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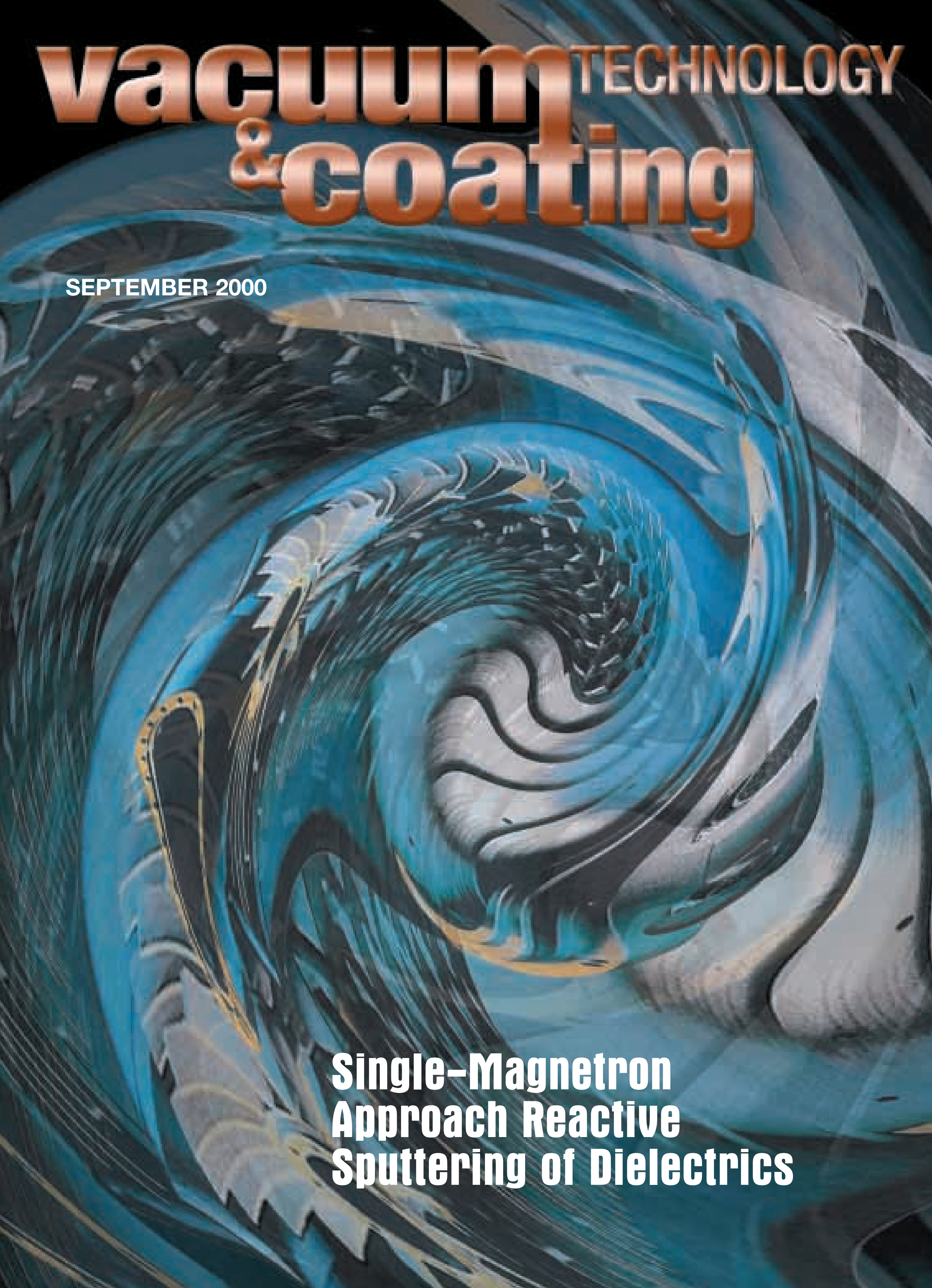

