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Control of Majorana edge modes by a g-factor engineered nanowire spin transistor

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ABSTRACT

We propose the manipulation of Majorana edge states via hybridization and spin currents in a nanowire spin transistor. The spin transistor is based on a heterostructure nanowire comprising of semiconductors with large and small *g*-factors that form the topological and non-topological regions respectively. The hybridization of bound edge states results in spin currents and 4π-periodic torques, as a function of the relative magnetic field angle – an effect which is dual to the fractional Josephson effect. We establish relation between torques and spin-currents in the non-topological region where the magnetic field is almost zero and spin is conserved along the spin–orbit field direction. The angular momentum transfer could be detected by sensitive magnetic resonance force microscopy techniques.

1. Introduction

It is believed that nanowires with strong spin–orbit interactions can realize topologically protected quantum bits (qubits) [1–3] based on Majorana zero energy modes [4–8]. Some of the other proposals to realize topologically protected qubits include schemes based on topological insulators [9,10], fractional quantum Hall states [11], cold atom systems [12,13], p-wave superconductors [14] and superfluids in ^{3}He–B phase [15].

Typically proposals for observing these Majorana zero energy modes are based on quantum tunneling and transport type phenomena [16–21]. Some exciting recent proposals for observing these edge modes are based on the unconventional Josephson effect with a 4π periodicity [22–25]. A dual effect has also been suggested in which case a torque between magnets exhibits 4π periodicity in the field orientations [26,27,48].

It is this dual of the Josephson effect that could in fact be employed in spintronic devices that can in principle be employed in spintronic devices. In particular, it is important to understand the role of mechanical torques that should inevitably accompany Majorana hybridization due to conservation of angular momentum. It has been predicted that conservation of angular momentum in macrospin molecules can result in quantum entanglement of a tunneling spin with mechanical modes [28,29]. A flow of spin current between two magnets has been demonstrated to induce spin-transfer torque effect [30,31] and mechanical torques [32,33], also by conservation of angular momentum. A flux qubit has been shown to decohere due to exchange of angular momentum between the qubit and elastic modes of a solid [34].

In this paper we propose the manipulation of Majorana edge states via hybridization and spin currents using a gated nanowire spin transistor. For our calculations we consider a spin transistor that comprises of GaSb–GaAs–GaSb type-II quantum well with strong spin–orbit interactions. Our choice of semiconductors is based on a number of factors. First the formation of topological and non-topological regions of the wire is determined by the relative *g*-factors of the wires. While GaSb has a large $g \approx -9$, the relatively smaller $g \approx -0.3$ for (GaAs) gives an excellent *g*-factor contrast of about 30. GaSb–GaAs nanowires and other Sb containing hetero-junction nanowires have been grown [35–38]. Though InSb has a much higher *g*-factor and InSb–InAs heterojunction nanowires have been grown [39,40], their *g*-factor contrast is only about 4. Second, the relatively small conduction band offset of these two materials leads to the formation of a shallow type-II quantum well, thereby only requiring a small gate voltage to raise the chemical potential in the well region.

Typically strong quantum confinement effects can strongly alter the electronic *g*-factors and drive it towards the bare electron value due to effects of orbital angular momentum quenching [41,42] in materials with sufficiently strong spin–orbit coupling. In the case of InAs–InP nanowire quantum dots it has been shown that the *g*-factor can be tuned through zero [43,44]. Therefore in the case of GaAs (which has a small negative bulk *g*), a sufficiently small quantum well should drive *g* towards 0, thus making it a perfect non-topological region.

