Distant spin entanglement via fast and coherent electron shuttling

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In the quest for large-scale quantum computing, networked quantum computers offer a natural path towards scalability. While recent experiments have demonstrated nearest neighbour entanglement for electron spin qubits in semiconductors, on-chip long-distance entanglement could bring more versatility to connect quantum core units. Here, we employ the moving trapping potential of a surface acoustic wave to realize the controlled and coherent transfer of a pair of entangled electron spins between two distant quantum dots. The subsequent electron displacement induces coherent spin rotations, which drives spin quantum interferences. We observe high-contrast interference as a signature of the preservation of the entanglement all along the displacement procedure, which includes a separation of the two spins by a distance of 6 μm. This work opens the route towards fast on-chip deterministic interconnection of remote quantum bits in semiconductor quantum circuits.

Creating and manipulating entanglement among an assembly of qubits is a key ingredient for exploiting quantum parallelism in quantum computers. Demonstrating it at distance has enabled quantum communication and quantum teleportation protocols where quantum states can be displaced at will in quantum circuits. This has been demonstrated in several quantum systems but remains a key functionality to be implemented for electron spins in semiconductor quantum circuits. Following the first nearest-neighbour entanglement demonstrations, research efforts focus on several distinct strategies to implement a long-range quantum mediator: coupling to a single microwave photon, long-range spin–spin interaction mediated through quantum dot systems or controllable displacement of electron spins.

In semiconductor circuits, two transfer approaches have been identified to preserve quantum information during the electron shuttling. In a first strategy, the electron is displaced in a static array of quantum dots via a tunnelling process. To protect the state coherence, the passage from one dot to another must be an adiabatic tunnelling process. Coherent electron transfer across 5 μm has been demonstrated with a speed of approximately 100 m s⁻¹, limited by the tunnel coupling between the dots. The second strategy consists in shuttling electrons by moving the trapping potential along the channel. Efficient and fast electron transfer protocols between two distant quantum dots have been established using surface acoustic waves (SAW), with a speed of 2,700 m s⁻¹ in AlGaAs heterostructures.

In this Article, we exploit the moving trap transfer associated with the propagation of an SAW to controllably separate and recombine two entangled electron spins on fast timescales. This is realized by the following three-step procedure: (1) two electrons are prepared in a singlet spin state in the source dot; (2) the two electrons are sequentially transferred using an SAW; (3) the electrons are recombined in the reception dot and single-shot spin read out is performed to evaluate the two-electron singlet state probability. To preserve and demonstrate long-distance entanglement, we rely on several important quantum functionalities, co-implemented in the same device: high-fidelity initialization and read out of two-electron spin states at both ends of the channel, a nanosecond-controlled electron separation and transfer procedure using SAW, and high-fidelity coherent rotations induced by the individual electron displacement.

**Experimental setup.** The sample, made from a GaAs/AlGaAs heterostructure, is represented in Fig. 1. The electrons, initially located on the right double quantum dot, are picked up by the propagating potential modulation and travel in moving quantum dots at the SAW velocity (2,700 m s⁻¹), completing the displacement across the channel in tₛ = 2.1 ns. The injection and capture between static and moving dots are carried out in the so-called isolated reservoir for the singlet and triplet spin states, as illustrated in Fig. 2a. The fidelity of the spin read out reaches a maximum of 0.95 in the reception dot (Fig. 2a and Supplementary Section 3 for details).

**Controlled injection into moving quantum dots.** To preserve the coherence of the electron spins, timescales where the electrons are separated have to be shorter than the decoherence time, T₂ = 12.2 ns (see Fig. 2b). A precise control of the delay between the two-electron transfer is therefore required. It is implemented by triggering the transfer process with nanosecond pulses (represented in Fig. 3a), which load the electrons in the moving potential. Because of the Coulomb interaction, a 400 mV pulse on RPI is able to send the first electron, while a 750 mV pulse is required to send the second electron. By varying the delay, Δt, between these two voltage pulses, we effectively control the delay between the electron transfers. The shortest delay is obtained when the two pulses...
**Fig. 1 | Electron transfer protocol.** False-colour scanning electron micrograph of an identical device. Two double quantum dots are connected by a 6 µm depleted channel (green gates), and probed by a local electrometer. The dotted circles represent the positions of the four quantum dots. Two electrons initially loaded in the source dot (right dot) are propelled towards the reception dot (left dot) with the help of a propagating sinusoidal electric field induced by an SAW, generated 2 mm away on the right side of the structure.

