Arc Handling Considerations for DC Sputtering Power Supplies


ABSTRACT
Sputtering is an important physical vapor deposition (PVD) method in the manufacture of many products. However, sputtering processes are prone to arcing, which can cause damage to the work piece. Therefore, arcs must be detected and extinguished in a timely manner to minimize damage. Instantaneous arc rate and total arcs per process step are useful data for assessing PVD chamber health, and determining when maintenance is required. Arc handling is now a standard feature of many PVD power supplies. It is beneficial for the PVD power supply to include a digital communication interface to allow the host control system to access the arc sensor data and to dynamically configure the arc handling settings. The sputtering process arcing problem will be reviewed, including references to early experimental work implying the influence of oxides in the glow to arc transition, as well as selected history of the evolution of arc handling for sputtering processes. PVD power supplies, with the ability to report arc frequency and total arc count, will be discussed. Finally, automated target conditioning enabled by integrated arc handling will be presented. It gradually increases output power in an adaptive manner, minimizing arcing, until the target is fully conditioned.

INTRODUCTION
Magnetron sputtering is an important technique for production of both consumer and commercial goods. A schematic representation of the Al sputtering process is shown in Figure 1 [1]. As one key example, metal sputtering is used in the course of semiconductor device fabrication. Applications include both Al metal layers [2] and Cu seed layers deposited in vias (“vertical” conductors between metal layers) or trenches to provide a seed for subsequent filling by wet chemistry Cu electroplating in the dual damascene process [3-5].

One of the challenges in the practical realization of DC and pulsed mid-frequency magnetron sputtering is that it will support two stable discharge modes. The desired discharge mode is a glow or abnormal glow discharge at low current density. The undesired discharge mode is a cathodic arc discharge, at very high current density [6-8]. The cathodic arc mode causes damage to both target and workpiece, so it must be detected and quenched by the sputtering power generator. An additional challenge is real-time assessment of the health of the process. As process conditions degrade, it is necessary at some point to stop the process in order to maintain the process equipment and restore it to an acceptable state.

DISCUSSION
In the magnetron sputtering process, the desired glow discharge mode is sustained by secondary emission of electrons induced by ion impact at the target surface. These secondary electrons perform bulk ionization of process gas neutrals by electron impact [8] and possibly sequential secondary processes such as Penning ionization and multiple body collisions. The undesired cathodic arc discharge mode is sustained
by explosive emission of ions and electrons from small craters on the target surface [6]. In the cathodic arc mode, target material macro-particles are also explosively emitted from arc craters, often landing on the substrate and resulting in product yield issues. Early work on the transition from the glow to the cathodic arc mode showed the importance of oxide on the target surface for sustaining an arc [9-13]. When ultra pure noble gases were used, it was essentially impossible to sustain an arc. In some experiments, the Ar gas was purified in situ with the arc operating. When a high level of purity was attained, the arc mode discharge ceased and only a glow discharge was possible. This result was attributed to formation of oxides on the surface. When the gas was purified, the oxides were eventually removed by the arc. This early work at least suggests the importance of process gas and target material purity in metal sputtering processes, and the expectation that target arcing could develop when reactively sputtering oxides.

Recent work on understanding the nature of arc formation and quenching in sputtering magnetron discharges shows arc movement in the racetrack magnetic field by high speed photography, as seen in Figure 2 [14]. The pictures are snapshots of different arcs (not a “video” of the progress of a single arc), representing the typical evolution of the racetrack plasma and the arc plasma as a function of time following the onset of the arc. The magnetic field of the magnetron causes arcs to move around the “racetrack.” When micro-arc handling is disabled, small arcs rapidly develop into hard arcs that extinguish the toroidal plasma, allowing only the arc discharge to survive.

**Figure 2.** Images showing the formation of hard arcs: when micro-arc handling is disabled, small arcs rapidly develop into hard arcs that extinguish the toroidal plasma [14].

