Magnetic properties of Fe_3Si/GaAs(001) hybrid-structures

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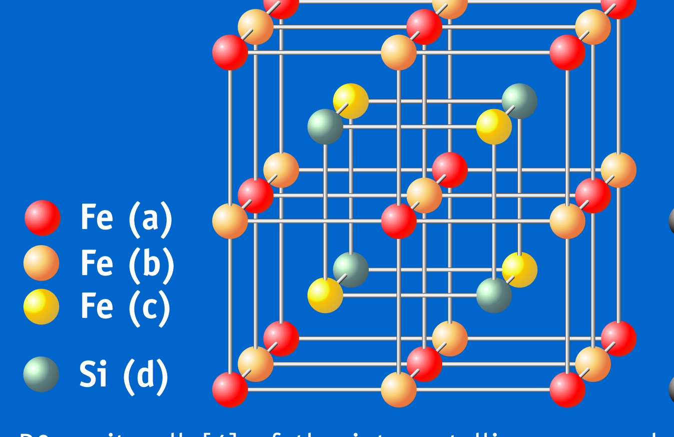
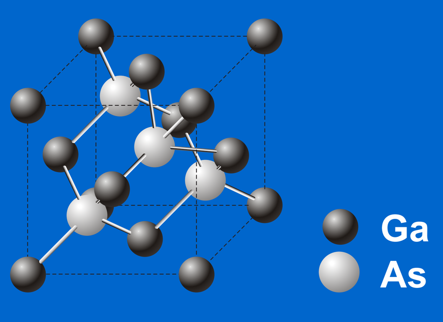
Abstract

The magnetic properties of Fe_3Si/GaAs(001) hybrid structures are studied. These epitaxial ferromagnetic films of 33 and 39 nm thickness show a high crystalline and interfacial perfection [1]. Structural characterization and SQUID magnetometry has been done [2]. We present ferromagnetic resonance (FMR) studies [3] determining the uniaxial and fourfold anisotropy. The easy axis of magnetization is the in-plane [010] direction. The full angular dependence of the resonance field reveals a small uniaxial in-plane anisotropy field of 6 Oe which increases with the Fe concentration. Thus, the [1$\bar{1}$0] direction is not equivalent to the [110] direction, anymore. Moreover, these samples show an exceptional narrow linewidth of 13 Oe confirming a high structural homogeneity.

Structure and sample preparation of Fe_3Si/GaAs(001)



DO_3 unit cell [4] of the intermetallic compound Fe_3Si. It is similar to a binary Heusler alloy. The sites are represented by *a,b,c* and *d*. *a* and *b* sites are equivalent and occupied by Fe atoms. In stoichiometric Fe_3Si the Si atoms occupy the *d* sites.



Structure of GaAs(001).

Substrate preparation:
- epi-ready GaAs(001) substrate (350 µm)
- 70 nm thick GaAs buffer evaporated at 580°C
- As-rich (2×1) reconstruction by cooling down to 400°C under As_4 flux to avoid formation of macroscopical defects in the film structure
- verification by RHEED

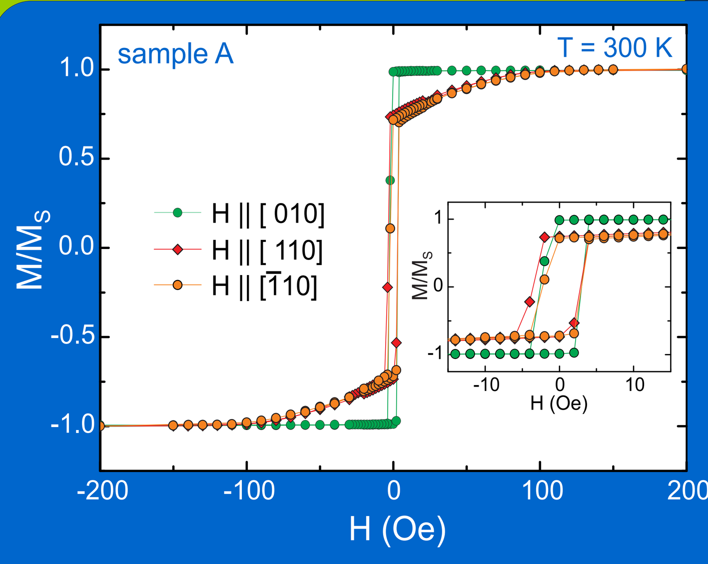
Film growth [1]:
- codeposition of Fe and Si from high temperature effusion cells
- growth temperature: 200°C
- growth rate: 0.4 nm/min
- Fe cell temperature: 1350°C
- Si cell temperature: 1360..1410°C (depending on concentration)
- verification by RHEED and DCXRD

