Peer Review File

Manuscript Title: Fast universal quantum gate above the fault-tolerance threshold in silicon

Reviewer Comments & Author Rebuttals

Reviewer Reports on the Initial Version:

Referee #1 (Remarks to the Author):

Noiri et al. demonstrate high fidelity quantum control of a two-qubit quantum processor in silicon. These results are very significant, as up until recently, only trapped ion and superconducting qubit systems have enabled two qubit gate fidelities exceeding the threshold for fault tolerance. Related work by the Delft group, arXiv:2107.00628, reports similar fidelity numbers. There are some significant differences in the detail. Noiri explore two-qubit gates in a regime where the exchange interaction is "always-on," whereas the Delft work implements a CZ gate by pulsing on exchange. Delft uses gate set tomography to characterize the two qubit gate, while Noiri apply the more widely accepted randomized benchmarking protocol. Both papers are of high quality, and in my opinion, merit publication in Nature.

Suggested improvements:
1. The single qubit RB curves go out to fairly short sequence lengths and do not yet saturate. The text mentions in the couple of locations that error bars are determined using a Monte Carlo simulation. My impression is that the error bars are rather optimistic and I encourage the authors to provide a more adequate explanation of how the tight error bars are arrived it. For example, the procedure could be outlined in a short section of the supplemental material.
2. Figure 3 may not provide value to the general Nature reader. At low powers the qubit is coherence limited and at high powers the qubit is no longer in the linear drive regime. Best performance is expected inbetween these regimes - as is shown. Consider moving Fig. 3 to the supplemental section.
3. High readout visibility will be required for full fault tolerant operation with error correction. Could the authors please comment in the main text on what the visibility is and what is limiting it?

Referee #2 (Remarks to the Author):

The paper by Noiri et al. presents experimental universal quantum gate operation and two proof-of-principle algorithm demonstrations in a system of two spin qubits in silicon quantum dots The reported gate fidelities are exceedingly high and well-characterized, and with >99% they surpass the threshold for fault-tolerant quantum computation.

In my view, this is a real breakthrough result. Together with a roughly simultaneous report by the Vandersypen group (Xue et al., arXiv:2107.00628, unpublished) they provide an impressive demonstration of the viability and power of silicon-based quantum information processing. These qubits also have a high potential for scaling to many qubits, due to their microscopic nature and the possibility of applying advanced semiconductor microfabrication techniques.

The work is done in a highly careful manner and the performance of quantum gate and circuit operations are assessed precisely using randomized benchmarking.

Based on the importance of the result and the high quality of the work, I recommend publication of this paper in Nature.

However, before publication, I have a number of comments listed below that I'd ask the Authors to consider.

1) line 39: The sqrt{SWAP} gate for universal quantum computation as a result of the exchange coupling was proposed by Loss and DiVIncenzo in their seminal paper in 1998 which could be mentioned here along with the other references.

2) line 52: should be "Planck" rather than "plank"

3) line 85: in the Hamiltonian, the Rabi frequencies Omega_1 = gamma_1 * B appearing in the off-diagonal 2x2 blocks and
Omega_2= gamma_2 * B appearing in the off-diagonal elements of the diagonal blocks are fundamentally different because
the gyromagnetic ratios gamma_1 and gamma_2 are usually different. Can the Authors explain here why they chose these two Rabi frequencies to be equal? Is this fine-tuned or approximated?

4) line 117: The "maximum operation time" is quoted as 100 us, but in the extended data Fig. 2c it looks like
it is actually 10 ms. I also found the term "maximum operation time" a bit unclear, perhaps "maximum measurement time" might be better?

5) line 122: is is a coincidence that Fp1 and Fp2 are exactly equal within their 4-digit precision or is there a deeper reason behind it?

6) Around lines 115-132: RB allows for an impressive characterization of the gate fidelities which are explored in this paper. But wouldn't it also be possible to extract the SPAM (state preparation and measurement) errors from the same data? If so, I recommend including those in the main text. (see also Methods section)

7) The order of References 18 and 19 should be switched because what is now Ref. 19 was submitted first and published first.

8) In the Figure caption of Fig. 1, panels e and f, perhaps a quick mention of the synchronization condition J/f_R=\sqrt{15} could be made to explain the combined horizontal axes.

