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Adjustment of plasma properties in magnetron sputtering by pulsed powering in unipolar/bipolar hybrid pulse mode

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ABSTRACT

A new method of pulsed powering the magnetron discharge using a pulsed switching of the anode has been developed. Practically, this hybrid pulse mode is a combination of the conventional unipolar and bipolar pulsed powering, where the time slices of both pulse modes can be freely adjusted at a time scale smaller than 1 ms, i.e. much shorter than necessary for the deposition of one monolayer. This allows varying the average plasma parameters freely between the typical values of unipolar and bipolar pulse mode. During deposition of piezoelectric AlN, the film stress could be shifted in a wide range by changing the pulse mode ratio. In combination with the other known process parameters, it was possible to shift the film stress between compressive and tensile while maintaining piezoelectric properties. Hence, in addition to classical deposition parameters such as pressure or temperature, this new parameter gives an additional degree of freedom for optimization of film properties independent from sputtering power and deposition rate.

1. Introduction

For sputtering of thin films, there is a wide range of possible processes available, e.g. DC-sputtering, MF-pulsed sputtering or RF-sputtering. In pulsed magnetron sputtering it is known, that the pulse mode, either unipolar pulsed or bipolar pulsed, may have a significant influence on plasma density and electron temperature in substrate vicinity [1]. These plasma properties determine the energetic ion bombardment of the substrate. The ion flux density is determined by plasma density and ion energy mainly associated with electron temperature considering ambipolar diffusion [2]. Especially in bipolar pulse mode the energetic ion bombardment may dominate the variety of contributions to thermal substrate load, such as energetic neutrals, photons, heat of condensation, heat of reaction [1,3]. Table 1 gives values of plasma density and electron temperature in unipolar and bipolar pulse mode for SiO_2 sputtering (from [4]). Because of the differences, the bipolar mode may be used to deposit more dense films due to the stronger substrate bombardment, whereas the unipolar pulse mode is more suited to deposit films on temperature sensitive substrates with lower stress.

For many thin film applications, the desired process and film properties lead to contradictory requirements on the level of energetic ion bombardment of the substrate. One example is the deposition of very dense films on plastic substrates, for example as barrier films. The higher film density needs a strong substrate bombardment, while a more moderate substrate bombardment is necessary to prevent thermal heating of the substrate to reach a critical level. Another example is the deposition of piezoelectric thin films, e.g. for SAW, BAW or Energy Harvesting applications. These films require a specific film stress and crystalline quality. The film stress increases towards more compressive stress with higher substrate bombardment. This effect is caused by "atomic peening" or "ionic peening" [5]. The crystal quality of AlN needs a minimum of energy input, either through substrate bombardment or higher energy of deposited atoms [6,7,8]. Thus, the substrate bombardment must be high enough to reach good crystal quality but low enough to prevent high film stress from causing delamination or cracks. In our previous work, we demonstrated the effect of unipolar and bipolar pulse mode, as well as pressure during deposition, on film stress for highly piezoelectric AlN thin films [9]. The aim of this work was to find a new method for fine adjustment of energetic substrate bombardment by plasma ions by an unipolar/bipolar hybrid pulse mode.

2. Material and methods

2.1. Coating equipment and processes

All depositions were done at a cluster tool by reactive pulse magnetron sputtering using the Double Ring Magnetron DRM 400 sputter source developed by Fraunhofer FEP [10]. This type of magnetron combines two concentric discharge targets to deposit uniform films on substrates with a diameter of up to 200 mm. Fig. 1 shows a schematic diagram of the deposition set-up. In the case of AlN depositions, pure Al targets (5 N) were used, whereas the Si depositions were done with pure Si targets (5 N). Argon (5 N) and nitrogen (5 N) were used as inert gas and as reactive gas, respectively.

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Table 1
Results of Langmuir Probe and temperature measurements in substrate vicinity for SiO_2 sputtering at 7.5 kW (from [4]).

Pulse mode	Unipolar	Bipolar
Plasma density [1/cm^3]	$1.8 \cdot 10^{10}$	$11.0 \cdot 10^{10}$
Electron temperature [eV]	10	6
Thermal substrate load [W/cm^2]	0.15	0.75

The Argon gas flow (30…60 sccm) was used to adjust the pressure in the range of 0.3…0.7 Pa. For reactive AlN depositions, a closed loop reactive gas control was applied to stabilize the process in the transition mode [10]. The resulting nitrogen flow rates were between 25 sccm and 40 sccm. There was no additional substrate heating or cooling. The base pressure before depositions was 10^{-6} mbar.

Using the pulse unit UBS-C2 developed by FEP and standard dc power supplies, the pulse mode of the pulse magnetron sputtering process can be adjusted as either unipolar or bipolar. The principle of both pulse modes is shown in Fig. 1. In the unipolar pulse mode, a pulsed dc is applied between each of the two targets and the separate anode component. In the bipolar pulse mode, a voltage with alternating polarity is applied between the two targets of the DRM 400. The targets act alternately as anode and cathode of the discharge. The separate anode component is not connected to the discharge.

The unipolar/bipolar hybrid pulse mode was realized by a hardware solution, the anode pulse unit. It includes an electronic switch, which periodically connects and disconnects the separate anode component to and from the discharge. If the anode component is connected to the discharge, it is operated in unipolar mode, if disconnected in bipolar mode. The time of one connecting/disconnecting cycle is 1 ms. This is schematically depicted in Fig. 1. The resulting voltages and currents over time are schematically shown in Fig. 2, showing the transition from unipolar to bipolar pulse mode for two complete cycles.

