Focused Ion Beam Prepared Contacts of Tungsten to Silicon Characterized by a Cross-Bridge Kelvin Resistor Approach

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Focused ion beam chemical vapor deposition of tungsten is widely used for circuit repair and prototyping. An extension of this direct write approach from the interconnect metallization level to the device level in CMOS technology requires the demonstration of ohmic low resistance contacts to both types of highly doped source and drain regions. We investigated the metal-silicon contacts of 50 keV Ga^+ FIB deposited tungsten by a cross-bridge Kelvin resistor approach to extract the contact resistances and we found nonrectifying contacts to both p^+- and n^+-silicon. For p^+-silicon a resistivity of 5.33×10^{-6} Ωcm^2, whereas for n^+-silicon a higher value of 9.96×10^{-3} Ωcm^2 is found. Thermal treatment at 450°C for 15 minutes deteriorates the contact properties of p^+-silicon. In contrast, the annealing process reduced the resistivity of the tungsten to n^+-silicon contacts by factor of 100 to a value of 1.07×10^{-4} Ωcm^2.

The experimental setup to characterize the contacts relies on Kelvin type four point cross-bridge structures providing terminals that allow a separate measurement of the forced electrical current through the contact region and the resulting voltage drop at the contact. As shown in Fig. 1, the metal tracks are connected to the doped silicon region via the contact zone consisting of a metal filled contact hole embedded in the dielectric layer separating the two conducting layers.

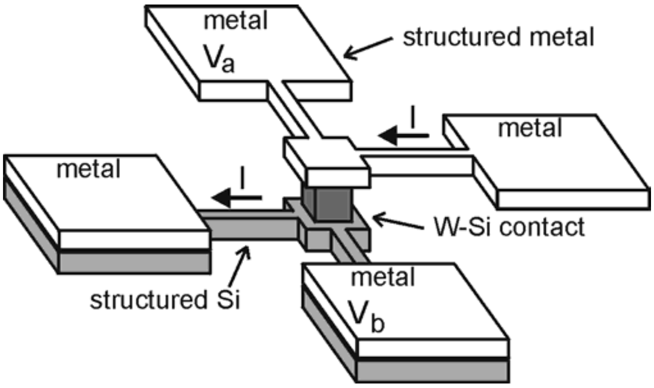

Fig. 1: Cross-bridge Kelvin resistor

The filling of the contact hole is made by FIB-CVD of tungsten. The striking advantage of the four-point measurement is that the detection of the voltage drop $\Delta V = V_a - V_b$ can be measured directly at the contact region. The contact resistance R_C of an ohmic metal-semiconductor contact investigated by means of the described Kelvin structure is then

$$R_C = \frac{V_a - V_b}{I} = \frac{\Delta V}{I} . \qquad (1)$$

Figure 2 shows a cross sectional FIB secondary electron microscope (FIB-SEM) image of the contact region of one Kelvin structure.

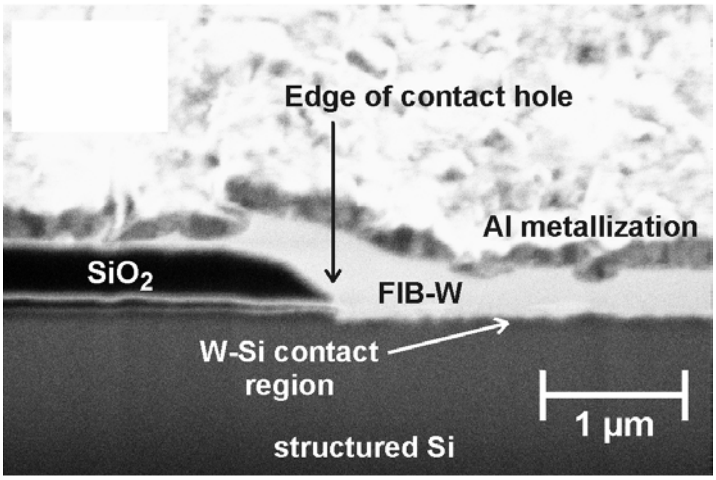

Fig. 2: FIB-SEM image of a FIB cross section through a contact region.

On the left side of the image, the SiO_2 interlayer is visible as a dark region forming a tapered sidewall to the contact hole. The FIB tungsten filling appears bright and compact and is covered with the aluminum metallization. The relationship between the contact resistance R_C measured on the structure and the actual contact resistivity ρ_C is determined by

$$\rho_C = R_C A\,, \qquad (2)$$

where *A* is the area of the metal-semiconductor contact region.

To determine the contact resistance of the FIB-CVD tungsten-silicon contact the voltage-current characteristics of the Kelvin structures were measured. The resulting ΔV versus *I* plots showed linearity (i. e. ohmic characteristics) and allowed the extraction of R_C referring to (1). The measured contact resistance data are summarized in Table 1.

Table 1: Resistivity data for FIB-CVD-tungsten-silicon contacts

substrate	annealing process	contact resistivity	standard deviation
p^+-Si	none	5.33×10^{-6} Ωcm^2	2.5%
p^+-Si	15 min at 450°C	1.48×10^{-5} Ωcm^2	28.2%
n^+-Si	none	9.96×10^{-3} Ωcm^2	4.4%
n^+-Si	15 min at 450°C	1.07×10^{-4} Ωcm^2	7.1%

The lowest contact resistivity of 5.33×10^{-6} Ωcm^2 is obtained when tungsten is deposited on the p^+-silicon substrate and the sample is not subjected to any thermal treating after deposition.

As a conclusion, we found that FIB-CVD tungsten to silicon contacts are not simply metal-semiconductor interfaces, but exhibit an architecture characterized by an intermedial layer of tungsten-silicide, which is a key issue to the understanding of the electrical and the thermal behavior of these contacts.