9) In Figure 4, panels a and b, the meaning of the last single-qubit gates as I *or* X/2 *or* Y/2 *or* X could perhaps be explained in the figure caption for clarity.

10) In the figure capon of the extended data Fig. 3 (line 523), one could write "J=18.85 MHz= \sqrt{15} f_R"
in order to again clarify how these numbers follow from the synchronization condition.

Referee #3 (Remarks to the Author):

In the manuscript "Fast universal quantum control above the fault-tolerance threshold in silicon," the authors report a spin-based quantum processor with average single- and two-qubit gate fidelities above 99%. They measure gate fidelities across a range of different single-qubit transition frequencies, allowing for some optimization of system parameters. The authors then demonstrate the capabilities of their device by briefly report the execution of two-qubit Deutsch-Jozsa and Grover search algorithms.

The manuscript is interesting, and the work is of high quality. However, I find that there are some fundamental issues that limit the importance of the work and therefore its suitability for publication in a high impact journal such as Nature. Specifically, here are the main weaknesses of this manuscript:

1. One issue is that the coupling between the two qubits in this device cannot be switched off. This problem can be overcome in a two-qubit device, by essentially combining two-qubit gates to obtain single-qubit gates. Of course, this approach is not scalable. In fact, it would be quite challenging to even extend it to a three-qubit system.

2. There are infidelity sources that are not well understood.

3. The algorithms near the end of the manuscript seem to be an afterthought. They do not really add much to the paper. There is an extremely brief discussion (a small paragraph) on this part of the work.

4. A different group has already demonstrated a universal gate set above 99% in this system (arXiv:2107.00628). In this preprint, the authors demonstrated a more scalable system, with the ability to switch off J. They also presented a more meaningful application of their gates in the demonstration of a simple VQE algorithm.

Some additional questions/comments the authors may want to consider:

-It would strengthen the paper if the authors gave some physical explanation about the dependencies appearing in Fig. 3.
-The statement "We find that the infidelity due to dephasing is only 0.1% and therefore it is no longer the main limiting factor" could be explained more. It is not clear to the reader how this was inferred.
-The Bell state fidelity is not provided. This would have a been a useful metric that is quite standard in two-qubit gate characterization.

Author Rebuttals to Initial Comments:

We thank the reviewers for their careful considerations on the manuscript. Below we list our point-by-point responses to all comments from the reviewers. All changes in the manuscript (except those of the reference numbers) are highlighted in red. We believe that all the comments in the referees' reports are addressed and that our manuscript is now appropriate for publication in *Nature*.

Response to Reviewer #1:

Comment #1

Noiri et al. demonstrate high fidelity quantum control of a two-qubit quantum processor in silicon. These results are very significant, as up until recently, only trapped ion and superconducting qubit systems have enabled two qubit gate fidelities exceeding the threshold for fault tolerance. Related work by the Delft group, arXiv:2107.00628, reports similar fidelity numbers. There are some significant differences in the detail. Noiri explore two-qubit gates in a regime where the exchange interaction is "always-on," whereas the Delft work implements a CZ gate by pulsing on exchange. Delft uses gate set tomography to characterize the two qubit gate, while Noiri apply the more widely accepted randomized benchmarking protocol. Both papers are of high quality, and in my opinion, merit publication in Nature.

Response: We thank the reviewer for correctly understanding the importance of our work and thereby recommending publication in *Nature*.

Comment #2

Suggested improvements:

1. The single qubit RB curves go out to fairly short sequence lengths and do not yet saturate. The text mentions in the couple of locations that error bars are determined using a Monte Carlo simulation. My impression is that the error bars are rather optimistic and I encourage the authors to provide a more adequate explanation of how the tight error bars are arrived it. For example, the procedure could be outlined in a short section of the supplemental material.

Response: We thank the reviewer for the useful comment. As demonstrated in refs. 7, 19, 41, and 42, the saturation value of the sequence fidelity is zero so that we do not need to measure it with a large sequence length (see Methods). The error bars are obtained by a Monte Carlo method assuming that the measured single-shot probabilities follow multinomial distributions. Single-shot probabilities from these distributions are sampled randomly and we obtain the gate fidelity by the procedure described in lines 349-363. We repeat this procedure 1,000 times to obtain the fidelity distribution. Then, the obtained fidelity distribution is fitted by the Gaussian distribution and extract its standard deviation.

