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Effective reactive pulsed magnetron sputtering of aluminium oxide – Properties of films deposited utilizing automated process stabilizer

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ABSTRACT

The formation of dielectric composites on a target surface (target poisoning) reduces the deposition rate of a reactive magnetron deposition process in comparison to the deposition rate of metals. One way of minimizing this reduction is shifting the magnetron operating point from the dielectric to the transient mode. The goal of this paper is to show that a stable process of efficient aluminium oxide deposition can be carried out in a transient mode. An automated stabilizer driven by the electrical parameter of the magnetron power supply was used for process stabilization. The approach of process stabilization in the transient mode resulted in about seven times higher deposition rate of aluminium oxide than that of a standard dielectric mode and only two times lower than the deposition rate of aluminium. The optical properties of the thus obtained aluminium oxide films were studied by means of ellipsometric analysis. The model of film structure, consisting of stoichiometric aluminium oxide, metallic inclusions and voids, was proposed and dispersion characteristics were calculated. The complex refractive index characteristics were similar to those typical of aluminium oxide deposited during a standard pulsed reactive magnetron sputtering process.

1. Introduction and motivation

One of the main disadvantages of the reactive magnetron sputtering technology is the relatively low deposition rate of compounds (especially dielectrics). The formation of dielectric composites on the target surface (target poisoning) highly reduces the deposition rate, since the sputtering yield of most of the composites is much lower than that of metals. The coverage factor of the target surface by a composite is often used as an indicator of the magnetron sputtering mode (the operating point of the magnetron source). The influence of target poisoning on the dynamics and parameters of the sputtering process was widely described by Berg et al. [1]. The changes in the parameters of the reactive deposition process (e.g. a decrease in the discharge power, an increase in reactive gas partial pressure) shift the magnetron source operating point from the metallic mode (target surface free of the compound) through the transient mode (partially covered surface) to a dielectric one (target is fully covered by the compound to be deposited). The problem may be even more complex if the transition from the dielectric to the metallic mode is considered. In the case of such a transition only the racetrack region of the target surface is free of the compound and operates in the metallic mode. The target surface in the regions of weak ion bombardment, the regions where the target material is not effectively sputtered (e.g. the regions of magnetic pole pieces), may still be coated with a dielectric. Therefore, all modes may exist on the target surface at the same time, but each on a different part of the target surface.

Moreover, these changes of the sputtering mode act in a hysteresis manner, hence they cause some problems with the process control. This is especially important in the transient mode where even small fluctuations of the process conditions may lead to significant changes of the magnetron operating point. A few ways of avoiding instabilities in the reactive magnetron sputtering process have been described, including avoiding the hysteresis effect [2] or operating with a magnetron close to a metallic mode [3]. The reactive sputtering process can be controlled in several different ways – with target voltage [4], mass spectrometer signal [5], OES signal [6], etc., and there are several different indicators for defining sputtering modes, e.g. target voltage, emission line intensity, reactive gas pressure. Such control is a standard and a well-defined feature of any relevant industrial process in which efficiency, stability and reproducibility are of the highest importance. The above

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mentioned means of control of reactive sputtering processes were widely studied and described in literature. The monitoring of the sputtering mode with the usage of sophisticated tools, such as OES or mass spectrometer systems, is more expensive than the usage of a simple electrical indicator, e.g. the target voltage. Certainly such simple indicators may be of limited applicability – limited by the parameters of sputtered material or by the type of used power supply (direct current, impulse), but they may be interesting as low cost solutions. The previous papers of the Authors presented another simple *in situ* method of monitoring the target condition during the reactive deposition process using the electrical parameter of the impulse power supply [7–11]. This method was based on the concept of **circulating power** (P_C), which is an electrical parameter of the DORA Power Systems medium frequency power supply [9]. This is a rather untypical power supply because of its resonant power stage which by the very design introduces simplicity and reliability at low cost. The circulating power P_C value depends on discharge impedance – thus subsequently depends (among others) on target material parameters, in particular on the ion induced secondary electron emission coefficient, ISEE [7,8].

