Chapter 1

An Overview of Hard Ferrites: Types and Structures

Rohit Jasrotia\textsuperscript{1,2*}, Suman\textsuperscript{3}, Ankit Verma\textsuperscript{4*}, Rahul Kalia\textsuperscript{1}, Himanshi\textsuperscript{1}, Rajat Kaushal\textsuperscript{1}, Jyoti Prakash\textsuperscript{1}, Sachin Kumar Godara\textsuperscript{5}, and Pooja Puri\textsuperscript{6}

\textsuperscript{1} School of Physics and Materials Science, Shoolini University, Bajhol, Solan, H.P., India
\textsuperscript{2} Himalayan Centre of Excellence in Nanotechnology, Shoolini University, Bajhol, Solan, H.P., India
\textsuperscript{3} Department of Mathematics, School of Basic and Applied Sciences, Maharaja Agrasen University, Baddi, Himachal Pradesh, India
\textsuperscript{4} Faculty of Science and Technology, ICFAI University, Himachal Pradesh, India
\textsuperscript{5} Department of Apparel and Textile Technology, Guru Nanak Dev University, Amritsar
\textsuperscript{6} Department of Chemistry, Bahra University, Waknaghat, Solan, H.P., India
rohitsinghjasrotia4444@gmail.com, ankitvermaarki26@gmail.com

Abstract

In 1950s, after the discovery of hexagonal ferrites called as hexaferrites, there has been an increasing level of curiosity in hexaferrites and still, it is increasing exponentially. Commercially and technologically, hexaferrites belong to a category of important magnetic materials due to their utilization in various applications such as permanent magnets, recording media, storage devices, rod antennas, high frequency devices, microwave devices etc. There are six types of hexagonal ferrites as M-type, Z-type, Y-type, X-type, U-type and W-type respectively, out of which, the most worldwide manufactured hexagonal ferrite is Barium M-type hexagonal ferrite named as BaM\textsuperscript{1}. All categories of hexaferrites shows ferrimagnetic behaviour as their magnetic nature is inherently related to their crystal structure. The current chapter focuses on the classification and structure of hexagonal ferrites. In this book chapter, firstly, we report the six categories of hexaferrites as M, Y, W, X, Z, W and then, we provide a detailed comprehensive review of two approaches called as spinel and S/R/T based model for reporting the structure of hexagonal ferrites respectively. After that, we reported a comprehensive structure of each hexaferrite. Lastly, the concluding remarks have been presented in the current chapter.
Keywords
Hexaferrites, Classification, Structure, Spinel Model, S/R/T Model

List of Abbreviations
PM Permanent magnets
RM Recording media
SD Storage devices
MD Microwave devices
HFD High frequency devices
DC Dielectric constant
FMR Ferromagnetic resonance
GHz Giga Hertz
SC Satellites communications
LAN Local area network
RST Remote sensing
MA Microwave absorbers
RAM Radar absorbing materials
EMI Electromagnetic interference
SD Storage devices

Contents
An Overview of Hard Ferrites: Types and Structures........................................1
1. Introduction..................................................................................................3
2. Classification and characteristics of hexaferrites.................................4
   2.1 M-type hexaferrite ........................................................................5
   2.2 Z-type hexaferrite ........................................................................6
   2.3 Y-type hexaferrite ........................................................................7
   2.4 W-type hexaferrite ........................................................................7
   2.5 X-type hexaferrite ........................................................................7
   2.6 U-type hexaferrite ........................................................................8
3. A brief description of the solid-state chemistry of hexaferrites............8
4. Approaches for better understanding of crystal structure of hexaferrites.........................................................................................10
1. Introduction

In the last few decades, ferrites become important magnetic materials due to their superfluous magnetic characteristics which makes them useful for a number of research applications such as permanent magnets, storage devices, recording media etc. [1–10,10]. In 1950, according to the statement of Richard Feynman, ferrites are very difficult to investigate as a theoretical study but, as a part of technology and utilization, it is considered as one of the superior issues to analyse [11]. The first permanent magnet was found in 1951 and moreover, it was synthesized on the phenomenon of barium M-type hexaferrite usually named as BaM hexaferrite [12,13]. The researchers as well as scientists have paid great attention towards the fabrication of ferrites and hexaferrites for various applications in a well-defined way after their discovery in the 1950s [14]. Therefore, in 1955, the hexaferrites were synthesized for gyromagnetic applications in a defined manner [15,16]. The hexagonal ferrites are now the subject of a great deal of experimental investigation in the laboratory. [17]. Hexaferrites are fabricated for commercial use as well as technology use in various research areas. The hexagonal ferrites are classified into six different categories as M-type, Z-type, Y-type, W-type, X-type and U-type [18,19]. The magnetic characteristics of hexaferrites are inherently related to their crystal structure having crystalline behaviour, therefore, they show ferrimagnetic behaviour respectively and also, it indicates induced magnetization with a preferable orientation within the hexagonal based crystal structure [14,20]. As all the hexaferrites show magneto crystalline anisotropy, thus,
on this phenomenon, they have been categorized further into two groups as uniaxial and ferroplana/hexaplana hexaferrites. The uniaxial hexaferrites have an easy axis of magnetisation whereas, the ferroplana/hexaplana are those hexaferrites with an easy plane of magnetisation [21,22]. The number of publications under the category of hexagonal ferrites from 1991-2020 is presented in figure 1. The current book chapter concentrate on the brief description of hexagonal ferrites especially, containing divalent metal cations as barium and strontium along their classification and structure of each of hexaferrites respectively.

![Yearwise Publications (Hexagonal Ferrites)](image)

*Figure 1: Year wise publications under the category of hexagonal ferrites from 1991 to 2020 (Using Scopus Database)*

2. **Classification and characteristics of hexaferrites**

In 1925, the first magnetic mineral called magnetoplumbite was explained and therefore, the hexagonal crystal structure was derived with the chemical formula, PbFe$_{7.5}$Mn$_{3.5}$Al$_{0.5}$Ti$_{0.5}$O$_{19}$ in the year 1938 respectively. The pure form of magnetoplumbite mineral was found to be PbM or PbFe$_{12}$O$_{19}$ [23]. At the time of the Second World War, various isomorphous compounds-based materials along with an inclusion of BaM were proposed but they were not investigated structurally till that time. BaM or BaFe$_{12}$O$_{19}$ called as barium hexaferrite having hexagonal like crystal structure was reported by Went et al.
In 1950s, at the Philips laboratories, a comprehensive investigation of all the major phases of hexagonal ferrites were published, concluding in a book named as “Ferrites” by Smit and Wijn’s in 1959 [25]. All these compounds comprise of a hexagonal like structure with two crystal lattice parameters called “a” and “c” representing thickness of hexagonal plane and altitude of a crystal. The hexagonal ferrites have been categorized as uniaxial and ferroplana/hexaplana as provided in table 1. Moreover, table 1 provides a comprehensive study of hexagonal ferrites about their types, chemical composition and characteristics. The hexagonal ferrites are categorized into six types as listed below [26].

