



Article

Investigation into the Structural, Spectral, Magnetic, and Electrical Properties of Cobalt-Substituted Strontium W-Type Hexaferrites

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Abstract: The solid-state reaction method is used to synthesize W-type Sr hexagonal ferrites $\text{Sr}_{0.8}\text{Pr}_{0.2}(\text{Zn}_{1.0-x}\text{Co}_x)_2\text{Fe}_{16}\text{O}_{27}$ ($x = 0.00, 0.15, 0.30, 0.45, 0.60, 0.75$). The results of XRD for the W-type hexagonal ferrites, when Co content (x) is $0.00 \leq x \leq 0.75$, exhibit that they are in the single W-type hexaferrite phase. As shown by morphological analysis, the particles are hexagonal-shaped platelets. The saturation magnetization (M_s) and magneton number (n_B) increases with Co content (x) from 0.00 to 0.60. M_s and n_B begins to decrease at Co content (x) ≥ 0.60 . With increasing Co content (x) from 0.00 to 0.75, the magnetic anisotropy field (H_a), first anisotropy constant (K_1), and coercivity (H_c) decrease gradually. The values of DC electrical resistivity for W-type hexagonal ferrites $\text{Sr}_{0.8}\text{Pr}_{0.2}(\text{Zn}_{1.0-x}\text{Co}_x)_2\text{Fe}_{16}\text{O}_{27}$ ($0.00 \leq x \leq 0.75$) are in the range of $20.854 \times 10^7 \Omega\text{-cm}$ and $22.755 \times 10^7 \Omega\text{-cm}$.



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Keywords: W-type hexagonal ferrites; solid-state reaction method; X-ray diffraction; magnetic properties; electrical resistivity

1. Introduction

W-type hexagonal ferrites with chemical formula $\text{AMe}_2\text{Fe}_{16}\text{O}_{27}$, in which A is alkaline earth metal ions and Me is divalent transition element ions, were first reported as a mixture of M-type and X-type hexaferrites in 1952 [1]. W-type hexaferrites have potential applications as permanent magnets, magnetic recording media, and microwave absorption devices [2]. W-type hexaferrites have a combined structure of cubic and hexagonal units, containing seven Fe^{3+} ions in different positions. The main structure of W-type hexagonal ferrites is composed of $\text{SSRS}^*\text{S}^*\text{R}^*$, where the S^* or R^* indicate that the block is individually rotated 180° along the c-axis [3].

Various synthesis methods of W-type hexagonal ferrites have been proposed, such as the hydrothermal method [4], the glass crystallization method [5], the tartrate precursor method [2], the sol-gel method [6], the sol-gel auto-combustion method [7], the chemical co-precipitation route [8], the combined co-precipitation and molten salt method [9], and the solid-state reaction method [10]. Compared with other methods, the solid-state reaction method has the advantages of simplicity, high productivity, and controllable grain size, so it is used here to synthesize W-type hexagonal ferrites.

The magnetic features of W-type hexagonal ferrites can be significantly improved by the suitable substitution of divalent cations because the selected ions are more likely to occupy the desired crystal positions [11]. Many experiments have reported that different magnetic or nonmagnetic cations, or their combinations, have been replaced to improve structural, electrical, and magnetic properties [12–15]. Ali et al. synthesized polycrystalline W-type hexagonal ferrites with the chemical formulae $\text{Ba}_{0.5}\text{Sr}_{0.5}\text{Co}_{2-x}\text{Me}_x\text{Fe}_{16}\text{O}_{27}$ ($x = 0, 0.5,$

Me = Mn, Mg, Zn, Ni) using sol-gel autocombustion, and studied the effects of the different cation substitutions in W-type hexagonal ferrites on the structural and magnetic behavior, as well on the dielectric properties [12]. The microstructural, magnetic, and physical properties of Co-substituted BaFe₂ W-type hexagonal ferrites prepared by the solid-state reaction have been discussed by Tang et al. [14]. Nanoparticles of Co-substituted W-type hexaferrites SrCd_{2-x}Co_xFe₁₆O₂₇ (0.0 ≤ x ≤ 2.0) have been synthesized by the tartrate precursor method, and the effects of Co content on the structural, electrical, and magnetic properties of strontium cadmium W-type hexaferrite have been investigated [15]. The microwave properties of BaZn_{2-z}Co_zFe₁₆O₂₇ synthesized by the sol-gel process have been reported by Zhang et al. [16]. Ali Ghasemi reported the magnetization reversal mechanism in the highly magnetized W-type hexaferrite SrCo_{2-x}Mn_xFe₁₆O₂₇ (0 ≤ x ≤ 0.5) prepared by the chemical co-precipitation method and hot pressing [17]. The DC conductivity for the W-type hexagonal ferrite BaZn_{2-x}Cu_xFe₁₆O₂₇ has been reported [18]. The microwave absorption and magnetic properties of Ba(Zn_xCo_{1-x})₂Fe₁₆O₂₇ W-type hexagonal ferrites, prepared by chemical co-precipitation route, are reported by Zi et al. [19]. The conduction mechanism for the W-type hexaferrite BaZn_{2-x}Mg_xFe₁₆O₂₇, prepared by the ceramic route, has been discussed [20].

In this paper, we prepare W-type Sr hexagonal ferrites Sr_{0.8}Pr_{0.2}(Zn_{1.0-x}Co_x)₂Fe₁₆O₂₇ (x = 0.00, 0.15, 0.30, 0.45, 0.60, 0.75) by the solid-state reaction method. We investigate the influence of cobalt substitution on the structural, spectral, electric, and magnetic properties of strontium W-type hexaferrites. In addition, the present article extends our previously published work [21] where the effects of Pr substitution on the microstructural, electrical, and magnetic properties of W-type hexagonal ferrites were studied. W-type Sr hexagonal ferrites with soft magnetic behavior, arising due to high saturation magnetization and low coercivity, could be used as microwave-absorbing materials [12,16].

2. Experimental Details

2.1. Materials

In this study, the starting materials were SrCO₃ (99.5%) powder, Pr₆O₁₁ (99.9%) powder, ZnO (99%) powder, CoO (99%) powder, and Fe₂O₃ (99.3%) powder. All raw materials were purchased from Aladdin Reagent Company, China. All raw materials were directly used with no further chemical decontamination.

