
Supplementary information

Controlling the helicity of light by electrical magnetization switching

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Controlling the helicity of light by electrical magnetization switching

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Note 1: Spin injection in spin-lasers with lateral spin injectors

The existing proposals for electrical modulation of circular polarization rely on a pair of spin-injection electrodes with antiparallel magnetization, M , on the top of spin-light emitting diodes (LEDs)¹ or spin-lasers, known also as spin-vertical cavity surface emitting lasers (VCSELs)^{2,3} (**Fig. S1a**). Such lasers can be viewed as LEDs with resonant cavities adding optical gain. Typically, the resonant cavity is defined by distributed Bragg reflectors (DBRs) as their mirrors, while the gain (active) region is formed from semiconductor quantum wells (QWs) or quantum dots (QDs). By varying the injection current, I , from each electrode, one expects to achieve both helicity switching and tuning of the circular polarization¹, $P_c = (S^{\sigma^+} - S^{\sigma^-}) / (S^{\sigma^+} + S^{\sigma^-})$, where $S^{\sigma^{\pm}}$ is the right (left) circularly polarized photon density. There are two disadvantages for such a design: (i) The placement of the spin injector around the base of the laser mesa requires electron spin transport across several μm to reach the gain (active) region of the laser. Over this length, spin relaxation and spin diffusion diminish the electron spin polarization, P_e , and only $P_c \sim 23\%$ was obtained at 50 K in a spin-VCSEL with a Fe/Al_{0.1}Ga_{0.9}As injector⁴ (**Fig. S1b**). (ii) Each P_c change requires an alternating injection step using a different electrode, losing advantages compared to the intensity-modulation method. For a very high-data rate and long-distance transmission, the total carrier density in the active part of the laser source should be kept constant while modulating the P_c to reduce parasitic effects and avoid the linewidth broadening by the laser chirp⁵.

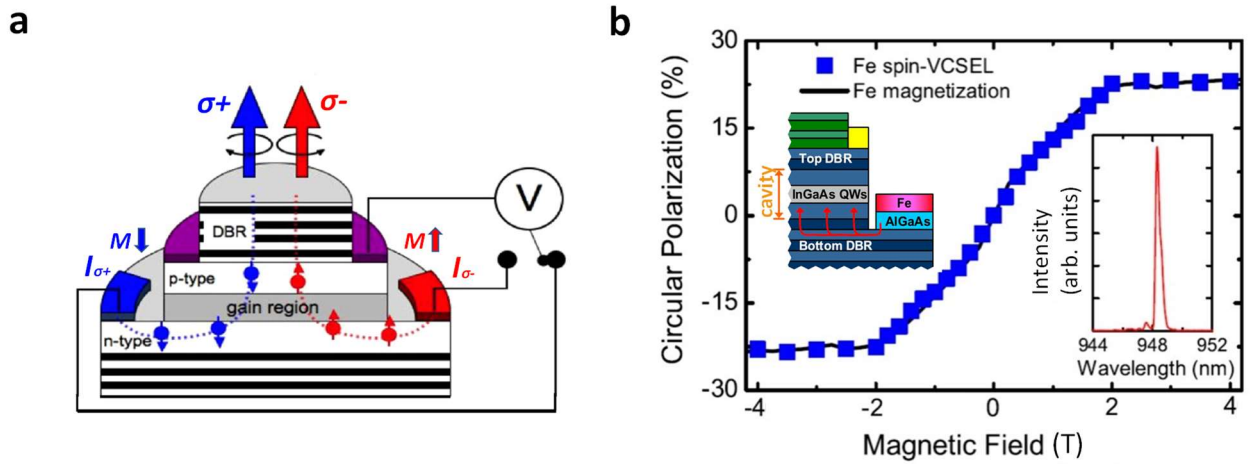


Figure S1: (a) Schematic for modulation of the circular polarization, P_c , in a spin-laser (spin-VCSEL). Electrons of opposite spin (arrows) are injected in VCSELs from ferromagnets with opposite magnetization, M . The resonant cavity is defined by the two DBR mirrors. Emitted light with opposite helicities ($S^{\sigma^+}, S^{\sigma^-}$). Reproduced from Ref. [3], with the permission of NPG. **(b)** P_c as a function of an applied magnetic field for a spin-VCSEL measured at 50 K. From the optical selection rules for the circularly polarized emission, the field is needed to rotate the in-plane M of the Fe-based spin injector. Left inset: Fe spin-polarized VCSEL design. Right inset: Electroluminescence spectrum. Reproduced from Ref. [4], with the permission of APS.

Note 2: Obstacles for developing SOT spin injectors

A significant obstacle for spin-orbit torque (SOT) magnetization (M) switching in LEDs is the shunting problem due to the n - i - p LED structure. **Figure S2a** shows the schematic of the spin-LED structure and its equivalent circuit model. When the injector is integrated in the n - i - p LED structure, the equivalent circuit should be considered by adding a parallel conduction channel from the semiconductor part under the injector. If the switching current is sufficiently low, the metal-insulator-semiconductor (MIS) Schottky barrier will help to block the current entering the semiconductor part. However, if the switching current is large, the voltage drop, V , on both ends of the injector will be large enough to break down the MIS Schottky barrier, where $V=R_{\text{cha}} \times I_{\text{pulse}}$, with R_{cha} the effective channel resistance (including injector channel resistance, MIS Schottky contact, n -GaAs resistance) and I_{pulse} the pulsed current for M switching. In such a case, the shunting current through the semiconductor will significantly reduce the current density in the injector channel and prevent M switching.

We have grown spin-LEDs with an injector stack consisting of MgO(2.5 nm)/CoFeB(1.1 nm)/Ta(2 nm)/MgO(3.2 nm)/MgAlO_x(2.5 nm). This type of spin injector has already shown a high spin-injection efficiency with a good perpendicular magnetic anisotropy (PMA)⁶. Grown on an **undoped GaAs substrate**, the injector M can be switched with a critical current of 35 mA at 50 K and 15 mA at 200 K. However, we are not able to switch the injector M in a LED structure due to the current shunting problem. **Figure S2b** displays the measured R_{cha} as a function of I_{pulse} in the channel measured at 50 K. When $I_{\text{pulse}} > \pm 5$ mA, R_{cha} drops dramatically. As a consequence, one cannot achieve the SOT M switching in LED structures. With $I_{\text{pulse}} = 5$ mA, the voltage drop on the two ends of the injector channel can reach 14 V with $R_{\text{cha}} = 2.8$ k Ω . This high voltage is large enough to break down the MgO/GaAs Schottky barrier and creates a shunting current through the semiconductor. **Figure S2c** shows I - V_{bias} curves of a LED after different I_{pulse} switching. It can be seen that the I - V_{bias} characteristic changes significantly when $|I_{\text{pulse}}| > 5$ mA, which means the Schottky barrier is partially damaged by the switching current. This interface damage is irreversible because the I - V_{bias} curve will not return back to the initial state, even after smaller current switching.