**Fig. 2 | Local spin manipulation.** a, Histogram of the reflectometry signal $V_{rf}$ after spin-to-charge conversion performed on the left double quantum dot, for two different spin initializations and for 200 µs integration time. To evaluate the two-electron spin state, a 16 µs voltage pulse abruptly increases the coupling to the reservoir, bringing the system in a configuration where a triplet spin state has a greater probability to tunnel-out to the reservoir. After this pulse, the system is brought back to the isolated regime and charge is read out for 200 µs, leading to the assertion of a singlet spin state if two electrons remain (and a triplet state otherwise). The fidelity of this read out reaches 95% in the reception dot, and has been calibrated according to Supplementary Section 3. b, Time evolution of the two-spin mixing when the electrons are separated in the reception double dot. The two electrons, initially prepared in a singlet spin state, are separated in adjacent dots for a few nanoseconds before recombination and spin read out. The resulting time evolution of the calibrated singlet probability ($P_{cal}$) is fitted with a Gaussian decay of characteristic time $T_2 = 12.2$ ns, imposed by the difference of nuclear environment between the two dots. The error bars correspond to the standard deviation of the mean probability over the 5,000 realizations.

Completely overlap and is estimated to be limited by the pulse rise time, equal to 0.5 ns. Thus, the two electrons are never transferred in the same moving quantum dot.

To characterize the efficiency of the time-resolved, two-electron transfer, we realize a pump–probe experiment by adding a pulse excitation on the reception dot (Fig. 3a). In this way, electron catching is prevented until a voltage step on gate LP1 is applied. By varying the time delay of this step with respect to the first sending pulse, we can resolve the arrival time of each electron. If this step occurs after the electron arrival time, the catching process does not occur. Figure 3b shows the average charge caught as a function of the sending and catching pulse delays. Three different charge regions are observed and correspond to the catching voltage step happening before, between or after the arrival of the two electrons, leading to the capture of 2, 1 or 0 electrons in the receiver dot, respectively.

This two-electron transfer procedure is efficient, with a probability above 95 ± 1% to send both electrons. The singlet probabilities hereafter are always given assuming a successful transfer of both electrons. The shuttling errors are post-selected out of the spin analysis by a charge read out performed immediately after reception (see Methods). In addition, the probability for the two electrons to be injected with the intended delay reaches 86 ± 2% of the successful sendings. From the data presented in Fig. 3, we therefore conclude that we are able to control the electron separation time by adjusting the time delay, $\Delta t$, between the two injection voltage pulses with high efficiency.

**Coherent rotation-induced by displacement.** To achieve single-spin coherent manipulation we exploit the strong spin–orbit coupling in GaAs combined with the high velocity of the displacement induced by the SAW. The resulting effective magnetic field $B_{SO}$ induced by spin–orbit interaction therefore overcomes the Overhauser field $B_{HF}$ experienced by the electron during the transfer ($B_{SO}/B_{HF} \approx 15$). Along the transfer sequence, $B_{SO}$ is turned on non-adiabatically (with a timescale of 0.5 ns, much smaller than $T_2^*$) when the electron is injected into a moving quantum dot. It is aligned in the plane of the two-dimensional electron gas and contributing to the total magnetic field experienced by the electron with the orthogonal external magnetic field $B_z$. As a consequence, each displaced electron is coherently rotated by a characteristic angle $\theta$.
about an axis \( \vec{a} \), dependent on the strength of the spin–orbit interaction along the electron path, the external magnetic field and the channel length. We designed the channel such that \( \theta \) is around \( 3\pi/4 \) at \( B_z = 0 \) mT and permits coverage of a large variety of possible two-electron spin states when varying the magnetic field \( B_z \). The resulting unitary transformation \( U_m \) is expressed in the spin basis of one electron (\(| \uparrow \rangle, | \downarrow \rangle \)) as:

\[
U_m = \exp\left(-\frac{i\omega_{SO} mT}{2}\sigma_x + B_z \sigma_z t_T \right)
\]

\[
= \begin{pmatrix}
U_\alpha & -iU_\beta \\
-iU_\beta & U_\alpha
\end{pmatrix},
\]

with

\[
U_\alpha = \cos\left(\frac{\omega_{SO} mT}{2}\right) + i \frac{\omega}{\omega_{SO}} \sin\left(\frac{\omega_{SO} mT}{2}\right),
\]

\[
U_\beta = \frac{\omega}{\omega_{SO}} \sin\left(\frac{\omega_{SO} mT}{2}\right),
\]

and

\[
\alpha_{tot} = \frac{\omega}{\hbar} \sqrt{B_0^2 + B_z^2}.
\]