2.2. Preparation of W-Type Hexaferrites

The solid-state reaction method was used to prepare the cobalt-substituted W-type Sr hexagonal ferrites Sr_{0.8}Pr_{0.2}(Zn_{1.0-x}Co_x)₂Fe₁₆O₂₇ (x = 0.00, 0.15, 0.30, 0.45, 0.60, 0.75). In a planetary ball mill, the required amount of starting material was wet-mixed in water for 3 h at a speed of 300 rpm with a ball-to-powder ratio of approximately 6:1. Then, the ground powder was dried and compressed into circular pellets with a diameter of 30 mm and a thickness of 20 mm. The pellets were then calcined in air for 2.0 h in a muffle furnace at 1308 °C to obtain the W-type hexaferrite phase. The fine powder, with particle size ranging from 2 μm to 5 μm, was obtained by crushing the calcined pellet by vibration mill. In order to alleviate stress, the crushed particles were annealed for 3.0 h in a muffle furnace at 780 °C.

2.3. Characterizations

We used an X-ray diffractometer equipped with Cu K_α (λ = 1.5406 Å) radiation to carry out the X-ray diffraction (XRD, Rigaku Smartlab, Rigaku Corporation, Japan) study. A Fourier transform infrared (FTIR) spectrometer (Nicolet 6700, Thermo Scientific, USA) was used for infrared spectral analysis in the wavenumber range of 400 to 4000 cm⁻¹. A field-emission scanning electron microscope (FE-SEM, Hitachi S-4800, Hitachi, Ltd., Tokyo, Japan) was used to analyze the morphology of the W-type hexagonal ferrites. The magnetic hysteresis loops of the strontium W-type hexaferrites were recorded at room temperature under an applied magnetic field of 24,000 Oe using the vibrating sample

magnetometer (VSM) (VSM 3100, Beijing Oriental Chenjing Technology Co., Ltd., Beijing, China). The DC electrical resistivity (ρ) of the W-type strontium ferrites was measured by the double-probe method (Resistivity testing system, Ningbo rooko FT-353, Ningbo, China) at room temperature.

3. Results and Discussion

3.1. X-ray Diffraction Analysis

The XRD patterns of the W-type Sr hexagonal ferrites ($x = 0.00, 0.15, 0.30, 0.45, 0.60, 0.75$) are depicted in Figure 1. Compared with the standard JCPDS card (no. 75-0406), it can be seen from Figure 1 that no impurities or undesirable phases were detected in the XRD patterns of the W-type hexaferrites $\text{Sr}_{0.8}\text{Pr}_{0.2}(\text{Zn}_{1.0-x}\text{Co}_x)_2\text{Fe}_{16}\text{O}_{27}$ ($0.00 \leq x \leq 0.75$), and all W-type hexaferrites were single-phased W-type hexagonal ferrites. This demonstrates that the single-crystalline phase was formed.

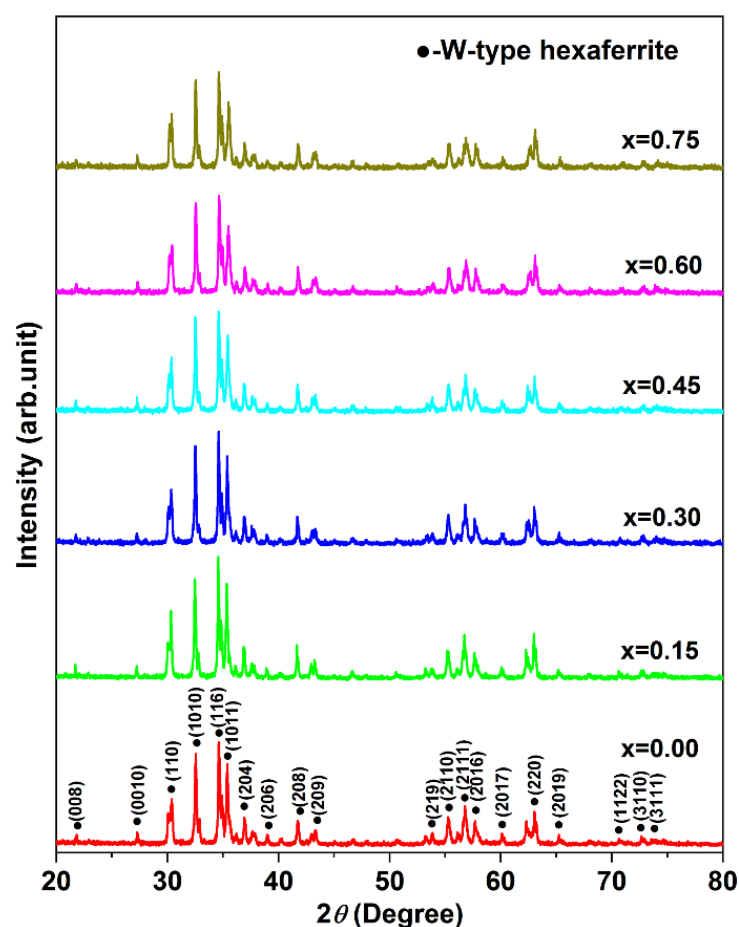


Figure 1. XRD patterns of the W-type Sr hexagonal ferrites $\text{Sr}_{0.8}\text{Pr}_{0.2}(\text{Zn}_{1.0-x}\text{Co}_x)_2\text{Fe}_{16}\text{O}_{27}$ ($x = 0.00, 0.15, 0.30, 0.45, 0.60, 0.75$).

The lattice parameters c and a of the W-type hexaferrites were obtained from the d_{hkl} values, corresponding to the (1010) and (116) planes by the below formula [22]:

$$\frac{1}{d_{hkl}^2} = \frac{4 \sin^2 \theta}{\lambda^2} = \frac{4}{3} \left(\frac{h^2 + hk + k^2}{a^2} \right) + \frac{l^2}{c^2} \quad (1)$$

where d_{hkl} is the parallel spacing in the XRD pattern, θ is one of the Bragg angles, h , k and l are the Miller indices, and λ is the wavelength of the X-ray diffractometer using $\text{CuK}\alpha$ radiation ($\lambda = 1.54046 \text{ \AA}$). Figure 2 shows the lattice constants c and a of the strontium W-type hexaferrites $\text{Sr}_{0.8}\text{Pr}_{0.2}(\text{Zn}_{1.0-x}\text{Co}_x)_2\text{Fe}_{16}\text{O}_{27}$ ($x = 0.00, 0.15, 0.30, 0.45, 0.60, 0.75$).

As can be seen in Figure 2, there was not much change in the lattice constants c and a of the W-type hexaferrites with increasing Co content (x). The ionic radii of Co^{2+} and Zn^{2+} were 0.82 Å and 0.82 Å, respectively [8]. The ionic radius of Co^{2+} is equal to that of Zn^{2+} . Therefore, the lattice constants did not change much.

