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Tunable ion flux density and its impact on AlN thin films deposited in a confocal DC magnetron sputtering system

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ABSTRACT

An in-situ coil implemented in a confocal magnetron sputtering system is used to modify the ion flux impacting the substrate, thereby tuning the ion-to-neutral ratio. Plasma characterization performed at the substrate is used to map the spatial dependence of the ion flux density and the total energy flux density across the substrate holder. In addition, spatially-resolved temperature measurements are performed for different plasma conditions. Aluminum nitride (AlN) thin films were deposited by reactive sputtering in the fully poisoned mode on Si (100) and borosilicate glass substrates using the open field configuration. Texture, growth morphology, and residual stress of the films were determined and correlated with the plasma conditions and substrate temperatures obtained by applying the coil's magnetic field. All AlN films were stoichiometric and showed a hexagonal structure with (001) texture. The film stress was found to change from 0.9 GPa (tensile) to 4 GPa (compressive) with increasing ion flux density. Electron microscopy revealed an evolution from an open grain boundary to a dense film morphology compatible with the observed residual stress dependence of the films on the ion flux. No change in residual stress and film morphology was observed within the 100 °C–500 °C temperature range used here.

1. Introduction

In sputter deposition processes the ion impact on the growing film can be utilized advantageously to control the film microstructure and microchemistry [1-3]. For example, increasing the energy flux of the ions hitting the substrate, a compact film microstructure can be obtained already at a lower deposition temperature.

The ion bombardment processes are governed by the flux of incoming ions j_{ion} and their energy E_{ion}. The ion energy determines the mechanism of momentum transfer and the resulting effects [4]. In the case of low energy ion bombardment (E_{ion} < 50 eV) decremental effects of ion irradiation (e.g. creation of defects or vacancies, implantation) are avoided and the adatom mobility is enhanced collisionally. The latter results in an enhanced surface diffusion and rearrangement for atoms on the surface of the growing film. For a given E_{ion} the flux of incoming ions j_{ion} determines the total amount of energy transferred to the growing film.

It is crucial to control these two parameters independently, as their combination, the average energy per deposited atom, is not a universal parameter [5]. The ion flux and ion energy are also influenced by pressure and applied substrate bias. The pressure determines the mean free path of both the ions and neutral particles, and thereby influences the energy and flux of both species. The application of a bias controls the ion impact energy but may lead to implantation of the process gas, which leads to strain fields and lattice distortions [6].

The importance of controlling E_{ion} and j_{ion} directly and independently is widely recognized and a variety of approaches to control the plasma flux in deposition systems have been proposed and are still developed further [7]. Petrov et al. used a variable magnetic field generated by a pair of Helmholtz coils placed around the chamber of their single magnetron deposition system to directly control the flux of the ions impacting the sample [8]. Engström et al. adapted the use of a coil to a dual magnetron system designed for the deposition of thin film multilayers [9]. Here we present how this approach can be used for a multiple magnetron system that allows deposition of compound films from elemental targets. Within this work we also compare the open field to the closed field configuration of confocal magnetron sputtering as it was observed that the magnetic orientation of the magnetrons relative to each other has a strong influence on the plasma flux towards the substrate [10]. Confocal reactive sputtering is widely employed in

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research and production for deposition of compound films from elemental targets. As an example we deposited aluminum nitride (AlN) thin films by reactive sputtering, which is the base material for many interesting compounds such as AlSiN for tribological or AlScN for piezoelectric applications [11,12].

AlN thin films have been studied extensively for applications in microelectronic, electroacoustic and optoelectronic devices [13-16]. In order to obtain good piezoelectric properties, polycrystalline wurtzite AlN films with a pronounced c-axis orientation must be achieved [16,13]. For their application in MEMS devices the preferred film properties need to be obtained at low deposition temperatures, and residual stress must be well controlled [17,18]. To achieve these properties appropriately adjusted ion flux and ion energy are advantageous.

2. Experimental setup

The experiments were performed on an AJA ATC 1500F sputtering system with 33 cm in height and a diameter of 37 cm, containing four magnetrons. Two of them were confocally inclined at an angle of 25° with respect to the z-axis and with the center of the targets separated by 15 cm, as schematically shown in Fig. 1, while the other two remained upright along the chamber walls. The magnetrons are unbalanced of type II [19] with an unbalancing factor of $K = \Phi_{mag}^{out}/\Phi_{mag}^{in} = 13$.

Elemental aluminum targets (99.999% purity) with a diameter of 5 cm were used, and the power supplies (Advanced Energy MDX 500) were operated in direct current constant power mode at 200 W and connected to a common ground. The heatable substrate holder, with a diameter of 89 mm, was oriented face down and its center located at a distance of 12 cm from the center of the targets.

Argon (6.0 purity) was used as a process gas and nitrogen (5.0 purity) was added for the case of reactive sputtering. Purifiers (Alphagaz O_2-free) were installed on both gas lines to further reduce the remaining oxygen concentration and moisture. The chamber is equipped with a turbomolecular pump (210 ls)and the base pressure of the chamber was better than 5×10^{-7} mbar.

