

Effect of Post-deposition Annealing on Fe₃O₄ Thin Film Deposited via Electron Cyclotron Resonance Sputtering

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Introduction: Magnetite (Fe₃O₄), a half-metallic ferromagnetic material, has garnered significant attention for spin transport applications in spintronics due to its high Curie temperature (~860 K) and excellent electrical conductivity at room temperature (RT) [1]. Fe₃O₄ thin film deposition has been extensively studied using magnetron sputtering techniques [1–3]. Electron cyclotron resonance (ECR) sputtering is an alternative sputtering technique, which is working at a much lower pressure (<10⁻² Pa) compared to magnetron sputtering (~10⁻¹–10¹ Pa) and keeping the plasma away from the sample. As a result, ECR sputtering allows easier lift-off processing, which is useful for precise patterning of thin films in microfabrication, enabling the creation of well-defined structures for device applications without etching, than magnetron sputtering. Furthermore, post-deposition annealing of Fe₃O₄ thin films has been also studied to enhance magnetic and electrical properties [1], making it a crucial step in optimizing film performance. We report here Fe₃O₄ thin film deposition via ECR sputtering and effect of its post-deposition annealing.

Experiment: The thin film was deposited using an Fe₃O₄ target, with Ar gas generating plasma in the sputter chamber. The operating pressure was 6.5×10⁻³ Pa, and the deposition time and thickness were 100 minutes and ~110nm, respectively. Post-deposition annealing was conducted at 300°C, 400°C, and 500°C in an Ar (90%) + H₂ (10%) atmosphere. Four samples were categorized by annealing temperatures: **a** (unannealed), **b** (300°C), **c** (400°C), and **d** (500°C). Annealing significantly influenced magnetic properties as shown in Fig. 1. Sample **c** shows the highest saturation magnetization. Figure 2 shows x-ray diffraction (XRD) curves. Only GaAs peaks were observed in all samples, that indicates the samples remain amorphous before or after annealing. Those tendencies are almost the same as the literature [1]. Table 1 shows intensity ratios of Fe³⁺, Fe²⁺, and Fe estimated by x-ray photoelectron spectroscopy (XPS). By annealing, Fe³⁺ ratio decreased, and Fe²⁺ and Fe ratios increased. That suggests partial Fe ion valency reduction, driven by elevated temperatures, local oxygen deficiency, and thermal decomposition. We think that the combination of Fe₃O₄ and metallic Fe enhances saturation magnetization by promoting better magnetic domain alignment. Excessive annealing in sample **d** causes a slight decrease in magnetization due to decreased Fe²⁺ and Fe ratios compared to sample **c**. These improved properties will make it a promising candidate as a ferromagnetic source and drain for spin field-effect transistors.

References:

- [1] L. Cao et al., J. Mater. Sci.: Mater. Electron. 32 (2021) 23653.
- [2] L. Pan et al., Thin Solid Films 473 (2005) 63.
- [3] Y. Peng et al., J. Appl. Phys. 93 (2002) 7957.

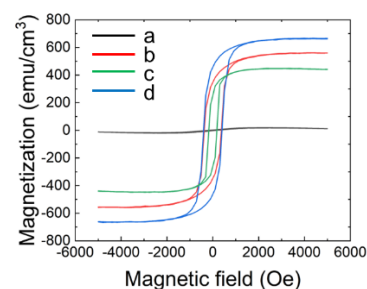


Fig. 1: Magnetization curves.

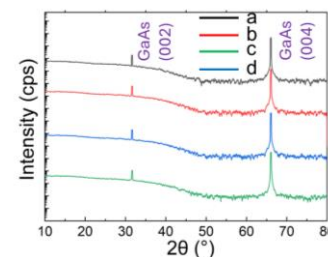


Fig. 2: X-ray diffraction curves.

Table 1: Intensity ratios by x-ray photoelectron spectroscopy.

	Fe ³⁺	Fe ²⁺	Fe
a	74%	26%	0%
b	63%	32%	4%
c	60%	35%	5%
d	65%	31%	4%