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Layered materials as a platform for quantum technologies

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Supplementary Information for Layered Materials As A Platform For Quantum Technologies

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1 Acronyms and symbols

ZPL: zero-phonon line.
$g^2(0)$: photon-photon correlation function at zero delay time, or single-photon purity. It is ideally 0.
QD: quantum dot.
HOM: Hong-Ou-Mandel. The HOM visibility is a measure of photon indistinguishability, and is ideally 1.
OMCVD: organo-metallic chemical vapour deposition.
MOVPE: metalorganic vapour-phase epitaxy.
AFM: atomic-force microscopy.
hBN: hexagonal boron nitride.
1L: monolayer.
2L: bilayer.
V_B^-: boron vacancy.
The hyphen in some cells, ”-”, represents the lack of experimental papers regarding that quantity. Sometimes predictions, theoretical studies or suggestions are included.

2 Semiconductor quantum dots

2.1 Optical properties

Platform	ZPL emission energy (eV)	ZPL Quantum efficiency	Natural Debye-Waller factor	Excited-state lifetime	$g^2(0)$	HOM visibility	Deterministic positioning: lateral accuracy	Electroluminescence?
InGaAs in GaAs	0.95-1.37[1–5]	>0.96[6]	0.85-0.95[7, 8]. Almost 1 if Purcell-enhanced [9]	Hundreds of ps to order of 1 ns[10, 11]	0.0028[10], <0.006[12]	Single emitter: 0.94 to >0.99[12–14]. Remote emitters: >0.93[15]	OMCVD on pre-patterned substrate: [16]. MOVPE on pre-patterned substrate[17, 18]. Pre-patterning with nanoholes[19–27]. Stressors[28, 29]	Yes[30–34]
GaAs in AlGaAs	1.55-1.77[35–37]	Similar to InGaAs QDs	Similar to InGaAs QDs	Hundreds of ps[38]	$\sim 10^{-4}$[39], $6.7\text{x}10^{-3}$[40]	Single emitter: >0.9[40]. Remote emitters: >0.5[41]	OMCVD on pre-patterned substrate[42, 43]	-

Table S1. Optical properties of some semiconductor quantum dots.

2.2 Spin and entanglement properties

Platform	Spin T_2^*	Spin T_2	Single-qubit π gate rate and fidelity	Spin-spin entanglement rate and fidelity	Ancilla qubit?
InGaAs in GaAs	For electrons: ns to tens of ns[44–46]. For holes: 70 ns[47]	For electrons: up to several µs[44]. For holes: >4 µs[47]	NOT gate: 154 MHz with fidelity >98%[45]	Electrons: 7.3 kHz, fidelity 0.62[15]. Holes: 2.3 kHz, fidelity: 0.55 [48]	Nuclear magnons[49]
GaAs in AlGaAs	2.55 ns[50] (strain-free)	113 µs[50] (strain-free)	0.993 fidelity[50] (strain-free)	-	Potentially nuclear spin bath.

Table S2. Spin and entanglement properties of some semiconductor quantum dots.

3 Point defects in diamond

3.1 Optical properties

Platform	ZPL emission energy (eV)	ZPL Quantum efficiency	Natural Debye-Waller factor	Excited state lifetime	$g^2(0)$	HOM visibility	Deterministic positioning: lateral accuracy	Electroluminescence?
NV^-	1.95[51, 52]	0.5-1[53]	0.03-0.05[51]	12 ns[54–57]	<0.05[58]	Two remote (2 meters): 0.35[59]. Two on the same diamond chip: 0.66[60]	Laser writing (singles): down to 20 nm[61, 62]. Maskless implantation (singles): hundreds of nm[63, 64]. Implantation + AFM tip (>singles): 25 nm[65, 66]. Masked implantation (singles): <100 nm[67]	Not with NV^-, but yes for NV^0[68, 69]
SiV^-	1.68[70, 71]	0.003-0.1[72, 73], up to 0.67[74, 75]	0.65-0.9[76–78]	1.8 ns[79, 80]	<0.1 as extracted from Ref. [81]	Two remote: 0.72[82]	Focused ion beam: 32 nm[83]	Yes[84, 85]
GeV^-	2.06[86, 87]	>0.4[88]	0.6[86–88]	5-6 ns[86, 88]	<0.05 as extracted from Ref. [86]	-	Focused ion beam: tens of nm[89]	-
SnV^-	2[90, 91]	0.8[91]	0.6[92]	6 ns[90, 93]	0.09[93], 0.03[94]	0.63 (single)[94]	Yes with masked shallow ion implantation [95]	-

Table S3. Optical properties of some point defects in diamond.

