Evolution of Tungsten Film Deposition Induced by Focused Ion Beam

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Direct write metallization is an important approach for circuit modification and prototyping. We investigate the evolution of the chemical vapor deposition of tungsten induced by a 50 keV focused Ga^+ ion beam. Time resolved imaging in combination with atomic force microscopy reveals that chemical vapor deposition of tungsten by focused ion beam proceeds via two clearly distinguishable regimes of layer growth. Deposition starts with the nucleation of nanoscale tungsten deposits scattered over the substrate surface. Despite the local impact of the ion beam no correlation of the nucleation sites with the scan path of the beam can be found. The nanoscale tungsten particles preserve their positions and typical shapes during further deposition. Only after merging the particles to a contiguous tungsten layer, the second regime of growth characterized by deposition of tungsten on a tungsten surface sets on. In this regime the deposition process is determined by the total ion dose and the average current density the sample was subjected to. Deposition yields up to 3.5 atoms per incident gallium ion are achieved. The layer quality is determined by Auger analysis, showing the fractions of Ga and C in the W layer.

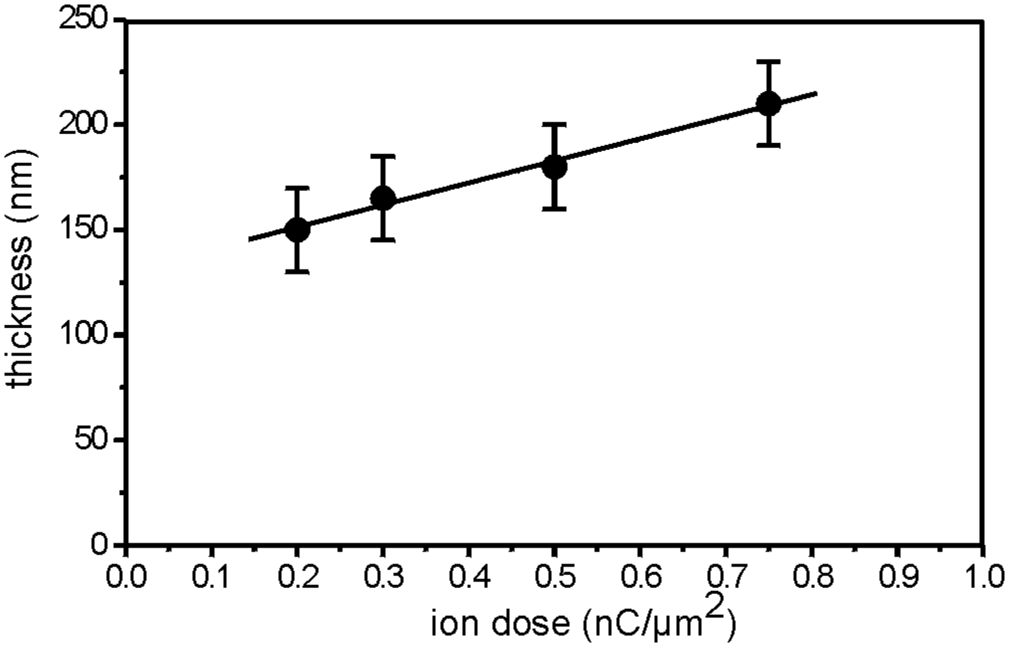

Fig. 1: Tungsten layer thickness versus total ion dose. The solid line represents a linear fit to the data.

Depth profiling by secondary ion mass spectra showed the depth profiles of these constituents and confirmed the existence of a 50 – 100 nm thick transition zone between the tungsten layer and the substrate. Electrical sheet resistances of the metal layer of

200 μΩcm and current densities up to 3.5×10^6 A/cm^2 are measured by means of van der Pauw test structures. In order to give a concise description of the experimental findings the data were interpreted utilizing an analytic model mainly incorporating precursor gas coverage, precursor gas transformation cross section, and ion induced sputtering. The critical ion current density where ion sputtering exceeds deposition was identified by the model. Because the model shows excellent agreement with the measurement it should be suitable for further survey concerning focused ion beam process development.