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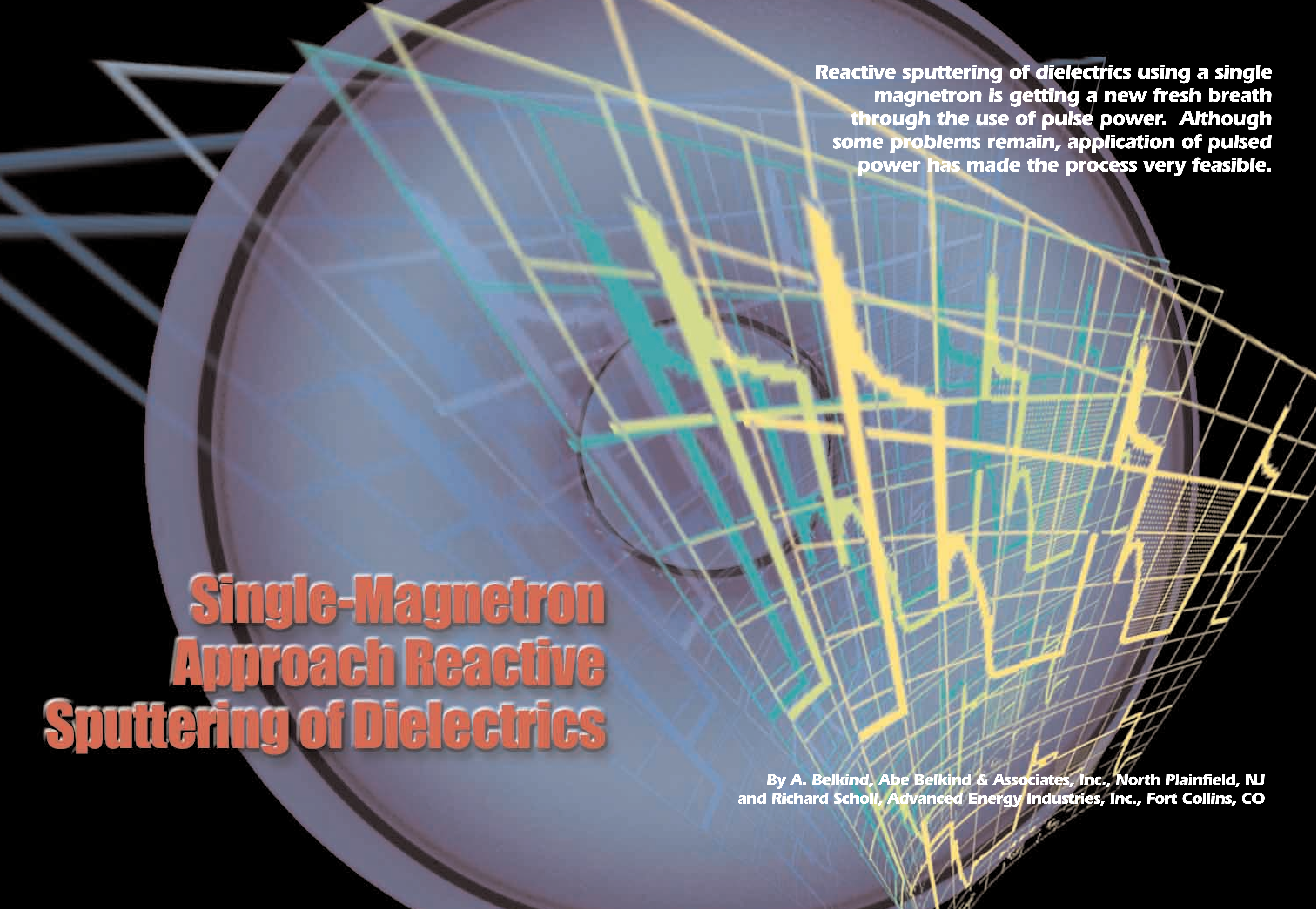

Reactive sputtering of dielectrics using a single magnetron is getting a new fresh breath through the use of pulse power. Although some problems remain, application of pulsed power has made the process very feasible.

Single-Magnetron Approach Reactive Sputtering of Dielectrics

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Thin dielectric films (Al_2O_3, SiO_2, AlN, and others) find constantly increasing industrial implementation. Reactive sputtering is an efficient technology for depositing large area coatings, but implementation of reactive sputtering to deposit thin films of dielectrics has been limited by the necessity of avoiding both electrical charge build-up on their surfaces that can cause arcing, and anode coating that can cause disruption of power supply electrical circuitry. These problems are solved efficiently by using the recently introduced AC and Pulsed Power Reactive Sputtering and a single magnetron.