Here, \( \sigma_x \) and \( \sigma_z \) are the Pauli matrices along x and z, \( \hbar \) is the reduced Planck constant, \( g \) is the electron \( g \)-factor in the two-dimensional electron gas, and \( \omega_{SO} \) is the Larmor frequency under the spin–orbit equivalent magnetic field \( B_{SO} \). Examples of single-spin trajectories for different external magnetic fields are shown in Fig. 4a. As \( B_z \) is increased, the single-spin rotation leads to a smaller exploration of the Bloch sphere, the rotation axis converging towards the pole. At \( B_z = B_{SO} = 25 \) mT, the unitary transformation \( U_m \) is close to a Hadamard gate, mapping each pole to two opposite points of the equator.

When combining the controlled nanosecond-delay transfer protocol with the initialization and spin read out sequences, quantum interferences are observed, with high-contrast oscillations of the singlet population (see Fig. 4c). In addition to the spin rotation induced by the electron motion, the electron spins are experiencing the Larmor precession during the time they are separated. It results in a phase shift between the two spin states dependent on \( B_z \), and the sending delay \( \Delta t \).

\[
U_s = \begin{pmatrix}
e^{i\phi/2} & 0 \\
0 & e^{-i\phi/2}
\end{pmatrix}
\]

with \( \phi = \alpha z \Delta t = \frac{\omega}{\hbar} B_z \Delta t \).

In the two-electron spin basis, the complete transformation associated with the nanosecond-delay transfer procedure, illustrated in Fig. 4b, is thus:

\[
U_{tot} = U_s U_m \otimes U_m U_s.
\]

After recombination, the singlet spin probability is equal to:

\[
P_S = \left| 1 + \frac{U_s}{U_m} \right|^2 \left( \cos(\alpha z \Delta t) - 1 \right)^2.
\]

For the condition \( B_z = B_{SO} = 25 \) mT previously discussed, the interferences should exhibit a unity contrast (\(|U_s|^2 = 1\)). In this case, a maximum coherent transfer of population between the parallel and anti-parallel spin basis is achieved. Following this model, we perform the simulation of the experiment and compute the singlet probability as a function of \( \Delta t \) and \( B_z \), as shown in Fig. 4d. This simulation is in qualitative and quantitative agreement with the data when taking into account the decoherence mechanisms as described in Supplementary Section 5. In particular, a spin–orbit length of \( l_{SO} = 8.5 \) \( \mu m \), in good agreement with the literature\(^{26,31,32,}\), is extracted.

At zero magnetic field, the singlet state is preserved after transfer because of time-reversal symmetry, and thus no oscillations are observed. Up to a 5 ns separation time, we measure a high singlet spin probability, which confirms an efficient coherent transfer between the two distant dots. Quantitatively, we obtain a 0.895 ± 0.003 fidelity of the singlet transfer at zero time delay and zero magnetic field (0.824 ± 0.003 without the spin to charge fidelity calibration). The small loss of fidelity is not captured by the simulation and is probably due to spin mixing occurring during the injection.

