Side-gated, enhancement mode, InAs nanowire double quantum dot devices—toward controlling transverse electric fields in spin-transport measurements

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Abstract

A double quantum dot system with a definitive transverse electric field in the plane of the sample is defined by combining a facile side-gating technique with enhancement mode InAs nanowires. Positive bias on the plunger gates enhance quantum dot segments along the nanowire, negative bias on barrier gates deplete regions, and situating gates biased at opposite polarities on opposing sides of the nanowire allows an electric field to be engineered. With sufficiently biased barrier regions stable bias triangle features are observed in the weak interdot coupling regime. The singlet-triplet energy splitting $\Delta_{ST}$ in Pauli spin-blockaded features is studied as a function of an external magnetic field applied perpendicular to the sample plane. We interpret an apparent absence of mixing between singlet and triplet states as an indication that the spin–orbit field is oriented out of the sample plane due to the induced electric field. Finally, we discuss the potential of combining advanced gating architectures with enhancement mode nanowires to control the orientation of the spin–orbit field—a prospect that could enable multiple, nanowire-based spin-qubits to be operated on a single chip with a fixed-angle external magnetic field applied.

Supplementary material for this article is available online

Keywords: nanowire, quantum dot, Pauli spin blockade, spin–orbit interaction

(Some figures may appear in colour only in the online journal)

1. Introduction

Double quantum dot systems remain attractive candidates toward realizing solid state qubits for quantum computation [1]. Material systems enabling fast spin rotation and electrical readout are required, and those with large Landé $g$-factors offer easier control over spin in an applied magnetic field. Furthermore, materials with strong spin–orbit interactions (SOI) may enable purely electrical manipulation of individual spins [2, 3], and the SOI has been shown to have an anisotropic behavior [4]. III–V materials such as Indium Antimonide (InSb) and Indium Arsenide (InAs) exhibit both strong SOI and large Landé $g$-factors. This SOI anisotropy has been reported for III–V nanowire double quantum dot devices in InSb [5] and InAs [6] in the Pauli spin-blockaded regime [7]. It has recently been predicted that the application and control of transverse electric fields can be used to enhance the SOI properties of InSb and InAs nanowire devices [8].

Electrons transporting through InAs nanowire devices experience an internal spin–orbit magnetic field $\vec{B}_{SO}$, which is directly related to the SOI and dependent on the electron momentum. The anisotropy of the SOI is translated into an...
anisotropy of $B_{SO}$ [9, 10], which can be determined by probing the anisotropy of the spin–orbit energy gap, $\Delta_{SO}$ [11–13]. Knowledge of the orientation of $B_{SO}$ in the double dot device is desirable to avoid unwanted transitions and leakage current in the presence of an external magnetic field [14, 15]—enhancing fidelity in the spin-qubit initialization and readout stages [16]. The orientation of $B_{SO}$ has been mapped out in InSb [5], and recently in InAs [17], nanowire double quantum dot devices in experimental setups where the orientation of an external magnetic field is varied. With the recent mapping of the orientation of $B_{SO}$ in nanowire double quantum dot devices, a logical future direction would be to systematically control the orientation to eliminate the need for a rotating external magnetic field. Engineering applied electric fields using gating architectures may be a viable approach toward this goal.

The conductivity of InAs nanowires varies as a function of diameter [18, 19]. In this paper we use thin InAs nanowires, which require an enhancing gate bias to conduct. Enhancement mode nanowires create the possibility for multiple devices to cohabit a single nanowire without being electrically connected. This can be advantageous for applications such as capacitively-coupling a charge sensor to a quantum dot device where close proximity is desirable. Devices could be defined using standard nanofabrication techniques in a few steps without the need for precise placement of several nanowires via patterning [20, 21] or micromanipulation [22]. Another interesting application of enhancement-mode nanowires is that electrostatically defined quantum dots in these nanowires can utilize both negative (barriers) and positive (dot) gate biases. This creates the opportunity to apply transverse electric fields by positioning gates biased at different polarities on opposing sides of the nanowire.