As independent parameter, the share of bipolar pulse mode S_b is chosen, i.e. the ratio between the time slice of bipolar mode t_b with respect to the total time of one cycle of unipolar/bipolar hybrid pulse mode, i.e. $S_b = t_b / (t_u + t_b)$. S_b can be adjusted between 0 and 100%. The time slices of unipolar (t_u) or bipolar pulse (t_b) mode are therefore each less than or equal to 1 ms. This is much faster than the time necessary for the deposition of one monolayer (typically >20 ms), but still slower than the 50 to 10 µs between the pulses corresponding to the respective discharge pulse frequency of 20…100 kHz.

2.2. Characterization

Measurements of time averaged plasma properties were carried out using a double Langmuir probe. The plasma density n_e and electron temperature T_e were then calculated according to the method of Sonin [11].

The stress measurements were done using the wafer curvature method based on Stoney's equation [12]. The substrates were polished

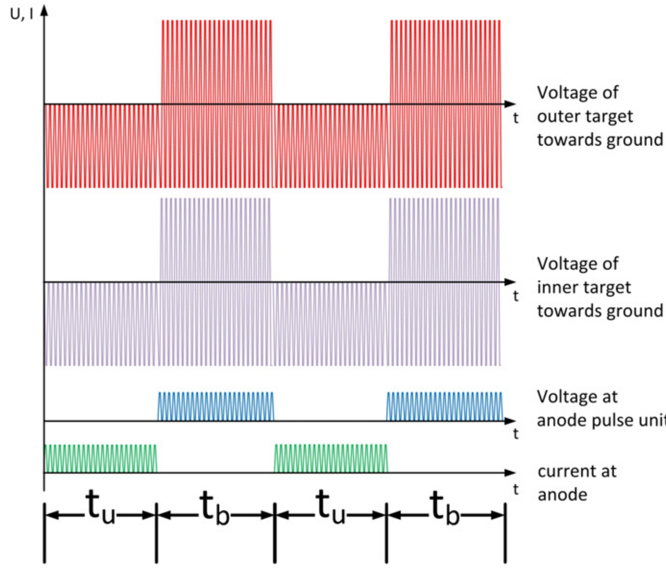

Fig. 2. schematic depiction of voltage of outer target, inner target and anode pulse unit and current at anode pulse unit for hybrid pulse mode during two complete cycles with unipolar (t_u) and bipolar (t_b) time share.

4 in. Si-Wafers (orientation 100, thickness 525 µm). The measurements were done with a surface profiler P15-Ls (KLA Tencor, San Jose, CA).

For the evaluation of piezoelectric properties, a simple ultrasound transducer test layout consisting of a three-layer structure was used. A circular aluminum bottom electrode with 10 mm diameter and a contact pad was deposited on an isolated silicon wafer. An AlN circular layer with a diameter of 13 mm was deposited, followed by the aluminum top electrode with 10 mm diameter to fabricate the transducer. The piezoelectric measurements to determine the piezoelectric charge constant d_{33} were done using a PM300 piezometer (Piezotest Ltd., London, UK).

3. Results

3.1. Plasma characterization

The characterization of the plasma properties in substrate vicinity was done for the sputter process of metallic Si at target powers of 2.0 kW and 0.5 kW for the outer and inner target, i.e. at total target power of 2.5 kW and deposition pressure 0.4 Pa.

The results for the plasma density n_e depending on the share of bipolar pulse mode S_b are shown in Fig. 3. The plasma density increases linearly from 7.7×10^9 cm^{-3} in the pure unipolar pulse mode to 2.5×10^{10} cm^{-3} in the pure bipolar pulse mode.

The electron temperature T_e shows a slight decrease with increasing S_b, as seen in Fig. 4. The electron temperature in the pure bipolar pulse

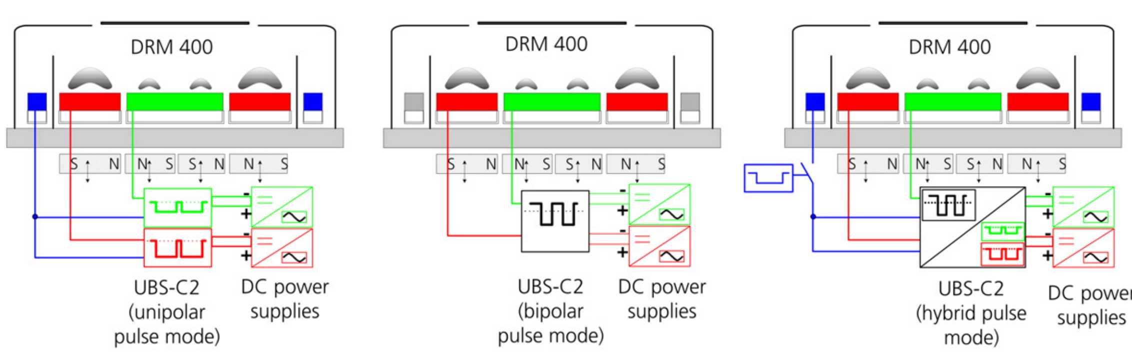

Fig. 1. Deposition setup for sputter deposition by DRM 400 for unipolar, bipolar and unipolar/bipolar hybrid pulse mode.