To reduce the critical current for M switching and avoid the shunting current problem, we have developed two other types of spin injectors. The first strategy is to use a topological insulator (TI) with a giant spin-Hall angle to switch M of a ferromagnet (F)⁷. The spin injector consisting of TI material Bi_xSe_{1-x}⁸ has a stack structure: GaAs LED sub//MgO(2 nm)/CoFeB(0.8 nm)/Gd (1.2 nm)/CoFeB(0.5 nm)/Ta(0.5 nm)/Bi_xSe_{1-x}(4 nm)/MgO(2 nm)/Ta(2 nm). The injector exhibits good PMA from 50 to 300 K. However, the I - V_{bias} characteristics of the LED show a much higher current at lower bias, which signifies a worse Schottky barrier than for the normal MgO/CoFeB/Ta injector. The reason is due to the Ar⁺ plasma cleaning procedure prior to the TI injector growth in an individual

sputtering system. Finally, the shunting problem still exists and M switching was not achieved. This experiment emphasizes the critical role of the injector/semiconductor interface for M switching in LED structures. The second strategy is to develop an Fe_4N -based spin injector. Recently, a field-free M switching has been reported in $\text{Au}/\text{Fe}_4\text{N}$ bilayer films with a very low current density of $6.8 \times 10^5 \text{ A/cm}^2$ at room temperature (RT)⁹. By using plasma-assisted molecular beam epitaxy, we have grown a spin injector consisting of a $\text{MgO}(2.5 \text{ nm})/\text{Fe}_4\text{N}(3 \text{ nm})/\text{Au}(3 \text{ nm})$ structure. The injector has an in-plane and out-of-plane mixed M structure, and the out-of-plane component indeed can be switched on the LED substrate even at zero field. Unfortunately, the electroluminescence (EL) characterization of the spin-LED does not show any P_c related to the spin injection, which could be attributed to the low spin-polarization efficiency of Fe_4N due to the complex magnetic structure⁹.

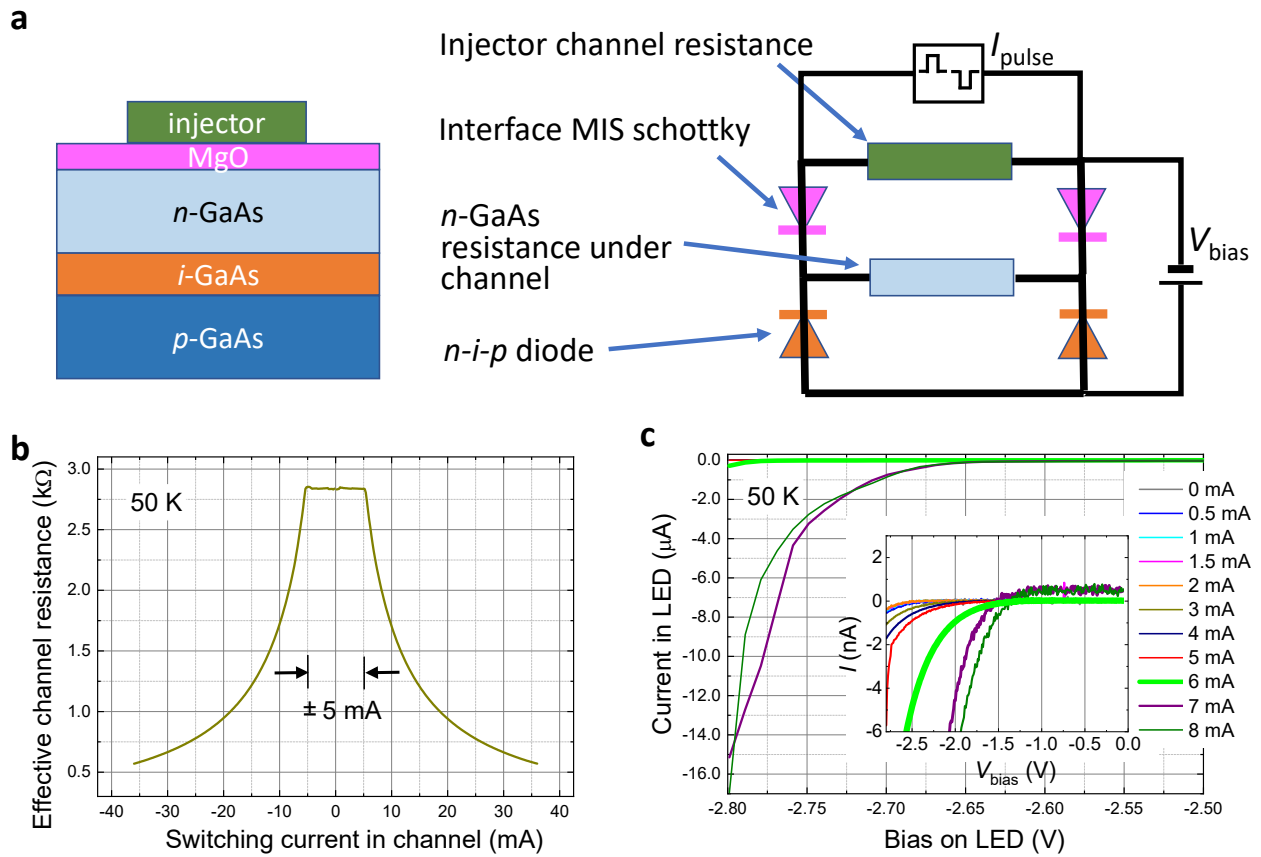


Figure S2: (a) Schematic of the spin-LED structure and its equivalent circuit. (b) Effective channel resistance of spin injector, R_{cha} , as function of the M switching pulsed current, I_{pulse} , in the channel measured at 50 K. When $|I_{\text{pulse}}| > 5 \text{ mA}$, R_{cha} drops significantly. (c) I - V_{bias} curves of the LED after different I_{pulse} switching. Inset: A magnified view of the small current region showing that I - V_{bias} curves strongly change when I_{pulse} is larger than 5 mA.

