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Conductance and gating effects at sputtered oxide interfaces

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Citation

Yin, C. (2019, July 3). *Conductance and gating effects at sputtered oxide interfaces*. *Casimir PhD Series*. Retrieved from <https://hdl.handle.net/1887/74527>

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Author: Yin, C.

Title: Conductance and gating effects at sputtered oxide interfaces

Issue Date: 2019-07-03

References

- [1] P. Zubko, S. Gariglio, M. Gabay, P. Ghosez, and J.-M. Triscone. Interface physics in complex oxide heterostructures. *Annual Review of Condensed Matter Physics*, 2:141–165, 2011.
- [2] H. Y. Hwang, Y. Iwasa, M. Kawasaki, B. Keimer, N. Nagaosa, and Y. Tokura. Emergent phenomena at oxide interfaces. *Nature Materials*, 11:103–113, 2012.
- [3] J. H. Ngai, F. J. Walker, and C. H. Ahn. Correlated oxide physics and electronics. *Annual Review of Materials Research*, 44:1–17, 2014.
- [4] J. Chakhalian, A. J. Millis, and J. Rondinelli. Whither the oxide interface. *Nature Materials*, 11:92–94, 2012.
- [5] V. M. Goldschmidt. Die gesetze der krystallochemie. *Die Naturwissenschaften*, 14:477–485, 1926.
- [6] N. Reyren, S. Thiel, A. D. Caviglia, L. F. Kourkoutis, G. Hammerl, C. Richter, C. W. Schneider, T. Kopp, A.-S. Ruetschi, D. Jaccard, M. Gabay, D. A. Muller, J.-M. Triscone, and J. Mannhart. Superconducting interfaces between insulating oxides. *Science*, 317:1196–1199, 2007.
- [7] J. A. Bert, B. Kalisky, C. Bell, M. Kim, Y. Hikita, H. Y. Hwang, and K. A. Moler. Direct imaging of the coexistence of ferromagnetism and superconductivity at the $\text{LaAlO}_3/\text{SrTiO}_3$ interface. *Nature Physics*, 7:767–771, 2011.
- [8] H. Kroemer. Nobel lecture: Quasielectric fields and band offsets: teaching electrons new tricks. *Reviews of Modern Physics*, 73:783793, 2001.
- [9] A. Ohtomo and H. Y. Hwang. A high-mobility electron gas at the $\text{LaAlO}_3/\text{SrTiO}_3$ heterointerface. *Nature*, 427:423–426, 2004.
- [10] A. Brinkman, M. Huijben, M. Van Zalk, J. Huijben, U. Zeitler, J. C. Maan, W. G. Van Der Wiel, G. Rijnders, D. H. A. Blank, and H. Hilgenkamp. Magnetic effects at the interface between non-magnetic oxides. *Nature Materials*, 6:493–496, 2007.

- [11] Ariando, X. Wang, G. Baskaran, Z. Q. Liu, J. Huijben, J. B. Yi, A. Annadi, A. Roy Barman, A. Rusydi, S. Dhar, Y. P. Feng, J. Ding, H. Hilgenkamp, and T. Venkatesan. Electronic phase separation at the $\text{LaAlO}_3/\text{SrTiO}_3$ interface. *Nature Communications*, 2:188, 2011.
- [12] L. Li, C. Richter, J. Mannhart, and R. C. Ashoori. Coexistence of magnetic order and two-dimensional superconductivity at $\text{LaAlO}_3/\text{SrTiO}_3$ interfaces. *Nature Physics*, 7:762–766, 2011.
- [13] B. Kalisky, J. A. Bert, B. B. Klopfer, C. Bell, H. K. Sato, M. Hosoda, Y. Hikita, H. Y. Hwang, and K. A. Moler. Critical thickness for ferromagnetism in $\text{LaAlO}_3/\text{SrTiO}_3$ heterostructures. *Nature Communications*, 3:922, 2012.
- [14] D. V. Christensen, Y. Frenkel, Y. Z. Chen, Y. W. Xie, Z. Y. Chen, Y. Hikita, A. Smith, L. Klein, H. Y. Hwang, N. Pryds, and B. Kalisky. Strain-tunable magnetism at oxide domain walls. *Nature Physics*, 2018.
- [15] J.-S. Lee, Y. W. Xie, H. K. Sato, C. Bell, Y. Hikita, H. Y. Hwang, and C.-C. Kao. Titanium d_{xy} ferromagnetism at the $\text{LaAlO}_3/\text{SrTiO}_3$ interface. *Nature Materials*, 12:703–706, 2013.
- [16] M. Salluzzo, S. Gariglio, D. Stornaiuolo, V. Sessi, S. Rusponi, C. Piamonteze, G. M. De Luca, M. Minola, D. Marré, A. Gadaleta, H. Brune, F. Nolting, N. B. Brookes, and G. Ghiringhelli. Origin of interface magnetism in $\text{BiMnO}_3/\text{SrTiO}_3$ and $\text{LaAlO}_3/\text{SrTiO}_3$ heterostructures. *Physical Review Letters*, 111:087204, 2013.
- [17] F. Bi, M. Huang, S. Ryu, H. Lee, C.-W. Bark, C.-B. Eom, P. Irvin, and J. Levy. Room-temperature electronically-controlled ferromagnetism at the $\text{LaAlO}_3/\text{SrTiO}_3$ interface. *Nature Communications*, 5:5019, 2014.
- [18] M. B Shalom, M. Sachs, D. Rakhmilevitch, A. Palevski, and Y. Dagan. Tuning spin-orbit coupling and superconductivity at the $\text{SrTiO}_3/\text{LaAlO}_3$ interface: A magneto-transport study. *Physical Review Letters*, 104:126802, 2010.
- [19] D. A. Dikin, M. Mehta, C. W. Bark, C. M. Folkman, C. B. Eom, and V. Chandrasekhar. Coexistence of superconductivity and ferromagnetism in two dimensions. *Physical Review Letters*, 107:056802, 2011.
- [20] A. Joshua, J. Ruhman, S. Pecker, E. Altman, and S. Ilani. Gate-tunable polarized phase of two-dimensional electrons at the $\text{LaAlO}_3/\text{SrTiO}_3$ interface. *Proceedings of the National Academy of Sciences*, 110:9633–9638, 2013.

