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# TECHNICAL REVIEWS

# Review of performance metrics of spin qubits in gated semiconducting nanostructures

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Abstract | This Technical Review collects values of selected performance characteristics of semiconductor spin qubits defined in electrically controlled nanostructures. The characteristics are envisaged to serve as a community source for the values of figures of merit with agreed definitions allowing the comparison of different spin-qubit platforms. We include characteristics on the qubit coherence, speed, fidelity and qubit size of multi-qubit devices. The focus is on collecting and curating the values of these characteristics as reported in the literature, rather than on their motivation or significance.

Spin qubits are among platforms pursued to serve as quantum computing hardware. In this Technical Review, we focus on spin qubits hosted in semiconducting nanostructures controlled and probed electrically. Their prospect for scalability stems from their compatibility with modern silicon industrial fabrication. Even restricted to gated nanostructures, the field of spin qubits is vast. There is a host of variants on the sample material and structure, device design or qubit encoding. Although this versatility in the qubit types is beneficial for overcoming possible roadblocks, it also makes comparison of different spin qubits difficult. The main motivation for this Technical Review is to provide a basis for such a comparison and for an assessment of the progress of various spin-qubit types over time. We believe that for such tasks, a reliable database of figures of merit normalized to common definitions is of primary importance, and this is what we provide here.

### Scope, format and aim

The restriction to gated nanostructures suggests what is not covered in this Technical Review. We do not include other than solid-state qubits; within the solid state, we do not include superconducting qubits and qubits based on optically accessed impurities and self-assembled dots. We also omit qubits based on the spin of atomic nuclei, that is, hyperfine-spin qubits. Even though spin-related, we sacrifice these possible extensions to keep the Technical Review manageable in length and in preparation time. However, we include some characteristics of charge qubits, that is, qubits with states encoded into the charge degree of freedom of a confined particle. One reason is that often the experimental devices are identical for both spin-qubit and charge-qubit experiments. Another reason is that there are configurations where the spin and charge degrees of freedom are hybridized and tunable. With the character continuously tunable from fully spin-like to fully charge-like, it would be difficult to decide objectively which cases to include and which not. Finally, we point out that this Technical Review is not meant as an overview of the physics of spin qubits, such as principles of their operation and measurements, the decoherence channels and so on. The reader interested in these aspects can consult, for example, REFS.<sup>1–13</sup>. In particular, we point out a recent extensive review<sup>14</sup> as an excellent complement, covering the aspects intentionally omitted here.

The core of this Technical Review is the plots in the main text and the tables in the Supplementary Information of selected qubit characteristics on the qubit coherence, operation speed, operation fidelity, quality factors and size of multi-qubit arrays. The related quantities are defined, and their values collected from the literature given, in the respective sections below.

We hope that this Technical Review will become useful and used as a database for spin-qubit characteristics. To this end, it is crucial that the database is up-to-date, error-free, and contains relevant quantities. These goals can hardly be met without active participation by the spin-qubit community. We encourage the members of the community to provide us with feedback on any errors or omissions, or with suggestions for changes.

A database of values. Although not necessarily of concern for the reader, we note that the presented collection reflects a formally defined database. This fact might be useful to understand certain nomenclature, details of the presentation, and requirements on the included values and possible extensions. Let us briefly explain these aspects.

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### **Key points**

- Spin qubits hosted in semiconducting nanostructures controlled and probed electrically are among platforms pursued to serve as quantum computing hardware.
- Their prospect for scalability stems from their versatility and compatibility with modern silicon industrial fabrication.
- To serve as quantum hardware, qubits have to fulfil a number of stringent criteria concerning their operation, stability and interactions.
- The overview of experimentally achieved values on coherence, speed, fidelity and multi-qubit array size quantifies the progress of semiconducting spin qubits over the past two decades.

Every 'value' given in this Technical Review belongs to a certain 'attribute'. These two basic elements define the database and constitute keywords with precise meaning. The 'attributes' are used as headers in tables and axis labels in plots. For example, the second line of Table I in the Supplementary Information contains the value 'LD/e' under the attribute 'Qubit'. It means that the corresponding experiment used a qubit encoded into the spin of an electron. Although most of the attributes are self-explanatory, they are additionally listed alphabetically, together with their definitions, in the Glossary section of the Supplementary Information. To draw attention to their special role, we mark the attributes with single quotation marks. This distinction is made only in this (first) section and the Glossary section of the Supplementary Information.

### Spin-qubit types, device geometries, material choices.

Before we discuss specific characteristics, we comment on their common aspects. These stem from the fact that each 'value' inherits a set of characteristics from the publication in which it was reported and the experimental device with which it was measured. We describe these common aspects below.

Every value given in this Technical Review (such as a coherence time of 10 ns) is a result of a measurement with a specific device and qubit type, reported in a published reference. Note that although we count arXiv preprints as 'published references', the absolute majority of the entries are from peer-reviewed journal publications. The current reference list in the Supplementary Information contains twelve arXiv preprints, only two of which were uploaded before 2021. This means, first of all, that we include only numbers explicitly stated and directly measured. We do not include extrapolations to other conditions or materials. Also, we do not usually derive the values ourselves even if it would be possible. For example, if the reference gives the operation time and the dephasing time, but does not state the quality factor, we do not evaluate the latter ourselves. However, if a quantity is discussed and presented as a figure (for example, the operation time implied from oscillations displayed by a resonantly driven qubit), we might include a value read off from the figure. In such cases, the table entry contains a 'Note' with keywords 'derived' or 'estimated', which are explained in the Supplementary Information. With this requirement, every value given in this Technical Review should be easy to find using the reference, given under the attribute 'Reference', and within the reference as

described by the attribute 'Source'. An example of the latter is, say, "page 4 and Fig. 1b". One possible difference between the value given here and in the original work is normalization. In that case, a 'Note' explains how the value was converted. Any additional information, for example, alerting the reader to an unusual configuration or a specific method used in the experiment, is also given as a 'Note'.

The second group of common characteristics concerns the details of the qubit. We found it useful to categorize the following: the sample material, the geometry of the host and the qubit type. They belong to the attributes 'Material', 'Host' and 'Qubit', respectively. Although the value for material, for example 'Si/SiGe', is self-explanatory, in some figures we group several different materials under a common tag, such as 'Si'.

Qubits based on silicon dioxide structures are one case that needs a comment. A unique identification in this Technical Review for such structures is the value 'Si/SiO<sub>2</sub>' of the attribute 'Material'. The attribute 'Host' is typically also straightforward to assign, being either '2D', for example for an epilayer, or '1D' for finFETs or structures denoted as nanowires by their authors. One can often find further specifications for such devices, such as: [complementary-]metal-oxide-semiconductor ([C] MOS), silicon-on-insulator (SOI), field-effect-transistor (FET), foundry-compatible and similar, including their combinations. These specifications hint to the fabrication details and the degree of compatibility with industrial silicon technology. However, they are sometimes used interchangeably, even within one laboratory. As the fabrication details are not our focus, we do not include such additional specifications even if given in the original work.