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**Fig. 3 | Controllable injection in moving quantum dots.** a. Scheme of the injection timing measurement. Two voltage pulses of a 2.5 ns duration, synchronised with the SAW burst, are applied on gate RP1 of the sending dot to trigger the injection of the two electrons into the moving quantum dots. To measure the electron distribution in the moving dots, the reception dot is kept in a configuration where electron catching is unlikely until a positive voltage pulse on LP1 is applied. We take the first electron injection as the reference time \( t = 0 \) ns. b. Average charge caught on the reception dot (\( \langle N_r \rangle \)), depending on the injection and catching pulse delays. Each pixel is the average of 4,000 single-shot realizations. The vertical and diagonal boundaries correspond to the arrival time of the first and second electron, respectively. The vertical boundary begins at \( t = 2.1 \) ns as a consequence of the time of flight at the SAW velocity of the first electron between the two static dots. Moreover, the clean and sharp diagonal boundary with unity slope confirm our ability to control the separation of two electrons by up to 70 ns with a nanosecond resolution, using a double AWG voltage pulse. The precision of the sending is measured close to a nanosecond and fixed by the rise time of the AWG.
Fig. 4 | Two-electron-spin quantum interferences. a, Illustration of the spin–orbit driven single-spin rotations for an external magnetic field (orthogonal to the plane of the two-dimensional electron gas) of $B_z=0,12.5,25,37.5$ and $50\text{ mT}$ (blue to indigo) and assuming $B_{so}=25\text{ mT}$ and $\Delta t=2.1\text{ ns}$. b, Scheme of the sequence seen by the two electron spins during transport. The spin–orbit interaction drives identical single-spin rotations on each electron during its displacement. Between these two single-spin operations, the parallel spin states accumulate opposite phases $2\phi = \omega_s \Delta t$ with respect to the anti-parallel states. c, Measured singlet spin probability as a function of the sending delay and the external magnetic field. The observed quantum interferences are due to the coherent Larmor precession of the parallel spin states $|\uparrow\downarrow\rangle$ and $|\downarrow\uparrow\rangle$ when the two electrons are static and separated by $6\mu\text{m}$. The oscillations are fitted with a frequency $\omega_s = g_s B_z \hbar$, with $g_s = -0.425 \pm 0.01$. Decoherence towards large separation time is attributed to the hyperfine interaction with the fluctuating nuclear spin environment, acting as an additional random magnetic field of standard deviation $\approx 2\text{ mT}$ during the separated phase. Each pixel corresponds to 10,000 single-shot realizations. d, Numerical simulation, performed with the parameters $B_{so}=25\text{ mT}$ and $g_s = -0.425$ and using 100 repetitions for each pixel. The decoherence mechanisms are reproduced by adding for each repetition a Gaussian nuclear magnetic field of standard deviation of $2\text{ mT}$ on each side of the structure and a perturbed electron trajectory. To take into account the charge injection uncertainty, an exponential noise of width $0.5\text{ ns}$ is added to the sending delay. The full model is discussed in Supplementary Section 4.
spins in an entangled state, applying single-spin rotations separated by a phase accumulation, and finally measuring the singlet probability after recombination. It leads to important population oscillations between the anti-parallel states \((S, T_\uparrow)\) and the parallel states \((T_\downarrow, T_\uparrow)\), whose magnitude is only permitted by quantum correlations between the two electrons. Thus, the proof of the entanglement preservation lies in the interference contrast.

In the case of an entangled state \(\rho\) made of antiparallel spin states, the spin evolution is characterized by oscillations, with a maximum singlet probability at \(\Delta t=0\) ns for any \(B_z\) and a minimum singlet probability for the condition \(U_\rho^{t_i} = \frac{1}{2}\). In the latter case, corresponding to \(B_z = \pm 22.5\) mT, the triplet parallel states are populated after transfer. The extracted contrast between these two points is equal to \(\langle \rho_{\uparrow\downarrow} + \rho_{\downarrow\uparrow} \rangle / 2 - \text{Re} \langle \rho_{\uparrow\downarrow}^{t_i} \rangle\). For a perfect state preparation in singlet the contrast is expected to be 1, whereas completely mixed antiparallel spin states are characterized by a maximum of 0.5 oscillation contrast. A contrast above 0.5 necessarily implies a singlet fidelity above the 0.5 threshold \((F = \langle \rho_{\uparrow\downarrow} + \rho_{\downarrow\uparrow} \rangle / 2 + \text{Re} \langle \rho_{\uparrow\downarrow}^{t_i} \rangle > 0.5\), which is an entanglement proof\(^{30,35}\). In the experimental data presented in Fig. 4c, the singlet probability close to \(\Delta t=0\) ns is characterized by a coherent oscillation in \(B_z\) and reaches a maximum of 0.890 ± 0.003 at \((B_z = 0\text{ mT}; \Delta t = 2.5\) ns). The minimum singlet probability is 0.249 ± 0.005 at \((B_z = -22.5\text{ mT}; \Delta t = 4.17\) ns). It corresponds then to an oscillation contrast of 0.641 ± 0.006. At constant \(B_z\), a maximum oscillation contrast of 0.5668 ± 0.0067 is obtained. This reduction is the result of the coherent evolution at \(\Delta t \approx 0\) ns, due to the minimum delay between the two electrons. Both contrasts are larger than 0.5, which demonstrates the preservation of entanglement along the transfer process. Concomitantly it proves the creation of remote entanglement at 6 μm in a semiconductor quantum circuit. Note that even when the fidelity of the spin read out is not taken into account to calibrate the experimental data, we still observe a contrast well above this threshold (0.575 ± 0.006 for the 2D contrast and 0.5085 ± 0.0061 for the oscillation at \(B_z = -12\text{ mT}\)).

