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博 士 論 文 概 要

論　文　題　目

Study on Spin-Transfer Torque Magnetic Tunnel Junction Modeling for Magnetic Memories and Spiking Neural Networks

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Over the past decades, several emerging memory devices have been introduced with the aim of enhancing circuit performance. Spin-transfer torque magnetic tunnel junction (STT-MTJ) is one of the most promising emerging memories and has found widespread applications because of its excellent physical properties, scalability potential and compatibility with CMOS technology.

To leverage the potential of STT-MTJ, it is necessary to develop circuit simulation models within electronic design automation (EDA) tools. For different types of applications, there are varying requirements for STT-MTJ simulation models. These requirements encompass various aspects such as model accuracy, CPU time, memory requirement and information on magnetization dynamics. The primary objective of this article is to develop appropriate circuit simulation models for STT-MTJ tailored to different types of applications. These models will be used to simulate various applications and validate their utility.

For STT-MTJ, the stochastic Landau-Lifshitz-Gilbert-Slonczewski (s-LLGS) equation provides the rigorous description of the dynamics in magnetization. However, the model based on solving the equation leads to long simulation times and high memory requirements since it requires calculating a random Langevin field at each timestep and using a smaller timestep for accurate results. The s-LLGS equation based model costs an unacceptable CPU time for large-scale circuits simulations such as spin-transfer torque magnetoresistive random-access memory (STT-MRAM). Under this situation, a circuit simulation model based on switching probability which includes several equations to describe the switching characteristics for different current conditions is proposed. Compared with the s-LLGS equation based model, it significantly reduces simulation time. Unlike other circuit simulation models based on switching probability, the proposed model addresses a limitation of that there is no physical model for a certain range of injection current by introducing a framework that connects existing equations which were derived from two extreme physical condition.

However, the switching probability based model cannot be used for the applications which need the information on magnetization change such as spiking neural networks (SNNs). For this requirement, a simulation model based on the Fokker-Planck equation (FPE) which is the master equation of the s-LLGS equation is proposed. The FPE is solved by the finite difference method (FDM) and the impact of the solvers on computational efficiency and accuracy is analyzed. A framework is proposed which traces dynamics of a particular STT-MTJ's theta between the magnetic moments of the free and the pinned layers and achieves performance comparable to that of the s-LLGS equation is achieved. The proposed model represents the first model for STT-MTJ based on the FPE to be implemented into a defacto-standard circuit simulator HSPICE.

The two proposed models show excellent accuracies when compared with experimental data and they demonstrate high CPU time efficiency in comparison with other models for large scale circuit simulations. The models were applied to two different applications to verify their effectiveness in practical use. Specifically, these applications are STT-MRAM and a spiking neural network (SNN) that is proposed by the author. The two applications utilize different characteristics of STT-MTJ. The results show that the proposed models have been applied well in different types of circuits. Furthermore, the simulation results validate that the proposed SNN implements an automatic reset function on the neuron and can be used in recognition tasks. It achieves a low-power SNN with an energy consumption of 0.23pJ per synaptic operation, which is a significant improvement compared with existing designs.

The dissertation contains seven chapters as follows:

Chapter 1 provides an introduction to the underlying principles and historical development of MTJ, as well as an overview of its basic physical properties. This chapter also introduces an overview of the s-LLGS model and its limitations in circuit simulation.

Chapter 2 describes the switching probability models which includes the Sun model and Néel-Brown model for the injection current much larger and smaller than the critical current, respectively. A problem that there is no physical model around the critical current is explained. A mathematical framework is proposed to calculate the switching characteristics in the vicinity of the critical current based on two existing models. The model for the resistance and Joule heating effect are also shown. The model is compared with experimental data and the results validate the effectiveness.

In Chapter 3, we present a circuit simulation model based on the FPE that utilizes the finite difference method (FDM) for solving the FPE. We analyze various forms of FDM and demonstrate that the implicit form of FDM offers the best trade-off between computation time and accuracy. We also propose a framework for extracting theta information of the magnetization from the probability density distribution of the theta. The simulation results obtained from the FPE based model are in good agreement with both experimental data and the results of the s-LLGS model.

Chapter 4 shows two specific applications that are applied by the two different circuit simulation models. The first application utilizes the resistance characteristics of STT-MTJ and focuses on the simulation of 4T2MTJ STT-MRAM. The both models were evaluated for their performance in simulating STT-MRAM, and the results demonstrate their effectiveness. The second application demonstrates the use of theta information in STT-MTJs to design an SNN with STT-MTJ-based auto-reset neurons and synapses. The simulation results have confirmed the effectiveness of the proposed model based on the FPE for analyzing the circuit operations in the SNN. Additionally, the simulation confirms the efficient implementation of the proposed SNN neuron and the overall SNN system has achieved a low energy which can be reduced to 0.23pJ/SOP. Overall, these specific applications provide further evidence of the practical applicability and versatility of the proposed circuit simulation models.

Chapter 5 shows a comparison between proposed models and existing circuit simulation models, examining their basic characteristics and CPU time requirements. The results indicate that the proposed switching probability based model is unique in solving the intermediate regime problem and accommodating time-varying currents. The proposed FPE model is the first circuit simulation model based on the FPE equation. The comparison of CPU time across circuits of varying sizes and complexities indicates that the switching probability based model requires the least amount of CPU time. Moreover, the FPE based model can provide the same information as the s-LLGS equation based model but with only 1/30 of the CPU time. At last Chapter 5 concludes the dissertation.