- M-type hexagonal ferrite (BaM)
- Z-type hexagonal ferrite (Co2Z)
- Y-type hexagonal ferrite (Co2Y)
- W-type hexagonal ferrite (Co2W)
- X-type hexagonal ferrite (Co2X)
- U-type hexagonal ferrite (Co2U)

All these types of hexagonal ferrites can be fabricated for commercial or technological use with the utilization of various synthesis methods such as sol-gel, auto-combustion, co-precipitation, hydrothermal, citrate precursor, solid-state or conventional ceramic, microemulsion, green synthesis [7] and many more [8,10,27]. The different categories of hexagonal ferrites have been explained as given below.

<table>
<thead>
<tr>
<th>Hexaferrite</th>
<th>Chemical Composition</th>
<th>Room Temperature Magnetisation</th>
</tr>
</thead>
<tbody>
<tr>
<td>M-type</td>
<td>BaM/BaFe_{12}O_{19}/SrFe_{12}O_{19}</td>
<td>Uniaxial</td>
</tr>
<tr>
<td>Z-type</td>
<td>Co2Z/Ba3Co2Fe24O_{41}/Ba3Me2Fe24O_{41}</td>
<td>In plane</td>
</tr>
<tr>
<td>Y-type</td>
<td>Co2Y/Ba2Co2Fe_{12}O_{22}/Ba2Me2Fe_{12}O_{22}</td>
<td>In plane</td>
</tr>
<tr>
<td>W-type</td>
<td>Co2Ba2Co2Fe_{12}O_{22}/Ba2Me2Fe_{12}O_{22}</td>
<td>In cone</td>
</tr>
<tr>
<td>X-type</td>
<td>Co2X/Ba2Co2Fe_{28}O_{46}/Ba2Me2Fe_{28}O_{46}</td>
<td>In cone</td>
</tr>
<tr>
<td>U-type</td>
<td>Co2U/Ba4Co2Fe_{36}O_{60}/Ba4Me2Fe_{36}O_{60}</td>
<td>In plane</td>
</tr>
</tbody>
</table>

2.1 M-type hexaferrite
The barium M-type hexagonal ferrite called as BaM was firstly confirmed in the year 1936 and moreover, at that time, their crystal structure was unconfirmed. Initially, the barium hexaferrite was called as ferroxdure in order to differentiate it from the spinel-based ferrite. The M-type hexagonal ferrite have the chemical composition MeFe_{12}O_{19}, where Me is any divalent metal cation as Ba^{2+}, Sr^{2+} or Pb^{2+}, etc. with a high uniaxial room temperature magnetisation along the c-axis [28]. The molecular weight and hardness of barium M-type
hexaferrite is found to be 1112 g and 5.9 GPa respectively [29,30]. Also, the strontium M-type hexaferrite called as SrM has a molecular weight of 1062 g in which the Sr$^{2+}$ ions replaced the Ba$^{2+}$ ions in the crystal structure of BaFe$_{12}$O$_{19}$ hexaferrite [18]. The physical characteristics of BaM shows similar behaviour to that of the characteristics of SrM hexaferrite respectively [21]. The physical characteristics of BaM and SrM Hexagonal ferrite provided in table 2.

<table>
<thead>
<tr>
<th>Hexaferrite</th>
<th>Chemical Composition</th>
<th>Molecular Weight (g)</th>
<th>Density (g/cm$^3$)</th>
<th>Melting Point (Kelvin)</th>
<th>Lattice Parameters (a &amp; c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BaM</td>
<td>BaFe$<em>{12}$O$</em>{19}$</td>
<td>1112</td>
<td>5.295</td>
<td>1611</td>
<td>a = 5.888, c = 23.189</td>
</tr>
<tr>
<td>SrM</td>
<td>SrFe$<em>{12}$O$</em>{19}$</td>
<td>1062</td>
<td>5.101</td>
<td>1692</td>
<td>a = 5.884, c = 23.063</td>
</tr>
</tbody>
</table>

2.2 Z-type hexaferrite

When the Y-type ferroxolana hexaferrites were discovered, the Z-type hexaferrites with the chemical composition Ba$_3$Me$_2$Fe$_{24}$O$_{41}$ were discovered at the same time. Where ‘Me’ represents the divalent metal cations, and moreover, it has parallel uniaxial anisotropy corresponding to the c-axis and a-axis, respectively [31]. At low temperatures, Z-type hexagonal ferrite exhibits a simple cone magnetization, with a 65° magnetization angle matching to the c-axis. The preferred magnetisation remains in the basal plane until between 207 and 242 degrees Celsius, when it switches to the c-axis. [25, 32]. Z-type hexagonal ferrite has the following physical characteristics, which are listed in Table 3.

<table>
<thead>
<tr>
<th>Hexaferrite</th>
<th>Chemical Composition</th>
<th>Molecular Weight (g)</th>
<th>Density (g/cm$^3$)</th>
<th>Melting Point (Kelvin)</th>
<th>Lattice Parameters (a &amp; c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z-type</td>
<td>Co$_2$Z/Ba$<em>3$Me$<em>2$Fe$</em>{24}$O$</em>{41}$</td>
<td>2522</td>
<td>5.35</td>
<td>1611</td>
<td>a = 5.91, c = 52.30</td>
</tr>
</tbody>
</table>
2.3 Y-type hexaferrite

The Y-type hexagonal ferrite called as Co$_2$Y having the chemical formula Ba$_2$Me$_2$Fe$_{12}$O$_{22}$ was the first ferroxplana hexaferrite ever discovered, where Me indicates the small divalent metal cation [33]. At room temperature, all the Co$_2$Y hexaferrites have a preferable plane of magnetisation at 90° angle corresponding to the hexagonal c-axis respectively and also, out of all these Co$_2$Y hexaferrites, Cu$_2$Y is the only hexaferrite with a preferable uniaxial direction of magnetisation [34]. In addition, below -58°C, the room temperature planar magnetic anisotropy of Y-type hexaferrites has been converted to a cone of magnetisation. Table 4 indicates the physical parameters of Y-type hexagonal ferrite.