Conclusions. In this Article, we demonstrate that two entangled electron spins can be separated and displaced controllably at the nanosecond timescale. During the transfer, each electron experiences a single-spin coherent rotation under the influence of the spin–orbit interaction, due to the fast electron transfer procedure. The system exhibits spin quantum interferences, which demonstrates the coherent nature of the initial singlet state in the individual electron spin basis. The spin transfer process is highly coherent with a maximum fidelity close to 90%, and produces highly entangled electron spins separated by 6 μm. In comparison with precedent demonstrations of coherent shuttling\(^{30,36}\), the demonstrated displacement allows a qubit coherent motion over 6 μm at a timescale of 2.1 ns. When combined with fast coherent exchange of spin between two adjacent electrons, it permits us to envision long-range coupling between distant qubits at frequencies above 100 MHz. Transposing this technique to a non-piezoelectric film, such as silicon would require the use of a piezoelectric film, as recently achieved with the generation of SAWs in Si (ref.\(^{34,40}\)) or to exploit the electron–photon interaction to induce a similar moving potential. Providing sufficient protection (deep quantum rails), SAWs could be compatible with the proposed large-scale architectures\(^{31,42}\), and would provide a coherent quantum link between distant quantum dot arrays. More generally, we feel that the type of nanostructures used in this work can be exploited to investigate the impact of electron shuttling among magnetic field gradients, charge traps and nuclei in the electron path. In this context, the constant speed of the SAW and the large spin–orbit coupling make GaAs heterostructures a relevant test bed for future more complex architectures.

Online content

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Methods

Sample and setup. Our device was fabricated using a Si-doped AlGaAs/GaAs heterostructure grown by molecular beam epitaxy, with a two-dimensional electron gas 110 nm below the crystal surface, which has a carrier mobility of \(9.1 \times 10^5\) cm\(^2\) V\(^{-1}\) s\(^{-1}\) and an electron density of \(2.79 \times 10^{11}\) cm\(^{-2}\). It is anchored to the cold finger, which is in turn mechanically attached to the mixing chamber of a homemade dilution refrigerator with a base temperature of 60 mK. It is placed at the centre of a superconducting solenoid generating the static out-of-plane magnetic field. Quantum dots are defined and controlled by the application of negative voltages on Ti/Au Schottky gates deposited on the surface of the crystal. Homemade electronics ensure fast changes of both chemical potentials and tunnel couplings with voltage pulse rise times approaching 100 ns and refreshed every 16 \(\mu\)s.

A Tektronix 5014C arbitrary waveform generator with a typical channel voltage rise time \(20\text{–}80\%\) of 0.9 ns is used to rapidly change the LP1 and RP1 gate voltages. The charge configurations are read out on each side by two local electrometers (sensing dots) connected to a reflectometry setup of resonant frequencies 197 MHz (left) and 136 MHz (right). The electrometer is tuned so that the depth of each resonance depends on the conductance through the sensing dot, which in turn is sensitive to the charge occupancy of the neighbour double quantum dot. After demodulation and filtering, each electrometer signal is acquired by a National Instruments analogue-to-digital converter with a 100 kHz bandwidth.

To shuttle electrons across the channel, a 100 ns microwave burst at the resonant frequency of the inter-digital transducer (2.79 GHz) is applied by a Rohde & Schwarz SMA100A signal generator, with a power of 18 dBm on the sample. Because of the IDT geometry, the SAW burst has a 25 ns ramp-up phase followed by a 75 ns maximum amplitude plateau and a 25 ns ramp-down phase. As explained in the main text, we controllably inject two electrons when the SAW maximum amplitude reaches the right double-dot, 740 ns after the pulse generation.

Data analysis and simulation. In order to remove from the spin analysis the few occurrences \((4\%)\) when the two electrons are not caught in the receiver dot, we measure the charge configuration on the left dot twice: before and after spin-to-charge conversion. From the first signal we select only the successful charge transfers, and from the second we infer the singlet probability. This spin-to-charge conversion and its fidelity, together with the spin initialization, are covered in the Supplementary Section 3.

The error bars on the probabilities correspond to the standard deviation of the mean probability over \(N\) realizations \(dP = \sqrt{P(1-P)/N}\). The numerical simulation presented in Fig. 4d is described in detail in the Supplementary Section 4.

Data availability

The datasets used in this work are available online from the Zenodo repository at https://doi.org/10.5281/zenodo.4115984.

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Author contributions

B.J. fabricated the sample and performed the experiments with the help of P.-A.M., T.M. and C.B.; B.J. and T.M. interpreted the data and wrote the manuscript with input from all the other authors. A.L. and A.D.W. performed the design and molecular-beam-epitaxy growth of the high-mobility heterostructure. All authors discussed the results extensively, as well as the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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