THE RISING BAR FOR SPUTTERING POWER SUPPLY ARC HANDLING PERFORMANCE

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INTRODUCTION
Magnetron sputtering is an important technique for the production of both consumer and commercial goods [1]. Even for those of us in the vacuum coating community, it is challenging to grasp just how pervasive this technique is. 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 layer for subsequent filling by wet chemistry Cu electroplating in the dual damascene process [3–5]. However, sputtering plays some role in what would seem to be every electronic product on the market. Conceptually, magnetron sputtering seems simple enough. However, commercial realization of high-quality, high-value coatings is far from trivial. 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 supply. 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.

THE SCHIZOPHRENIC NATURE OF MAGNETRON SPUTTERING
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, as an individual process. An individual process means that one ion incident on the surface results in emission of some number of secondary electrons (the ion impact being primary), with some probability. 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 in what could be considered a collective process [6]. This is a collective process because the current flowing in the arc provides heat to the arc spot, which in turn causes melting and explosive emission of a “collection” of target material atoms. In the cathodic arc mode, target material macro-particles are also explosively emitted from arc craters, often landing on the substrate, resulting in product yield issues.

Electrical discharge devices with the ability to operate in arc and glow regimes have been studied for some time now. 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 [8–10]. 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. The motivation for this work was likely to understand how to make arc sources work better. Now we are interested in keeping sputtering processes out of the arc regime. This early work at least suggests the importance of process gas and target material purity in metal sputtering continued on page 30.

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ARC HANDLING

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processes, and perhaps sets the expectation that target arcing could develop when reactively sputtering oxides. Even so, formation of arcs in the magnetron sputtering process is still not well understood fundamentally. Issues with arcing in sputtering processes are handled predominantly with the “know-how” of power supply designers and sputtering practitioners.

THE EVOLUTION OF DC SUPPLY ARC HANDLING

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 to 100 Joules. Arc quenching took at least 2.5 ms, resulting in currents that could exceed hundreds of amperes before shutoff. Arc handling in these supplies was based on over-current detection to protect both the supply and target. They were adequate for metal layer deposition on large structure devices (TTL chips of the 1970s 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 interface ports, allowing hard arc counting for process quality assessments. The arc energy was about 100 mJ/kW due to fast arc shutoff 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 and could be combined to powers exceeding 100 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 [14] 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 that may bridge target shield gaps during sputtering. TCC is a useful 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. 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 µJ/kW as described in U.S. patent 6,943,317 [15]. Arc diagnostics include counters for arcs per run and arc rate, for both hard arcs and micro arcs. Arc counter values are available over data communication interfaces such as Profinet. Arcs are detected by voltage collapse and current increase, with provisions to set thresholds and detect delay time and shut-down time.

ARC SUPPRESSION CONSIDERATIONS

An example of arc quenching is shown in Figure 1. 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

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reverse current conducted by the remaining plasma after the current in the power cable decays (3.6 µs after shut off).

Figure 1. Arc quenching waveforms for arc handling by output voltage reversal.

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 toward 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 SnOx and ZnOx [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 that 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 many if not most cases they provide a reasonable starting point for optimizing arc handling settings. For example, if just two presets were provided, the choices could be simply “metal” (like Al) and “non-metal” (like C or Si).

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 include 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) monitoring provide useful fault detection tools. 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 2 [17]. 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, 17]. The arc count plots are for various reverse times in an asymmetric pulsed DC reactive sputtering process.

It can be seen that as the reverse time (shown in the boxes accompanying the plots) is increased, the process is stable for a longer time before going out of control due to arcing.

Figure 2. Arc count data collection example [17] showing that the onset of increased arcing can be mitigated by longer reversal times.

SUMMARY

Integrated arc handling solutions have been incorporated in sputtering supplies since the early 1980s. Advances in arc handling have resulted in constantly decreasing delivered arc energies. Sputtering power supplies with integrated arc handling and a variety of data communication interfaces are available today. These power supplies are actively used in computer-controlled environments in semiconductor, data storage, and flat panel display applications. Integrated arc diagnostics enable fault detection and process health assessment for magnetron sputtering processes.

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