Focused Ion Beam Induced Local Tungsten Deposition

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Direct writing of metal lines is a widely used approach to interconnect prototype circuits and to rewire defective circuits at the very backend of the process line. However, the application of these direct written metal structures to contact devices is actually an open topic. In the presented metallization process a metal organic compound is decomposed by a focused ion beam (FIB) to form metal layers on several substrates. A variety of test structures allows the application of analytical methods and to quantify electrical properties. In addition, the detection of secondary electrons gives rise to time resolved *in situ* surface imaging of deposited metal layers. A direct characterization of the layers is obtained by atomic force microscopy (AFM).

1. Introduction

A widely used approach to interconnect prototype circuits and to rewire defective circuits is direct writing of metal lines at the very backend of the process line by means of FIB induced deposition. Primary beam related contaminations, intermixing effects, and unintentional local charging are the most important issues to be overcome if an application of FIB is viable close to the frontend. In this work we investigate the ion beam induced metallization process focusing on nucleation, intermixing, and growth, involving in situ characterization, AFM topography, SIMS, and electrical measurements.

2. Experimental

2.1 Layer Formation and Characterization

Based on a volatile metal organic tungsten compound ($W(CO)_6$) W-layers were deposited on thermal oxide layers by a Ga^+ ion beam [1]. Time resolved *in situ* surface imaging of the growth process addressing the primary steps in layer formation including nucleation and nuclei coalescence are involved. Characterization of the surface topography of the layers is done by atomic force microscopy (AFM). The chemical composition of the layers and the intermixing effects are both evaluated by secondary ion mass spectroscopy (SIMS) measurements.

2.2 Electrical Characterization

Electrical measurements are issuing the onset of the electrical conductivity, the specific resistance, and the maximum current densities the deposited material is capable to carry. To quantify the ohmic resistivity and maximum current densities in the metal, specific test structures were developed. Figure 1 shows a typical van der Pauw test structure for measuring sheet resistances. In the left viewgraph, the structure is already crossectioned by FIB to determine the associated layer thickness.

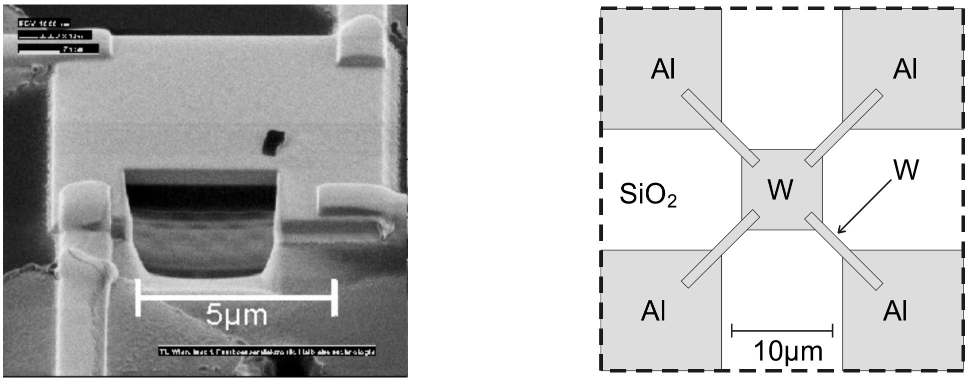
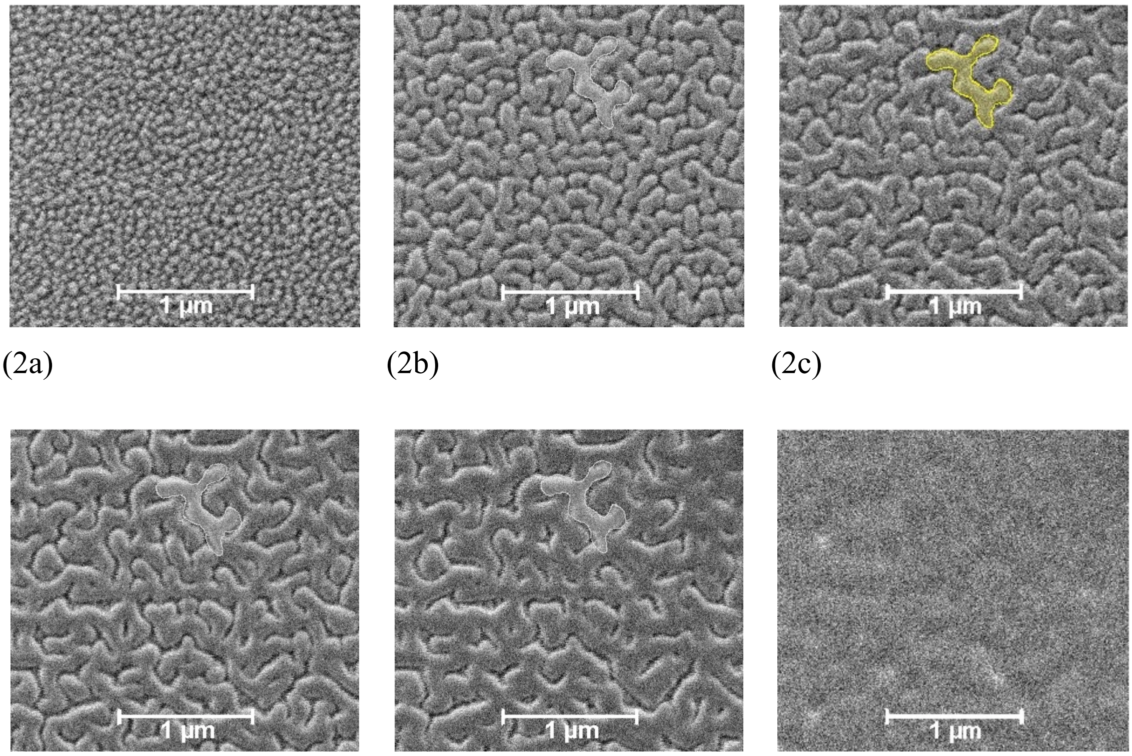


