# Development, fabrication and characterization of soft-magnetic thin films for high frequency applications


## Abstract

This submitted manuscript describes the development, fabrication and characterization of soft-magnetic thin films for high frequency applications up to GHz frequencies. These high frequency suitable films were investigated with the prospective use as magnetic core material, for the assembly of micro inductors or micro sensors for the micro electronic and micro system technology. Within the scope of this work amorphous CoB and FeCoBSi films as well as nanocrystalline FeTaN films were deposited by means of magnetron sputtering and characterized regarding their film constitution and film properties. The main development goal was the realization of films with high ferromagnetic resonance frequencies, low eddy current losses and suitable hf-permeabilities up to the GHz range.

As a concept for the realization of high frequency suitable film systems the direct deposition of films with a uniaxial anisotropy was traced. The film fabrication was carried out by means of magnetic field deposition table (substrate holder), which induced a magnetic field within the film plane. As film materials initially amorphous thin films were deposited with different sputtering targets ($Co_{79}B_{21}$[2], $Fe_{67}Co_{18}B_{14}Si_1$ und $Fe_{60}Co_{15}B_{15}Si_{10}$) with a target diameter of 75 mm. By varying the deposition conditions (Ar sputtering pressure and hf-sputtering power) an optimization of the film fabrication was carried out with respect of the deposition of films with low internal stress.

These optimized amorphous films show a strong uniaxial anisotropy within the film plane. With a saturation magnetization ($\mu_0 M_s$) of 1.8 T and an anisotropy field ($\mu_0 H_k$) of 3.5 mT $Fe_{68}Co_{18}B_{13}Si_1$ films reach the highest values ($Co_{84}B_{16}$: $\mu_0 M_s = 1.2$ T, $\mu_0 H_k = 1.5$ mT, $Fe_{58}Co_{18}B_{12}Si_{12}$: $\mu_0 M_s = 1.2$ T, $\mu_0 H_k = 1.5$ mT). Along the easy axis direction these films exhibit high permeabilities ($Co_{84}B_{16}$: 2340, $Fe_{58}Co_{18}B_{12}Si_{12}$: 1825, $Fe_{68}Co_{18}B_{13}Si_1$: 3340) which were damped at higher excitation frequencies in the kHz range.

Along the hard axis direction the permeabilities of the films are lower ($Co_{84}B_{16}$: 690, $Fe_{58}Co_{18}B_{12}Si_{12}$: 830, $Fe_{68}Co_{18}B_{13}Si_1$: 520) but stay constant for the hole frequency range. For thin films (0.1 µm) permeabilities up to the GHz range ($Co_{84}B_{16}$: 1.3 GHz, $Fe_{58}Co_{18}B_{12}Si_{12}$: 1.5 GHz, $Fe_{68}Co_{18}B_{13}Si_1$: 2.3 GHz) are observed along the hard axis direction. These experimentally determined permeabilities and ferromagnetic resonance frequencies are in good agreement with the theoretically calculated values using the static magneti-


[2] Chemical Composition in At.-%.

zation measurements. With the prospective use of the films as magnetic core material in micro inductors the dependence of the hf-permeability on the film thickness was investigated. These experiments reveal that only for thin films (up to 0.2 µm for $Fe_{68}Co_{18}B_{13}Si_1$) the spectrum of the hf-permeability is limited by the ferromagnetic resonance frequency. For thicker films the eddy current losses increase whereas the resonance frequencies shift to lower values.

The thermal stability of the magnetic properties of the films was investigated to rate the process compatibility of the different film materials. It was shown that the amorphous films start to crystallize at temperatures above 300°C and exhibit no uniaxial anisotropy after the annealing. Since these crystallized films show no hf-permeability up to the GHz range, these amorphous films have only a limited suitability for the established semiconductor fabrication with its high process temperatures (400 - 500°C).

For the realization of first micro inductors as testing devices on larger substrates (100 mm Si-Wafern) an up-scaling of the film fabrication using a $Fe_{66}Co_{17}B_{16}Si_1$ target with a diameter of 152 mm is carried out. The films deposited with that target exhibit high anisotropy fields of about 33 mT and reach ferromagnetic resonance frequencies of about 4.7 GHz with permeabilities of 110. Not only magnetic field induced processes could be considered as reason for these remarkable high anisotropy fields but also parts of stress induced or structural anisotropy as the results of the magnetic field annealing reveal.

Because of the insufficient thermal stability of the magnetic properties of the investigated amorphous films it was started with the deposition of nanocrystalline FeTaN films. The fabrication of these nanocrystalline films was carried out using a 152 mm $Fe_{95}Ta_5$ target in different Ar/ $N_2$-atmosphere in the sputtering gas. The nitrogen content of the FeTaN films was varied from 0 At.-% (at 0 Vol.-% $N_2$ in Ar) up to about 40 At.-% (at 30 Vol.-% $N_2$ in Ar). Due to the increasing nitrogen content in the films the resistivity of the films increases and the saturation magnetization degreases down to the super paramagnetic range (about 30 At.-% N in the films). $Fe_{64}Ta_4N_{32}$ films with a uniaxial anisotropy reach ferromagnetic resonance frequencies of 1.5 GHz with a permeability of about 40. Compared to the non annealed film a $Fe_{79}Ta_5N_{16}$ film annealed at 500°C shows soft magnetic behavior with clear uniaxial anisotropy of 0.4 mT. Due to the better thermal stability of the magnetic properties these nanocrystalline films exhibit in contrast to the amorphous films a higher potential for the prospective integration in established semiconductor fabrication processes.