In the original manuscript, we discussed the procedure only briefly. To explain the above, we have modified the manuscript as follows:

In lines 387-391:
The errors of the gate fidelities are obtained by a Monte Carlo method[4] assuming that the measured single-shot probabilities follow multinomial distributions. Single-shot probabilities from these distributions are sampled randomly and we obtain the gate fidelity by the above procedure. We repeat this procedure $1{,}000$ times to obtain the fidelity distribution. Then, the obtained fidelity distribution is fitted by the Gaussian distribution and extract its standard deviation.

Comment #3

> *2. Figure 3 may not provide value to the general Nature reader. At low powers the qubit is coherence limited and at high powers the qubit is no longer in the linear drive regime. Best performance is expected in between these regimes - as is shown. Consider moving Fig. 3 to the supplemental section.*

Response: One of our main findings in this work is that we identify the gate condition where the universal quantum gate fidelity exceeding the fault-tolerance threshold. Figure 3 clearly shows the condition and therefore we decided to keep it as Figure 3. In the original figure, this message might not be clear enough, and therefore we updated the figure to highlight the gate condition where the gate fidelity exceeding the fault-tolerance threshold.

Comment #4

> *3. High readout visibility will be required for full fault tolerant operation with error correction. Could the authors please comment in the main text on what the visibility is and what is limiting it?*

Response: We thank the reviewer for the comment. They are extracted from single-qubit randomized benchmarking measurements as follows. We fit the sequence fidelity $F_{\mathrm{s}}(n)$ by $(A_{\mathrm{s}} - B_{\mathrm{s}})p_{\mathrm{s}}^{n}$ to obtain the fitting parameter $A_{\mathrm{s}} - B_{\mathrm{s}}$ and p_{s}. Then the readout visibility for each qubit is obtained as $A_{\mathrm{s}} - B_{\mathrm{s}} = 0.602$ for Q_1 and 0.672 for Q_2. Since the readout visibilities do not affect our main result of randomized benchmarking measurements, we do not carefully optimize the readout condition. The visibilities should be mostly limited by an unoptimized ratios of the tunneling in/out rates between the quantum dots and the adjacent reservoirs, the readout time, and the measurement bandwidth. To explain the above, we have modified the manuscript as follows:

In line 280:

The visibilities are 0.602 and 0.672 for Q_1 and Q_2.

In lines 358-359:

Here the fitting parameter $A_s - B_s$ represents the readout visibility and absorbs the state preparation and measurement errors.

In lines 363-366:

We obtain $A_s - B_s = 0.602$ for Q_1 and 0.672 for Q_2 (Fig. 2c). Since $F_{p,m}$ is obtained independently of the readout visibility, we do not carefully optimize the readout condition. The visibilities are most likely limited by unoptimized ratios of the tunneling in/out rates between the quantum dots and the adjacent reservoirs, the readout time, and the measurement bandwidth.

Response to Reviewer #2:

Comment #1

The paper by Noiri et al. presents experimental universal quantum gate operation and two proof-of-principle algorithm demonstrations in a system of two spin qubits in silicon quantum dots The reported gate fidelities are exceedingly high and well-characterized, and with >99% they surpass the threshold for fault-tolerant quantum computation.

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The work is done in a highly careful manner and the performance of quantum gate and circuit operations are assessed precisely using randomized benchmarking.

Based on the importance of the result and the high quality of the work, I recommend publication of this paper in Nature.

However, before publication, I have a number of comments listed below that I'd ask the Authors to consider.

Response: We thank the reviewer for understanding the significance of our work and thereby recommending the publication in *Nature*. We have modified the manuscript to address all the comments raised by the reviewer.

Comment #2

1) line 39: The sqrt{SWAP} gate for universal quantum computation as a result of the exchange coupling was proposed by Loss and DiVIncenzo in their seminal paper in 1998 which could be mentioned here along with the other references.

Response: We thank the reviewer for reminding us for the lack of the reference. We have cited the paper as reference 21.

Comment #3

2) line 52: should be "Planck" rather than "plank".

Response: We thank the reviewer for pointing out the typo. We have corrected it (in line 51).