Thin dielectric films (Al_2O_3, SiO_2, AlN, and others) find constantly increasing implementation as electrical barrier and protective layers in microelectronics, as permeation barriers in packaging and microelectronics devices, optical layers in optical and electronics devices, and as thermal barrier coatings, among others. Reactive sputtering is one of the most attractive thin film deposition technologies when requirements call for large surface areas, low substrate temperatures, good adhesion, high film density, and low cost.

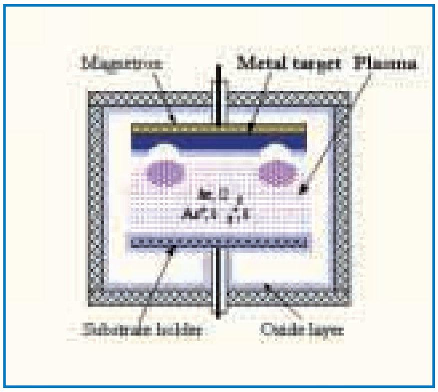


Figure 1. Reactive sputtering of an oxidizing metal in a mixed Argon and Oxygen atmosphere.

Reactive sputtering is based on sputtering from a metal target in reactive atmosphere that, in the case of making oxides, contains oxygen (**Figure 1**). In this case, plasma activated oxygen atoms and molecules oxidize all surfaces, including not only the metal target, but also the metal deposited on the substrate, the anode, the walls, and all other surfaces that can be oxidized. If the oxide layers are non-conductive, the surface of these layers can accumulate electrical charges, producing high potentials which result in appearance of both small and large arcs. Using DC power, the most severe arcing appears on the cathode (target) surface, especially near the target racetrack area (sputtering area) (**Figure 2**)[1,2]. The oxide layer grown near a racetrack area rapidly charges positively and can experience dielectric breakdown, accompanied by an arc, or might be discharged through a surface arc to the neighboring bare metal area. In addition, gradual covering of the whole anode surface with a dielectric layer eventually interrupts the electrical path, extinguishing the discharge.

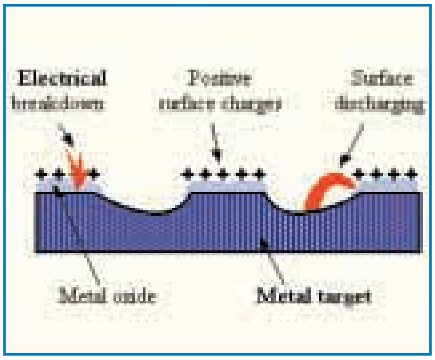


Figure 2. Microarcing on the target surface during reactive sputtering of dielectrics.

To avoid these arcing and anode problems, reactive sputtering of dielectrics was done initially using RF power[3,4]. Regretfully, deposition rates are low in this case, RF power supplies are relatively expensive, and scale-up of an RF system is a difficult task. In spite of these problems, RF sputtering was used for many years, for the lack of an acceptable alternative.

Breakthroughs in the solution of the reactive sputtering problems have been achieved in the last few years. First, a mid-frequency AC power has been utilized, principally using a dual magnetron configuration[5-7]. Second, pulsed DC power has been introduced[8-13]. In this latter case, any magnetron configuration can be used. The deposition rates in both cases are comparable, and the choice between the two approaches, in most cases, depends on what magnetron configuration is employed. Implementation of pulsed power results, for example, not only in non-arcing sputtering conditions, but also in deposition of a dense dielectric layer with a smooth surface (**Figure 3**).


Photo A


Photo B

Figure 3. Cross-sections of alumina films made by reactive sputtering using PinnaclePlus (AE) pulsed power supply at the University of Salford, U.K.. The deposition was made using pulsing frequencies and reverse times: photo a: 100 kHz at 2 µsec and photo b: 225 kHz at 2.2 µsec.

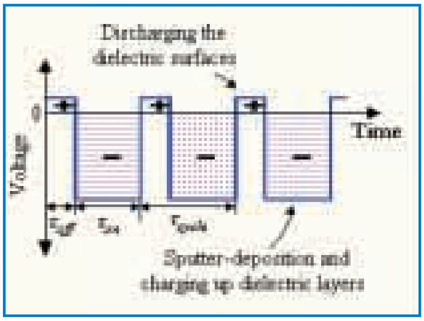


Figure 4. Schematic of pulsing voltage forms.