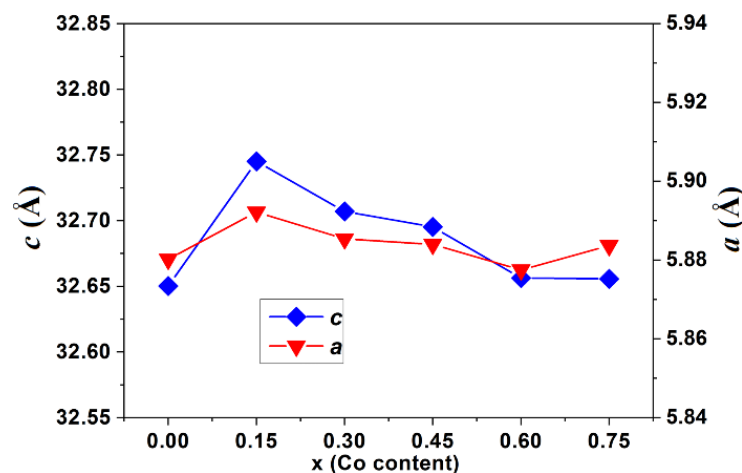


Figure 2. Lattice constants c and a of the W-type Sr hexagonal ferrites $\text{Sr}_{0.8}\text{Pr}_{0.2}(\text{Zn}_{1.0-x}\text{Co}_x)_2\text{Fe}_{16}\text{O}_{27}$ ($x = 0.00, 0.15, 0.30, 0.45, 0.60, 0.75$).

3.2. FT-IR Analysis

The structural changes and the presence of different crystal phases in the calcined powders during the calcination process were observed with the FTIR spectrometer. FT-IR spectra for the W-type hexagonal ferrites were measured in the wavelength range of 400–4000 cm^{-1} . Figure 3 presents the FTIR spectra of calcined powders of the investigated W-type hexaferrites $\text{Sr}_{0.8}\text{Pr}_{0.2}(\text{Zn}_{1.0-x}\text{Co}_x)_2\text{Fe}_{16}\text{O}_{27}$ ($x = 0.00, 0.15, 0.30, 0.45, 0.60, 0.75$). The spectra of the W-type Sr hexagonal ferrites with different Co content (x) indicated that the characteristic absorption bands, at about 3393 cm^{-1} (v_1) and about 1630 cm^{-1} (v_2), were caused by the stretching vibration of the surface hydroxy group (-OH), which was caused by the moisture content of the W-type hexagonal ferrites obtained in the preparation process [23].

The absorption band in the frequency range of 400–800 cm^{-1} resulted from the vibrational bonds of the hexagonal ferrites [24]. The absorption bands at about 590 cm^{-1} (v_3) and about 438 cm^{-1} (v_4) were caused by the stretching vibrations of the octahedral metal ions and oxygen bonds, and the stretching vibrations of the tetrahedral metal ions and oxygen bonds, respectively [25]. The values of v_1 , v_2 , v_3 and v_4 are displayed in Table 1. As seen from Table 1 and Figure 3, there was no obvious change in the position of the absorption band. It is also observed that the normal vibration mode of tetrahedral clusters was higher than that of octahedral clusters. This is mainly due to the shorter bond length of tetrahedral clusters and the longer bond length of the octahedral clusters [26].

Table 1. FT-IR spectroscopy absorption bands of the W-type Sr hexagonal ferrites $\text{Sr}_{0.8}\text{Pr}_{0.2}(\text{Zn}_{1.0-x}\text{Co}_x)_2\text{Fe}_{16}\text{O}_{27}$ ($x = 0.00, 0.15, 0.30, 0.45, 0.60, 0.75$).

Al Content (x)	v_1 (cm^{-1})	v_2 (cm^{-1})	v_3 (cm^{-1})	v_4 (cm^{-1})
0.00	3393	1628	590	438
0.15	3393	1630	590	438
0.30	3393	1630	590	438
0.45	3395	1630	590	438
0.60	3393	1630	590	438
0.75	3393	1632	590	438

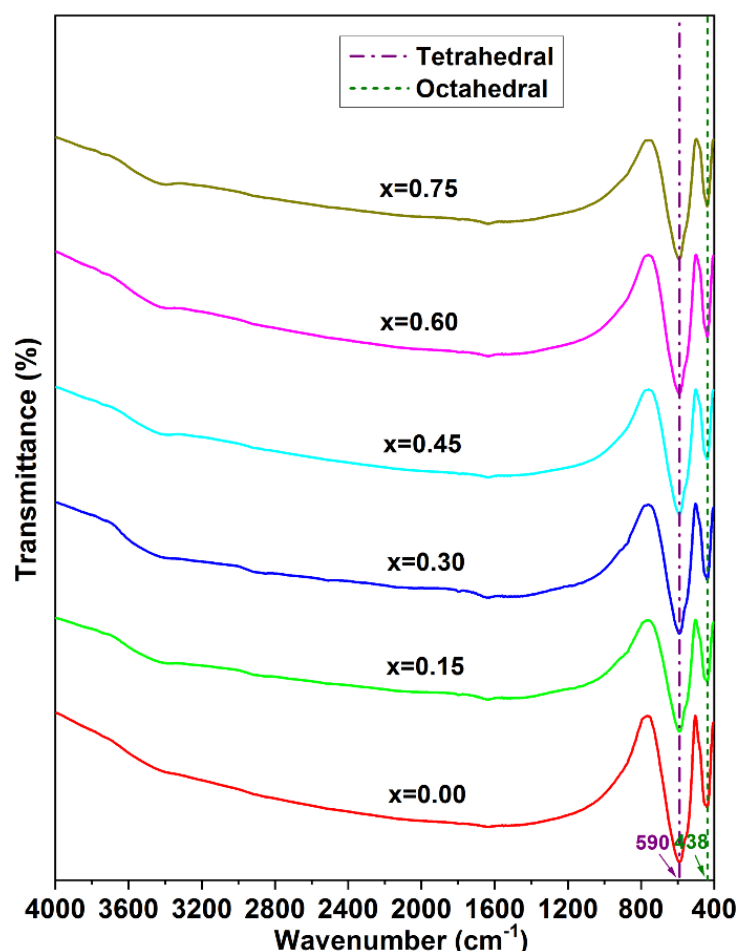


Figure 3. FT-IR spectra of the W-type Sr hexagonal ferrites $\text{Sr}_{0.8}\text{Pr}_{0.2}(\text{Zn}_{1.0-x}\text{Co}_x)_2\text{Fe}_{16}\text{O}_{27}$ ($x = 0.00, 0.15, 0.30, 0.45, 0.60, 0.75$).

