Development of Thermal Conductivity Enhancement Materials Using Ferromagnetism Properties

박나림, 이지현, 이지형, 권주미, 한명준
서울 시립대학교 프로젝트 종합설계

INTRODUCTION

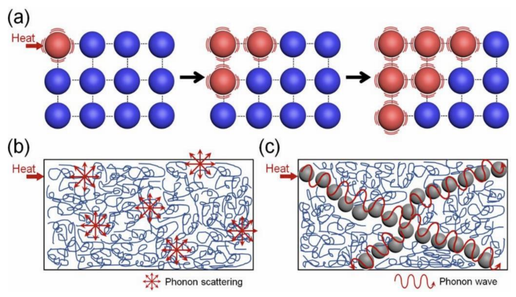

Fig 1. Heat transfer mechanism by phonon

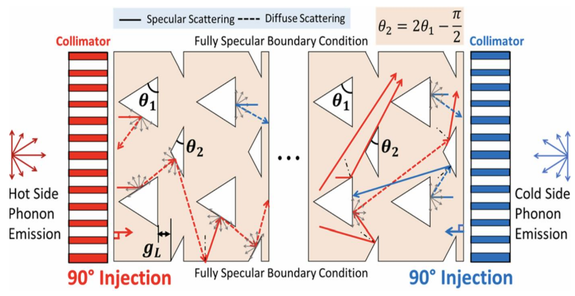

Fig 2. Effect on phonon wave by hole

Phonons are virtual particles that represent the thermal vibrations propagating in the form of waves, also referred to as sound waves. As depicted in Figure 1(a), phonons move in a wave-like pattern during lattice vibrations, facilitating the transfer of thermal energy. Figure 1(b) illustrates phonon scattering, where phonons are scattered by other phonons or lattice structures. An increase in phonon scattering results in a decrease in thermal conduction by phonons. Figure 1(c) depicts a phonon wave, showing that the length of the phonon wave decreases due to phonon scattering.

$\lambda = \left(\frac{1}{3}\right) * \mathrm{C} * u * l$ $(\lambda: Thermal\ conductivity,\ \mathrm{C}: Heat\ capacity,$
$u: Average\ velocity\ of\ phonons,\ l: Mean\ free\ path\ of\ phonons)$

Examining the thermal conductivity equation, it can be observed that the speed of phonons is almost constant. Therefore, the thermal conductivity of the material is determined by the mean free path of phonons. If phonon scattering decreases, leading to an increase in the mean free path of phonons, the material's thermal conductivity increases.

Phonon waves experience boundary scattering at the interfaces within the material. Therefore, reducing the porosity of the material decreases phonon scattering, facilitating the formation of an effective heat pathway and resulting in an increase in the material's thermal conductivity. This mechanism explains that when the material's porosity decreases, phonon scattering decreases, and a well-formed heat pathway leads to an increase in the material's thermal conductivity. Consequently, increasing the material's orderliness enhances its thermal conductivity..

METHOD & MATERIALS

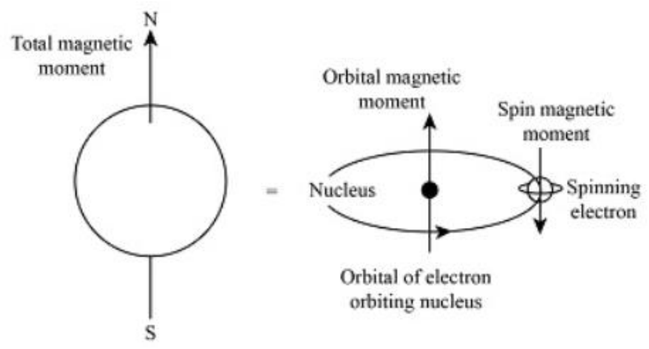

Fig 3. Representation of total magnetic moment

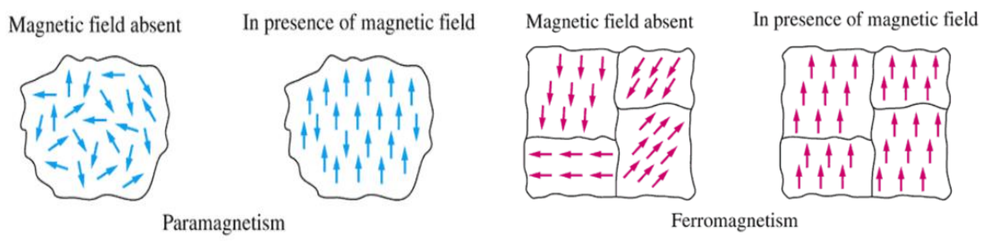

Fig 4. Magnetic property of paramagnetism and ferromagnetism

In Bohr's atomic model, electrons follow orbits around the nucleus and develop an orbital magnetic moment according to Fleming's law. The total magnetic moment is represented by the sum of the orbital and spin magnetic moments. If the spin and orbital magnetic moments are incompletely canceled, we have a permanent dipole moment. Paramagnetism is randomly arranged in the absence of a magnetic field, but ferromagnetism is aligned in one direction within a domain even in the absence of a magnetic field.

