# DEVELOPMENT OF RARE-EARTH FREE PERMANENT MAGNETS WITH IMPROVED MAGNETIC PROPERTIES

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**for the Award of Degree**

## DOCTOR OF PHILOSOPHY

**By**


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# CHAPTER 9

## SUMMARY AND FUTURE SCOPE

The present chapter provides summarized results of the thesis work and gives insights into the future scopes of work.

### 9.1 Summary

Permanent magnets are essential to many application areas of modern human life. The key features of PM make them indispensable due to the characteristics of facilitating electrical to mechanical energy conversion, transmission & distribution of electric power, enabling microwave communications, and data storage support. The present technological demand for PMs is leading to the overall production of magnets and is expected to have a \$34.7 billion market value by 2026. It is being implemented in a wide range of application perspectives at technological and industrial-scale from engineering (like motor/generator, automobile, telecommunication device, computer device, recording media, microwave absorber) to medical (like magnetic resonance imaging, hyperthermia, drug delivery, medical tool) sectors. In the present work, the dependency on rare-earth contained permanent magnets is tried to reduce by the 'development of rare-earth free permanent magnet with improved magnetic properties'. For this purpose, ongoing research on modified strontium hexaferrite has been further extended here, and a summary of the thesis work is as follows:

- The effect of Co-Cr substitution in SrM hexaferrite having a composition of $SrFe_{12-x-y}Co_xCr_yO_{19}$ ($0 \leq x, y \leq 1$) is studied. Co substitution is found favorable to improve $M_s$ value with a drastic decrease in $H_c$, resulting in a soft magnetic behavior. $SrFe_{11}Co_{0.75}Cr_{0.25}O_{19}$ (70.08 emu/g) and $SrFe_{11}CoO_{19}$ (71.18 emu/g) compositions have shown a good improvement in $M_s$ of strontium hexaferrite. In contrast, Cr substitution is observed to significantly enhance $H_c$ value without adversely affecting the $M_s$, resulting in a better hard magnetic behavior. In $SrFe_{11}CrO_{19}$, $M_s$ of 59.89 emu/g and $H_c$ of 6.26 kOe are obtained. Substitutions of both these elements have improved the ac-resistivity of the strontium hexaferrite.

- The effect of Cr-Zn substitution in strontium hexaferrite having a composition of $Sr_{1-x}Cr_xFe_{12-y}Zn_yO_{19}$ ($0 \leq x \leq 0.8$; $0 \leq y \leq 1$) is studied. Cr substitution at Sr site is also found favorable to improve the $H_c$ value but not as significant as observed at Fe site, and a small negative impact on $M_s$ is observed. Zn substitution at Fe site of SrM is found to improve the $M_s$ value significantly by diminishing the $H_c$ value, resulting in a soft magnetic behavior. In $SrFe_{11}ZnO_{19}$ composition, $M_s$ value is enhanced to ~78 emu/g, which is even higher than the maximum theoretical $M_s$ value of SrM (~72 emu/g), with an extreme dilution in $H_c$ value ~63.9 Oe. Despite the sharp $H_c$ dilution due to $Zn^{2+}$ ion, $Cr^{3+}$ substitution has retained the hard magnetic characteristic of samples because the observed $H_c$ values in $Cr^{3+}$ contained samples are still greater than 1 kOe. Substitutions of both these elements have improved the ac-resistivity of the strontium hexaferrite.
- The effect of Ni-Al substitution in strontium hexaferrite having a composition of $SrFe_{12-x-y}Ni_xAl_yO_{19}$ ($0.005 \leq x \leq 0.02$; $1 \leq y \leq 4$) is studied. Substitution of $Ni^{2+}$ ion is observed to increase the $M_s$ value of the composition without adversely affecting the $H_c$. Substitution of $Al^{3+}$ is found liable for smaller grain sizes and higher $H_c$ in the samples. In this series, the highest ever $H_c$ value of 24.44 kOe in any rare-earth free magnet is attained for the $SrFe_{7.98}Ni_{0.02}Al_4O_{19}$ composition with $M_s$ of 9.9 emu/g. In the $SrFe_{8.985}Ni_{0.015}Al_3O_{19}$ composition, a $H_c$ value of 17.12 kOe is obtained with 20.1 emu/g of $M_s$ value, which is anticipated to be suitable for

different PM applications. The high $H_c$ value of the $SrFe_{8.985}Ni_{0.015}Al_3O_{19}$ (17.12 kOe) composition is even higher than the NdFeB (15.07 kOe) magnets, which could also rectify the drawback of demagnetization risk in ferrite based permanent magnet applications. A 16.2 MGOe value of $(BH)_{max}$ is estimated for this composition, which indicates a strong potential of SrM-based magnet to be utilized in high-power motor applications. Substitutions of both these elements have improved the ac-resistivity of the strontium hexaferrite.

