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Si-based electromagnetic noise suppressors integrated with a magnetic thin film

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Electromagnetic noise suppressors on Cu transmission lines and oxidized Si substrate integrated with a SiO_2 dielectric and a Co–Fe–Al–O magnetic layer are presented. Extremely large signal attenuation is achieved (−90 dB at 20 GHz) while the signal reflection is relatively small, being below −10 dB. These characteristics are attributed to the distributed capacitance (C) formed by the Cu and the oxidized Si substrate and the $Cu/SiO_2/Co-Fe-Al-O$ and the distributed inductance (L) due to the magnetic thin film. The main loss mechanism is the L-C resonance and this emphasizes the role of the magnetic thin film providing the inductance. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2719681]

Electromagnetic noise is of significant technical importance as the operational frequency and degree of integration of electronic devices increase. One good example is mobile phones with an extremely compact design with their operational frequency currently reaching the gigahertz range. The frequency of electromagnetic noise can be even higher with the generation of harmonics. The fundamental operational frequency combines with harmonics to form repetitive nonsinusoidal distorted waves, which cause the different frequencies to flow back into the electrical system, even though they do not perform any useful work. These harmonics reduce the current capacity of the wiring system, causing overheating of the electrical apparatus. Moreover, they can disturb the normal voltages causing serious electromagnetic wave interference, eventually leading to a malfunction of electronic devices. Significant research has focused on suppressing the electromagnetic noise using magnetic materials with encouraging results.[1–6] Good signal attenuation characteristics combined with the high resonance frequencies of approximately 10 GHz were observed in integrated-type noise suppressors utilizing a nanogranular Co–Fe–Al–O magnetic thin film,[5,6] making them suitable for high frequency noise suppressors. The main mechanism for the generation of loss was found to be the L-C resonance, with two minor contributions of the eddy current and ferromagnetic resonance losses.[5,6] However, these noise suppressors do not perform in monolithic microwave integrated circuit (MMIC) devices because they are based on a glass substrate. In this work, the possibility of MMIC noise suppressors is sought by fabricating a coplanar waveguide transmission line integrated with a SiO_2 dielectric layer and a nanogranular Co–Fe–Al–O magnetic thin film on an oxidized Si substrate.

The coplanar transmission line with a characteristic impedance of 50 Ω was designed on a Si substrate (relative permittivity $\varepsilon_r = 11.9$) using the Muller and Hilberg equation.[7] A cross-sectional view and a schematic representation of the present device are shown in Figs. 1(a) and 1(b), respectively. The overall stack consisted of a nanogranular Co–Fe–Al–O magnetic thin film (1 μm)/SiO_2 (0.1 μm)/Cu transmission line (3 μm)/SiO_2 (2.5 μm)/Si substrate (500 μm). The insulating SiO_2 layer on top of the Si substrate is essential because the Si substrate (a standard B-doped p-type Si) is not a complete insulator. Of course, no insulating layer is required if glass is used as the substrate.[1–6] It should be noted that the length of the transmission line is 0.2 mm longer than that of the dielectric and magnetic layers in order to provide room for electrical contact. However, it is specified by the length of the dielectric and magnetic layers throughout this letter for convenience. A conventional microfabrication process, including photolithography, was used to fabricate the integrated noise suppressor.[5,6] A nanogranular

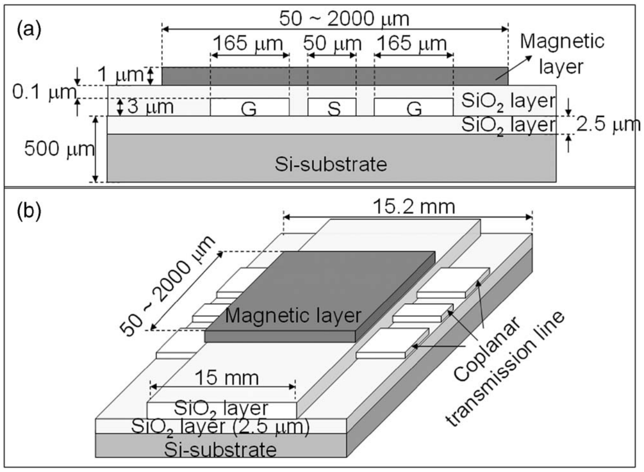

FIG. 1. (a) Cross-sectional view of the CPW transmission line, together with the dielectric and magnetic layers, on a Si substrate coated with a SiO_2 layer. (b) Schematic diagram showing the overall device structure. Note that the dimensions are not drawn to scale.