- [21] Y.-Y. Pai, A. Tylan-Tyler, P. Irvin, and J. Levy. Physics of SrTiO₃-based heterostructures and nanostructures: a review. *Reports on Progress in Physics*, 81:036503, 2018.
- [22] Z. Huang, Ariando, X. R. Wang, A. Rusydi, J. Chen, H. Yang, and T. Venkatesan. Interface engineering and emergent phenomena in oxide heterostructures. *Advanced Materials*, 30(47):1802439, 2018.
- [23] N. Nakagawa, H. Y. Hwang, and D. A. Muller. Why some interfaces cannot be sharp. *Nature Materials*, 5:204–209, 2006.
- [24] G. A. Baraff, Joel A. Appelbaum, and D. R. Hamann. Self-consistent calculation of the electronic structure at an abrupt GaAs-Ge interface. *Physical Review Letters*, 38:237–240, 1977.
- [25] W. A. Harrison, E. A. Kraut, J. R. Waldrop, and R. W. Grant. Polar heterojunction interfaces. *Physical Review B*, 18:4402–4410, 1978.
- [26] S. Thiel, G. Hammerl, A. Schmehl, C. W. Schneider, and J. Mannhart. Tunable quasi-two-dimensional electron gases in oxide heterostructures. *Science*, 313:1942–1945, 2006.
- [27] M. I. Reinle-Schmitt, C. Cancellieri, D. Li, D. Fontaine, M. Medarde, E. Pomjakushina, C. W. Schneider, S. Gariglio, P. Ghosez, J.-M. Triscone, and P. R. Willmott. Tunable conductivity threshold at polar oxide interfaces. *Nature Communications*, 3:932, 2012.
- [28] M. Ben Shalom, C. W. Tai, Y. Lereah, M. Sachs, E. Levy, D. Rakhmilevitch, A. Palevski, and Y. Dagan. Anisotropic magnetotransport at the SrTiO₃/LaAlO₃ interface. *Physical Review B*, 80:140403(R), 2009.
- [29] C. Bell, S. Harashima, Y. Kozuka, M. Kim, B. G. Kim, Y. Hikita, and H. Y. Hwang. Dominant mobility modulation by the electric field effect at the LaAlO₃/SrTiO₃ interface. *Physical Review Letters*, 103:226802, 2009.
- [30] A. D. Caviglia, S. Gariglio, C. Cancellieri, B. Sacépé, A. Fête, N. Reyren, M. Gabay, A. F. Morpurgo, and J.-M. Triscone. Two-dimensional quantum oscillations of the conductance at LaAlO₃/SrTiO₃ interfaces. *Physical Review Letters*, 105:236802, 2010.
- [31] Y. Segal, J. H. Ngai, J. W. Reiner, F. J. Walker, and C. H. Ahn. X-ray photoemission studies of the metal-insulator transition in LaAlO₃/SrTiO₃ structures grown by molecular beam epitaxy. *Physical Review B*, 80:241107(R), 2009.

- [32] S. A. Chambers, M. H. Engelhard, V. Shutthanandan, Z. Zhu, T. C. Droubay, L. Qiao, P. V. Sushko, T. Feng, H. D. Lee, T. Gustafsson, E. Garfunkel, A. B. Shah, J.-M. Zuo, and Q. M. Ramasse. Instability, intermixing and electronic structure at the epitaxial $\text{LaAlO}_3/\text{SrTiO}_3(001)$ heterojunction. *Surface Science Reports*, 65:317–352, 2010.
- [33] M. Takizawa, S. Tsuda, T. Susaki, H. Y. Hwang, and A. Fujimori. Electronic charges and electric potential at $\text{LaAlO}_3/\text{SrTiO}_3$ interfaces studied by core-level photoemission spectroscopy. *Physical Review B*, 84:245124, 2011.
- [34] E. Slooten, Zhicheng Zhong, H. J. A. Molegraaf, P. D. Eerkes, S. De Jong, F. Massee, E. Van Heumen, M. K. Kruize, S. Wenderich, J. E. Kleibeuker, M. Gorgoi, H. Hilgenkamp, A. Brinkman, M. Huijben, G. Rijnders, D. H. A. Blank, G. Koster, P. J. Kelly, and M. S. Golden. Hard x-ray photoemission and density functional theory study of the internal electric field in $\text{SrTiO}_3/\text{LaAlO}_3$ oxide heterostructures. *Physical Review B*, 87:085128, 2013.
- [35] G. Berner, A. Müller, F. Pfaff, J. Walde, C. Richter, J. Mannhart, S. Thiess, A. Gloskovskii, W. Drube, M. Sing, and R. Claessen. Band alignment in $\text{LaAlO}_3/\text{SrTiO}_3$ oxide heterostructures inferred from hard x-ray photoelectron spectroscopy. *Physical Review B*, 88:115111, 2013.
- [36] Y. Chen, N. Pryds, J. E. Kleibeuker, G. Koster, J. Sun, E. Stamate, B. Shen, G. Rijnders, and S. Linderoth. Metallic and insulating interfaces of amorphous SrTiO_3 -based oxide heterostructures. *Nano letters*, 11:3774–3778, 2011.
- [37] G. Herranz, F. Sánchez, N. Dix, M. Scigaj, and J. Fontcuberta. High mobility conduction at (110) and (111) $\text{LaAlO}_3/\text{SrTiO}_3$ interfaces. *Scientific Reports*, 2:758, 2012.
- [38] A. Annadi, Q. Zhang, X. R. Wang, N. Tuzla, K. Gopinadhan, W. M. Lü, A. Roy Barman, Z. Q. Liu, A. Srivastava, S. Saha, Y. L. Zhao, S. W. Zeng, S. Dhar, E. Olsson, B. Gu, S. Yunoki, S. Maekawa, H. Hilgenkamp, T. Venkatesan, and Ariando. Anisotropic two-dimensional electron gas at the $\text{LaAlO}_3/\text{SrTiO}_3$ (110) interface. *Nature Communications*, 4:1838, 2013.
- [39] L. Yu and A. Zunger. A polarity-induced defect mechanism for conductivity and magnetism at polar–nonpolar oxide interfaces. *Nature Communications*, 5:5118, 2014.
- [40] J. F. Schooley, W. R. Hosler, and M. L. Cohen. Superconductivity in semiconducting SrTiO_3 . *Physical Review Letters*, 12:474–475, 1964.

