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A Novel Multi-Layered Hetero-Structure of Ni-Zn Ferrite/TaN Buffer for Effective Magnetic Core in On-Chip Inductors

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1. Introduction

Integration of magnetic film into the CMOS-LSI is expected to achieve high-efficiency on-chip inductors with a magnetic core as well as to block the EMI noise propagation in mobile-chip application [1]. In the previous work, low-loss Ni-Zn ferrite ($Ni_{0.5}Zn_{0.5}Fe_2O_4$) film was sputtered at 300°C, compatible with Cu/low-k BEOL process [2]. Here, the TaN film acts not only as the barrier layer to block the out-diffusion of metal element in the NiZn-ferrite film, but also as a buffer layer to enhance the crystallization of spinel ferrite, improving the magnetic properties.

In this work, we investigate the further improvement of the magnetic properties in the ferrite film. Here, a hetero-structure of the ferrite/TaN stack is sputtered repeatedly to form the multi-layered hetero-structure. Electromagnetic property of the multi-layered structure is investigated with relation to the film microstructure.

2. Experimental

The Ni-Zn ferrite ($Ni_{0.5}Zn_{0.5}Fe_2O_4$) films were deposited by RF magnetron sputtering at 300°C. The sputtering gas condition was 8%-O_2/Ar, which was optimized for the spinel ferrite crystallization [2]. Besides the single-layer with different ferrite thickness on TaN, multi-layered ferrite/TaN hetero-structures were investigated, where the 200 nm-thick ferrite was split into two to four layers with 25 nm-thick TaN separation layer (Fig.2). Cross-sectional TEM observation and XRD analysis revealed the microstructure of the ferrite film. The magnetic hysteresis was measured by Vibrating Sample Magnetometer (VSM) with applying in-plane magnetic field. Thermally-evaporated Au electrode was deposited through shadow mask to measure the electric resistivity of the ferrite film. Finally, electromagnetic simulation (HFSS) characterized the effect of multi-layered hetero-structure on the induced magnetic field in the on-chip inductor.

3. Results and Discussion

Since thicker magnetic film might have more magnetic moment, increase in the thickness is expected to improve the magnetic property. The magnetic hysteresis for the single-layer ferrite on the TaN, however, was independent of the ferrite thickness (Fig.3). XRD analysis found that the $(311)_{spinel}$ peak intensity, which directly correlates with the magnetic property, unchanged for the various ferrite thicknesses. (Fig. 4). The TEM observation convinces that the lower layer on TaN had a fine and dense grain structure, compared to the upper layer (Fig.5(a)). The high-quality layer reaches up to approximately 50 nm from the TaN interface. Namely, the crystal quality changes in a vertical direction of the thick ferrite during the sputtering. The upper layer, which is less crystallized than the lower layer on TaN, has poor magnetic property.

The above result gives us an idea that the multi-layer of high-quality films, formed by repetitive sputtering of the thin-ferrite/TaN stack, improves the magnetic property. TEM observation (Fig 5(b)) shows that the each ferrite layer, sandwiched between 25 nm-TaN layers, has the fine grain structure, implying that the ferrite film in the ferrite/TaN interface region is well crystallized. The XRD peak intensity of $(311)_{spinel}$ is enhanced with the increase of the separation layer, even though the total ferrite thickness was fixed to 200nm (Fig. 6). This multi-layered structure achieved both high Ms and low Hc in the magnetic hysteresis (Fig. 7).

In order to discuss the magnetic property of the multi-layered structure, bi-layer model is proposed, where the 50 nm-thick high-quality (311)-orientated layer (A) and the less-orientated one (B) form each ferrite layer. Magnetic hysteresis for A and B is expressed as hyperbolic tangent [3] with different parameters. Linear combination of the hysteresis models, based on fraction of thickness in the total structure, represents hysteresis shape of every structure. (Fig.8). Extracted Hc and Ms of the all structures through the model analysis have almost the same values as the experimental data (Fig.9). This indicates that the fraction of the (311)-orientation region is important to improve the magnetic properties.

Separation of the ferrite film with the conductive TaN layer gave no impact on the electrical resistivity for the various multi-layers with the total ferrite thickness of 200 nm (Fig.10). All structures maintained high resistivity, ρ~10 MΩcm, desirable for the low-loss characteristics under high frequencies.

Finally, the effect of multi-layered hetero-structure is investigated by electromagnetic simulation of planar inductor, covered with the 4-layered ferrite or single-layered ferrite structures (Fig.11). The induced magnetic field in the inductor with 4-layered ferrite is greater than with the single-layer ferrite, resulted from the higher magnetic-confinement effect of the multi-layer than of the single layer.