Pulsed Power and Non-Arcing Conditions

Pulsed power can be applied to a cathode, controlling power, or voltage, or current. In the case of a single magnetron arrangement, the pulsing voltage form is shown schematically in **Figure 4**. It has been called by several researchers the "pulsed unipolar DC mode," on the basis that there is a single magnetron (one pole, or "unipolar") and the basic DC power source is pulsed.

How does pulsed power avoid arcing? In **Figure 4**, during the on-time, τ_{on}, a negative potential is applied to the target. The plasma is established and sputtering takes place, mainly in the racetrack area. The arrival of sputtering ions causes the dielectric layer on the target and all dielectric surfaces in the chamber to charge (**Figure 1**). If the pulse duration, τ_{on}, is kept short enough to keep charge buildup on the dielectric surfaces at the end of τ_{on} lower than a critical value, no arcing occurs. This means that ?on should be less than certain critical on-time, $\tau_{on,crit}$. The negative sputtering pulse is followed by a short pulse, during which a small positive potential is applied. This may be called the "off pulse," the "zero pulse," or "reverse pulse." During the off-pulse, electrons and ions of the decaying plasma discharge the dielectric surfaces. The duration of this off-time pulse, τ_{off}, is determined by the requirement to fully discharge the surfaces, i.e. the off-time should be longer over a critical value (*critical off-time*, $\tau_{off} > \tau_{off,crit}$). If the discharge is not completed, additional step-by-step charge accumulation during many sequential periods takes place, and layer breakdown may still occur. Increasing the on-time duration increases the charge accumulated during each sputtering cycle, resulting in the necessity to make the off-time duration longer.

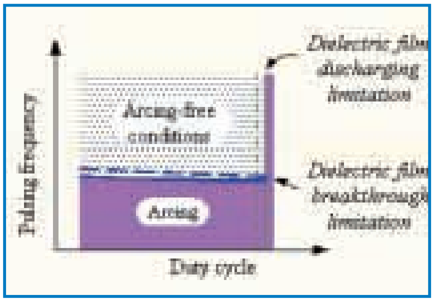


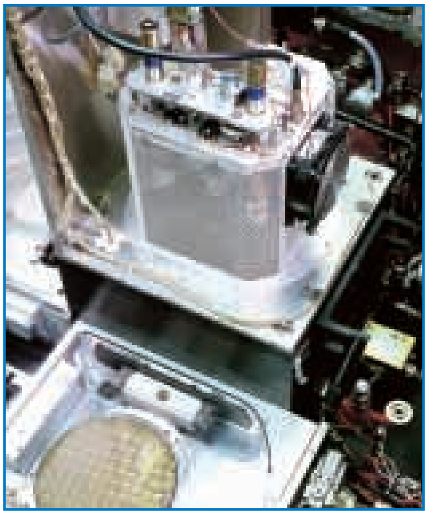
Figure 5. First-approximation view of arcing-free conditions in the 2-d space of pulsing frequency & duty cycle and two different currents: I_1 (solid lines) & I_2 (dotted lines): $I_1 < I_2$.

The critical off-time also depends on the current. Increasing the current increases the charge accumulated on a dielectric layer surface during a single on-time, and therefore, requires a longer off-time to discharge it.

The relationship between the critical on-time and critical off-time, and restrictions on the on-time value, determine the range of pulsing frequencies and duty cycles (defined as the ratio $\tau_{on}/(\tau_{on} + \tau_{off})$ that allows reactive sputtering of dielectrics without arcing[14-16]. This range is shown schematically in **Figure 5**[17]. For increasing current or power, a higher frequency and lower duty cycle must be chosen. These non-arcing conditions are usually satisfied when a pulsing frequency and duty cycle are chosen properly from the ranges of about 20-350kHz and 0.5-0.9, respectively.

Voltage and Current Pulse Forms

Oscillograms (pulses) of the voltage, current, and/or plasma optical emission provide information that helps both to understand the pulsed plasma behavior and to control the deposition process[14-16]. The forms of these pulses (**Figure 6**) are determined by plasma decay during the off-time and plasma reestablishment during the initial part of the on-time. The plasma decays by electron and ion bipolar diffusion to various charged and uncharged inside chamber surfaces during the off time, and the plasma density decreases, in the first approximation, exponentially with a time constant of a few tens of microseconds. The off-time is usually in the order of a few microseconds. Therefore, the plasma density at the end of the off-time is still substantial. This residual plasma density is responsible for fast plasma reestablishment, over a period of only about one or two microseconds, and one does not observe a large voltage overshoot.