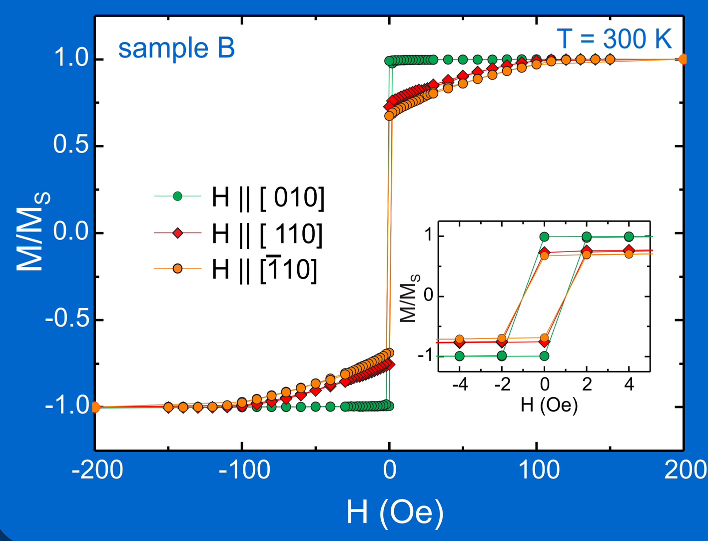
Parameters of investigated samples

	sample A	sample B
Si-content (%)	25,5	16,5
$\Delta a/a$ (%)	-0,22	1,41
thickness (nm)	39	33
M_s (emu/cm^3)	790	1050
$\bar{\mu}_{tot}$ (μ_B/Fe-Atom)	1,3	1,55

- sample A: stoichiometric
- sample B: Fe-rich
- high Curie temperature (839 K)
- interface thermally stable up to 700 K

SQUID magnetization curves





Magnetization curves of sample A and B along three in-plane directions [2].

The data is normalized to the saturation magnetization and is recorded at RT.

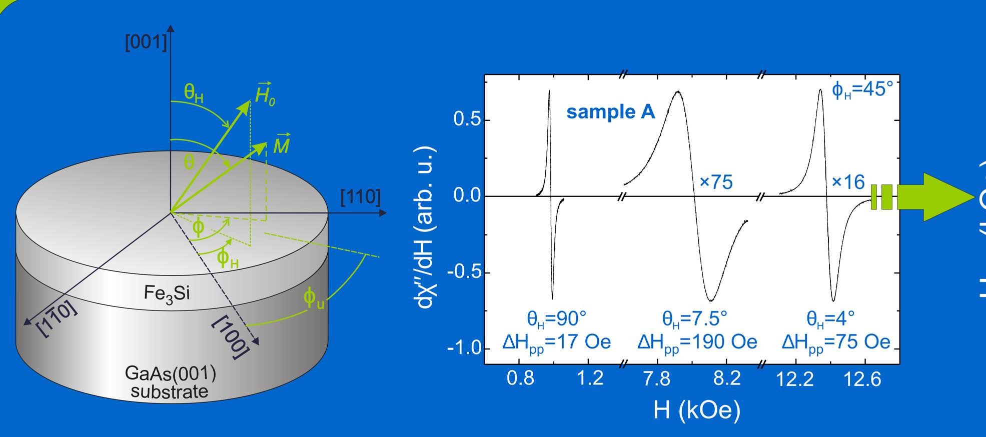
The [010] direction is the easy axis. The <110> in-plane axes are intermediate ones.