In this paper we combine side-gating with enhancement mode InAs nanowires to define a double quantum dot system while simultaneously applying a transverse electric field $E_{\perp}$ in the sample plane. We observe Pauli-spin blockaded features in the weak interdot coupling regime and study the singlet-triplet energy spacing as a function of an applied external magnetic field oriented perpendicular to the sample plane. We observe no apparent spin–orbit energy gap or evidence of an avoided crossing, which we believe to be explained by $B_{SO}$ being oriented out of the sample plane. If so, this study demonstrates that $B_{SO}$ can be manipulated using an engineered gating architecture in a nanowire double quantum dot system. We discuss the potential for enhancement mode nanowires in conjunction with novel gating architectures to control the strength, and localization, of transverse electric fields as well as the possibility of full spatial control over $B_{SO}$ about the nanowire axis by simply tuning gate biases.

2. Experimental details

2.1. Device fabrication

Wurtzite InAs nanowires 35–40 nm in diameter and 5 μm in length were grown in the (111)B orientation using chemical beam epitaxy [23]. The nanowires were dry distributed onto pre-patterned sample chips made on a degenerately doped Si substrate with an electrically insulating SiO$_2$ layer; enabling global backgating with the application of a bias, $V_{BG}$. Electrical contacts and gates were defined using one iteration of electron beam lithography and thermal evaporation. Completed devices can be seen in figure 1. Conductance in the nanowires was found to freeze out at low temperatures and enhancing gate biases were needed to turn on the channel [18]. Detailed information on device fabrication, and nanowire characterization at 77 K, is provided in the supplementary information sections 1 and 2, respectively, available online at stacks.iop.org/NANO/30/144002/mmedia.

Source, $S$, and drain, $D$, electrodes were spaced 920 nm apart. Five finger-gates were patterned along the wire and are, from source to drain, $V_L$, $V_{PG1}$, $V_M$, $V_{PG2}$ and $V_R$. Figure 1(a) shows device 1, which was designed for four terminal measurements. The outer electrodes were electrically floated in measurements since the 175 nm nanowire segments between them and $S/D$ were not electrically conducting without biasing of the backgate, $V_{BG} = 0$ V. Device 2 is seen in figure 1(b). A capacitively-coupled charge sensor circuit was designed to operate on the same nanowire and couple to dot2. The double quantum dot device and intended charge sensing circuit can be seen in figure 1(c). The sensor-enhancing electrode (denoted by the red *) did not have ample coupling along the length of the sensor channel due to a design...
oversight, and all data presented in this paper is in terms of drain current, $I_D$.

2.2. Double quantum dot measurements

Measurements were performed in a dilution refrigerator with a base temperature of 14 mK and an electron temperature, $T_{electron} < 100$ mK. Yokogawa 7651, or GS210, model DC voltage sources were used for all gate biases, and for DC $V_{SD}$ biasing. A Femto DLPCA-200 current preamplifier was used to collect the drain current. For AC measurements, a Stanford Research SR830 lockin amplifier was used to source an AC signal, dropped over a 1:100 voltage divider, and to measure the drain current as a voltage signal after amplification by the Femto. For DC measurements, the amplified drain current signal was read out by an Agilent 34401a multimeter. A background of 200 fA has been subtracted from all of the data presented in this paper to account for an output offset in the preamplifier. Each line in the experimental setup has a total of 3.26 kΩ cold-filtering resistance, which has not been removed from the data.

