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著者	Sohn Jaecheon, Han S. H., Yamaguchi M., Lim S. H.
journal or publication title	Applied Physics Letters
volume	89
number	10
page range	103501
year	2006
URL	http://hdl.handle.net/10097/51549

doi: 10.1063/1.2335389

Tunable electromagnetic noise suppressor integrated with a magnetic thin film

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(Received 20 February 2006; accepted 20 June 2006; published online 5 September 2006)

A tunable electromagnetic noise suppressor based on a coplanar waveguide transmission line integrated with a magnetic thin film is presented. High resonance frequencies (above 10 GHz) and good signal attenuation characteristics are observed in the device, making it suitable for high frequency noise suppressors. The main mechanism of the loss generation is found to be the *L-C* resonance, not ferromagnetic resonance observed in previous similar devices. With the inclusion of a magnetic material, the resonance frequency can be tuned during the operation with an applied magnetic field. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2335389]

An overwhelming tendency in electronics technology is the continued increase in the operational frequency and degree of integration. An example are extremely compact wireless communications devices with their operational frequency nowadays reaching the gigahertz range. On the road to this technical development, a problem related with electromagnetic noise, among many others, needs to be solved. Magnetic materials have played an important role in tackling this problem. Electromagnetic noise suppressors based on Co–Zr–Nb and Co–Pd–Al–O sputtered magnetic films and spin sprayed Ni–Zn–(Co) soft ferrite films were previously reported.[1] The device structure mainly consisted of a coplanar waveguide (CPW) transmission line covered with a magnetic thin film. In this type of noise suppressors, unwanted noises (usually harmonics in power circuits) are mainly absorbed by the loss generation due to ferromagnetic resonance (FMR). Very recently, the present authors reported a similar, nonintegrated-type noise suppressor[2] incorporated with a nanogranular Co–Fe–Al–O thin film,[3,4] mainly to test the suitability of the Co–Fe–Al–O thin film as a high frequency noise suppressor. A small magnitude of noise absorption was observed from the device due to a large separation between the CPW transmission line and the magnetic thin film which can be expected from the nonintegrated nature of the device. The main aim of the present work was to solve this problem by integrating the magnetic thin film onto the CPW transmission line.

Following the Muller and Hillberg equations,[5] a CPW transmission line with a characteristic impedance of 50 Ω was designed for a signal linewidth of 50 μm and a thickness of 3 μm on a Corning glass (7059) substrate.[1,2] A cross-sectional view of the designed transmission line and a schematic showing the overall device structure are shown in Fig. 1. The overall stack consisted of the Co–Fe–Al–O magnetic thin film (0.1–1 μm)/SiO_2 (0.1–0.5 μm)/Cu transmission line (3 μm)/glass substrate (1 mm). A conventional microfabrication process including photolithography was used to fabricate the integrated noise suppressor. A nanogranular magnetic film with the composition $Co_{41}Fe_{38}Al_{13}O_8$ (in atomic percent) was deposited by rf magnetron sputtering under a static magnetic field of 1 kOe to form an induced anisotropy.[3,4] For measurements, two ground-signal-ground (GSG) pin-type wafer probes were in mechanical contact with both ends of the CPW transmission line. The *S* parameters (S_{11} and S_{21}) were measured with an HP 8720D network analyzer in the frequency range of 0.1–20 GHz.

The present $Co_{41}Fe_{38}Al_{13}O_8$ nanogranular thin film exhibits excellent soft magnetic properties at high frequencies and important properties are summarized as follows:[4] an electrical resistivity (ρ) of 374 $\mu\Omega$ cm, a H_K of 50 Oe, a hard axis coercivity of 1.25 Oe, a saturation magnetization ($4\pi M_S$) of 12.9 kG, and a resonance frequency (f_R) of 2.24 GHz.

Figure 2(a) shows the frequency dependence of the transmitted (S_{21}) and reflected (S_{11}) scattering parameters for the bare CPW transmission lines with various lengths of 2, 5, 10, and 15 mm. In all cases, the attenuation of the transmitted signal is relatively small over the whole frequency range investigated in this work. The difference in S_{21} depending on

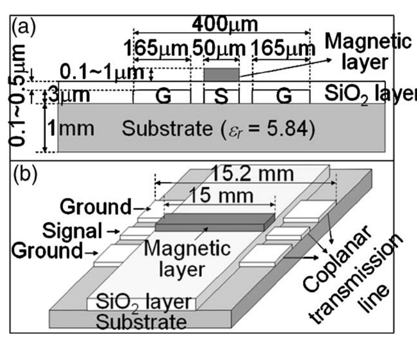

FIG. 1. (a) Cross-sectional view of the present device and (b) a schematic showing the overall device structure. The illustrations are for a magnetic thin film with a width of 50 μm (the same as the signal linewidth) and a length of 15 mm. Note that the dimensions are not in a proper scale.