Table 4: Physical parameters of Y-type hexaferrite [19,33]

<table>
<thead>
<tr>
<th>Hexaferrite</th>
<th>Chemical Composition</th>
<th>Molecular Weight (g)</th>
<th>Density (g/cm$^3$)</th>
<th>Lattice Parameters (a &amp; c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y-type</td>
<td>Co$_2$Y/ Ba$<em>2$Me$<em>2$Fe$</em>{12}$O$</em>{22}$</td>
<td>1410</td>
<td>5.40</td>
<td>a = 5.88, c = 43.50</td>
</tr>
</tbody>
</table>

2.4 W-type hexaferrite

The W-type hexagonal ferrites with the chemical composition BaMe$_2$Fe$_{16}$O$_{27}$, were found as an assorted phase of both M-type and X-type hexaferrites, where ‘Me’ indicates transition divalent metal cations. FeW called as BaFe$_2$Fe$_{16}$O$_{27}$ was the first reported W-type hexaferrite having an easy axis of magnetisation along the c-axis of hexagonally based lattice structure and moreover, all W-type hexaferrites except Co$_2$W have a uniaxial anisotropy respectively. Table 5 represents the physical parameters of W-type hexaferrite [21,35].

Table 5: Physical parameters of W-type hexaferrite [21,35]

<table>
<thead>
<tr>
<th>Hexaferrite</th>
<th>Chemical Composition</th>
<th>Molecular Weight (g)</th>
<th>Density (g/cm$^3$)</th>
<th>Lattice Parameters (a &amp; c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W-type</td>
<td>Co$<em>2$W/ BaMe$<em>2$Fe$</em>{16}$O$</em>{27}$</td>
<td>1581</td>
<td>5.31</td>
<td>a = 5.83, c = 32.84</td>
</tr>
</tbody>
</table>

2.5 X-type hexaferrite

A uniaxial anisotropy along the c-axis of the hexagonally based crystal structure was seen in 1952 in the first known X-type hexagonal ferrite, Fe2X, which was discovered in 1952. For example, the chemical composition Ba$_2$Me$_2$Fe$_{28}$O$_{46}$ denotes the first-row transition
divalent metal cations, whereas ‘Me’ denotes the second-row transition divalent metal
cations. It has been observed as a mixed phase of M-type/W-type hexaferrite with room
temperature uniaxial magnetic anisotropy, with the exception of Co₂X. A cone of
magnetisation is seen in both directions along the c-axis of Co₂X hexaferrite when viewed
at an angle of 74°. As shown in Table 6, the physical characteristics of X-type hexaferrite
are given.

Table 6: Physical parameters of X-type hexaferrite [21]

<table>
<thead>
<tr>
<th>Hexaferrite</th>
<th>Chemical Composition</th>
<th>Molecular Weight (g)</th>
<th>Density (g/cm³)</th>
<th>Lattice Parameters (a &amp; c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>U-type</td>
<td>Co₂U/ Ba₂Me₂Fe₂₈O₄₆</td>
<td>2688</td>
<td>5.29</td>
<td>a = 5.889, c = 86.303</td>
</tr>
</tbody>
</table>

2.6 U-type hexaferrite

The U-type hexagonal ferrite with the chemical composition, Ba₄Me₂Fe₃₆O₆₀, where ‘Me’
represents the first-row transition metal cations have uniaxial anisotropy. Except all U-type
hexaferrites, Co₂U have room temperature planar anisotropy respectively. The table 7
indicates the physical parameters of U-type hexagonal ferrites.

Table 7: Physical parameters of U-type hexaferrite [21]

<table>
<thead>
<tr>
<th>Hexaferrite</th>
<th>Chemical Composition</th>
<th>Molecular Weight (g)</th>
<th>Density (g/cm³)</th>
<th>Lattice Parameters (a &amp; c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>U-type</td>
<td>Co₂U/ Ba₄Me₂Fe₃₆O₆₀</td>
<td>3622</td>
<td>5.01</td>
<td>a = 5.89, c = 113.22</td>
</tr>
</tbody>
</table>

3. A brief description of the solid-state chemistry of hexaferrites

The solid-state reactions of the BaO.Fe₃O₃.MeO system have been extensively
investigated utilising a conventional ceramic synthesis method based on barium carbonate
and barium oxides as starting materials. Using the Vinnik-created phase diagrams (see
Figure 2), the x-ray spacings for specimens of barium hexaferrites containing more than
50% of Fe₂O₃ were calculated for the M-type, Y-type, Z-type, and W-type varieties of the
material. Neither Co₂X nor Co₂U hexaferrites could be identified in polycrystalline
specimens after two hours of calcination at 1200 °C followed by four hours of annealing
at 1250 °C [36]. Additionally, the existence of a little amount of variation in the values of
the lattice parameters (a & c) for specimens of phase diagrams of both W- and Z-type
hexagonal hexaferrites shows that the M, Y, and W-types may absorb in Z-type hexaferrite. Additionally, it was revealed that M-type hexaferrite absorbs more effectively in W-type hexaferrite than in Y- or Z-type hexaferrites.