3.3. Morphological Study

FE-SEM images of the W-type Sr hexagonal ferrites $\text{Sr}_{0.8}\text{Pr}_{0.2}(\text{Zn}_{1.0-x}\text{Co}_x)_2\text{Fe}_{16}\text{O}_{27}$, with Co content (x) of $x = 0.00$, $x = 0.15$, and $x = 0.60$, are shown in Figure 4. The perfect hexagonal grains of W-type hexaferrites can be observed from the images. It can be seen that the synthesized W-type hexaferrites showed a clear hexagonal plate shape, had high density, and almost uniform particle size distribution. The results show that the grain shape and morphology were not significantly affected by Co content (x). In this study, the average particle size was found to be about $2.7\ \mu\text{m}$ for the calcined W-type hexaferrites. The higher sintering temperature and longer sintering time may be the reason for the larger average grain size of these samples.

3.4. Magnetic Study

Figure 5a,b show the magnetic hysteresis loops of the W-type Sr hexagonal ferrites $\text{Sr}_{0.8}\text{Pr}_{0.2}(\text{Zn}_{1.0-x}\text{Co}_x)_2\text{Fe}_{16}\text{O}_{27}$ ($x = 0.00, 0.15, 0.30, 0.45, 0.60, 0.75$). Figure 5 shows that the synthesized W-type Sr hexagonal ferrites exhibited ferromagnetic behavior. The hysteresis loops of the hexagonal ferrites may have been affected by many factors, such as their chemical composition, calcination conditions, sintering conditions, magnetocrystalline anisotropy, grain size, etc. [27]. The saturation magnetization (M_s), remanent magnetization (M_r), and coercivity (H_c) of the W-type Sr hexagonal ferrites with different Co content (x) were calculated from the hysteresis loops.

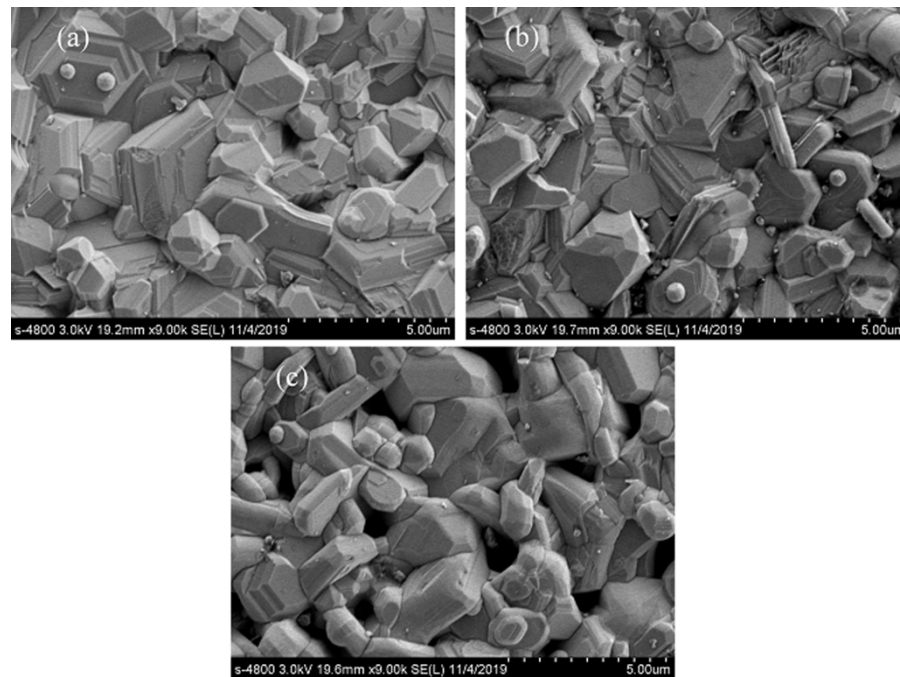


Figure 4. FE-SEM images of the W-type Sr hexagonal ferrites $\text{Sr}_{0.8}\text{Pr}_{0.2}(\text{Zn}_{1.0-x}\text{Co}_x)_2\text{Fe}_{16}\text{O}_{27}$ with Co content (x) of (a) $x = 0.00$, (b) $x = 0.15$, and (c) $x = 0.60$.

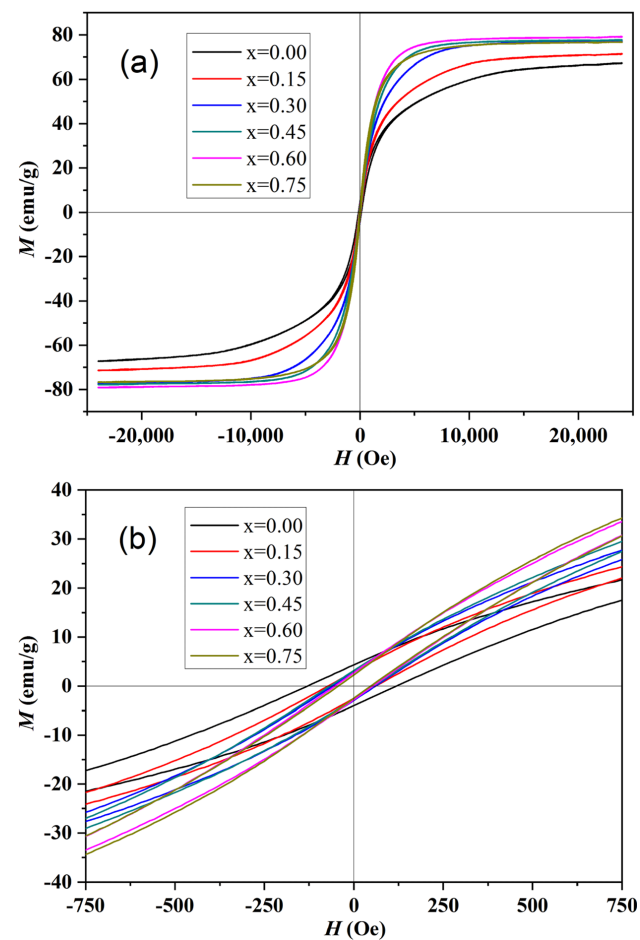


Figure 5. (a) Magnetic hysteresis loops within the range of $\pm 24,000$ Oe, and (b) the enlarged diagrams of hysteresis loops within the range of ± 750 Oe for the W-type Sr hexagonal ferrites $\text{Sr}_{0.8}\text{Pr}_{0.2}(\text{Zn}_{1.0-x}\text{Co}_x)_2\text{Fe}_{16}\text{O}_{27}$ ($x = 0.00, 0.15, 0.30, 0.45, 0.60, 0.75$).