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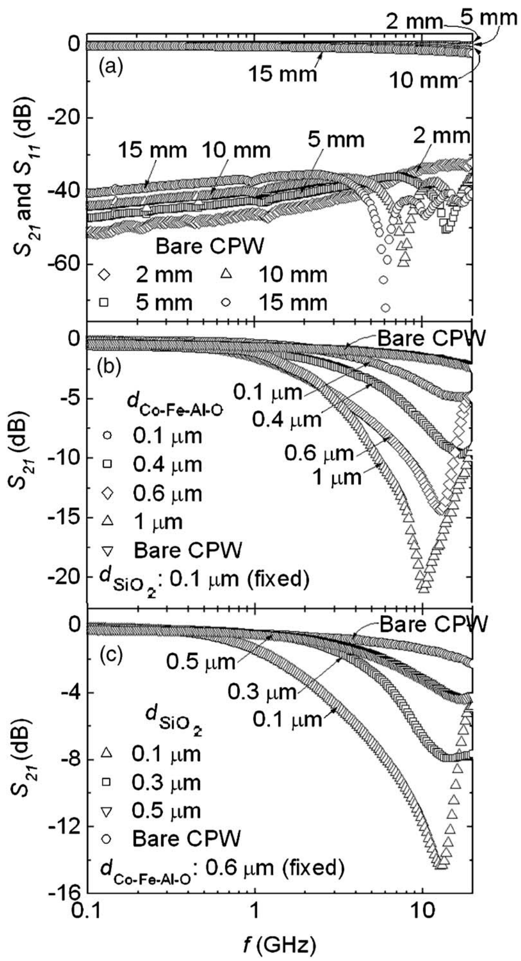

FIG. 2. (a) Frequency dependences of S_{21} (the upper part of the data) and S_{11} (the lower part of the data) for the bare CPW transmission lines at various lengths. [(b) and (c)] The frequency dependence of S_{21} for the present integrated noise suppressors at varying thicknesses of the magnetic thin film and of the SiO_2 dielectric layers.

the line length is not clearly visible except for the frequency range higher than 10 GHz where the signal attenuation increases progressively with increasing line length. Obviously, the signal attenuation is due to Ohmic losses caused by the conductive elements of the bare CPW line itself and accordingly the results for S_{21} can be well understood. The amount of reflected signal (S_{11}) is also very small being less than −30 dB in all cases. At low frequencies, the magnitude of reflected signal is higher at longer CPW transmission line length and it increases with increasing frequency. At high frequencies, however, no obvious tendency is seen, mainly due to the appearance of sharp minima (dips) in S_{11}. These dips are known to be caused by dimensional resonance losses which occur during the phase change at the half guided wavelength of the reflected signals.[6]

Figure 2(b) shows the frequency dependence of S_{21} for the present integrated noise suppressors with varying thicknesses of the magnetic thin film. The thickness of the magnetic layer (d_{mag}) was varied from 0.1 to 1 μm, while other device parameters were held constant; namely, the thickness of the SiO_2 dielectric layer was fixed at 0.1 μm and the width and length of the magnetic layer were 50 μm and 15 mm, respectively. At low frequencies below 1 GHz, no substantial difference is visible in the signal attenuation depending on the thickness of the magnetic thin film. However, a significant difference is clearly visible at high frequencies, mainly due to large dips in S_{21} occurring at frequencies higher than 10 GHz. These dips in S_{21} are typical of resonance and this resonance behavior is more prominent at larger d_{mag} values. As d_{mag} increases, the signal attenuation increases while the resonance frequency (f_R) decreases. At the smallest thickness ($d_{mag}=0.1$ μm), this behavior is not obvious, possibly due to a weak resonance or no resonance in the measured frequency range.