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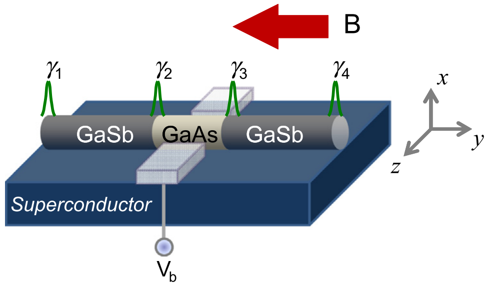

Fig. 1. (Color online) A semiconductor nanowire with an embedded type-II GaSb–GaAs–GaSb quantum well placed on top of s-wave superconductor in the presence of a magnetic field. The relatively much smaller *g*-factor of GaAs makes it a non-topological region. The gate voltage, V_b, can be used in order to control the hybridization between the edge modes formed at the hetero-junction interface.

The topological region semiconductor should have strong spin–orbit interactions and large Zeeman splitting. The schematic of our proposal is shown in Fig. 1. The wire is proximity-coupled to an *s*-wave superconductor which results in proximity induced pairing in the wire. The spin transistor allows the bound edge states to hybridize thus resulting in spin-current induced 4π-periodic torque, as a function of the relative magnetic field angle. As an example of application for our proposal, arrays of nanowires with zero energy edge modes could be used as quantum memory – in which case there arises a need to efficiently read out information from memory elements. The spin and angular momentum flows discussed here could be employed for that. In general the nanowire architecture allows the combination of various lattice mismatched materials and have attracted much attention due to their potential electronic and optoelectronic applications such as single electron transistors, field sensors, and low-power electronics [38,45,46].

We also establish relation between torques and spin-currents in the non-topological region where the magnetic field is almost zero and spin is conserved along the spin–orbit field direction. Sensitive magnetic resonance force microscopy measurements can provide further evidence for the existence of these edge modes and their hybridization. Finally, we show that this non-dissipative spin current can be controlled by the external gate voltage (see Fig. 1) which leads to similar functionalities as the Datta and Das spin-field-effect transistor [47].

2. Tight binding calculations for spin currents and edge hybridization

Consider a semiconducting quantum wire, with the Rashba spin-splitting, placed on top of a superconducting substrate (as per the coordinates shown in Fig. 1). In this solid state system, Majorana modes are charge less, localized zero-energy collective quasiparticle excitations of the superconducting ground state that satisfy the Bololiubov-de Gennes (BdG) Hamiltonian:

$$\mathcal{H}=\frac{k^2}{2m}\tau_z+i\alpha_{so}k_y\tau_z\sigma_z+\mathbf{\Delta}'\cdot\boldsymbol{\tau}+\mathbf{B}\cdot\boldsymbol{\sigma}. \quad (1)$$

where we have used the Nambu spinor basis $\Psi^T=(\psi_\uparrow,\psi_\downarrow,\psi^\dagger_\downarrow,-\psi^\dagger_\uparrow)$, $\boldsymbol{\sigma}$ and $\boldsymbol{\tau}$ are Pauli vectors that respectively act on particle and hole sectors. Here α_{so} is the strength of Rashba spin-splitting term, $\mathbf{B}=[B_o\cos\theta,-B_o\sin\theta,-B_z]$ is the magnetic field vector, $\mathbf{\Delta}'=[\Delta\cos\phi,\Delta\sin\phi,-\mu]$, μ is the chemical potential and $\Delta e^{i\phi}$ is the superconducting pairing potential. In general, the energy spectrum of the BdG Hamiltonian supports gapped and gapless phases. The overall phase diagram is more complicated than TI edge systems [26,27] due to the presence of the $k^2\tau_z$ term. Here, we limit our consideration to the $\Delta^2>B_z^2$ part of the phase diagram where the energy bands are always gapped. There are two gaped phases, – topological (T) for $\Delta^2-B_z^2<B_o^2-\mu^2$ and non-topological (N) for $\Delta^2-B_z^2>B_o^2-\mu^2$,separated by a quantum phase transition at $\Delta^2-B_z^2=B_o^2-\mu^2$.

