

2.1 Growth temperature dependence of the interface structure and magnetic properties of $\text{Co}_2\text{FeSi}/\text{GaAs}(001)$ hybrid structures

Half-metallic ferromagnets (HMF), which have 100% spin-polarized carriers at the Fermi level, are promising candidates for spintronic devices. Heusler alloys are considered potential HMFs and are especially attractive because of their high Curie temperature T_C and close lattice-matching with semiconductors. A recent study suggests that Co_2FeSi , the Heusler alloy with the highest T_C (> 1100 K), the largest magnetic moment ($6 \mu_B$), and a small lattice-mismatch to GaAs ($\sim 0.08\%$), is indeed a half-metallic ferromagnet.

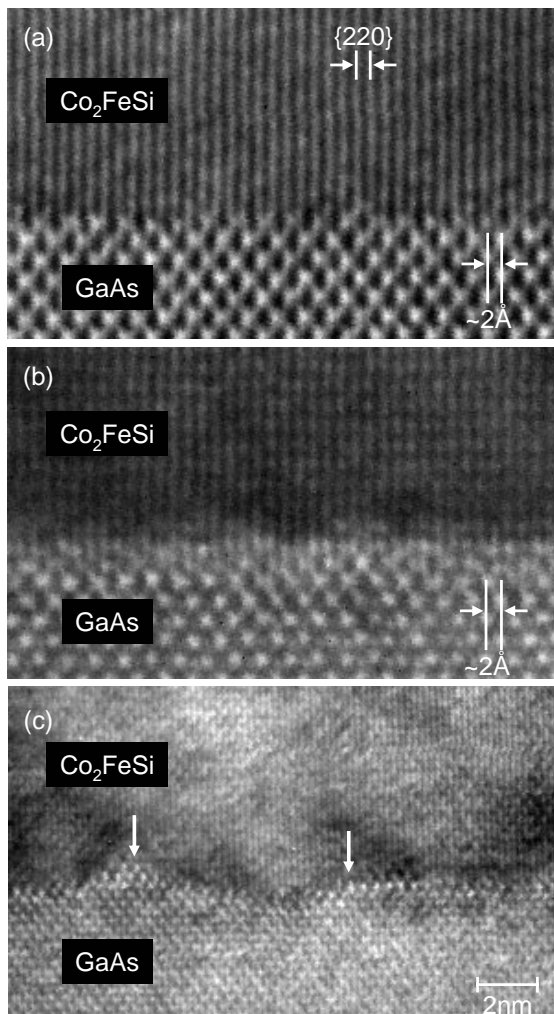


Fig. 3. Cross-sectional HRTEM images along the $[110]$ zone axis of $\text{Co}_2\text{FeSi}/\text{GaAs}(001)$ grown at (a) 100, (b) 200, and (c) 350 °C.

The spin injection efficiency is known to depend on the interface perfection of the ferromagnet/semiconductor (FM/SC) hybrid structures. The growth of a FM layer on SC substrates at high growth temperature generally leads to the formation of magnetically modified interfacial compounds, which could result in a reduction of the spin-polarization of injected carriers. Therefore, a comprehensive understanding of Heusler-alloy/SC interface structures is of crucial importance for the realization of high-efficiency electrical spin injection.

The Co_2FeSi layers were grown on As-terminated GaAs(001) substrates by molecular-beam epitaxy at growth temperatures T_s ranging from 100 to 400 °C with a low growth rate of about 0.1 nm/min. Figures 3(a), 3(b), and 3(c) show cross-sectional high-resolution transmission-electron-microscopy (HRTEM) images along the $[110]$ zone axis of the Co_2FeSi films grown at 100, 200, and 350 °C, respectively. The film grown at 100 °C shows an atomically abrupt interface [Fig. 3(a)], which is identified from a distinct difference in the interference patterns between Co_2FeSi and GaAs. We see a perfect matching of the $\text{Co}_2\text{FeSi}(220)$ and $\text{GaAs}(220)$ atomic planes across the interface, i.e., the layer is coherently strained. However, for the film grown at 200 °C, we observe a modified layer of 1–2 ML, which has lattice fringes similar to the ones of Co_2FeSi , but a contrast different from GaAs as well as Co_2FeSi [cf. Fig. 3(a)]. This modification of the interface structure indicates

the onset of interfacial reaction for this T_s . For $T_s = 350$ °C, the interface of the film shows undulations and large steps marked by arrows in Fig. 3(c), indicating further progress of the reaction due to the enhanced mobility of diffusing atoms.