Figure 2: Schematic scheme of BaO–Fe₂O₃–MeO system [21]

Because the other phases dissolve considerably more slowly, dissolving the BaFe₂O₄ in HCl may remove the non-magnetic hexagonal ferrite from the mixture [37]. It was observed that producing a single-phase specimen of polycrystalline Y-type, Z-type, or W-type hexaferrite is very difficult, and the original specimen required to be reduced to a single phase by grain grinding. A flux approach was used to synthesise a high melting point hexaferrite hexamer consisting of Co₂W/Co₂Z/Co₂X/Co₂U hexaferrites, however single crystal growth of Co₂Y and Fe₂W proved challenging. All hexaferrites, according to Neckenburger and Severin's investigation, overlap at the same temperature [24, 38]. Hexaferrite phases of the U- and X-type are often unclear against this backdrop of mixed phases. Due to the comparable x-ray diffraction patterns and magnetic characteristics of hexagonal ferrites, hexaferrites contain similar basic building blocks inside their hexagonal structures. The Y-type, Z-type, and W-type phases have ceased to exist at temperatures greater than 1300 °C. This is due to the transformation of ferric ions into ferrous ions. Lotgering combined oriented grains of barium M-type hexaferrite with non-oriented grains of other non-magnetic materials to create oriented polycrystalline crystals with hexagonal shapes. This reaction produced orientated W, Y, and Z hexaferrites, as well as substituted M-type hexaferrites [39]. The co-precipitated precursors have been widely investigated for
their use in the synthesis of M, Y, Z, and W hexaferrites. The nitrate salts were agitated until a concentration was obtained in a solution of ammonium oxalate. At this time, precipitation occurred, resulting in a mixture of partially degraded oxalates. They were then completely decomposed at 500°C, calcined at 800°C, and then burnt at 1100-1400°C. Around 650°C, the spinel phase starts to form. The BaM phase is formed around 800°C. Sudakar et al. investigated the BaO–NiO–Fe2O3 system between 80 and 90°C. At 750°C, the nanopowder precursors all contained the required hexaferrite phase in the single-phase hexagonal hexaferrite crystal structure [40].

4. Approaches for better understanding of crystal structure of hexaferrites

The structure of six types of hexaferrites can be explained on the phenomenon of two types of approaches called as spinel-based model and S/R/T blocks-based model [2]. The magnetic mineral magnetoplumbite was first described in the 1920s. It was described as a hexagonal crystal of the empirical formula, PbFe7.5Mn3.5Al0.5O19 [21]. Philips Laboratories conducted many research in the 1950s to replicate a synthetic version of this mineral (PbFe12O19) and its analogs, for starting the development of the young field of hexaferrite. In these synthetic hexaferrites, lead was substituted for large divalent cations, namely strontium (SrFe12O19) and barium (BaFe12O19). At a chemical level, hexaferrite can be understood as the combination of spinel ferrites, Y-type/M-type hexaferrites. For instance, the Z-type hexaferrites may be represented as the sum of the Y-type and M-type hexaferrites. Crystallographically, all hexaferrites can be understood as a composition of spinel and hexagonal layers. The unit cell of each subgroup of hexaferrite would be created by different stacking arrangements of these basic components. Therefore, the family of hexaferrites do not differ in their crystallographic framework. This wide range of stacking possibilities has a massive effect on their magnetic properties.

4.1 Spinel based model

The hexaferrites have a crystal structure that is similar to that of spinel ferrites, consisting of plates of cubic densely packed oxygen anions interspersed with lesser sized metal cations. They are found in the interstices of the metal cation complex (tetrahedral site-A) and (octahedral site-B). Additionally, the spinel crystal structure is determined by the four oxygen atom-based layers that repeat the three vertical levels, forming an ABCABC crystal lattice between each layer. The interstices between the layers are filled by one B-site/three B-sites and two A-sites. Hexaferrites have a crystal structure composed of two plates, designated S4 and S6, which are joined together by layers (B1 and B2) containing two barium atoms. As a result, the M-type, Y-type, and Z-type hexaferrites are composed of a single plate designated as S4, the X-type is composed of two plates designated as S4 and
S₆, and the W-type hexaferrite is composed of a single plate designated as S₆. In contrast, the B₁ layer acts as a single hexagonal layer, whereas the B₂ layer behaves as two hexagonal layers. Additionally, the B₁ layer is found in M, W, and Z-type hexaferrites, which contain one barium atom in the location of 4 oxygen anions. On the other hand, the B₂ layer is found in Z-type hexaferrites, which contain two Ba atoms in the location of 8 oxygen anions, and the B₃ layer is found in M-type hexaferrites, which contain 2 Ba atoms in By combining the S and B layers, which are referred to as S₂, M₅, and Y₆ units, the crystal structure of hexaferrites may be investigated in great detail. The S₂ layer represents the spinel layers, the M₅ layer represents B₁ inserted between the four spinel layers, and the Y₆ layer represents two B₂ layers placed between the four spinel layers, as shown in Figure 3 [2].

Figure 3: Cross-sectional interpretation of B₁ layer, B₂ layer and M₅, Y₆ and S₂ units [2]
4.2 **S/R/T blocks based model**

All known hexagonal ferrites are composed of structural blocks S, R, and T, and their crystalline structure is a superposition of these three blocks. When the letters S, R, and T are rotated 180 degrees around the hexagonal c-axis, they become the letters S, R, and T. The viewpoint, space-filling, ball, and sticky views of S/R/T blocks in hexaferrite crystal structure are shown in Figures 4a and 4b.

![Figure 4: (a) Perspective (b) Space-filling, ball and sticky view of S/R/T blocks in the crystal structure of hexaferrites [21] (Image)](image)

The repeating unit 'S' is composed of \([\text{Me}^{2+}\text{Fe}^{4+}\text{O}_8]^0\) (S^0) or \([\text{Fe}^{6+}\text{O}_8]^2+\) (S^2+), each of which has an uncompensated or neutral charge of +2. The 'R' subunit is composed of \([\text{Me}^{2+}\text{Fe}^{6+}\text{O}_{11}]^-\), while the 'T' unit is composed of \([\text{Ba}^{2+}\text{Fe}^{8+}\text{O}_{14}]^0\). The subunit 'R' interacts with the subunit 'S^{2+}' to form the neutral block (RS), which has the chemical formula \(\text{MeFe}_{12}\text{O}_{19}\) (M-phase). Similar, the 'T' subunit interacts with the S^0 to generate the neutral block (TS), which has the chemical formula \(\text{Ba}_2\text{Me}_2\text{Fe}_{12}\text{O}_{22}\) (Y-phase). Other stacking sequences of cubic and hexagonal basic units are also known [41–43], resulting in a variety of hexaferrite compositions including W, X, Y, Z, and U-type hexaferrite.
(M-phase). Similar to the previous example, the 'T' subunit interacts with the S° to produce the neutral block (TS), which has the chemical formula Ba$_2$Me$_2$Fe$_{12}$O$_{22}$ (Y-phase). Additionally, other stacking sequences of cubic and hexagonal basic units are known [41–43], resulting in a range of hexaferrite compositions, including W, X, Y, Z, and U-type hexaferrite.

