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Ionized sputtering with a pulsed hollow cathode magnetron

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ABSTRACT

A hollow cathode magnetron has been operated with a HiPIMS power supply at duty cycles around 1%, and the non-reactive sputtering of several target materials such as copper, aluminum and carbon has been investigated. Systematically varying pulse length, frequency, discharge voltage, pressure and geometry of the magnetic field, waveforms of discharge voltage and current have been recorded. Beyond a material-specific voltage level, the pulse current always shows a runaway behavior stopped only at current densities above 10 A/cm^2 due to the limits of the power supply. Furthermore, the plasma has been characterized by time-averaged and time-resolved optical emission spectroscopy as well as by energy-resolved ion mass spectroscopy. The optical spectra showed the contribution of self-sputtering and the portion of metal ions rising with elapsing time during the pulse. Measurement of ion energy distribution functions of different species mostly revealed a low (below 30 eV) and a high (around 100 eV) energy part. Moreover, the portion of singly and doubly charged target ions is increased with the pulsed discharge current. Deposited layers show a dense, fine-grained structure, indicating a high degree of ionization of the layer-forming particles.

1. Introduction

Nowadays ionized sputtering is mostly associated with the concept of high power impulse magnetron sputtering (HiPIMS). It represents an extreme variant of pulsed magnetron sputtering with comparatively low duty cycle (around 1%) and repetition frequency (100–1000 Hz), but very high current density (>1 A/cm^2) during the pulse-on time [1–4]. In the last 15 years, HiPIMS has developed from an exotic idea towards a technology well understood and controlled to a large extent in laboratory scale, and now being on the cusp of industrial application [5–7]. Especially the high degree of ionization of the plasma species allows for efficient pre-cleaning processes and the deposition of layers with outstanding properties [8–13]. However, a limit in peak current density becomes apparent at levels of 2–3 A/cm^2, which is primarily caused by effects like gas rarefaction and electron losses across the magnetic field lines, and which cannot be exceeded for the majority of target materials [14,15].

To overcome this limit, the hollow cathode magnetron (HCM) might represent a promising alternative to the commonly used planar magnetron design. Developed at the end of the 1990s for applications in the semiconductor industry, it combines the cup-shaped target and the annular plasma zone along the inner cylinder wall of an inverted magnetron with a special design of the magnetic field to control the fluxes of charged particles [16–19]. In this way, a collimated sputtering [20] can be realized already by DC powering and without the usage of mechanical devices. It can be used for instance for trench filling in wafer metallizing processes.

In this paper, the operation of a hollow cathode magnetron with a HiPIMS power supply at duty cycles around 1% is presented, and the non-reactive sputtering of several target materials such as copper, aluminum and carbon is described. The aim of the study primarily is to demonstrate that for almost any target material a runaway behavior with discharge current densities of more than 10 A/cm^2 can be reached when the electron losses from the zone of highest plasma density are minimized. Examples of current waveforms, optical emission spectra and ion energy distribution functions are discussed, and the first deposited layers are shown.

2. Experimental setup

All experiments have been performed with a modified LAVOPLAS plasma source commercialized by FEP [21,22]. For this, the central parts for the generation of the hollow cathode arc discharge (tantalum cathode tube, graphite heat radiation shield and aperture cap) have been removed and replaced by a cup-shaped target alternatively made from the materials aluminum, copper and graphite. This results in the fundamental setup shown in Fig. 1. The cup-shaped target (28 mm inner diameter, 88 mm length) of the cathode is arranged within the combined field of a ring of permanent magnets and a solenoid coil. A porous sintered body from stainless steel in the base plate of the target acts as gas inlet.

By adequate selection of strength and polarity of both subfields, magnetic field lines are generated, that run predominantly parallel to the cylinder walls inside the cathode and bend outwards in the orifice

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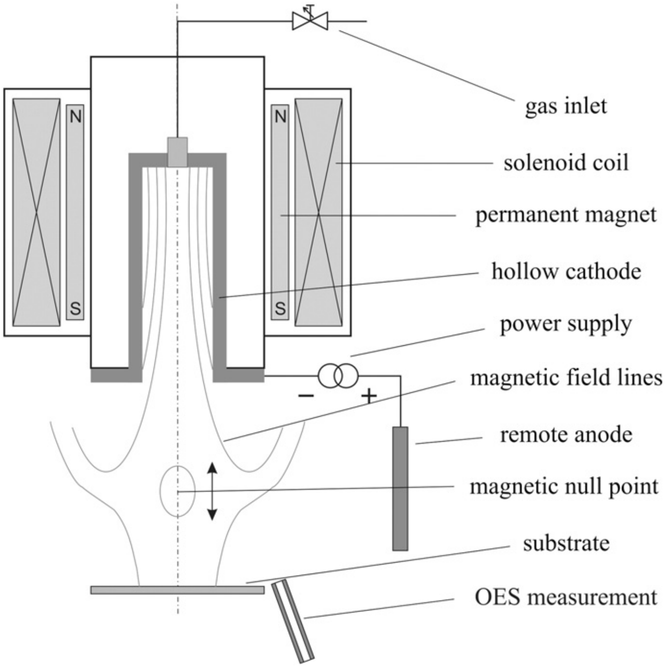

Fig. 1. Schematic view of the hollow cathode magnetron source and the deposition and measurement arrangement.

area. On the cathode axis, 20 mm above the base plate, magnetic field strength values between 20 and 40 mT have been measured. A specific feature of the magnetic field is the null point, forming on the cathode axis in a variable distance to the cathode orifice. By varying the solenoid coil current and consequently changing the location of the null point, the magnetic confinement of the electrons generated inside the cathode during operation can be varied. The shape of the cathode and magnetic field results in a toroidal plasma zone inside the cathode that expands with rising discharge current towards the center and the orifice of the cathode, finally forming a plasma jet, which is directed outwards. The electron losses are minimized on the one hand by the above-mentioned magnetic field geometry and on the other hand by the hollow cathode effect, i.e. the oscillation of electrons between two surfaces of the same (negative) potential.