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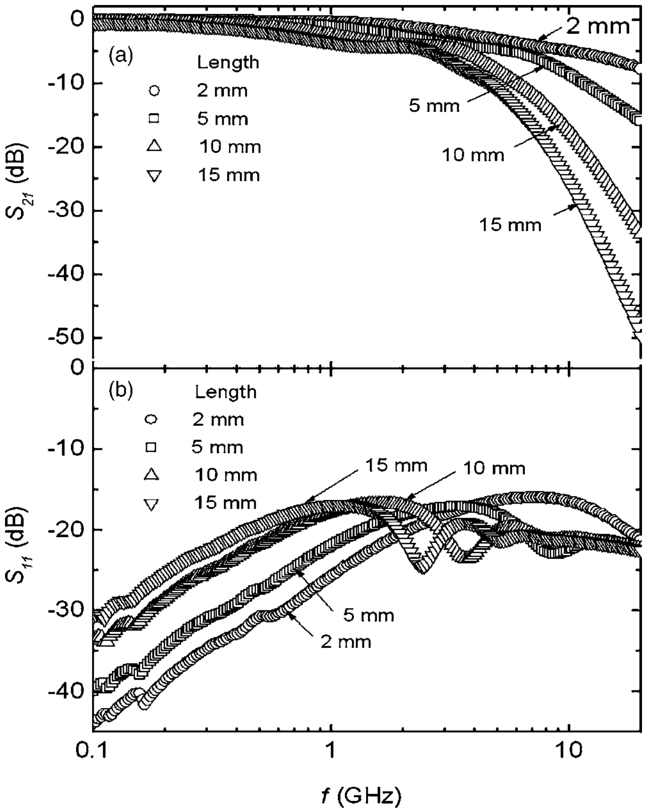

FIG. 2. Frequency dependences of (a) S_{21} and (b) S_{11} for the Si-based bare CPW transmission lines with various lengths of 2, 5, 10, and 15 mm. The coplanar transmission lines were fabricated on a 2.5 μm thick, 2 mm wide SiO_2 layer/a 500 μm thick Si substrate.

magnetic film with the composition of $Co_{41}Fe_{38}Al_{13}O_8$ (in at. %) was deposited by rf magnetron sputtering under a static magnetic field of 1 kOe to form an induced anisotropy.[8,9] For the measurements, two ground-signal-ground pin-type wafer probes were in mechanical contact with both ends of the coplanar waveguide (CPW) transmission line. The *S* parameters (S_{11} and S_{21}) were measured using a HP 8720D network analyzer at frequencies ranging from 0.1 to 20 GHz.

The $Co_{41}Fe_{38}Al_{13}O_8$ nanogranular thin film exhibits excellent soft magnetic properties at high frequencies and the important properties are summarized as follows:[8,9] an electrical resistivity (ρ) of 374 $\mu\Omega$ cm, an anisotropy field (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.

Figures 2(a) and 2(b) respectively, show the frequency dependency of the transmitted (S_{21}) and reflected (S_{11}) scattering parameters for the "bare" CPW transmission lines with lengths of 2, 5, 10, and 15 mm. Geometrically, the bare structure based on a Si substrate is similar to that based on a glass substrate[1–6] in that there were no dielectric (SiO_2) and magnetic (Co–Fe–Al–O) layers on the transmission line. However, in the viewpoint of wave transmission, a large difference is expected due to the existence of a distributed capacitor in the Si-based device formed by the Cu transmission line/SiO_2/Si substrate.

