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TEM characterization of $Fe_3Si/Ge/Fe_3Si$ thin film stacks grown epitaxially on GaAs(001)

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Fe_3Si is a ferromagnetic metal with high Curie temperature (576°C) and lattice matched to GaAs and Ge. Fe_3Si films have already been grown on Ge and GaAs substrates by molecular beam epitaxy (MBE). Excellent magnetic properties with a small coercivity (0.9 Oe) and electrical properties with Schottky barrier height of 0.52 eV were obtained.[1,2] Spin transistors, consisting of Ge channel and ferromagnetic source/drain for spin injection were envisaged. Vertical structures like metal/Ge/metal are most promising for next-generation devices. Ge films on Si-terminated Fe_3Si films were recently grown by MBE on Ge(111) substrates.[3,4] In the present work we grow and analyze metal/Ge/metal structures on GaAs(001): Fe_3Si /Ge/ Fe_3Si layer stacks have been grown by MBE. This is an example for the overgrowth of a metal by a semiconductor, a difficult task due to chemical reactivity and poor wetting.

The structures have been characterized by transmission electron microscopy (TEM), electron backscattered diffraction (EBSD), and high-resolution x-ray diffraction (XRD). Interface quality and crystal properties of the films were studied in dependence of the substrate temperature T_S during Ge deposition. The first Fe_3Si epitaxial film on GaAs is always single crystalline. The structural properties of the Ge film and the second Fe_3Si layer depend on the substrate temperature during Ge deposition. Different orientation distributions of the grains in the Ge and the upper Fe_3Si film were found. The lowest substrate temperature T_S = 150°C during Ge deposition ensures smooth interfaces, and intermediate temperatures result in poly-crystalline films with small grain size. Growth at the highest T_S =350°C delivers smooth interfaces and single crystal films in a considerable part of the sample (about 80% of the area as shown by EBSD). In the remaining part however, islands with different crystallographic orientation are formed and the interfaces are damaged by chemical reaction below those islands.

Figure 1 demonstrates the high-resolution TEM image of a sample near the GaAs/Fe_3Si interface. The Ge layer of the sample was grown at the lowest substrate temperature of T_S = 150°C. As demonstrated previously [5] the GaAs/Fe_3Si interface is extremely smooth for the given growth conditions of the first Fe_3Si film. The Fe_3Si/Ge interface above however had a slightly increased roughness. First mono-layers of the Ge film grew well oriented, however the material above was not a single crystal any more. Figure 2 demonstrates the XRD curve of the sample near the GaAs 002 reflection. The curve could be simulated taking into account merely the first Fe_3Si film with a thickness of 9 nm. The contribution of the upper films could be neglected for high-resolution XRD near the GaAs 002 maximum. Although in the sample the upper Fe_3Si film was not single-crystalline as well as the underlying Ge film, the low temperature growth seems to be most promising for technological purposes on a larger scale, as temperature treatment of Ge after growth allows for recrystallization (solid phase epitaxy).

The overgrowth of a metallic Fe_3Si film with a Ge film up to now was demonstrated only recently using a Si-terminated Fe_3Si film on a Ge(111) substrate.[3] We have used the more common 001 orientation of the Fe_3Si film on the corresponding GaAs substrate for the overgrowth. We could avoid chemical reaction with the Ge. The quality of the Ge films largely depends on the substrate temperature during deposition, the structural quality of the following Fe_3Si film is influenced by the parameters of the Ge film itself.