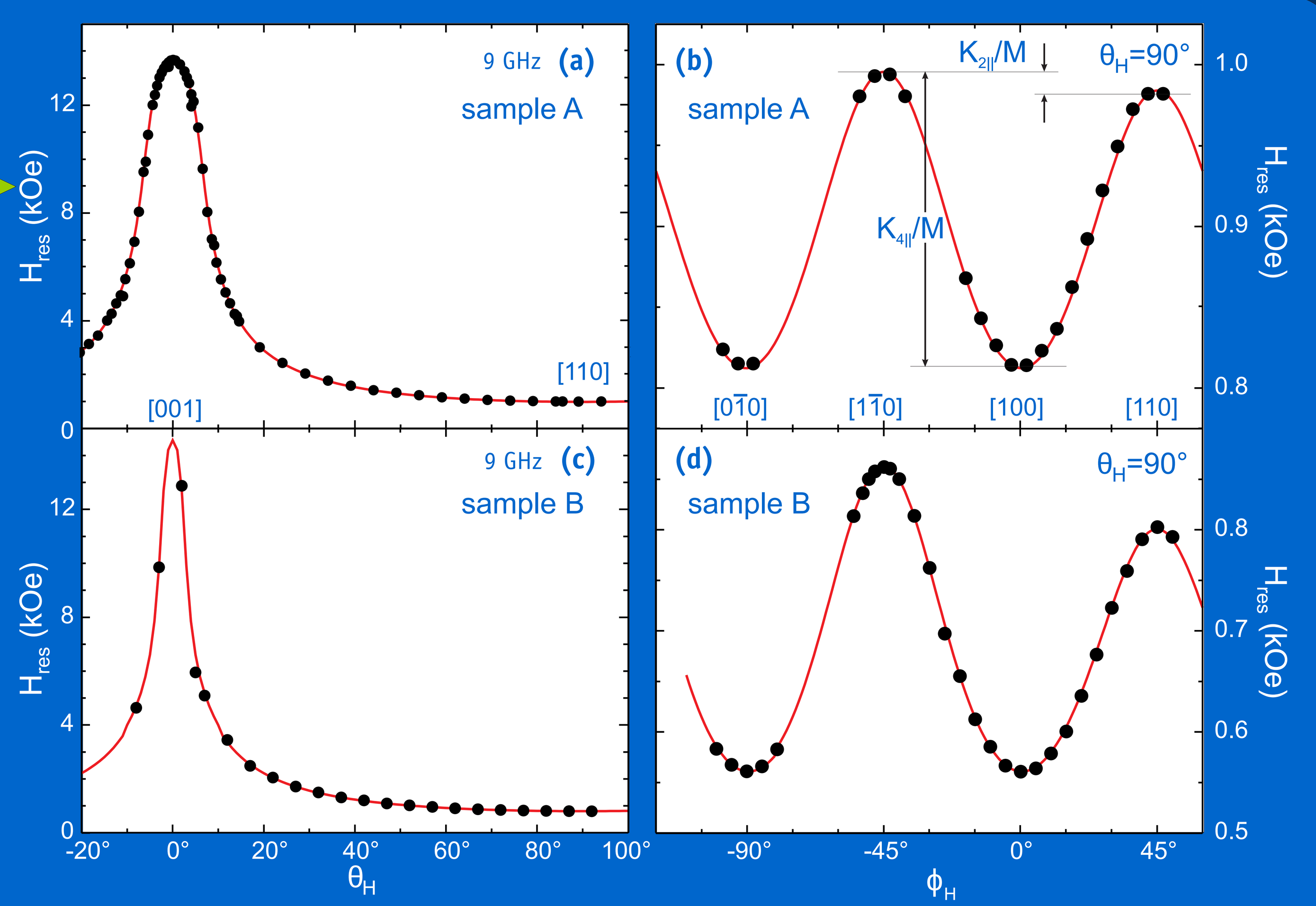
The [110] and [$\bar{1}$10] directions are almost equal for sample A. In contrast, for sample B a slight difference is visible, due to a uniaxial in-plane anisotropy.

The demagnetizing fields for sample A constitute 110 Oe in both directions and 120/130 Oe for sample B along the [110]/[$\bar{1}$10] directions.

The coercivity for sample A is $H_c \approx 2.5$ Oe and $H_c \approx 1$ Oe for sample B.