Table 8: Basic properties of six types of Hexaferrites where *represents 180° rotation of block around the c-axis [2,21]

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Type of Hexaferrite</th>
<th>Chemical Formula</th>
<th>Spinel plate and hexagonal layers</th>
<th>S/R/T blocks Crystal structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>M</td>
<td>BaFe$<em>{12}$O$</em>{19}$</td>
<td>2M$_5$=B$_1$S$_4$B$_1$S$_4$</td>
<td>SRS<em>R</em></td>
</tr>
<tr>
<td>2</td>
<td>W</td>
<td>BaMe$<em>2$Fe$</em>{16}$O$_{27}$</td>
<td>2W$_7$=B$_1$S$_6$B$_1$S$_6$</td>
<td>SSRS<em>S</em>R*</td>
</tr>
<tr>
<td>3</td>
<td>X</td>
<td>Ba$<em>2$Me$<em>2$Fe$</em>{28}$O$</em>{46}$</td>
<td>3X$_{12}$=B$_3$S$_4$B$_1$S$_6$B$_1$S$_6$B$_1$S$_6$B$_1$S$_6$B$_1$S$_6$B$_1$S$_6$</td>
<td>SSRS<em>S</em>R*</td>
</tr>
<tr>
<td>4</td>
<td>Y</td>
<td>Ba$<em>2$Me$<em>2$Fe$</em>{12}$O$</em>{22}$</td>
<td>2Y$_6$=B$_2$S$_4$B$_2$S$_4$B$_2$S$_4$</td>
<td>3(ST)</td>
</tr>
<tr>
<td>5</td>
<td>Z</td>
<td>Ba$<em>3$Me$<em>2$Fe$</em>{24}$O$</em>{41}$</td>
<td>2Z$_{11}$=B$_2$S$_4$B$_1$S$_4$B$_2$S$_4$B$_1$S$_4$</td>
<td>STSRS<em>T</em>S<em>R</em></td>
</tr>
<tr>
<td>6</td>
<td>U</td>
<td>Ba$<em>4$Me$<em>2$Fe$</em>{36}$O$</em>{60}$</td>
<td>U$_{16}$=B$_1$S$_4$B$_2$S$_4$B$_1$S$_4$</td>
<td>SRS<em>R</em>S<em>T</em></td>
</tr>
</tbody>
</table>

5. Crystal structure of hexaferrites

The hexagonal ferrite belongs to a class of hexaferrites having a hexagonal crystal structure along with a distinct c-axis. The composition of hexaferrites is provided in figure 5.
Hexaferrites' magnetic properties are related to their crystalline formations. Hexaferrites and hexaplan ferrites are two different forms of hexagonal ferrites having anisotropic magnetism. Hexaferrites have a typical composition of MFe₁₂O₁₉, where ‘M’ is a divalent metal cation such as Ba, Sr, or Pb [24, 44, 45]. While both hexaferrite and spinel ferrite have a similar crystal structure, with densely packed oxygen ions, the primary distinction is that certain layers in hexaferrite include metal ions with the same ionic radius as the oxygen ions. The metals occupy three distinct locations in the crystal structure (octahedral, trigonal bi-pyramid, and tetrahedral), which was further subdivided into five sublattice categories denoted as 12k, 2a, 2b, 4f₁, and 4f₂, respectively. Three sublattices, 12k, 2a, and 2b, have a high spin, while 4f₁ and 4f₂ have a low spin. There are six subtypes of hexagonal ferrites, denoted by the letters M, W, X, Y, Z, and U [1] [2] [5] [6], while (MO + MeO) and Fe₂O₃ are present in the proportions of 1:6, 3:8, 4:6, 4:14, 5:12, and 6:18 in the M, W, Y, X, Z, and U hexaferrites, respectively. ‘Me’ represent the transition cation (e.g., magnesium, zinc, manganese, cobalt, etc.) or a combination of cations comparable to spinel, where M represents the ions Ca, Sr, lead, barium, and lattice. Furthermore, other trivalent cations, such as Ga³⁺, Al³⁺, Sc³⁺, and In³⁺, may be employed to substitute Fe³⁺ ions in a variety of applications [46]. The dense packing of oxygen ion layers in hexagonal ferrite results in a crystalline structure that is hexagonal in shape. Substitutional entry of the heavy Ba or Sr ions into the oxygen layers is seen, while the divalent and trivalent metallic cations are detected in interstitial locations in the hexagonal crystal structure.

5.1 M-type hexaferrite

M-type hexaferrite was discovered initially and remains the most economically relevant hexagonal ferrite [47]. In the early 1950s, Phillips [21] was the first to explore and analyse it magnetically. M-type hexaferrite is a solid solution with the same structure as magnetoplumbite. Its chemical formula is MeO.₆Fe₂O₃ or MeFe₁₂O₁₉, where Me may be divalent ions such as Ba²⁺, Sr²⁺, or Pb²⁺ [48,49]. It is composed of spinel blocks connected by a barium or strontium ion block R. Each spinel block has two oxygen layers, S and S*. On each side of the barium layer are two oxygen layers. The cross-sectional picture in Figure 6 shows M-type Hexaferrite. Between the layers containing the barium ion, four oxygen layers are packed in a cubical way. To avoid the barium ion's basal plane being identical to the R block, the blocks immediately before and following the R block must be rotated 180 degrees. A molecule is composed of five oxygen layers, whereas a unit cell is composed of two molecules. The crystal structure is denoted by RSR*S*, whereas the space group is denoted by P6₃/mmc [49]. The hexagonal structure of M-type hexaferrite crystallises with 64 ions per unit cell and 11 symmetry points. As a result, the unit cell consists of 38 oxygen ions, 24 ferric ions, and two metal cations (Me = Ba²⁺, Sr²⁺, Pb²⁺, and La³⁺). The 24 ferric ions are kept in six separate locations denoted by the
designations 2a, 2b, 4f1, 4f2, and 12k. Sublattices 2a, 4f2, and 12k are octahedral, 4f1 is tetrahedral, and the last is tetrahedral, with the ferric ion surrounded by five oxygen atoms to produce the 2b site, a trigonal bipyramidal site. The cross-sectional picture in Figure 7 shows barium M-type hexaferrite. The arrows represent the direction in which Fe ions spin polarise. The unit cell contains 38 O2- ions, two Sr2+ ions, and 24 Fe3+ ions. The spins of Fe3+ ions at 12k, 2a, and 2b sites are up, while those in 4f1 and 4f2 sites are down, resulting in a net total of eight spins up and a total moment of (8*5) = 40B per unit cell containing two Sr2+ ions. It is composed of five distinct crystallographic orientations of strontium hexaferrite (SrFe12O19).

