Automated magnetic domain analysis using an physics-based explainable AI: extended Landau free energy model

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Magnetic domain structures, dictated by intricate microstructural features, have traditionally been analyzed through empirical and qualitative methods. In this invited lecture, we introduce a novel physics-based explainable AI framework—the **Extended Landau Free Energy Model**—which automatically constructs the energy landscape of magnetic domains. This model elucidates the mechanisms behind phenomena such as domain wall pinning and energy dissipation, offering significant promise for guiding energy-efficient device design.

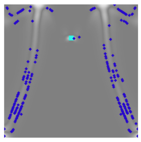
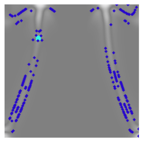
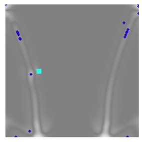
	Device A	Device B	Device C
Visualization	 400 nm		 Concentration of energy barrier; Defect
Demagnetization	1.2×10^{-10}	1.1×10^{-10}	8.2×10^{-11} Min
Exchange	6.5×10^{-12}	1.6×10^{-12} Min	1.8×10^{-12}
Total Energy	1.3×10^{-10}	1.2×10^{-10}	0.8×10^{-10} Min

Figure 1. Visualization results by extended Landau Free Energy Model

Magnetic materials underpin advanced technologies ranging from spintronics and data storage to high-performance motors. The macroscopic properties of these materials are closely linked to the microstructural configuration of magnetic domains. Our work integrates rigorous physical modeling with AI to automate the quantitative analysis of the causal mechanisms in magnetic property.

Our approach employs **persistent homology** to extract topological features—such as domain walls and vortices—from magnetic domain images, thereby capturing the essential microstructural details. These high-dimensional features are reduced via **principal component analysis (PCA)** to form a low-dimensional energy landscape. Using **ridge regression**, we quantitatively predict exchange and demagnetization energies. Energy gradient analysis with structural feature enables the automatic identification of the causal links magnetic domain and energy consumption.

Application of the Extended Landau Free Energy Model to magnetic domain data reveals detailed visualizations of energy barriers near defects and domain walls. Our model quantitatively delineates how localized demagnetization energy, influenced by defect positions, interacts with exchange energy to stabilize or destabilize magnetic domains. Moreover, analysis of energy consumption provides actionable insights into the design principles for optimizing device efficiency. These results underscore the model's capability to uncover previously elusive mechanistic details, thereby validating its utility as both an analytical and predictive tool.

The Extended Landau Free Energy Model represents a transformative step toward the automated, quantitative analysis of magnetic microstructures. By merging physical rigor with advanced AI techniques, our approach provides a clear understanding of the **causal relationships between domain structures and energy phenomena**. Future endeavors will extend this methodology to more complex systems—such as soft magnetic alloys and skyrmions—and integrate it into inverse design frameworks aimed at enhancing energy efficiency and device performance.

References

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