Memristors based on heteroepitaxial SiGe structures

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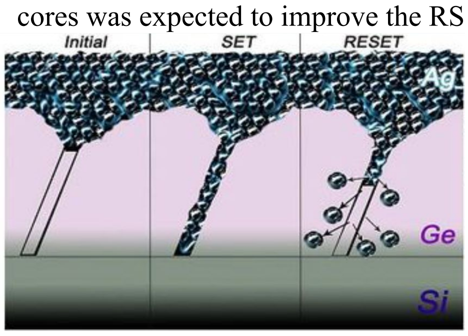
The work is devoted to investigation of the resistive switching (RS) in the novel type memristors – so-called Epitaxial Resistive Random Access Memory (EpiRRAM) devices based on the Me/Si-Ge/Si(001) stacks (Me = Ag, Ru) with relaxed Si and Ge epitaxial layers (ELs). In such devices, the conductive filaments (CFs) are the chains of the Me atoms filling the cores of threading dislocations growing though Si and Ge ELs. The prototype memristors based on the *p*-Ge/n^+-Si(001), low-doped *p*-Si/*p*-Ge/n^+-Si(001), and *p*-Ge/*p*-Si(001)/n^+-Si(001) heterostructures were studied.

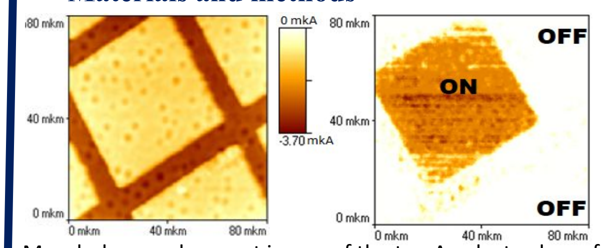
▪Introduction. Memristors are the elements of a new generation of non-volatile computer memory [1] and neuromorphic computing systems [2]. Recently, a new type of memristors based on epitaxial $Si_{0.9}Ge_{0.1}$/Si(001) heterostructures (Epitaxial RRAM or EpiRRAM) was demonstrated [3]. We have shown that the Ag/Ge/Si(001) memristor structures exhibit nonvolatile RS associated with the formation of conductive filaments from Ag atoms in the threading dislocations in the Ge EL [4]. The lateral confinement of the CFs inside the dislocation cores was expected to improve the RS stability and endurance.



RS mechanism in Ag/Ge/Si memristors

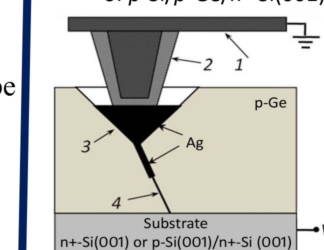
The goal of the wok: to study of the RS mechanism in the prototype memristors based on *p*-Ge/n^+-Si(001), p^--Si/*p*-Ge/n^+-Si(001), and *p*-Ge/*p*-Si(001)/n^+-Si(001) epitaxial heterostructures

▪Materials and methods



Morphology and current image of the top Ag electrode surface of *p*-Si/*p*-Ge/n^+-Si(001) based memristor V_g=-0.1 V

▪The RS of the prototype memristors based on *p*-Ge/n^+-Si(001), p^--Si/*p*-Ge/n^+-Si(001), and *p*-Ge/*p*-Si(001)/n^+-Si(001) heterostructures with 60x60 μm² mesas and the top electrodes of Ag and Ru were studied using Agilent B1500A semiconductor device analyzer in the dc voltage sweep mode with a step of ~1 mV. The voltage was applied to the top electrode, the Si substrate was grounded.

