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Iron and Permalloy based magnetic monolithic tunable microwave devices

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We fabricated a series of magnetic monolithic tunable microwave notch-filters and phase shifters. In contrast to previous work with molecular beam epitaxy grown metallic ferromagnets, our devices were created by magnetron sputtering. Single crystal GaAs (001) was used as a substrate. Iron and Permalloy were used as magnetic materials in a coplanar waveguide geometry. The transmission characteristics of the filters were observed to depend on substrate quality, film deposition parameters (Argon pressure, growth rate, power, etc.), and grain size. In addition we observed a substantial increase in the resonance frequency for the Fe based notch-filters. This increase in the resonance frequency is due to a growth-induced uniaxial anisotropy field of 40 kA/m in the Fe films. This is an unexpected and important result especially because the observed anisotropy is growth and not field induced. The resonance frequency shifted from 9.3 GHz at zero applied magnetic field to 15 GHz for an applied static magnetic field as low as 72 kA/m (0.9 kOe). The Fe based notch filter attenuation was greater than 35 dB/cm over the whole applied field range at the resonance condition. The phase shift of the Fe structures was up to 100°/cm at 8 GHz. The Permalloy based filters show, over the same magnetic field range, a shift in the resonance frequency from 2 to 9 GHz. The attenuation of the Permalloy filters at resonance (6 dB/cm) is substantially lower than in the Fe based filters. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1557856]

INTRODUCTION

The development of hybrid structures formed by thin metallic magnetic films, e.g., Fe, Permalloy, etc., on semi-insulating substrates[1–4] has received considerable attention as a technique for integrating microwave devices with semiconductor technology. This allows construction of high frequency microwave and millimeter wave monolithic integrated circuits (MMIC). In this article we concentrate on the coplanar waveguide (CPW) structure, because it is especially suitable for the magnetic-MMIC design, due to the easy implementation of additional microwave components without via holes.[3]

Recent work on magnetic-MMIC has focused on the use of metallic ferromagnetic materials because their high saturation magnetization allows for operation of the devices at higher frequencies than with conventional insulating ferrites. Most of the ferromagnetic metal-based MMIC devices fabricated up to now have used molecular beam epitaxy (MBE) growth, a process that is generally not compatible with industrial mass production techniques. In contrast, we report here on the manufacturing of magnetic MMIC devices by magnetron sputtering, a technique widely used in the industry. The magnetron sputtering has an additional advantage. While MBE grown films are generally thin, on the order of 100 nm or less, the microwave MMIC devices often require films with thicknesses that are much larger, on the order of 1 to 2 μm or so. This is because the film thickness should generally be comparable or larger than the skin depth in magnetic material. This thickness can be more easily achieved by sputtering techniques.

EXPERIMENTS

The CPW lines were fabricated by depositing thick magnetic layers of either Fe (650 nm) or Permalloy (750 nm) on top of insulating GaAs substrates to reduce the microwave loss. A thin 10 nm Ti film was used to increase adhesion. The background pressure in our deposition system was 13 μPa (1.0×10^{-7} Torr). The deposition was made using an rf/dc magnetron source at a rate of $\sim$0.1 nm/s and with argon (Ar) pressure 0.27–0.53 Pa (2–4 mT). A thin layer of Ag was deposited on top to prevent oxidation of the magnetic film. The films were photolithographically patterned followed by ion milling in an Ar atmosphere. The CPW structure was designed for a characteristic impedance of 50 Ω. Two right-angle bends are introduced at the ends of the transmission line to allow for the commercial microprobes to make contact, and also make the component of the oscillating radio-frequency microwave field, h_{rf}, perpendicular to the applied bias static magnetic field.[5] In this geometry the energy of the electromagnetic wave propagating along the CPW structure is coupled into the magnetic films and incurs ferromagnetic resonance phenomena. The resulting resonance frequency can then be tuned by varying the external magnetic field.

We characterized the CPW transmission lines at frequencies from 0.5 to 20 GHz using an automated vector network-

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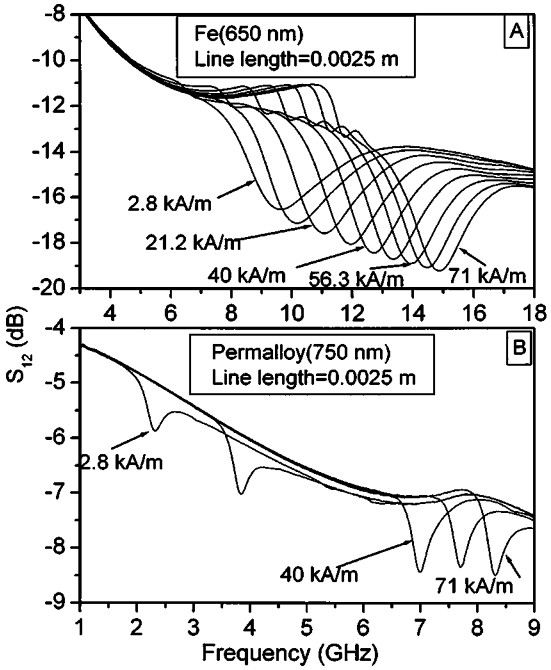

FIG. 1. Attenuation for Fe (a) and Permalloy (b) based coplanar waveguides as a function of frequency for different applied fields.

analyzer (VNA) and a microprobe station; the on wafer calibration was done using the NIST Multical® software for the through-short-line (TRL) calibration procedure.[6] The longest and the shortest lines used for calibration were 0.0071 and 0.0025 m to cover the entire frequency range of interest.