- [41] A. Kalabukhov, R. Gunnarsson, J. Börjesson, E. Olsson, T. Claeson, and D. Winkler. Effect of oxygen vacancies in the SrTiO₃ substrate on the electrical properties of the LaAlO₃/SrTiO₃ interface. *Physical Review B*, 75:121404(R), 2007.
- [42] W. Siemons, G. Koster, H. Yamamoto, W. A. Harrison, G. Lucovsky, T. H. Geballe, D. H. A. Blank, and M. R. Beasley. Origin of charge density at LaAlO₃ on SrTiO₃ heterointerfaces: Possibility of intrinsic doping. *Physical Review Letters*, 98:196802, 2007.
- [43] G. Herranz, M. Basletić, M. Bibes, C. Carrétéro, E. Tafrá, E. Jacquet, K. Bouzouane, C. Deranlot, A. Hamzić, J.-M. Broto, A. Barthélémy, and A. Fert. High mobility in LaAlO₃/SrTiO₃ heterostructures: Origin, dimensionality, and perspectives. *Physical Review Letters*, 98:216803, 2007.
- [44] M. Basletic, J.-L. Maurice, C. Carrétéro, G. Herranz, O. Copie, M. Bibes, É. Jacquet, K. Bouzouane, S. Fusil, and A. Barthélémy. Mapping the spatial distribution of charge carriers in LaAlO₃/SrTiO₃ heterostructures. *Nature Materials*, 7:621–625, 2008.
- [45] C. Cancellieri, N. Reyren, S. Gariglio, A. D. Caviglia, A. Fête, and J.-M. Triscone. Influence of the growth conditions on the LaAlO₃/SrTiO₃ interface electronic properties. *EPL (Europhysics Letters)*, 91:17004, 2010.
- [46] Z. Q. Liu, C. J. Li, W. M. Lü, X. H. Huang, Z. Huang, S. W. Zeng, X. P. Qiu, L. S. Huang, A. Annadi, J. S. Chen, J. M. D. Coey, T. Venkatesan, and Ariando. Origin of the two-dimensional electron gas at LaAlO₃/SrTiO₃ interfaces: The role of oxygen vacancies and electronic reconstruction. *Physical Review X*, 3:021010, 2013.
- [47] N. C. Bristowe, P. B. Littlewood, and E. Artacho. Surface defects and conduction in polar oxide heterostructures. *Physical Review B*, 83:205405, 2011.
- [48] Y. Li, S. N. Phattalung, S. Limpijumnong, J. Kim, and J. Yu. Formation of oxygen vacancies and charge carriers induced in the n-type interface of a LaAlO₃ overlayer on SrTiO₃(001). *Physical Review B*, 84:245307, 2011.
- [49] R. Moos and K. H. Härdtl. Electronic transport properties of Sr_{1-x}La_xTiO₃ ceramics. *Journal of Applied Physics*, 80:393–400, 1996.
- [50] P. R. Willmott, S. A. Pauli, R. Herger, C. M. Schlepütz, D. Martocchia, B. D. Patterson, B. Delley, R. Clarke, D. Kumah, C. Cionca, and Y. Yacoby. Structural basis for the conducting interface between LaAlO₃ and SrTiO₃. *Physical Review Letters*, 99:155502, 2007.

- [51] A. S. Kalabukhov, Yu. A. Boikov, I. T. Serenkov, V. I. Sakharov, V. N. Popok, R. Gunnarsson, J. Börjesson, N. Ljustina, E. Olsson, D. Winkler, and T. Claeson. Cationic disorder and phase segregation in $\text{LaAlO}_3/\text{SrTiO}_3$ heterointerfaces evidenced by medium-energy ion spectroscopy. *Physical Review Letters*, 103:146101, 2009.
- [52] T. Ohnishi, M. Lippmaa, T. Yamamoto, S. Meguro, and H. Koinuma. Improved stoichiometry and misfit control in perovskite thin film formation at a critical fluence by pulsed laser deposition. *Applied Physics Letters*, 87:241919, 2005.
- [53] T. Ohnishi, K. Shibuya, T. Yamamoto, and M. Lippmaa. Defects and transport in complex oxide thin films. *Journal of Applied Physics*, 103:103703, 2008.
- [54] E. Breckenfeld, N. Bronn, J. Karthik, A. R. Damodaran, S. Lee, N. Mason, and L. W. Martin. Effect of growth induced (non)stoichiometry on interfacial conductance in $\text{LaAlO}_3/\text{SrTiO}_3$. *Physical Review Letters*, 110:196804, 2013.
- [55] M. Golalikhani, Q. Y. Lei, G. Chen, J. E. Spanier, H. Ghassemi, C. L. Johnson, M. L. Taheri, and X. X. Xi. Stoichiometry of LaAlO_3 films grown on SrTiO_3 by pulsed laser deposition. *Journal of Applied Physics*, 114:027008, 2013.
- [56] H. K. Sato, C. Bell, Y. Hikita, and H. Y. Hwang. Stoichiometry control of the electronic properties of the $\text{LaAlO}_3/\text{SrTiO}_3$ heterointerface. *Applied Physics Letters*, 102:251602, 2013.
- [57] I. M. Dildar, D. B. Boltje, M. H. S. Hesselberth, J. Aarts, Q. Xu, H. W. Zandbergen, and S. Harkema. Non-conducting interfaces of $\text{LaAlO}_3/\text{SrTiO}_3$ produced in sputter deposition: The role of stoichiometry. *Applied Physics Letters*, 102:121601, 2013.
- [58] I. M. Dildar, M. Neklyudova, Q. Xu, H. W. Zandbergen, S. Harkema, D. Boltje, and J. Aarts. Growing $\text{LaAlO}_3/\text{SrTiO}_3$ interfaces by sputter deposition. *AIP Advances*, 5:067156, 2015.
- [59] M. P. Warusawithana, C. Richter, J. A. Mundy, P. Roy, J. Ludwig, S. Paetel, T. Heeg, A. A. Pawlicki, L. F. Kourkoutis, M. Zheng, M. Lee, B. Mulcahy, W. Zander, Y. Zhu, J. Schubert, J. N. Eckstein, D. A. Muller, C. Stephen Hellberg, J. Mannhart, and D. G. Schlom. LaAlO_3 stoichiometry is key to electron liquid formation at $\text{LaAlO}_3/\text{SrTiO}_3$ interfaces. *Nature Communications*, 4:2351, 2013.
- [60] K. Van Benthem, C. Elsässer, and R. H. French. Bulk electronic structure of SrTiO_3 : Experiment and theory. *Journal of Applied Physics*, 90:6156–6164, 2001.
- [61] M. Salluzzo, J. C. Cezar, N. B. Brookes, V. Bisogni, G. M. De Luca, C. Richter, S. Thiel, J. Mannhart, M. Huijben, A. Brinkman, G. Rijnders, and G. Ghiringhelli. Orbital