Comment #4

*3) line 85: in the Hamiltonian, the Rabi frequencies Omega_1 = gamma_1 * B appearing in the off-diagonal 2x2 blocks and Omega_2= gamma_2 * B appearing in the off-diagonal elements of the diagonal blocks are fundamentally different because the gyromagnetic ratios gamma_1 and gamma_2 are usually different. Can the Authors explain here why they chose these two Rabi frequencies to be equal? Is this fine-tuned or approximated?*

Response: We thank the reviewer for the question. We agree with the reviewer that Omega_1 ≠ Omega_2 in general case as the gyromagnetic ratios of Q_1 and Q_2 are different and also the oscillating field B is different as the spin-electric coupling is different between the qubits. Nevertheless, experimentally we can tune the Rabi frequencies for both qubits to a single target value of f_R when they are rotated as the effect of off-diagonal (diagonal) blocks vanish when Q_1 (Q_2) is rotated. To explain the above, we have modified the manuscript as follows:

In lines 81-87:

Under an EDSR control with a Rabi frequency of $f_{R,1}$ and $f_{R,2}$ for Q_1 and Q_2 , a microwave frequency of f_{MW} and its phase ϕ, a Hamiltonian for the two-qubit system in the basis of $|\uparrow\uparrow\rangle$, $|\widetilde{\uparrow\downarrow}\rangle$, $|\widetilde{\downarrow\uparrow}\rangle$, and $|\downarrow\downarrow\rangle$ can be approximated as[16]

$$H = \frac{h}{2}\begin{pmatrix} 2E_Z & \Omega_2 & \Omega_1 & 0 \\ \Omega_2^* & -\mathrm{d}\tilde{E}_Z - J & 0 & \Omega_1 \\ \Omega_1^* & 0 & \mathrm{d}\tilde{E}_Z - J & \Omega_2 \\ 0 & \Omega_1^* & \Omega_2^* & -2E_Z \end{pmatrix},$$

where hE_Z is the average Zeeman energy, $h\mathrm{d}\tilde{E}_Z = h\sqrt{\mathrm{d}E_Z^2 + J^2}$ is the effective Zeeman energy difference between the qubits, and $\Omega_m = f_{R,m}\mathrm{e}^{i2\pi f_{MW}t+i\phi}$ (m = 1 or 2) is the EDSR driving.

In lines 94-96:

Since $f_{R,1}$ and $f_{R,2}$ for the target qubit rotations are tuned independently by adjusting the applied microwave amplitude (Methods), we always calibrate both Rabi frequencies to the same target Rabi frequency f_R.

In lines 408-416:

Then the Hamiltonian is described by $H_R(t) = RHR^\dagger - \frac{ih}{2\pi}\frac{\partial R}{\partial t}R^\dagger$

$$= \frac{h}{2}\begin{pmatrix} 0 & f_{R,2}e^{-i2\pi(f_{2,\uparrow}-f_{MW})t+i\phi} & f_{R,1}e^{-i2\pi(f_{1,\uparrow}-f_{MW})t+i\phi} & 0 \\ f_{R,2}e^{i2\pi(f_{2,\uparrow}-f_{MW})t-i\phi} & 0 & 0 & f_{R,1}e^{-i2\pi(f_{1,\downarrow}-f_{MW})t+i\phi} \\ f_{R,1}e^{i2\pi(f_{1,\uparrow}-f_{MW})t-i\phi} & 0 & 0 & f_{R,2}e^{-i2\pi(f_{2,\downarrow}-f_{MW})t+i\phi} \\ 0 & f_{R,1}e^{i2\pi(f_{1,\downarrow}-f_{MW})t-i\phi} & f_{R,2}e^{i2\pi(f_{2,\downarrow}-f_{MW})t-i\phi} & 0 \end{pmatrix}.$$

The off-diagonal terms result in a CROT gate by choosing one of the resonance frequencies $f_{1,\downarrow}$, $f_{1,\uparrow}$, $f_{2,\downarrow}$, and $f_{2,\uparrow}$. Here the effect of fast oscillating terms (with $f_{R,1}$ ($f_{R,2}$) when $f_{MW} = f_{2,\downarrow}$ or $f_{2,\uparrow}$ ($f_{1,\downarrow}$ or $f_{1,\uparrow}$)) is averaged out during the $\pi/2$ CROT time t_{hp}. Generally, $f_{R,1}/f_{R,2} \neq 1$ as the gyromagnetic ratios of Q_1 and Q_2 are different and also spin-electric coupling is different between the qubits. Nevertheless, we can tune the Rabi frequencies for both qubits to a single target value of f_R when they are rotated as the target qubit since the terms for the control qubit vanish.