Note 3: Structural and chemical characterization of InAs QDs

Figure S3a shows the scanning transmission electron microscopy (STEM) high-angle annular dark-field (HAADF) image of the QD layer, and their corresponding elemental maps (In, Ga, As) are displayed in **Figs. S3b-d**. The electron energy loss spectroscopy (EELS) map of In allows to identify the location of the QDs. Their sizes are measured from the intensity curves in the In elemental map. From the lateral intensity profile of the In concentration (**Fig. S3e**), the diameter of the QDs, d , can be evaluated to be $7\text{ nm} < d < 12\text{ nm}$. From the intensity of the depth profile (**Fig. S3f**), the height of the QDs can be evaluated to be close to 2 nm.

Due to In-Ga interdiffusion during the GaAs capping layer growth, the “InAs” QD has a lower In concentration. As previously studied in a publication of the coauthors responsible for the QD LED growth¹⁰, a method based on the quantitative analysis of the (002) dark-field (DF) image contrast in cross-sectional transmission electron microscopy has been employed to measure the composition distribution of $\text{In}_x\text{Ga}_{1-x}\text{As}/\text{GaAs}$ QDs. **Figure S4a** shows a typical cross-sectional (002) DF TEM image of a GaAs-capped InAs/GaAs QD with a lens shape. **Figure S4b** shows the measured composition profiles across different regions of the QD shown in **Fig. S4a**. In the central part (curve a), the In concentration gradually increases from $x=0.30$ to $x=0.42$ within 2.2 nm and then drops very rapidly (over 1 nm) down to few percent at the interface with the capping GaAs.

Another way to determine the composition is from the wavelength of the EL peak. In Ref.¹¹, the authors have calculated the ground state (GS) transition energy as a function of In composition for the InGaAs QD by using the nextnano software¹². **Figure S4c** shows the GS transition energy of the (In,Ga)As QD as a function of the In composition. By using the $E_{\text{GS}}=1.22\text{eV}$ determined from our RT EL spectra (QD peak at around 1016 nm in the net spectra after correction of spectrometer and CCD response), we can obtain $x=0.33$. If taking account of the inhomogeneity of the In concentration (shoulder peak at around 1047 nm, see **SI Note 5**), the In composition is in the range from $x=0.33$ to $x=0.38$ which is in a good agreement with the concentration determined by DF TEM.

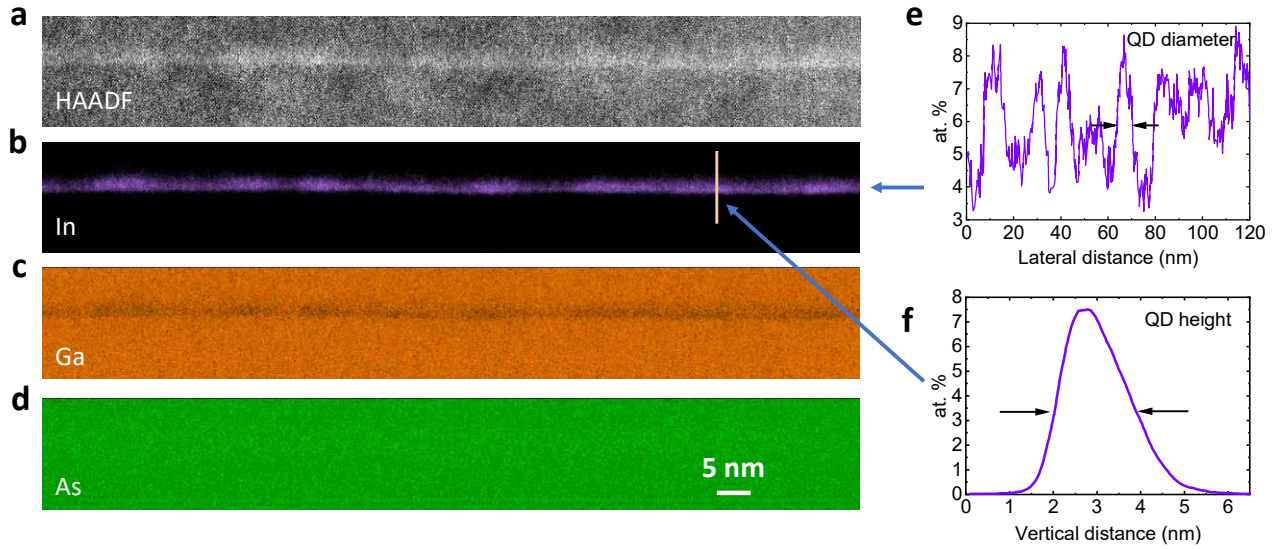


Figure S3: (a) STEM HAADF image showing the QD layer. (b-d) EELS maps showing the chemical concentration variation in the QD layer for (b) In, (c) Ga and (d) As. (e) The lateral profile of the In concentration allows to determine the QD diameter. (f) The intensity of the depth profile allows to determine the QD height.