- reconstruction and the two-dimensional electron gas at the $\text{LaAlO}_3/\text{SrTiO}_3$ interface. *Physical Review Letters*, 102:166804, 2009.
- [62] A. Fête. *Magnetotransport experiments at the $\text{LaAlO}_3/\text{SrTiO}_3$ interface*. PhD thesis, University of Geneva, 2014.
- [63] A. Joshua, S. Pecker, J. Ruhman, E. Altman, and S. Ilani. A universal critical density underlying the physics of electrons at the $\text{LaAlO}_3/\text{SrTiO}_3$ interface. *Nature Communications*, 3:1129, 2012.
- [64] Y. Kim, R. M. Lutchyn, and C. Nayak. Origin and transport signatures of spin-orbit interactions in one- and two-dimensional SrTiO_3 -based heterostructures. *Physical Review B*, 87:245121, 2013.
- [65] C. H. Ahn, J.-M. Triscone, and J. Mannhart. Electric field effect in correlated oxide systems. *Nature*, 424:1015–1018, 2003.
- [66] S. M. Sze and K. K. Ng. *Physics of Semiconductor Devices*. John Wiley & Sons Incorporated, 2006.
- [67] C. H. Ahn, A. Bhattacharya, M. Di Ventura, J. N. Eckstein, C. D. Frisbie, M. E. Gershenson, A. M. Goldman, I. H. Inoue, J. Mannhart, A. J. Millis, A. F. Morpurgo, D. Natelson, and J.-M. Triscone. Electrostatic modification of novel materials. *Reviews of Modern Physics*, 78:1185–1212, 2006.
- [68] C. Cen, S. Thiel, J. Mannhart, and J. Levy. Oxide nanoelectronics on demand. *Science*, 323:1026–1030, 2009.
- [69] B. Förg, C. Richter, and J. Mannhart. Field-effect devices utilizing LaAlO_3 - SrTiO_3 interfaces. *Applied Physics Letters*, 100:053506, 2012.
- [70] W.-N. Lin, J.-F. Ding, S.-X. Wu, Y.-F. Li, J. Lourembam, S. Shannigrahi, S.-J. Wang, and T. Wu. Electrostatic modulation of $\text{LaAlO}_3/\text{SrTiO}_3$ interface transport in an electric double-layer transistor. *Advanced Materials Interfaces*, 1:1300001, 2014.
- [71] A. D. Caviglia, S. Gariglio, N. Reyren, D. Jaccard, T. Schneider, M. Gabay, S. Thiel, G. Hammerl, J. Mannhart, and J.-M. Triscone. Electric field control of the $\text{LaAlO}_3/\text{SrTiO}_3$ interface ground state. *Nature*, 456:624–627, 2008.
- [72] A. D. Caviglia, M. Gabay, S. Gariglio, N. Reyren, C. Cancellieri, and J.-M. Triscone. Tunable Rashba spin-orbit interaction at oxide interfaces. *Physical Review Letters*, 104:126803, 2010.

- [73] A. Fête, S. Gariglio, A. D. Caviglia, J.-M. Triscone, and M. Gabay. Rashba induced magnetoconductance oscillations in the LaAlO_3 - SrTiO_3 heterostructure. *Physical Review B*, 86:201105(R), 2012.
- [74] G. Herranz, G. Singh, N. Bergeal, A. Jouan, J. Lesueur, J. Gázquez, M. Varela, M. Scigaj, N. Dix, F. Sánchez, and J. Fontcuberta. Engineering two-dimensional superconductivity and Rashba spin-orbit coupling in $\text{LaAlO}_3/\text{SrTiO}_3$ quantum wells by selective orbital occupancy. *Nature Communications*, 6:6028, 2015.
- [75] H. Liang, L. Cheng, L. Wei, Z. Luo, G. Yu, C. Zeng, and Z. Zhang. Nonmonotonically tunable Rashba spin-orbit coupling by multiple-band filling control in SrTiO_3 -based interfacial d-electron gases. *Physical Review B*, 92:075309, 2015.
- [76] E. Lesne, Y. Fu, S. Oyarzun, J. C. Rojas-Sánchez, D. C. Vaz, H. Naganuma, G. Sicoli, J.-P. Attané, M. Jamet, E. Jacquet, J.-M. George, A. Barthélémy, H. Jaffrès, A. Fert, M. Bibes, and L. Vila. Highly efficient and tunable spin-to-charge conversion through Rashba coupling at oxide interfaces. *Nature Materials*, 15:1261–1266, 2016.
- [77] M. Ben Shalom, A. Ron, A. Palevski, and Y. Dagan. Shubnikov-de Haas oscillations in $\text{SrTiO}_3/\text{LaAlO}_3$ interface. *Physical Review Letters*, 105:206401, 2010.
- [78] A. Fête, S. Gariglio, C. Berthod, D. Li, D. Stornaiuolo, M. Gabay, and J.-M. Triscone. Large modulation of the Shubnikov-de Haas oscillations by the Rashba interaction at the $\text{LaAlO}_3/\text{SrTiO}_3$ interface. *New Journal of Physics*, 16:112002, 2014.
- [79] G. Cheng, P. F. Siles, F. Bi, C. Cen, D. F. Bogorin, C. W. Bark, C. M. Folkman, J.-W. Park, C.-B. Eom, G. Medeiros-Ribeiro, and J. Levy. Sketched oxide single-electron transistor. *Nature Nanotechnology*, 6:343–347, 2011.
- [80] G. Cheng, M. Tomczyk, S. Lu, J. P. Veazey, M. Huang, P. Irvin, S. Ryu, H. Lee, C.-B. Eom, C. S. Hellberg, and J. Levy. Electron pairing without superconductivity. *Nature*, 521:196–199, 2015.
- [81] A. Annadi, G. Cheng, H. Lee, J.-W. Lee, S. Lu, A. Tylan-Tyler, M. Briggeman, M. Tomczyk, M. Huang, D. Pekker, C.-B. Eom, P. Irvin, and J. Levy. Quantized ballistic transport of electrons and electron pairs in $\text{LaAlO}_3/\text{SrTiO}_3$ nanowires. *Nano Letters*, 18:4473–4481, 2018.
- [82] A. M. R. V. L. Monteiro, D. J. Groenendijk, N. Manca, E. Mulazimoglu, S. Goswami, Ya. Blanter, L. M. K. Vandersypen, and A. D. Caviglia. Side gate tunable josephson junctions at the $\text{LaAlO}_3/\text{SrTiO}_3$ interface. *Nano Letters*, 17:715–720, 2017.

- [83] M. Hosoda, Y. Hikita, H. Y. Hwang, and C. Bell. Transistor operation and mobility enhancement in top-gated $\text{LaAlO}_3/\text{SrTiO}_3$ heterostructures. *Applied Physics Letters*, 103:103507, 2013.
- [84] P. D. Eerkes, W. G. van der Wiel, and H. Hilgenkamp. Modulation of conductance and superconductivity by top-gating in $\text{LaAlO}_3/\text{SrTiO}_3$ 2-dimensional electron systems. *Applied Physics Letters*, 103:201603, 2013.
- [85] S. Goswami, E. Mulazimoglu, L. M. K. Vandersypen, and A. D. Caviglia. Nanoscale electrostatic control of oxide interfaces. *Nano Letters*, 15:2627–2632, 2015.
- [86] W. Liu, S. Gariglio, A. Fête, D. Li, M. Boselli, D. Stornaiuolo, and J.-M. Triscone. Magneto-transport study of top- and back-gated $\text{LaAlO}_3/\text{SrTiO}_3$ heterostructures. *APL Materials*, 3:062805, 2015.
- [87] S. Hurand, A. Jouan, C. Feuillet-Palma, G. Singh, J. Biscaras, E. Lesne, N. Reyren, A. Barthélémy, M. Bibes, J. E. Villegas, C. Ulysse, X. Lafosse, M. Pannetier-Lecoer, S. Caprara, M. Grilli, M. Lesueur, and N. Bergeal. Field-effect control of superconductivity and Rashba spin-orbit coupling in top-gated $\text{LaAlO}_3/\text{SrTiO}_3$ devices. *Scientific Reports*, 5:12751, 2015.
- [88] S. Hurand, A. Jouan, C. Feuillet-Palma, G. Singh, E. Lesne, N. Reyren, A. Barthélémy, M. Bibes, J. E. Villegas, C. Ulysse, M. Pannetier-Lecoer, M. Malnou, J. Lesueur, and N. Bergeal. Top-gated field-effect $\text{LaAlO}_3/\text{SrTiO}_3$ devices made by ion-irradiation. *Applied Physics Letters*, 108:052602, 2016.
- [89] A. E. M. Smink, J. C. de Boer, M. P. Stehno, A. Brinkman, W. G. van der Wiel, and H. Hilgenkamp. Gate-tunable band structure of the LaAlO_3 - SrTiO_3 interface. *Physical Review Letters*, 118:106401, 2017.
- [90] A. E. M. Smink, M. P. Stehno, J. C. de Boer, A. Brinkman, W. G. van der Wiel, and H. Hilgenkamp. Correlation between superconductivity, band filling, and electron confinement at the $\text{LaAlO}_3/\text{SrTiO}_3$ interface. *Physical Review B*, 97:245113, 2018.
- [91] S. Smink. *Manifold field effects at a complex oxide interface*. PhD thesis, The University of Twente, 2019.
- [92] A. M. Goldman. Electrostatic gating of ultrathin films. *Annual Review of Materials Research*, 44:45–63, 2014.
- [93] J. T. Ye, S. Inoue, K. Kobayashi, Y. Kasahara, H. T. Yuan, H. Shimotani, and Y. Iwasa. Liquid-gated interface superconductivity on an atomically flat film. *Nature Materials*, 9:125–128, 2009.