Ion beam induced deposition occurs if the adsorbed hexacarbonyl molecules are decomposed during ion beam exposure. After a contiguous tungsten layer formation, the deposition process is characterized by homological growth of tungsten on tungsten and the thickness of deposited metal correlates with the total ion dose like shown in Fig. 1. The analytic model used to describe the deposition kinetics is based on differential rate equations describing the precursor gas kinetics and its coverage of the sample surface. This equations rely on the following parameters: molecular precursor gas flux Φ (cm^{-2} s^{-1}), density of surface sites for precursor gas adsorption n_0 (cm^{-2}), precursor transformation cross section σ (cm^2), the atomic sputter yield Y_S, and average ion current density J (cm^{-2} s^{-1}). In this case the average ion current density J is defined as the number of impinging ions per cm^2 per second and related to j simply by $J = j/e$, with e being the unit charge. For the steady state condition the resulting expression for the atomic deposition yield is

$$Y_A = \frac{\sigma n_0 (\Phi/J - Y_S)}{\sigma n_0 + \Phi/J}. \qquad (1)$$

In Fig. 2 the atomic deposition yield Y_A determined by experiments is plotted versus the average ion current density. The negative yield values correspond to conditions where the sputter effect of the ions exceeds the ion induced deposition.

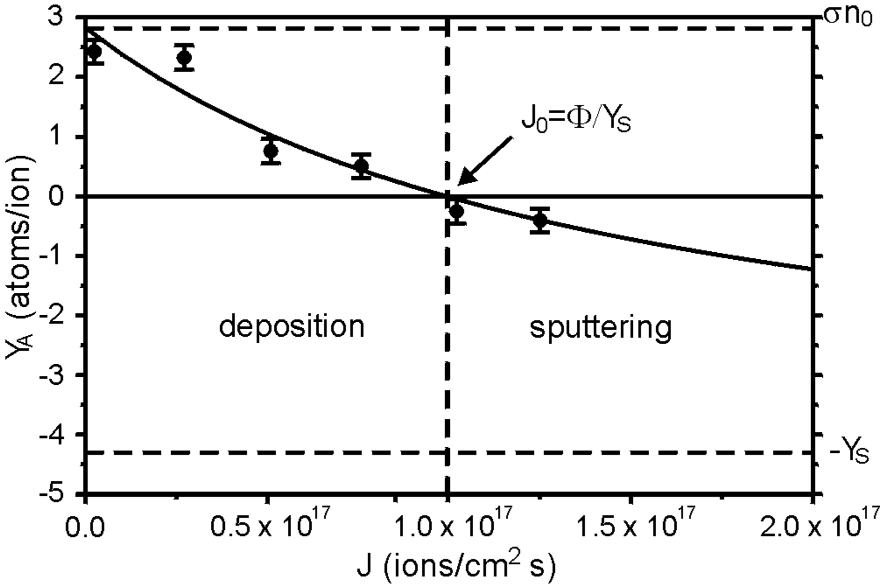

Fig. 2: Atomic deposition yield of tungsten hexacarbonyl under ion exposure as a function of the average ion current density. The solid line represents a fit due to the analytic model.

The solid line represents a fit of eq. (1) to the data. This expression contains three independent parameters: Φ, σn_0, and Y_S. The first two where extracted from a least square fit to the data. Y_S was determined by an independent sputter experiment without any gas contribution. $-Y_S$ is the limit of Y_A for very high ion current densities. The value obtained for the molecular precursor gas flux Φ is in the order of magnitude of values found by Melngailis and coworkers from their FIB experiments. The extracted value for the dimensionless parameter σn_0 is the limit of eq. (1) when J reaches zero and can be interpreted as the asymptotic deposition yield at very low ion current densities. When J is increasing the yield is decreasing because of the depletion of precursor gas molecules due to an accelerated precursor conversion.

In addition, the model allows to calculate the critical value for the current density J_0, from where on sputtering exceeds deposition resulting in a negative atomic yield. Exactly at J_0 deposition and sputtering are in dynamic equilibrium.