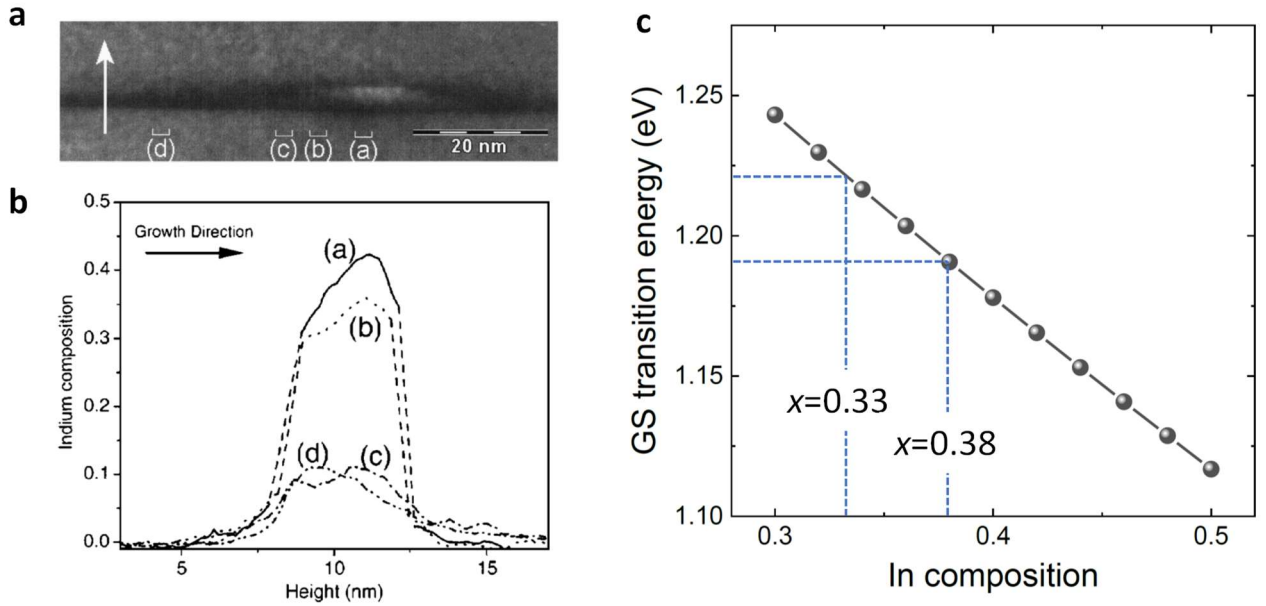


Figure S4: (a) (002) DF TEM images of InAs/GaAs QDs capped with GaAs. The arrow indicates the growth direction. (b) In composition profiles obtained along the growth direction for the regions marked in panel (a). In profiles (a) and (b), regions where the In composition varies too quickly to be accurately determined are represented by straight dashed lines. Reproduced from Ref. [10], with the permission of AIP Publishing. (c) Calculated GS transition energy as a function of the In composition. These calculations are conducted at a lattice temperature of 298 K. Reproduced from Ref. [11], with the permission of APS. The In composition is determined in a range from $x=0.33$ to $x=0.38$ from the EL peak position of this work.

Note 4: W-based spin injectors for rapid M switching

To improve the M -switching speed, we have developed another spin injector consisting of MgO(2.5 nm)/CoFeB(1.2 nm)/W(3 nm)/Cr(3 nm) by replacing Ta with W. This is motivated by the fact that the β -phase W is reported to have an even larger spin Hall angle ($\theta_{\text{SH}} \sim 0.33$)¹³ than Ta ($\theta_{\text{SH}} \sim 0.15$)¹⁴. **Figure S5** shows the measured R_{AHE} of the injector by the out-of-plane field switching (**Fig. S5a**) and I_{pulse} switching (**Figs. S5b and S5c**). A clear square loop feature in **Fig. S5a** indicates a good PMA of the W-based spin injector. **Figures S5b and S5c** display the R_{AHE} variation with t_{pulse} from 100 ms to 10 μs with a small in-plane field $H_x = -10$ mT and $+10$ mT, respectively. The full M switching can be realized even with 10 μs pulse, which is at least 100 times faster than Ta-based spin injector. We note that 10 μs is the limitation of our instrument (Keithley 6221), such that it is only an upper limit, while the actual times might be even shorter. A faster current switching for *in-plane* magnetized W/CoFeB/MgO-based three terminal magnetic tunnel junctions with $t_{\text{pulse}} = 50$ ns has already been reported¹⁵. Upon the reversal of H_x (**Fig. S5c**), the polarity of the current-induced switching loop also reverses, which proves the SOT driven M -switching mechanism. We find that the critical current, I_c , increases when reducing t_{pulse} (**Fig. S5d**). For $t_{\text{pulse}} > 1$ ms, I_c only changes slightly with t_{pulse} and scales approximately linearly with $\log(t_{\text{pulse}})$, which suggests a thermally activated regime where stochastic thermal fluctuations help M to overcome the reversal energy barrier^{16,17}. For $t_{\text{pulse}} < 1$ ms, I_c increases quickly with the decrease of t_{pulse} and scales linearly with $1/t_{\text{pulse}}$, as shown in **Fig. S5e**. This behavior suggests that M switching occurs by domain nucleation followed by domain wall propagation¹⁸. In such a case, the switching time is the time for a nucleated domain wall to travel across the channel. Surprisingly, a full M can be realized even at zero *in-plane* magnetic field (**Fig. S5f**), although I_c is slightly larger than for the switching with a small *in-plane* field. Field-free SOT switching in a perpendicularly magnetized trilayer CoFeB/W/CoFeB has been reported¹⁹, which is enabled by an in-plane effective field experienced by the switching layer through the exchange coupling with an additional in-plane synthetic antiferromagnet. In our case, the in-plane effective field could be induced by the oblique columnar growth in the layer structure, especially for the W/Cr structure²⁰.

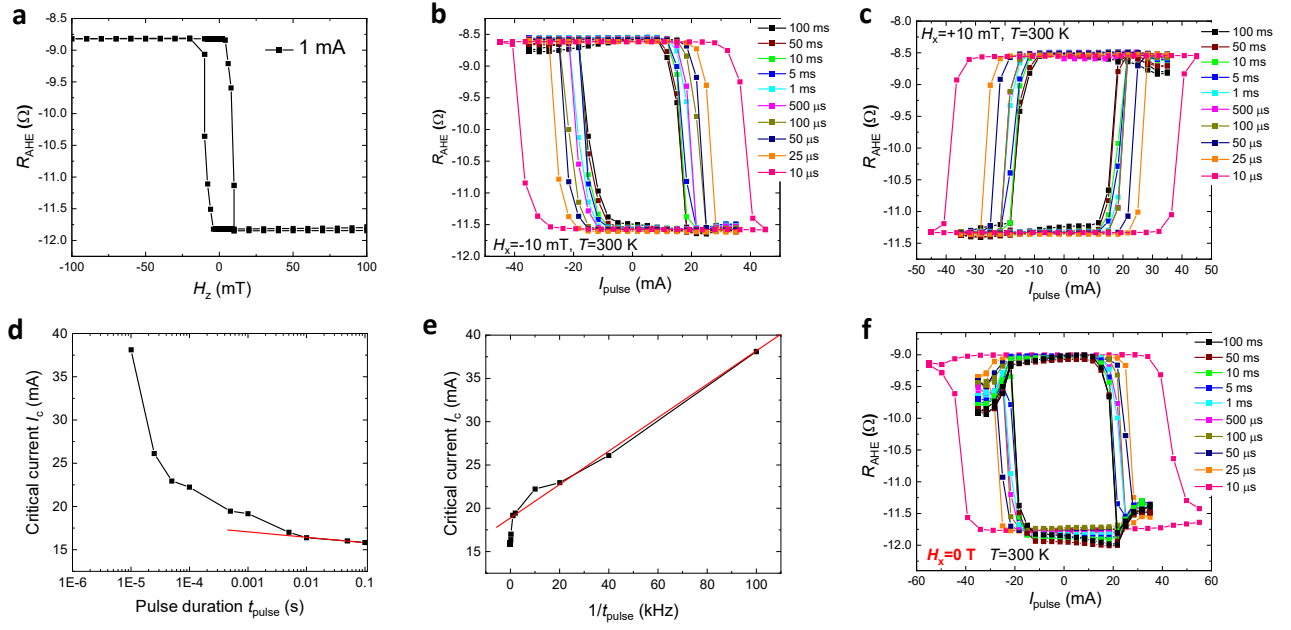


Figure S5: (a) Anomalous Hall effect resistance, R_{AHE} , of a W-based spin injector as a function of out-of-plane magnetic field at room temperature in LED structures with 1 mA channel current. (b,c,f) R_{AHE} of a W-based spin injector as a function of I_{pulse} with different t_{pulse} under small in-plane field H_x : (b) -10 mT, (c) +10 mT and (f) 0 T. (d) I_c as a function of t_{pulse} (in log scale) for $H_x = -10$ mT (positive pulse current switching). The red line is a guide of the linear relationship for $t_{\text{pulse}} > 1$ ms. (e) Plot of I_c vs. $1/t_{\text{pulse}}$ for the same set of data in (d). The red line is a guide of the linear relationship for $t_{\text{pulse}} < 1$ ms.