Concerning the host geometry, we discriminate (qubits based on gating) the structures that are (quasi-)'2D', for example, a 2D electron gas (2DEG), (quasi-)'1D', for example a nanowire, and quasi-zero-dimensional, denoted by 'imp', an example being an implanted impurity. Some of these are not clear-cut cases, for example hut-wires with a flat cross-section<sup>15</sup>, or some variants of CMOS devices<sup>16</sup>; nevertheless, we assign both to '1D'. Finally, perhaps the largest variation exists among the qubit types. We distinguish the charge carrier: conduction electron, valence hole and atomic impurity; and the spin-encoding: spin-1/2 ('LD'), singlet-triplet ('ST'), and hybrid ('HY') qubits. We have not found it beneficial to subdivide the hybrid qubits further: everything that is not a spin-1/2 or a singlet-triplet is assigned the value hybrid here. A note might give additional information on the qubit type. The reader would benefit from consulting the Glossary section in the Supplementary Information now, to understand the database organization through attributes and values.

*The choice of values to collect is subjective.* A disclaimer is in order here: assigning a single specific value for each characteristic is necessary for creating a curated database. However, converting an experimental investigation into a single number is inevitably a huge compression. The choice of the value to quote requires subjective judgement: in a typical experiment, the value of a given

figure of merit is seldom a unique value, but rather spans a range, sometimes a very large range, such as several orders of magnitude. We tend to take the most beneficial values, but it does not mean that we simply take the largest one. Especially when an experiment presents a set of values for different characteristics, we try to choose a representative set measured at a common setting. For example, in an experiment with three qubits, where each is measured for relaxation, dephasing and the echo coherence time, we do not simply take the largest value seen among all experiments. We choose a qubit and quote the three numbers for this particular qubit. We proceed similarly when several characteristics are measured under various conditions. Our overall approach is to adopt values that are mutually consistent (such as the coherence time and the operation speed) as much as possible. Nevertheless, we warn the reader that all such choices are largely subjective. The final authority to judge the value meaning and importance is the original reference itself.

What we do and what we do not do. We would like to reiterate our goals, as this work is not a standard review. Our primary target is to provide a database of figures of merit and make its content accessible. This includes downloadable tables and figures, including an interface to produce figures and tables according to





the user's design, and a public repository including the environment for feedback and discussions. This content is accessible through a public data depository (see the Code Availability Statement at the end). The repository includes detailed instructions on how to provide feedback, although writing an email directly to the corresponding author is also encouraged. However, giving a subjective view of the spin-qubit field in the form of qubit-suitability judgements, interpretations, outlooks, summaries, recommendations, predictions and similar is not our target, and the reader will not find much of that type of content here.

After these preliminaries, we now present the spin-qubit figures of merit published until the end of year 2021.

### **Coherence times**

The largest amount of published data on spin qubits refers to their coherence times. Qualitatively, a coherence time extracted in an experiment has the meaning of a time during which state oscillations stemming from quantum mechanical superpositions can be observed.

**Definition and meaning of experimentally extracted coherence times.** Additional specifications of the conditions under which such a superposition decay is observed lead to several variants of the coherence time. The inhomogeneous dephasing time  $T_2^*$  implies a Ramsey experiment, meaning the following sequence: the qubit is initialized to a state polarized within the equatorial plane of the Bloch sphere, for example along the *x* axis, and is left to precess freely for time *t* after which the in-plane polarization is measured; the evolution time *t* is varied, and for each value of *t* the sequence is repeated to gather enough statistics. A typical timetrace of the averaged signal fits a cosine with a Gaussian decay envelope f(t),

$$P_{x}(t) = f(t) \frac{1 + \cos\omega t}{2}$$
  
=  $\exp[-(t/T_{2}^{*})^{2}] \frac{1 + \cos\omega t}{2},$  (1)

where  $\omega$  is the precession frequency. This curve is plotted in FIG. 1a.

The decay of a spin qubit in a Ramsey experiment described by equation (1) is often due to fluctuating nuclear spins. The strong effect of nuclei on the spin coherence was predicted in 200217,18 and confirmed experimentally in 2005<sup>19</sup>. Because the dynamics of nuclear spins is slow, one can protect the spin-qubit coherence using the spin-echo techniques developed in the field of nuclear magnetic resonance<sup>20</sup>. The simplest protecting protocol is the Hahn echo<sup>21</sup>. It means that the spin is flipped (rotated around an in-plane axis by angle  $\pi$ ) in the middle of the free evolution, at time t/2, of the described Ramsey sequence. The coherence time measured under a Hahn echo is denoted in this Technical Review as  $T_2^{\text{Echo}}$ . In REF.<sup>19</sup>, the Hahn echo prolonged the spin-qubit coherence by a factor of 100. There are more elaborate protocols, applying more echo pulses, that prolong the coherence further. Although there are

several different variants of such protocols<sup>22</sup>, here we assign any sequence containing more than a single echo under a common category, denoting the coherence time as  $T_2^{\text{DynD}}$ . A typical member of this family is the Carr–Purcell–Meiboom–Gill (CPMG) protocol, with which the coherence of a singlet–triplet spin qubit was prolonged to almost a millisecond in REF.<sup>23</sup>.

All these protocols aim at prolonging the coherence of an idling spin qubit. The decay of a driven spin, meaning the decay of coherent Rabi oscillations, is another important timescale that is often reported. It is denoted here as  $T_2^{\text{Rabi}}$ . The understanding that the decay of coherence of a driven and idling spins can strongly differ goes back to Alfred Redfield<sup>24</sup> and has been demonstrated with a spin qubit<sup>25</sup>. Finally, we also include the time  $T_1$ , called the relaxation time, to denote the decay of qubit energy. That it is a different type of process is denoted by its subscript '1' as opposed to '2' for the times describing the decay of phase. These subscripts refer to the notation usual in Bloch equations, where these two processes with distinct physical origin are called the 'longitudinal' and 'transverse' relaxation, respectively<sup>26</sup>. See the Supplementary Information for the notation of various decay times.

Although we attributed the Gaussian decay in equation (1) to nuclei as an example, the coherence-times nomenclature applies in the same way, irrespective of the noise source. Low-frequency charge and high-frequency phonon noise, influencing the spins through spin–orbit interactions, are most relevant. More importantly for the coherence-time measurement, the functional form of the envelope f(t) in equation (1) is often different from the Gaussian. Another typical case is an exponential,

$$f(t) = \exp(-t/T_1).$$
 (2)

We have suggestively used  $T_1$  for the timescale, as the energy relaxation is often described by such an envelope. The function is plotted in FIG. 1b. Because of the superimposed oscillations in equation (1), it is not easy to discriminate between the exponential and Gaussian decay envelopes. Although the functions differ strongly in their exponential tails, these tails are basically never resolvable, owing to measurement errors and statistical fluctuations. If the discrimination is possible, it is based on the different shape of the two functions at small times: linear versus quadratic.