3.2 Spin and entanglement properties

Platform	Spin T_2^*	Spin T_2	Single-qubit π gate rate and fidelity	Spin-spin entanglement rate and fidelity	Ancilla qubit?
NV^-	From µs to 1.5 ms[96–100]	From ms to >1 s[97, 98, 100–105]	Different studies giving rate beyond 1 GHz[106] and fidelities up to 0.999952(6) [107]	>1/hour over 1.7 km with fidelity 0.92[108]. Two nodes (up to 10's of meters separated): >0.8 fidelity at up to 10 Hz[57, 109, 110]. Three nodes (up to 10's meters separated): 1/90 s, F = 0.538 for GHZ state[109],	^{14}N and ^{13}C nuclei[99, 111, 112]
SiV^-	1.5-13 µs (100 mK)[113]. Tens to >100 ns at 4 K[114, 115]	13 ms (100 mK)[113]. ∼100 ns (4 K)[113]	Rabi in Refs. [113, 115]	0.82, 30 kHz in the same diamond chip[116]	^{13}C[117]
GeV^-	19 ns[118].	-	-	-	-
SnV^-	1.3 µs[119]	0.33 ms µs[119]	0.83 at 3.6 MHz[119]	-	-

Table S4. Spin and entanglement properties of some point defects in diamond.

4 Point defects in SiC

4.1 Optical properties

Platform	ZPL emission energy (eV)	ZPL Quantum efficiency	Natural Debye-Waller factor	Excited state lifetime	$g^2(0)$	HOM visibility	Deterministic positioning: lateral accuracy	Electroluminescence?
Divacancy, $V_{Si}V_C^0$; 4H-SiC; 4 orientations	Different ZPL lines 1.08-1.20[120–122]. Can be stabilised[123]	-	0.07 (*kk*)[124]	14 ns[125]	0.096[126]	-	For an example, see Ref.[122]	-
Si vacancy, V_{Si}^-; 4H-SiC; 2 orientations	1.35 (V_2), 1.43 (V_1)[127]. Can operate up to 20 K[128]	0.3 (V_1)[129].	0.06-0.09 (V_1 and V_2)[130, 131]	5-6 ns (V_1), 8 ns (V_2)[129, 132, 133]	0.04[134]	Single emitter: 0.7[135]	$<$100 nm[134, 136–139]	-

Table S5. Optical properties of some point defects in SiC.

4.2 Spin and entanglement properties

Platform	Spin T_2^*	Spin T_2	Single-qubit π gate rate and fidelity	Spin-spin entanglement rate and fidelity	Ancilla qubit?
Divacancy, $V_{Si}V_C^0$; 4H-SiC	Up to tens of µs (*kk*) or hundreds of µs (*kh*)[140–143]	Up to $>$10 ms, order of $\sim$1 ms[140–144], $\sim$5 s[145]	Fidelity: 0.99984[140]	-	^{29}Si[140, 146] and ^{13}C
Si vacancy, V_{Si}^-; 4H-SiC	Up to 300 ns[147, 148], 30 µs[149]	Order of one ms[138, 149] up to $\sim$20 ms[147]	Rabi oscillations in [149]	-	^{29}Si[138, 150] and ^{13}C[151] are possible

Table S6. Spin and entanglement properties of some point defects in SiC.

5 Rare-earth ions

The numbers and citations in this section, or lack thereof, generally refer to *single* rare-earth ions.

