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Anti-damping intrinsic spin-orbit torque in GaMnAs arising from Berry phase

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Recent observations of in-plane-current induced magnetization switching at ferromagnet/normal-conductor interfaces have important consequences for future nonvolatile magnetic memory technology. In one interpretation, the switching originates from carriers with spin-dependent scattering time giving rise to a relativistic anti-damping spin-orbit torque (SOT), which the carriers exert on uniform magnets with broken spatial inversion symmetry. The alternative interpretation combines the relativistic spin Hall effect (SHE), which turns the normal-conductor into an injector of a spin-current, with the non-relativistic anti-damping spin-transfer torque (STT) acting on the ferromagnet. Remarkably, the SHE in these experiments originates from the Berry phase in the band structure of a clean crystal and the anti-damping STT is also based on a disorder independent transfer of spin angular momentum from carriers to the magnetization. In this paper we report the observation of an anti-damping relativistic SOT, which stems from an analogous Berry phase effect as the SHE. The SOT alone can therefore induce magnetization dynamics based on a scattering independent physical principle. In our combined theoretical and experimental study we focus on the ferromagnetic semiconductor (Ga,Mn)As which has a broken spatial inversion symmetry in the bulk crystal. This allows us to consider a bare ferromagnetic film without a symmetry breaking interface with another non-magnetic conductor, thus eliminating by design any SHE related contribution to the observed spin torque. The experimentally observed symmetry and amplitude of the anti-damping torque are consistent with the Berry phase origin for which we provide an intuitive physical picture as well as a numerical solution of the microscopic Kubo formula for the studied (Ga,Mn)As samples..