Fig. 1: Van der Pauw structure with FIB cross-sectional view and schematic illustration.



(2a) (2b) (2c)

(2d) (2e) (2f)

Fig. 2: Evolution of an ion beam induced CVD tungsten process on thermal silicon dioxide.

3. Results and Discussion

3.1 FIB Induced Growth Process

In order to determine the evolution of the tungsten deposition process, *in situ* observations of the developing nanoscale structures are done by detecting the secondary charges (electrons or ions) emitted from the surface during focused ion beam irradiation. After each ion induced deposition step, an image scan over the same sample region is done. By the way, time resolved *in situ* surface images of the evolving metal layers are obtained. Figures 2a to 2f are a sequence of images showing how the process of tungsten layer formation proceeds.

At the beginning of the deposition process (Fig. 2a) the time resolved investigation shows nucleation at spots that are stochastically but homogeneously distributed over the area exposed to the ion beam. Then the nuclei grow during the deposition and start to collapse to form larger connected structures. Its remarkable that the formations grown in the early deposition steps are preserved in their shape during the consecutively following steps. They are not destroyed by the ion beam. This can be verified observing the weakly enlightened region in the upper part of Figs. 2b – 2e. After the exposure to an accumulated ion dose of about $1.7\ 10^{16}$ ions/cm^2 the merging process of formerly separated “islands” results in a closed metal surface (Fig. 2f).

3.2 Topography

Direct characterizations of the surface topography of the layers are obtained by atomic force microscopy (AFM). Figure 3 shows a three dimensional plot of the AFM data corresponding to a tungsten layer deposited with the same ion dose as the one in Fig. 2c. As seen in this figure, the topographic view is in close correspondence with the FIB imaging.

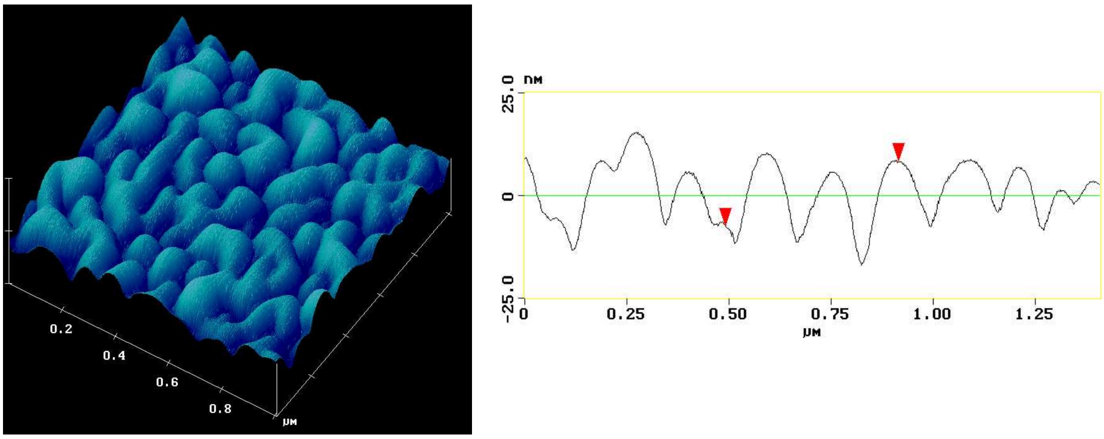


Fig. 3: Three dimensional plot of AFM surface scan (left). AFM analysis of the as grown tungsten surface (right).

The AFM section analysis of a tungsten surface in Fig. 3 exhibits a surface roughness value of up to 40 nm peak to peak.

3.2.1 Chemical

A SIMS based chemical analysis confirms a tungsten layer on the top of the substrate. In addition, however, to the direct observation, SIMS evidences, that no sharp interface to the substrate is formed. The exposure to the Ga beam leads to an intermixing region. Approaching the interface a clear pile up in the WSi concentration is seen, demonstrating the presence of a 50 nm interface layer between the tungsten layer and the substrate (Fig. 4).