The unit cell of W-type hexaferrite is built up by the superimposition of four spinel blocks (S block) and two hexagonal blocks (R block) [28]. The cations of W-type hexaferrite contain seven different crystallographic sites: four octahedral sites (12k, 4f_{VI}, 4f, and 6g), two tetrahedral sites (4e and 4f_{IV}), and one trigonal bipyramidal site (2d). The spin directions for the 12k, 4f, 6g, and 2d sublattices are spin-up, whereas those of the 4e, 4f_{VI}, and 4f_{IV} sublattices are spin-down [28]. The nearest cations are coupled by super-exchange interactions through the O²⁻ ions [28]. Therefore, the magnetic properties of the substituted W-type hexaferrites are strongly dependent on the occupation of sites by different cations [29–31].

The dependence of saturation magnetization (M_s) and remanent magnetization (M_r) on Co content (x) for the W-type Sr hexagonal ferrites of $\text{Sr}_{0.8}\text{Pr}_{0.2}(\text{Zn}_{1.0-x}\text{Co}_x)_2\text{Fe}_{16}\text{O}_{27}$ are presented in Figure 6. It is observable that the value of M_s first increases from 67.248 emu/g at $x = 0.00$ to 79.193 emu/g at $x = 0.60$, and then decreases with Co content ($x \geq 0.60$), while the value of M_r decreases quickly from 4.158 emu/g at $x = 0.00$ to 2.706 emu/g at $x = 0.15$, then increases gradually with increasing Co content (x) from 0.15 to 0.45, and decreases gradually when Co content ($x \geq 0.45$). The trends in M_s and M_r are consistent with those of $\text{BaZn}_{2-x}\text{Co}_x\text{Fe}_{16}\text{O}_{27}$ prepared by the stearic acid gel method reported by Wang et al. [32]. However, the values of M_s and M_r in this article are much higher than those reported by Wang et al. [32]. The magnetic moment of Zn^{2+} ion is 0.0 μ_B and the magnetic moment of Co^{2+} ion is about 4.0 μ_B . The changing trend in M_s with Co content (x) can be attributed to the distribution of Zn^{2+} and Co^{2+} ions in the W-type Sr hexagonal ferrites. The Zn^{2+} ions prefer to occupy the tetrahedral sites (4e and 4f_{IV}) with spin-down [33,34], while the Co^{2+} ions are located at the octahedral 6g site with spin-up and the octahedral 4f_{VI} site with spin-down [35,36]. On the one hand, the enhancement of M_s with Co content (x) from 0.00 to 0.60 can be explained as the below reason. This is because Zn^{2+} ions preferentially occupy the tetrahedral position [33] and Co^{2+} ions occupy the octahedral position [36]. With an increase in Co content (x) and decrease in Zn ion content, the Fe^{3+} ions which occupied the octahedral position replaced the non-magnetic Zn^{2+} ions which occupied the tetrahedral position; thus, the super-exchange between the tetrahedral position and the octahedral position was enhanced. This resulted in an increase in total magnetic moment. Thus, the saturation magnetization (M_s) was increased for the Co-substituted W-type hexaferrites. On the other hand, with the increase in Co content (x) from 0.60 to 0.75, the reduction in M_s can be assigned to the below factor. When the Co content (x) was further increased from 0.60 to 0.75, Fe^{3+} ions at the octahedral position entered the tetrahedron to replace Zn^{2+} ions due to the substitution of Co^{2+} ions for the original Fe^{3+} ions. As a result, the regular arrangement of Fe^{3+} ions was affected, resulting in a certain tilt of the magnetic moment direction of Fe^{3+} ions. Furthermore, the magnetic moment of Co^{2+} ion (4.0 μ_B) was smaller than that of the Fe^{3+} ion (5.0 μ_B). When the substitution of Co^{2+} ions reached a certain degree, the super-exchange was weakened and the saturation magnetization (M_s) was decreased.

The Bohr magneton number (n_B) of the W-type hexagonal ferrites was calculated using the below relation between M_s and the Bohr magneton number (n_B) of $\text{Sr}_{0.8}\text{Pr}_{0.2}(\text{Zn}_{1.0-x}\text{Co}_x)_2\text{Fe}_{16}\text{O}_{27}$ ($0.00 \leq x \leq 0.75$) [23]:

$$n_B = \frac{M_W \times M_s}{5585} \quad (2)$$

where M_W is the molecular weight. The values of the M_r/M_s ratio for all samples are calculated from M_r and M_s . Figure 7 shows the changing trends in the magneton number (n_B) and M_r/M_s with Co content (x) for the W-type Sr hexagonal ferrites of $\text{Sr}_{0.8}\text{Pr}_{0.2}(\text{Zn}_{1.0-x}\text{Co}_x)_2\text{Fe}_{16}\text{O}_{27}$. As can be seen from Figure 7, with increases in Co content (x), the value of n_B enhanced from 18.720 μ_B at $x = 0.00$ to 21.935 μ_B at $x = 0.60$ and began to descend at Co content ($x \geq 0.60$). n_B , M_s shown in Figure 6 shows the same changing trend. This indicates that the magnetic moment is the reason behind the change in M_s . The M_r/M_s ratio is known as the squareness ratio. It can be observed from Figure 7, that the

value of the M_r/M_s ratio descended quickly from 0.0618 at $x = 0.00$ to 0.0379 at $x = 0.15$, and then basically kept mostly constant at about 0.0380 with the increase in Co content (x) from 0.15 to 0.45, then began to decrease gradually when Co content (x) ≥ 0.45 . The results exhibit that W-type Sr hexagonal ferrites with different Co content (x) have multi-domain structures [15].

