Pulsed-DC selfsputtering of copper

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Abstract. At standard magnetron sputtering conditions (argon pressure $\sim 0.5$ Pa) inert gas particles are often entrapped in the formed films. Inert gas contamination can be eliminated by using the self-sustained magnetron sputtering process because it is done in the absence of the inert gas atmosphere. The self-sustained sputtering (SSS) gives also a unique condition during the transport of sputtered particles to the substrate. It is especially useful for filling high aspect ratio submicron scale structures for microelectronics. So far it has been shown that the selfsputtering process can be sustained in the DC operation mode (DC-SSS) only. The main disadvantage of DC-SSS process is instability related to possible arc formation. Usage of pulsed sputtering, similarly to reactive pulsed magnetron sputtering, could eliminate this problem. In this paper results of pulsed-DC self-sustained magnetron sputtering (pulsed DC-SSS) of copper are presented for the first time. The planar magnetron equipped with a 50 mm in diameter and 6 mm thick copper target was powered by DC-power supply modulated by power switch. The maximum target power was about 11 kW ($\sim 550$W/cm$^2$). The magnetron operation was investigated as a function of pulsing frequency (20-100 kHz) and duty factor (50-90%). The discharge extinction pressure was determined for these conditions. The plasma emission spectra (400-410nm range) and deposition rates were observed for both DC and pulsed DC sustained self-sputtering processes. The presented results illustrate that stable pulsed DC-SSS process can be obtained at pulsing frequency in the range of 60-100 kHz and duty factor of 70-90%.

1. Introduction
A presence of working gas (e.g. inert gas like argon) is required at standard sputtering process since the positive ions of this gas cause sputtering of negatively biased target (sputtered material ions do not take significant part in the target surface sputtering). The working gas atoms may affect the deposition process in several ways, they can: i) be entrapped in the deposited layer (contamination); ii) distort spatial distribution of sputtered material flux through collisions; iii) decrease the sputtered species energy (termalization).

In the DC self-sustained magnetron sputtering (DC-SSS) process [1, 2], the discharge plasma is maintained only by the sputtered target material. The absence of the inert gas makes possible deposition of high purity metallic films at final pressure of vacuum system. The selfsputtering process allows deposition on substrates placed at substrate-target distance shorter than the mean free path leading to directional deposition of metal into deep trenches for microelectronics applications [3, 4]. However, the DC-SSS processes are often affected by instabilities caused by uncontrolled arc discharges typically associated with high-density plasmas. Such discharges can cause not only defects
in deposited layers but also damages to the magnetron source. That could be one of the reasons why the self-sustained sputtering mode has not found wide use in industrial applications.

The pulsed magnetron powering eliminates target surface arcing and enables very stable deposition process of conductive and dielectric layers. In such process the plasma is switched on and off cyclically. An effective contribution of sputtered material ions (self-sputtering phenomenon) to the sputtering process was reported for pulse frequency of ~n x 10^{-1} - ~n x 10^{3} Hz (HIPIMS method) [12] and ~n x 10^{4} - ~n x 10^{5} Hz [5, 6]. However, no reports on pulsed self-sustained mode [7] were published to the author’s knowledge.

2. Experimental

2.1. Pulsed-DC unit

The pulsed DC power unit consisted of a quasi-DC power supply and a MOSFET switch. The quasi-DC power supply was a combination of the medium frequency (MF) power supply [8, 9] with capacitor C1 in the output circuit (Fig.1). With this additional capacitance the output voltage waveform of the power supply contains significant AC (110 kHz) component and that is why it was called quasi-DC. The original MF power supply and the resulted quasi-DC one were capable of driving magnetron plasma with maximum power of 11 kW.

2.2. Sputtering apparatus

The sputtering processes were performed in a vacuum system characterized by the final pressure of about 3x10^{-3} Pa. The planar magnetron source equipped with a 50 mm in diameter and 6 mm thick copper target was used during the experiments.