A water-cooled coil was built and installed inside the vacuum chamber around the substrate holder. The coil consists of Kapton insulated copper wire with a core diameter of 1.7 mm. A total of 149 turns fit over a length of 58 mm and an inner and outer diameter of 176 mm and 244 mm respectively. The magnetic field of the coil ($\overrightarrow{B}_{coil}$) reaches 180 mT at the substrate holder surface for a coil current (I_{coil}) of 26 A. The magnetic field strength along the z-axis for $I_{coil} = 26$ A is included in the schematic of the setup shown in Fig. 1.

2.1. Plasma diagnostics

Several methods were employed to measure selected plasma parameters in the open field (OF) and closed field (CF) configurations, and for varying $\overrightarrow{B}_{coil}$ (see Fig. 1).

The substrate holder was used as an electrical probe to measure the floating potential (V_{float}) and the ion saturation current (I_{sat}). For the latter, a bias of $V_{bias} = -60$ V was applied to the substrate holder.

A commercial Langmuir probe (LP) acquisition system (ALP, Impedans LTD) was used to acquire current-voltage data (I–V data). A cylindrical tungsten wire, with a diameter $r_{LP} = 50$ μm and a length $l_{LP} = 10$ mm, was used as a probe tip. The probe was installed on a linear positioner to measure the ion current density (j_p), the plasma potential (V_p) and V_{float} as a function of the x-position (see Fig. 1).

An active thermal probe (ATP) was alternatively installed onto the same positioner to measure the total energy flux to the substrate. The ATP consist of a Pt100 resistor embedded in an insulating ceramic 7 mm wide and 10 mm long [20].

The LP and ATP were positioned about 13 mm below the substrate holder. The measurements mentioned above were conducted in a pure Ar atmosphere to avoid the problem arising from the formation of an insulating layer on the probes' surfaces. The Ar flow was set to 15 sccm and the pumping speed was adjusted to obtain a working pressure of approximately 5 μbar.

2.2. Depositions

AlN thin films were deposited onto Si (100) and borosilicate glass substrates, both 6×6 mm^2, using the open field configuration. The samples were mounted close to the center (position x_i in Fig. 1), at a middle radius (x_m) and at the outer rim (x_o) of the substrate holder. Note that the substrate holder was not rotated during the deposition process. Prior to the deposition process, the substrates were ultrasonically cleaned for 10 minutes in a mixture of acetone and ethanol.

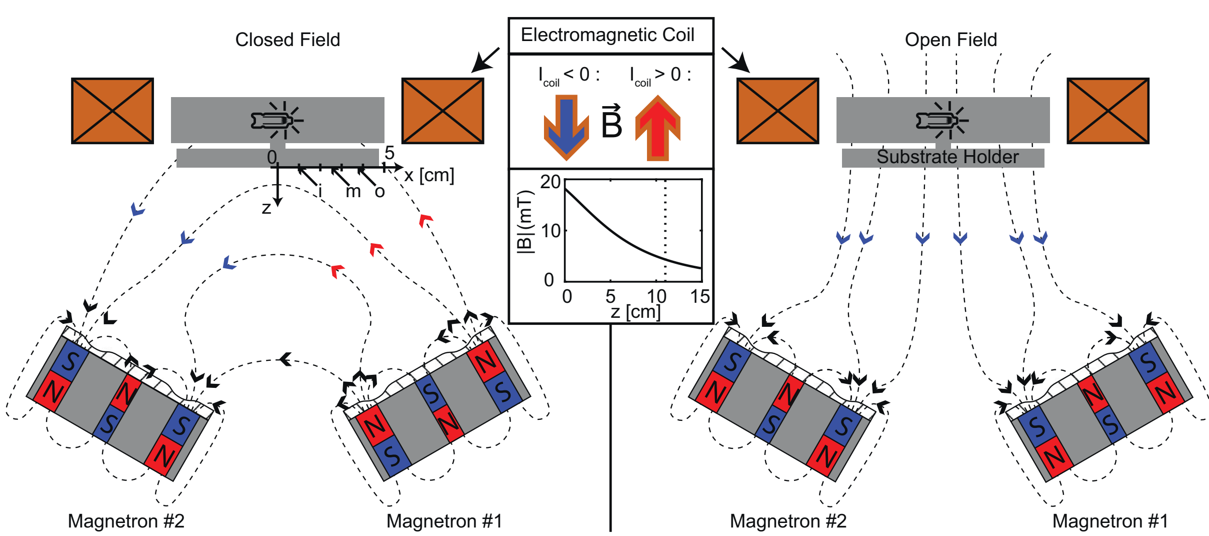

Fig. 1. Schematics of the experimental setup showing the closed field (left side) and open field (right side) configuration with a qualitative representation of the magnetic field lines arising from the magnetrons ($I_{coil} = 0$ A). The substrates were placed at three different positions along the x-axis ($x_i = 1$ cm, $x_m = 2.5$ cm, $x_o = 3.75$ cm). By inverting the current inside the electromagnetic coil the direction of the magnetic field can be reversed. The graph shows the magnetic field strength as a function of the vertical position along the central axis of the coil for $|I_{coil}| = 26$ A. Position $z = 0$ corresponds to the substrate holder surface position and the dotted line indicates the z-position of the target. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)