The most prominent feature is that the resonance frequencies observed in the present integrated devices are greater than 10 GHz, being much higher than those observed previously in similar devices, where FMR is known to be mainly responsible for the loss generation and eddy currents play a secondary role.[1,2] Noise suppressors reported so far including the nonintegrated devices using the same Co–Fe–Al–O magnetic thin film by the present authors[2] were well explained by the combined role of FMR and eddy currents. In the case of the nonintegrated devices with the Co–Fe–Al–O magnetic thin film, the dip in signal attenuation was observed to occur at 3.3 GHz, which was higher than the *intrinsic* FMR frequency of 2.24 GHz independently measured with a high frequency permeameter.[4] Considering that the magnetic thin film used in the nonintegrated device and for the permeameter measurement was exactly the same, this discrepancy appeared difficult to understand. No substantial shape anisotropy is expected since the dimensions of the magnetic thin film are 4 mm $\times$ 4 mm $\times$ 0.1 μm (thickness). Later, it was found that there exists an *effective* shape anisotropy in the nonintegrated device, because the field generated from the CPW signal line is very much localized, resulting in localized magnetization. Detailed calculations using a commercial program package (HFSS 9.2.1 of Ansoft Co.) show that the width of localized magnetization is slightly greater than the width of the transmission line.[2]

The very high resonance frequencies observed in the present integrated devices are simply too high to be explained in terms of FMR and the effective shape anisotropy. Furthermore, the present results for the d_{mag} dependence of the resonance frequency are completely opposite to those expected from FMR and the shape anisotropy. The shape anisotropy increases with increasing d_{mag}, so the resonance frequency should increase with increasing d_{mag}. This indicates that FMR is not responsible for the loss generation in the present integrated devices. One possibility is the *L-C* resonance, because the trilayer structure, the Co–Fe–Al–O magnetic thin film/SiO_2 dielectric layer/Cu transmission line, can form a distributed capacitor and the magnetic layer can be a distributed inductor. In the present case, the values of distributed capacitance (C) are expected to be identical to one another due to the same capacitor geometry including the dielectric layer thickness (fixed at 0.1 μm). The value of distributed inductance (L) differs, however, since the thickness of the magnetic layer is different; it will be highest (lowest) at the largest (smallest) thickness of the magnetic thin film. The well-known equation for the *L-C* resonance, $f_{LC}=1/2\pi\sqrt{LC}$, predicts that at a constant value of C (a situation similar to the present case), the *L-C* resonance frequency decreases with increasing L (increasing d_{mag}), in accord with the observed experimental results.

The results observed in other sets of integrated devices can also be explained similarly by the *L-C* resonance and one example is shown in Fig. 2(c) where the results for the frequency dependence of S_{21} are displayed at various thicknesses of the SiO_2 dielectric layers. The thickness of the dielectric layer (d_{SiO_2}) was varied from 0.1 to 0.5 μm, while other device parameters were held constant; namely, the thickness of the magnetic film was fixed at 0.6 μm and the width and length of the magnetic layer were maintained constant at 50 μm and 15 mm, respectively. With the fixed thickness of the magnetic thin film, the magnitude of distributed L remains nearly constant in all cases. However, the value of distributed C should increase with decreasing (d_{SiO_2}). So, similar to the case shown in Fig. 2(b), the shift of the signal attenuation dip can readily be explained.

The results for the frequency dependence of S_{21}, calculated by using the program package (HFSS 9.2.1 of Ansoft Co.), further confirm the L-C resonance as the main mechanism. The results, not shown here due to space limitation, indicate that the resonance occurs at approximately 10 GHz being similar to the present results and also the resonance frequency is little affected by FMR. Measurements were also performed in the presence of an applied magnetic field (by approaching a Nd–Fe–B permanent magnet to the device) and no change was observed in the resonance frequency, providing another evidence of the L-C resonance.

So far, the discussion on the present integrated devices has been confined to S_{21}, although characteristics of S_{11} are equally important in applications. The value of S_{11}, detailed results being not shown here due to space limitation, is very low; in most cases, it is below −20 dB at frequencies below 1 GHz and below −10 dB at the highest measured frequency of 20 GHz. This level of S_{11} is expected to be good enough for most device applications.

