Spin relaxation benchmarks and individual qubit addressability for holes in quantum dots

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We investigate hole spin relaxation in the single- and multi-hole regime in a 2x2 germanium quantum dot array. We use radiofrequency (rf) charge sensing and observe Pauli Spin-Blockade (PSB) for every second interdot transition up to the (1.5)-(0.0) anticrossing, consistent with a standard Fock-Darwin spectrum. We find spin relaxation times $T_1$ as high as 32 ms for a quantum dot with single-hole occupation and 1.2 ms for a quantum dot occupied by five-holes, setting benchmarks for spin relaxation times for hole quantum dots. Furthermore, we investigate the qubit addressability and sensitivity to electric fields by measuring the resonance frequency dependence of each qubit on gate voltages. We are able to tune the resonance frequency over a large range for both the single and multi-hole qubit. Simultaneously, we find that the resonance frequencies are only weakly dependent on neighbouring gates, and in particular the five-hole qubit resonance frequency is more than twenty times as sensitive to its corresponding plunger gate. The excellent individual qubit tunability and long spin relaxation times make holes in germanium promising for addressable and high-fidelity spin qubits in dense two-dimensional quantum dot arrays for large-scale quantum information.

Qubits based on spin states are well established candidates for quantum information processing [1]. Pioneering studies were conducted on low-disorder gallium arsenide heterostructures [2-3], but quantum coherence remained limited due to hyperfine interaction with nuclear spins. These interactions can be eliminated by using isotopically enriched group IV semiconductors as the host material [4]. In silicon this has led to landmark achievements, such as extremely long quantum coherence [5] and relaxation times [6], single qubit gates with fidelities beyond 99.9% [7, 8], execution of two-qubit gates [9, 10], quantum algorithms [11], and the operation of single qubit rotations [12] and two-qubit logic [13] above one Kelvin as a key step toward quantum integrated circuits [14-15].

In its natural form, germanium contains only 7.76% isotopes with non-zero nuclear spin and, like silicon, can be isotopically enriched [17] to eliminate nuclear spin dephasing. Recent advances in materials science enabled high mobility strained planar germanium (Ge/SiGe) heterostructures [18] for the fabrication of stable gate-defined quantum dots that can confine holes [19], which are predicted to have a multitude of favourable properties for quantum control [21-22]. The inherent strong spin-orbit coupling of holes allows for fast qubit control [23-24] without integrating external components that complicate scalability, such as nano-magnets and microwave antennas. Moreover, holes do not suffer from valley degeneracy and their small effective mass of $m^* = 0.05 m_e$ gives rise to large orbital splittings at the band center. These beneficial aspects thereby position holes in germanium as a promising material for quantum information [27].

While it has been demonstrated that both single- and multi-hole qubits can be coherently controlled and read out in planar germanium [25-28], an open question remains which hole occupancy is most advantageous for quantum operation. Electron spin qubits in silicon have been operated with quantum dots containing one, three and even more electrons, with more electrons typically performing favourably in terms of driving speed when driven electrically due to greater wave function mobility [30-31]. Here, we focus on single and multi-hole spin qubit operation in germanium and concentrate on two critical elements for quantum information with quantum dots: the spin relaxation time and the qubit addressability. We find that both the spin relaxation times of the single-hole ($T_{1,n=1}$) and five-hole ($T_{1,n=5}$) qubits are long, with the longest relaxation time for single-holes measured to be $T_{1,n=1} = 32$ ms. Furthermore, we observe that single and multi-hole qubits exhibit a strong but comparable resonance frequency dependence on electric gate voltage. Interestingly, we find that while the qubit resonance frequency can be significantly tuned on electric gate voltage. Interestingly, we find that while the qubit resonance frequency can be significantly tuned with the corresponding plunger gate, it is only weakly dependent on neighbour plunger gates. We thereby conclude that hole spin qubits can be locally addressed, crucial for the operation of dense qubit arrays.

