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Electrical Characterization of Tungsten Nanowires Deposited by Focused Ion Beam (FIB) *

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Abstract. The deposition of nanowires for interconnects in nanoelectronic devices were studied morphologically by scanning electron microscopy (SEM), atomic force microscopy (AFM) and by in-situ resistance measurements. The deposition and basic characterization of nanometer size tungsten wires by gas injection (GIS) and focused ion beams (FIB) was carried out in-situ in a LEO 1540 XB workstation. The $I(V)$ measurement showed that the deposited W wires have ohmic characteristic. The variation of the resistance during an ex-situ heating was linear with a low thermal coefficient (4% of the pure metallic W).

Keywords: FIB, W deposition, electrical characterisation

Introduction

Recently, the semiconductor technology has reached the nanometer size range. Focused Ion Beam (FIB) systems previously used to repair, and modify lithographic masks, failed microcircuitry and for rapid prototyping, became a promising tool for nanoelectronic device fabrication, too. To measure the electrical characteristics of a nanodevice, it should be contacted. Fabrication of nanowires by deposition of W or Pt with FIB [1,2] is very useful in the fast and reliable contacting of individual nanodevices, located

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and observed in the high resolution Scanning Electron Microscope (SEM) operation mode of a cross-beam FIB/SEM. When using the Gas Injection System (GIS) for depositing nanowires, the milling and deposition process are in competition [3], and the FIB beam current, scan speed and gas flow should be optimized for enhancing the deposition process.

Our aim in the present work is to investigate the influence of deposition parameters on deposition speed, morphology, electrical behaviour (resitivity) of deposited wires, and the dependence of the wire parameters on annealing. A special sample for predetermined cleavage and a micro-hotplate [4] both developed in MTA MFA were used, to achieve cross sectional examination in the SEM and annealing of the deposited wires.

Experimental

The deposition and characterization of nanometer size wires was carried out in a LEO 1540 XB workstation, a cross beam system consisting of a high resolution Zeiss Gemini SEM column, an Orsay Physics Canion FIB column using 30 keV Ga focused ion beam for milling, and a gas injection system (GIS) to perform ion beam assisted deposition.

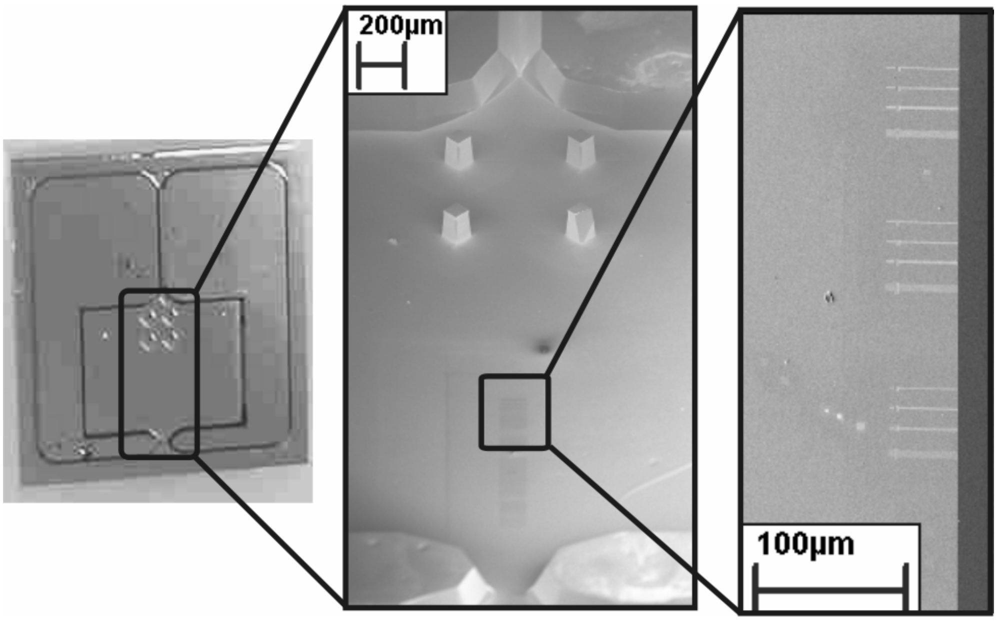

Fig. 1. Overview (left), general view with the deposition area and (middle) cleaved cross section (right) of the special cleavage sample used for the study of stripe cross-sections in the SEM