The coupling between a magnetic field and the spin of an electron is determined by the *g*-factor, which would therefore determine whether the semiconductor is in the N or T phase. Hence it is possible to engineer a nanowire quantum well structure that can form $T|N|T$ or $N|T|N$ regions even when placed in a uniform magnetic field. For a $T|N|T$ type system, the hybridization across the N region (which forms the well) can be gate controlled. Our proposed spin transistor that comprises of GaSb–GaAs–GaSb type-II quantum well within a nanowire is shown in Fig. 1.

In order to treat arbitrary 1D heterostructures and non-uniform magnetic fields, we transform the BdG Hamiltonian, Eq. (1), onto the following tight binding model with nearest neighbor hopping:

$$\mathcal{H}=\sum_{j,\sigma,\sigma'}\left[c^\dagger_{j+1\sigma}\left(-t_0\sigma_0+i\frac{\alpha_j}{2}\sigma_z\right)_{\sigma\sigma'}c_{j\sigma'}+H.c.\right]+\sum_{j,\sigma}(2t_0-\mu_i)c^\dagger_{j\sigma}c_{j\sigma}+\sum_j(\tilde{\Delta}_i c^\dagger_{j\uparrow}c^\dagger_{j\downarrow}+H.c.)+\sum_j(\tilde{B}_j c^\dagger_{j\uparrow}c_{j\downarrow}+H.c.) \quad (2)$$

where we have used the complex parameters $\tilde{\Delta}=\Delta\exp(i\phi)$, $\tilde{B}=B_o\exp(-i\theta)$ and $c^\dagger_{j\sigma}(c_{j\sigma})$ creates (annihilates) an electron of spin σ on site j. The proximity induced gap $\Delta=0.5$ meV. Here $t_0=\hbar/2m^*a^2$ is the hopping strength, $\alpha_j=\alpha^{(j)}_{so}/a$ where a is the lattice spacing. In our calculations, we use the following parameters for GaSb and GaAs, $m_{GaSb}=0.041m_e$, $m_{GaAs}=0.067m_e$, $\alpha^{GaSb}_{so}=0.187$ eV A and $\alpha^{GaAs}_{so}=0.024$ eV A. The magnetic field at each site is given by $\tilde{B}_j=g_j\mu_B\mathcal{B}/2$, where μ_B is the Bohr magneton, g_j is the Lande *g*-factor of the semiconductor at that given lattice site and $\mathcal{B}$ is the applied field. Although quantum confinement effects can alter the electronic *g*-factors in materials with sufficiently strong spin–orbit coupling [41,42,44], as we are considering non-topological well regions that are fairly large – we use the bulk *g*-factors: $g_{GaAs}=-0.32$ and $g_{GaSb}=-8.72$.

The overall length of the wire was taken to be 3 μm corresponding to 300 grid sites for a grid spacing of $a=10$ nm. Typically the GaSb section of the nanowires is about 60 nm in diameter, while the GaAs sections are about 40 nm wide [36]. Taking the effective masses, the transverse quantization, the bandgaps and the valance band offset of these semiconductors into account, we estimate that the barrier height of the quantum well is about 52 meV.

In Fig. 2 we show the edge states from our tight binding calculations as a function of bias voltage applied to the non-topological GaAs well region for two different well widths. The respective energies of these states are shown in Fig. 3. It is clearly seen that the shorter non-topological well region results in higher hybridization energies due to more dominant finite size effects. In the absence of any bias, the quantum well prevents the hybridization of the edge modes as indicated by the separate red and blue edge states. This separation of the edge modes persists till the threshold $V_b\approx30$ mV is reached at which point a split in the energy spectrum is seen due to hybridization of the edge modes. As V_b is further increased, the edge modes abruptly return to their unhybridized state as the bias voltage now acts as a barrier preventing any tunneling effects. The unhybridized Majorana edge modes (γ_1 and γ_4) are formed at the ends of the structure and they have nearly zero energy. The hybridized edge modes (γ_2 and γ_3) are formed in the middle and they have non-zero energy due to finite size effects. This non-zero energy edge mode can now be manipulated by spin currents and magnetic field gradients.