The experiments are performed on a two-dimensional 2x2 quantum dot array fabricated using a multi-layer gate stack [20] (See Fig 1a). Four plunger gates $P_{1-4}$ define four quantum dots, whose interdot tunnel couplings are controllable via barrier gates $B_{12-41}$. Four metallic reservoirs $O_{1-4}$ can be controllably coupled to each quantum dot via their respective barrier gates $RB_{1-4}$. We operate in a configuration whereby electrostatic gates $P_1$, $B_{12}$ and $P_2$ define one large quantum dot, serving as single-hole transistor (SHT) for charge sensing, shown in Fig 1b. By connecting an inline NbTiN kinetic inductor of $L \approx 2 \mu H$ to the ohmic $O_1$, we form a resonant tank...
Figure 1. (a) Coloured scanning electron microscope image of a nominally identical 2x2 quantum dot array. Each quantum dot is defined by a plunger gate, P1-4 (yellow) and barrier gates B12-41 (blue) are used to set the tunnel coupling. In addition, each quantum dot is coupled to a reservoir, O1-4 (green), via a barrier gate RB1-4. A cut off gate, CO1-4, is present for good confinement of the quantum dots. Ohmics 1 and 3 are bonded to an inductor to create a tank circuit with the parasitic capacitance of the device to ground. A radiofrequency tone is applied to the ohmics and the reflected signal returns via a directional coupler and is read out. (b) Reflected signal of the two tank circuits. Two clear resonances occur at $f_{O1} = 150.7$ MHz and $f_{O3} = 143.3$ MHz for tank circuits connected to ohmics O1 and O3 respectively. (c) Single-hole transistor (SHT) Coulomb oscillations measured in the tank circuit response by applying a microwave tone of 150.7 MHz. A sensing quantum dot is formed underneath the plunger gates P1 and P2, by opening the interdot barrier gate B12.

We now assess the spin relaxation of the single- and five-hole qubits. All experiments were performed at a magnetic field $B = 0.67$ T, allowing for a comparison with previous germanium hole spin qubit experiments in a similar magnetic field regime. Figure 3a shows the pulse sequences used to measure the spin relaxation times of the hole spins in each quantum dot. Each pulse sequence consists of an initialization (I), load (L), and read (R) phase, with two ramps between the I and L phases ($t_{IL}$), and the L and R phases ($t_{LR}$). Using the first two sequences (red and blue in Fig. 3a) a randomly orientated spin is loaded into the quantum dot defined under P4 or P3 respectively. This allows deterministic probing of the spin relaxation time of each dot, by varying the load wait time $t_L$.
The third pulse sequence (yellow in Fig. 3a) initializes the system in the singlet state with charge configuration \((N_{P3},N_{P4}) = (0,6)\) \((|S_{0,6}\rangle)\). The system is then tuned to the charge configuration \((N_{P3},N_{P4}) = (1,5)\) \((|S_{1,5}\rangle)\). We pulse with a ramp time \(t_{RL} = 100\) ns, resulting in a diabatic movement through the charge section, and through fast charge relaxation we expect to initialize the \(|\uparrow,\downarrow\rangle\) and \(|\downarrow,\uparrow\rangle\) states randomly with equal probability. This initialization then allows us to efficiently measure both spin relaxation times in a single measurement and is useful since it allows for fast measurements even when the quantum dot-reservoir couplings are low.

In Fig. 3b, we show the spin relaxation times of the quantum dots using the three sequences. We find \(T_{1,|n=5\rangle} = 1.0\) ms and \(T_{1,|n=1\rangle} = 4.23\) ms by fitting exponential decays to the individual measurements. The measurement corresponding to the sequence with randomly preparing a spin up state in one of the two quantum dots is fitted with a double exponential curve using the time constants of the individual decays, and we have left the amplitudes and asymptotes as free fitting parameters. We find approximately equal amplitudes for each decay, in correspondence with an equal loading of both anti-parallel spin states.

We can further increase the single-hole relaxation time by reducing the quantum dot-reservoir coupling. Using the barrier gate RB3, we tune the quantum dot-reservoir coupling of the single-hole quantum dot from 81.43 KHz to 27.45 KHz (see supporting information section I). The spin relaxation decay shown in Fig. 3c has been analysed using the above mentioned double exponential fit and we find an significantly increased single-hole spin relaxation time \(T_{1,|n=1\rangle} = 32\) ms. This spin relaxation time is significantly longer than results reported for planar germanium quantum dots \((T_{1,|n=1\rangle} = 1.2\) ms \([28]\)) and silicon \((T_{1} = 8.3\) µs \([41]\)) at similar magnetic fields. Spin states in planar germanium thereby define the benchmark for spin relaxation in hole based quantum dots.