3. Results and discussion

3.1. Enhancing dot occupancy—varying interdot tunnel coupling

Drain current data from device 1 (figure 1(a)) as a function of plunger gate (PG) biases is presented in figure 2. Left and right barrier gates, and the backgate, are not biased ($V_L = V_R = V_{BG} = 0$ V). The middle barrier is biased at a small negative bias $V_M = −0.1$ V, and an AC $V_{SD} = 100$ μV (rms) excitation is applied. Quantum dot regions were formed along the nanowire using positive $V_{PG}$ biases. As $V_{PG}$ increases, the size of the enhanced dots increases until electrons are able to tunnel through the remaining barrier segments of the nanowire. For $V_{PG} < 2.6$ V, weak interdot coupling is observed as discrete triple point features (bright spots). For more positive $V_{PG}$, biases the interdot coupling becomes stronger as evident by the dark wavy lines around $V_{PG} = 2.7$ V. Intermediate interdot coupling regimes are seen as honeycomb patterns around $V_{PG} = 2.55$ V and also in regions where the PGs are asymmetrically biased with one plunger strongly positively biased, for example within $2.6$ V < $V_{PG} < 2.7$ V and $2.3$ V < $V_{PG} < 2.5$ V.

The data in figure 2 illustrates two key points. First, a double dot system is successfully formed within the nanowire and features are stable over relatively large $V_{PG}$ ranges. We find that the side-gating technique is overall very stable. There is no need to use an insulating oxide layer between the gate and the nanowire, which can give rise to interface trap states and charge fluctuations [24]. The second point that we want to address is that the positively-biased $V_{PG}$ work against the negative bias of $V_{LR}$, resulting in the changes to the interdot coupling throughout the data set—moving from weak interdot coupling in the bottom left to strong interdot coupling in the top right of figure 2. Neglecting $V_{LR}$ initially, we argue that if the data set were to be repeated for a more negative $V_M$ bias a potential barrier higher in energy and wider along the nanowire would be created. Stronger $V_{PG}$ biases would be needed to counteract the barrier, and the features in figure 2 would be shifted to more positive values in $V_{PG}$-space as a result. Returning now to $V_{LR}$, these biases would likely need to be tuned as well to replicate features by maintaining tunnel rates into (out of) the double dot system.

3.2. Pauli spin-blockaded features

For controlled studies of bias triangles in the weak interdot coupling [5–7, 14–17, 25, 26], significant changes to the interdot coupling as a function of $V_{PG}$ are not desirable. To minimize these effects, stronger negative biases are applied to $V_{LM,R}$. Figure 3 shows charge stability diagrams from device 2 for $V_{BG} = 0$ V, and $V_L = V_M = V_R = −1$ V. In figure 3(a) $I_{SD}$ as a function of $V_{PG}$, and $V_{BG}$, is plotted for an AC $V_{SD} = 2$ mV rms. Dashed lines act as a guide to the eye, and effective charge occupation numbers ($m$, $n$) represent the number of electrons in dot1 and dot2, respectively. Due to problems with the capacitively-coupled charge sensor on this device ($m$, $n$) are not exact, and we know at least two more electrons are in dot2 from bias triangles at more positive $V_{PG}$ (not shown). We note the anomalous triangular structure along the $(1, 0) → (0, 0)$ boundary. While we can not explain this feature, we believe that it may arise from an additional resonance in dot2.

An AC excitation was used initially to locate bias triangles that showed Pauli spin blockade, and also to search for the equal occupancy line—the boundary at which spin blockade switches from occurring in bias triangles of positive

Figure 2. Charge stability diagram in plunger gate space from device 1 for $V_L = V_R = V_{BG} = 0$ V, $V_M = −0.1$ V and an AC-bias $V_{SD} = 100$ μV rms. Increasingly positive bias on $V_{PG}$ increases the dot sizes, and varies the interdot tunnel coupling from weak (bottom left) to strong (top right). The maximum current plotted was limited to 15 pA to be able to see all areas of interest on the same scale. The wavy horizontal features in the blue shading limit are a measurement artifact caused by sweeping $V_{PG}$ too quickly in the AC setup.
Since the InAs nanowires of this study were depleted without an enhancing gate bias, it was not possible to individually act on dot1.

For the methods described in van der Wiel et al [27] to extract the capacitance and lever arm values of the double dot system from the data in figure 3, a model of the system is presented in figure 4. A model of the system is presented in figure 4. A model of the system is presented in figure 4.