The AE Sparcle line of pulsing units combine with a separate DC power supply to provide flexible pulsing

High Deposition Rates

Reactive sputtering shows a hysteresis behavior in its main characteristics when partial pressure or gas flow of the reactive gas is varied. This is due to the existence of two stable target surface conditions: the *metallic* condition, and the *reactive*, or fully oxidized (in the case making oxides) mode. The deposition rates of metals in the metallic condition are usually much higher that the deposition rates of a compound (oxide) from an oxidized target. At the same power, deposition rate of Al metal in the metallic target condition is more than 10 times the deposition rate of Al_2O_3 films in the oxide mode. Fast transitions from one mode to another are obtained when varying the partial pressure of reactive gas in the chamber. Between these two stable modes, the

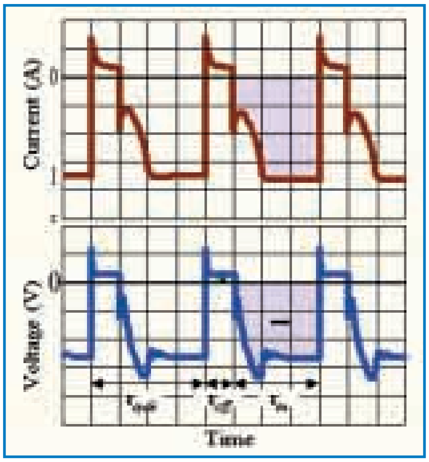


Figure 6. Schematic of current and voltage oscillograms in reactive sputtering using a power supply's constant power mode.

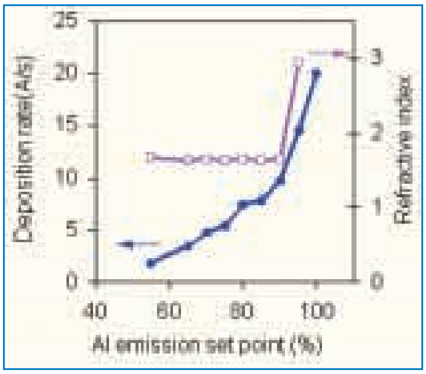


Figure 7. Deposition rate and refractive index of $A1_2O_3$ films deposited using various closed-loop control set points. Pulsed power: 2 kW, 100 kHz.

deposition process can be realized by maintaining the target in some quasi-stable intermediate condition. This can be achieved using closed-loop gas flow control based, for example, on measuring plasma optical emission of a metal line and monitoring reactive gas flow.

An example of such closed-loop control implementation for deposition of Al_2O_3 films is shown in **Figure 7**. The data show that, using a closed-loop control system, Al_2O_3 films can be deposited with a rate of more than 50% of the metallic aluminum deposition rate.

Anode Arrangement

The following discussion assumes that the reaction product of the reactive sputtering process is an insulator (dielectric). The most commonly used circuit arrangement for a single-magnetron system employs the deposition chamber itself as a grounded anode. Such an anode has a large surface area, and covering it thoroughly with a dielectric layer can take a relatively long time. Nevertheless, in the long run, the anode surface does get coated with an insulating layer, which causes variations in the effective anode circuit impedance, consequential voltage redistribution, and, as a final result, even circuit interruption (this has been called the "disappearing anode" problem). The simplest (but unpleasant and time-consuming) solution of the anode problem is periodic anode cleaning. Another solution is to use a self-cleaning anode, where self-cleaning is provided by a discharge confined near the anode.

A self-cleaning anode system consists, for example, of two anodes and a single magnetron, powered by an AC supply (**Figure 8**). This novel configuration is called "Multi-anode" or "Redundant Anode" Sputtering[18]. In **Figure 8**, two anodes are provided, each connected to one side of a center-tapped AC power source. The center point, or "tap," of the power supply is connected to a single magnetron source of the ordinary variety. The system works so that each of the anode elements acts alternatively as a true anode (electron collector) and as a sputtered cathode (ion collector), depending upon the polarity of the AC power supply. The continuous reversal of voltage and current will also keep any insulating regions of an anode from charging, and therefore inhibits anode arcing. The magnetron is always a cathode, relative to a different anode on each half of the cycle. Further, charged areas of the target are discharged twice each cycle, as the voltage across the transformer passes through zero. Thus the target discharging rate is twice the driving frequency.