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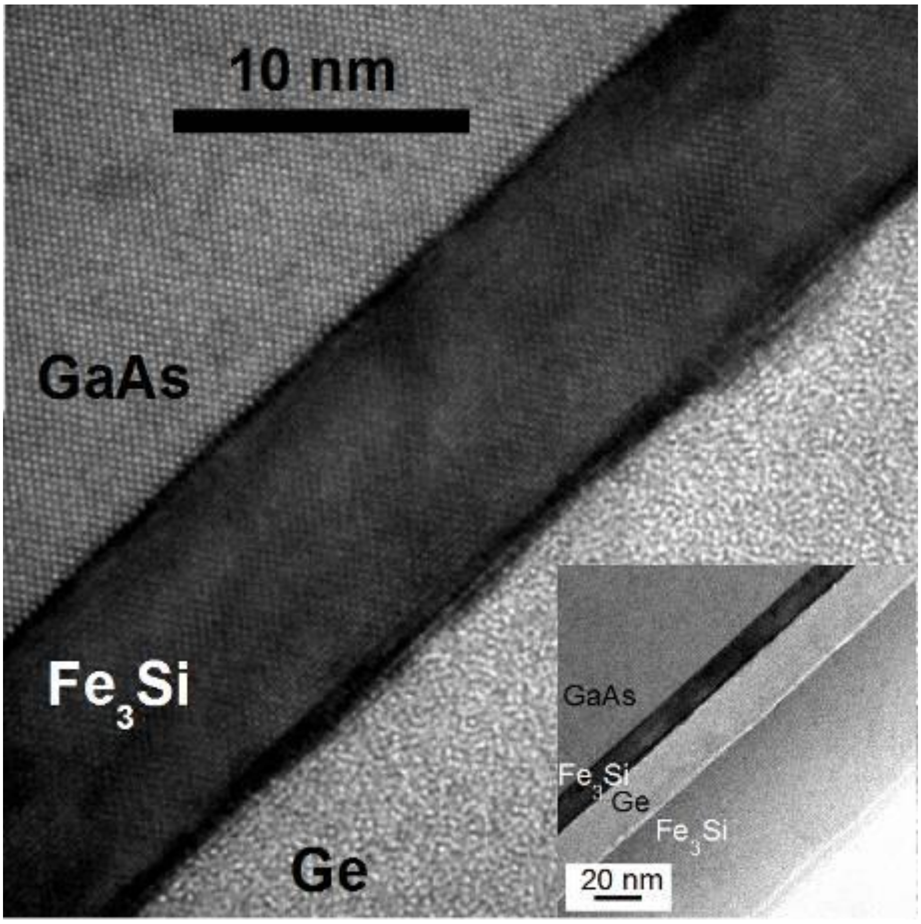

Figure 1. High resolution TEM image of a sample with GaAs/Fe_3Si and the Fe_3Si/Ge interfaces. The Ge layer of that sample was grown at the lowest substrate temperature of T_S= 150°C. The GaAs/Fe_3Si interface is smooth. The Fe_3Si/Ge interface has only a slightly larger roughness than the bottom IF. The inset shows the complete structure at lower magnification.

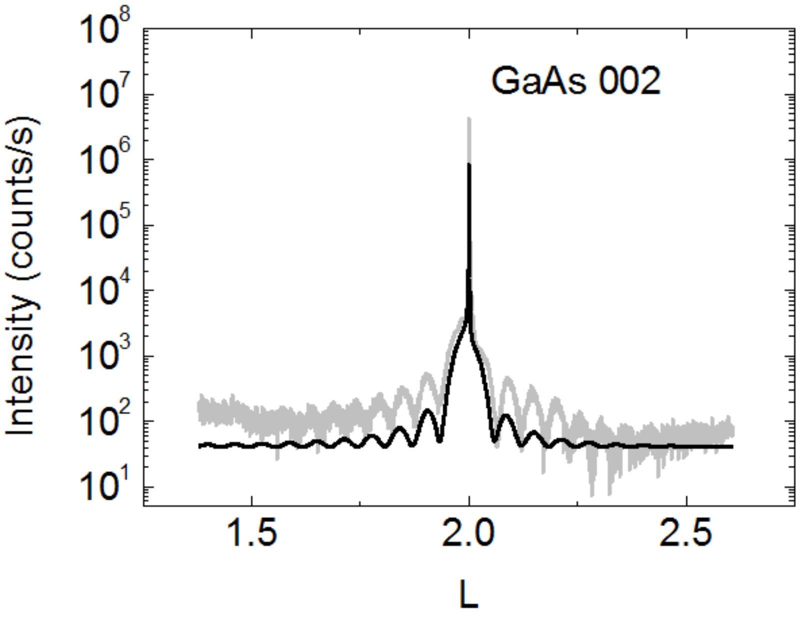

Figure 2. XRD curve of the sample shown in Figure 1 in the vicinity of the GaAs 002 reflection and the corresponding simulation. For the simulation only the first Fe_3Si film of 9 nm thickness had to be taken into account. The upper polycrystalline films could be neglected for high resolution XRD near the GaAs 002 reflection.