To study the singlet-triplet energy spacing \( \Delta_{ST} \) in blockaded features, bias triangles were recorded using a DC \( V_{SD} \). In figures 3(b)/(c) bias triangles for the (1, 1) \( \rightarrow \) (2, 0) transition can be seen for \( V_{SD} = \pm 2 \) mV, respectively. Similarly, figures 3(d)/(e) shows bias triangles for the (1, 1) \( \rightarrow \) (0, 2) transition. Pauli spin-blockade is visible in figures 3(b)/(e).

3.3. Extracting capacitances

Since the InAs nanowires of this study were depleted without an enhancing gate bias, it was not possible to individually define quantum dots for characterization. Instead, we rely on the methods described in van der Wiel et al [27] to extract the capacitance and lever arm values of the double dot system from the data in figure 3. A model of the system is presented in figure 4. A model of the system is presented in figure 4. A model of the system is presented in figure 4.

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\[ C_{L,M,R} = C_{L(R)} + C_{PG1(2)} + C_{M} + C_{PG2(1)} \]

Here \( C_{L,M,R} \) represent the capacitances of the left, middle and right barriers, respectively. \( C_{PG1(2)} \) is the capacitance of PG1(2) acting on dot1(2), and the cross-capacitance \( C_{PG1(2)} \) is the capacitance of PG2(1) acting on dot1(2). A more detailed description of the method used to extract the cross-capacitances is provided in the supplementary information.

Using the model illustrated in figure 4, all relevant lever arms and capacitances were extracted. The results can be seen in table 1. We first point out that the couplings of PG1(2) are very similar, as illustrated by the values of \( \alpha_{PG1(2)} \). This is explained by the pattern’s alignment to the nanowire, and demonstrates that reproducible gate couplings are feasible using our side-gated technique. We further note that the cross-capacitance lever arms for our device are up to 33 \% of \( \alpha_{PG1(2)} \)—stronger than would be expected in a bottom gate defined device. This is understandable given that there is no metallic structure between the PGs in our device that would
act to screen cross talk. Finally, we point out that $\alpha_{\text{PG}_2}$ is twice as strong as $\alpha_{\text{PG}_1}$. Here we believe that the presence of the sensor electrode near dot 2 may screen some of the cross talk, despite being situated on the other side of the nanowire (figure 1(b)).

Unfortunately, a complementary data set for device 1 does not exist for comparison. Analysis of differences in cross talk for various electrode arrangements would be interesting. We propose that an optimized architecture for side-gating enhancement mode nanowires may include all five gates mirrored on each side of the nanowire. In this arrangement, cross-talk could be reduced by the presence of an extra electrode between PG1 and the middle barrier electrode to be applied perpendicular to the sample plane. If indeed only a small portion of $\vec{E}$ couples into the nanowire in our system, further tuning of the field strength would be needed to experimentally observe the SOI enhancement predicted by Campos et al [8].

In our system, due to the structure and growth orientation of our nanowires, we expect structure-inversion asymmetry, SIA (the Rashba effect), to already be the dominant SOI contribution [30]. The Fermi level pins in the conduction band along the surface of the InAs nanowire [31, 32], and the nanowire acts as a cylindrical two-dimensional electron gas. Electrons traveling along the nanowire experience $\vec{B}_{SO}$ arising from SIA differently depending on their location around the circumference of the nanowire. In the absence of gate electrodes, or an applied electric field, the system holds spatial inversion symmetry and no net contribution is observed. It is not until the spatial inversion symmetry is broken that the spin–orbit field survives [33], and a measurable contribution can be observed. The sidegate biases break this symmetry in our experiment.

Given the anisotropic behavior of the SOI [4] we are interested in probing the relationship between the orientation of $\vec{E}$ applied, and the resulting orientation of $\vec{B}_{SO}$. To demonstrate the effect of applying a transverse electric field in the sample plane of our device, we study the singlet-triplet splitting along the detuning cut line noted by the red arrow in figure 3(e) across the blockaded (1,1)→(2,0) transition. A magnetic field, $\vec{B}_{cy}^*\parallel$ is applied perpendicular to the sample plane, as illustrated in figure 1(b).

