Effective g-factor in Majorana Wires

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We use the effective g-factor of subgap states, \( g^* \), in hybrid InAs nanowires with an epitaxial Al shell to investigate how the superconducting density of states is distributed between the semiconductor core and the metallic shell. We find a step-like reduction of \( g^* \) and improved hard gap with reduced carrier density in the nanowire, controlled by gate voltage. These observations are relevant for Majorana devices, which require tunable carrier density and \( g^* \) exceeding the \( g^* \)-factor of the proximitizing superconductor. Additionally, we observe the closing and reopening of a gap in the subgap spectrum coincident with the appearance of a zero-bias conductance peak.

The electronic properties of a semiconductor nanowire can be altered dramatically by contacting it to a superconductor. If the nanowire has strong spin-orbit coupling, the application of a magnetic field can induce a transition from trivial to topological superconductivity, with Majorana zero modes localized at the ends of the nanowire \cite{1, 2}. The Majorana bound states (MBSs) are predicted to exhibit non-Abelian statistics, and can serve as a basis for topological quantum computing \cite{3, 4}. Following concrete theoretical proposals to generate MBSs in these systems, several experiments have reported zero-bias conductance peaks \cite{7, 8, 9} consistent with theoretical expectation in a number of ways. More recently, the development of epitaxial InAs/Al hybrid nanowires \cite{10} has improved the superconducting gap \cite{11}, making evident the coalescence of Andreev bound states (ABBS) to form the zero-bias conductance peak \cite{12}.

The rate of motion of the subgap ABSs toward zero energy as a function of magnetic field defines an effective g-factor, denoted \( g^* \). Studies on hybrid InAs/Al nanowires found \( g^* \) ranging from 4 to 50 \cite{8, 12, 13}, substantially different from the bulk value, \( g_{\text{InAs}} \sim -15 \) \cite{14, 15}. ABSs with \( g^* \) up to \( \sim 6 \) have been observed in InAs/InP core/shell quantum dots coupled to a superconductor \cite{16}. Measurements on bare InAs based quantum dots report on an effective g-factor fluctuating between 2 and 18 \cite{17}. Electric and magnetic field tunable \( g^* \)-factor has been demonstrated in InAs double quantum dots \cite{18}. Some suppression of \( g^* \) can be attributed to confinement \cite{19, 20} as shown experimentally in Ref. \cite{21}, while enhancement of \( g^* \) can result from a combination of Zeeman and orbital contributions in higher subbands \cite{22}.

In this Letter, we show that the effective g-factor of ABSs depends sensitively on the carrier density in the wire, controlled by electrostatic gate voltages. We interpret this observation as revealing how the superconducting density of states is distributed throughout the cross section of the hybrid system. The semiconducting InAs nanowire has large spin-orbit coupling and large negative g-factor, whereas the superconducting Al shell, which induces the proximity effect, has small spin-orbit coupling, and \( g_{\text{Al}} \sim 2 \). At high carrier density in the wire, subgap states predominantly reside in the nanowire, reflecting the properties of the semiconductor; as carriers in the nanowire are depleted, the remaining portion of the states are confined against the InAs/Al interface, with relatively small \( g^* \) and strong proximity effect.

Six devices, denoted 1 to 6, were investigated. All were \( \sim 2 \mu m \) long, made from MBE-grown [0001] wurzite InAs nanowires with hexagonal cross-section \cite{10}. Two devices (2 and 5) had epitaxial Al on two facets, the rest (1, 3, 4, 6) had epitaxial Al on three facets (Figs. 1c, 1d).

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{(a) False-color electron micrograph of Device 1, showing InAs nanowire (green), three-facet Al shell (blue), Ti/Au contacts (yellow) and bottom gates (grey). (b) Schematic cross section of Device 1, showing orientation of applied magnetic field, \( B \), and Al shell relative to bottom gate. (c) Magnitude of effective g-factor, \( |g^*| \), of the lowest subgap state showing a step-like dependence on bottom-gate voltage, \( V_g \). Error bars are root-mean-square difference between upper (electron) and lower (hole) branches. (d) Differential conductance, \( dI/dV \), as a function of source-drain bias, \( V_{\text{bias}} \), at gate voltage \( V_g = 0.0 \text{ V} \). Dashed lines correspond to \( |g^*| = 34 \). (e) Similar to (d), but taken at gate voltage \( V_g = -7.5 \text{ V} \), giving \( |g^*| = 4.3 \).}
\end{figure}
To form a tunnel probe, the Al shell was removed by wet-etching at one end, leaving a ~100 nm segment of bare InAs next to one of the normal-metal leads. The tunneling rate was controlled with the cut-off-gate voltage, $V_c$. The nanowire density in Devices 1, 3, 5 and 6 was controlled with bottom gates at voltage $V_g$ [Fig. 2(a)]. Device 2 used a conducting substrate at voltage $V_{bg}$. Device 4 used only side gates at voltage $V_{bg}$ [Fig. 2(a)]. For all devices, gates were positioned on the side of the nanowire opposite to the Al shell. The magnetic field was orientated along the nanowire axis using a three-axis vector magnet. Standard ac lock-in techniques were used in a dilution refrigerator with a base temperature of ~20 mK.