Note 5: Influence of spectral calibration and wavelength dependence of P_c

For our EL measurements, the signal is detected in the Faraday geometry and analyzed by a spectrometer (*Acton SP2500 Princeton Instruments*) equipped with an 80 grooves/mm grating (*blazed at 870 nm*) and detected by a Si-based CCD camera (*Pylon Excelon 400 BR from Princeton instruments*). The P_c of EL is analyzed by a quarter-wave retarder and a linear polarizer. As the wavelength of the light emitted by the spin-LED approaches the limitation of the Si-based detector, the shape of the EL spectra is partially deformed due to the spectral response of the spectrometer and the Si-based CCD detector. **Figure S6a** shows the efficiencies of the CCD camera, grating, and mirror as a function of wavelength. To extract the net spectra, the total response efficiency (η_{total}) should take into account the efficiencies of the grating ($\eta_{grating}$) and the two mirrors (η_{mirror}) inside the spectrometer and the Si-based CCD camera (η_{CCD}), which can be expressed as $\eta_{total} = \eta_{grating} \times \eta_{mirror}^2 \times \eta_{CCD}$. The obtained total response efficiency is plotted as a green line in **Fig. S6a**. **Figure S6b** displays the raw data and the net spectra treated by the total response. The main EL peak related to the X^+ trion transition at 993 nm in the raw data has been shifted to 1016 nm in the net spectra accompanied by a shoulder at 1047 nm. This shoulder is probably due to the inhomogeneity of the QDs²¹. In addition, the peak assigned to the InGaAs wetting layer at 930 nm becomes less important.

Although the total response efficiency has an influence on the shape of the spectra, the spectral variation of P_c is unaffected by the correction process because the σ^+ and σ^- spectra are divided by the same total response efficiency. In **Figs. S6c** and **S6d**, we have plotted the wavelength dependence of P_c from the raw data and from the net spectra, respectively. To better illustrate the variation of P_c , we also show in **Figs. S6e** and **S6f** the P_c extracted from the spectra after 10-point FFT smoothed data. In this work, all P_c values are analyzed at the maximum EL peak (from smoothed raw data) as shown by the dashed line in **Fig. S6e**. The wavelength dependence of P_c shows that the maximum P_c is located at the EL peak in the net spectra as shown in **Figs. S6d** and **S6f**. However, the difference of P_c at EL peak maximum in both cases is quite small ($\sim 1\%$), which does not change the conclusions in the main text.