**SELECTED HISTORY OF DC SPUTTERING SUPPLIES**

The earliest solid state regulated sputtering supplies existed prior to 1983. They were based on silicon-controlled rectifier (SCR) technology. With no arc counting or even micro arc detection, they had arc energies in the range of 10 - 100 Joules. Arc quenching took at least 2.8ms, resulting in currents that could exceed hundreds of amperes before shut off. Arc handling in these supplies was based on over-current detection to protect the supply and target. They were adequate for metal layer deposition on large structure devices (TTL chips of the 1970’s with > 1 µm Al-interconnects) and for some industrial applications.

In 1983 5 kW and 10 kW switch mode power supplies with arc handling were introduced to the market. These historical first switch mode sputtering supplies included access to arc information via analog and serial ports allowing hard arc counting for process quality assessments. The arc energy was about 100 mJ/kW due to fast arc shut off and low stored energy. Two levels of arc handling were incorporated. The first was the passive “arc-out” circuit with the ability to quench the arc in a few microseconds, proving to be very effective for target cleaning and deposition. The second was over current-protection for the supply, which could often detect a hard arc not quenched by the fast “arc-out” circuit.

In 1990, another generation of switch mode sputtering supplies was introduced at power levels of 15 kW and 30 kW. These supplies had arc counting information available from the analog and serial ports, including arc density in arcs per second. The observed arc energy was about 10 mJ/kW. Besides the previously mentioned “arc-out” circuit, these supplies added both voltage arc detection, able to detect arcs within 1 µsec, and current mode arc detection with a user-adjustable current threshold to improve process quality.

A three phase resonant mode DC sputtering supply with extremely low delivered arc energy was introduced in 1995. It is based on a three phase RF-resonant topology [15], and exhibits delivered arc energy less than 2 mJ/kW. This supply includes arc counting, arc rate measurement, and inter-supply communication to synchronize arc handling of multiple supplies feeding one plasma chamber. Very fast voltage based arc detection and handling with completely adjustable arc settings enables its automated target conditioning cycle (TCC) and burn-off of flakes which may bridge target shield gaps during sputtering. This supply is able to drive essentially every DC sputtering process.
A further technical evolution of the switch mode sputtering supply was introduced in 2004. A notable improvement is an active arc switch with ultra fast reaction, resulting in delivered arc energy below 200 \( \mu \text{j/kW} \). Arc diagnostics include counters for arcs per run and arc rate, for both hard arcs and micro arcs. Arc counter values are available over SensorBus interfaces such as ModBus/TCP and DeviceNet. Arcs are detected by voltage collapse and current increase, with provisions to set thresholds and detect delay time and shut down time.

**ARC SUPPRESSION**

An example of arc quenching is shown in Figure 3. The discharge voltage falls below the arc voltage trip level in about 500 ns. The current into the plasma increases during this time, resulting in a maximum at the time when the output is shut off to handle the arc. The generator reverses the output voltage to speed the arc current reduction. This reverse voltage results in a reverse current conducted by the remaining plasma after the current in the power cable decays (3.6us after shut off).

![Figure 3. Arc quenching waveforms for arc handling by output voltage reversal.](image)

Arc detection can be accomplished by either current detection, voltage detection, or a combination of the two. For current detection, an arc is detected by monitoring the current. An arc is considered to occur when the current exceeds the trip level. This is typically the slower detection method due to the inductive nature of the power supply output circuit. For voltage detection, an arc is detected by monitoring the voltage. An arc is considered to occur when the voltage drops below the trip level. Very fast detection is possible, with detection times as short as 500 ns. Combined current and voltage arc detection can offer the benefit of an additional degree of freedom for handling especially difficult processes. The trip levels can be varied to establish optimum arc handling parameters by application, for example, target cleaning versus deposition.