RESULTS AND DISCUSSION

Figure 1 shows the on-wafer calibrated transmission scattering matrix coefficient S_{21} as a function of frequency for Fe (a) and Permalloy (b) 0.0025 m long CPW lines. The transmitted signal shows a dip at the ferromagnetic resonance frequency due to the coupling of microwave energy to the magnetic spin system. For an isotropic material this resonance frequency (f_{res}) is given by

$$f_{\mathrm{res}}=\left(\frac{|\gamma|}{2\pi}\right)\sqrt{H(H+M_s)}, \tag{1}$$

where H is the applied field, M_s is the saturation magnetization, and γ is the gyromagnetic ratio $|\gamma|=2.31\times10^8$ m/kA s. The observed resonance frequency of 9.53 GHz for the Fe CPW with saturation magnetization of $\mu_0\times M_s=2$ T, with $\mu_0=4\pi\times10^{-7}$ H/m as the permeability of the vacuum, and a bias field of 2.4 kA/m (0.03 kOe) does not follow the prediction from Eq. (1). We determined that our deposited Fe film had a substantial uniaxial anisotropy field, H_U, along the direction of the applied static bias field. If the uniaxial anisotropy, with an easy axis oriented along the applied static bias field, is taken into account the resonance frequency is given by

$$f_{\mathrm{res}}=\left(\frac{\gamma}{2\pi}\right)\sqrt{(H+H_U)(H+M_s+H_U)}. \tag{2}$$

The presence of the uniaxial anisotropy is important for possible applications. If one would be able, during the process of the deposition, to align the easy axis parallel to the center-conductor of the CPW it would allow the initial resonance frequency (the frequency when $H=0$) of magnetic MMIC devices to be controlled. We will address this issue more closely later in the text. At the moment, we wish to emphasize that the experimental results for the Fe CPW devices show a significant uniaxial anisotropy even though they were made by magnetron sputtering.

We followed the resonance behavior of the magnetic-MMIC devices by measuring the calibrated two-port scattering matrix coefficients S_{ij} of the particular device while tuning the resonance frequency of the device up to 15 GHz by applying a small external magnetic field from 0 to 72 kA/m (0.9 kOe). From the measured scattering transmission matrix coefficient S_{21} we estimated that the attenuation at resonance for the Fe CPW filter was ~35 dB/cm in the entire applied magnetic field range. As seen in Fig. 1(a), the total loss in the measured device has an additional nonmagnetic insertion loss of 12 dB that will be addressed later in the text.

In contrast, the transmission scattering matrix coefficient S_{21} for the Permalloy-based CPW filter, shown in Fig. 1(b), exhibits resonance at a much lower frequency that the Fe-based filters for the same magnetic bias field. For example, for the bias field of 2.4 kA/m (0.03 kOe), the resonance is at 2.3 GHz in the Permalloy devices while it is 9.5 GHz for the Fe-based devices at the same applied field. This decrease in the resonance frequency is due to the smaller saturation magnetization $\mu_0\times M_s=1$ T along with a much smaller uniaxial anisotropy typical of Permalloy films. The resonance frequency in the Permalloy CPW was tuned up to 8.5 GHz by increasing the bias field up to 72 kA/m (0.9 kOe). The resonance attenuation obtained for this filter is ~10 dB/cm with an additional nonmagnetic insertion loss of ~7 dB.

The investigated magnetic MMIC CPW filters show some performance limitations that will have to be addressed in the future. These are mainly the nonmagnetic insertion loss as well as the background frequency dependence of the devices. The limitations are primarily due to the construction design of the CPW line; the sharp 90° turns are a source of radiation losses and substrate mode generation which contribute to the observed nonmagnetic insertion loss and the smoothness of the transmission curve. Since the skin depth becomes comparable to the conductor thickness below 20 GHz, the field penetration effects are also important in the entire frequency range studied.

Figure 2 shows the dependence of the resonance frequency on the applied bias static magnetic field. The solid line represents the theoretical calculation using Eq. (2) and the symbols show the experimental results. To fit the experimental data for the Fe CPW filter we had to use a relatively large uniaxial anisotropy of 37. 6 kA/m (0.47 kOe). As already mentioned above, this is a surprising result since one would expect isotropic behavior in sputtered devices. We attribute this to the effect of the single crystal (001) oriented GaAs substrate, which was apparently slightly miscut. The Permalloy samples that were grown on a different set of

