2.3 Anisotropic spin transport in (110) GaAs quantum wells

When electrons move in a III-V crystal, they experience a virtual magnetic field $\mathbf{B}_{\rm int}$ arising from the spin-orbit (SO) interaction, that depends on their momentum $\hbar\mathbf{k}_{\rm e}$. While providing a mechanism to handle spins, $\mathbf{B}_{\rm int}$ may also cause spin decoherence, unless the orbital carrier motion is carefully controlled. In a (110) GaAs quantum well (QW), $\mathbf{B}_{\rm int}$ is given by

$$\mathbf{B}_{\rm int}(\mathbf{k}_{\rm e}) = \mathrm{B}_{\rm int}\hat{\mathbf{z}} \approx \frac{1}{2}\left(\frac{\gamma}{g_e\mu_B}\right) k_{e,y}\left(\frac{\pi}{d_{\rm eff}}\right)^2 \hat{\mathbf{z}}. \tag{2}$$

Here, g_e denotes the electron g-factor, μ_B the Bohr magneton, γ the conduction band SO-splitting constant, $k_{e,y}$ the in-plane momentum along the $\mathbf{y} = [\bar{1}10]$-direction, and $\hat{\mathbf{z}}$ the unit vector along $\mathbf{z}$. The effective thickness $d_{\rm eff}$ includes the nominal QW thickness as well as the wave function penetration in the barriers. Note that $\mathbf{B}_{\rm int}$ is always oriented along the $\mathbf{z} = [110]$ growth direction and can, therefore, not induce the precession of $\mathbf{z}$-oriented spins. This special property, which arises from the symmetry of the QWs, leads to much longer dephasing times τ_z for spins along $\mathbf{z}$ than in conventional (100) QWs.

The long spin dephasing times only apply for spins oriented along $\mathbf{z}$. For other spin orientations, fluctuations in $\mathbf{B}_{\rm int}$ induced by momentum scattering lead to fast spin dephasing. In fact, short dephasing times have been observed if the spin direction is rotated away from $\mathbf{z}$ by the application of an external magnetic field $\mathbf{B}_{\rm ext} \parallel \mathbf{y}$. We demonstrate that the spin dynamics depends on the propagation direction of the spins in the QW plane, thus reflecting the anisotropy of the spin-orbit interaction expressed by Eq. (2).

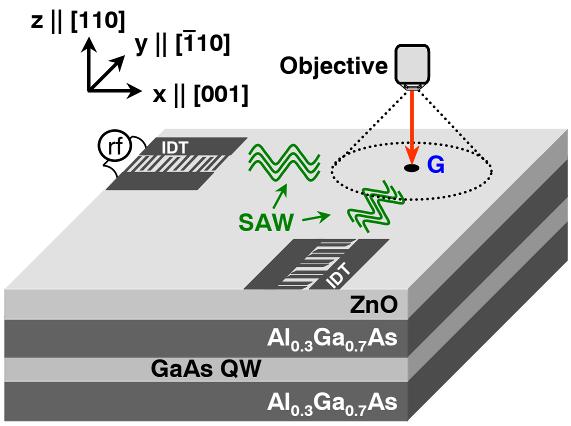

Fig. 8. Sketch of the experimental setup: spin packets photoexcited in the GaAs QW by a laser focused onto spot G are transported by a SAW beam along the $\mathbf{x}$=[001] or $\mathbf{y}$=[$\bar{1}$10] directions. The acoustic beam is generated by an interdigital transducer deposited on the sample surface.

The experiments were carried out by using surface acoustic waves (SAWs) to transport spins along the $\mathbf{x} = [001]$ and $\mathbf{y} = [\bar{1}10]$ directions of a GaAs (110) QW (cf. Fig. 8). The spin polarization ρ_z was generated using a circularly polarized laser beam focused onto spot G. By measuring the degree of circular polarization of the photoluminescence (PL) emitted by the carriers during transport, ρ_z of the carriers transported away from G was determined. The triangles in Figs. 9(a) and 9(b) display ρ_z for transport along $\mathbf{x}$ and $\mathbf{y}$, respectively. In both cases, we obtain from the decay rate a spin dephasing time $\tau_z = 20 \pm 2$ ns, corresponding to coherent transport over a length of approximately 60 μm.