A redundant anode system can provide sustainable anodes and periodically discharges anode and cathode (target) surfaces, avoiding arcing. It does not result in high anode falls, does not exhibit plasma decay on every half cycle and resulting voltage spike. A redundant anode system can be more easily retrofit into existing DC single-target systems, does not experience the difficulty of source matching and uneven source erosion that is typical for dual-magnetron systems. Film contamination with anode material, if a problem, may be avoided by using for the anode the same material as the cathode and/or by placing a deposition shield so as to prevent deposition of material sputtered from an anode from reaching the substrate. Comprehensive investigation of the redundant anode approach is in progress.

Substrate Biasing

Using various special circuit arrangements for reactive sputtering of dielectrics, such as dual magnetrons or redundant anodes, creates problems in substrate biasing. Even in the simplest case, employment of a single magnetron powered by pulsed power and unprotected anode, substrate biasing can be tricky.

At least three main issues of substrate biasing should be considered in the case of reactive sputtering of dielectrics. One issue is more general and related to the substrate: is it conductive or not? The second issue is connected to the depositing dielectric film, and the third relates to how to apply bias voltage if the whole cathode-anode system is floating with respect to the chamber and substrate, as described in the previous sections on these systems.

Let us suppose initially that we know how to apply power to the substrate and we are using a balanced planar magnetron. Then the question is: what power should we use? If the substrate is conductive and the thickness, for example, of Al_2O_3 film is 500 nm, it takes about a few milliseconds to charge up the films and get a bias potential of about -100 V. This means that AC or pulsed power at frequencies of only about 0.1 kHz can be used for biasing. At higher frequencies, the efficiency of biasing will be lower.

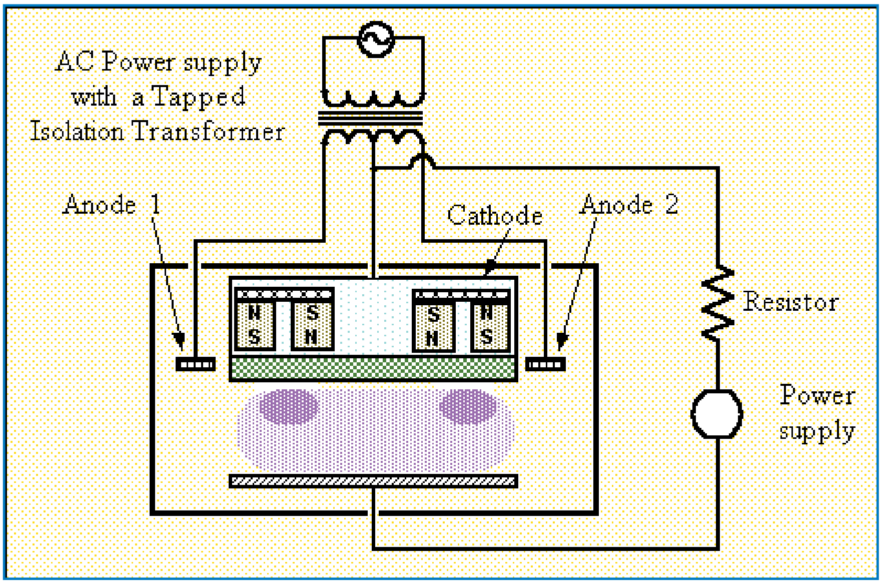


Figure 8. Schematic of redundant anode sputtering system with substrate connection to the cathode.

The useful frequency range depends on the plasma density near the substrate surface and will drop as the density increases - for example, by replacing a balanced magnetron by unbalanced one. When the substrate is electrically nonconductive, its surface will charge to a given potential in less time, because of its substantially smaller capacitance. Therefore, in this case, the useful frequency range may lie even in the MHz region.

In the case of a floating cathode-anode power circuitry and a dual anode arrangement, the substrate can be connected to the cathode to provide a bias potential, through a resistor alone, and/or a with an additional bias power supply (**Figure 8**). If there is no resistor or additional power supply in the substrate circuitry (i.e., the substrate is connected directly to the cathode), the substrate works as an additional cathode, and the plasma density near the substrate determines the current through the substrate. A resistor in the substrate circuitry lowers the ion current through it (as well as the voltage and so the energy of the arriving ions), while a positive potential applied to the substrate can cause the substrate to attract electrons for heating (i.e., to work as an anode).

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