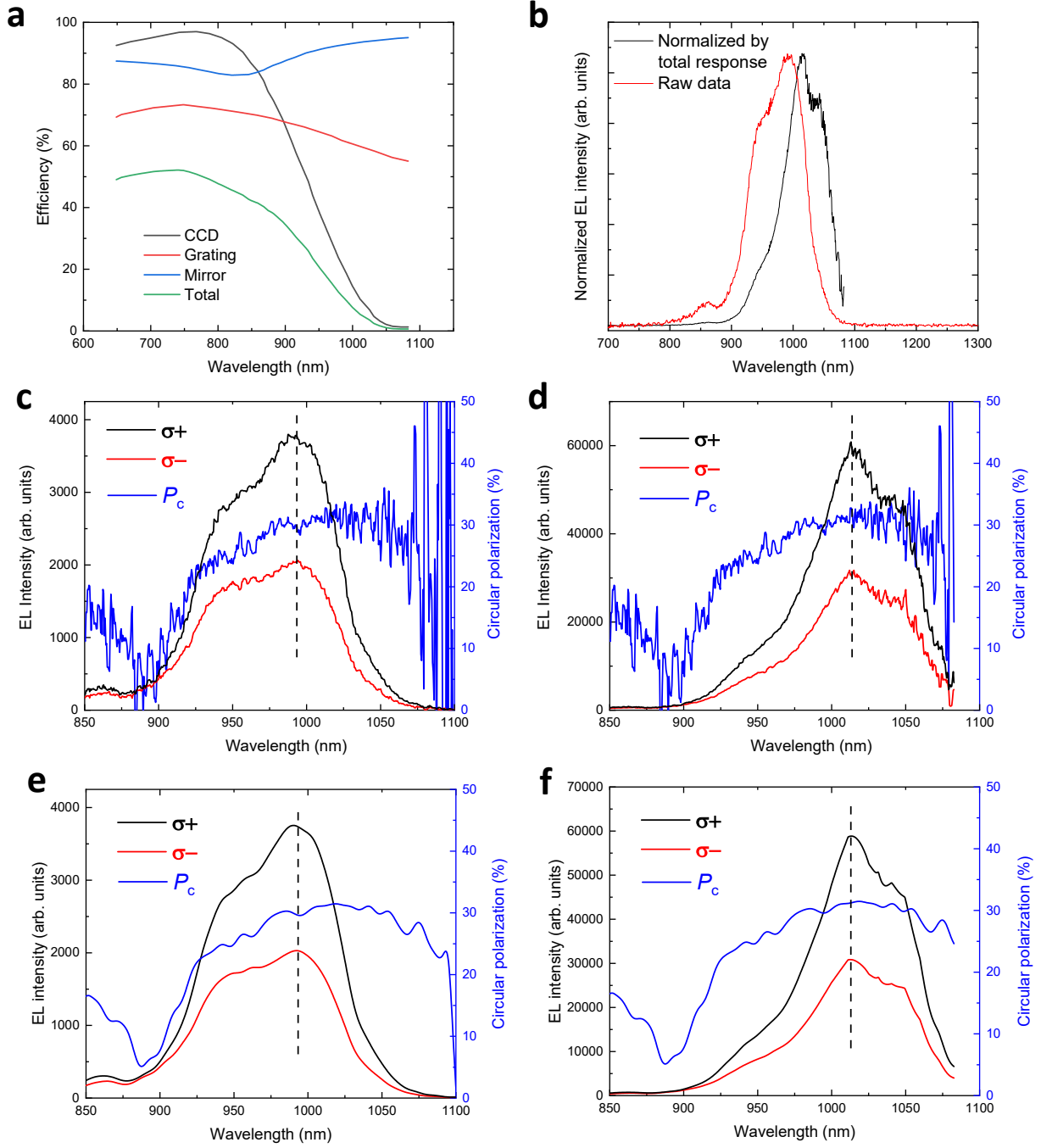


Figure S6: (a) The efficiencies of the CCD camera (η_{CCD}), grating (η_{grating}) and mirror (η_{mirror}) as a function of wavelength. The total efficiency (η_{total}) is calculated as $\eta_{\text{total}} = \eta_{\text{grating}} \times \eta_{\text{mirror}}^2 \times \eta_{\text{CCD}}$. (b) Comparison of the untreated spectra and the net spectra corrected by the total response. Both spectra are normalized to their maximum. (c,e) Untreated polarization-resolved EL spectra of the SOT spin-LED measured at 300 K with a bias of 1.9 V under zero out-of-plane field. The wavelength dependence of P_c is calculated from (c) raw data and (e) 10 point-FFT smoothed data. (d,f) Net polarization-resolved EL spectra after dividing by the total response efficiency. The wavelength dependence of P_c is calculated from (d) raw data and (f) 10 point-FFT smoothed data.

Note 6: Benchmark with existing spin-LED work

We have listed below the main spin-LED works published since 1999. According to the light detection geometry, they can be mainly divided into two classes of devices. One is in Faraday geometry, where the light is detected from the surface. The other is in the edge-emitting geometry. Up to now, most of the spin-LED devices are based on the Faraday geometry. The advantage of the Faraday geometry is a simple and direct relationship between the carrier spin state in the active region and the circularly polarized emission via the optical selection rules for QW and QD active regions. Furthermore, one benefits from easy optical collection and high device density. However, according to the optical selection rules, the spin injector should have a perpendicular magnetic anisotropy to emit circularly polarized light without external magnetic field. Since most ferromagnetic injectors have in-plane magnetization, the necessary alignment of emission direction and magnetic moment is easier to achieve in edge-emitting geometry. However, circularly polarized emission of light, which is directly connected to the spin state of the carriers, can only be obtained in the edge-emitting geometry if the active region is based on bulk-like structures or QDs with appropriate symmetry. Our strategy is to focus on the Faraday geometry to develop out-of-plane spin injectors. For practical application, it is indispensable that the spin-LED can operate at room temperature and without applied magnetic field. As shown in **Table S1** and **S2**, by fair comparison of *pure spin injection effects only*, without considering optical anisotropy related effects, we confirm that the results obtained with our novel SOT-based spin-LED concept presented in this work hold the highest record of circular polarization to satisfy both room temperature and zero magnetic field operation conditions.

Table S1. Spin-LED in Faraday geometry

Spin-injector	Magnetization anisotropy	Interface contact	Emitter	Circular polarization (%)	Ref.
BeMnZnSe	In plane	Ohmic contact	AlGaAs/GaAs QW	43% (3T, 5K)	Fierderling 1999 [22]
ZnMnSe	In plane	Ohmic contact	AlGaAs/GaAs QW	50% (5T, 4.2K)	Jonker 2000 [23]
ZnMnSe	In plane	Ohmic contact	GaAs/InGaAs QW	35% (6T, 5K)	Loffler 2005 [24]
ZnMnSe	In plane	Ohmic contact	GaAs/InAs single QD	60% (4T, 3.7K)	Ghali 2007 [25]
ZnMnSe	In plane	Ohmic contact	GaAs/InAs single QD	83% (2T, 5K) 96% (6T, 5K)	Asshoff 2011 [26]
CdCr ₂ Se ₄	In plane	Ohmic contact	AlGaAs/GaAs QW	4% (1T, 5K)	Kioseoglou 2004 [27]
GaMnAs	In plane	Ohmic contact	GaAs/InGaAs QW	4% (2.5T, 5K)	Young 2002 [28]
MnAs	In plane	Schottky barrier	GaAs/InGaAs QW	1% (1T, 80K)	Ramsteiner 2002 [29]
MnAs	In plane	Schottky barrier	GaAs/InAs single QD	8% (1.5T, 5K)	Bhattacharya 2010 [30]

Co ₂ MnGe	In plane	Schottky barrier	AlGaAs/GaAs QW	13% (1T, 2K)	Dong 2005 [31]
Co _{2.4} Mn _{1.6} Ga	In plane	Schottky barrier	GaAs/InGaAs QW	13% (0.5T, 5K)	Hickey 2005 [32]
Co ₂ FeSi	In plane	Schottky barrier	AlGaAs/GaAs QW	17% (2T, 20K)	Ramsteiner 2008 [33]
Fe	In plane	Schottky barrier	GaAs/InGaAs QW	2% (5T, 300K)	Zhu 2001 [34]
Fe	In plane	Schottky barrier	AlGaAs/GaAs QW	13% (3T, 4.5K)	Hanbicki 2002 [35]
Fe	In plane	Schottky barrier	AlGaAs/GaAs QW	30% (2.5T, 2K) 10% (2.5T, 295K)	Adelmann 2005 [36]
Fe	In plane	MgO barrier	AlGaAs/GaAs QW	9% (1.3T, 300K)	Manago 2007 [37]
Fe	In plane	Schottky barrier	GaAs/InAs multi wetting layer	27% (2T, 5K)	Li 2007 [38]
Fe	In plane	AlO _x barrier	AlGaAs/GaAs single and multi (110) QW	4% (3T, 40K) SQW 2.6% (3T, 300K) MQW	Yokota 2015 [39]
Fe	In plane	Al ₂ O ₃ barrier and Schottky barrier	AlGaAs/GaAs 50nm	20% (2T, 5K) (Al ₂ O ₃ barrier) 15% (2T, 5K) (Schottky barrier)	van't Erve 2004 [40]
Fe	In plane	Schottky barrier	GaAs/InAs QD	5% (2T, 5K)	Li 2005 [41]
Fe	In plane	Schottky barrier	GaAs/InAs QD	4% (0.06T, 15K)	Itskos 2006 [42]
Fe	In plane	MgO barrier	GaAs/InGaAs multi QD	8% (2.2T, 298K)	Etou 2021 [11]
Fe	In plane	MgO barrier	GaAs/InGaAs QD coupled to Ga(N,As) QW	7% (2.2T, 295K)	Etou 2023 [43]
Co	In plane	Schottky barrier	AlGaAs/GaAs QW	4% (0.8T, 22K)	Liu 2003 [44]
Co	In plane	Al ₂ O ₃ barrier	GaAs/InAs QD	15% (2T, 1.7K)	Lombes 2007 [45]
Co,Fe,NiFe	In plane	Al ₂ O ₃ barrier	AlGaAs/GaAs QW	0.5% (1.3T, 300K)	Manago 2002 [46]
CoFe	In plane	Al ₂ O ₃ barrier	AlGaAs/GaAs 100nm	2 (0.6T, 80K)	Motsnyi 2002 [47]
CoFe	In plane	Al ₂ O ₃ barrier	AlGaAs/GaAs QW	4% (0.5T, 80K)	Motsnyi 2003 [48]
CoFe	In plane	AlO _x barrier	AlGaAs/GaAs 100nm	1% (0.6T, 300K)	Dorpe 2003 [49]
NiFe	In plane	CoFe/Al ₂ O ₃ /CoFe/NiFe hot electron injection	GaAs/InGaAs QW	10% (2T, 1.4K)	Jiang 2003 [50]
Co ₇₀ Fe ₃₀	In plane	MgO barrier	AlGaAs/GaAs QW	52% (5T, 100K) 32% (5T, 290K)	Jiang 2005[51]