The top panel of figure 5 shows that the $T_s(1,1)\rightarrow S(0,2)$ state rises up toward the $T_s(1,1)\rightarrow T_c(0,2)$ state as the magnetic field is increased. Here, S(0,2) denotes the singlet for the (0,2) charge state and $T_s$ denotes the spin-up triplet states. The difference in energy between the singlet and triplet states, $\Delta_{ST}$, is plotted in the bottom panel of figure 5. The spacings were measured by analyzing detuning cut lines and identifying the peaks of the singlet and triplet states. Beyond $B = 2$ T the singlet peak was no longer discernable as it merges into the triplet peak. $\Delta_{ST}(B)$ decreases linearly as

### Table 1. Capacitance and lever arm values extracted from the data in figure 3.

| Capacitances | Lever arms | Charging energies |
|--------------|------------|-------------------|
| $C_{\text{PG}_1}$ | 1.02 aF | $\alpha_{\text{PG}_1}$ | 0.081 21 |
| $C_{\text{PG}_2}$ | 1.11 aF | $\alpha_{\text{PG}_2}$ | 0.080 49 |
| $C_{\text{PG}_1\rightarrow_{0.11}}$ | 0.33 aF | $\alpha_{\text{PG}_1}$ | 0.026 74 |
| $C_{\text{PG}_1\rightarrow_{0.14}}$ | 0.14 aF | $\alpha_{\text{PG}_1}$ | 0.050 12 |
| $C_L$ | 10.25 aF | $C_{\text{LM}}$ | 11.61 aF |
| $C_r$ | 0.92 aF | $C_{\text{CM}}$ | 12.52 aF |
| $C_1$ | 12.52 aF | $E_{C_1}$ | 12.80 meV |
| $C_2$ | 13.78 aF | $E_{C_2}$ | 11.63 meV |

**3.4. Transverse electric field**

An interesting application of using side gating to define double quantum dot devices in enhancement mode nanowires is that control is gained over the strength of the applied transverse electric field. We make a general estimate of the electric field strength across the nanowire for the data in figure 3 using a simple parallel plate capacitor model. Considering $V_m = -1$ V, $V_{\text{PG}0.11} \approx 1$ V and the distance between either PG electrode and the middle barrier electrode to be $\sim 290$ nm, an electric field strength of $\sim 6.9$ MV m$^{-1}$ (6.9 MV m$^{-1}$) is calculated, and the orientations of the electrode-to-electrode components of the field are illustrated by the yellow arrows in figure 1(b).

A transverse electric field of comparable strength has recently been predicted to give rise to significant spin–orbit coupling in InSb and InAs nanowires due to the Rashba effect [8]. Finite element modeling (FEM) would be interesting to more accurately estimate the applied electric field within the nanowire cross-section. By using FEM, Roddaro et al [29] find that only about 12.5 % of an electric field of comparable strength applied in a similar setup is transmitted into the nanowire. They attribute this to the large mismatch in dielectric constant between the nanowire and the surrounding vacuum.
the triplet states split in energy according to Zeeman splitting $E_z = \pm \hbar g |\mu_B| B$, where $\pm z_{\text{SO}}$ is $+1$, $0$, $-1$ and $\mu_B$ is the Bohr magneton. From the fit, a Landé g-factor $|g| = 7.9 \pm 0.3$ is extracted, which is in good agreement with previous InAs nanowire studies [6, 25, 34, 35].