To determine the geometry of the deposited stripes, a special crystalline Si chip was developed with one well defined cleaving direction (*Fig. 1*). W stripes from tungsten hexacarbonyl precursor gas with different parameters were deposited perpendicular to the predefined cleavage line. Keeping the deposition time, the ion beam intensity and the parameters of the GIS system constant (reservoir temperature 70ºC and chamber vacuum values 1.2 mPa) wires with widths of 100 nm, 300 nm, 500 nm, 1000 nm, 2000 nm, 5000 nm were deposited. After the deposition, mechanical stress was applied to cleave the sample along the predefined cleavage direction, to make possible the investigation of the cross section of the wires. The stripe surfaces and cross section morphology were studied by SEM. For quantitative determination of the deposition height, AFM measurements were performed using a VEECO NanoScope IIIa instrument operated in tapping mode using Si tips.

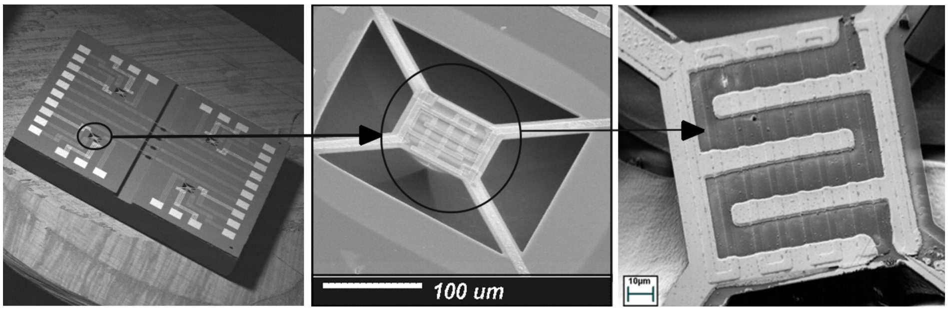

Fig. 2. The special micro-hotplate used for electrical characterisation of deposited W wires

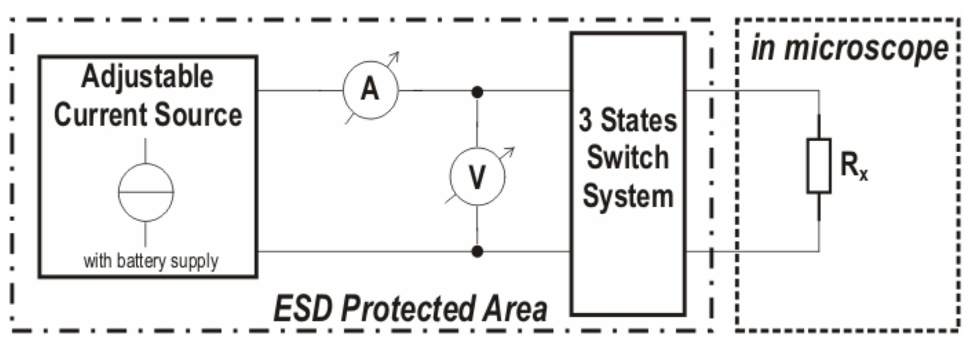

Fig. 3. Schematic presentation of the measuring circuit used for the in-situ, ground free resistance measurements

The electrical characterization of the deposited wires was carried out on a special micro-hotplate [4], (*Fig. 2*) prepared by photolithographic method with characteristic dimension of 100 × 100 μm, consisting of a substrate, conductive Pt wire for thermal heating, insulator layer, and Au electrodes. W nanowires with width of 300 nm were deposited between the fingers of interdigitated Au electrodes, with the characteristic distance of 10 μm. As we found to be problematic the measurement of the current flow in the wires using a usual ohm-meter, a special, ground free device was built (*Fig. 3*) to avoid the melting of deposited wires due to static charge introduced in the system when connecting.