The discrimination becomes even more difficult in experiments where the qubit is probed in the frequency domain. A typical example is recording the amplitude and phase response of a resonant electrical circuit of which the qubit is a part. Both of these quantities are parametrized by the circuit reflection coefficient, a complex number. A standard result for it reads (see equation (A15) in REF.<sup>27</sup>; alternatively, REF.<sup>28</sup> gives an analogous result in its equation (57)):

$$r(\omega_{\rm p}) = \frac{\omega_{\rm r} - \omega_{\rm p} + i\kappa/2 + \chi(\omega_{\rm p})}{\omega_{\rm r} - \omega_{\rm p} - i\kappa/2 + \chi(\omega_{\rm p})}.$$
(3)

Here,  $\omega_p$  is the frequency of the signal probing the circuit,  $\omega_r$  is the circuit resonant frequency,  $\kappa$  is the circuit-field decay rate, and  $\chi$  is the qubit response function, proportional to the Fourier transform of the decay envelope -if(t). For a qubit described by an exponential decay, the latter becomes<sup>27,28</sup>

$$\chi(\omega_{\rm p}) = -\frac{g^2}{\omega_{\rm q} - \omega_{\rm p} - i\Gamma_2}D,\tag{4}$$

with  $\hbar \omega_q$  the energy difference of the qubit excited and ground states, *g* the qubit–circuit coupling, *D* the difference of the population probability of the qubit ground and excited state, and  $\Gamma_2 = \Gamma_1/2 + \Gamma_{\varphi}$  is defined in the Supplementary Information. These formulas are also valid when the qubit itself is driven, the so-called two-tone spectroscopy<sup>29</sup>. In that case, all parameters on the right-hand side of equation (4) should be replaced by the corresponding quantities in the rotating reference frame<sup>30</sup>. From equation (3), one can express the fraction of the reflected power,  $|r|^2$ , through the following formula:

$$r(\omega_{\rm p})^2 - 1 = \frac{2\kappa {\rm Im}\{\chi\}}{(\kappa/2 - {\rm Im}\{\chi\})^2 + ({\rm Re}\{\chi\} - \omega_{\rm p} + \omega_{\rm r})^2}.$$
 (5)

In the dispersive regime where  $|\omega_p - \omega_r|$  is the largest frequency, the denominator can be approximated by a constant and equation (5) reduces to a constant times Im{ $\chi$ }. Scanning the probe frequency  $\omega_p$  around the resonance  $\omega_p = \omega_q$ , one observes a dip in the circuit steady-state response, and the width of the dip gives  $2\Gamma_2$ . The articles give the dip width as either the full-width at half-maximum (FWHM) or half-width at half-maximum (HWHM) in frequency (and not angular frequency) units, or, in more general scenarios,  $\Gamma_2$  as one of the fit parameters in fitting the data to equation (5) or its analogues. In these cases, we evaluate the inhomogeneous dephasing time using

$$T_2^* = (\Gamma_2)^{-1} = (2\pi\Delta f_{\rm HWHM})^{-1}.$$
 (6)

Coming back to the possibility of discriminating between the decay envelopes, we now consider the Fourier transforms  $\chi(\omega)$  for the above two examples. Whereas the Fourier transform of a Gaussian is a Gaussian, the exponential transforms into a complex function with the imaginary part a Lorentzian:

Gaussian 
$$f(t) \xrightarrow{\text{FT}} \chi(\omega) = -i \exp(-\omega^2 T^2/4),$$
 (7a)

Exponential 
$$f(t) \xrightarrow{\text{FT}} \chi(\omega) = \frac{-\omega T - i}{\omega^2 T^2 + 1}$$
. (7b)

In these equations, we Fourier-transformed (FT) equations (1) and (2) multiplied by -i, normalized the results to the same value at zero frequency, and dropped the timescale subscripts. To discriminate the two cases given in equation (7) in the frequency domain is even more difficult than in the time domain, as both Gaussians and Lorentzians are quadratic at small frequencies.

The two functions differ more strongly at their tails (that is, for large  $\omega$ ), with algebraic and exponential decay, respectively. However, as already stated, these tails are seldom accessible with the required precision. The three envelope functions discussed so far are plotted in FIG. 1c for comparison.

The reason for discussing the discrimination between different functional forms of the decay envelopes is that it hints to the origin of the noise causing the decay. A minimal description of noise is to give its autocorrelation function, either in the time or frequency domain. If it is the latter, the function is called the noise spectrum. The form of the noise spectrum decides what will be the decay envelope. Noises with different physical origins, for example nuclear spins versus charge impurities, will have different spectra. The functional form of the decay envelope then can serve as an alternative to obtaining the noise spectrum, in hinting at the possible origin of the dominant noise affecting the qubit. Finally, we note that the above three possibilities, Gaussian, exponential and Lorentzian, are not the only ones. For example, going to the next order in the calculation reveals that algebraic tails in the decay exist<sup>30</sup>. Algebraic tails were also obtained in calculations considering the back-action of the qubit on its environment giving rise to non-Markovian behaviour<sup>31</sup>.

To sum up the discussion, the coherence times are typically extracted from fits to simple functional forms. Some are given above, and there are more, such as the 'stretched exponential' used to fit data from dynamical-decoupling sequences. (The standard result is REF.<sup>32</sup>, which derived  $\log f(t) \sim (t/T_2)^{1+\alpha}$  as the envelope for decay under a generic dynamical-decoupling sequence assuming noise spectrum  $1/f^{\alpha}$ . In fitting the experimental data in GaAs, REF.<sup>33</sup> found that a more robust way is to fit the observed decay time to  $T_2 \propto n^{\gamma}$ , where *n* is the number of echoes and, for the CPMG sequence, the noise-spectrum exponent is related to the fit parameter  $\gamma$  by  $\alpha = \gamma/(1-\gamma)$ ). The true decay envelope is a complicated function, which can hardly be parameterized by a single number. A typical fit returns the timescale over which the envelope decays to a fraction of its initial value, for example 1/*e*. This operational definition should be the first guess for the meaning of a coherence time in the tables we give. Not much is implied about the functional form itself, let alone the decay long-time tails.

The data on coherence times are listed in Supplementary Table I. We additionally present the data here in figures, discussing them shortly. We split the figures to two groups, separating the charge qubits, the states of which do not rely on the spin degree of freedom in any way, from qubits that rely on spin at least to some degree. We start with the latter group.