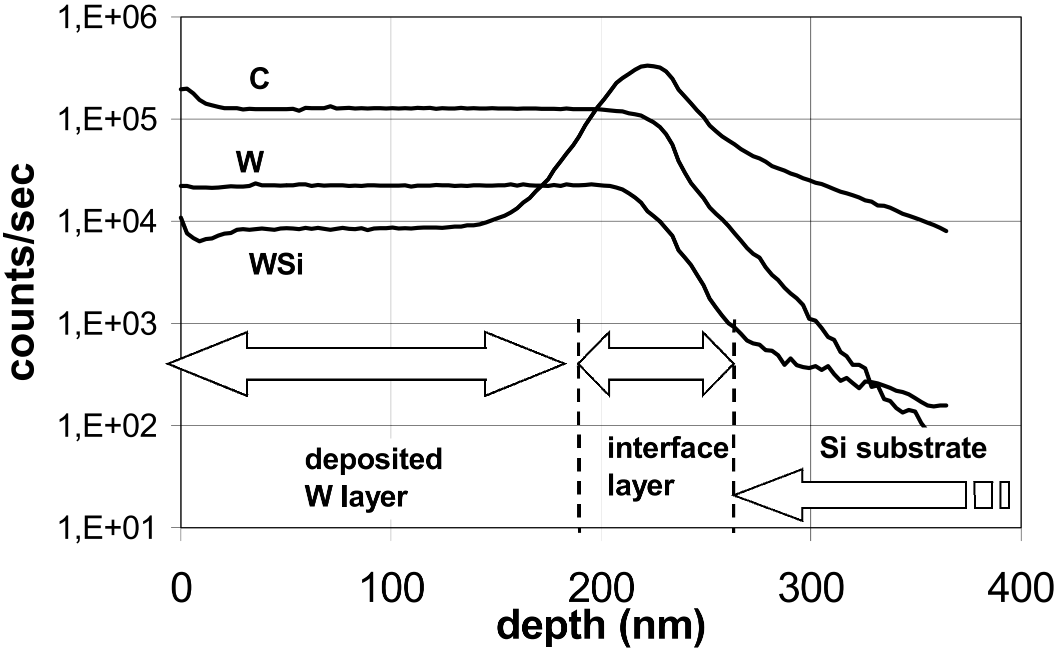


Fig. 4: SIMS profiles of C, W and WSi.

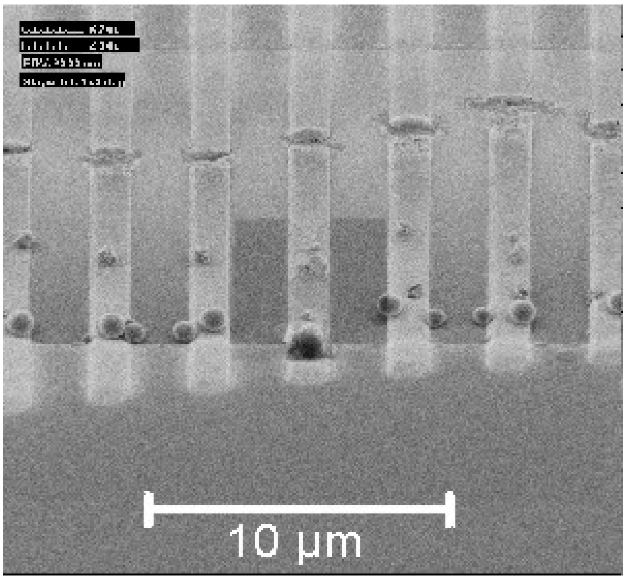


Fig. 5: Current stressed tungsten lines.

3.2.2 Electrical

The sheet resistance of a 280 nm layer is typically 3 Ω/square. The resistivity of the metal was calculated to be in a typical range of 200 – 300 μΩcm. The maximum current densities, indicating the robustness of the material were estimated using arrays of identical parallel W-lines (1 μm wide, 280 nm thick) connecting two contact pads. Maximum current densities up to 3.5 10^6 A/cm^2 were obtained. The array of current stressed tungsten lines is depicted in Fig. 5. A remarkable feature are the spherical hillocks visible at the lower ends of the lines because they give a strong indication for the fact that electromigration took place before the lines broke down due to the local ohmic heating.

4. Summary and Conclusion

Direct writing of metal lines is a suitable approach to interconnect prototype circuits and to rewire defective circuits at the very backend of line. The application of these direct written metal structures to contact devices is actually an open topic. In the presented metallization process a metal organic compound is decomposed by a focused ion beam (FIB) to form metal layers on several substrates. A variety of test structures allows the application of analytical methods and to quantify electrical properties. In addition, the detection of secondary electrons gives rise to time resolved *in situ* surface imaging of deposited metal layers. A direct characterization of the layers is obtained by atomic force microscopy (AFM).

References

[1] T. Kodas, M. Hampden-Smith, *The Chemistry of Metal, CVD*, VCH, Weinheim (1994).