We now return our attention to the top panel of figure 5. Interestingly, we do not see a spin–orbit gap $\Delta_{\text{SO}}$, or any evidence of an avoided crossing, where the two states meet. In previous studies using InAs nanowires values for $\Delta_{\text{SO}}$ of 140–250 $\mu$eV in bottom-gated [26, 34] and 200 $\mu$eV for top-gated devices [25] are reported, and an avoided crossing of 2$\Delta_{\text{SO}}$ is observed. Nadji-Perge et al also observe the absence of a spin–orbit gap in InSb nanowires when the external magnetic field $B_{\text{ext}}$ is aligned with the spin–orbit field $B_{SO}$ of the nanowire [5]. We believe the absence of $\Delta_{\text{SO}}$ in our data suggests that $B_{SO}$ is elevated highly out of, if not perpendicular to, the sample plane. Only recently has the orientation of $B_{SO}$ been reported with an azimuthal angle in InAs nanowire double quantum dots where a positive backgate bias was used in conjunction with top-gating [17].

The applied external magnetic field $B_{\text{ext}}$ plays a crucial role in the measuring the SOI contribution, which manifests as $\Delta_{\text{SO}}$ or as a leakage current in the blockaded regime [14, 15] and is dependent on the orientations of both $B_{\text{ext}}$ and $B_{SO}$. When the fields $B_{SO}$ and $B_{\text{ext}}$ are orthogonal, mixing occurs between singlet and triplet states and $\Delta_{\text{SO}}$ is at its maximum. With the fields aligned, mixing between the states is suppressed and $\Delta_{\text{SO}}$ closes. For studies of single devices, the use of a vector magnet system is ample to orientate $B_{\text{ext}}$ with respect to $B_{SO}$. This approach fails short, however, in the prospect of implementing circuits with multiple spin-qubits. Instead, full electrical control over the orientation of $B_{SO}$ via gate biases is desired, as it would allow the alignment of $B_{SO}$ in each device to be changed with respect to an external magnetic field without changing sample orientation. If the orientation of $B_{SO}$ is indeed controllable in nanowires via gating architectures, it would serve as a useful tool toward increasing the fidelity of nanowire spin-qubit initialization and readout [16].

4. Conclusions

We have engineered transverse electric fields in the sample plane of enhancement mode InAs nanowire double quantum dot devices via a simple side-gating architecture. We demonstrated that a double dot system can be formed using positive biases on PGs and gave insight into how the PG biases can offset depleted barrier regions. In the weak interdot coupling regime finite bias spectroscopy of charge state transitions was conducted, and we have extracted all capacitances and lever arm values for the double dot system. Pauli spin blockade was observed in the lowest occupancy features and the singlet-triplet energy spacing was studied as a function of a magnetic field oriented perpendicular to the sample plane. We interpret the absence of a spin–orbit energy gap in our data as an indication that the spin–orbit field is strongly oriented out of the sample plane resulting from the electric field applied by our setup. This is, to our knowledge, the first demonstration of orienting $B_{SO}$ out of the sample plane using an engineered transverse electric field in a nanowire double quantum dot device. Finally, we would like to discuss potential future directions for side-gated, enhancement mode nanowires for spin-transit studies.

We proposed earlier that it would be possible to shift features to more positive values of $V_{PG1,2}$ by more negatively biasing $V_{L,M,B}$. Initially, this would require incremental steps in the barrier biases and sweeps of $V_{PG1,2}$ to characterize the ratios of the biases changed. Once characterized, effective control over the transverse $E_x$ strength would be gained while studying the same features in the charge stability diagram. Additionally, by smart design of the device architecture and position of the enhancing PGs and depleting barrier gates, it is possible to localize electric fields to different regions along the device.

A further step would be to combine gating architectures with pre-patterned bottom gates [36]. By aligning the nanowire to bottom gates, and subsequently aligning side gates, control over the applied transverse $E_x$ extends out of the sample plane. Additionally, including a second insulating layer and an overlying top gate would further enhance the spatial control over $E_x$, assuming trap states at the insulator-nanowire interface can be eliminated. Development of such devices would ideally be accompanied by finite element methods to engineer the applied fields. The combined architecture could allow orientation of $E_x$ to be manipulated around the axis of the nanowire resulting in electrical control over the orientation of $B_{SO}$ in enhancement mode nanowire double quantum dot devices.

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