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Preparation and Evaluation of NiGe Gate Electrodes for Metal-Oxide-Semiconductor Devices

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Metal gate electrodes are indispensable for sub-50 nm generation of ultra large scale integrated circuits in order to eliminate gate depletion. Gate material must have a suitable work function, interface stability with underlying high-k films, and low resistivity. In this work, we focus on NiGe because of its thermal stability to SiO_2 and other high-k dielectrics. Work function, sheet resistance and crystalline structures of NiGe were examined.

A p-type Si (100) wafer (2-4 Ω·cm) is used as a substrate. In order to estimate the work function of metal electrodes, metal-oxide-semiconductor (MOS) capacitors with various SiO_2 thicknesses ranging from 3.5 nm to 10.0 nm were fabricated. Thermal oxidation was performed at 800°C in O_2 ambient for all samples. 40-nm-thick amorphous Ge and 20-nm-thick Ni were sequentially deposited on the SiO_2/Si substrate by electron bean evaporation at room temperature. Then, rapid thermal annealing was performed at a temperature of 400, 500 or 600°C in N_2 ambient for 30 sec to form NiGe films. For comparison, MOS capacitors with Ni gate electrodes were also prepared. The crystalline structure of the films was analyzed by X-ray diffraction (XRD) and transmission electron microscopy (TEM). Electrical resistivity of the films was measured by four-probe method. The work function was obtained from capacitance-voltage (C-V) characteristics of the MOS capacitors.

XRD profiles of NiGe/SiO_2/Si samples annealed at 400, 500 and 600°C showed almost similar patterns consisting of diffraction peaks related to polycrystalline NiGe phases. Figure 1 shows a cross-sectional TEM image of a 500°C-annealed sample. It is clearly observed that a NiGe film with a thickness of about 48 nm was uniformly formed on a SiO_2 layer and had a columnar grain structure.

Figure 2 shows the flat-band voltages (V_{fb}) depending on the capacitance equivalent thickness (CET), which were measured from C-V characteristics of the MOS capacitors. The slopes of lines obtained by least-square fitting to the data correspond to the effective densities of oxide charge and they appeared to be almost independent of the annealing temperature. It is, therefore, deduced that NiGe hardly reacted with underlying SiO_2 gate dielectric films. For the 400°C-annealed sample, since the plotted data seem to be scattered around the fitting line, small amount of non-reacted Ge may remain at the NiGe/SiO_2 interface. The extrapolation of the line to the y-axis allows us to obtain the work function difference (Φ_{MS}) between the metal electrode and the p-type Si substrate. The work function of metal (Φ_M) can be calculated by subtracting that of Si (Φ_{Si}) from Φ_{MS}. Resultant work function of Ni was 5.12 eV, which is comparable to the previously reported value of 5.3 eV.[1) The work functions of NiGe films were found to depend on the annealing temperature and obtained to be 4.89 eV (400°C), 5.12 eV (500°C), and 5.22 eV (600°C).

Figure 3 shows resistivities and work functions of NiGe films as a function of the annealing temperature. The resistivity decreases while the work function increases with the temperature. The sheet resistances of 48-nm-thick films fabricated in this experiment are in the range of 4.25 to 5.51 Ω/sq and these values are enough low to meet the International Technology Roadmap for Semiconductors (ITRS) specifications of sub-50 nm node technology.

In conclusion, electrical and structural properties of NiGe applicable to the gate metal have been examined. We showed that the potentiality of NiGe in terms of its sheet resistance and work function. Since NiSi with a work function of 4.7 eV was reported to be a candidate of the metal gate [2)], it can be expected that combination of NiSi and NiGe allows us to adjust the gate work function for the integration of CMOS devices.

1) I. Polishchuk et al., IEEE Electron Device Lett., vol. 23, NO. 4 (2002).
2) Ming Qin et al., J. Electrochem. Soc. **148(5)**, G271-G274(2001).
3) J. Seger et al., Appl. Phys. Lett. **81**, 11 (2002).

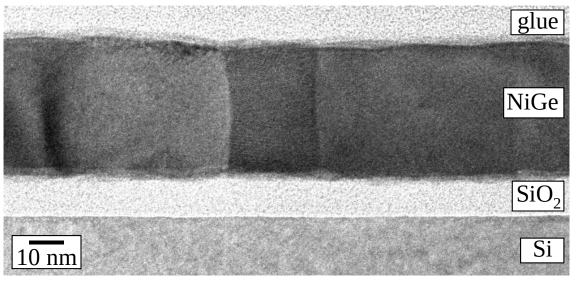

Figure 1. Cross-sectional TEM image of a film annealed at 500°C. Columnar NiGe grains were observed.

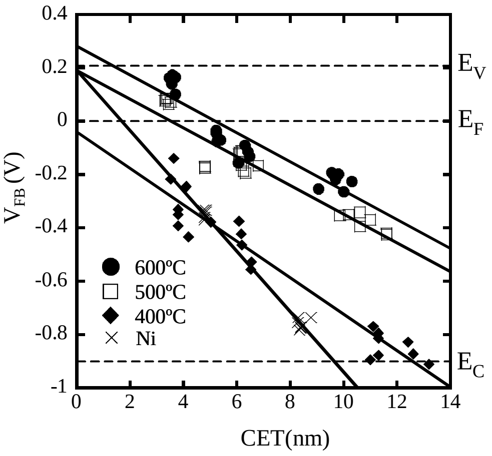

Figure 2. Flat band voltage versus CET. The extrapolation of the fitting line to the y-axis gives the work function difference (Φ_{MS}) for each sample.

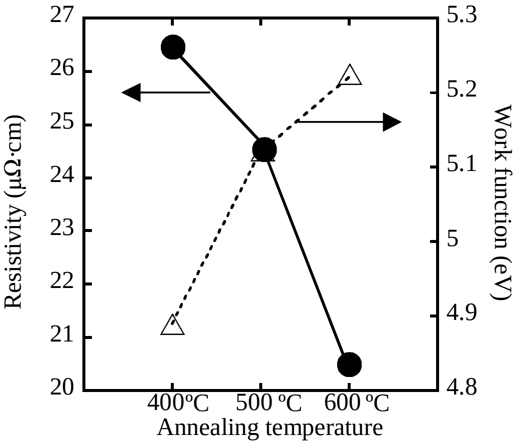

Figure 3. Measured resistivity and work function depending on the annealing temperature.