論文内容の要旨
論文題目及び氏名

Si-based spin MOSFETs with epitaxial ferromagnetic MnAs source and drain : Growth, Schottky junction, transistor, and spin-dependent transport properties.
By Kuniaki Sugiura

エピタキシャル強磁性 MnAs ソース・ドレインを有するスピン MOSFET:
成長、ショットキー接合特性、トランジスタ特性およびスピン依存伝導現象
杉浦　邦晃

Recently, Si-based spin electronics has attracted considerable attention, because it can lead to a variety of spin-electronic devices, which utilize spin degrees of freedom and well-established Si technologies. In this respect, recently proposed Si-based spin MOSFETs, which consist of a MOS gate capacitor and ferromagnetic source and drain (S/D), are promising. Previous theoretical studies showed that the spin MOSFETs can be potentially used for reconfigurable logic gates and nonvolatile memory, since the output characteristics can be controlled by both the gate voltage and magnetization of the S/D. One of the most practical devices is a spin MOSFET with ferromagnetic metals for the S/D, which can be simply realized by substituting ferromagnetic metals for the S/D of an ordinary Schottky MOSFET.

To realize both high electrical performance and spin-dependent characteristics in spin MOSFETs, thermally stable ferromagnetic metal/Si junctions with low Schottky barrier heights are strongly needed. It is well-recognized that spin injection from a ferromagnetic metal into a semiconductor is the most important issue for spin MOSFETs, and that the spin injection efficiency is considerably affected by the ferromagnet/semiconductor interface quality, its Schottky barrier height, and the spin-polarization of the ferromagnet. Furthermore, like the ordinary Schottky MOSFETs, low Schottky barrier height is required for high-performance electrical output characteristics of the spin MOSFETs. From the viewpoint of device fabrication processes, high thermal stability of the ferromagnetic metal/Si junction is also needed, since there are usually thermal annealing processes at a few hundred degree centigrade. CoFe and CoFeB, which are widely used in spin-valve devices, would not be suitable for S/D of spin MOSFETs, since the formation of intermixing layer can proceed easily, in spite of their high spin polarization of ~ 0.5.

Ferromagnetic MnAs is a good candidate for S/D of spin MOSFETs, because it has high spin-polarization of ~ 0.5, and epitaxial MnAs/Si(001) junctions with an atomically flat interface can be fabricated by molecular beam epitaxy (MBE). On the other hand, there are no reports evaluating the thermal stability and the Schottky barrier height of MnAs/Si junctions. The aim of this thesis is to fabricate Si-based spin MOSFETs with MnAs S/D and clarify their characteristics. Crystalline properties, thermal stability, and the Schottky barrier height of MnAs/Si(001) junctions are evaluated, and their influence on the device characteristics are examined. Spin MOSFETs with MnAs S/D are fabricated on silicon-on-insulator (SOI) substrates, and their transistor performance and spin-dependent transport are investigated.

In chapter 2, fundamental properties of epitaxial MnAs films were described. Growth was performed by low temperature molecular beam epitaxy (LT-MBE), and Si(001) wafers were used as substrates. In order to obtain good magnetic properties and crystalline quality, the growth condition was optimized by the *in-situ* reflective high energy electron diffraction (RHEED) observations, the *ex-situ* atomic force microscopy (AFM) observations, and their ferromagnetic properties were measured by a superconductive quantum interference device (SQUID) magnetometer. Furthermore, in order to examine the thermal stability of the MnAs films, the magnetic properties were measured after post-growth annealing at 400°C, 500°C, and 600°C. The ferromagnetic behavior was preserved when the annealing temperature were 400°C and 500°C, whereas it disappeared when the annealing temperature was 600°C. As a result, MnAs films on Si substrates were found to have sufficiently high thermal stability in thermal processes up to 500°C.

In chapter 3, the Schottky barrier height of the MnAs/Si junction was evaluated comparing with that of $Co_{90}Fe_{10}$/Si, and $(Co_{90}Fe_{10})_{70}B_{30}$/Si junctions. From current-voltage (*I-V*) measurement in the temperature range of 300 K to 450 K, MnAs/Si junctions found to have a low Schottky barrier height of 0.16 eV for electrons, while the $Co_{90}Fe_{10}$/Si, and $(Co_{90}Fe_{10})_{70}B_{30}$/Si junctions have mid-gap Schottky barrier heights of 0.73 eV and 0.75 eV for electrons, respectively. Thus, MnAs is a promising material for ferromagnetic S/D in spin MOSFETs. A further evaluation of the MnAs/Si interface through secondary ion mass spectroscopy (SIMS) revealed that a substantial amount of As atoms (10^{18} ~ 10^{19} cm^{-3}) are likely to be present near the interface. It is a possible origin of the low Schottky barrier height of the MnAs/Si junction.

In chapter 4, a spin MOSFET with epitaxial MnAs S/D were fabricated on thin-film silicon-on-insulator (SOI) substrates, and measurements of the transistor characteristics were performed. A spin MOSFET with $(Co_{90}Fe_{10})_{70}B_{30}$ S/D was also fabricated for comparison. From the drain current – drain voltage (I_{DS} - V_{DS}) characteristics, the spin MOSFET with MnAs S/D exhibited ~100 times higher in current drivability than the spin MOSFET with $(Co_{90}Fe_{10})_{70}B_{30}$ S/D. From the drain current – gate voltage (I_{DS} – V_{GS}) characteristics, the spin MOSFET with MnAs S/D showed the high on-off ratio of ~ 10^8, which is comparable to that in conventional MOSFETs with pn junction S/D. High electrical performances of the spin MOSFET with MnAs S/D, which were expected in the chapter 3, have been demonstrated. Postgrowth annealing effect on the transistor performance was also investigated. It was found that the I_{DS} - V_{DS} and I_{DS} – V_{GS} characteristics were not degraded, but rather improved, when the postgrowth annealing temperature was done at 500ºC.

In chapter 5, the spin-dependent transport properties of the spin MOSFET with MnAs S/D was explored in the temperature range of 2.8 – 50 K. At 2.8 K, the drain current – magnetic field (I_{DS} – H) characteristics exhibited hysteresis behavior depending on the gate voltage V_{GS} and temperature. This phenomenon could be explained by theoretical studies by other reports. The maximum of the obtained magnetocurrent ratio was - 1.6 %, and the hysteresis of I_{DS} – H loops were preserved up to 20 K at high V_{GS} >100 V. Since the magnitude of the magneto-current signal is larger than that of the estimated signals of various parasitic magnetization-dependent signals, such as anisotropic magneto-resistance (AMR) of the MnAs film, the magneto-resistance of the non-magnetic Si layer, and local Hall effect (LHE), this signal probably originates from the spin-dependent transport of the spin MOSFET.