Additional information on the interface perfection as well as atomic ordering of the Co_2FeSi layer are deduced from the magnetic properties of the films. Figure 4(a) shows the two in-plane magnetic anisotropy (MA) constants, namely the uniaxial (K_u^{eff}) and the cubic (K_1^{eff}), as a function of T_s . These constants are obtained by applying a magnetic field along the hard axis ($[1\bar{1}0]$ direction) and fitting the reversible magnetization curve with an analytical expression, which can be derived from the free-energy density. K_u^{eff} and K_1^{eff} are an interface-related and a volume-related term, respectively, as reflected in their thickness dependence. The origin of the uniaxial MA in cubic-FM/zincblende-SC systems is attributed to an anisotropic bonding at the interface. Therefore, a formation of interfacial compounds and/or a modification of the interface structure are expected to reduce the uniaxial MA constant K_u^{eff} .

As shown in Fig. 4(a), both K_u^{eff} and K_1^{eff} have a maximum at about $T_s = 200$ °C. This indicates that the optimum T_s to obtain an abrupt and ordered $\text{Co}_2\text{FeSi}/\text{GaAs}$ interface is around 200 °C, which is consistent with the TEM results. K_u^{eff} decreases above 200 °C in correlation with the progress of the interfacial reaction. The simultaneous decrease of K_1^{eff} above 200 °C most likely originates from the increasing atomic disorder in the Co_2FeSi layer caused by diffusion of Co into the substrate. The saturation magnetization M_S also decreases above $T_s = 250$ °C [cf. Fig.4(b)]. The in-diffusion of Co and the resulting formation of paramagnetic CoAs at the interface causes the gradual reduction of M_S with increasing T_s .

We conclude from the above results that the reaction temperature of the $\text{Co}_2\text{FeSi}/\text{GaAs}(001)$ interface is about 200 °C. This is significantly higher than the one of Fe and Co grown on GaAs, for which reaction temperatures of 95 and -10 °C, respectively, were reported. These results demonstrate that the interface between Co_2FeSi and GaAs has a much higher thermal stability than interfaces between those conventional ferromagnets and GaAs.

(M. Hashimoto, J. Herfort, A. Trampert, H.-P. Schönherr, K. H. Ploog)

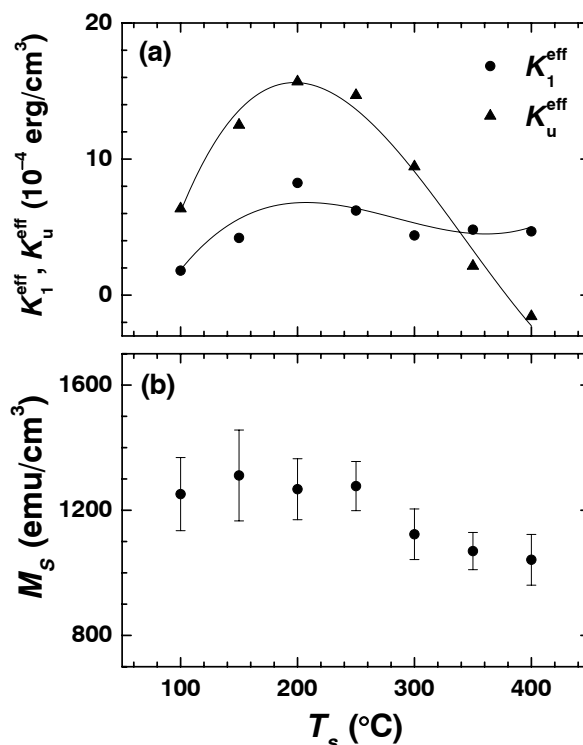


Fig. 4. Growth temperature dependence of (a) uniaxial MA constant K_u^{eff} (triangle) and cubic MA constant K_1^{eff} (circle) and (b) saturation magnetization M_S of Co_2FeSi .