- [94] K. Ueno, S. Nakamura, H. Shimotani, A. Ohtomo, N. Kimura, T. Nojima, H. Aoki, Y. Iwasa, and M. Kawasaki. Electric-field-induced superconductivity in an insulator. *Nature Materials*, 7:855–858, 2008.
- [95] K. Ueno, S. Nakamura, H. Shimotani, H. T. Yuan, N. Kimura, T. Nojima, H. Aoki, Y. Iwasa, and M. Kawasaki. Discovery of superconductivity in KTaO_3 by electrostatic carrier doping. *Nature Nanotechnology*, 6:408–412, 2011.
- [96] J. T. Ye, Y. J. Zhang, R. Akashi, M. S. Bahramy, R. Arita, and Y. Iwasa. Superconducting dome in a gate-tuned band insulator. *Science*, 338:1193–1196, 2012.
- [97] A. T. Bollinger, G. Dubuis, J. Yoon, D. Pavuna, J. Misewich, and I. Bozović. Superconductor–insulator transition in $\text{La}_{2-x}\text{Sr}_x\text{CuO}_4$ at the pair quantum resistance. *Nature*, 472:458–460, 2011.
- [98] X. Leng, J. Garcia-Barriocanal, B. Yang, Y. Lee, J. Kinney, and A. M. Goldman. Indications of an electronic phase transition in two-dimensional superconducting $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ thin films induced by electrostatic doping. *Physical Review Letters*, 108:067004, 2012.
- [99] S. Zeng, W. Lü, Z. Huang, Z. Liu, K. Han, K. Gopinadhan, C. Li, R. Guo, W. Zhou, H. H. Ma, L. Jian, T. Venkatesan, and Ariando. Liquid-gated high mobility and quantum oscillation of the two-dimensional electron gas at an oxide interface. *ACS Nano*, 10:4532–4537, 2016.
- [100] Z. Chen, H. Yuan, Y. Xie, D. Lu, H. Inoue, Y. Hikita, C. Bell, and H. Y. Hwang. Dual-gate modulation of carrier density and disorder in an oxide two-dimensional electron system. *Nano Letters*, 16:6130–6136, 2016.
- [101] V. Yu Vasilyev. *Thin film chemical vapor deposition in electronics: equipment, methodology, and thin film growth experience*. Nova Science Publishers, Inc., 2014.
- [102] N. M. Sbrockey, M. Luong, E. M. Gallo, J. D. Sloppy, G. Chen, C. R. Winkler, S. H. Johnson, M. L. Taheri, G. S. Tompa, and J. E. Spanier. $\text{LaAlO}_3/\text{SrTiO}_3$ epitaxial heterostructures by atomic layer deposition. *Journal of Electronic Materials*, 41:819–823, 2012.
- [103] J. P. Podkaminer, T. Hernandez, M. Huang, S. Ryu, C. W. Bark, S. H. Baek, J. C. Frederick, T. H. Kim, K. H. Cho, J. Levy, M. S. Rzchowski, and C. B. Eom. Creation of a two-dimensional electron gas and conductivity switching of nanowires at the $\text{LaAlO}_3/\text{SrTiO}_3$ interface grown by 90° off-axis sputtering. *Applied Physics Letters*, 103:071604, 2013.

- [104] W. R. Grove. On the electro-chemical polarity of gases. *Philosophical Transactions of the Royal Society of London*, 142:87–101, 1852.
- [105] J. J. Thomson. *Rays of positive electricity and their application to chemical analyses*. Longmans, Green and Co., 1913.
- [106] K. H. Kingdon and I. Langmuir. The removal of thorium from the surface of a thoriated tungsten filament by positive ion bombardment. *Physical Review*, 22:148–160, 1923.
- [107] C. B. Eom, J. Z. Sun, K. Yamamoto, A. F. Marshall, K. E. Luther, T. H. Geballe, and S. S. Laderman. In situ grown $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ thin films from single target magnetron sputtering. *Applied Physics Letters*, 55:595–597, 1989.
- [108] C. B. Eom, J. Z. Sun, B. M. Lairson, S. K. Streiffer, A. F. Marshall, K. Yamamoto, S. M. Anlage, J. C. Bravman, T. H. Geballe, S. S. Laderman, R. C. Taber, and R. D. Jacowitz. Synthesis and properties of $\text{YBa}_2\text{Cu}_3\text{O}_7$ thin films grown in situ by 90° off-axis single magnetron sputtering. *Physica C: Superconductivity*, 171:354–383, 1990.
- [109] G. Koster, B. L. Kropman, G. J. H. M. Rijnders, D. H. A. Blank, and H. Rogalla. Quasi-ideal strontium titanate crystal surfaces through formation of strontium hydroxide. *Applied Physics Letters*, 73:2920–2922, 1998.
- [110] G. Binnig, C. F. Quate, and Ch. Gerber. Atomic force microscope. *Physical Review Letters*, 56:930–933, 1986.
- [111] B. E. Warren. *X-ray diffraction*. Dover Publications, 1990.
- [112] L. J. van der Pauw. A method of measuring specific resistivity and Hall effect of discs of arbitrary shape. *Philips Research Reports*, 13:1–9, 1958.
- [113] L. J. van der Pauw. A method of measuring the resistivity and Hall coefficient on lamellae of arbitrary shape. *Philips Technical Review*, 20:220–224, 1958/59.
- [114] F. Gunkel, C. Bell, H. Inoue, B. Kim, A. G. Swartz, T. A. Merz, Y. Hikita, H. K. Harashima, S. and Sato, M. Minohara, S. Hoffmann-Eifert, R. Dittmann, and H. Y. Hwang. Defect control of conventional and anomalous electron transport at complex oxide interfaces. *Physical Review X*, 6:031035, 2016.
- [115] N. W. Ashcroft and N. D. Mermin. *Solid state physics*. Cengage Learning, 2011.