*Measured coherence times of spin qubits.* The coherence times of spin qubits are given in FIG. 2a. The values started at around 10 ns inhomogeneous dephasing time in early experiments with qubits in GaAs. Echo techniques can extend the coherence by orders of magnitude, as can a different material choice. The coherence times published during 2021 span six orders of magnitude, depending on the qubit type, material and protection measures.

To examine the influence of some of these factors, we plotted separately each type of coherence in FIG. 3. The separation allows us to group the values additionally according to qubit type, being the discrete category on the horizontal axis. To reflect the publication date for easier comparison, we displace the data within each category horizontally. For example, FIG. 3a shows that the most recent electron spin-1/2 qubits implemented in purified silicon reach longer coherence times than singlet–triplet qubits, in turn longer than hole qubits. Impurity spins hold record coherence times in each category where data for them exist.

We next turn to the energy relaxation time. For a spin qubit, this time can be made very long by: isolating



Fig. 2 | **Spin coherence and relaxation times. a** | Coherence time according to publication date. The colour shows the device material and the symbol indicates the coherence type as given in the legend. The plotted data are values from Supplementary Table I excluding the data on the relaxation time  $T_1$ . **b**,**c** | Both panels show the same data, the relaxation times from Supplementary Table I. The datapoint colour shows the material. In panel **b** the horizontal axis shows the publication date and the datapoint symbol shows the qubit type. In panel **c** the qubit type is on the horizontal

axis as a discrete category. The publication date is reflected by shifting the points horizontally: more recent data are shifted to the right within the area delineated by the vertical dashed lines, which is normalized to the year span 2003–2022.  $T_2^*$ , inhomogeneous dephasing time;  $T_2^{\text{DynD}}$ , coherence time measured under dynamical decoupling;  $T_2^{\text{Echo}}$ , coherence time measured under a Hahn echo;  $T_2^{\text{Rabi}}$ , decay of coherent Rabi oscillations. HY/e, LD/e, ST/e, LD/h, LD/i, ST/i qubit types are defined in the Supplementary Information.

the qubit from reservoirs, so that the electron does not escape the dot; minimizing its dipole moment, so that the qubit couples weakly to phonons; and decreasing the transition energy, typically using a lower magnetic field, so that the available phase space for the process is reduced<sup>34,35</sup>. Under these conditions, relaxation times have reached seconds and can be considered not of concern for quantum computing. However, the relaxation times remain of concern if these conditions are not met: for example, a finite relaxation time of two-electron singlet and triplet states is the main limitation for the spin measurement fidelities<sup>36-38</sup>. Because of this crucial role, there are numerous values on the relaxation time for (mostly the triplet states of) singlet-triplet qubits, either explicitly reported or implicitly implied in many experiments using Pauli spin blockade for the spin measurement. As the relaxation time in this setting is a by-product of the maximization of the measurement fidelity, rather than a figure of merit maximized itself, we normally do not include singlet-triplet relaxation rates in this Technical Review. We do include a few values, either from early experiments, or when they are the article's main topic.

The reported relaxation times are shown in FIG. 2b,c, plotting the same set of data in two different ways. FIGURE 2b gives them according to the publication date. One can see how the longest-reached times developed: in the first decade, electron one-half spin-qubits were in the lead. From 2010, impurities took over. Currently, the record is back with a single electron in GaAs, with a relaxation time of 1 minute<sup>39</sup>. As already noted, while reaching such long times is not directly improving other figures of merit of the qubit, the increase of the record time illustrates the experimental progress with the given qubit platform. FIGURE 2c groups the times according to qubit types, making it easier to judge the progress over the years within each group.

*Measured coherence times of charge qubits.* We end the overview of coherence times by looking at charge qubits. As already mentioned, we include them even though they implement qubits that do not rely on spin. The reason is a close relation between the devices in which the two types of experiment are typically done and the techniques used: for example, the measurement of spin is done indirectly, converting different spin states to different charge states, which are then detected.

All types of coherence times of charge qubits, including the relaxation time, are gathered in FIG. 4. In the three panels of the figure, the same data are shown according to the publication date, the device material and the coherence type. One can see several differences



Fig. 3 | **Spin coherence times.** Data from FIG. 2a are split into the four panels according to the coherence type denoted in the legend. **a** | $T_2^*$ , inhomogeneous dephasing time, also called free induction decay (FID) time. **b** | $T_2^{\text{Echo}}$ , coherence time measured under a Hahn echo. **c** | $T_2^{\text{DynD}}$ , coherence time measured under dynamical decoupling. **d** | $T_2^{\text{Rabi}}$ , decay of coherent Rabi oscillations. In each panel, the horizontal axis uses the qubit type as a discrete category. All vertical-axes ranges are the same, and the datapoint colours show the material. LD/e, ST/e, LD/h, LD/i, ST/i qubit types are defined in the Supplementary Information. In all panels, the datapoints are displaced horizontally according to their publication date within the area delineated by the vertical dashed lines, as in FIG. 2c.



Fig. 4 | **Charge coherence**. **a**–**c** | Every panel plots the same data, the values from Supplementary Table II. The panels differ in their horizontal axis, plotting the data according to the quantity given as the horizontal-axis label: **a**, publication date; **b**, device material; **c**, coherence type. Concerning the datapoint symbols and colours, panel **a** is analogous to FIG. 2a. In panels **b** and **c**, the role of the datapoint colours and the horizontal axis is swapped.  $T_2^*$ , inhomogeneous dephasing time;  $T_2^{\text{DynD}}$ , coherence time measured under dynamical decoupling;  $T_2^{\text{Echo}}$ , coherence time measured under a Hahn echo;  $T_2^{\text{Rabi}}$ , decay of coherent Rabi oscillations,  $T_1$  relaxation time. In panels **b** and **c**, the datapoints are displaced horizontally according to their publication date within the area delineated by the vertical dashed lines, as in FIG. 2c.

compared with spin qubits. First, the relaxation times are often comparable to coherence times, unlike for most spin-qubits where they can be pushed to be by far the longest scale. Therefore, the relaxation is a bigger issue for charge qubits even in single-qubit experiments. Second, unlike for spin gubits, the echo techniques do not prolong coherence substantially. Third, there is much less variation among the data: despite an upward trend in  $T_2^*$  over time, the increase is not marked. As the charge-qubit dephasing time  $T_2^*$  is related to charge noise directly, a clear trend would indicate an overall improvement of the available samples and devices concerning the level of charge noise. Finally, as one would expect based on the nuclear-spin noise being irrelevant for charge qubits, there is no apparent difference between devices made in Si and III-V materials concerning charge-qubit coherence.

