are also pushed away from the Fermi level, mediating a transition to a (topologically trivial) insulating state. From electronic structure calculations, Lin and colleagues not only confirmed the experimentally observed electronic structure evolution under tensile strain, but also predicted that by applying compressive strain, it should be possible to drive $TaSe_3$ across another topological phase transition into a so-called weak topological phase, where the protected surface states exist only for certain surface orientations of the crystal. While it could not be realized experimentally, this prediction certainly motivates future experiments with strain cells optimized for applying compressive strains[7].

While previous studies have shown that it is possible to use mechanical strain to modify the surface states of topological insulators[5], by a careful choice of a material sitting close to the borderline between several topologically distinct phases, Lin and colleagues have demonstrated that it is possible to deterministically, and reversibly, switch a material between topologically trivial and non-trivial phases. Exploiting this effect in technologies would still require developing scalable methods suited for device applications, but Lin and colleagues' findings represent an exciting proof of concept result, while already providing a platform for fundamental study. Indeed, many interesting questions remain. Is it possible to access the weak topological phase experimentally[9] as mentioned above? Do the topological surface states of this bulk superconductor themselves support an elusive topological superconductivity, or do they simply coexist with a topologically trivial superconductivity as in some other superconducting topological materials[10]? Can strain tuning across the topological phase transitions shed light on this? Beyond this specific material, it is clear that uniaxial strain combined with advanced spectroscopic probes is rapidly becoming a promising tool for studying the electronic structure evolution of quantum materials, where many more discoveries can be expected. ❐

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Competing interests

The author declares no competing interests.

QUANTUM COMPUTATION

Hole spin qubits work at mT magnetic fields

A singlet-triplet hole spin qubit in a Ge quantum well is demonstrated to be fast, coherent, and compatible with operation at magnetic fields below 10 mT, opening the door to integration with superconducting technologies.

Floris Braakman and Pasquale Scarlino

The implementation of useful quantum algorithms will require the operation of a large number of qubits, with stringent constraints in terms of coherence, speed, power consumption, and area footprint. Qubits based on the spin states of unfilled valence band states (holes) confined in semiconductor quantum dots (QDs) are prime contenders for implementing scalable quantum computation. Within only a few years, such hole spin qubits have been developed to be on par with, or in various aspects superior to, their more famous electron spin counterparts. Hole spin qubits usually experience a strong spin–orbit interaction (SOI), allowing for fast quantum logic, while at the same time they can have long coherence times, due to a reduced hyperfine interaction and the absence of valley degeneracy. Writing in *Nature Materials*, Daniel Jirovec and colleagues[1] now demonstrate a fast and coherent qubit based on the spin state of two holes, confined in a double QD in a planar Ge/SiGe heterostructure.

Hole spin qubits have been experimentally demonstrated in various industrially significant material platforms[2,3]. Germanium, especially, has recently taken centre stage, with realizations of hole spin qubits in Ge hut wires[4], Ge/Si core/shell nanowires[5], and planar Ge/SiGe heterostructures[6]. The hole spin qubits are confined in QDs created in the Ge layer through the application of voltages on nanoscale metal gate electrodes. In planar Ge/SiGe, holes have very high mobility and very low effective mass, which facilitates robust hole confinement and controllable formation of QDs, with only modest requirements on gate dimensions. Furthermore, the use of undoped heterostructures and the possibility of isotopic purification can significantly reduce the noise affecting spin qubits. These beneficial properties have in the last two years been exploited to demonstrate fast universal quantum logic, featuring fast manipulation with relatively high coherence[6], recently extended to three- and four-qubit operations[7].

Confining and controlling individual spins, whether of electrons or holes, in QDs allows for the definition of qubits in a variety of encoding schemes. The most straightforward and most often implemented type of qubit (also called the Loss–DiVincenzo (LD) qubit[8]) employs the down and up states $|\downarrow\rangle$ and $|\uparrow\rangle$ of a single spin to define the qubit basis states $|0\rangle$ and $|1\rangle$. This encoding is appealing because of its natural simplicity, yet LD qubits come with some disadvantages, such as vulnerability to dephasing caused by fluctuations of the energy splitting between $|\uparrow\rangle$ and $|\downarrow\rangle$, as well as the need to generate a local time-dependent magnetic field $B(t)$ oscillating at GHz frequencies. For hole LD qubits, the strong SOI can be used to electrically generate a large $B(t)$ by periodically displacing the hole wave function. However, the strong SOI together with charge noise opens up an additional decoherence channel.