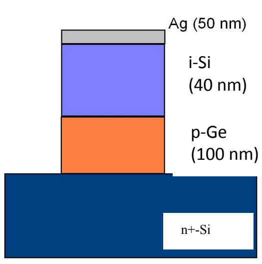


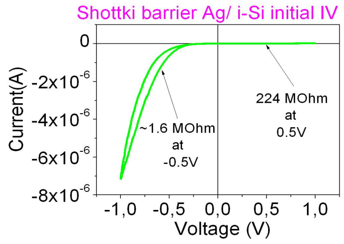
Studies of RS in individual filaments of memristor stacks by AFM

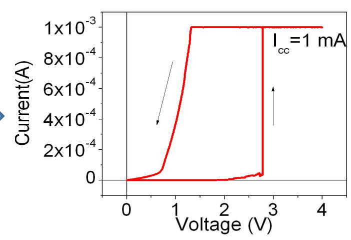
▪To study RS in individual filamenst, the Ag electrodes were removed by grazing incidence (~3°) Ar^+ ion sputtering (2 keV). The Ag particles remained inside the etch pits.

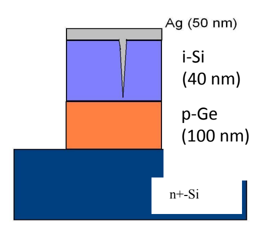
▪The RS studies in individual filaments were performed on the Solver Pro AFM (NT-MDT), by measuring the I-V curves of the AFMprobe contact (HA_HR_DCP) to the metal particles both inside and outside of the etch pits

Investigation of the 60×60 μm² mesa memristor RS mechanism

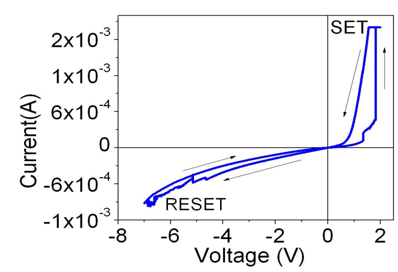






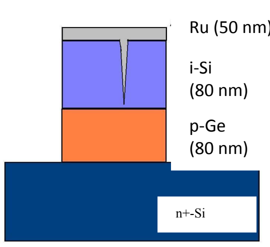


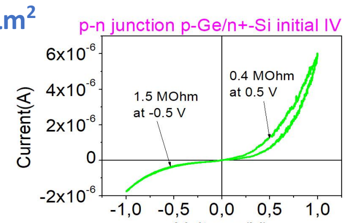
Electroforming on Ag/ i-Si interface and CB filament of Ag growing



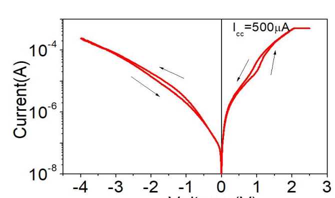
RS on the base of diode-like I-V of p-n Ge/n^+-Si

Structure for mesa 60×60μm²

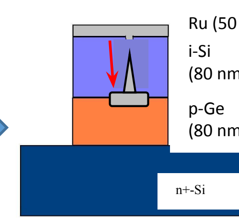




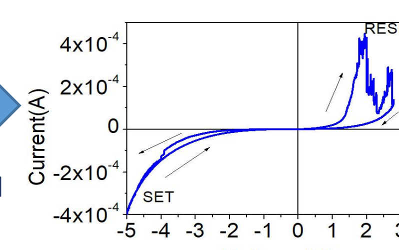
Initial CB-like amount of Ru ions in Si layer



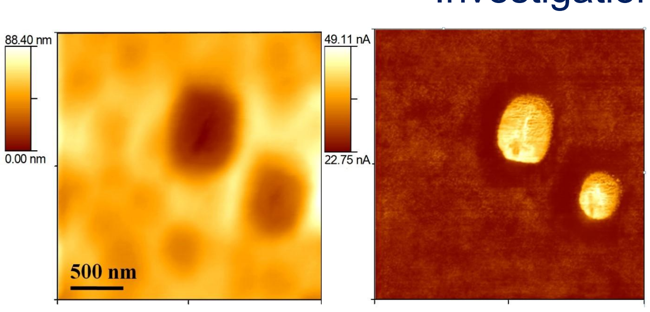
Injection of Ru ions into *p*-Si/*p*-Ge interface during RS