### **Operation times**

The second-most abundant data exist on characteristics of spin-qubit operations. We consider the qubit gates, measurements and initializations as three operation types, treated on equal footing. We are motivated by their actual physical realizations, which are similar: all three types of operation are typically implemented by pulsing the system to a specific configuration, or driving it resonantly, for a fixed time. Another reason is that whereas the algorithms considering logical qubits might assign initializations to the beginning and measurements to the end of the algorithm only, physical qubits will need error correction. In this case, the initializations and measurements are used heavily, interspersing the application of gates.

There is an additional attribute introduced in this section, the number of qubits that a given operation involves, '#Qubits'. The typical cases are one-qubit (1Q) and two-qubit (2Q) gates, even though the first three-qubit gate has already been used in an error-correction demonstration<sup>40</sup>.

**Definition of experimentally extracted gate times.** The advantage of looking at gate times is that they reveal the natural timescale for a given qubit and that they can be compared to the coherence times. However, they also have a shortcoming that arises if they are not compared to any coherence time: a fast qubit does not automatically mean a good qubit, as the judgement largely depends also on the coherence time. Conversely, a qubit with extremely long coherence becomes less appealing if the corresponding gates are also extremely slow. This shortcoming, namely a dimensionful quantity having a limited meaning without comparison to other dimensionful quantities, also applies to the coherence times presented in the previous section.

Let us specify the normalization for the operation times. For the measurements and initialization, the definition is straightforward, even though one should also count the preparation if it is a necessary part of the measurement or initialization sequence. More ambiguity exists for gates, as gates are realized as unitary evolutions induced by certain Hamiltonians. A typical signal that is interpreted as a gate being applied looks like that in FIG. 1a. Neglecting the decay for now, and taking a single-qubit case, the oscillating signal is due to a unitary evolution such as

$$U(t) = \exp(-i\omega ts_z) \equiv \exp(-i2\pi f ts_z).$$
(8)

Here, we have used  $f = \omega/2\pi$  for the signal frequency and  $s_z = \sigma_z/2$  for the rotation generator, with  $\sigma_z$  being the Pauli matrix. At various times, various gates are carried out on the qubit: for ft = 1/2, one gets a *Z* gate, for ft = 1 an identity, whereas ft = 1/4 gives a  $\pi/2$  rotation, often used to prepare coherent superpositions such as  $|0\rangle + |1\rangle$ . If such a continuous signal is presented, we define the operation time to be one-half of the signal period,

$$T_{\rm op} \equiv \frac{1}{2f}.$$
(9)



Fig. 5 | **Operation times and fidelities.**  $\mathbf{a}$ - $\mathbf{c}$  | Operation times are shown for: **a**, gates; **b**, measurements; and **c**, initializations. In all panels, the horizontal axis shows the qubit type, restricted to those for which values exist. Within each type, the publication date is reflected by shifting the points horizontally, as in FIG. 3. The vertical axis shows the operation time in nanoseconds. The datapoint colour indicates the material and its symbol the number of qubits involved in the operation, according to the panel legend.  $\mathbf{d}$ - $\mathbf{f}$  | Fidelities are shown for:  $\mathbf{d}$ , gates;  $\mathbf{e}$ , measurements; and  $\mathbf{f}$ , initializations. In all panels, the

horizontal axis shows the qubit type. The vertical axis shows the fidelity  $\mathcal{F}$  in per cent. The datapoint colour indicates the material and its symbol the number of qubits involved in the operation, according to the individual panel legend. LD/e, ST/e, LD/h, LD/i, ST/i qubit types are defined in the Supplementary Information. 1Q, one-qubit gate; 2Q, two-qubit gate; 3Q, three-qubit gate. In all panels, the datapoints are displaced horizontally according to their publication date within the area delineated by the vertical dashed lines, similarly as in FIG. 2c.

In the case of equation (8), the value t = 1/(2f) would be taken as the operation time, and it would correspond to the *Z* gate, that is a spin rotation by  $\pi$ . Note that this definition is different from the one adopted for the quality factor (see below).

Measured values of gate times. Let us now look at the reported values plotted in FIG. 5a. As the set of operations is diverse, we present the data with the qubit type as the primary category on the horizontal axis. The data are additionally tagged according to the device material and the number of qubits. The shortest in the set are the times of single-qubit gates on charge qubits, being below 0.1 ns. One can deduce more instances of such short times in the literature than those shown on the figure. The reason is that these values are perhaps not claimed explicitly in the experiments: for charge qubits, the gate speed is limited by the experiment electronics, rather than the qubit itself. (Instead of quoting the gate speed, the qubits are often judged by how strongly they couple to a microwave cavity field, using the charge-photon coupling strength. At the moment that figure of merit is not included in this Technical Review). The hybrid qubits can reach similar speeds, as they can be tuned into a configuration where they resemble a charge qubit. Arguably, this tunability is their biggest advantage. When they are tuned into a

spin-like configuration, their gate (and coherence) times go up. Similarly, a strong direct coupling to the electric field can also be exploited for holes, with gate speeds in hundreds of megahertz seen. Such electric-dipole spin resonance driving is less efficient for electron spin-1/2 qubits, for which the highest speeds were reached with design-optimized micromagnets providing large magnetic-field gradients, or materials with strong spinorbit interaction (for example, InAs). As seen from the times in the singlet-triplet column of the figure, the singlet-triplet oscillations can reach gigahertz frequencies. Fast exchange-based gates were demonstrated for both one-qubit and two-qubit operations of spin-1/2 qubits and singlet-triplet qubits, and for two-qubit operations of hole and impurity qubits. Finally, we would like to note that the exchange-based gate for, first, a pair of one-half spins and, second, the singlet and triplet two-electron states is an identical process. Whether such a process should be interpreted as a one-qubit gate or two-qubit gate depends on additional functionalities implemented, or implementable, in the given experiment. The boundary between the two cases is blurry.

**Definition and values of measurement times.** We do not review the measurement times of charge qubits because the task of measuring a charge qubit is the

task of detecting a charge — typically an elementary charge — in a nanodevice. First, this task is separable from, and not exclusive to, spin qubits, and thus not our focus. Second, the analysis of methods and results of this task is a topic rich enough for a review in its own right. For our purposes, it is enough to give the following minimum. The charge detection is typically characterized through the detection sensitivity *s*. Here are a few numbers that one can find in the literature for it, all in  $10^{-4} e \text{Hz}^{-1/2}$ : 10 in REF.<sup>41</sup>, 10 in REF.<sup>42</sup>, 30 in REF.<sup>43</sup>, 63 in REF.<sup>44</sup>, 0.8 in REF.<sup>45</sup>, 0.37 in REF.<sup>46</sup>, 8.2 in REF.<sup>47</sup>, 4.1 in REF.<sup>48</sup>, 21 in REF.<sup>49</sup>, 0.60 in REF.<sup>50</sup>. Therefore, for what follows we adopt a typical value

$$s = a \text{ few } \times 10^{-4} e / \sqrt{\text{Hz}} \,. \tag{10}$$

This parameter quantifies the reliability of the output of a charge-meter signal if integrated for time  $T_{\rm M}$ , through the variance

$$\operatorname{var}[q] = s^2 / T_{\mathrm{M}}.$$
 (11)

Assuming that one aims to distinguish a signal of one elementary charge,  $q_1 = e$ , from the signal of zero charge,  $q_2 = 0$ , where 'to distinguish' means to make the signal error,  $\sqrt{\text{var}[q]}$ , as small as the signal magnitude,  $|q_1 - q_2| = e$ , would give the required time

$$T_{\rm M} = s^2/e^2 \sim 100 \,\,{\rm ns.}$$
 (12)

Although higher sensitivity<sup>51</sup> and shorter times<sup>52</sup> for elementary charge detection were reported, let us take this value for the measurement time  $T_{\rm M}$  as a lower limit realistic for many experimental configurations.