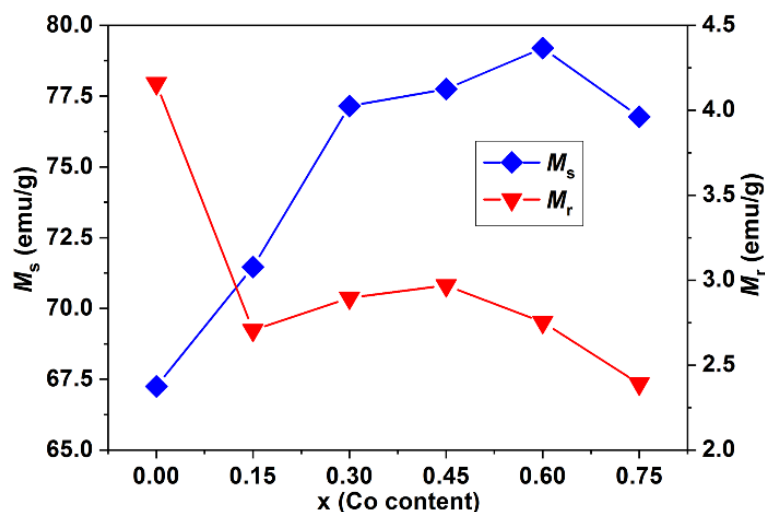


Figure 6. The changing trends in saturation magnetization (M_s) and remanent magnetization (M_r) with Co content (x) for the W-type Sr hexagonal ferrites of $\text{Sr}_{0.8}\text{Pr}_{0.2}(\text{Zn}_{1.0-x}\text{Co}_x)_2\text{Fe}_{16}\text{O}_{27}$.

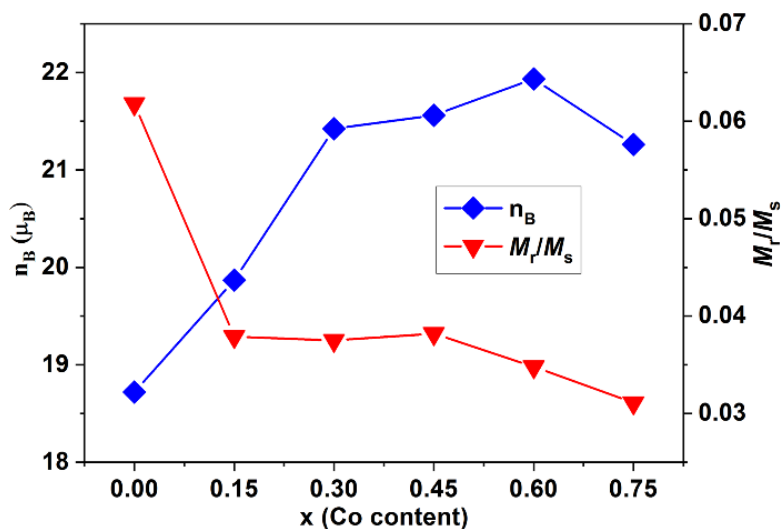


Figure 7. Changing trends in magneton number (n_B) and M_r/M_s with Co content (x) for the W-type Sr hexagonal ferrites of $\text{Sr}_{0.8}\text{Pr}_{0.2}(\text{Zn}_{1.0-x}\text{Co}_x)_2\text{Fe}_{16}\text{O}_{27}$.

According to the law of approach to saturation, we can determine the magnetocrystalline anisotropy constant (K_1) and magnetic anisotropy field (H_a) [37]. The connection between the magnetization (M) and sufficiently high magnetic fields (H) is shown in the following expression [38]:

$$M = M_s \left(1 - \frac{A}{H} - \frac{B}{H^2} \right) + \chi H \quad (3)$$

where M_s is saturation magnetization, A is a constant arising from the inhomogeneities, H represents the applied magnetic field, and χ is magnetic susceptibility. The constant A is approximately equal to zero. Under a strong magnetic field, χ can be ignored; thus, the expression (3) can be reduced to the below formula [38]:

$$M = M_S \left(1 - \frac{B}{H^2} \right) \quad (4)$$

As seen from Equation (4), in a strong magnetic field, the graph of M and $1/H^2$ gives a straight line. The relationship of magnetization (M) versus $1/H^2$ for the W-type Sr hexagonal ferrite $\text{Sr}_{0.8}\text{Pr}_{0.2}(\text{Zn}_{0.55}\text{Co}_{0.45})_2\text{Fe}_{16}\text{O}_{27}$ is presented in Figure 8. The slope gives the value of B , and the constant B is related to the magnetocrystalline anisotropy constant. Thus, the first anisotropy constant (K_1) can be determined by the below Formula (5), and the value of K_1 is used to calculate the magnetic anisotropy field (H_a) of W-type hexagonal ferrites through the following Formula (6) [39]:

$$K_1 = M_S \left(\frac{15B}{4} \right)^{0.5} \quad (5)$$

$$H_a = \frac{2K_1}{M_S} \quad (6)$$

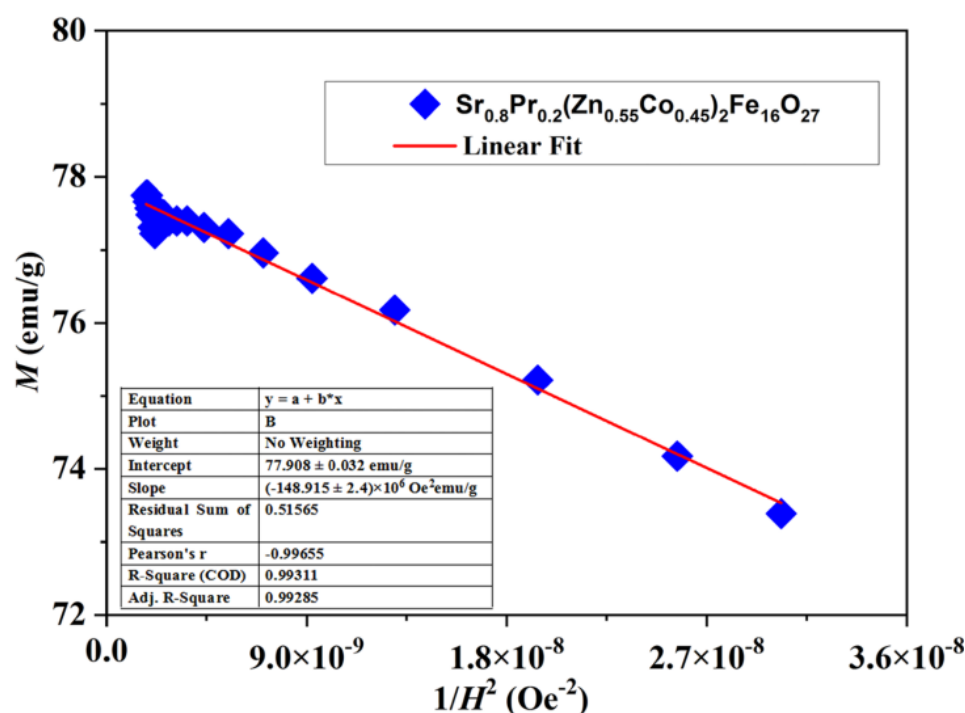


Figure 8. The relationship of magnetization (M) versus $1/H^2$ for the W-type Sr hexagonal ferrite $\text{Sr}_{0.8}\text{Pr}_{0.2}(\text{Zn}_{0.55}\text{Co}_{0.45})_2\text{Fe}_{16}\text{O}_{27}$.