Ferromagnetic resonance measurements



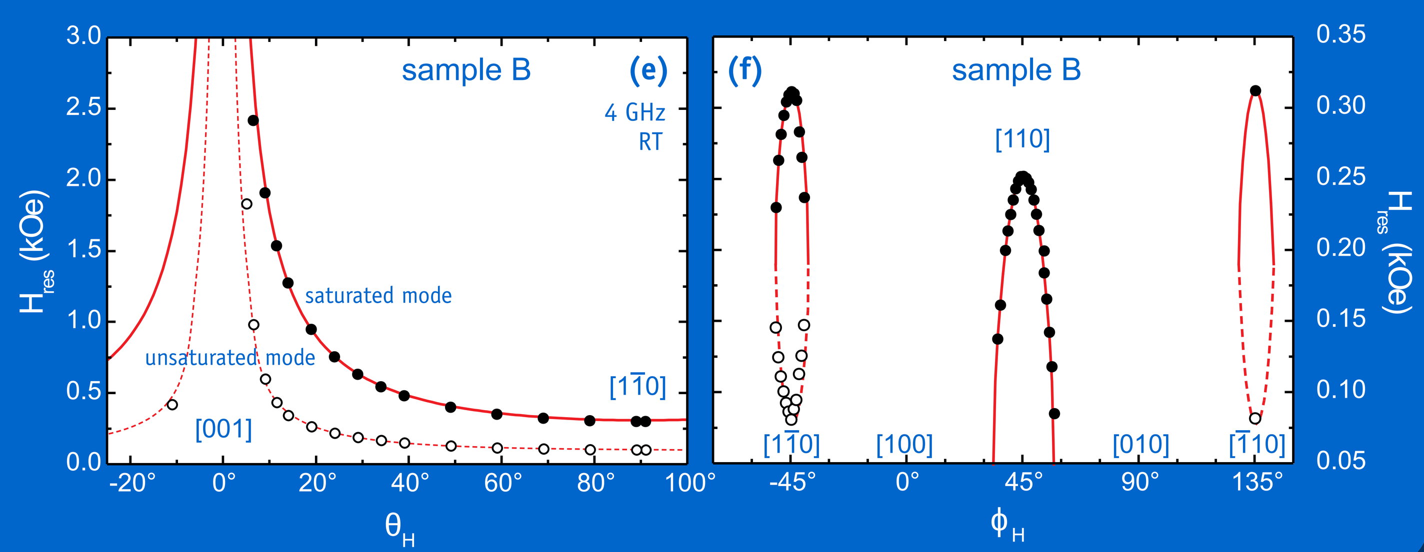


Polar (left column) and azimuthal (right column) angular dependencies for sample A (a,b) and sample B (c,d) measured at 9 GHz. (e,f) corresponding measurements for sample B at 4 GHz. The red solid lines are fits according to the resonance equations derived from the Smit&Beljers-Ansatz using the free energy density *F*.

Free energy density

$$F = -M \cdot H_0\,[\sin\theta \sin\theta_H \cos(\phi - \phi_H) + \cos\theta \cos\theta_H] - (2\pi M^2 - K_{2\perp}) \sin^2\theta - K_{2\parallel} \sin^2\theta \cos^2(\phi - \phi_u) - \frac{1}{2} K_{4\perp} \cos^4\theta - \frac{1}{8} K_{4\parallel}(3 + \cos 4\phi) \sin^4\theta$$

- **Both samples show a clear two-fold symmetry in polar orientation with the [001] direction being the hard axis.**
- **In the film plane a four-fold anisotropy ($K_{4\parallel}$) is found which favors the <100> in-plane axes.**
- **The four-fold symmetry is modulated by a uniaxial contribution ($K_{2\parallel}$) favoring the [110] direction like in Fe/GaAs(001).**
- **Even for the nearly stoichiometric sample A a small uniaxial in-plane anisotropy is found.**
- **The anisotropy fields increase with Fe concentration: $K_{2\parallel}/M$ increases by a factor of 5, whereas M_{eff} or $K_{4\parallel}/M$ only increase by 30-50%.**