- [116] C. Yin, D. Krishnan, N. Gauquelin, J. Verbeeck, and J. Aarts. Controlling the interfacial conductance in $\text{LaAlO}_3/\text{SrTiO}_3$ in 90° off-axis sputter deposition. *Physical Review Materials*, 3:034002, 2019.
- [117] C. Remeijer. Influence of oxygen in the sputter gas on creating a conducting interface in $\text{LaAlO}_3/\text{SrTiO}_3$. Master's thesis, Leiden University, 2019.
- [118] G. Liu, Q. Lei, M. A. Wolak, Q. Li, L.-Q. Chen, C. Winkler, J. Sloppy, M. L. Taheri, and X. Xi. Epitaxial strain and its relaxation at the $\text{LaAlO}_3/\text{SrTiO}_3$ interface. *Journal of Applied Physics*, 120:085302, 2016.
- [119] L. Qiao, T. C. Droubay, T. Varga, M. E. Bowden, V. Shutthanandan, Z. Zhu, T. C. Kaspar, and S. A. Chambers. Epitaxial growth, structure, and intermixing at the $\text{LaAlO}_3/\text{SrTiO}_3$ interface as the film stoichiometry is varied. *Physical Review B*, 83:085408, 2011.
- [120] O. Marina. Thermal, electrical, and electrocatalytical properties of lanthanum-doped strontium titanate. *Solid State Ionics*, 149:21–28, 2002.
- [121] R. Groenen, J. Smit, K. Orsel, A. Vaillionis, B. Bastiaens, M. Huijben, K. Boller, G. Rijnders, and G. Koster. Research update: Stoichiometry controlled oxide thin film growth by pulsed laser deposition. *APL Materials*, 3:070701, 2015.
- [122] C. Yin, A. E. M. Smink, I. Leermakers, L. M. K. Tang, N. Lebedev, U. Zeitler, W. G. van der Wiel, H. Hilgenkamp, and J. Aarts. New insights into the electron trapping mechanism in $\text{LaAlO}_3/\text{SrTiO}_3$ heterostructures. *arXiv preprint*, 2019.
- [123] R. C. Neville, B. Hoeneisen, and C. A. Mead. Permittivity of strontium titanate. *Journal of Applied Physics*, 43:2124–2131, 1972.
- [124] A. F. Santander-Syro, O. Copie, T. Kondo, F. Fortuna, S. Pailhès, R. Weht, X. G. Qiu, F. Bertran, A. Nicolaou, A. Taleb-Ibrahimi, P. Le Fèvre, G. Herranz, M. Bibes, N. Reyren, Y. Apertet, P. Lecoeus, A. Barthélémy, and M. J. Rozenberg. Two-dimensional electron gas with universal subbands at the surface of SrTiO_3 . *Nature*, 469:189–193, 2011.
- [125] J. Biscaras, S. Hurand, C. Feuillet-Palma, A. Rastogi, R. C. Budhani, N. Reyren, E. Lesne, J. Lesueur, and N. Bergeal. Limit of the electrostatic doping in two-dimensional electron gases of LaXO_3 ($X = \text{Al}, \text{Ti}$)/ SrTiO_3 . *Scientific Reports*, 4:6788, 2014.

- [126] G. N. Daptary, P. Kumar, A. Dogra, and A. Bid. Effect of multiband transport on charge carrier density fluctuations at the $\text{LaAlO}_3/\text{SrTiO}_3$ interface. *Physical Review B*, 98:035433, 2018.
- [127] K. Rubi, J. Gosteau, R. Serra, K. Han, S. Zeng, Z. Huang, E. Snoeck, R. Arras, B. Warot-Fonrose, Ariando, M. Goiran, and W. Escoffier. Aperiodic quantum oscillations in the two-dimensional electron gas at the $\text{LaAlO}_3/\text{SrTiO}_3$ interface. *arXiv*, 2019.
- [128] J. Biscaras, N. Bergeal, S. Hurand, C. Grossetête, A. Rastogi, R. C. Budhani, D. Leboeuf, C. Proust, and J. Lesueur. Two-dimensional superconducting phase in $\text{LaTiO}_3/\text{SrTiO}_3$ heterostructures induced by high-mobility carrier doping. *Physical Review Letters*, 108:247004, 2012.
- [129] Y. C. Liao, T. Kopp, C. Richter, A. Rosch, and J. Mannhart. Metal-insulator transition of the LaAlO_3 - SrTiO_3 interface electron system. *Physical Review B*, 83:075402, 2011.
- [130] K. S. Novoselov, A. K. Geim, S. V. Morozov, D. Jiang, Y. Zhang, S. V. Dubonos, I. V. Grigorieva, and A. A. Firsov. Electric field effect in atomically thin carbon films. *Science*, 306:666–669, 2004.
- [131] T. Ihn. *Semiconductor nanostructures: quantum states and electronic transport*. Oxford University Press, 2015.
- [132] S. Gariglio, A. Fête, and J.-M. Triscone. Electron confinement at the $\text{LaAlO}_3/\text{SrTiO}_3$ interface. *Journal of Physics: Condensed Matter*, 27:283201, 2015.
- [133] F. Stern. Self-consistent results for n-type Si inversion layers. *Physical Review B*, 5:4891–4899, 1972.
- [134] N. Scopigno, D. Bucheli, S. Caprara, J. Biscaras, N. Bergeal, J. Lesueur, and M. Grilli. Phase separation from electron confinement at oxide interfaces. *Physical Review Letters*, 116:026804, 2016.
- [135] D. Li, S. Lemal, S. Gariglio, Z. Wu, A. Fête, M. Boselli, P. Ghosez, and J.-M. Triscone. Probing quantum confinement and electronic structure at polar oxide interfaces. *Advanced Science*, 5:1800242, 2018.
- [136] M. Sing, G. Berner, K. Goß, A. Müller, A. Ruff, A. Wetscherek, S. Thiel, J. Mannhart, S. A. Pauli, C. W. Schneider, P. R. Willmott, M. Gorgoi, F. Schäfers, and R. Claessen. Profiling the interface electron gas of $\text{LaAlO}_3/\text{SrTiO}_3$ heterostructures with hard x-ray photoelectron spectroscopy. *Physical Review Letters*, 102:176805, 2009.