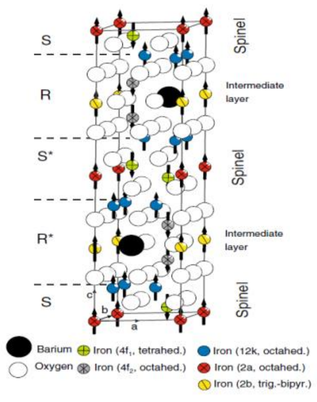

Fig 5. Crystal Structure of Barium hexaferrite showing a unit cell and position of ionic sites in the four spinel blocks(SRS*R*) and relative orientation of magnetic moments of Fe^{3+} ions

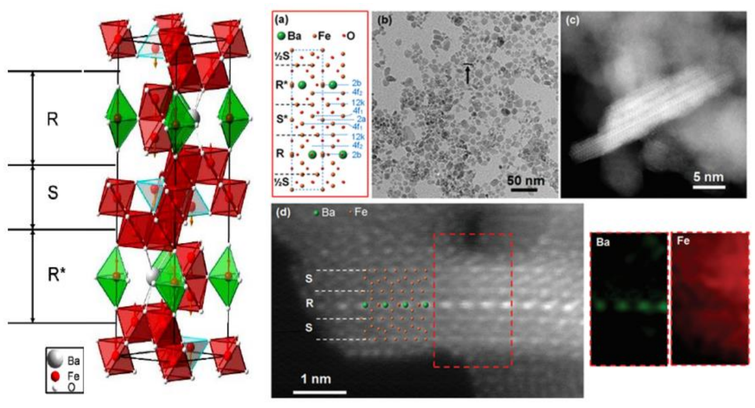

Fig 6. HAADF STEM image of nanoplatelet(sample BF80) oriented edge-on

The Fe cations are the sole source of magnetic moment. The general structure of M-type hexaferrite is constructed from 4 building blocks, namely S, S*, R, and R*. The S and S* blocks are spinels with 2 oxygen layers and six Fe^{3+} ions. Four of these Fe3+ ions are in the octahedral sites with their spins aligned parallel to each other. The remaining two Fe^{3+} ions are in tetrahedral sites and have their spins antiparallel to those that are at the octahedral sites. As for the hexagonal R and R* blocks, each R block contains six Fe^{3+} ions, of which five are in octahedral sites, three having spin up and two having spin down polarization. Thus, the magnetic dipole is formed in the c-axis, [001] direction.

Barium hexaferrite grows as a nanoplatelet(NPL) structure due to its anisotropic crystal structure. The direction of the magnetic dipole indicates a direction perpendicular to the NPL.

RESULTS & DISCUSSION

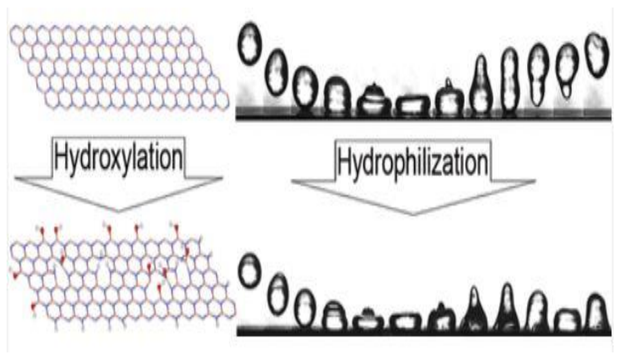

Fig 7. Surface modification of hBN

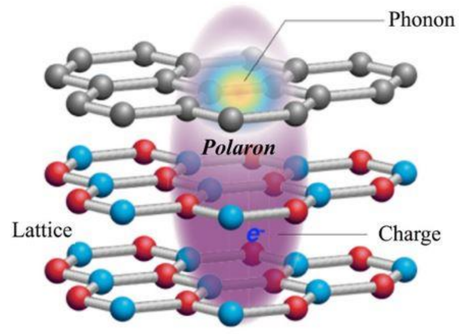

Fig 8. Van der Waals force

Through surface modification, hydroxyl groups attach to the electrophilic boron sites on the surface of hexagonal boron nitride (h-BN). As depicted in the diagram, hydroxyl groups attach to boron sites 1 and 3 on the hBN hexagonal structure, rendering the material surface polar and hydrophilic. Barium ferrite nanoplates, possessing permanent magnetic dipoles, and hBN nanoplates modified for surface polarity can mechanically adsorb to each other when they come into contact in the [001] direction due to Van der Waals forces between the surfaces.