It is seen from Fig. 2(a) that, for a given transmission line length (l), the signal attenuation increases monotonically with increasing frequency, except for a small plateau near 2 GHz at $l=10$ and 15 mm. At a given frequency, the attenuation increases with increasing transmission line length, which is more obvious at higher frequencies. At the lowest measured frequency, 100 MHz, there was no obvious difference in the signal attenuation regardless of the length, but differences begin to appear at 200 MHz. At $l=2$ mm, only a moderate frequency dependence of the signal attenuation is observed over the entire frequency range. However, at longer lengths, a rather steep signal attenuation begins to occur at certain frequencies: 6 GHz at $l=5$ mm and 2–3 GHz at $l=10$ and 15 mm. The magnitudes of the signal attenuation at the highest measured frequency of 20 GHz are −7.5 dB at $l=2$ mm, −16 dB at $l=5$ mm, −33.5 dB at $l=10$ mm, and −50 dB at $l=15$ mm. This frequency dependence of the signal attenuation showing a monotonic behavior indicates the absence of resonance in the measured frequency range, possibly due to the absence or a small magnitude of the distributed inductance component in the bare structure. The amount of reflected signal (S_{11}), as shown in Fig. 2(b), is relatively small, being less than −15 dB in all cases. At low frequencies, the magnitude of the reflected signal increases progressively with increasing length. However, no obvious tendency is seen at high frequencies because of the appearance of sharp minima (dips) in S_{11}. These dips are caused by dimensional resonance losses, which occur when the length of the transmission line is an integer multiple of the half guided wavelength of the electromagnetic wave.[10–13]

It is of interest to compare the results for the bare transmission lines based on the Si substrate with those for the bare structure based on the glass substrate reported previously.[5,6] In the case of the bare structure based on the glass substrate, the attenuation of the transmitted signal is very small over the whole frequency range (at low frequencies, in particular), the highest being −2.3 dB at the highest frequency of 20 GHz and the longest length of 15 mm.[5,6] In addition, the amount of reflected signal is also very small, being less than −30 dB in all cases.[5,6] The main reason for the large difference can be the formation of a distributed capacitor even in the bare transmission line of the Si-based device. No capacitor component is expected in the glass-based bare structure where the Cu transmission line is on top of the dielectric glass. In this case, the scattering parameters and power loss can be determined mainly by the eddy current losses with a minor contribution from the distributed inductance of the Cu transmission line itself.

The dielectric and magnetic thin films were subsequently coated to the bare structure to form complete integrated devices. Figures 3(a) and 3(b) show the frequency dependences of S_{21} and S_{11}, respectively. The thicknesses of the SiO_2 and Co–Fe–Al–O thin films are 0.1 and 1 μm, respectively. The length of the transmission line was fixed to 15 mm (the longest), while the width of the magnetic thin film was varied from 50 to 2000 μm. With the additional dielectric and magnetic layers on top of the transmission line, another distributed capacitor can be formed by the trilayer structure, which is the Cu transmission line/SiO_2 dielectric layer/Co–Fe–Al–O magnetic thin film. Furthermore, the magnetic thin film can form an additional component in a distributed inductor. This additional inductance component due to the magnetic thin film is of significant importance in explaining the large difference of the results shown in Figs. 2(a) and 2(b) for the bare structure and in Figs. 3(a) and 3(b) for the full devices. This is because the transmission and reflection characteristics of the latter devices are greatly affected by the