Comment #5

4) line 117: The "maximum operation time" is quoted as 100 us, but in the extended data Fig. 2c it looks like it is actually 10 ms. I also found the term "maximum operation time" a bit unclear, perhaps "maximum measurement time" might be better?

Response: We thank the reviewer for the comment. We actually fix the time for operation stage at 100 μs for all of the measurement except for Extended Data Fig. 2c. In Extended Data Fig. 2c, we intentionally make the operation stage longer to see how strong the spin relaxation effect is. To make this point clearer, we have modified the manuscript as follows:

In lines 118-120:

The spin relaxation times for both qubits are much longer than the maximum operation time of 100 μs used to characterize the gate fidelities (Extended Data Fig. 2c) and therefore the spin relaxation effect is negligible in the gate performances.

Comment #6

5) line 122: is a coincidence that Fp1 and Fp2 are exactly equal within their 4-digit precision or *is there a deeper reason behind it?*

Response: We thank the reviewer for the question. We find $F_{\mathrm{p},1} = 99.840 \pm 0.004\%$ and $F_{\mathrm{p},2} = 99.844 \pm 0.004\%$ and the difference is actually very small. This suggests that the fidelity is mostly limited by gate pulse imperfections and calibration errors and is not limited by the qubit intrinsic properties such as coherence time and Rabi decay. To explain the above, we have modified the manuscript as follows:

In lines 553-555:

Around the best condition, the fidelities are uniformly high suggesting that the fidelity is mostly limited by pulse imperfections and calibration errors rather than dephasing and Rabi decay effects.

Comment #7

6) Around lines 115-132: RB allows for an impressive characterization of the gate fidelities which are explored in this paper. But wouldn't it also be possible to extract the SPAM (state preparation and measurement) errors from the same data? If so, I recommend including those in the main text. (see also Methods section)

Response: We thank the reviewer for the suggestion. Actually, the SPAM fidelity ($1 -$ SPAM error) is the same as the readout visibility as pointed out by the reviewer #1. The SPAM fidelity is obtained as the fitting parameter $A_\mathrm{s} - B_\mathrm{s}$ for each qubit. To include the SPAM fidelity, we have modified the manuscript as follows:

In line 280:

The visibilities are 0.602 and 0.672 for Q_1 and Q_2.

In lines 358-359:

Here the fitting parameter $A_\mathrm{s} - B_\mathrm{s}$ represents the readout visibility and absorbs the state preparation and measurement errors.

Comment #8

7) The order of References 18 and 19 should be switched because what is now Ref. 19 was submitted first and published first.

Response: Following the reviewer's suggestion, we have changed the order of references 18 and 19.

Comment #9

8) In the Figure caption of Fig. 1, panels e and f, perhaps a quick mention of the synchronization condition J/f_R=¥sqrt{15} could be made to explain the combined horizontal axes.

Response: We agree with the reviewer that it is better to give the relation between J and f_{R} in the caption of Fig. 1e and f. Therefore, we have modified the caption of Fig. 1 as follows:

In lines 264-265:

e, J (and $f_{\mathrm{R}} = J/\sqrt{15}$) dependence of the dephasing times (Extended Data Fig. 2d-f).

In lines 267-269:

f, f_{R} (and $J = \sqrt{15} f_{\mathrm{R}}$) dependence of the Rabi decay during a $\pi/2$ CROT obtained from the Rabi decay curves (Extended Data Fig. 2j-l).

Comment #10

*9) In Figure 4, panels a and b, the meaning of the last single-qubit gates as I *or* X/2 *or* Y/2 *or* X could perhaps be explained in the figure caption for clarity.*

Response: We agree with the reviewer that the meaning of pre-rotation is worth adding in the caption of Fig. 4 as it was only explained in the Methods. Therefore, we have modified the caption of Fig. 4 as follows:

In lines 310-311:

$\mathrm{I}, \mathrm{X}/2, \mathrm{Y}/2,$ and X acting on both qubits at the end change the measurement axis to implement the state tomography (Methods).

Comment #11

10) In the figure capon of the extended data Fig. 3 (line 523), one could write "J=18.85 MHz= ¥sqrt{15} f_R" in order to again clarify how these numbers follow from the synchronization condition.