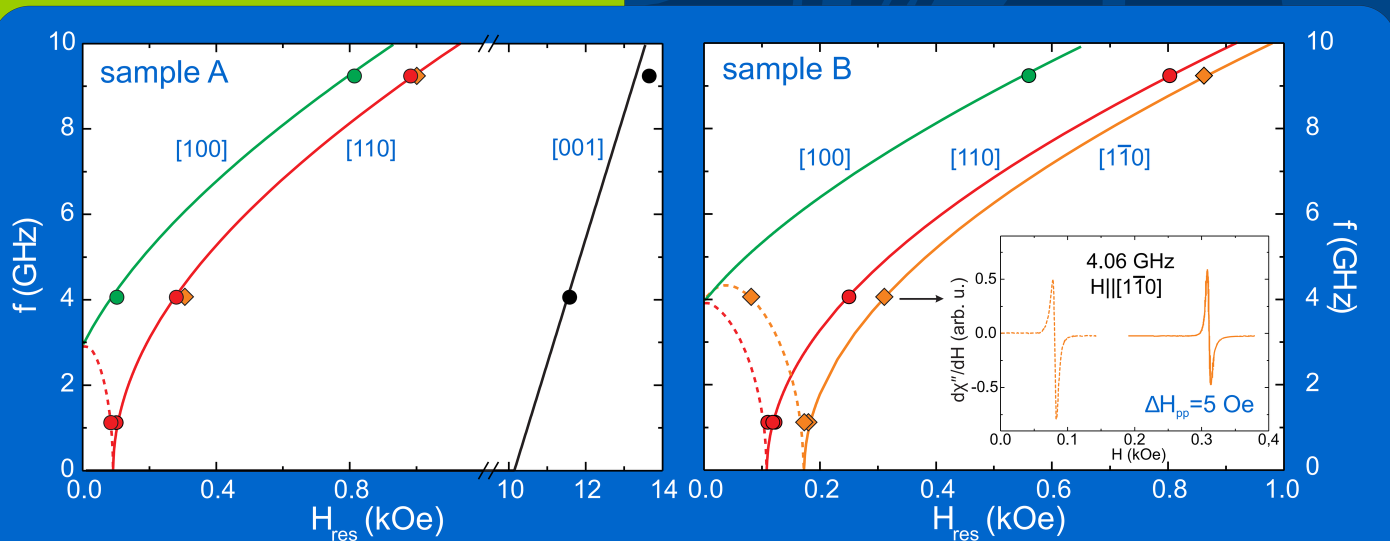
	sample A	sample B
	25.5% Si	16% Si
$4\pi M - 2K_{2\perp}/M$ (kG)	10.10(2)	13.50(2)
$2K_{2\parallel}/M$ (Oe)	6(1)	32(1)
$2K_{4\perp}/M$ (Oe)	-40(3)	0(1)
$2K_{4\parallel}/M$ (Oe)	94(2)	140(2)

Anisotropy constants

Anisotropy constants and effective magnetization of sample A and B compared to a 21 nm Fe_3Si/GaAs(001) sample [5] and a 9.3 nm Fe/GaAs(001) film [6]. The bulk-value of $K_{4\parallel}$ for Fe_3Si is 0.54×10^5 erg/cm^3 [7]