Some important arc handling settings in modern sputtering power supplies are detect time, shutdown time, recovery time, and arc voltage trip level. Detect time is how long the arc is permitted to burn after detection and before the power supply acts to quench the arc. Shutdown time is how long the power supply shuts off to quench the arc. Recovery time is how fast the power supply increases the power towards the set point after an arc response shutdown. Arc voltage trip level is the discharge voltage magnitude below which the unit will trigger the arc response.

Increased detect time will increase the energy delivered into an arc causing the target to be cleaned around the arc seed. This can be beneficial for long term stable processes in some cases, particularly for low melting point oxides such as SnO\(_2\) and ZnO\(_x\) [16]. Shutdown time should be only as long as needed to quench all arcs around the target surface. Deposition of Si requires special attention because of its lower conductivity. In the case of Si, slower detection and target damage are issues which must be avoided by good arc handling and proper setup of the arc handling parameters. Some newer sputtering power supplies have arc handling presets to provide a process dependent starting point for the user. These presets may be adequate for many processes, and in any case they provide a reasonable starting point for optimizing arc handling settings. Where two presets are provided, the choices may be simply Metal (like Al) and Non-metal (like C or Si).

Pulsed-DC arc handling was introduced in the early 1990’s [17] and has become an important technique in the arsenal of the sputtering process engineer. Pulsed-DC offers several sputtering advantages. A primary advantage is dramatically reduced arcing, especially for reactive sputtering processes (arc prevention), but with process characteristics very similar to the pure DC approach. Further advantages include low arc energy, reduced particle generation, and reduced sensitivity to imperfections in magnetron targets and process gases. An example of pulsed-DC arc handling is shown in Figure 4. In normal operation, the sputtering power is delivered in a periodic pulse train in which a positive voltage on the order of 5% to 20% of the magnitude of the sputtering voltage is applied after every sputtering pulse. This positive voltage tends to discharge voltage build-up on any oxide which is on the target surface, actually preventing the occurrence of process arcs. When an arc on the target is detected, the output voltage is immediately reversed to quench the arc, after which the pulsing sequence resumes.
Modern sputtering power supplies feature arc data collection. Arc data can be viewed from the front panel and may also be collected by the host computer through the data interface. Data available includes arc density (rate), presented as a frequency in units of arcs/sec (Hz), and total arc count for the recipe step. Arc rate (arcs/second) and arc count (entire recipe step and intra recipe step) monitoring provides a useful fault detection and classification (FDC) tool. Typical faults include improper gas flow, dirty chamber conditions, material defects, improper work piece placement and cathode end of life. An example of arc count data collection is shown in Figure 5 [18]. In this case, micro-arc counts as a function of time show when the process is going out of control due to excessive arcing. This type of evaluation is critical for proper setting of the reversal time in pulsed-DC sputtering [16,18].

Target conditioning cycle (TCC) is a useful advanced equipment control (AEC) technique used to clean contaminated targets in reduced time. It utilizes a closed loop control algorithm to adjust delivered power to minimize the arc rate during the target conditioning step. Both the integrated arc handling and the intelligent control capabilities of the power delivery system enable the implementation of TCC. The typical result is minimized time for target conditioning versus conditioning by manual control.

An example of a closed loop DC arc fault detection and classification (FDC) architecture is shown in Figure 6. The arc sensor information in the power supply is accessed via a process control network such as SensorBus or EDA. This approach is actively used in the manufacturing of data storage media. The supervisory computer is connected directly to the DC generator with a secondary sensor port over a SensorBus network.

SUMMARY

Integrated arc handling solutions have been incorporated in sputtering supplies since the early 1980's. Advances in arc handling have resulted in constantly decreasing delivered arc energies, and pulsed-DC sputtering has enabled the prevention of arcs, particularly in reactive sputtering processes. Sputtering power supplies with integrated arc handling and SensorBus interfaces are available today. These power supplies are actively used in APC environments in semiconductor, data storage, and flat panel display applications. Integrated arc diagnostics enable FDC capability for DC and pulsed-DC sputtering processes.

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REFERENCES