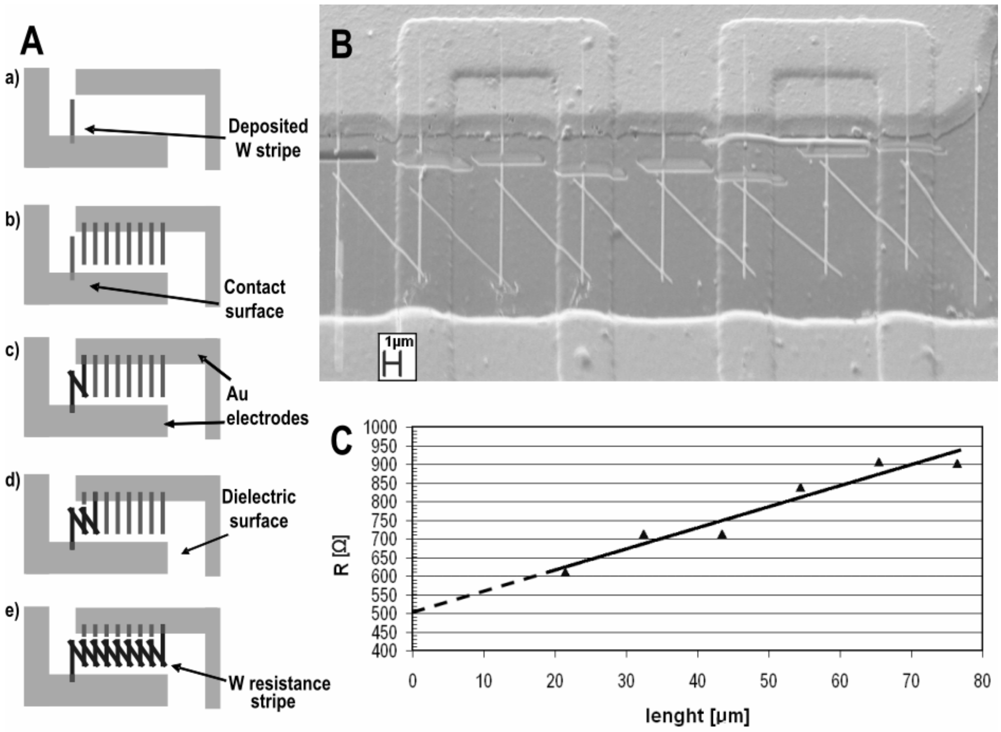

Fig. 4. Schematic presentation of the sample preparation steps for contact resistance measurement (A), illustrated on a SEM image (B), the resistance as a function of deposited wire length (C)

In order to determine the dependence of the resistance on the wire length, a multiple step deposition–cutting process was applied. In the first step a wire was deposited having contact to electrode E_1 (*Fig. 4*). This was followed by the deposition of several parallel wires under the same angle with respect to the wire connected to the electrode. The first wire crossing the wire deposited initially (and connected to the electrode E_1) was contacted to the electrode E_2 by a new wire. The resistance was measured between electrodes E_1 and E_2. In the fourth step, the wire connection to electrode E_2 was cut, and a new wire deposited connecting the first and second angularly deposited wires to electrode E_2 (*Fig. 4A*). The resistance was again measured between the electrodes. Repeating the cycle, it was possible to determine the resistance of a wire with successively increasing length. *Figure 4B* shows the SEM image of the above described sample in the final stage. The resistance of gold electrodes was estimated by measuring a defective short circuited sample, we got $R_e = 1.2\ \Omega$.

The temperature dependence of the resistance of the 300 nm wide wire was measured in situ between 200 to 320°C using the platinum heating wire of the micro hot plate on which the nanowire was deposited.

Results and discussion

In order to select a defect free area for the experiments, the site of the deposition was checked on the ion beam induced secondary electron image (FIB-SEI). During the deposition, the secondary electron image of the SEM was used to monitor the process (SEM-SEI) in cross beam, i.e. tilted position. After deposition, SEM-SEI images were also used to observe the morphology of the deposited stripes in top and cross-sectional view. SEM and AFM imaging were used to study the cross sectional shape of the stripes (*Fig. 5*). The shape of cross section is far from the ideal rectangle. The speed of deposition, i.e. the volume deposited during unit time was found to be constant, 0.002–0.004 $\mu m^3/s$, regardless the duration and the size of deposited wires.