The OES system input light signal was collected from the discharge area through the view port window (transparent in 200-1200 nm range) by an optical plastic fiber. The discharge light was directed to the view port by a stainless steel tube – diameter of 7 mm and length of 500 mm. The end of the tube was placed at the level of the target surface.

3. Results and discussion

3.1. Optical emission spectra

The sputtered material ionization level can be qualitatively estimated using emission spectra of the discharge. In case of the copper the emission lines of atoms Cu*(402, 406 nm) and ions Cu^+ (404 nm) are present within the 400-410 nm spectral range [10, 11]. An important parameter that allows estimation of sputtered material ionization level is the ratio (\(I_{rel}=I_{Cu^+404nm}/I_{Cu*402nm}\)) of Cu^+ ions line intensity to intensity of Cu* atoms.

The threshold target power of the DC-SSS operating mode was about 5.5 kW (~280W/cm^2) and that corresponded to an \(I_{rel}=0.95\). Using the MF power supply (11kW) the \(I_{rel}\) was equal to 1.02, but the self-sustained sputtering mode was not achieved. The quasi-DC magnetron plasma discharge operating at 11 kW had the \(I_{rel}=1.2\). In this case the self-sustained sputtering mode of magnetron...
operation had been achieved. It has been postulated that the self-sustained sputtering mode was not achieved using the MF power supply because of pulses shape. In this powering mode variations of the charge density are too large to sustain the plasma even if the average $I_{\text{rel}}$ value has been higher than that required for DC-SSS.

3.2. Pulsed DC magnetron selfsputtering

![Figure 2. Discharge extinction pressure as a function of duty factor](image)

During the standard pulsed DC sputtering processes (with working gas) a periodic plasma ignition during $t_{\text{ON}}$ time and extinction of the discharge (plasma decay) during the $t_{\text{OFF}}$ time occurs. Since the discharge plasma density (density of electrons, working gas ions and target material ions) after target voltage off decreases during the $t_{\text{OFF}}$ time it was stated that the discharge extinction pressure should be a function of the $t_{\text{OFF}}$ time (at constant pulsing frequency). In Fig.2 the minimum argon pressure, $p_{\text{Ar min}}$, required to sustain the discharge (extinction pressure) is shown as a function of the duty factor and pulsing frequency of the target voltage. The measurements were taken at the target power of 11 kW. One can see that the value of $p_{\text{Ar min}}$ decreases with increase of the duty factor in the entire investigated duty factor range (50-90%). At pulsing frequency higher than 40 kHz and the duty factor higher than 70% the $p_{\text{Ar min}}$ value approaches the final pressure of the vacuum chamber (about $3 \times 10^{-3}$ Pa). At frequency higher than 50 kHz and duty factor higher than 80% the $p_{\text{Ar min}}$ was as low as the final pressure of the vacuum chamber – the magnetron was working in the Pulsed DC-SSS mode.

3.3. Deposition rates

![Figure 3. Deposition rate of pulsed DC selfsputtering processes in comparison to DC and MF ones](image)

The values of the deposition rates (135 mm target to substrate distance) measured during the pulsed DC-SSS magnetron processes (11 kW) are shown in Fig.3. The measurements of the deposition rate were performed at the duty factor of 80% and frequency of 60, 80 and 100 kHz. The deposition rate was slightly dependent on the pulse frequency and in all investigated cases it was close to 0.73 µm/min. For comparison, the deposition rate of 0.87 µm/min was achieved for MF sputtering (11 kW) and 1 µm/min for DC sputtering at 7.5 kW power. Those values are indicated in Fig.3 as well.
4. Summary
In this paper it has been demonstrated that the self-sustained sputtering mode of magnetron operation can be maintained using Pulsed DC powering. The results obtained during the experiments have shown that the Pulsed DC magnetron self-sputtering of copper could be obtained within pulsing frequency range of 60-100 kHz and duty factor higher than 80%.

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