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Charge and spin transport in Nb-doped SrTiO3 using Co/AlOx spin injection contacts

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Appendix A

Appendix

In this appendix I provide detailed information of the value I used for the literature review in chapter 5.2.3.

Table A.1 displays the values of the different parameters related to the spin accumulation as reported in the various papers reviewed. These are:

- Ref. - reference number of the paper in chapter 5.
- SC - semiconductor
- D - diffusion constant
- ρ - semiconductor resistivity
- d - semiconductor channel depth
- τ - (in-plane) spin lifetime
- λ - calculated spin relaxation length using $\sqrt{D\tau}$
- Area - junction area
- w - width of the 3-T contact
- SRA_T - calculated theoretical value of the SRA, using $P = 0.1$
- SRA_E - experimental value of SRA extracted from the paper
- $ChRA_E$ - experimental value of ChRA extracted from the paper
- λ/d - if $\lambda/d \gtrsim 1$ the device is in the narrow channel regime
- λ/w - if $\lambda/w \gtrsim 1$ the device is in the narrow contact regime

Note that the value for $ChRA_E$ can have a somewhat larger uncertainty since it sometimes has to be estimated from $I - V$ curves in the paper. As can be observed from the λ/d parameter all the junctions are in the thin channel regime. This means that the expression for the SRA should be altered by including a correction factor as discussed in chapter 2.2.4. Hence I used the expression $SRA = P^2\rho\lambda(\lambda/d)$.

However, for a few junction the contact width is similar to or smaller than the spin relaxation length. For this another correction factor should be used, but it has also been shown in metallic spin valves that a full 2-dimensional treatment is needed to account for all the physics. In the current values used in the review no correction is made for narrow contacts.

In table A.2 I provide some additional parameters extracted from the papers as well as some comments related to specifics of the papers which I believed to be of particular importance.

- FM - ferromagnetic material used for the 3T contact, all contacts are epitaxial (except for Ref. 14 which I could not verify). Note that for two paper the contacts are not Schottky contacts but include an MgO oxide tunnel barrier.
- TSP - tunnel spin polarization as mentioned in the paper
- g - g-factor mentioned in the papper
- T - measurements temperature range used in the paper
- invH - If inverted Hanle was observed, n.m = not mentioned

Comment in table A.2 ‡: As far is I could understand the paper reports strange values: 1) they use an extremely high resistivity of around 2000 Ω cm. Hence huge influence of the 30 nm high δ-doped region could be expected. Note that they mention a ρ of 100 Ω cm, why they use a different ρ in the calculation is unclear to me. 2) Their ChRA is much lower than the SRA. 4TNL Hanle signal is 100 times smaller than the spin valve amplitude. They do observe a strong T-dep of τ (both in 3T and 4T). The contact size they mention in the caption of fig. 1 seems wrong.

Ref. #	SC	D $\left[\frac{cm^2}{s}\right]$	ρ [Ω cm]	d [nm]	τ [ns]	λ [μm]	Area [μm^2]	w [μm]	SRA_T [k$\Omega \mu m^2$]	SRA_E [k$\Omega \mu m^2$]	$ChRA_E$ [M$\Omega \mu m^2$]	λ/d	λ/w
30	n-Si	40	2.5	75	1.3	2.28	100	1	17	1.15	2.5	30.5	2.3
11	n-Si	3.45	5	200	2.5	0.929	$\dagger^1$	$\dagger^2$	2.2	$53 - 2{\cdot}10^3$	0.2 - 0.5	4.6	
12	n-Ge	27.7	$1.56{\cdot}10^{-3}$	100	0.132	0.606	8000	40	$6{\cdot}10^{-4}$	20	80	6	0.015
13	n-Si	3.45	0.1	100	3	1.02	2000	10	0.1	2 - 500	0.02 - 1	10	0.1
31	n-Si	3.45	5	100	2	0.831	2000	10	3.45	10 - 143	40 - 920	8.3	0.083
32	n-Si	8	0.05	200	0.3	0.49	100	1	$6{\cdot}10^{-3}$	11	1	2.5	0.49
18	n-Ge	27.7	1E-3	100	0.11	0.552	8000	40	$3{\cdot}10^{-4}$	1.4 - 8	1.6 - 10	5.5	0.014
33	n-GaAs	0.169	0.00113	85	0.2	0.058	10	?	$4.5{\cdot}10^{-6}$	0.014 - 0.15	0.004	0.7	–
34	n-Si	40	0.3	75	1.3	2.28	100	1	2.08	1.65	20	30.4	2.3
20	n-Ge	40	0.1	100	0.12	0.693	8000	40	0.048	1 - 20	2 - 80	6.9	0.017
35	n-Si	3.32	0.0034	80	8.5	1.68	42	2	0.012	$3{\cdot}10^{-4}$	$3.6{\cdot}10^{-4}$	21	0.84
35	n-Si	3.32	0.0034	80	4.44	1.21	7.35	0.35	$6{\cdot}10^{-3}$	$36{\cdot}10^{-5}$	$3.6{\cdot}10^{-4}$	15.2	3.47
36	n-Ge	4	100	330	0.9	0.6	150	3	11	5 - 50	0.006	1.8	0.2
14	n-AlGaAs	–	–	2000	1.5	–	500	10	–	1	–	–	–
37	n-GaAs	30	0.02	2500	3.3	3.15	250	5	$8{\cdot}10^{-3}$	0.13	–	1.26	0.63