Figure 9 shows the changing trends in the magnetic anisotropy field (H_a) and the first anisotropy constant (K_1), with regard to Co content (x), for the W-type Sr hexagonal ferrites of $\text{Sr}_{0.8}\text{Pr}_{0.2}(\text{Zn}_{1.0-x}\text{Co}_x)_2\text{Fe}_{16}\text{O}_{27}$. As exhibited in Figure 9, the values of K_1 and H_a decreased from 4.785×10^5 erg/cm³ and 13.94 kOe at $x = 0.00$ to 1.823×10^5 erg/cm³ and 4.75 kOe at $x = 0.75$, respectively. The decrease in the magnetic anisotropy field (H_a) can be attributed to the following reasons. It has been reported that due to the strong magnetic magnetocrystalline anisotropy of Fe^{2+} ions, Fe^{2+} ions could increase the magnetic anisotropy field [40]. For the W-type hexaferrites of $\text{Sr}_{0.8}\text{Pr}_{0.2}(\text{Zn}_{1.0-x}\text{Co}_x)_2\text{Fe}_{16}\text{O}_{27}$, there are a certain amount of Fe^{2+} ions on account of the substitution of Sr^{2+} by Pr^{3+} in W-type Sr hexagonal ferrites $\text{Sr}_{0.8}\text{Pr}_{0.2}(\text{Zn}_{1.0-x}\text{Co}_x)_2\text{Fe}_{16}\text{O}_{27}$. When the Zn^{2+} ions are substituted by Co^{2+} ions in W-type Sr hexagonal ferrites of $\text{Sr}_{0.8}\text{Pr}_{0.2}(\text{Zn}_{1.0-x}\text{Co}_x)_2\text{Fe}_{16}\text{O}_{27}$, a small amount of Co^{2+} ions may replace the Fe^{2+} ions. This results in the descending magnetic anisotropy field (H_a).

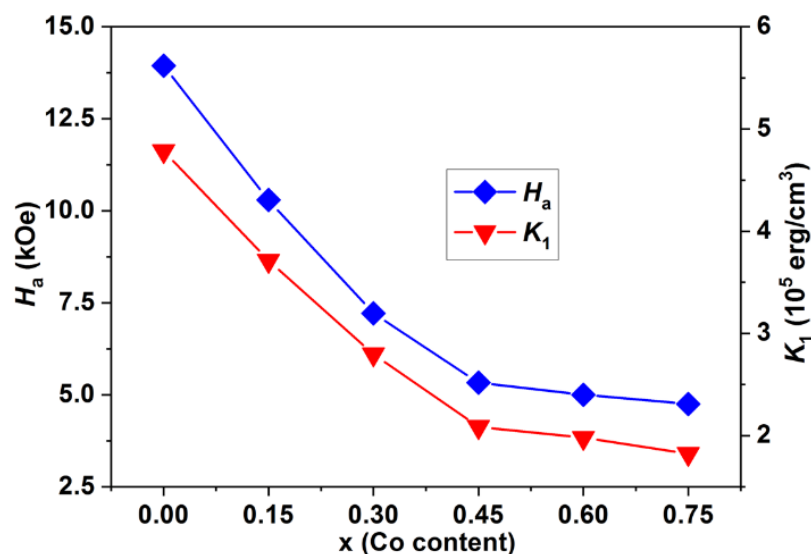


Figure 9. Changing trends in the magnetic anisotropy field (H_a) and first anisotropy constant (K_1) with regard to Co content (x) for the W-type Sr hexagonal ferrites of $\text{Sr}_{0.8}\text{Pr}_{0.2}(\text{Zn}_{1.0-x}\text{Co}_x)_2\text{Fe}_{16}\text{O}_{27}$.

The variation in coercivity (H_c) with Co content (x) for the W-type Sr hexagonal ferrites of $\text{Sr}_{0.8}\text{Pr}_{0.2}(\text{Zn}_{1.0-x}\text{Co}_x)_2\text{Fe}_{16}\text{O}_{27}$ is exhibited in Figure 10. It is clear that with the increase in Co content (x), the value of H_c descended from 125 Oe at $x = 0.00$ to 60 Oe at $x = 0.30$, basically kept mostly constant in Co content (x) from $x = 0.30$ to $x = 0.45$, and then fell from 61 Oe at $x = 0.45$ to 46 Oe at $x = 0.75$. The changing trend in H_c is basically in agreement with that of $\text{BaZn}_{2-x}\text{Co}_x\text{Fe}_{16}\text{O}_{27}$ prepared by the stearic acid gel method reported by Wang et al. [32]. However, the values of H_c in this article are much lower than that reported by Wang et al. [32]. The main reason is due to the different preparation methods used in this article and reference [32]. Intrinsic magnetic parameters and microstructure are used to correct the coercivity (H_c) of all samples according to the following equation [41]:

$$H_c = PH_a - N(k + 1)M_s \quad (7)$$

where P is the grain size factor; N is the grain demagnetization factor and has an enhancement tendency once the grain shape becomes more platelet; and k is the constant, and is related to the orientation, density, and so on. As shown in Figure 4, the grain shape and morphology are not significantly affected under Co substitution. Thus, P and N remain basically the same. It can be concluded from Formula (7) that the decrease in H_c is mainly due to the decrease in H_a , as shown in Figure 9. Therefore, the magnetic properties of W-type Sr hexagonal ferrites can be adjusted by the substitution of Co^{2+} ions for Zn^{2+} ions.