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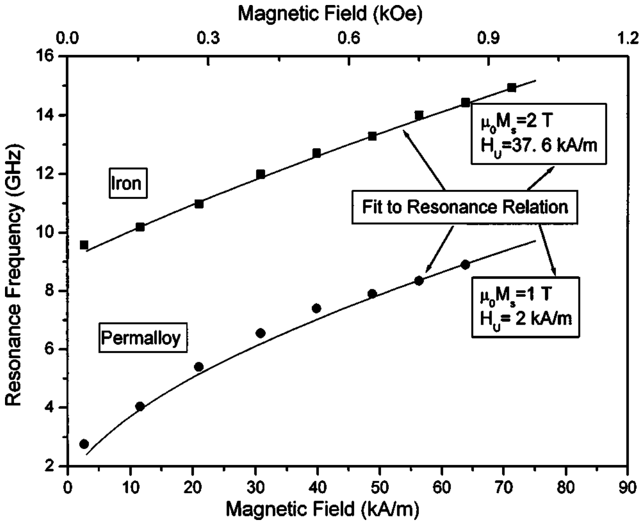

FIG. 2. Resonance frequency as a function of applied field for Fe and Permalloy.

GaAs substrates showed only a very small growth-induced magnetic anisotropy.

The misorientation of the GaAs substrate introduced a growth-induced anisotropy in the Fe films during the deposition. Earlier experiments[4] with MBE grown ultrathin Fe films (3 nm and below) on the same single crystal GaAs substrates also showed very large anisotropies, up to 160 kA/m (2 kOe). Angular FMR measurements proved that the observed anisotropies in the MBE grown films were uniaxial in nature. The fact that our sputtered films were much thicker that the MBE grown films, and still showed significant anisotropy, indicates that the single crystal GaAs substrate induces stresses throughout the Fe film, resulting in a large uniaxial anisotropy field H_U.

The large uniaxial anisotropy in the Fe structures could be very important for device development since it boosts the operational frequency substantially. It is interesting to speculate whether a deliberately miscut substrate could be utilized in the future design of sputtered thin film magnetic-MMIC devices. Additional research should be done to explore the possibility of obtaining even larger uniaxial anisotropies in sputtered Fe films by proper orientation of single crystal GaAs substrates, possibly in combination with deposition in a magnetic field.

The CPW notch filters can also be used, in principle, as phase shifters. The results for phase shifter operation are presented in Fig. 3 for the Fe-based CPW structures. The top panel shows the phase angle of the transmitted signal as a function of the frequency for different values of the applied field. Although substantial changes are seen near resonance, the attenuation of the device at these frequencies is high (the device performs as a notch filter close to resonance) which makes operating the device as a phase shifter unsuitable at these frequencies. By close inspection of the measured data, we observed that away from the resonance there is still a shift of the phase angle with the applied field. This change in phase angle away from resonance, as a function of the applied field, is plotted in Fig. 3(b). Note that at 8 GHz, a phase shift of 100 deg/cm was measured with only a 2 dB change of insertion loss. At lower frequencies the observed attenuation as well as the phase change are both smaller.

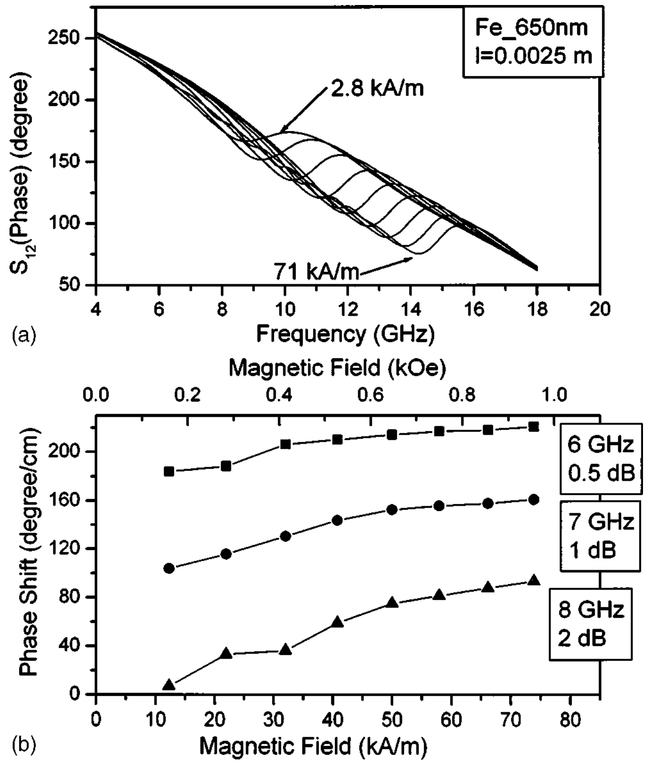

FIG. 3. Transmitted phase (a) as a function of frequency for Fe based devices, and phase shift (b) as a function of applied magnetic field.

In conclusion, we constructed a set of microwave devices using Fe and Permalloy grown by magnetron sputtering. From the observed data we can conclude that devices grown by magnetron sputtering have performance characteristics that are similar to the characteristics of devices grown by MBE. An intriguing development is the observed large uniaxial anisotropy in sputtered materials. This growth-induced anisotropy is important from the device design standpoint because it can significantly increase the operational frequency of microwave ferromagnetic metal devices.

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