4. Conclusions

Multi-layered hetero-structure of the Ni-Zn ferrite/TaN is developed by RF magnetron sputtering at 300°C to improve the magnetic property. The ferrite film in the ferrite/TaN interface region is well crystallized with (311)-orientation. This multi-layered structure achieves higher Ms and lower Hc than the single-layer. Magnetic hysteresis model reveals that the fraction of the (311)-orientation region in the total ferrite thickness is important to improve the magnetic properties. The high-μ multi-layer stack is effective to enhance the induced magnetic field in the on-chip inductor, desirable for RF/mobile applications.

References

[1] Donald S. Gardner, et al., IEDM Tech Dig.,2006,p221
[2] K.Kaneko, et al., Jpn. J. Appl. Phys.48 (2009) 04C030
[3] N.Inoue, et al., IEEE Trans. Electron Devices.48 (2001) 226.

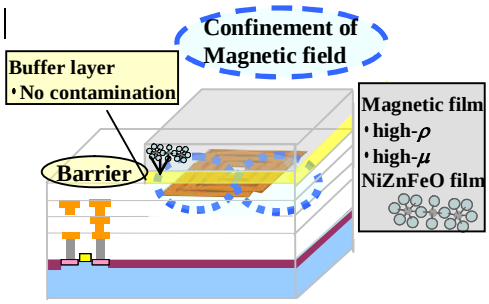

Fig.1 High-μ magnetic material with high resistivity (ρ) is a promising candidate for low loss inductors. The ferrite and barrier buffer layer process should be compatible with the Cu/low-k BEOL process less than 350°C.

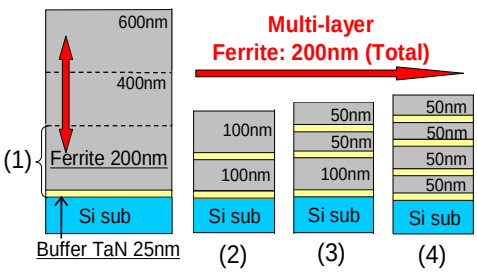

Fig.2 Evaluated sample structures. (1) Single layer with different ferrite thickness. (2)-(4) Multi-layered structures with total ferrite thickness of 200 nm.

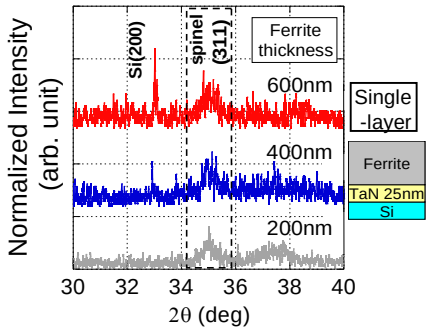

Fig.3 XRD spectra for ferrite films with different thickness on buffer TaN. These $(311)_{spinel}$ peak intensities are independent of ferrite thickness.

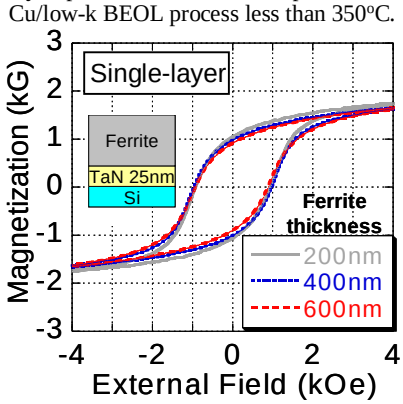

Fig.4 Magnetic hysteresis loops of the single-layer structure with various ferrite thickness, corresponding to the films in Fig.3. Magnetic property is independent of ferrite thickness.

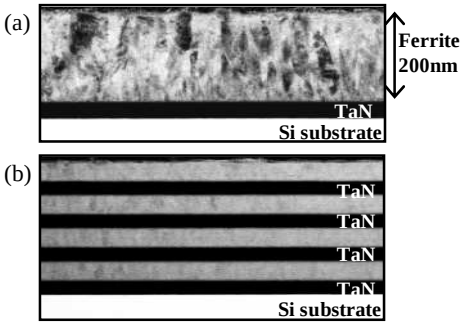

Fig.5 Cross sectional TEM images of (a) single ferrite/TaN layer and (b) multi-layer stack. The ferrite with fine-grained structure grows up to approximately 50 nm from the TaN interface.

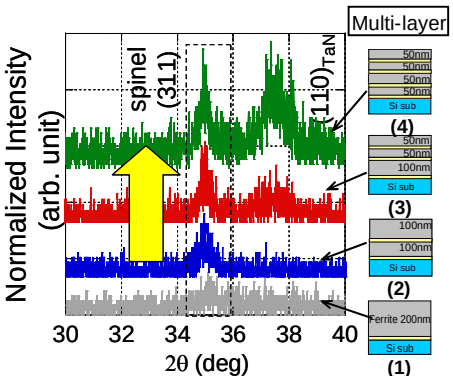

Fig.6 XRD spectra for various multi-layered structures. $(311)_{spinel}$ peak intensity is enhanced with increasing the number of ferrite/TaN interface.