- [137] N. Reyren, S. Gariglio, A. D. Caviglia, D. Jaccard, T. Schneider, and J.-M. Triscone. Anisotropy of the superconducting transport properties of the $\text{LaAlO}_3/\text{SrTiO}_3$ interface. *Applied Physics Letters*, 94:112506, 2009.
- [138] V. V. Bal, Z. Huang, K. Han, Ariando, T. Venkatesan, and V. Chandrasekhar. Electrostatic tuning of magnetism at the conducting (111) $(\text{La}_{0.3}\text{Sr}_{0.7})(\text{Al}_{0.65}\text{Ta}_{0.35})/\text{SrTiO}_3$ interface. *Applied Physics Letters*, 111:081604, 2017.
- [139] A. V. Bjørli, M. von Soosten, R. Erlandsen, R. T. Dahm, Y. Zhang, Y. Gan, Y. Chen, N. Pryds, and T. S. Jespersen. Nanoscale patterning of electronic devices at the amorphous $\text{LaAlO}_3/\text{SrTiO}_3$ oxide interface using an electron sensitive polymer mask. *Applied Physics Letters*, 112:171606, 2018.
- [140] V. Metlenko, A. H. H. Ramadan, F. Gunkel, H. Du, H. Schraknepper, S. Hoffmann-Eifert, R. Dittmann, R. Waser, and R. A. de Souza. Do dislocations act as atomic autobahns for oxygen in the perovskite oxide SrTiO_3 ? *Nanoscale*, 6:12864–12876, 2014.
- [141] J. Hanzig, M. Zschornak, F. Hanzig, E. Mehner, H. Stöcker, B. Abendroth, C. Röder, A. Talkenberger, G. Schreiber, D. Rafaja, S. Gemming, and D. C. Meyer. Migration-induced field-stabilized polar phase in strontium titanate single crystals at room temperature. *Physical Review B*, 88:024104, 2013.
- [142] Y. Lei, Y. Li, Y. Z. Chen, Y. W. Xie, Y. S. Chen, S. H. Wang, J. Wang, B. G. Shen, N. Pryds, H. Y. Hwang, and J. R. Sun. Visible-light-enhanced gating effect at the $\text{LaAlO}_3/\text{SrTiO}_3$ interface. *Nature Communications*, 5:5554, 2014.
- [143] Y. Li, S. J. Peng, T. T. Mao, D. J. Wang, K. M. Wu, J. R. Sun, and J. Zhang. A novel structural expansion in SrTiO_3 tuned by electric field and visible-light. *AIP Advances*, 7:055821, 2017.
- [144] N. Shanthi and D. D. Sarma. Electronic structure of electron doped SrTiO_3 : $\text{SrTiO}_{3-\delta}$ and $\text{Sr}_{1-x}\text{La}_x\text{TiO}_3$. *Physical Review B*, 57:2153–2158, 1998.
- [145] D. D. Cuong, B. Lee, K. M. Choi, H.-S. Ahn, S. Han, and J. Lee. Oxygen vacancy clustering and electron localization in oxygen-deficient SrTiO_3 : LDA+ U study. *Physical Review Letters*, 98:115503, 2007.
- [146] C. Baeumer, C. Funck, A. Locatelli, T. O. Montes, F. Genuzio, T. Heisig, F. Hensling, N. Raab, C. M. Schneider, S. Menzel, R. Waser, and R. Dittmann. In-gap states and band-like transport in memristive devices. *Nano Letters*, 19:54–60, 2018.

- [147] S. Caprara, F. Peronaci, and M. Grilli. Intrinsic instability of electronic interfaces with strong Rashba coupling. *Physical Review Letters*, 109:196401, 2012.
- [148] D. Bucheli, M. Grilli, F. Peronaci, G. Seibold, and S. Caprara. Phase diagrams of voltage-gated oxide interfaces with strong Rashba coupling. *Physical Review B*, 89:195448, 2014.
- [149] C. Yin, P. Seiler, L. M. K. Tang, I. Leermakers, N. Lebedev, U. Zeitler, and J. Aarts. Tuning Rashba spin-orbit coupling at $\text{LaAlO}_3/\text{SrTiO}_3$ interfaces by band filling. *arXiv preprint*, 2019.
- [150] Y. A. Bychkov and E. I. Rashba. Properties of a 2d electron gas with lifted spectral degeneracy. *JETP Letters*, 39:78–81, 1984.
- [151] S. Datta and B. Das. Electronic analog of the electro-optic modulator. *Applied Physics Letters*, 56:665–667, 1990.
- [152] R. Winkler. *Spin-orbit coupling effects in two-dimensional electron and hole systems*. Springer, 2003.
- [153] Z. Zhong, A. Tóth, and K. Held. Theory of spin-orbit coupling at $\text{LaAlO}_3/\text{SrTiO}_3$ interfaces and SrTiO_3 surfaces. *Physical Review B*, 87:161102(R), 2013.
- [154] G. Khalsa, B. Lee, and A. H. MacDonald. Theory of t_{2g} electron-gas Rashba interactions. *Physical Review B*, 88:041302(R), 2013.
- [155] P. D. C. King, S. Mckeown Walker, A. Tamai, A. De La Torre, T. Eknapakul, P. Buaphet, S.-K. Mo, W. Meevasana, M. S. Bahramy, and F. Baumberger. Quasiparticle dynamics and spin-orbital texture of the SrTiO_3 two-dimensional electron gas. *Nature Communications*, 5:3414, 2014.
- [156] V. Galitski and I. B. Spielman. Spin-orbit coupling in quantum gases. *Nature*, 494:49–54, 2013.
- [157] P. Seiler. *Anti-localization in oxide heterostructures*. PhD thesis, University of Augsburg, 2018.
- [158] G. Dresselhaus. Spin-orbit coupling effects in zinc blende structures. *Physical Review*, 100:580–586, 1955.
- [159] A. Manchon, H. C. Koo, J. Nitta, S. M. Frolov, and R. A. Duine. New perspectives for Rashba spin-orbit coupling. *Nature Materials*, 14:871–882, 2015.

- [160] H.-Z. Lu and S.-Q. Shen. Weak localization and weak anti-localization in topological insulators. *arXiv*, 2014.
- [161] H.-Z. Lu and S.-Q. Shen. Finite-temperature conductivity and magnetoconductivity of topological insulators. *Physical Review Letters*, 112:146601, 2014.
- [162] P. A. Lee and T. V. Ramakrishnan. Disordered electronic systems. *Reviews of Modern Physics*, 57:287–337, 1985.
- [163] S. Hikami, A. I. Larkin, and Y. Nagaoka. Spin-orbit interaction and magnetoresistance in the two dimensional random system. *Progress of Theoretical Physics*, 63:707–710, 1980.
- [164] S. V. Iordanskii, Yu. B. Lyanda-Geller, and G. E. Pikus. Weak localization in quantum wells with spin-orbit interaction. *JETP Letters*, 60:206–211, 1994.
- [165] R. J. Elliott. Theory of the effect of spin-orbit coupling on magnetic resonance in some semiconductors. *Physical Review*, 96:266–279, 1954.
- [166] Y. Yafet. g factors and spin-lattice relaxation of conduction electrons. *Solid State Physics*, 14:1–98, 1963.
- [167] J. L. Cheng, M. W. Wu, and J. Fabian. Theory of the spin relaxation of conduction electrons in silicon. *Physical Review Letters*, 104:016601, 2010.
- [168] J. Fabian, A. Matos-Abiague, C. Ertler, P. Stano, and I. Zutic. Semiconductor spintronics. *Acta Physica Slovaca*, 57:565–907, 2007.
- [169] M. I. D'yakonov and V. I. Perel'. Spin orientation of electrons associated with the interband absorption of light in semiconductors. *Soviet Physics JETP*, 33:1053–1059, 1971.
- [170] P. Boross, B. Dóra, A. Kiss, and F. Simon. A unified theory of spin-relaxation due to spin-orbit coupling in metals and semiconductors. *Scientific Reports*, 3:3233, 2013.
- [171] P. Seiler, J. Zabaleta, R. Wanke, J. Mannhart, T. Kopp, and D. Braak. Antilocalization at an oxide interface. *Physical Review B*, 97:075136, 2018.
- [172] J. Ruhman, A. Joshua, S. Ilani, and E. Altman. Competition between Kondo screening and magnetism at the $\text{LaAlO}_3/\text{SrTiO}_3$ interface. *Physical Review B*, 90:125123, 2014.