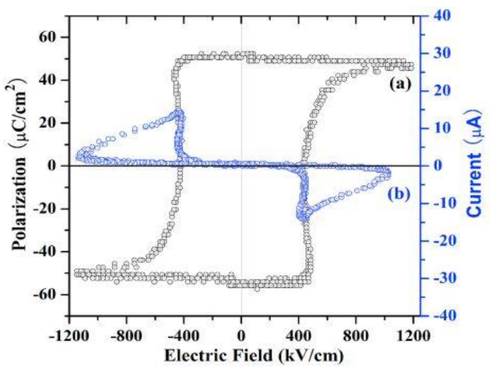

Fig 9. Magnetic Property of Barium Ferrite

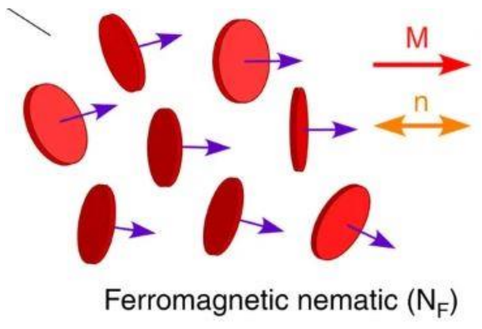

Fig 10. Ferromagnetic nanoplate magnetic field response

When a magnetic field is applied to this combined hBN-Barium Ferrite NPL, the hBN is aligned to the magnetic field with disappearing the Rotational Degeneracy according to the ferromagnetic characteristics of Barium Ferrite.

CONCLUSIONS

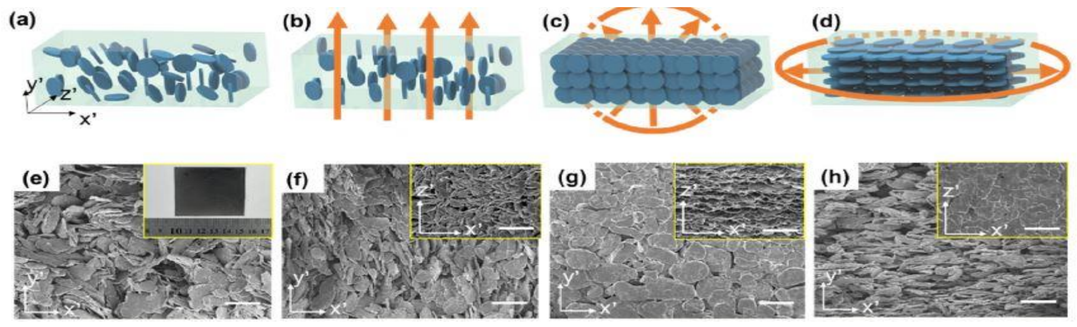

Fig 11. The schematic and SEM images of composites prepared without magnetic field, with a static magnetic field, with a magnetic field rotating around z' axis and y' axis, respectively: DGNPs/PVA (a) and (e), PVGNPs/PVA(b) and (f), CVGNPs/PVA(c) and (g), and CHGNPs/PVA (d) and (h).

This study discusses a paper in which graphene, possessing properties similar to BN, was aligned using a magnetic field. By employing a rotating magnetic field, graphene nanoplates were arranged in polyvinyl alcohol (PVA), leading to an enhancement in thermal conductivity. Leveraging this property resulted in approximately a tenfold improvement in thermal conductivity compared to disorderedly distributed graphene composites. As graphene is a magnetic material, it aligns itself according to the magnetic field when subjected to it. The paper introduces a total of three types of aligned graphene composites: GNP aligned using a static magnetic field, coplanar vertically aligned GNPs/PVA (CVGNPs/PVA) aligned using a dynamic magnetic field, and coplanar horizontally aligned GNPs/PVA.

Among these, the method employing a static magnetic field resulted in low assembly and low thermal conductivity due to the application of magnetic dipoles in a single direction. On the other hand, when a dynamic magnetic field was employed, the graphene nanoplates were densely and orderly oriented in a direction orthogonal to the rotating magnetic field.

The coplanar arranged vertical GNPs/PVA (CVGNPs/PVA) composites exhibited a thermal conductivity of approximately 11.78 W m−1 K−1 in the through-plane direction. In the case of Figures 2(g) and (h), it can be observed that the alignment is denser and more orderly compared to (f) utilizing a static magnetic field.

The through-plane thermal conductivity of the composite improved from 1.14 W /m K (DGNPs/PVA) to 6.75 W /m K (PVGNPs/PVA), which is due to the alignment of GNPs in the static magnetic field. The through-plane thermal conductivity of the CVGNPs/ PVA composite increased even further to 11.78 W /m K . This demonstrates the effectiveness of a rotating magnetic field in providing orderly aligned GNPs. The value is approximately 1.8 and 10 times higher than that of PVGNPs/PVA and DGNPs/PVA composites, respectively. In conclusion, eliminating rotational degeneracy resulted in an increase in thermal conductivity.