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Spin reorientation transition in CoFeB/MgO/CoFeB tunnel junction enabled by ultrafast laser-induced suppression of perpendicular magnetic anisotropy

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Electronic supplementary information

Experimental

The multilayer MTJ structure Ta(5.0)/CoFeB(1.2)/MgO(1.2)/CoFeB(1.4)/Ta(5.0)/Ru(3.0) was grown on the thermally oxidized silicon substrate by magnetron sputtering in an ultra-high vacuum chamber using Co-Fe-B targets with nominal composition Co:Fe:B = 0.2:0.6:0.2 as described elsewhere [1]. Here numbers in parentheses stand for the layers thicknesses in nm (see Fig. 1a in the main text). The resulting composition of the ferromagnetic layers in the stack is Co:Fe:B = 0.26:0.54:0.20.

For low-temperature measurements, the sample was placed in a helium-flow cryostat. Static external magnetic field generated by an electromagnet was applied either in the sample plane (IP geometry) or perpendicularly to this plane (PP geometry). The magnetic field strength was varied up to 0.8 T at T = 295 K and up to 0.5 T at T = 140 K.

The pump pulses with a wavelength of 515 nm used in our experiments were generated with β-barium borate single crystal to double the photon energy of a regenerative amplifier output (Light Conversion, PHAROS). Regenerative amplifier delivers pulses with a duration of 170 fs and a wavelength of 1030 nm at 5 kHz repetition rate. The pump pulses were focused onto the sample surface to a spot with a diameter of about 200 μm using plano-convex spherical lens. The pump-induced dynamics were measured in a reflection geometry. The linearly polarized probe pulses with wavelength of 1030 nm were focused onto the sample plane to a spot with a diameter about 100 μm with the incidence angle of 12°. The magneto-optical Kerr effect was traced by the polarization ellipticity $\Delta\varepsilon(\Delta t)$ of the reflected probe pulse, which was measured with the quarter-wave plate, Wollaston prism, and a balanced photodetector. Lock-in detection scheme was used to demodulate the pump-induced changes $\Delta\varepsilon(\Delta t)$ of the Kerr ellipticity. For this purpose, the probe beam was modulated at 625 Hz by the mechanical chopper.

In all experiments the transient changes of the ellipticity $\varepsilon(\Delta t)$ of the probe pulses were measured in the positive ($+H_{ext}$) and negative ($-H_{ext}$) applied fields, and the magneto-optical Kerr ellipticity was calculated as $\Delta\varepsilon(\Delta t,\ H_{\mathrm{ext}}) = 0.5[\varepsilon(\Delta t, +H_{\mathrm{ext}}) - \varepsilon(\Delta t, -H_{\mathrm{ext}})] \propto \Delta M_z(\Delta t, H_{\mathrm{ext}})$ in order to eliminate possible nonmagnetic contributions to the measured signal. As the total thickness of the CoFeB/MgO/CoFeB MTJ structure including the 8-nm-thick Ta/Ru capping layer amounts to 11.8 nm, transient changes of the magnetizations of both ferromagnetic layers contribute to $\Delta\varepsilon(\Delta t, H_{\mathrm{ext}})$. This is confirmed by the static hysteresis curve measured in the PP geometry, which reveals clearly distinguishable states with parallel and antiparallel magnetizations of the CoFeB layers (Fig. 1b in the main text).

Fitting pump-probe traces

Frequency f of the laser-induced precession was obtained by fitting the experimental curves to the function $\varepsilon_0(\Delta t) = A \cdot \cos(2\pi f \Delta t + \xi_0) \cdot e^{-t/\tau_1} + Be^{-t/\tau_2}$, where A is the amplitude, ξ_0 is the initial phase, and τ_1 the damping time of the magnetization precession. The term Be^{-t/τ_2} describes the laser-induced demagnetization along with the variation of the direction of effective field $\mathbf{H}_{\mathrm{eff}}$, where B is the initial step-like change, and τ_2 is the relaxation time.

Extracting the values of anisotropy parameters

The parameters $K_{\mathrm{eff}}(J)$ and $K_{\mathrm{IA}}(J)$ characterizing the effective and interfacial anisotropies of the optically excited fixed CoFeB layer were calculated as a function of the reduced saturation magnetization $M_S'(J)$ with the aid of the Smit-Suhl formula [2,3], which links the precession frequency $f(J)$ to the derivatives of the effective volumetric energy density $F_{\mathrm{m}} = (K_{\mathrm{IA}}/d + \mu_0 M_S^2/2)m_z^2 - \mu_0\, M_S \mathbf{m} \cdot \mathbf{H}_{\mathrm{ext}}$. Variations of M_S' with the pump fluence J were determined using the data on the laser-induced demagnetization measured in PP geometry (see Fig. 3e) and taking the magnetization M_S of the non-excited fixed layer to be 0.9×10^6 A/m at $T = 295$ K and 1×10^6 A/m at $T = 140$ K [1]. The values of $K_{\mathrm{eff}}(J)$ and $K_{\mathrm{IA}}(J)$ were found by numerically solving the equation $f[K_{\mathrm{eff}}(J), M_S'(J), H_{\mathrm{ext}}] = f_{\mathrm{exp}}(J)$ at the magnetic field strength $\mu_0 H_{\mathrm{ext}} = 0.2$ T for $T = 295$ K and $\mu_0 H_{\mathrm{ext}} = 0.35$ T for $T = 140$ K.

References

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