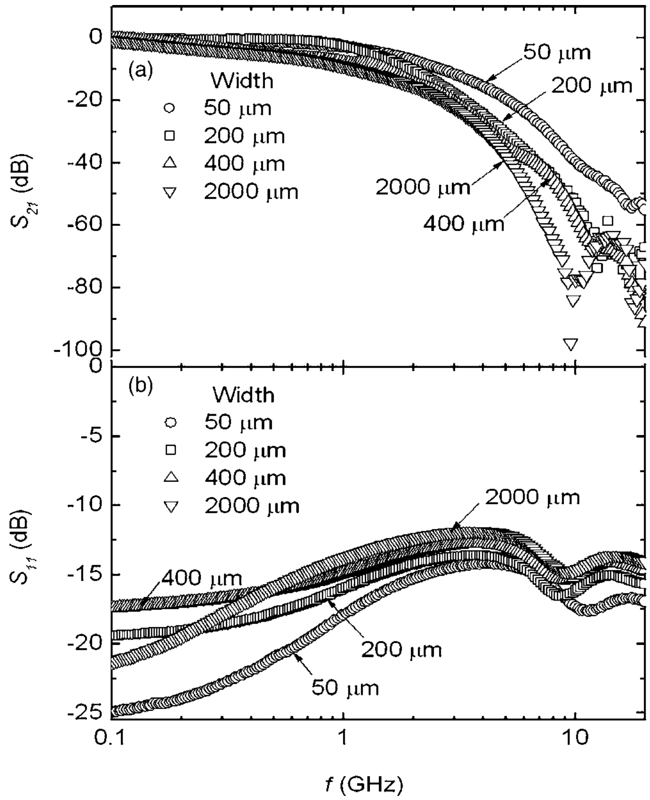

FIG. 3. Frequency dependences of (a) S_{21} and (b) S_{11} for the Si-based noise suppressors integrated with the dielectric (0.1 μm thick) and magnetic (1 μm thick) layers above the Cu transmission lines. The layers below the coplanar transmission lines were a 2.5 μm thick, 2 mm wide SiO_2 layer and a 500 μm thick Si substrate. The length of the magnetic thin film was fixed to 15 mm, but the width of the magnetic thin film was varied as 50, 200, 400, and 2000 μm.

L-C resonance, although, unlike the full devices based on a glass substrate,[5] a clear resonance signal is not observed in this work. It appears from the results in Figs. 3(a) and 3(b) that the resonance frequency of the present Si-based devices is near or higher than the highest measured frequency of 20 GHz. The role of the magnetic thin film can further be emphasized by considering the situation that a nonmagnetic nanogranular thin film with similar physical properties including electrical resistivity is used instead of the magnetic thin film. In this case, no *L-C* resonance will occur due to the absence of the inductance component and it will correspondingly affect the transmission and reflection characteristics. Other effects such as ferromagnetic resonance or ac losses due to a large electrical resistance of the granular Co–Fe–Al–O thin film may also be operative, but, judging from the results observed in glass-based devices,[5] these will play only a minor role.

The signal attenuation is increased with the incorporation of the dielectric and magnetic layers, as shown in Figs. 3(a) and 3(b). The signal attenuation tends to increase with increasing magnetic film width (w) and also increasing frequency. The value of S_{21} is below −50 dB for all samples at the highest measured frequency of 20 GHz, even approaching −90 dB for the w=400 and 2000 μm devices. This level of signal attenuation is probably highest for rf noise suppressors with similar lateral dimensions. As shown in Fig. 3(b), the amount of signal reflection increases with increasing width, which is a behavior similar to those observed previously.[6] In all cases, the value of S_{11} are below −10 dB over the whole frequency band, suggesting that the input signal distortion due to the reflected signals may not be serious when used as noise suppressors.

The Si-based CPW transmission lines integrated with a SiO_2 dielectric and a nanogranular Co–Fe–Al–O magnetic thin film are found to show very good noise attenuation characteristics. The value of S_{21} is as low as −90 dB at the highest measured frequency of 20 GHz. This level of signal attenuation is probably among the highest for the rf noise suppressors with similar lateral dimensions. The signal reflection is relatively small, being below −10 dB. Three important components can be identified for the good characteristics: (1) the distributed capacitance formed by the Cu transmission line/SiO_2 dielectric layer/Co–Fe–Al–O magnetic thin film, (2) the distributed inductance due to the magnetic thin film, and (3) the additional distributed capacitance formed by the Cu transmission line/SiO_2/Si substrate. It is noted that the first two components already exist in the usual glass-based devices where the main loss mechanism is the *L-C* resonance.[5] Considering this, the extremely large signal attenuation of the Si-based devices results from the third component, the additional distributed capacitance formed by the Cu transmission line/SiO_2/Si substrate. It is believed that these noise suppressors based on the Si substrate, with their good signal attenuation and reflection characteristics, will be an important step in the realization of MMIC noise suppressors.

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