- The effect of $Bi_2O_3$ (sintering aid) doping and different sintering temperature in strontium hexaferrite having a composition of $SrFe_8Al_4O_{19}\_xBi_2O_3$ ($0 \leq x \leq 5$ wt%) is studied. A 3 wt% of $Bi_2O_3$ doping is optimized here to realize a higher value of $M_s$ ~16.42 emu/g in $SrFe_8Al_4O_{19}$ with the sintering temperature of 1050ºC. For this composition, a $(BH)_{max}$ value of 5.5 MGOe is estimated. It can be used in low-power rated motor applications. Also, it can be used in other permanent magnet applications where the device size is not an issue; then, high $(BH)_{max}$ can be achieved accordingly by increasing the magnet volume. Both dopings of $Bi_2O_3$ and $T_{sin}$ variation have reduced the ac-resistivity compared to pristine strontium hexaferrite (still higher than NdFeB ~1.5 μΩ-m).
- The effect of Al-Zn substitution in strontium hexaferrite having a composition of $SrFe_{8-x}Al_4Zn_xO_{19}$ ($0 \leq x \leq 1$) is studied. The effect of $Zn^{2+}$ ion is more prominent in improving the $M_s$ of compositions but at little expense of $H_c$. An improvement in both $M_s$ and $H_c$ is observed for small $Zn^{2+}$ ion content (x = 0.2). For the $SrFe_{7.8}Al_4Zn_{0.2}O_{19}$ composition, a large $H_c$ ~18.51 kOe is observed with $M_s$ ~21.87 emu/g. A $(BH)_{max}$ of 19.15 MGOe is estimated for this composition. It is not equivalent to NdFeB (~ 50 MGOe) but still much better than the $(BH)_{max}$ of commercial SrM magnets (~4 MGOe). Substitution of Zn improves the ac-

resistivity of Al-substituted SrM, but it is less than pristine strontium hexaferrite (still higher than NdFeB ~1.5 μΩ-m). It represents a little successful step towards our objective.

Improvement in magnetic properties of strontium hexaferrite based magnets proposed that rare-earth free magnets can be utilized in different permanent magnet applications and can help to reduce the dependency on rare-earth contained magnets. In NdFeB magnets, there are a few drawbacks like a negative temperature coefficient of $H_c$ and low $T_c$ of 588 K. These problems can be rectified by the modified SrM as the positive temperature coefficient of $H_c$ exhibits in SrM magnets, making them less sensitive to sudden demagnetization. A high $T_c$ (693-732 K) is obtained for the proposed compositions, which ensures a suitable operating temperature of SrM based magnets for different applications. Also, SrM magnets possess electrical resistivity $10^8$ times to the electrical resistivity of NdFeB magnets. Electrical resistivity is desirable to be high for negligible eddy current loss and beneficial for practical applications of permanent magnets. Further improvisation in the different properties of these magnets can be a revolutionary breakthrough in the magnet industry which is passionately searching for a rare-earth free strong permanent magnet.

## 9.2 Future Scope

The improvement in the energy density of strontium hexaferrite based magnets favors its utilization in high-performance permanent magnet applications and the present work can be further extended as follow:

- A next-level study on the magnetic properties of strontium hexaferrite magnets through different structural changes and controlled microstructures.
- The economical strontium hexaferrite based magnets can be tested in different application areas including soft to hard magnet applications by using its magnetic

tunability due to the properties like high $T_c$, good thermal stability, high oxidation & corrosion resistance.

- The feasibility of these magnets can also be explored in the high-frequency application areas, where high demand for dielectric resonator antennas and magnetic absorbers can be expected in the coming year due to 5G technology.