Response: Following the reviewer's suggestion, we have modified the caption of Extended Data Fig. 3 as follows:

In lines 546-547:

$f_{\mathrm{R}} = 4.867$ MHz and $J = 18.85$ MHz $= \sqrt{15} f_{\mathrm{R}}$ are used.

Response to Reviewer #3:

Comment #1

In the manuscript "Fast universal quantum control above the fault-tolerance threshold in silicon," the authors report a spin-based quantum processor with average single- and two-qubit gate fidelities above 99%. They measure gate fidelities across a range of different single-qubit transition frequencies, allowing for some optimization of system parameters. The authors then demonstrate the capabilities of their device by briefly report the execution of two-qubit Deutsch-Jozsa and Grover search algorithms.

The manuscript is interesting, and the work is of high quality. However, I find that there are some fundamental issues that limit the importance of the work and therefore its suitability for publication in a high impact journal such as Nature. Specifically, here are the main weaknesses of this manuscript:

Response: We thank the reviewer for carefully reading the manuscript and finding it interesting and high quality.

Comment #2

1. One issue is that the coupling between the two qubits in this device cannot be switched off. This problem can be overcome in a two-qubit device, by essentially combining two-qubit gates to obtain single-qubit gates. Of course, this approach is not scalable. In fact, it would be quite challenging to even extend it to a three-qubit system.

Response: We agree with the reviewer that 'always-on' approach used in this work does not have scalability. However, we can make a resonantly driven CNOT gate scalable by switching the coupling on and off by the barrier gate as demonstrated in ref 18. This needs pulsed control of exchange coupling and additional idle time to cancel unwanted phase accumulation by the exchange pulse. We found that the additional idle time does not degrade the two-qubit gate fidelity much ($< 0.1\%$ at Rabi frequency of ~ 5 MHz) and the pulsed exchange control can be implemented with high fidelity as demonstrated in ref. 37. Therefore, we believe that the CNOT gate fidelity exceeding the fault-tolerance threshold is within reach and this is a good target in a future work. In the original manuscript, we did not comment on the quality of pulsed exchange control. Therefore, we have modified the manuscript to include it.

In lines 442-443:

Combined with a high-fidelity pulsed exchange control[37], we anticipate a CNOT gate fidelity higher than 99% with exchange pulses is within reach.

Comment #3

2. There are infidelity sources that are not well understood.

Response: We obtain the two-qubit gate infidelity of 0.5% at the best condition as shown in Fig. 2g and obtain the infidelity due to dephasing of 0.1% from the simulation. The effect of Rabi decay should be less than 0.16% as we obtain the single-qubit gate infidelities of 0.16%. The remaining ~0.3% error comes from other sources such as gate pulse calibration errors and long-term fluctuations in the device condition. This discussion has been already included in the original manuscript. We stress that the main point of the work is demonstrating universal quantum gate fidelity above the fault tolerance threshold and identifying the gate condition to achieve this. Detailed gate infidelity characterization is out of scope in this work. In future work, it will be elucidated, for example, by a gate set tomography.

Comment #4

3. The algorithms near the end of the manuscript seem to be an afterthought. They do not really add much to the paper. There is an extremely brief discussion (a small paragraph) on this part of the work.

Response: We realize a high-fidelity universal gate set and by using our gate set, we implement quantum algorithms with high success rates. Of course, the high success rates are naturally expected from the demonstrated high fidelity of the gates, however, we believe that seeing an enhancement of the success rates by the high-fidelity gates is interesting for general readers. Furthermore, demonstrating the ability of high-fidelity quantum processing adds more messages than just showing characterization of the gate fidelities. Therefore, we kept the algorithm part as it was. Actually, demonstration of two-qubit algorithms is widely adopted way to show the ability of quantum processing [e.g. refs. 19,35,36, L. DiCarlo et al., Nature 460, 240-244 (2009)]. We believe that the original manuscript has already included a sufficient discussion to show the ability of quantum processing with high fidelity.

Comment #5

4. A different group has already demonstrated a universal gate set above 99% in this system (arXiv:2107.00628). In this preprint, the authors demonstrated a more scalable system, with the ability to switch off J. They also presented a more meaningful application of their gates in the demonstration of a simple VQE algorithm.