![Cross-sectional view of structure of M-type hexa ferrite](image)

*Figure 6: Cross-sectional view of structure of M-type hexaferrite [2]*

This ferrimagnetic material's high saturation magnetism and coercivity are owed to its strong magneto-crystalline anisotropy field. Throughout the stacking of M-type hexagonal ferrite, layers of spinel (S = Fe8O82+) and hexagonal (R = MFe6O112-) ferrite alternated. The O2- ions are layered densely, with the M2+ ions filling the hexagonal layer in lieu of an O2-
ion. Three parallel (2a, 12k, and 2b) and two antiparallel (4f1 and 4f2) sublattices are connected through a super-exchange interaction with O2− ions [51, 52]. In M-type hexaferrite, anisotropy appears in two forms: c-axis and c-plane. Simple magnetization along the c-axis and in the c-plane distinguishes each kind. Following the four oxygen ion levels, three oxygen ions and one Ba2+ ion are added, followed by the same sequence but with the Ba2+ ion from the preceding layer diametrically opposite the Ba2+ ion from the preceding layer; and finally, the same sequence but with the Sr2+ ion. In the interstices of these ten layers, Fe3+ ions are plentiful. On the other hand, the trigonal bi-pyramid site is unusual in the spinel structure due to the presence of five oxygen ions in the same layer as the Ba2+ ion. These are the triple symmetry axes, shown by spin orientation arrows. A primordial cell is composed of four layers of large hexagonal ions. Four oxygen ions are included in this layer, whereas three oxygen ions and one barium ion are contained in the fifth layer. The ionic sites in Barium M-type hexaferrite are classified according to their block and magnetic moment orientations in Table 9.

Table 9: Classification of ionic sites in Barium hexaferrite using blocks and the relative orientation of magnetic moments [53]

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Sites</th>
<th>Blocks</th>
<th>Site types</th>
<th>Relative direction of magnetic moments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Fe1</td>
<td>S</td>
<td>Octahedral</td>
<td>Up</td>
</tr>
<tr>
<td>2</td>
<td>Fe2</td>
<td>R</td>
<td>Bipyramidal</td>
<td>Up</td>
</tr>
<tr>
<td>3</td>
<td>Fe3</td>
<td>S*</td>
<td>Tetrahedral</td>
<td>Down</td>
</tr>
<tr>
<td>4</td>
<td>Fe4</td>
<td>R*</td>
<td>Octahedral</td>
<td>Down</td>
</tr>
<tr>
<td>5</td>
<td>Fe5</td>
<td>R/S</td>
<td>Octahedral</td>
<td>Up</td>
</tr>
</tbody>
</table>

The crystal structure of Ba and Sr hexaferrites is comparable to the M-type hexagonal ferrite. Only sintered magnets with higher coercivity than BaFe12O19 (SrM) have a similar crystalline structure and magnetic characteristics. A super-exchange interaction connects two iron ions (Fe3+) magnetic moments aligned along the c-axis [53]. Iron-orange-ferromagnetism is determined by the angle produced between ferric cations and oxygen [25]. A single crystal's ferromagnetic resonance line width may range from 10 to 20 Oe. One use for M-type Strontium hexaferrite is magneto-optical. The DC electrical resistivity of Strontium hexaferrite is important for determining its applicability for microwave devices. Generally, high direct current resistivity materials are better for use in microwave devices. M-type hexaferrite is a commonly utilised material in permanent magnet manufacture, accounting for over 90% of yearly production due to its low cost and good magnetic properties. Aside from permanent magnets, permanent magnetic materials are
used in a range of other items such as loudspeakers and moving coil instruments like galvanometers and ammeters. Magnetic motors are utilised in many applications, including automotive windshield wipers, heating fans, electric cutting blades, toothbrushes, and various home goods. Other uses for higher gigahertz microwaves include radar, stealth systems, satellite communication, precision navigation, and remote sensing. Microwave absorbers are in great demand for military applications. Putting a microwave absorbent coating on military planes and vehicles may help them evade detection. M-type hexaferrite is now commonly employed in the upper gigahertz range [54–56].

5.2 W-type hexaferrite

Philip's research laboratories discovered the W-type hexaferrite with the chemical formula BaMe2Fe16O27 in 1980, where 'Me' represents transition divalent metal cations [36], which were later named after him. Figures 7(a) and 7(b) illustrate different orientations of W-type hexaferrites from a perspective and cross-sectional viewpoint, respectively (b). As is the case with M-type hexaferrite, it shows magnetic uniaxial anisotropy parallel to the axis of the hexagonal structure. Due to its moderate magnetic characteristics, chemical stability, cheap cost, strong coercivity, and high magnetic energy product, this hexaferrite has gained increasing attention in recent decades [57,58]. When compared to the M-type structure, the W-type structure is more similar to it since it contains one barium layer for every seventh oxygen layer inside the spinel structure. The saturation magnetization and Neel temperature of W-type hexaferrite may be tailored to the application by altering the divalent metal ions used.

This structure is a superposition of R and S blocks along the hexagonal c-axis (R = BaFe6O112- hexagonal and S = Fe6O82+ cubic spinel). The O2- ions are concentrated in thick layers, one Ba2+ ion is concentrated in the R block, and five Fe3+ ions are concentrated in the interstitial sublattices. The R block has one Ba2+ ion in place of an O2- ion. Permanent magnets, bubble domain memories (including flash memory), high-frequency microwave devices (including satellites), and data processing systems all use W-type hexaferrite [59,60]. The method of manufacture, the sintering temperature, the kind and quantity of substitution all have an effect on the structural and magnetic characteristics of W-type hexaferrite. [61,62]. Spin reorientation transitions (SRTs) may occur in W-type ferrites AMe2Fe16O27 (M = magnesium, manganese, Fe, Co, Ni, Cu, Zn) as a result of temperature or magnetic field changes [62–64]. Chemical reactions inside the mixture may cause the transition temperatures to fluctuate (substitution of divalent metal cation). Additionally, some SRT may be of the first order, meaning that W-type hexaferrites might be employed for refrigeration at ambient temperature [65]. There are three types of coordination: 12k (octahedral), 4e, 4fIV (tetrahedral), and 2d (bipyramidal) [66,67]. W-type hexaferrites bind
lations through seven non-equivalent sublattices with varying amounts of R-blocks (including a Ba layer) and S-blocks [68] (containing a spinel layer). The coordination, spin orientation, block, and number of Fe ions at each W-type hexaferrite site are listed in Table 10.