- [173] G. Bergmann. Weak localization in thin films: a time-of-flight experiment with conduction electrons. *Physics Reports*, 107:1–58, 1984.
- [174] F. G. Pikus and G. E. Pikus. Conduction-band spin splitting and negative magnetoresistance in A_3B_5 heterostructures. *Physical Review B*, 51:16928–16935, 1995.
- [175] W. Knap, C. Skierbiszewski, A. Zduniak, E. Litwin-Staszewska, D. Bertho, F. Kobbi, J. L. Robert, G. E. Pikus, F. G. Pikus, S. V. Iordanskii, V. Mosser, K. Zekentes, and Yu. B. Lyanda-Geller. Weak antilocalization and spin precession in quantum wells. *Physical Review B*, 53:3912–3924, 1996.
- [176] H. Nakamura, T. Koga, and T. Kimura. Experimental evidence of cubic Rashba effect in an inversion-symmetric oxide. *Physical Review Letters*, 108:206601, 2012.
- [177] S. Maekawa and H. Fukuyama. Magnetoresistance in two-dimensional disordered systems: Effects of zeeman splitting and spin-orbit scattering. *Journal of the Physical Society of Japan*, 50:2516–2524, 1981.
- [178] C. Yin, K. Prateek, W. Gelling, and J. Aarts. Tunable magnetic interactions in $LaAlO_3/SrTiO_3$ heterostructures by ionic liquid gating. *arXiv preprint*, 2019.
- [179] Y.-J. Kim, Y. Matsuzawa, S. Ozaki, K. C. Park, C. Kim, M. Endo, H. Yoshida, G. Masuda, T. Sato, and M. S. Dresselhaus. High energy-density capacitor based on ammonium salt type ionic liquids and their mixing effect by propylene carbonate. *Journal of The Electrochemical Society*, 152:A710–A715, 2005.
- [180] T. A. Petach, K. V. Reich, X. Zhang, K. Watanabe, T. Taniguchi, B. I. Shklovskii, and D. Goldhaber-Gordon. Disorder from the bulk ionic liquid in electric double layer transistors. *ACS Nano*, 11:8395–8400, 2017.
- [181] P. Gallagher, M. Lee, T. A. Petach, S. W. Stanwyck, J. R. Williams, K. Watanabe, T. Taniguchi, and D. Goldhaber-Gordon. A high-mobility electronic system at an electrolyte-gated oxide surface. *Nature communications*, 6:6437, 2015.
- [182] F. J. Wong, R. V. Chopdekar, and Y. Suzuki. Disorder and localization at the $LaAlO_3/SrTiO_3$ heterointerface. *Physical Review B*, 82:165413, 2010.
- [183] M. Lee, J. R. Williams, S. Zhang, C. D. Frisbie, and D. Goldhaber-Gordon. Electrolyte gate-controlled Kondo effect in $SrTiO_3$. *Physical review letters*, 107:256601, 2011.
- [184] J. Kondo. Resistance minimum in dilute magnetic alloys. *Progress of Theoretical Physics*, 32:37–49, 1964.

- [185] R. Bulla, T. A. Costi, and T. Pruschke. Numerical renormalization group method for quantum impurity systems. *Reviews of Modern Physics*, 80:395–450, 2008.
- [186] W. Niu, Y. Zhang, Y. Gan, D. V. Christensen, M. V. Soosten, E. J. Garcia-Suarez, A. Risager, X. Wang, Y. Xu, R. Zhang, N. Pryds, and Y. Chen. Giant tunability of the two-dimensional electron gas at the interface of $\gamma\text{-Al}_2\text{O}_3/\text{SrTiO}_3$. *Nano letters*, 17:6878–6885, 2017.
- [187] V. K. Guduru, A. McCollam, A. Jost, S. Wenderich, H. Hilgenkamp, J. C. Maan, A. Brinkman, and U. Zeitler. Thermally excited multiband conduction in $\text{LaAlO}_3/\text{SrTiO}_3$ heterostructures exhibiting magnetic scattering. *Physical Review B*, 88:241301, 2013.
- [188] N. Nagaosa, J. Sinova, S. Onoda, A. H. MacDonald, and N. P. Ong. Anomalous hall effect. *Reviews of Modern Physics*, 82:1539–1592, 2010.
- [189] D. Stornaiuolo, C. Cantoni, G. M. De Luca, R. Di Capua, E. D. Gennaro, G. Ghiringhelli, B. Jouault, D. Marrè, D. Massarotti, F. M. Granozio, I. Pallecchi, C. Piamonteze, S. Rusponi, F. Tafuri, and M. Salluzzo. Tunable spin polarization and superconductivity in engineered oxide interfaces. *Nature materials*, 15:278–283, 2016.
- [190] Y. Lee, C. Clement, J. Hellerstedt, J. Kinney, L. Kinnischtzke, X. Leng, S. D. Snyder, and A. M. Goldman. Phase diagram of electrostatically doped SrTiO_3 . *Physical Review Letters*, 106:136809, 2011.
- [191] H. Zhang, X. Yan, H. Zhang, F. Wang, Y. Gu, X. Ning, T. Khan, R. Li, Y. Chen, W. Liu, S. Wang, B. Shen, and J. Sun. Magnetic two-dimensional electron gases with high curie temperatures at $\text{LaAlO}_3/\text{SrTiO}_3\text{:Fe}$ interfaces. *Physical Review B*, 97:155150, 2018.
- [192] P. Nozières. A "Fermi-liquid" description of the Kondo problem at low temperatures. *Journal of Low Temperature Physics*, 17:31–42, 1974.
- [193] Y.-Y. Pai, A. Tylan-Tyler, P. Irvin, and J. Levy. $\text{LaAlO}_3/\text{SrTiO}_3$: a tale of two magnetisms. *arXiv*, 2016.
- [194] S. Banerjee, O. Erten, and M. Randeria. Ferromagnetic exchange, spin-orbit coupling and spiral magnetism at the $\text{LaAlO}_3/\text{SrTiO}_3$ interface. *Nature Physics*, 9:626–630, 2013.