The difference between the two transport directions becomes clear when the transport experiments are carried out with an externally applied field $\mathbf{B}_{\rm ext}$. For transport along $\mathbf{x}$, $\mathbf{B}_{\rm ext}||\mathbf{y}$

induces a coherent precession of the average spin vector, leading to the temporal and spatial oscillations in ρ_z [cf. Fig. 9(a)]. The ρ_z oscillations, however, are strongly damped and persist for times much shorter than τ_z. In contrast, for transport along **y**, the decay times are not affected by $\mathbf{B}_{\text{ext}}||\mathbf{y}$ [circles in Fig. 9(b)], while the overall ρ_z levels are reduced.

The behavior described above can be understood by taking into account Eq. (2). For transport along **x**, the average momentum $\langle k_{e,y}\rangle$ (and, therefore, $\langle\mathbf{B}_{\text{int}}\rangle$) vanishes so that the precession dynamics becomes determined solely by the external field. Fluctuations in $k_{e,y}$ induced by carrier motion perpendicular to the SAW wavefronts dephase the **x** spin component, thus leading to an effective decay time for the oscillations $\tau_{\text{eff}} \approx 2.3$ ns — much shorter than τ_z. In contrast to this situation, motion along **y** induces a finite $\langle\mathbf{B}_{\text{int}}\rangle||\mathbf{z}$, thus forcing the spins to precess around a resultant field $\mathbf{B}_{\text{R}} = \mathbf{B}_{\text{ext}} + \langle\mathbf{B}_{\text{int}}\rangle$ with a component along **z** [cf. inset of Fig. 9(b)]. While the spin polarization component transverse to $\mathbf{B}_{\text{R}}$ only lasts for times comparable to τ_{eff} (as for transport along **x**), the longitudinal component (i.e., parallel to $\mathbf{B}_{\text{R}}$) thermalizes with a longer longitudinal decay time $\tau_l \approx 18$ ns [note the different scales in Figs. 9(a) and 9(b)]. The solid lines in Fig. 9 are fits to a model for the spin relaxation in an external field. The fits deliver an average amplitude $\langle B_{\text{int}}\rangle$ = (20± 3) mT and a spin orbit splitting constant $\gamma = (18 \pm 3)$ eVA^3. The latter is close to the values derived from spin transport by mobile potential dots in (100) GaAs QWs.

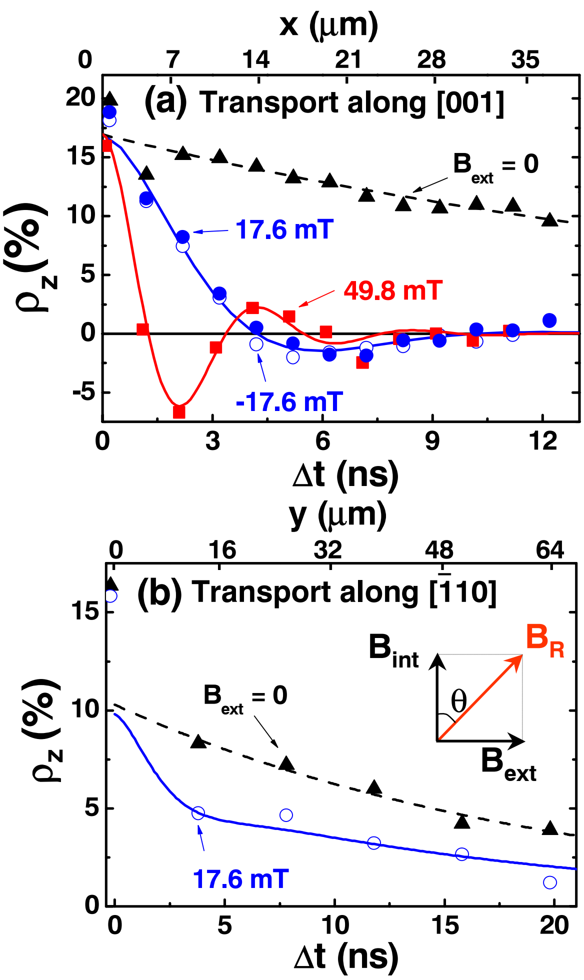

Fig. 9. Spin polarization ρ_z during transport along (a) $\mathbf{x}$ = [001] and (b) $\mathbf{y}$ = [$\bar{1}$10] under different external magnetic fields $\mathbf{B}_{\text{ext}}$ applied along **y**. The solid lines are fits to a spin dephasing model.

In conclusion, we have demonstrated that the dynamics of moving spins is anisotropic in the (110) plane, the anisotropy being associated with the SO coupling. The long spin lifetimes and transport distances make these QWs a model system for spin investigations as well as for spintronic applications.

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