The source is powered by a pulse power supply MagPuls QP 1000/100/1000 with a maximum pulse current of 1000 A at a maximum voltage of 1000 V. Typical pulse lengths are in the range of 50–200 μs, with repetition frequencies between 100 and 1000 Hz. A small planar magnetron located at a distance of 500 mm acts as anode and support for ignition. For this, a bipolar pulsed regime is used with short phases of inverse polarity previous to each regular discharge pulse. Since the targets made from the different materials are only screwed by hand into a water-cooled support allowing only a limited cooling effect, the time-averaged power input is restricted to 2 kW.

Discharge current and voltage were recorded with a digital storage oscilloscope Tektronix DPO 3034 with differential voltage probe P5210 and AC/DC current probe TCP 404XL with corresponding amplifier TCP A400.

Opposite to the source at a distance of 140 mm from the orifice either substrates (glass sheets or silicon wafers) for deposition experiments or an energy-resolved mass spectrometer (Balzers plasma process monitor PPM 422) with a mass range of 1–512 amu and an energy range of 0–512 eV (with respect to ground potential) were arranged. The extraction opening of the mass spectrometer was located on the cathode axis. Because the mass spectrometer measures energy per charge, the raw data for multiply charged ions have been corrected by multiplying the energies with the charge and by dividing the intensities by the same factor.

Alongside to the mass spectrometer but tilted by 15°, the collimator of a measurement system for optical plasma emission was arranged in such a way that a diagonal view into the cathode cavity was possible. By means of two optical spectrometers (Ocean Optics HR2000 + and IFU AOS 4) either the whole plasma emission spectrum in the wavelength range of 200–1000 nm or the time-resolved behavior of selected emission lines with a time resolution of better than 1 μs could be recorded.

All components were arranged in a cylindrical vacuum chamber of 1000 l volume, evacuated by two turbomolecular pumps down to a base pressure of $1 \cdot 10^{-4}$ Pa. The typical operating pressure of 1–10 Pa resulted from the sum of two gas flows controlled by separate mass flow controllers, one flowing through the HCM source and the second one let in directly into the vacuum chamber at a distant position. Argon was used as working gas at flow rates of 0–100 sccm (through the source) and 0–650 sccm (directly into the vacuum chamber) respectively. The minimum sum flow was 100 sccm.

The morphology of deposited layers has been investigated by a scanning electron microscope SU8000 (Hitachi Ltd. Corp.), and the sheet resistance has been measured by a four point probe measurement system FPP 5000 (Veeco Instruments Inc.).

3. Results and discussion

3.1. Discharge current and optical emission

The observed discharge behavior of the pulsed hollow cathode magnetron is similar to the HiPIMS operation of a planar magnetron [23], but shows some special features. During the ignition phase that takes some tens of microseconds dependent on the argon pressure, the discharge current increases exponentially. At about 100 A, what corresponds to a current density of 1.5 A/cm^2 related to the overall cathode area or 15 A/cm^2 related to the aperture area, differences become visible between the three investigated target materials.

For copper, the current waveform now shows a constant increase with a slope determined by the discharge voltage and the shape of the magnetic field, but not by the argon pressure anymore (see Fig. 2). Without any sign of saturation behavior or arcing the current keeps rising until the preset switch-off level is reached. In relation to the overall cathode area current densities of more than 10 A/cm^2 have been found.

For aluminum, at moderate discharge voltages of 600–700 V and not too strong magnetic fields (below 25 mT) a saturation behavior of the pulse current can be observed, whereas for higher voltages and field strengths a pulse shape with further linear current increase develops here as well (see Fig. 3). Due to the strong emission of secondary electrons on oxidized parts of the aluminum cathode particularly after an

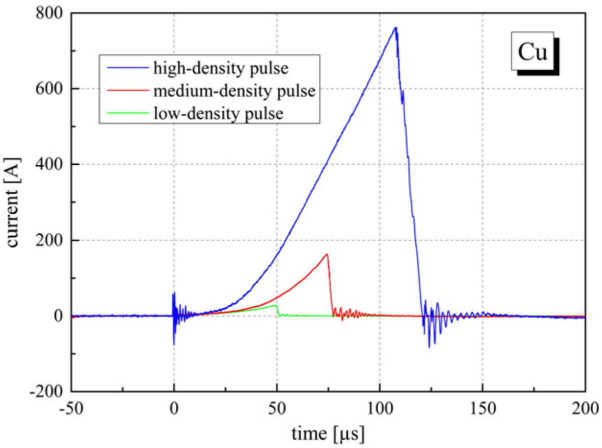

Fig. 2. Current pulse shapes for HCM sputtering of copper at different values of peak current density.