Response: The comment is deeply related to comment #2 and #4. The main difference of our work compared to that in ref. 37 (arXiv:2107.00628) is that we use resonantly driven CNOT gate and they use CZ gate with pulsed exchange control. As a CNOT gate and a CZ gate are one of the most useful elements of a universal quantum gate set, these demonstrations are equivalently important. In addition, as discussed in the response to comment #2, our resonantly driven CNOT has potential scalability as it is compatible with pulsed exchange control. Please refer the response to comment #2 for changes related to this comment.

The purpose of implementing two-qubit quantum algorithms is to demonstrate the feasibility of quantum processing with high fidelity. In that sense, the demonstration of the two-qubit Deutsch–Jozsa algorithm and the Grover search algorithm is sufficient. Actually, these two algorithms are widely used to demonstrate the ability of quantum processing as discussed in the response to comment #4.

Comment #6

Some additional questions/comments the authors may want to consider:

-It would strengthen the paper if the authors gave some physical explanation about the dependencies appearing in Fig. 3.

Response: In the slow (Rabi frequency < 2 MHz) operation regime, the gate performance is mainly limited by dephasing as the operation is not fast enough compared to the coherence time [e.g. ref. 16]. In the fast (Rabi frequency > 6 MHz) operation regime, it is limited by Rabi decay as the effect of Rabi decay drastically increases with increasing Rabi frequency in this regime as shown in Fig. 1f. In between the two regimes, both effects are well suppressed and high-fidelity single- and two-qubit gates can be achieved. This is why we observe the Rabi frequency dependencies on the gate fidelities in Fig. 3. We believe that the original manuscript has already included a sufficient physical explanation summarized above.

Comment #7

-The statement "We find that the infidelity due to dephasing is only 0.1% and therefore it is no longer the main limiting factor" could be explained more. It is not clear to the reader how this was inferred.

Response: The comment is related to comment #3. As we discuss in the response to comment #3, we obtain the total gate infidelity of ~0.5% and infidelity due to dephasing of 0.1%. This means the infidelity due to dephasing contributes only 20% to the total infidelity. This is why we inferred that dephasing is not the main limiting factor. Other possible error sources include Rabi decay, pulse calibration errors and long-term fluctuations in the device condition. Since we cannot clarify the number of error sources and their contributions to the total infidelity, we cannot omit the possibility that dephasing is still the main limiting factor although the contribution is only 20%. As the sentence "and therefore it is no longer the main limiting factor" is a bit vague, we have deleted it.

In line 148:

We find that the infidelity due to dephasing is only 0.1%.

Comment #8

-The Bell state fidelity is not provided. This would have a been a useful metric that is quite standard in two-qubit gate characterization.

Response: We thank the reviewer for the useful comment. Two-qubit gate fidelity can be characterized by a randomized benchmarking, process tomography and gate set tomography. The Bell state fidelity does not give a detailed information of the gate fidelity. However, we agree with the reviewer that the Bell state fidelity is used to roughly show the performance of the two-qubit gate in previous experiments [e.g. refs. 16,18,19]. Therefore, we have performed an extra measurement to obtain the Bell state fidelities and they are now included as the Extended Data Fig. 9.

In lines 612-619:

Extended Data Figure 9. Bell state tomography. a, Quantum circuit for the Bell state tomography. After the first $\pi/2$ rotation, $\mathrm{Z-CNOT_2}$ and $-\mathrm{Z_2}/2$ ($\mathrm{Z_2}/2$) are applied for **b** (**c**), $\mathrm{CNOT_2}$ and $\mathrm{Z_2}/2$ ($-\mathrm{Z_2}/2$) are applied for **d** (**e**). $\mathrm{I, X/2, Y/2,}$ and X acting on both qubits at the end change the measurement axis to implement the state tomography (Methods). **b-e,** Real part of the measured density matrix for the prepared the Bell states for Φ^- (**b**), Φ^+ (**c**), Ψ^- (**d**), and Ψ^+ (**e**). The absolute values of the matrix elements for the imaginary parts are less than 0.038 (**b**), 0.093 (**c**), 0.100 (**d**), 0.113 (**e**). The uncertainty in the state fidelities F are obtained by a Monte Carlo method[16,19,41].

We also commented on the value in lines 463-464:

We also obtain the Bell state fidelities of 96-97% (Extended Data Fig. 9b-e).