5.1 Optical properties

Platform	Optical transitions	Quantum efficiency	Natural Debye-Waller factor	State lifetime	$g^2(0)$	HOM visibility	Deterministic positioning: lateral accuracy	Electroluminescence?
Yb^{3+}	1.26 eV (984.5 nm) Yb^{3+}:YVO_4 $^2F_{5/2}$-$^2F_{7/2}$[152]	In general for rare earth ions: very high[153]	Very big	In general for rare earth ions: hundresds of µs to ms[153]. 2.27 µs for Yb^{3+}:YVO_4 in a cavity[152]	0.15[152]	-	-	-
Er^{3+}	0.81 eV (1536 nm) Er^{3+}:Y_2SiO_5 $^4I_{13/2}$-$^4I_{15/2}$[154, 155]	In general for rare earth ions: very high[153]	Generally big	11.4 ms[154], 16.2 µs in a cavity[154]	0.3[154], 0.055[155]	-	-	-
Pr^{3+}	Pr^{3+}:Y_2SiO_5 2.05 eV (606 nm) $^1D_2$-$^3H_4$[156], 2.54 eV (488 nm) $^3P_0$-$^3H_4$[156]; Pr^{3+}:LaF_3 1.98 eV (478 nm) $^3H_4$-$^3P_0$[157]; Pr^{3+}:YAG 2.54 eV (488 nm) $^3P_0$-$^3H_4$[158]	Close to 1[158]	Generally big	Pr^{3+}:Y_2SiO_5 166 µs $^1D_2$[156], 1.95 µs $^3P_0$[156]	Very close to 0 for Pr^{3+}:YAG[158]	-	34 nm for Pr^{3+}:YAG[159]	-
Nd^{3+}	Nd^{3+}:YVO_4 1.41 eV (880 nm) $^4F_{3/2}$-$^4I_{9/2}$[160]	-	Generally big	2.1 µs in a cavity[160]	0.09[160]	-		-
Ce^{3+}	Ce^{3+}:Y_2SiO_5 3.34 eV (371 nm) $^2D_{3/2}$-$^2F_{5/2}$[161]; Ce^{3+}:YAG 2.54 eV (489 nm) $^2D_{3/2}$-$^2F_{5/2}$[162]	Close to 1[163]	Generally big	-	-	-	-	-

Table S7. Optical properties of some single rare-earth ions.

5.2 Spin and entanglement properties

Platform	Spin T_2^*	Spin T_2	Single-qubit π gate rate and fidelity	Spin-spin entanglement rate and fidelity	Ancilla qubit?
Yb^{3+}	8.2 µs Yb^{3+}:YVO_4[152]	Up to 31 ms Yb^{3+}:YVO_4[152]	Rabi shown[152]	-	Nuclear spins of V^{5+} ions[164]
Er^{3+}	125 ns Er^{3+}:Y_2SiO_5[154, 155]	3.3 µs Er^{3+}:Y_2SiO_5[154, 155]	Rabi shown[154]	-	-
Ce^{3+}	310 ns Ce^{3+}:Y_2SiO_5[161]	124 µs Ce^{3+}:Y_2SiO_5[161]	Rabi shown[161]	-	^{29}Si Ce^{3+}:Y_2SiO_5[162]

Table S8. Spin and entanglement properties of some single rare-earth ions.

6 Layered materials

6.1 Optical properties

Transition-metal dichalcogenides, Janus materials, and III-metal monochalcogenides

Platform	ZPL emission energy (eV)	ZPL Quantum efficiency	Natural Debye-Waller factor	Excited state lifetime	$g^2(0)$	HOM visibility	Deterministic positioning: lateral accuracy	Electroluminescence?
WSe_2	1.51-1.72, at 4 K[165–172]. Additionally, they have been observed up to 150 K[173, 174]. Energy can be controlled by using piezos/ strain[175–177] or by applying a voltage[178]	0.015 but can be enhanced to 0.44[179]	0.6[180]	Usually in the ns range, up to >10 ns[165–167, 171, 172, 179, 181, 182]. Hundreds of ps when coupled to cavities or other photonic structures[179, 183]	Typically <0.1 or less[170, 174]. 0.022 has been achieved[180]	-	Patterned substrate (strain): ∼100 nm[170, 171, 174, 183, 184]. Cavity-induced (strain): Tens of nm[179]. Calligraphy: nanometer-scale[185]	Yes[186–189]
WS_2	1-77-2.07[170, 186, 190]	-	-	-	0.31 from electroluminescence[186]	-	Patterned substrate: ∼100 nm[170]	Yes[186]
$MoSe_2$	1.50-1.63[179, 191–193]	-	-	190 ps[191]	0.29[191]	-	Nanoholes: <100 nm[191]. Cavities (strain): tens of nm[179]	-
MoS_2	1.7-1.9[194]	-	-	1.73 µs (extracted from from g^2)[195]	0.23[195, 196]	-	He ion: down to 9 nm[194–197]	Not shown, but gate switchable [198]
$MoTe_2$	0.80 to 1.15[199]	-	-	Tens of ns[199]. Order of 1 µs in multi-exponential [199]	Can be below <0.1[199]	-	Patterned substrate: hundreds of nm[199]	-
WSeS (Janus)	1.77 to 1.82[200]	-	-	-	-	-	-	-
GaSe	1.7-2 (from 10 K to 300 K)[201, 202]	-	-	7 ns as extracted from g^2[202]	Down to 0.13[201]	-	Hints of strain playing a role[201]	-
InSe	1.30-1.36[203]	-	-	-	-	-	-	-