3.5. Electrical Study

In this work, we measured the DC electrical resistivity (ρ) of W-type strontium ferrites $\text{Sr}_{0.8}\text{Pr}_{0.2}(\text{Zn}_{1.0-x}\text{Co}_x)_2\text{Fe}_{16}\text{O}_{27}$ ($0.00 \leq x \leq 0.75$) with the double-probe method at room temperature [42–45]. The change in resistivity can be affected by different parameters, such as grain size, chemical composition, and sintering temperature. In fact, the spinel block of hexagonal ferrites has two positions, namely, tetrahedral and octahedral, and the number of iron ions in the octahedral positions determines the conductivity of these materials [46]. It has been reported that the conductivity of hexagonal ferrites is mainly due to ion transitions between the Fe^{3+} and Fe^{2+} ions in octahedral positions [18]. Figure 11 exhibits the impact of Co content (x) on DC electrical resistivity (ρ) for the W-type Sr hexagonal ferrites of $\text{Sr}_{0.8}\text{Pr}_{0.2}(\text{Zn}_{1.0-x}\text{Co}_x)_2\text{Fe}_{16}\text{O}_{27}$. As can be seen from Figure 11, with Co content (x) increasing from 0.00 to 0.75, the electrical resistivity (ρ) varied within a relatively small range. The values of DC electrical resistivity for the W-type Sr hexagonal ferrites with different Co content (x) were in the range of $20.85 \times 10^7 \Omega\text{-cm}$ and $22.76 \times 10^7 \Omega\text{-cm}$.

For the Co-substituted W-type Sr hexagonal ferrites of $\text{Sr}_{0.8}\text{Pr}_{0.2}(\text{Zn}_{1.0-x}\text{Co}_x)_2\text{Fe}_{16}\text{O}_{27}$, the substitution of Zn^{2+} by Co^{2+} did not lead to the imbalance of the valence state, this explains why the resistivity varies slightly. Small variations in resistivity may be due to microscopic differences such as grain size.

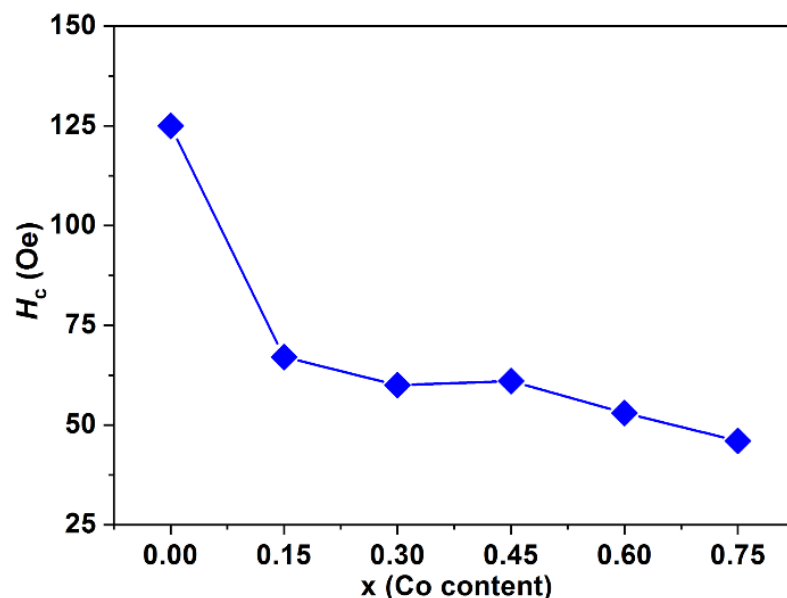


Figure 10. Variation in coercivity (H_c) with Co content (x) for the W-type Sr hexagonal ferrites of $\text{Sr}_{0.8}\text{Pr}_{0.2}(\text{Zn}_{1.0-x}\text{Co}_x)_2\text{Fe}_{16}\text{O}_{27}$.

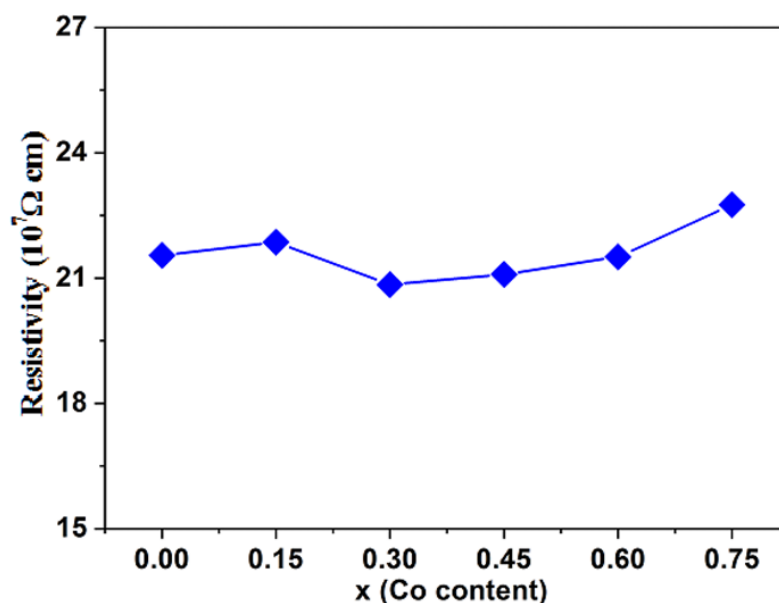


Figure 11. Impact of Co content (x) on DC electrical resistivity (ρ) for the W-type Sr hexagonal ferrites of $\text{Sr}_{0.8}\text{Pr}_{0.2}(\text{Zn}_{1.0-x}\text{Co}_x)_2\text{Fe}_{16}\text{O}_{27}$.

4. Conclusions

W-type Sr hexagonal ferrites of $\text{Sr}_{0.8}\text{Pr}_{0.2}(\text{Zn}_{1.0-x}\text{Co}_x)_2\text{Fe}_{16}\text{O}_{27}$ ($x = 0.00, 0.15, 0.30, 0.45, 0.60, 0.75$) were prepared by the solid-state reaction method. The patterns of XRD for the W-type hexagonal ferrites when Co content (x) was $0.00 \leq x \leq 0.75$ show that they formed a single W-type hexaferrite phase. As shown in the morphological analysis, the particles were hexagonal-shaped platelets. The magnetization properties of the W-type hexagonal ferrites were investigated at room temperature by VSM. M_s and n_B increased with Co content (x) from 0.00 to 0.60. The saturation magnetization (M_s) and magneton

number (n_B) began to decrease at Co content (x) ≥ 0.60 . With increasing Co content (x) from 0.00 to 0.75, H_a , K_1 , and H_c decreased gradually. The values of DC electrical resistivity for W-type hexagonal ferrites of $\text{Sr}_{0.8}\text{Pr}_{0.2}(\text{Zn}_{1.0-x}\text{Co}_x)_2\text{Fe}_{16}\text{O}_{27}$ ($0.00 \leq x \leq 0.75$) were in the range of $20.854 \times 10^7 \Omega\text{-cm}$ and $22.755 \times 10^7 \Omega\text{-cm}$. Their soft magnetic behavior means W-type Sr hexagonal ferrites can be used as microwave-absorbing materials.

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