Theory of Current-Driven Domain Wall Motion:
A Poorman’s Approach

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We formulate the problem of domain wall dynamics in the presence of electric current, and explore some new features such as current-induced depinning of the wall. We start from a microscopic Hamiltonian with an exchange interaction between conduction electrons and spins of a domain wall. With a key observation that the position $X$ and polarization $\phi_0$ of the wall are the proper collective coordinates to describe its dynamics, it follows straightforwardly that the electric current affects the wall motion in two different ways, in agreement with Berger’s observation[2]. The first is as a force on $X$, or momentum transfer, due to the reflection of conduction electrons. This effect is proportional to the charge current and wall resistance, and hence negligible except for very thin walls. The other is as a spin torque (a force on $\phi_0$), arising when an electron passes through the wall. Nowadays it is also called as spin transfer [3] between electrons and wall magnetization. This effect is the dominant one for thick walls where the spin of the electron follows the magnetization adiabatically.

The motion of a domain wall under a steady current is studied in two limiting cases. In the adiabatic case, we show that even without a pinning force, there is a threshold spin current, $j_{s}^{ct}$, below which the wall does not move. This threshold is proportional to $K_\perp$, the hard-axis magnetic anisotropy. Underlying this is that the angular momentum transferred from the electron can be carried by both translational motion ($X$) and polarization ($\phi_0$) of the wall, and the latter can completely absorb the spin transfer if the spin current is small, $j_s < j_{s}^{ct}$. The pinning potential $V_0$ for the wall position ($X$) affects $j_{s}^{ct}$ only if it is very strong, $V_0 > K_\perp/\alpha$, where $\alpha$ is the damping parameter in the Landau-Lifshits-Gilbert equation. In most real systems with small $\alpha$, the threshold would thus be determined by $K_\perp$. Therefore, the critical current for the adiabatic wall will be controllable by the sample shape and, in particular, by the thickness of the film, and does not suffer very much from pinning arising from sample irregularities. This would be a great advantage in application. The wall velocity after depinning is found to be $\langle \dot{X} \rangle \propto \sqrt{(j_s/j_{s}^{ct})^2 - 1}$.

In the case of thin wall, the wall is driven by the momentum transfer, which is proportional to the charge current $j$ and wall resistivity $\rho_w$. The critical current density in this case is given by $j_{s}^{ct} \propto V_0/\rho_w$.

References

