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XMCD study of $NiFe_2O_4$ coupled with 2D MXene layers

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1. Introduction: A spinel ferrite, nickel ferrite ($NiFe_2O_4$), is well known for its dielectric characteristics, modest saturation magnetisation (usually ~50–87 emu/g), and ferrimagnetic qualities, which make it appropriate for spintronics, EMI shielding, and microwave absorptions. Its magnetic losses, which are caused by ferromagnetic resonance and domain wall motion, efficiently reduce the magnetic component of electromagnetic waves, especially in the microwave frequency range (e.g., X-band, 8–12 GHz). However, Snoek's limit, which limitations the product of magnetic permeability and resonance frequency, inhibits the frequency-dependent performance of pure $NiFe_2O_4$. Other drawbacks include high density and minimal dielectric loss. In order to improve dielectric losses and overall shielding performance, researchers have investigated hybrid composites that combine $NiFe_2O_4$ with highly conductive components [1-3].

Ti_3C_2, a 2D transition metal carbide belonging to the MXene family, is distinguished by its high specific surface area, many surfaces functional groups (such as -OH and -F), and remarkable electrical conductivity (~10^4 S/m). Because of these characteristics, Ti_3C_2 is a perfect choice for EMI shielding, as it can cause dielectric polarisation and conduction losses. Ti_3C_2 layered structure makes it easier for conductive networks, which dissipate EM wave energy through ohmic losses. Meanwhile, its functional groups and defects help to create interfacial effects and dipole polarisation. However, Ti_3C_2 limited capacity to attenuate the magnetic component of electromagnetic waves is due to its lack of strong magnetic characteristics. A synergistic effect is produced when $NiFe_2O_4$ and Ti_3C_2 are combined. This results in improved EMI shielding effectiveness because the magnetic losses of $NiFe_2O_4$ balance the dielectric and conduction losses of Ti_3C_2.

One noteworthy feature of $NiFe_2O_4$-Ti_3C_2 composites is the noted decrease in magnetic properties when contrasted with pure $NiFe_2O_4$. This decrease, which is typified by decreased magnetic permeability and saturation magnetisation, results from several reasons. $NiFe_2O_4$ magnetic contribution is diluted by the non-magnetic Ti_3C_2 phase, and superexchange interactions between Fe^{3+} and Ni^{2+} ions are weakened by magnetic disorder introduced by interfacial interactions between ferrite nanoparticles and MXene layers. Magnetic characteristics can also be further diminished by structural changes like doping or lattice strain. Despite this, the composites have better EMI shielding performance [3], mostly because of improved impedance matching and dielectric losses. The heterogeneous interface between $NiFe_2O_4$ and Ti_3C_2 increases dielectric losses (ε'') by promoting Maxwell-Wagner polarisation, while the high conductivity of Ti_3C_2 creates a dissipative network that increases conduction losses. Through processes like ferromagnetic resonance, the moderate magnetic losses (μ) from $NiFe_2O_4$, being reduced, nevertheless contribute to the attenuation of electromagnetic waves, especially in the GHz region. Along with strong attenuation, the $NiFe_2O_4/Ti_3C_2$ composite achieves optimal impedance matching with empty space, resulting in a significant microwave absorption peak at 13.92 GHz that enhances absorption performance. MXene conductive nanosheets encourage electron transit for conductive losses, while the $NiFe_2O_4/Ti_3C_2$ interface adds flaws and polarisation to increase dielectric loss. Magnetic loss is driven by $NiFe_2O_4$ natural resonance, and the 2D structure of the composite allows for many internal reflections for increased energy dissipation. With variable characteristics based on MXene content via hydrothermal synthesis, increasing $NiFe_2O_4$ content increases magnetic loss while decreasing permittivity. It is still unknown, though, how MXene concentration affects magnetisation. In order to offer new insights on magnetic property modifications, this work uses soft X-ray magnetic circular dichroism (XMCD), an element-specific approach, to explore ferromagnetism in $NiFe_2O_4/Ti_3C_2$ MXene with varying Ti_3C_2 contents.

2. Experimental sections: MXene (Ti_3C_2), ultra-high molecular weight polyethylene (UHMWPE), and nickel ferrite ($NiFe_2O_4$) were the primary constituents of the two-step solution dispersion and compression moulding method used to create the $NiFe_2O_4/Ti_3C_2$ composites. Solution dispersion was used to create composite powders. Ti_3C_2 was ultrasonically dissolved in ethanol for 60 minutes to attain homogeneous dispersion, whereas UHMWPE was dissolved in ethanol separately and vigorously agitated for two hours at 110°C. A homogenous composite powder was created by adding the $NiFe_2O_4/Ti_3C_2$ dispersion to the UHMWPE solution and then stirring the resulting ternary combination at 400 rpm and 110°C until the ethanol was entirely evaporated.

The structural and magnetic characteristics of $NiFe_2O_4$ thin films were examined using advanced techniques. At the Ni and Fe $L_{2,3}$ edges, X-ray Absorption Spectroscopy (XAS) and X-ray Magnetic Circular Dichroism (XMCD) were carried out using the undulator beamline 16A (BL-16A) at the Photon Factory (KEK), Japan, for comprehensively element-specific magnetic investigations. The XMCD pattern was created by comparing the absorption coefficients (μ^+ and μ^-) for parallel and antiparallel photon helicities with respect to the prevailing spin direction. This allowed the investigation of magnetic characteristics using circularly polarised light. Analysing the magnetic field dependency of XMCD intensity allowed for the study of the connection between spin and orbital magnetic moments. The BL-16A monochromator produced circularly polarised light with an energy resolution of $E/\Delta E > 10,000$ and a polarisation degree of roughly 87% ± 4%. In a high-vacuum laboratory with a base pressure of 10^{-9} Torr, all tests were carried out at 300 K. Surface-sensitive measurements were made using the total electron yield (TEY) mode, and the probing depth was around 5 nm. An out-of-plane setup was used to gather XAS and XMCD data in a 2T magnetic field.