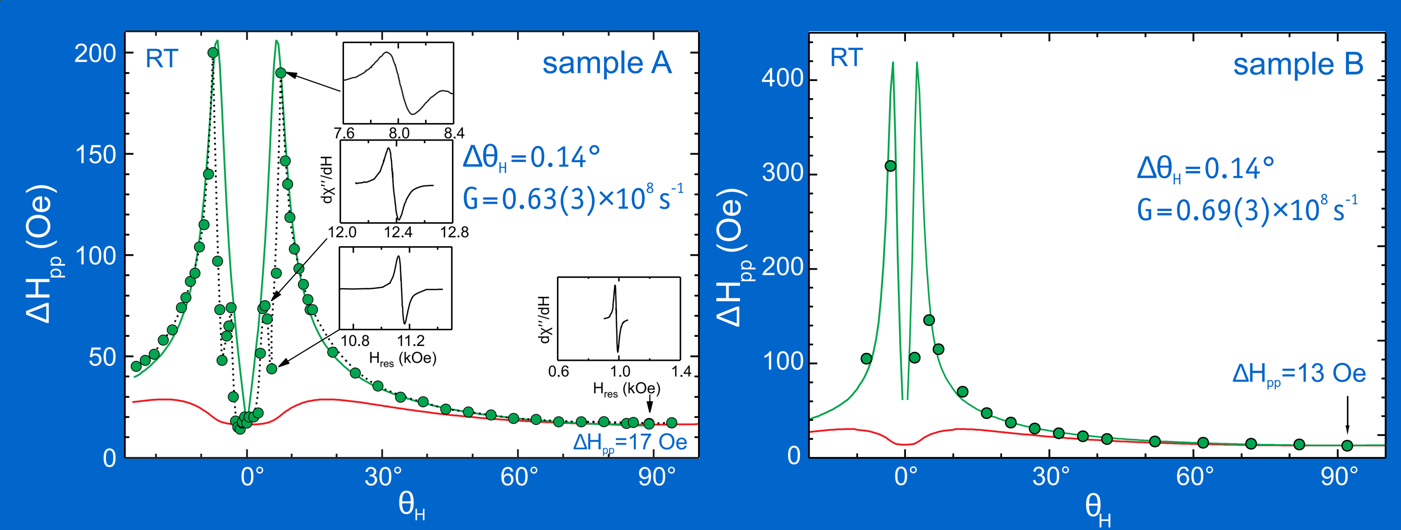
	sample A	sample B	Fe_3Si/GaAs(001)	Fe/GaAs(001)
	25.5% Si	16% Si	Ref. [5]	Ref. [6]
$4\pi M - 2K_{2\perp}/M$ (kG)	10.10(2)	13.50(2)	—	20.8
$K_{2\perp}$ (10^5erg/cm^3)	-0.68	-1.60	—	—
$K_{2\parallel}$ (10^5erg/cm^3)	0.02(1)	0.17(2)	0.0046(9)	0.4
$K_{4\perp}$ (10^5erg/cm^3)	-0.16(3)	0	—	—
$K_{4\parallel}$ (10^5erg/cm^3)	0.37(3)	0.74(5)	0.31(6)	3.2

FMR dispersion relation



Microwave frequency vs. resonance field. The samples were measured at 3 frequencies [3]. Below a threshold value of $f_t = 2.9$ GHz for sample A and $f_t = 4.3$ GHz for sample B two resonances are visible, i.e. the dashed branches correspond to unsaturated modes, the solid lines to the saturated modes.

Resonance linewidth and damping contributions



Resonance linewidth measured at 9.2 GHz as function of the polar angle θ_H for sample A and B. The green line (—) is a sum of mosaicity and Gilbert contribution (—). The dotted line is a guide to the eye. The insets show the FMR spectra at points marked with arrows.

Landau-Lifshitz-Gilbert equation:

$$\frac{\partial \vec{M}}{\partial t} = -\gamma(\vec{M} \times \vec{H}_{eff}) + \frac{G}{\gamma M_S^2}\left(\vec{M} \times \frac{\partial \vec{M}}{\partial t}\right)$$

Polar angular dependence of FMR linewidth [8]:

$$\Delta H_{pp}(\theta_H) = \underbrace{\left|\frac{\partial H_{res}}{\partial \theta_H}\right| \Delta\theta_H}_{\text{mosaicity}} + \underbrace{\frac{2}{\sqrt{3}} \frac{G}{\gamma^2 M} \frac{\omega}{\cos(\theta - \theta_H)}}_{\text{Gilbert damping}}$$

- **The linewidth is very narrow: 17 Oe resp. 13 Oe at 9 GHz).**
- **The small mosaicity (0.14°) is a proof of the sample homogeneity and quality [9].**
- **Gilbert damping constant is similar to bulk-Fe value [10].**

Conclusion

- **GaAs(001) is known to have an uniaxial bonding structure [11-13].**
- **A four-fold in-plane anisotropy dominates the uniaxial in-plane anisotropy.**
- **Only a very small uniaxial in-plane anisotropy is found in thin stoichiometric Fe_3Si/GaAs(001) films. The symmetric distribution of Fe and Si sites in the Heusler structure seems to break the uniaxial symmetry of the substrate.**
- **Increasing the Fe concentration causes an uniaxial contribution to develop like in Fe/GaAs(001) samples. The reason is, that in Fe-rich Fe_3Si the Fe atoms randomly occupy Si sites and vice versa [14].**
- **Compared to pure Fe/GaAs(001) the anisotropies are 5-10 times smaller.**
- **⇒ By varying the Fe content the uniaxial in-plane anisotropy of Fe_3Si/GaAs(001) can be adjusted.**

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