Revisiting Ru-Si-O as a nanocrystalline Schottky electrode for oxide semiconductors

Jakub Kaczmarski[1], Michał A. Borysiewicz[1], Andrzej Taube[1,2], Torben Boll[3], Marcin Myśliwiec[1,2], Krzysztof Piskorski[1], Marek Wzorek[1], Krystyna Stiller[3], and Eliana Kamińska[1]

[1] *Institute of Electron Technology, Al. Lotników 32/46, 02-668, Warsaw, Poland*
[2] *Institute of Microlelectronics and Optoelectronics, Warsaw University of Technology, Koszykowa 75, 00-662 Warsaw, Poland*
[3] *Department of Physics, Chalmers University of Technology, Fysikgränd 3, SE-412 96 Gothenburg, Sweden*

Ruthenium has been regarded as a promising gate electrode for wide bandgap devices due to its high work function, high conductivity, as well as chemical and thermal stability. However, due to its high chemical affinity to O_2, the deposition of a single metal on the surface of an oxide semiconductor leads to the drainage of oxygen from the subsurface region. This alters the charge distribution and the formation of accumulation region in the vicinity of metal/semiconductor interface, deteriorating Schottky barrier properties. The possible solution is a mictamic alloy being a mixture of two immiscible binary oxides with different crystalline structures, leading to crystalline frustration, and thus enhancing an amorphization of microstructure.

In this work we performed in-depth study of nanostructure, chemical composition, and transport properties of Ru-Si-O thin films fabricated by sputter-deposition under variable oxygen content in the deposition plasma. According to X-ray diffraction, all deposited films are amorphous. However, high resolution transmission electron microscopy revealed randomly oriented nanocrystalline inclusions embedded in an amorphous matrix. With the increase in $\%O_2$ one can observe an expansion of the amorphous matrix. The density recorded for the sample deposited without oxygen is 7.3 g/cm^3 and the final density is 2.42 g/cm^3, close to the density of amorphous SiO_2 (2.19 g/cm^3). Atom probe tomography studies enabled to identify nanoparticle as pure ruthenium with a Ru-O shell and the amorphous matrix as SiO_2. The resistivity increases from 6.2×10^{-4} $\Omega\cdot$cm for oxygen-free films up to 3.6×10^{4} $\Omega\cdot$cm for layers deposited at 100% of O_2. Values of work function extracted from internal photoemission spectroscopy changed from 5.65 to 5.85 eV for 0% and 30% O_2, respectively. The understanding of Ru-Si-O process-property relationship allowed us to introduce this mictamic alloy as a Schottky barrier and gate electrode of such IGZO-based devices as Schottky diodes and metal-semiconductor field-effect transistors (MESFET).

Ru-Si-O films deposited at $\%O_2$ equal to 20%, 30%, and 50% form Schottky contacts to amorphous IGZO with rectification ratios of 1×10^5, 3×10^5, and 9×10^2 respectively. Schottky barrier heights and ideality factors (n), evaluated by fitting exact solutions of the Schottky diode equation based on the thermionic emission model to experimental I-V curves for Ru-Si-O deposited at $\%O_2$ = 20%, 30% and 50% were $\Phi_B = 0.91$ eV, $n = 1.76$ $\Phi_B = 0.93$ eV, $n = 1.59$, and $\Phi_B = 0.69$ eV, $n = 3.57$, respectively. As a proof of concept, we designed and fabricated MESFETs on flexible PET and paper substrates with field-effect mobility exceeding 9 cm^2/Vs, on-to-off current ratio above 10^5, and subthreshold swing as low as 210 mV/dec.

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