The total electrical resistance (R_t) showed ohmic characteristic (*Fig. 6*). *Figure 4C* shows the dependence of the resistance on wire length. Assuming that the total resistance can be expressed in the form of Eq. (1), the length dependent and independent parts can be separated.

$$R_t = R_w + 2 \cdot R_e + 2 \cdot R_c. \quad (1)$$

Here, R_e denotes the partial resistances of gold electrodes, R_c the resistance of the contact between an electrode and a deposited nanowire and R_w the resistance of the nanowire. Only R_w depends on the wire length, the dependence is linear as it clearly seen in *Fig. 4C*. The contact resistance value (R_c) can be determined from the intersection of this line with the *Y* axis. The electrode resistance, $R_e = 1.2\ \Omega$ can practically be neglected since the extrapolated resistance at zero wire length is $R_w(0) = 500\ \Omega$. From this, the contact resistance, $R_c = 250\ \Omega$ can easily be calculated. Here we supposed that the wire deposited in segments has the same resistance as a straight wire with the same length. The r_c contact resistivity can be calculated from Eq. (2), using the surface (S = 1.76 µm^2) determined by SEM study of the cleaved sample, see above. We got r_c = 9.96 µΩcm^2.

$$r_c = R_c \cdot S. \tag{2}$$

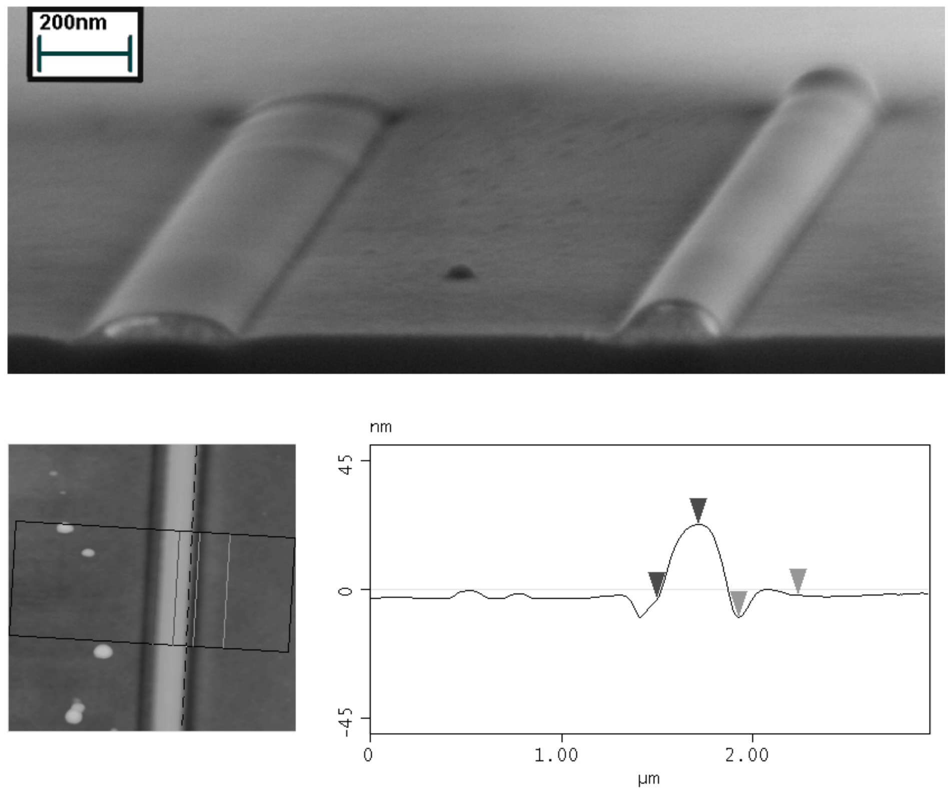

Fig. 5. SEM (*a*) and AFM image (*b*) of cross-section of deposited wires. Note the trenches on the left and right side of the deposited wires originating from the competitive processes of etching/deposition

From the measured geometrical dimensions and resistance values, the resistivity of the deposited tungsten wire material can easily be calculated ρ_w = 218.3 µΩcm from Eq. (3) (ρ = 5.51 µΩcm of bulk W):

