Spin-Torque in Systems with Inhomogeneous Magnetization

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I. OVERVIEW

The work performed under this grant focused on the phenomenon of *spin-transfer torque*. This is a quantum mechanical effect whereby the angular momentum of conduction electrons is transferred to the magnetization of ferromagnetic structures. Our work on this subject began with phenomenological drift-diffusion and Landau-Lifshitz-Gilbert equations to demonstrate unambiguously that unpolarized current flow from a nonmagnet into a ferromagnet can produce a precession-type instability of the magnetization. We then used Boltzmann calculations appropriate to spin-valve type magnetic heterostructures composed of a non-magnetic thin film sandwiched between two thin film layers with uniform magnetization. Perhaps our most important paper dealt with quantum and semi-classical calculations of spin-transfer torque in systems with domain walls and other inhomogeneous distributions of magnetization. The latter work caused us to suggest that the Landau-Lifshitz approach to magnetic damping provided a clearer picture of the physics than the more popular (but formally equivalent) Gilbert approach to damping. Finally, we returned to our Boltzmann calculations and made a serious effort to analyze experimental data on current-induced magnetization in switching in magnetic spin-valve structures.

II. PERSONNEL

All the salary money from this grant went to support a graduate student, Jiang Xiao, who received his PhD from Georgia Tech in 2006. He was co-advised by myself and Dr. Mark Stiles (NIST). Xiao is now a professor of physics at Fudan University in Shanghai, China. Stiles is a senior scientist at the National Institute of Standards and Technology. He collaborated fully in all the work performed under this grant. Two other senior scientists, Prof. Wayne Saslow of Texas A&M University and Dr. Mike Donahue of NIST collaborated with us for one paper.

III. PUBLISHED PAPERS

The refereed research papers published under this grant are listed below. The number in brackets at the end of each citation is the number of citations to each paper (to date) as listed by the Web of Science.

1. “Phenomenological theory of current-induced magnetization precession”, M.D. Stiles, J. Xiao, and A. Zangwill, *Physical Review B* **69**, 054408 (2004) [73]
2. “Boltzmann test of Slonczewski’s theory of spin-transfer torque”, J. Xiao, A. Zangwill, and M.D. Stiles, *Physical Review B* **70**, 172405 (2004) [74]
3. “Macrospin models of spin transfer dynamics”, J. Xiao, A. Zangwill, and M.D. Stiles, *Physical Review B* **72**, 014446 (2005) [88]
4. “Spin-transfer torque for continuously variable magnetization”, J. Xiao, A. Zangwill, and M.D. Stiles, *Physical Review B* **73**, 054428 (2006) [94]
5. “Adiabatic domain wall motion and Landau-Lifshitz damping”, M.D. Stiles, W.M. Saslow, M.J. Donahue, and A. Zangwill, *Physical Review B* **75**, 214423 (2007) [44]
6. “A numerical method to solve the Boltzmann equation for a spin valve”, J. Xiao, A. Zangwill, and M.D. Stiles, *European Physical Journal B* **59**, 415 (2007) [11].

IV. FOLLOW-UP

Our detailed applications of the Boltzmann equation to spin transport attracted the attention of Prof. Jack Bass, who directs experimental magnetism research at Michigan State University. Bass was interested to fabricate special spin valve samples for the purpose of putting our theory of spin-transfer torque to a quantitative test. The theoretical part of this work was done exclusively by Jiang Xiao and Mark Stiles (see Section II above). For that reason, I did not add my name to the two papers produced by that collaboration:

“Ballistic versus diffusive transport in current-induced magnetization switching”, N. Theodoropoulou, A.Sharma, W.P. Pratt, Jr., J. Bass, M.D. Stiles, and J. Xiao, *Physical Review B* **76**, 220408(R) (2007).

“Two simple tests of models of current-induced magnetization switching”, N. Theodoropoulou, A.Sharma, W.P. Pratt, Jr., J. Bass, M.D. Stiles, and J. Xiao, Journal of Applied Physics **103**,07A705 (2008).

V. SUMMARY & CONCLUSION

The work performed during the grant period falls under the much broader heading of *spintronics*. This is a world-wide effort to study and harness the transport of the electron’s spin similar to the long-standing and successful efforts of electronics to study and harness the transport of the electron’s charge. Our work on *spin torque* was one of the first sustained theoretical efforts in this direction in the United States. The payoff is just now being seen. In November of 2012, the Everspin Corporation announced the release of the first commercial spin-torque magnetoresistive random access memory.