![Figure 7: (a) Cross-sectional (b) Perspective view of the structure of W-type hexaferrite](Copyright permission with the license number: 5146980447011)[21]

The only five magnetically incompatible sub-lattices are as follows: The numbers 4e and IV create the fIV magnetic sub-lattice, while 6g and 4f form the 2b sub-lattice, also known as the b magnetic sublattice [69]. The cross-sectional and perspective architectures of W-type hexaferrite are shown in Figures 8(a) and 8(b), respectively (b). Numerous elements, including as manufacturing process, chemical composition, sintering temperature and duration, substitution type and amount, and others, all have an effect on the physical and magnetic properties of ferrites [70].
Table 10: Coordination, spin direction, block, and the number of Fe ions for each site of W-type hexaferrite [53]

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Magnetic site</th>
<th>Crystallographic site</th>
<th>Coordination</th>
<th>Spin</th>
<th>Block</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>f VI</td>
<td>4f VI</td>
<td>Octahedral</td>
<td>Down</td>
<td>R</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>a</td>
<td>6g 4f</td>
<td>Octahedral</td>
<td>Up</td>
<td>S-S</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>f IV</td>
<td>4e 4f IV</td>
<td>Tetrahedral</td>
<td>Down</td>
<td>S</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>K</td>
<td>12k</td>
<td>Tetrahedral</td>
<td>Up</td>
<td>R-S</td>
<td>6</td>
</tr>
<tr>
<td>5</td>
<td>B</td>
<td>2d</td>
<td>Hexagonal</td>
<td>Up</td>
<td>R</td>
<td>1</td>
</tr>
</tbody>
</table>

5.3 X-type hexaferrite

Its chemical formula is Ba$_2$Me$_2$Fe$_{28}$O$_{46}$, where 'Me' stands for divalent metal ions. Hexaferrite is a hexavalent iron oxide crystal. In the first row of transition components, he found it 50 years ago. Real-space coordinates for oxygen and barium ions as well as transition metal ions were reported by Braun for the first time in Ba$_2$Fe$_{30}$O$_{46}$ [71]. Three-oxygen layer blocks R (BaFe$_6$O$_{11}$) and S (Fe$_6$O$_8$) are comprised of BaFe$_6$O$_{11}$ and BaFe$_6$O$_8$. There are a total of six R and S blocks stacked along the hexagonal c-axis in the model SRS*S*S*R. It's not uncommon for Type X phases (hexagonal ferrites) to be confused for M and W phases. By stacking R and S blocks along the hexagonal c-axis, the X-type hexaferrite is formed, as illustrated in table 11.

Table 11: Coordination, spin direction and block of X-type hexaferrite [53]

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Block</th>
<th>Coordination</th>
<th>Number per block</th>
<th>Expected spin direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>R</td>
<td>Octahedral</td>
<td>2</td>
<td>Down</td>
</tr>
<tr>
<td>2</td>
<td>R</td>
<td>Trigonal bipyramidal</td>
<td>1</td>
<td>Up</td>
</tr>
<tr>
<td>3</td>
<td>R-S</td>
<td>Octahedral</td>
<td>3</td>
<td>Up</td>
</tr>
<tr>
<td>4</td>
<td>S</td>
<td>Octahedral</td>
<td>1</td>
<td>Up</td>
</tr>
<tr>
<td>5</td>
<td>S</td>
<td>Tetrahedral</td>
<td>2</td>
<td>Down</td>
</tr>
<tr>
<td>6</td>
<td>S-S</td>
<td>Octahedral</td>
<td>3</td>
<td>Up</td>
</tr>
</tbody>
</table>
R and S blocks have three octahedral cation sites, as do S and S blocks. An S-block has two tetrahedral and one octahedral bipyramidal site, resulting in an elementary cell with three chemical formula units (Z = 3), with the following properties: 5.88, 84.11, and 5.30 g/cm³. The unit cell in R₃m space symmetry [72, 73] is made up of four layers of M- and W-type structures stacked hexagonally. Figure 8 shows natural X-type hexaferrites cross-sectioned.

![Figure 8: Cross-sectional view of structure of X-type Hexaferrite](Copyright permission with the license number: 5146980447011) [21]

### 5.4 Y-type hexaferrite

Hexaferrites are blocks with spinel architecture constructed of Ba-O alternately laminated. An ST stacking block model represents each spinel layer and Ba-O block three times in a hexagonal unit cell. Ba represents alkaline earth metals, whereas Me represents divalent ions like Mg or Zn. It's at the vertices of an octahedron or tetrahedron depending on the ion's structure. Antiferromagnetic exchange interactions occur between neighbouring Fe³⁺ ions, resulting in a complicated magnetic structure [53]. It is composed of two fundamental layers, the first of which contains just oxygen and the second of which contains an orderly replacement of barium for every fourth oxygen. Smaller cations (e.g., Me²⁺ or Fe³⁺) present within the anion framework may be ignored in stacking relationships. The O and Ba-O
layers interlock to create blocks. S and T are two-layer blocks. Next is the ST unit. It has 18 oxygen layers, 6 oxygen layer repetition distance, and 43.56 Å c-axis length. The hexagonal symmetry unit cell contains 18 oxygen layers and a six repetition distance. It has four big ions in each layer. There are four layers of four oxygen ions each, and then two layers of three oxygen ions and one barium ion. The unit cell is made up of three formula units in the sequence STSTST. On the six sublattices, the metallic cations are shown in Table 12.