Alternatively, multiple spins can be used for qubit encoding, which typically requires two or more tunnel-coupled QDs, thus increasing fabrication and control complexity. However, these disadvantages can be outweighed by having faster qubit operations, all-electrical control at low frequencies, and robustness against various decoherence mechanisms. These multi-spin qubit encodings often exploit the electrically

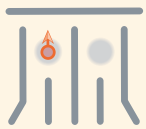
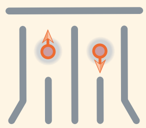
	Qubit encoding		f_{Rabi} (MHz)	T_2^* (μs)	B (T)	Ref.
LD qubit	$\vert 0\rangle : \vert\downarrow\rangle$ $\vert 1\rangle : \vert\uparrow\rangle$		85	0.06	0.144	2
			140	0.13	0.127	4
			435	0.011	0.206	5
			>100	0.833	1.65	6
			147	0.44	0.3	15
			542	0.082	0.1	16
ST_0 qubit	$\vert 0\rangle : \frac{1}{\sqrt{2}}(\vert\uparrow\downarrow\rangle - \vert\downarrow\uparrow\rangle)$ $\vert 1\rangle : \frac{1}{\sqrt{2}}(\vert\uparrow\downarrow\rangle + \vert\downarrow\uparrow\rangle)$		**150**	**1**	**<0.01**	1

Fig. 1 | Spin qubit encodings. Comparison between LD[2,4–6,15,16] and ST_0[1] spin qubits, including the qubit encoding, in a schematic illustration of electron or hole spins (red) occupying a generic double QD (grey), defined by voltage-biased gates (grey lines). The table on the right lists reported figures of merit of experimentally realized hole spin qubits, including Rabi frequencies f_{Rabi}, inhomogeneous dephasing times T_2^*, and applied magnetic fields B at which the listed value of f_{Rabi} was observed.

tunable and strong Heisenberg exchange interaction between adjacent spins to implement logical single- and two-qubit gates. The most explored scheme of this kind is the singlet-triplet (ST_0) qubit, where the singlet ($|S\rangle$) and unpolarized triplet ($|T_0\rangle$) states of two spins in a double QD are used to define the qubit basis states[9].

Jirovec and colleagues have now realized a ST_0 spin qubit based on holes. In their experiment, using a double QD in a planar Ge/SiGe heterostructure, the researchers demonstrate spin rotation frequencies and dephasing times already comparable to or better than those of LD hole spin qubits demonstrated before. Universal single-qubit logical operations of the ST_0 qubit are implemented using the exchange interaction and a large difference in Zeeman energy $\Delta E_Z = \Delta(g\mu_B B)$ between the two dots (where g is the Landé g-factor, μ_B the Bohr magneton, and B the magnitude of the magnetic field). Here, the strong and tunable SOI of the hole spins conveniently generates ΔE_Z through a large difference in g between the dots. This makes it unnecessary to incorporate micromagnets in the device or to polarize the nuclear spin bath, which is typically done for electron spin qubits to create a magnetic field gradient. Jirovec and co-authors demonstrate a large Zeeman energy difference of about 20 GHz T^{-1} created in this way. Importantly, by using this technique of generating ΔE_Z and by using the ST_0 encoding, the qubit could be operated at millitesla magnetic fields, 1–3 orders of magnitude lower than used for other spin qubits.

Figure 1 shows a comparison between these ST_0 hole spin qubits and other LD hole qubits experimentally realized in Ge or Si devices. As can be seen, the newly demonstrated hole ST_0 qubit really stands out with its combination of high Rabi frequency and long dephasing time, obtained at very low applied magnetic field.

The demonstrated operation at low magnetic fields can open important avenues for the practical use of spin qubits. In fact, semiconductor qubit–qubit coupling is typically short-range, effectively limiting inter-qubit distances to the spatial extent of the wave functions of the confined particles (a few 100 nm). A promising solution to overcome this limitation is to promote the coherent interaction between the orbital (charge) or the spin degree of freedom of electrons or holes confined in QDs and the electric field of microwave photons stored in superconducting resonators, which can then mediate qubit–qubit interactions at a distance[10–13]. However, the use of high magnetic fields for the operation of spin qubits (see Fig. 1) complicates the integration with superconducting resonators, usually degrading the resonator performance and ultimately suppressing superconductivity. The demonstration by Jirovec and co-authors of operating their hole ST_0 qubit at low magnetic fields could lead to simplified spin qubit integration into a hybrid superconducting architecture.

Coupling with superconducting microwave resonators is also important for implementing fast and high-fidelity single-shot measurement of qubit states, using the dispersive interaction between the spin qubit and the resonator. This read-out technique employs cryogenic microwave components, such as circulators, isolators, and cryogenic linear and parametric amplifiers, which allow to amplify the microwave signal coming from the device while protecting it from high-temperature noise sources and amplifier backaction. The strong magnetic field necessary to operate spin qubits usually implies that those microwave components should be positioned far away from the QD device and properly magnetically shielded, which increases the complexity of the setup and introduces further signal attenuation that reduces the achievable signal-to-noise ratio. In this respect, the possibility to operate spin qubits in a much-reduced magnetic field greatly simplifies the integration with those components, as well as with superconducting qubits and on-chip LC filters, and opens up the opportunity to make use of a broader class of superconducting materials and resonator geometries.

A newly proposed class of techniques for qubit read-out and coupling relies on longitudinal interaction between the qubit and the resonator photons, which is enacted by modulating the qubit or resonator with a frequency near the resonator frequency and has been predicted to enable fast and high-fidelity quantum-non-demolition readout[14]. The longitudinal interaction appears quite naturally for ST_0 qubits coupled to a resonator. ST_0 qubits thus provide a testbed to compare longitudinal and transverse couplings in a single experimental setting, and compare their unique advantages and disadvantages for quantum computing. The versatility of the demonstrated ST_0 qubit in Ge and the possibility to operate it in a very low magnetic field will allow pioneering experiments in this direction. ❐

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Competing interests

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