Table A.1: Table containing the most important values extracted from the papers to construct the figures in chapter 5.2.3. Note:$\dagger^1$: devA 1200 μm^2, devB 8000 μm^2, $\dagger^2$: devA 6 μm, devB 40 μm. SRA_T are calculated using P = 0.1.

Ref. [#]	Ref.	FM	TSP*	g	T [K]	invH	Comments
30	*Appl. Phys. Lett.* **99**, 132511 (2011)	CoFe	0.14 - 0.32	2	293	n.m.	They calculate SRA without taking in account thin channel.
11	*Appl. Phys. Lett.* **99**, 012113 (2011)	CoFe	-	2	25	n.m.	
12	*J. Appl. Phys.* **111**, 07C503 (2012)	Fe_3Si	-	1.563	50	no	I estimated ChRA from $I - V$ in paper, hence large error possible.
13	*Phys. Rev. B* **85**, 035320 (2012)	CoFe	-	2	40	n.m.	Strong T-dep of Rho (5 to 0.1 Ωcm), weak T-dep of ΔV. Inset Fig. 3 states R_{int} in Ω however, should likely be in kΩ.
31	*Appl. Phys. Lett.* **101**, 232404 (2012)	CoFe	0.43	2	40	-	ΔV does not scale linearly and almost independent of bias at $+I$.
32	*J. Appl. Phys.* **113**, 013916 (2013)	Fe_3Si	0.2	2	293	-	Note: they report sign inversion of spin polarization.
18	*J. Appl. Phys.* **113**, 183713 (2013)	Fe_3Si	–	1.563	20 - 200	no	Study both 3 and 4TNL. Device 2, ΔV exhibits significant T-dep. They claim inhomogeneous doping $\rightarrow$ uncertainty in area.
33	*Jap. J. Appl. Phys.* **52**, 063001 (2013)	CFAS	–	-0.44	LT	no	They do not account for thin channel in their SRA calculation. CFAS = $Co_2FeAl_{0.5}Si_{0.5}$.
34	*J. Appl. Phys.* **113**, 17C501 (2013)	CoFe	0.05	2	293	-	
20	*Thin Solid Films* **557**, 382 (2014)	Fe_3Si	0.2	1.563	293	no	They claim impedance mismatch plays a role.
35	*Appl. Phys. Lett.* **98**, 012508 (2011)	Fe/MgO	0.025	2	8 - 100	n.m.	Dev 3TF. Values at 8 K. τ reduces by factor 2 at 100 K, P by factor 2.5. 3T and 4T agree wrt. τ and change in ΔV vs. T
35	*Appl. Phys. Lett.* **98**, 012508 (2011)	Fe/MgO	0.028	2	8 - 100	n.m.	Dev 3TP. Note: not Schottky!
36	*Semicond. Sci. Technol.* **28**, 015018 (2013)	Fe/MgO	0.5	1.6	4	n.m.	‡
14	*Appl. Phys. Lett.* **104**, 082405 (2014)	Fe (epi?)	-	0.44	5 - 50	-	Strong bias dep. of τ, DNP effects visible in Hanle, weak T-dep of τ. I took τ at 5 K.
37	*Phys. Rev. B* **92**, 140201(R) (2015)	Co_2MnSi	-		60	n.m	DNP effects visible in Hanle. ChRA not mentioned.

Table A.2: Additional parameters and comments related to the reviewed papers.