Co ₇₀ Fe ₃₀	In plane	MgO barrier	AlGaAs/GaAs QW	30% (0.8T, 290K)	Salis 2005[52]
CoFeB	In plane	MgO barrier	AlGaAs/GaAs QW	32% (0.8T, 100K)	Lu 2008 [53]
CoFeB	In plane	MgO barrier	GaAs/InGaAs QW	24% (0.8T, 25K)	Barate 2014 [54]
CoFeB	In plane	MgO barrier	GaAs/InGaAs QW	21% (0.8T, 25K) 20% (0.8T, 250K)	Barate 2017 [55]
Fe	In plane	Al ₂ O ₃ barrier	Si p-i-n	3.5% (2T, 5K)	Jonker 2007 [56]
GaCrN	In plane	Ohmic contact	GaN/InGaN 40nm	6% (1T, 5K) 2.5% (0.05T, 200K)	Banerjee 2013 [57]
Ni-Fe ₃ O ₄ nanoparticles	In plane	Schottky contact	GaN/InGaN multi QW	11% (0.35T, 300K)	Chen 2014 [58]
Fe	In plane	Al ₂ O ₃ barrier	In _{0.01} Ga _{0.99} N/In _{0.25} Ga _{0.75} N multi QW	9% (0.8T, 300K)	Wu 2019 [59]
NiFe	In plane	Schottky contact	MoS ₂ /WSe ₂	20% (5T, 4.2K)	Sanchez 2016 [60]
LSMO	In plane	Schottky barrier	MAPbBr ₃	1% (0.2T, 10K)	Wang 2019 [61]
Mn-doped InAs QD	Out of plane	Ohmic contact	GaAs/InGaAs QD	6% (0T, 28K)	Chakrabarti 2005 [62]
FePt	Out of plane	MgO barrier	AlGaAs/GaAs QW	1.5% (0T, 300K) 11% (1T, 300K)	Sinsarp 2007 [63]
δ -MnGa	Out of plane	Schottky barrier	AlGaAs/GaAs QW	3.5% (0T, 20K)	Adelmann 2006 [64]
Fe/Tb	Out of plane	Schottky barrier	GaAs/InGaAs QW	0.4% (0T, 90K)	Gerhardt 2006 [65]
Fe/Tb	Out of plane	Schottky and MgO	AlGaAs/GaAs QW	3.5% (0T, 300K)	Hövel 2008 [66]
Fe/Tb	Out of plane	MgO barrier	GaAs/InAs QD	2.2% (0T, 295K)	Höpfner 2012 [67]
Co/Pt	Out of plane	MgO barrier	AlGaAs/GaAs QW	2.5% (0T, 20K)	Zarpellon 2012 [68]
CoFeB	Out of plane	MgO barrier	GaAs/InGaAs multi QWs	20% (0T, 25K) 8% (0T, 300K)	Liang 2014 [6]
CoFeB	Out of plane	MgO barrier	GaAs/InGaAs QW	10% (0T, 10K) 8% (0T, 300K)	Tao 2016 [69]
CoFeB	Out of plane	MgO barrier	GaAs/InGaAs QD	35% (0T, 9K) (single QD) 25% (0T, 9K) (ensemble QDs)	Cadiz 2018 [70]
CoFeB/Mo	Out of plane	MgO barrier	GaAs/InGaAs QW	10% (0T, 10K)	Tao 2018 [71]
CoFeB	Out of plane	MgO barrier	GaAs/InGaAs QD	19% (0T, 100K)	Giba 2020 [72]
MnGa	Out of plane	Schottky barrier	GaN/InGaN QW	0.3% (0T, 80K)	Zube 2018 [73]
GaMnAs	Out of plane	Schottky barrier	WS ₂	8% (0T, 10K)	Ye 2016 [74]
Fe ₃ GeTe ₂	Out of plane	hBN barrier	WSe ₂	8% (0T, 78K)	Li 2022 [75]
Chiral (R-/S-MBA) ₂ PbI ₄	CISS effect	Ohmic contact	CsPb(Br/I) ₃ Nano-crystal	2.6% (0T, 300K)	Kim 2021 [76]

CoFeB	Out of plane	MgO barrier	GaAs/InGaAs QD	36% (0T, 300K) standard injector 30% (0T, 300K) SOT injector	This work
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Table S2. Spin-LED in edge emission geometry

Spin-injector	Magnetization anisotropy	Interface contact	Emitter	Circular polarization (%)	Ref.
GaMnAs	In plane	Ohmic contact	GaAs/InGaAs QW	1% (0T, 6K)	Ohno 1999 [77]
GaMnAs	In plane	Ohmic contact	GaAs/InGaAs QW	0.9% (0T, 5K)	Johnston-Halperin 2002 [78]
GaMnAs	In plane	Ohmic contact	GaAs/InAs QD	1% (0T, 5K)	Chye 2002 [79]
Fe	In plane	AlO _x barrier	AlGaAs/InGaAs 500nm	14.5% (0T, 5K)	Nishizawa 2013 [80]
Fe	In plane	AlO _x barrier	AlGaAs/InGaAs 500nm	10% (0T, 5K)	Nishizawa 2014 [1]
Fe	In plane	AlO _x barrier	AlGaAs/GaAs 500nm	10% (0T, 300K)	Nishizawa 2018 [81]