Table 12: Number of ions per unit formula, coordination, and spin orientation for the various metallic sublattice of Y-type hexaferrite [53]

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Sublattice</th>
<th>Coordination</th>
<th>Block</th>
<th>Number of ions</th>
<th>Spin</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6c_{IV}</td>
<td>Tetrahedral</td>
<td>S</td>
<td>2</td>
<td>Down</td>
</tr>
<tr>
<td>2</td>
<td>3a_{VI}</td>
<td>Octahedral</td>
<td>S</td>
<td>1</td>
<td>Up</td>
</tr>
<tr>
<td>3</td>
<td>8h_{VI}</td>
<td>Octahedral</td>
<td>S-T</td>
<td>6</td>
<td>Up</td>
</tr>
<tr>
<td>4</td>
<td>6c_{VI}</td>
<td>Octahedral</td>
<td>T</td>
<td>2</td>
<td>Down</td>
</tr>
<tr>
<td>5</td>
<td>6c_{IV}</td>
<td>Tetrahedral</td>
<td>T</td>
<td>2</td>
<td>Down</td>
</tr>
<tr>
<td>6</td>
<td>3b_{VI}</td>
<td>Octahedral</td>
<td>T</td>
<td>1</td>
<td>Up</td>
</tr>
</tbody>
</table>

The T block has three octahedral ions of sublattices 6c_{VI} and 3b_{VI}, with the centre 3b_{VI} ion sharing two faces of coordination with each of the two 6c_{VI} ions on each side. Due to the increased electrostatic repulsion between the cations in this arrangement, the structure's potential energy is greater; as a consequence, low-charge ions are more likely to choose such places. The multiferroic properties of Y-type hexagonal ferrite have aroused the interest of a significant number of researchers in recent years [74,75]. These hexaferrites are used in a wide range of applications, including electronic communication and microwave devices [76,77]. In electronic communication, low-permeability materials (0–10 GHz) are needed for ferrite device reduction, hence Y-type hexaferrite is being investigated as a suitable option [78–80]. The high permeability of Y-type hexaferrite is due to spin rotation and domain wall motions inside the material's crystal structure. Additionally, Y-type hexaferrite is a soft magnetic material that is often utilised in the VHF and UHF bands [53]. Figure 9(a) and 9(b) illustrate Y-type hexaferrites in cross-section and from a perspective, respectively.
5.5 Z-type hexaferrite

Z-type hexaferrite is one of the most advanced compounds in the hexaferrite family, boasting high permeability up to GHz, high resistivity, and great chemical stability, among other features. Z-hexaferrite is generated when M- (BaFe12O19) and Y- (Ba2Me2Fe12O22) type hexaferrites are combined. The STSR block-based model [81] depicts the crystal structure as being formed of 33 layers stacked along the hexagonal c-axis and classified into S, R, and T blocks, which correspond to the STSR block-based model's S, R, and T blocks. The Z-type hexaferrite is shown in Figures 10(a) and (b) in cross-sectional and viewpoint perspective views, respectively.

Figure 9: (a) Cross-sectional (b) Perspective view of structure of Y-type hexaferrite (Copyright permission with the license number: 5146980447011) [21]
According to the periodic table, a Z-type hexaferrite unit cell has 140 atoms and is placed in the P63/mmc space group. Numerous metal ions, including Fe3+, Co2+, Zn2+, and Cu2+, occupy non-equivalent interstitial spaces. Z-type hexaferrite has tremendous promise as an anti-EMI material or as a radar absorbent material (RAM) for high-frequency magnetic devices. Due to their ferromagnetic resonance at high GHz frequencies, these ferrites are employed in inductor cores for UHF communications in microwaves [82,83].

5.6 U-type hexaferrite

The U-type hexaferrite, chemical formula Ba4Me2Fe36O60 (Me2U, where 'Me' is any of the following elements: Cu, Fe, Co, Mn, Mg, and so on), has the most intricate crystal structure and largest unit cell size of all ferrites. Due to the material's complex crystal structure, single-phase production of U-type hexaferrite is challenging. As seen in the image, their crystal structure is dictated by the stacking sequence RSR*S*TS* with the space group R3 m. The rhombohedral structure of the unit cell of a three-molecule U-type...
chemical is identified in the space group R3m. Two M-blocks and one Y-block are stacked along the c-axis to make the structure. U-type hexaferrite has exceptional electromagnetic characteristics in the microwave region [22], and this is especially true in the microwave range. For millimeter-wave applications, U-type hexaferrite is a material worth exploring [81, 84–86]. The cross-sectional picture of U-type hexaferrite is shown in Figure 11.

![Cross-sectional view of structure of U-type Hexaferrite](image)

Figure 11: Cross-sectional view of structure of U-type Hexaferrite (Copyright permission with the license number: 5146980447011) [21]

6. Applications of hexaferrites

The magnetic materials are utilized in various applications, for instance, motors, transformers, annetas, defence system, diagnostic devices, communication systems, storage devices, recording media, electron beams concentration, sensors, etc. [28,87,88]. The ferromagnetic as well as ferrimagnetic ceramic based materials are the widely used class of magnetic materials for this purpose [7]. Out of all these ceramic based materials, hexaferrites are utilized on a large scale and therefore, few of their applications are presented in the schematic representation as provided in figure 12.
Concluding Remarks

In the current chapter, we have reviewed the historical progresses of hexaferrites along with their classification, structure and applications in various research areas. Two approaches called as spinel based and S/R/T blocks-based model have been taken into practice for studying the structure of hexagonal ferrites. Under the crystallographic structure, each hexaferrite is made of various S/R/T blocks having different space geometry. The M-type/Z-type/W-type is made of RSR*S*/STSR/RSSR*S*S* blocks model having P63/mmc space geometry whereas the X-type/Y-type/U-type hexaferrite consists of SRS*S*R*/ST/RSR*S*TS* blocks with R3m geometry respectively. Lastly, the applications of hexagonal ferrites in different research areas are provided.

References


[10] S. Kour, R. Jasrotia, P. Puri, A. Verma, B. Sharma, V.P. Singh, R. Kumar, S. Kalia, Improving photocatalytic efficiency of MnFe 2 O 4 ferrites via doping with Zn 2+/La 3+ ions: photocatalytic dye degradation for water remediation, Environmental


[38] H.P.J. Wijn, A new method of melting ferromagnetic semiconductors. BaFe 18 O 27, a new kind of ferromagnetic crystal with high crystal anisotropy, Nature. 170 (1952) 707–708. https://doi.org/10.1038/170707a0