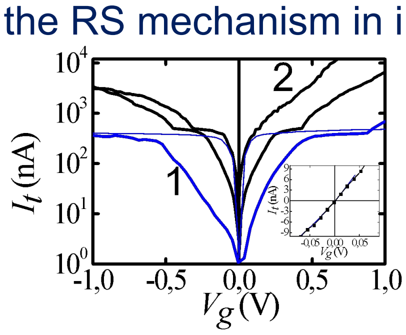
RS polarity changing [5]



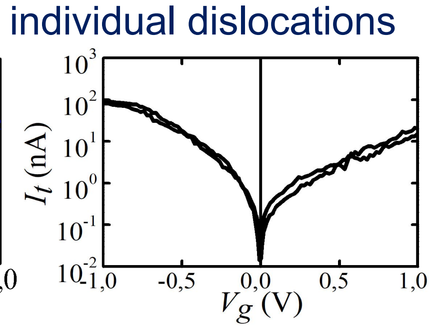
Investigation the RS mechanism in individual dislocations



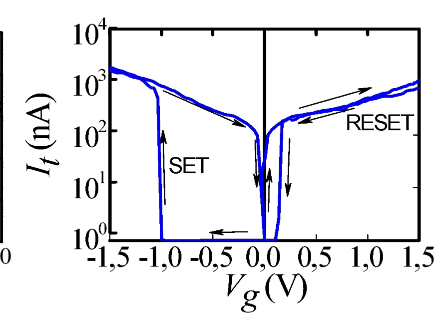
.Morphology (left) and current image (right) of individual Ag particles in the etch pitss on the Ag/*p*-Ge/n^+-Si strack V_g=+4B



I-V curves of AFM probe contact to Ag particle inside the etch pit on *p*-Ge/n^+-Si stack (1) and to the micron-sized mesa Ag/p^--Si/*p*-Ge/n^+-Si(001) stack (2)



A I-V curve of AFM probe contact to *p*-Ge/n^+-Si structure outside etch pits



I-V curve of AFM probe contact to Ag particle inside etch pit on the *p*-Ge/*p*-Si/n^+-Si heterostructure

The Ge and Si ELs were grown by low-temperature growth methods compatible with Si CMOS technology. The Ge ELs were grown by Hot Wire Chemical Vapor deposition, the Si ones – by Sublimation Molecular Beam Epitaxy in a single technological cycle at the substrate temperature 325 C. The threading dislocations were revealed on the EL surfaces by selective wet etching. Then, the top Me electrodes were deposited by magnetron sputtering. The fabricated prototype memristors manifested a bipolar RS between two resistance states. Transmission Electron Microscopy (TEM) with Energy Dispersion Spectroscope (EDS) microanalysis provided a direct confirmation of the RS mechanism based on the Me ion electromigration along the dislocations. Also, the accumulation of the Me atoms inside the misfit dislocations at the Ge/Si interface in the course of RS was observed. This effect may potentially limit the EpiRRAM durability. To investigate the RS mechanism in individual dislocations, we applied Conductive Atomic Force Microscopy (CAFM) combined with grazing incidence ion sputtering of the Me electrodes so that the metal nanoparticles remained inside the etch pits. The AFM probe played a role of a movable electrode providing a contact to the Me particles inside the etch pits. The current-voltage (*I-V*) curves of the individual dislocations agreed with the ones measured on the mesas of 60 by 60 mkm in size that confirms the operation of the prototype EpiRRAM devices to be based on filling/emptying of individual dislocations with the Me atoms. The memristors based on the *p*-Si/*p*-Ge/n^+-Si(001) heterostructures demonstrated the bipolar RS with asymmetric (rectifying) *I-V* curves in the low-resistance state related to the rectifying effect of the *p*-Ge/n^+-Si junction. Such a design allows combining a memristor and a diode selector in a single monolithic stack.

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