Note 7: Solution to minimize optical absorption of metallic injector in spin laser

The main advantage of our spin injector is its very small thickness, which allows it to be directly embedded into the optical cavity to form the VCSEL or vertical external cavity surface emitting laser (VECSEL) structure of the spin-laser. This will ensure a very short distance between the injector and the gain medium (<100 nm) to obtain a high spin-injection efficiency. To enable the laser diode to have a high-output efficiency, the main challenge is to reduce the optical absorption by the metallic spin-injector layer in the optical cavity. To overcome this challenge, the semiconductor structure will be designed to place the spin injector by sputtering method in one node of the stationary electromagnetic field on the surface of the VCSEL-like structure (also known as $\frac{1}{2}$ -VCSEL), which contains only the bottom DBR and a gain medium (based on the quantum dot or quantum well), without the top DBR, thus it has no optical cavity. This technique will allow to minimize the absorption by the ferromagnetic multilayer (FML). As already reported in our previous publication in a $\frac{1}{2}$ -VCSEL//2.6nm MgO/1.8nm Co/3nm Pt system⁸², by analyzing the Fourier transform infrared reflectivity spectra (FTIR) of the DBR FML system, we can see that the FML acts as a narrow frequency bandpass filter for the reflectivity (**Fig. S7**).

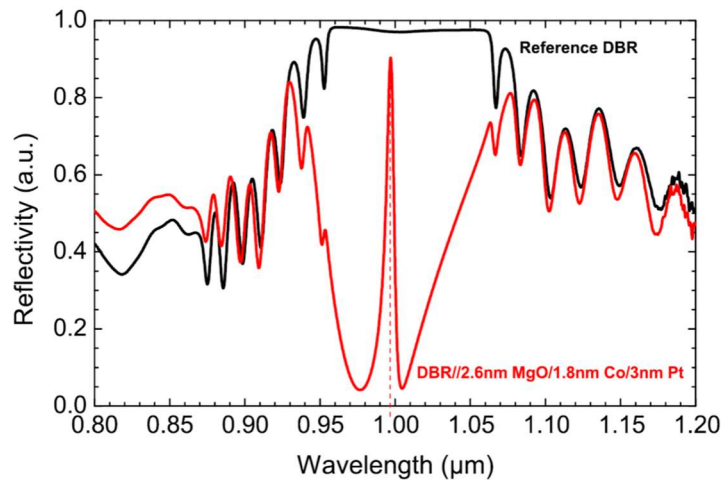


Figure S7: DBR and DBR+FML measured reflectivities as a function of the wavelength. The deposition of the FML strongly influences the reflectivity profile of the bottom DBR. By a careful design, we managed to keep a high reflectivity close to the QWs PL at $\lambda=980$ nm. The energy difference between the QWs gain peak and the DBR resonance peak ($\lambda=997$ nm) can be minimized by adjusting the laser temperature to maximize the laser output power. The shift of the QWs PL is about 0.35 nm/K. Reproduced from Ref. [82], with the permission of AIP Publishing.

Note 8: Dynamical operation for SOT spin-LEDs

For a high-rate data transmission over a long distance, the ideal operation mode for ultrafast optical communication is to maintain a constant light intensity while modulating P_c . To realize this operation, one should be able to switch M while maintaining a vertical bias current for light emission. As schematically shown in **Fig. S8a**, we have performed preliminary experiments by applying SOT switching current between contacts 1 and 2, while simultaneously applying bias voltage between contacts 4 and 5 for injecting a vertical current into the LED. The measured R_{AHE} as a function of I_{pulse} , under different vertical bias current is shown in **Figs. S8b, S8c, S8e, and S8f**. It clearly shows that the bias current induces an offset of R_{AHE} , which is proportional to the bias current (**Fig. S8d**). It means that an additional voltage between the contacts 3 and 4 is created by the bias current. However, the difference between the two R_{AHE} states always remains constant ($\Delta R_{\text{AHE}} \sim 0.4 \Omega$) (**Fig. S8g**). With the increase of bias current, the noise becomes important, but we still can achieve a full M switching with bias current of $100 \mu\text{A}$ without changing the critical current for M switching. This bias current is large enough to enable a constant light emission in QD LEDs⁷².

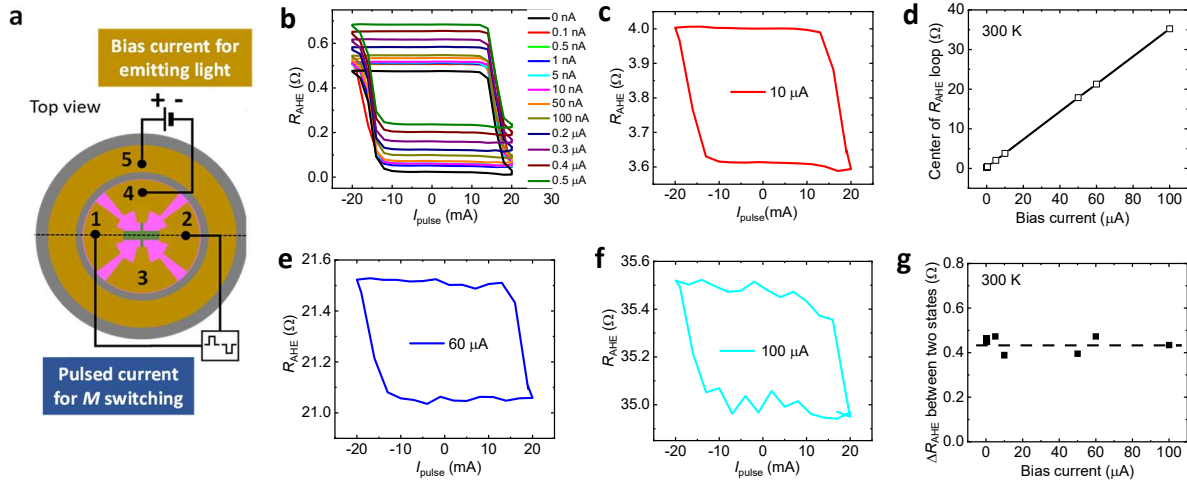


Figure S8: (a) Schematic top view of the SOT spin-LED device for dynamical operation. Pulsed current is injected in the transversal injector channel for M switching, while a constant vertical bias is applied to emit the light. (b,c,e,f) R_{AHE} loops as a function of I_{pulse} , with different amplitude for the vertical bias current: (b) 0-0.5 μA , (c) 10 μA , (e) 60 μA , (f) 100 μA . (d) Center of R_{AHE} as a function of bias current. (g) Difference of R_{AHE} between the two states as a function of bias current.

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