Table S9. Optical properties of point defects in transition-metal dichalcogenides, Janus materials, and III-metal monochalcogenides.

Hexagonal boron nitride

Platform	ZPL emission energy (eV)	ZPL Quantum efficiency	Natural Debye-Waller factor	Excited state lifetime	$g^2(0)$	HOM visibility	Deterministic positioning: lateral accuracy	Electroluminescence?
hBN: V_B^- (ensembles)	Emission centered at ∼1.46[204], ZPL at 1.61[205]	-	Likely more than NV^- in diamond	1.2 ns[204]	Measurements are on ensembles [204]	-	Focused ion beam (ensembles)[206]	-
hBN: carbon-related defect(s)	2.07-2.25(mostly around 2.12)[207, 208], 2.8[209]	0.87[210]	Likely more than NV^- in diamond	2-8 ns[209, 211]	0.20[207], 0.1 as extracted from Ref. [211]	-	-	-

Table S10. Optical properties of point defects in hBN.

Heterostructures

Platform	ZPL emission energy (eV)	ZPL Quantum efficiency	Natural Debye-Waller factor	Excited state lifetime	$g^2(0)$	HOM visibility	Deterministic positioning: lateral accuracy	Electroluminescence?
Heterostructure, non-moiré	1L-WS_2/1L-WSe_2: 1.34-1.45[212]. 1L-$MoSe_2$/1L-WSe_2: 1.27-1.45 eV[213–217]	-	-	1L-WS_2/1L-WSe_2: >1 μs[212]. 1L-$MoSe_2$/1L-WSe_2: tens of ns up to a few hundreds of ns[215–217]	1L-$MoSe_2$/1L-WSe_2: down to 0.01	-	1L-WS_2/1L-WSe_2: [212]. 1L-$MoSe_2$/1L-WSe_2: [215–217]	-
Heterostructure, moiré	1L-$MoSe_2$/1L-WSe_2: 1.30-1.40[218, 219]. 2L-$MoSe_2$/1L-WSe_2: 1.25-1.30[220]. Evidence of moiré structures [221–223]. Electric-field tunability[218]	-	-	1L-$MoSe_2$/1L-WSe_2: 12.1 ns[218]; tens of ns[219]	1L-$MoSe_2$/1L-WSe_2: 0.28[218]	-	Theoretically possible to create a perfect array[224]. In practice regularity is only over a few (tens of) nms, or reconstruction can also happen[222, 225–229]	-

Table S11. Optical properties of quantum emitters in layered-material heterostructures.

6.2 Spin and entanglement properties

Transition-metal dichalcogenides: in WSe_2 charging has been shown[230]. For ancilla qubits, nuclei with non-zero spin are available[231].

Hexagonal boron nitride

Platform	Spin T_2^*	Spin T_2	Single-qubit π gate rate and fidelity	Spin-spin entanglement rate and fidelity	Ancilla qubit?
hBN: V_B^- (ensembles)	-	1-2 µs[232, 233], 15 µs[234]	Rabi oscillations [232, 235, 236]	-	Coherent control of ^{14}N nuclei shown[237]. Other nuclear spins available.
hBN: carbon-related defect(s)	Not yet done, but spin is present[208]	-	-	-	Nuclear spins available.

Table S12. Spin and entanglement properties of point defects in hBN.

Heterostructures, moiré: signatures of spin[238, 239].

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