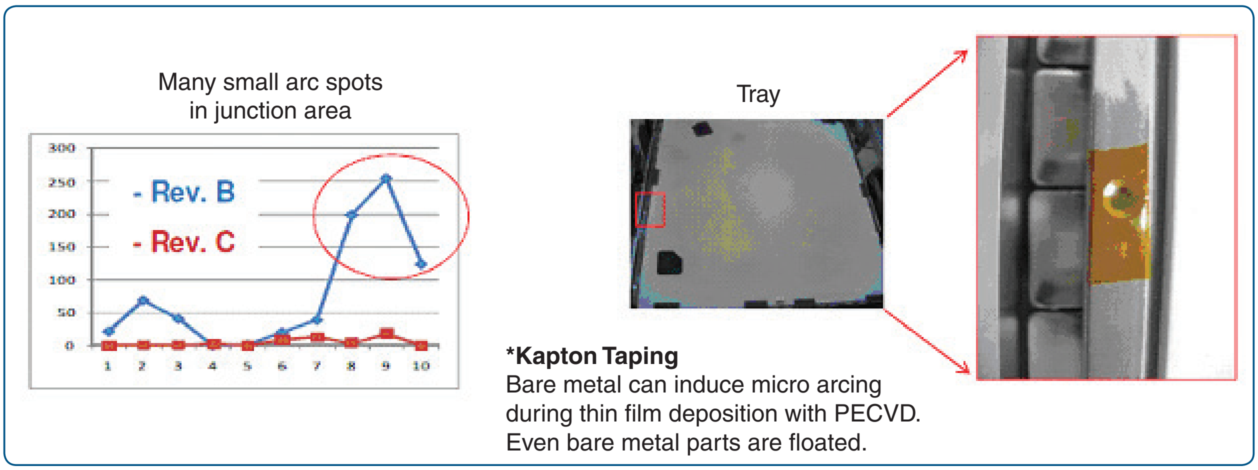


Figure 16 - PECVD field trial results