With 100 ns for the time required to detect an event involving elementary charge, we now look at the spin-qubit measurement times shown in FIG. 5b. We see that whereas the times start at about the elementary charge-detection limit of equation (12), they might become orders of magnitude longer. The variance reflects the fact that the spin is detected indirectly, by first converting it to a charge event, which is in turn resolved by a charge sensor. The time required for the spin-to-charge conversion can vary a lot, depending on the process details. One example for a spin-to-charge conversion is spin-dependent tunnelling: an electron with spin down can tunnel out of a quantum dot, whereas the one with spin up cannot, the difference originating in their Zeeman energies<sup>53</sup>. As the quantum dot has to be well isolated for the qubit to keep its coherence, the tunnelling out of the dot is slow. As a second example, the spin singlet and triplet can be discriminated according to being allowed or not allowed to traverse a double dot (the Pauli spin blockade introduced in REF.<sup>54</sup>). Although in this case the charge reconfiguration can be very fast, following the gate-voltage pulses on a nanosecond scale, the two charge configurations being discriminated differ only by a dot-size shift of an elementary charge. The discrimination of such states requires a longer time than those differing by the presence, rather than the displacement, of an elementary charge. A different class of measurements, called rf-based detection, relies on probing

the above-described spin-dependent charge reconfigurations by an oscillatory (radio-frequency) electric field. The shortest measurement times seen on FIG. 5b were obtained with rf-sensors.

*Values of initialization times.* The initialization times are shown in FIG. 5c. Only a few values are present. The reason might be that the most typical experimental scenario is to repeat a cycle: initialization–operation– measurement, where the measurement part plays the role of the initialization, and, therefore, the latter is not reported separately and explicitly. There are more values published on the initialization fidelities (see below).

### Operation fidelity

The operation fidelity is a dimensionless figure of merit allowing the comparison of diverse gubits. Using randomized benchmarking<sup>55</sup>, one can extract the gate errors independently of the measurement errors, even if the former are orders of magnitude smaller than the latter. Although it is not strictly correct, the fidelity is used to judge the progress towards error-correction thresholds required for fault-tolerant quantum computing. (The problem is that the fidelity, as defined below, is not the error parameter entering the threshold theorem. The two parameters can differ by orders of magnitude, in the unfavourable way: whereas the fidelity extracted by the randomized benchmarking can be low, the error rate can remain much larger<sup>56,57</sup>.) For all these reasons, evaluating the gate fidelities is popular, and impressive values have been reached.

**Definition and meaning of experimentally extracted fidelities.** The fidelity characterizes how close the actual operation is to the desired one. Although a fidelity of 1 means that the two operations are the same, the quantification of a measure when they are not the same is less straightforward. The usual definitions derive from the fidelity  $\mathcal{F}$ , in the sense of the distance between two quantum states described by their respective density matrices  $\rho$  and  $\rho'$ ,

$$\mathcal{F} = \left( \operatorname{tr} \sqrt{\sqrt{\rho} \, \rho' \, \sqrt{\rho}} \right)^2. \tag{13}$$

If one of the two states is pure, say  $\rho' = |\Psi\rangle\langle\Psi|$ , the formula simplifies to

$$\mathcal{F} = \operatorname{tr}(\rho |\Psi\rangle \langle \Psi|). \tag{14}$$

If the second state  $\rho$  is also pure,  $\mathcal{F}^{1/2}$  is closely related to an unambiguous discrimination of the two pure states<sup>58</sup>, whereas  $\operatorname{arccos} \mathcal{F}^{1/2}$  is a measure of their statistical distinguishability<sup>59</sup>. (What is the best measure to quantify distance of two operations is discussed at length elsewhere<sup>60</sup>.)

We use the definition of equation (13) leading to equation (14) because of its connection to the randomized benchmarking. Namely, the essence of the latter is to prepare a pure state  $|\Psi\rangle\langle\Psi|$ , apply to it a sequence of gates and then evaluate the overlap of the resulting density matrix  $\rho$  with the original state  $|\Psi\rangle$  using equation (14). In the sequence, the gates are randomly chosen from a discrete set, the Clifford group<sup>61</sup>, except for the last gate, which is such that the whole sequence reduces to the identity if all gates are perfect. The resulting fidelity, also called the probability of the survival of the initial state, falls off exponentially with the sequence length m,

$$\mathcal{F}(m) \approx Ap^m + B. \tag{15}$$

Experimentally, the three coefficients *A*, *B* and *p* are fitted. (Even though REF.<sup>62</sup> stresses that one should always use a more refined decay model, adding a term proportional to  $(m-1)p^m$  to the right-hand side of equation (15), this piece of advice does not seem to be followed in practice.) The first two parameters absorb the errors of the state preparation and measurement, so that the infidelity  $1 - \mathcal{F}$  can be found from the parameter *p* by using the formula

$$1 - \mathcal{F} = (1 - p)\frac{d - 1}{d}.$$
 (16)

Here,  $d = 2^n$ , with *n* the number of qubits; d = 2 for a single-qubit gate benchmarking. Some comments are in order. The exponential decay reflected by equation (15) happens under broad conditions investigated in detail elsewhere<sup>55,62</sup>. The fidelity extracted in this way is the average of  $\mathcal{F}$  in equation (14) over all pure input states  $|\Psi\rangle\langle\Psi|$  and over the gates in the Clifford group. There is an extension procedure called interleaved randomized benchmarking63, which can assign a fidelity - still averaged over all pure states - to a single specific gate from the Clifford group. The study in REF.60 presents further arguments against using the average fidelity  $\mathcal{F}$ , as extracted from randomized benchmarking, equation (16), and advocates for the use of entanglement fidelity  $\mathcal{F}_{e}$  instead. The two measures are related by  $(d+1)\mathcal{F} = d\mathcal{F}_e + 1$ . As most spin-qubit publications give  $\mathcal{F}$ , we stick to  $\mathcal{F}$  as the reported figure of merit.