The deposition of aluminium oxide was chosen as a model example because of two major factors. Firstly, aluminium oxide thin films are widely used in many mechanical, optical and microelectronic applications because of their excellent properties [12], mechanical strength and hardness, transparency, high abrasion and corrosion resistance, as well as insulating and optical [13] properties. Unfortunately, the deposition rate of Al_2O_3 is much lower than that of Al (as it was mentioned above), hence an increase in productivity is needed. Secondly, a strong difference in the ion induced secondary electron emission coefficient (ISEE) between Al and Al_2O_3 [14] makes these materials suitable for use with the circulating power concept. The ISEE value of Al and Al_2O_3 is of about 0.09 and 0.2, respectively (at ion energy of about 500 eV) [15,16]. The ISEE coefficient value has significant influence on plasma impedance [17] and subsequently on the changes of the circulating power. As plasma impedance depends on several other factors, such as: intensity and distribution of the magnetic field, target dimensions, composition and pressure of the sputtering gas mixture – they should be kept as constant as possible in order to use the circulating power concept to determine the operating point of a magnetron source. Constant monitoring of the dynamics and value of the circulating power provides precise information about the operating point of the magnetron source. The use of this method allowed the technologist to obtain good quality films of Al_2O_3 compound during effective the reactive pulsed magnetron sputtering process [10,11]. The obtainable deposition rate was in the range of 100 ÷ 150 nm/min, at 7.5 cm target to substrate distance and target power of 1.5 kW. For comparison (with the same target to sample distance and target power), the deposition rate of about 10 ÷ 25 nm/min was obtained when the magnetron operating point was set in the dielectric mode.

The effective reactive pulsed magnetron sputtering process mentioned above [10,11] was obtained by setting the operating point of the magnetron source in the transient mode. In this case it was convenient for the technologist to reach the transient mode by shifting the magnetron operating point from a metallic mode by the reactive gas partial pressure increase. This way of reaching the transient mode is easily controllable because it shifts the magnetron operating point along that part of the hysteresis process curve where intermediate points are easily observable (this issue is described in section 3 in detail). In this case the sputtering process had to begin in the metallic mode and the substrates had to be shielded by the shutter to prevent them from being coated with the metallic film during the initial phase. In this paper the Authors present the results of an approach for the automated stabilization of the effective reactive pulsed magnetron sputtering process of Al_2O_3 using the medium-frequency power supply parameter (circulating power, P_C). In this case the effective reactive pulsed magnetron sputtering process was obtained by setting the operating point of the magnetron source in the transient mode, reached by shifting it from the dielectric mode by a discharge power increase. This way of reaching the transient mode is not manually controllable because the shift of the magnetron operating point takes place along this part of the hysteresis process curve where the intermediate points are not noticeable (this issue is described in section 3 in detail). The motivation for the presented work was the expectation that this approach will eliminate the need for constant monitoring of circulating power by the technologist. In such a procedure, the substrates did not have to be shielded by the shutter to prevent them from being coated with the metallic film during the initial phase of the sputtering process.

1.1. The medium frequency power supply DPS

The design of the DPS (Dora Power Systems) power supply [9] enables monitoring of the mismatch between plasma–magnetron impedance and the resonant circuit of the output stage of the power supply through the circulating power. A detailed electrical schematic diagram of the switching resonance circuit of the DPS power supply and the way of measuring the circulating power was presented in previous papers [7,8]. Here, only a simple principle of operation will be given. The resonant power stage (about 100 kHz) of the DPS power supply is supplied with P_O power by the MOSFET H-bridge. This resonant power stage operates with the Q factor stabilization. As a result of this at high load impedance it operates as a voltage source (up to 1200 V) and P_O power is delivered to the load. The output power (load power, in this case it is the target power) was named by the designer the **effective power**, P_E. As the load impedance decreases, the power supply changes the way of operation from the voltage source to the current source (sinusoidal-shaped wave, constant amplitude) and only a part of P_O power is delivered to the load. The power of the difference P_O - P_E is transferred from the resonant power stage back to the tank capacitor – this is referred to as the **circulating power**, P_C. Thanks to the stabilization of the Q factor of the resonant power stage, additional circuitry usually required for power supply protection (arc suppression) is not needed. The main advantage of the Q factor stabilization circuitry is that the circulating power value is load impedance dependent and reflects the changes of technological conditions, e.g. the ISEE value of the target surface.

2. The experimental apparatus

The sputtering processes presented in this paper were performed in a cylindrical-shaped vacuum chamber with the base diameter of 50 cm. The vacuum chamber volume was $V = 140$ l. The inlet of the vacuum pumping system, equipped with diffusion (2000 l/s) and rotary pumps (40 m^3/h), was connected to the base of the vacuum chamber. The effective pumping speed of the vacuum chamber was about $S_E = 350$ l/s. The final pressure of the vacuum chamber was about 1×10^{-5} mbar. The ionization vacuum gauge was used for pressure measurements. The circular planar magnetron source WMK-50 (designed and developed at the Wroclaw University of Science and Technology, Poland) with a target of $W_{1/2} = 25$ mm in radius was used during the experiments. The magnetic null point of the WMK-50 magnetron source was measured to be placed $Z_{BZ} = 39$ mm away from the target surface, above the centre magnetic pole piece. Using the *Gencoa Ltd.* classification of balanced/unbalanced magnetrons with parameter $g = Z_{BZ}/W_{1/2}$, the magnetron source used during the reported