$$\rho_w = \frac{R_w \cdot A}{l}, \tag{2}$$

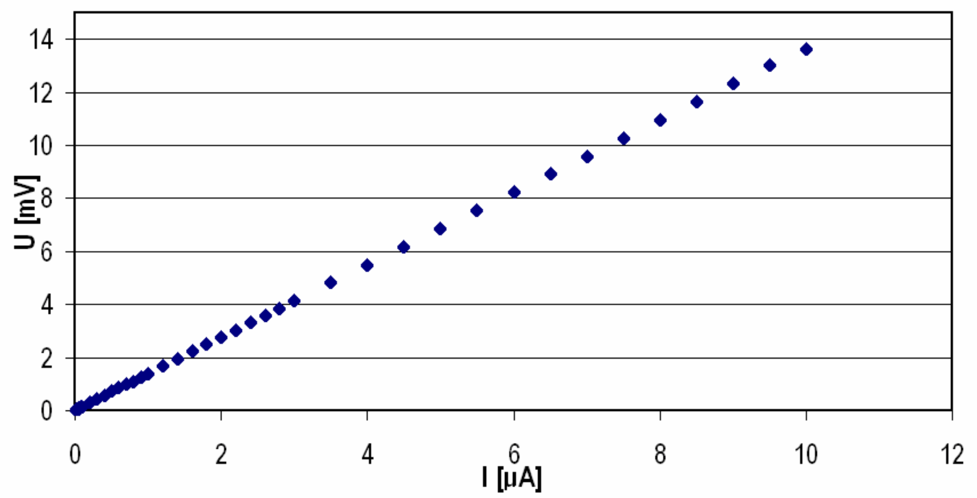

Fig. 6. The I (V) curve of a single W wire with 300 nm width

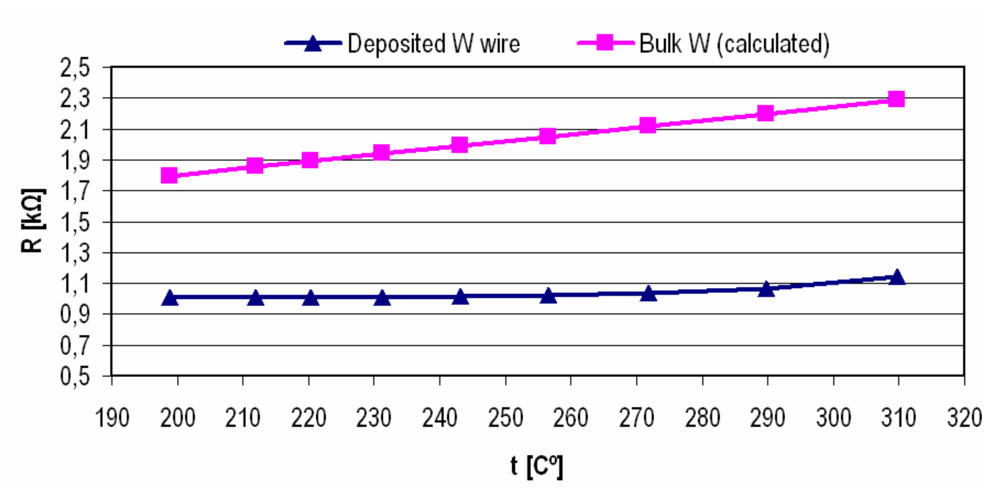

Fig. 7. Measured resistance during heat-up of the deposited wire (triangles) and the evolution expected for bulk W (squares), assuming the same room temperature resistance value for both the bulk W and the deposited wire

where R_w is the resistance of deposited wire, A is the cross-section area of the wire and l is the length of the wire. The temperature dependence of the resistance during heat-up from about 200 to 320°C showed a linear increase (*Fig. 7*) with $T^{\circ} = 0.16 \cdot 10^{-3}$ 1/°C coefficient, which is much less than that of pure W ($4.4 \cdot 10^{-3}$ 1/°C). A possible reason of the difference is the nanostructure of the deposited material, which is subject of further investigations.

Conclusion

The morphology and cross-sectional geometry of deposited W stripes on a specially designed cleavage sample and the electrical behaviour of the deposited wires on a micro-hotplate were studied. The deposited stripes have a non-ideal rectangular shape. The deposition speed was found to be constant. The measurement of resistance during heat-up showed a linear increase.

The deposited W wires have an ohmic characteristic. The partial resistances of gold fingers (R_e), the contact (R_c) and the deposited nanowire (R_w) can be separated and yielded a resistance of gold finger ($R_e \sim 1.2\ \Omega$), contact resistance ($r_c = 9.96\ \mu\Omega\text{cm}^2$) and resistivity ($\rho_w = 218.3\ \mu\Omega\text{cm}$).

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