Although the exponential decay form displayed by equation (15) relies on the discrete set being the



Fig. 6 | **Probabilities describing a two-outcome qubit measurement.** The two mutually orthogonal pure states are on the left. The two measurement outcomes are on the right. A perfect measurement would have unit probabilities  $p_{ii}$  with i=0,1 denoted by horizontal lines. Owing to imperfections, diagonal lines appear with non-zero probabilities. The infidelity defined by equation (19) gives for this diagram  $1 - \mathcal{F} = \frac{1}{2}(p_{01} + p_{10})$ ,  $\mathcal{F}$  being the fidelity.

Clifford group, many articles convert  $\mathcal{F}$  to fidelities of experiment-specific 'elementary' or 'primitive' gates, such as  $\pi/2$  and  $\pi$  rotations around various axes. Even though such a conversion is questionable<sup>62</sup>, we follow the prevailing practice, and in figures and tables we give the fidelity for the elementary-gate set (and not for the Clifford-gate set). For one-qubit or two-qubit gates, one Clifford gate requires typically a few elementary gates. Therefore, the infidelity of a Clifford gate would be around a factor of 2-3 larger than the infidelity of an elementary gate, the value quoted in this Technical Review. To give a few examples, REF.55 gives one list of elementary gates for a single-qubit case, resulting in the ratio of 1.875. For the two-qubit case, REFS.<sup>64,65</sup> used elementary-gate sets with the ratio of 2.57. However, larger ratios also appear: for example, 9.75 in REF.66.

The fidelities of initialization and measurement are less ambiguous to define as they can be based on equation (14), which is more intuitive than equation (13). Let us start with the measurement. The probability of getting an outcome *p* in measuring the state described by a density matrix  $\rho$  is given by equation (14) upon replacing the pure state  $|\Psi\rangle\langle\Psi|$  by a positive semi-definite operator A. The most general measurement with possible outcomes labelled by index i is specified by a set  $\{A_i\}_i$  of such operators summing to identity,  $\sum_i A_i = 1$ . In experiments, these operators are approximations of a set of mutually orthogonal projectors spanning the qubit basis  $A_i \approx |\Psi_i\rangle \langle \Psi_i|$ . Owing to experimental imperfections, these approximations are not exact. The probability of the measurement outcome *j* upon measuring the pure state  $\rho = |\Psi_i\rangle \langle \Psi_i|$  follows as

$$p_{ij} = \operatorname{tr}(|\Psi_i\rangle\langle\Psi_i|A_j). \tag{17}$$

Owing to the normalization of  $A_{i}$ , the probabilities fulfil

$$\sum_{j} P_{ij} = 1. \tag{18}$$

Were the measurement perfect, all non-diagonal probabilities would be zero. The infidelity of the measurement can be quantified through the off-diagonal probabilities. For example,

$$1 - \mathcal{F} = 1 - \frac{1}{d} \sum_{i} p_{ii} = \frac{1}{d} \sum_{i} \sum_{j \neq i} p_{ij}.$$
 (19)

Here, the first equality sign is a definition, the second one follows from the sum rule, equation (18). Also, the number of outcomes is assumed to be equal to the size of the Hilbert space *d*: for example, d=2 for a two-outcome measurement of a two-level system (a qubit). In this most common case, the measurement probabilities are quantified by two error probabilities,  $p_{01}$  and  $p_{10}$ , as depicted in FIG. 6. The resulting measurement infidelity according to the definition in equation (19) is  $(p_{01} + p_{10})/2$ .

Finally, let us consider the fidelity of the initialization. Typically, one is interested in an initialization into a single pure state  $|\Psi\rangle$ . In this case, we can use equation (14) to define the initialization fidelity with  $\rho$  the actual, perhaps imperfectly prepared, state.

*Measured values of fidelities.* FIGURE 5d–f shows the published fidelities of the gates, measurements and initializations, respectively. For the gates (FIG. 5d), electron spin-1/2 qubits previously reached the highest fidelities, well above 99.9%. Using silicon, both natural and isotopically purified, was crucial for this achievement. Recently, these values were overcome, and a new record at 99.99% was set by a hole in germanium<sup>67</sup>. There is notable progress in almost every qubit category, and increasing the fidelity of single-qubit gates is one of the most impressive achievements within the whole spin-qubit field.

FIGURE 5e shows the fidelities of measurements. Until recently, the infidelities remained above a few per cent. Relying on a 'latched' readout in the Pauli spin blockade<sup>37,38</sup>, the fidelities above 99% were achieved with singlet–triplet qubits. Comparable high-fidelity results for impurity spins rely on their exceedingly long lifetimes.

We conclude with a remark on two-qubit fidelities. In all categories, meaning gates, measurements and initializations, their infidelities remain one to two orders of magnitude above the single-qubit ones. There are fewer data published for the two-qubit versions. Concerning initializations, the more-qubit infidelities that we list are initializations into a non-trivial state achieved through some simple quantum algorithm: for example, initializing all individual qubits into single-qubit fiducial states, and then entangling them with gates into the desired entangled multi-qubit state, such as one of the two-qubit Bell states or the three-qubit Greenberger–Horne–Zeilinger (GHZ) state.

### Quality factor Q

The quality factor is another dimensionless measure allowing for the comparison of diverse qubits, similar to the gate fidelity. The quality factor is a product of a gate frequency and a characteristic timescale. We denote the former by  $f_{R}$ , with the subscript suggesting the most typical case where the gate is implemented by Rabi oscillations. There are two usual choices for the characteristic time, resulting in two groups of quality factors reported in the literature.

The first choice is using the inhomogeneous dephasing time. We call the resulting metric the qubit quality factor,

$$Q = f_{\rm R} T_2^*. \tag{20}$$

This *Q* counts the number of operations that can be performed on a given qubit before other qubits, waiting idly, lose their coherence. With the possibility of applying dynamical decoupling, one might consider using other coherence times instead of  $T_2^*$  as the time for which the other qubits can wait before losing coherence. However, we know only a single case<sup>68</sup> where a different choice was made for this type of quality factor,  $T_2^{Echo}$ , and therefore stick to equation (20).

The second choice is using the gate-signal decay time. Although it is not exclusive to Rabi-induced gates, we denote it using the symbol  $T_2^{\text{Rabi}}$  introduced before, again as the most typical scenario. We call the resulting quantity the gate quality factor,

$$Q = f_{\rm R} T_2^{\rm Rabi}.$$
 (21)

In this form, Q gives the number of oscillations at frequency  $f_{\rm R}$  during the decay time  $T_2^{\rm Rabi}$ . Loosely speaking, it gives the number of discernible oscillations on a plot showing the Rabi oscillation signal. (Indeed, REF.69 calls Q defined in equation (21) a 'number of gate oscillations', which might have been a better name than a 'quality factor'.) We note that many references reporting the gate quality factors use equation (21) with the right-hand side multiplied by a factor of 2. Although such a factor is understandable looking at equation (9), we adopt equation (21) to make it more directly comparable to equation (20). As a consequence, we have to divide several of the reported values for the gate quality factors by 2. Finally, we note that the gate quality factor is related to the gate fidelity, both being a qualitative measure of the gate imperfections. In the Supplementary Information we derive  $1 - \mathcal{F} \approx 1/4Q$  valid for a large Q in a toy model with exponential dephasing.