3. Results and Discussions: In **Fig. 1**, spin–orbit splitting into L_3 and L_2 components is revealed by X-ray absorption spectroscopy (XAS) at the Fe and Ni L-edges for $NiFe_2O_4/Ti_3C_2$ composites with the Ti_3C_2 contents under a 2T magnetic field. These occur at ~710 eV (L_3) and ~724 eV (L_2) for Fe, and at ~855 eV and ~872 eV for Ni, with a predicted branching ratio of 0.67, though electrostatic interactions may affect this. MXene causes changes in the electronic structure and redistribution of charges, as evidenced by the energy splitting and peak intensities. The X-ray magnetic circular dichroism (XMCD) spectra in **Fig. 1** verify element-specific ferromagnetic interactions. The inverse spinel structure of $NiFe_2O_4$ causes the magnetic moments of Fe to mostly cancel out across octahedral and tetrahedral sites, resulting in larger Ni L-edge signals than Fe.

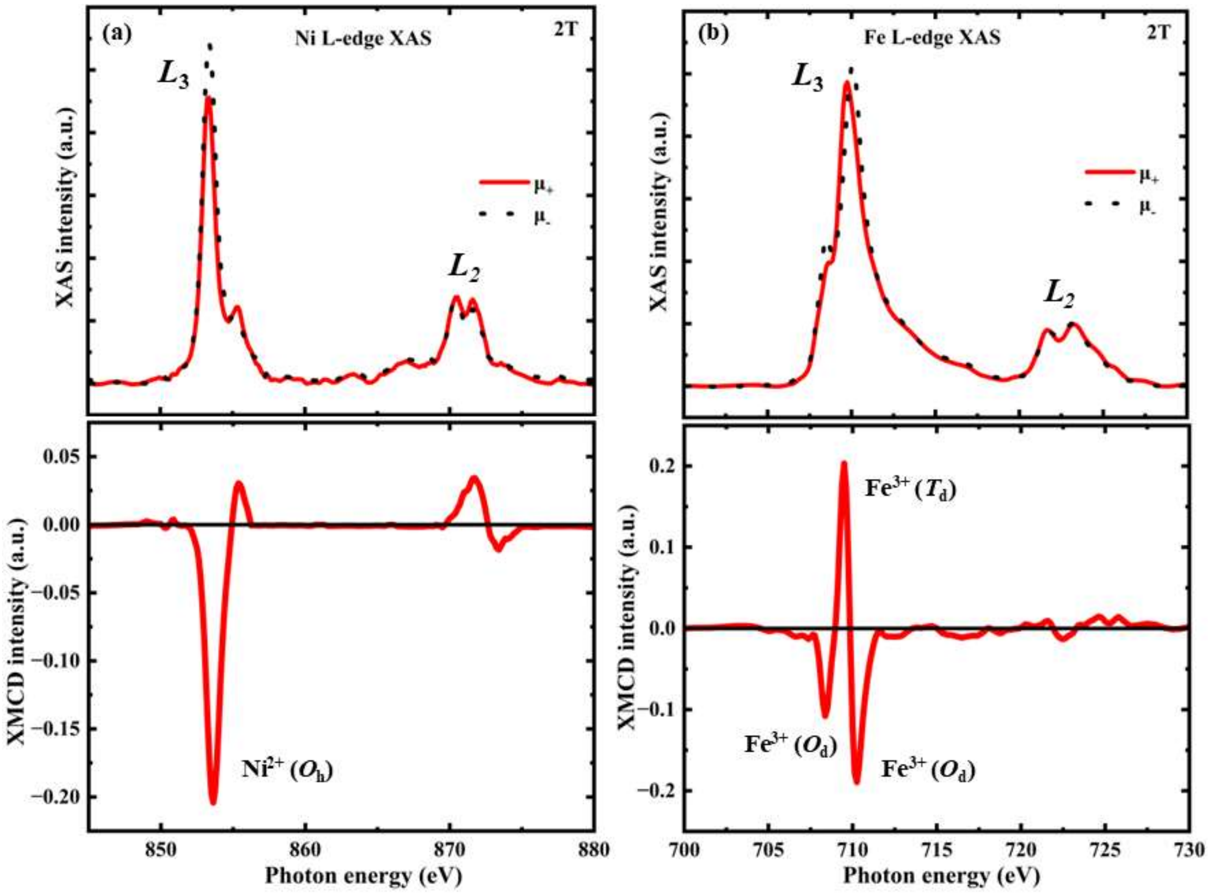

Figure 1: Ni and Fe $L_{2,3}$-edge XAS and XMCD of $NiFe_2O_4/Ti_3C_2$ composites.

We observed the ferromagnetic (FM) characteristics of $NiFe_2O_4/Ti_3C_2$ composites in this work. The results show that the inclusion of MXene consistently reduces magnetic characteristics [3]. These $NiFe_2O_4/Ti_3C_2$ composites show promise for electromagnetic shielding applications that reduce environmental electromagnetic pollution. Using Sum-rule [4-7], anyone can calculate spin and orbital magnetic moments at Ni and Fe *L*-edge.

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