Let us now consider the change in the main mechanism of loss generation from FMR to L-C resonance as the devices are integrated. The main difference between the two types of devices, from the viewpoint of resonance, is the magnitude of both L and C. The separation between the CPW transmission line and the magnetic thin film in nonintegrated devices is much larger than that in integrated devices (0.1–0.5 μm). This difference in the separation has a direct impact on the difference in distributed C, because the magnitude of distributed C is inversely proportional to the separation. Furthermore, the "filler" material of the condenser in integrated devices (SiO_2) has a higher relative dielectric constant [ε_r=3.79 for SiO_2 at 1 MHz, (Ref. 7)] than that in nonintegrated devices (air, ε_r=1.0). This results in higher distributed C values in integrated devices by the factor of 3.79. A rough estimate shows that the value of distributed C in integrated devices is greater than that in nonintegrated devices by a factor of at least 76, provided that the separation between the CPW transmission line and the magnetic thin film in nonintegrated devices is 10 μm. So, nonintegrated devices with very small LC values have a weak effect on the signal transmission and reflection and also they will have very high values of L-C resonance, probably much higher than the highest measured frequency of 20 GHz. It is of interest to mention that the main mechanism of loss generation in previous integrated devices is FMR, not L-C resonance. This can be understood because the separation between the CPW transmission line and the magnetic thin film is reported to be 2 μm being much higher than the present value of 0.1–0.5 μm. The filler material of the condenser in previous devices is polyimide with a relative dielectric constant of 3.4 at 1 MHz.[7] From these, the previous integrated devices have lower LC values than the present ones by a factor of 4–20.

Due to their good noise attenuation characteristics and high resonance frequencies above 10 GHz, the present integrated devices are considered to be promising as an electromagnetic noise suppressor for information technology (IT) devices such as mobile phones. The present devices can have an additional important advantage in that their attenuation characteristics including the resonance frequency can be tuned during the device operation by applying a magnetic field, since the magnitude of distributed inductance can be modulated with the applied magnetic field. This effect will be stronger at larger thickness of magnetic thin film. A key to this frequency modulation is to develop magnetic materials with high resonance frequencies so that a high level of permeability can be achieved at the frequency of interest. A potential candidate is an Fe–Co–Ni–B thin film with a very high resonance frequency of 6.8 GHz, which was fabricated by an oblique deposition method,[8] and work to incorporate the new thin film is currently in progress.

Financial support from the National Research Laboratory program and Korea-Italy cooperation program is gratefully acknowledged. The authors thank K. H. Kim (Youngnam University) for his valuable advice on this work.

[1]M. Yamaguchi, Ki-Hyeon Kim, Takashi Kuribara, and Ken-Ichi Arai, IEEE Trans. Magn. **37**, 3183 (2002); K. H. Kim, M. Yamaguchi, K. I. Arai, H. Nagura, and S. Ohnuma, J. Appl. Phys. **93**, 8002 (2003); K. H. Kim, M. Yamaguchi, S. Ikeda, and K. I. Arai, IEEE Trans. Magn. **39**, 3031 (2003); K. H. Kim, M. Yamaguchi, K. I. Arai, N. Matsushita, and M. Abe, Trans. Magn. Soc. Jpn. **3**, 133 (2003).

[2]J. C. Sohn, S. H. Han, K. H. Kim, M. Yamaguchi, and S. H. Lim (unpublished).

[3]S. Ohnuma, N. Kobayashi, T. Masumoto, S. Mitani, and H. Fujimori, J. Appl. Phys. **85**, 4574 (1997).

[4]J. C. Sohn, D. J. Byun, and S. H. Lim, J. Magn. Magn. Mater. **272-276**, 1500 (2004); Phys. Status Solidi A **201**, 1786 (2004).

[5]B. C. Wadell, *Transmission Line Design Handbook* (Artech House, Boston, 1991), Chap. 3, pp. 73–92.

[6]Walter Barry, IEEE Trans. Microwave Theory Tech. **34**, 80 (1986); W. B. Weir, Proc. IEEE **62**, 33 (1974); A. M. Nicolson and G. F. Ross, IEEE Trans. Instrum. Meas. **19**, 377 (1970).

[7]F. Cardarelli, *Materials Handbook: A Concise Desktop Reference* (Springer, London, 2001), Chap. 7, pp. 7299–7311.

[8]M. Pasquale, F. Celegato, M. Coisson, A. Magni, S. Perero, P. Kabos, V. Teppati, S. H. Han, J. Kim, and S. H. Lim, J. Appl. Phys. **99**, 08M303 (2006).