FIGURE 7a shows the published data on quality factors, both gate and qubit ones. Most of the values are within the range of a few to about 100. There are some exceptions that crawl toward 1,000. FIGURE 7b makes it easier to compare different qubit types and discriminate the gate and qubit quality factors. Of the two dephasing times,  $T_2^*$  is typically smaller than  $T_2^{\text{Rabi}}$ , so one expects the gate quality factors to reach higher values than qubit quality factors. There is some evidence in favour of this expectation, but more data are needed to decide on its generality.

### Size of qubit arrays

Scaling up devices to many qubits is the biggest current challenge of the field. The statement applies to all qubit platforms, not only to semiconducting qubits. For serious applications, being able to build large 2D arrays seems necessary, as the fault-tolerant thresholds for error correction in 1D arrays remain too low (see Table VIII in REF.<sup>70</sup>).

**Definition of qubit-array functionality levels.** Although it is possible to fabricate relatively large gated arrays with semiconductors, making them functional is a different story. Therefore, we discriminate several functionality levels. We note that the assignment of the levels as defined below to a specific experiment is often difficult. This assignment is perhaps the most subjective of all made in this Technical Review. The reader is advised to consult the original work to judge the details of the achievements.

We define the following values, in ascending order according to the device functionality:

- N-qubit device. A structure capable of hosting N qubits has been fabricated. The gating and charge sensing work, so that all qubit hosts can be brought into the required charge configuration. On top of this minimal requirement, the articles assigned to this category report a large variation of additional features: single electric-dipole spin resonance gates, tunable interdot tunnelling or coupling, controllable charge shuffling, spin detection based on Pauli spin blockade, estimations of qubit–qubit interaction strength, and so on.
- *N*-qubit simulator. First of all, the device is stable and tunable enough to search large regions in the



Fig. 7 | **Quality factors and size of the qubit arrays.** Panels **a** and **b** show the same data. **a** | Quality factor as a function of the publication date, with the datapoint colour indicating the material, and the datapoint symbol the qubit type, according to the panel legend. **b** | Quality factor as a function of the qubit type. The datapoint colour indicates the material, and its symbol discriminates the qubit and the gate quality factor as defined in equation (20) and equation (21), respectively. Panels **c** and **d** show the same data. **c** | Size of the qubit arrays as a function of the publication date, with the datapoint colour indicates the material, and the panel legend. **d** | Size of the qubit array as a function of the array functionality. The datapoint colour indicates the material and its symbol the host geometry, according to the panel legend. LD/e, ST/e, LD/h, LD/i, ST/i qubit types are defined in the Supplementary Information. In panels **b** and **d**, the datapoints are displaced horizontally according to their publication date within the area delineated by the vertical dashed lines, similarly to FIG. 2c.

high-dimensional charge diagram. For example, aiming at single-electron spin-1/2 qubits, the structure can be brought into the  $1-1-1 \cdots 1$  charge state, or the  $(11)-(11)-(11)\cdots(11)$  state for singlet-triplet qubits. In such a configuration, qubits can interact pairwise, and all *N* qubits are connected by an interaction path. The interactions are tunable. Either one qubit can be measured and manipulated at the single-qubit level, or at least qubit-qubit (being spin-spin) correlations can be measured.

• *N*-qubit processor. Every qubit (or most of them) has a two-axis control and can be measured. Qubits can interact pairwise through tunable interactions. The structure can perform *N*-qubit algorithms.

To cast more light on the ambiguities that we met and decisions we made to deal with them, let us make a few additional comments. First, we do not include many-qubit structures that were fabricated, but for which no functionality was demonstrated, no matter what their size was. We do not include experiments where multiple-dot structure was involved without any intention towards using it for qubits (for example, it was used in a transport experiment).

Second, the vast majority of the experiments within the spin-qubit field until now were done with a single dot implementing a spin-1/2 qubit or a double dot implementing a singlet-triplet qubit. Therefore, we normally do not include these two cases in our tables and figures. One exception is if the experiment is outstanding in some way, perhaps pioneering a spin qubit in a new material or platform. We included some of these.

Third, the number of qubits is not the same as the number of dots. For example, a double dot with two electrons can be viewed both as one singlet-triplet qubit and as two

qubits of spin-1/2 with a limited functionality. In these cases, we follow the primary intention of the experiment as we understood it from the reference. For example, a triple dot implementing a resonant-exchange qubit is counted as a single-qubit structure implementing a fully functional resonant-exchange qubit (that is, a hybrid qubit in our nomenclature), and not as a structure implementing three spin-1/2 qubits with a limited functionality.

Finally, in REFS.<sup>71,72</sup> there is no single-qubit gate nor measurement available. Still, we assign it to the quantumsimulator category, as in these experiments a simulation was the primary target and controllable spin–spin interactions played a critical role.

Sizes of qubit arrays achieved experimentally. The sizes of qubit arrays appearing in publications on experiments are displayed in FIG. 7. FIGURE 7c shows the progress over time. A lot of effort goes into scaling up the spin-qubit structures, with slow but nevertheless steady progress. It took about 10–15 years to bring the most basic structure of the spin-qubit field, the double dot, up to the functionality of a quantum processor, as defined in the above list. With the experiments starting<sup>19</sup> around 2005, REFS.<sup>69,73,74</sup> could be acknowledged to have reached the 'processor' level, and only in the most recent one were the fidelities high

enough to run the most elementary quantum circuits. We assign the accomplishment of the first fully functional 'processor' beyond the double dot to the year 2021, with REF.<sup>75</sup> using electrons in silicon and REF.<sup>76</sup> using holes in germanium. In FIG. 7d one can see that the recent couple of years have brought a surge of results demonstrating progress in building spin-qubit arrays with advanced functionality. The fact that these recent breakthroughs come from many groups and happen in diverse materials and geometries gives excellent reasons for optimism that the scaling up is finally taking off.

### Code availability

The GitHub project https://github.com/PeterStano/ ReviewOfSpinQubits gives the data that are plotted in figures as text files (more precisely, it contains the LaTeX source of the data tables as given in the Supplementary Information). The GitHub project also contains information on how to provide feedback to authors on the review content efficiently, and how to produce customized tables and figures. In addition to some of the references cited up to this point, the data were taken from REFS.<sup>77-325</sup>.

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### **Competing interests**

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