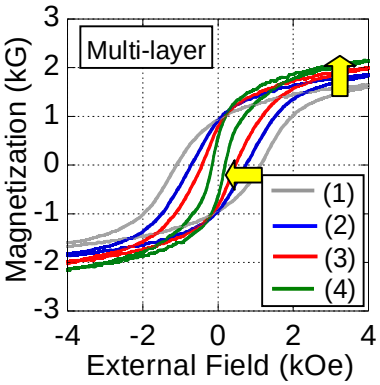

Fig. 7 Measured magnetic hysteresis loops for the multi-layered structures. Multi-layer stack decreases coercivity and increases magnetization of the films.

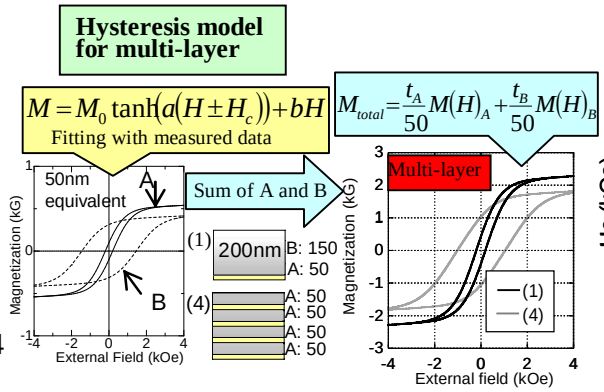

Fig.8 Hysteresis model for the multi-layer. Multi-layer is supposed to consist of a "50nm-thick well (311)-oriented layer (A)" and a "less-crystallized layer (B)". Multi-layer hysteresis is calculated by the sum of $M(H)_A$ and $M(H)_B$.

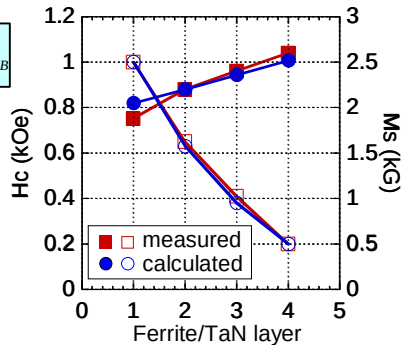

Fig. 9 Hc and Ms as a function of number of ferrite/TaN layers. Measured (Fig. 7) and calculated (Fig. 8) data are plotted.

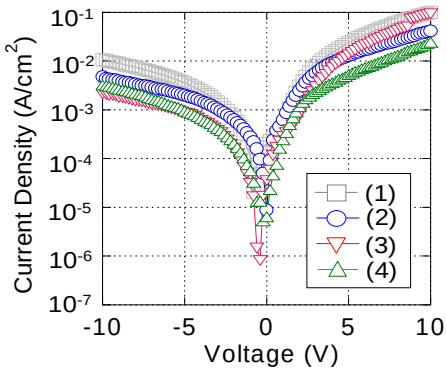

Fig. 10 Current density as a function of voltage for multi-layered structure. Resistivity of all structure is about 10 MΩcm range, irrespective of the number of ferrite/TaN layer.

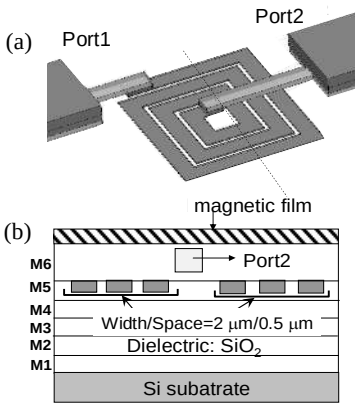

Fig.11 Simulated planar inductor structure covered with magnetic film. (a) bird's eye view of planar inductor and (b) cross-sectional view.

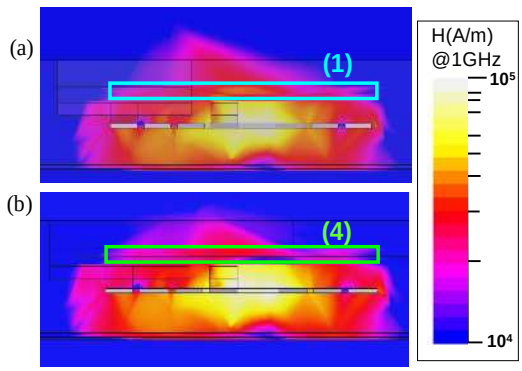

Fig.12 Simulated magnetic field distribution (@1GHz) around the inductor with (a) single ferrite/TaN layer and 4-layer stack. Four-layer stack enhances the induced magnetic field, leading to the high-efficiency inductor.