The presence of spin-orbit coupling allows for electrical and coherent control of the spin states without the need for additional structures such as striplines or micromagnets \([21-25]\). We investigate the individual tunability and addressability of the single-
and multi-hole qubits. In Fig. 4a, we show results where we have applied a microwave tone of length $t_{\text{mw}} = 400$ ns to the gate P4. We observe two resonance frequencies at 3.33 GHz and 3.53 GHz in Fig 4a, corresponding to an in-plane Zeeman energy difference $dE_z = 200$ MHz. Figures 4c,d show the dependence of each resonance frequency on the electrostatic gate voltages on the two relevant plunger gates P3 and P4. We initialize in the $|S_{(0,0)}\rangle$ singlet state, then load in different points in the (1,5) charge state by changing the potentials applied to P3 and P4. We then manipulate the spins by applying a microwave tone to P4 and read out in the PSB window. The resonance frequency dependence on gate voltage is approximately linear. For the five-hole qubit we find a dependence on its plunger gate voltage $df_1/dP_4 = -4.78$ MHz/mV and we find $df_1/dP_3 = -0.155$ MHz/mV. For the single-hole qubit we find a slightly stronger dependence on its plunger gate voltage $df_2/dP_3 = 6.78$ MHz/mV and we find a cross talk, $df_2/dP_4 = -1.79$ MHz/mV. This corresponds to a cross talk ratio of about 1/30 for the five-hole qubit and about 1/4 for the single-hole qubit. The cross talk for the single-hole qubit is comparable to the lever arm ratio (see supporting information section II) $\alpha_{P_4/P_3} (f_2) = 0.11$. Remarkably, the five-hole qubit has a lever arm ratio $\alpha_{P_4/P_3} (f_1) = 0.07$, significantly larger than the resonance frequency cross talk ratio.

In summary, we have demonstrated benchmarks for spin relaxation in hole quantum dots and found $T_{1,|n=1\rangle} = 32$ ms for a single-hole qubit and $T_{1,|n=5\rangle} = 1.2$ ms for a five-hole qubit and conclude that spin relaxation is not a bottleneck for quantum computation with holes. We have shown the presence of Pauli-spin blockade at different hole fillings and found it to be consistent with a Fock-Darwin spectrum that only involves spin degeneracy. We find that both the single-hole and multi-hole qubit resonance frequency can be tuned over a large range. We find that the resonance frequencies are only weakly dependent on neighbouring gates, which results in good local addressability. The observation of the sign difference in the resonance frequency dependence on gate voltage and the strength of the cross talk ratio of the resonance frequencies may provide insights in the nature of the driving mechanism of holes in planar germanium. This is relevant for future work and a possible scenario is that the reduced cross talk of the five-hole qubit originates from an increased heavy-hole light-hole mixing. Such a change may affect the qubit resonance frequency dependence on the amplitude and orientation of the electric field, but further research is needed to investigate this. The long spin lifetimes and excellent individual qubit addressabil-
ity are encouraging for the operation of hole qubits positioned in large two-dimensional arrays.

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Supporting Information

I. TUNNEL RATE ANALYSIS

We measure the dot-reservoir tunnel coupling of the quantum dot under plunger gate $P_3$. Before each measurement of spin relaxation in Figure 3 of the main text, we pulse from the (0,5) charge state to the measurement point (1,5) charge state, and measure the sensor response. We observe an exponential decay, the time constant of which determines our dot reservoir tunnel coupling. We pulse the virtual energy gate $U$ from the (0,5) to the (1,5) charge state. Supplementary Figures 3a-b show the resulting sensor response as a function of time in the (1,5) charge state for the spin relaxation measured in Main text figures 3b and 3c respectively. Due to the imperfect charge sensor compensation, we observe a short initial transient in the first few microseconds, followed by the actual charge state transient to which we fit an exponential decay, shown in the inset. We extract dot-reservoir load rates of 81.43 kHz to 27.45 kHz for the spin relaxation times measured in Main text figures 3b and 3c respectively.

![Graph](a)

Supporting Figure 1. Dot-Reservoir coupling between the singly occupied quantum dot defined under the plunger gate $P_3$. (a) A dot-reservoir coupling of 81.43 kHz is extracted from the dot loading transient for the spin relaxation measurement in in main text figure 3b, and (b) 27.45 kHz for main text figure 3c.

II. RELATIVE LEVER ARM

We extract the relative lever arms of the plunger gates $P_3$ and $P_4$ to the quantum dot potentials underneath them. We take these values from the charge addition line slopes in the stability diagram in figure 2g of the main text. Here, the figure is taken using a virtual gate matrix space of detuning and energy ($\epsilon, U$) which are defined as a linear combination of the voltages on gates $P_3$ and $P_4$ ($V_{P3}, V_{P4}$):

$$
\begin{bmatrix}
\epsilon \\
U
\end{bmatrix}
= 
\begin{bmatrix}
1 & -1.05 \\
1.05 & 1
\end{bmatrix}
\begin{bmatrix}
V_{P3} \\
V_{P4}
\end{bmatrix}
$$

By calculating the gradient of the single and multi hole qubit charge addition lines in main text figure 2g, we can solve for the changes in the plunger gate voltage space, and calculate the ratios for each quantum dot, giving $\alpha_{P3}/P_3 = 0.11$ and $\alpha_{P4}/P_4 = 0.07$. 