The Zeeman splitting of ABSs can be extracted from the differential conductance, $dI/dV$, as a function of applied source-drain bias, $V_{bias}$, and magnetic field, $B$, along the wire. The absolute value of the effective $g$-factor, $|g^*|$, was measured using the lowest-energy subgap state as it moved toward zero energy with $B$. Figure 1(c) shows $|g^*|$ of the lowest energy state as a function of bottom-gate voltage $V_g$ for Device 1, displaying a characteristic step-like behavior as a function of gate voltage. A $B$ sweep at $V_g = 0.0$ V displays a quasi-continuous band of ABSs with $|g^*| = 34$, as shown in Fig. 1(d). The superconducting gap is quenched at roughly $B = 0.2$ T, beyond which the evolution of levels cannot be easily tracked. When $V_g$ is changed from $-2$ V to $-4$ V, $|g^*|$ abruptly decreases, saturating at $|g^*| \approx 5$ for more negative values of $V_g$. In contrast to the behavior at $V_g = 0$ V where the continuum of states moved toward zero energy, evolution of single, discrete ABS can be clearly followed at $V_g = -7.5$ V [Fig. 1(e)]. In this case, the ABS with $|g^*| = 4.3$ reaches zero energy at $B = 1.5$ T, with hard gaps on both sides of the state throughout the sweep.

Device 2 showed qualitatively similar behavior. For back-gate voltages in the range of 4 V to 6 V, $|g^*|$ was $\sim 20$ [Fig. 2(c)]. A $B$ sweep taken at $V_{bg} = 4.9$ V shows a quasi-continuous band of subgap-states with $|g^*| = 19$ crossing zero-bias at $B = 0.4$ T, to become a quasi-continuum throughout the subgap region at higher field. For $V_{bg}$ in the range $-2$ V to $-8$ V, $|g^*|$ remained roughly constant at $\sim 5$. At $V_{bg} = -2.4$ V, a single sharp ABS was observed, with $|g^*| = 4.1$ coalescing at $B = 1$ T and sticking to zero energy for higher fields, consistent with the emergence of a MBS. The narrow zero-bias conductance peak remains insensitive to magnetic field from 1 to 2 T.

We propose two contributing factors to the step-like evolution of $|g^*|$ as carriers are depleted by the gate voltage. The first is the reduction of the orbital contribution to $|g^*|$ as the wire is depleted across most of its cross section [19] [20] [22]. The second is that the remaining density in the nanowire is predominately against the interface with the Al shell, strongly coupled to the superconductor [23] [24].

A clearer view of excited states above the lowest energy ABS, including the closing and reopening of a gap coincident with the appearance of a zero-bias conductance peak, can be seen for Device 3 in Figs. 3(a,b). A $B$ sweep at $V_g = -4.0$ V reveals a quasi-continuous band of ABSs with $|g^*| = 10$. At low field, the gap is hard on the low-energy side of the ABS edge, yielding small values of $dI/dV$ at higher fields, $dI/dV$ is nonzero throughout the subgap region. Around $B = 0.9$ T an excited subgap-state becomes visible. It increases in energy and merges with the higher-energy ABSs around $B = 1.1$ T. The lowest energy state evolves into a zero-bias peak at roughly $B = 1.0$ T. The zero-mode can be followed up to $\sim 1.7$ T, whereafter it merges with the high subgap density.

Lowering the gate voltage changes the picture qualitatively. The tunneling spectrum dependence on magnetic field, taken at $V_g = -9.4$ V displays a discrete, low-energy ABS with $|g^*| = 5.4$, see Fig. 3(c). The ABS merge at $B = 1.0$ T to form a well-defined zero-bias peak, clearly visible for the remaining measured range. The feature of gap closing-reopening is absent in this case. The subgap conductance is low throughout the sweep [Fig. 3(d)], suggesting a low-density ABS regime.

Qualitatively similar behavior was seen in multiple device. For Device 4, a $B$ sweep at $V_{bg} = -5.1$ V displays a quasi-continuous band of ABSs with $|g^*| = 10$ emerging from above the gap at $B = 0.3$ T. Around $B = 1.0$ T an excited subgap-state starts to gain energy with increas-
This is presumably due to the change in nanowire parameters. In Fig. 3(c), magnetic field sweeps show a single ABS closing then reopens at the same value of $B = 1.0$ T. In Fig. 4(a) show a gap to the lowest excited state that nearly closes then reopens at the same value of $B = 1.0$ T reveals an oscillatory subgap-state evolution [Fig. 4(e)]. A zero-bias peak with conductance exceeding $0.8 \, (e^2/\hbar)$ [Fig. 4(f)] spans the range from $V_b = -1.84 \, V$ to $V_b = -1.80 \, V$.

The evolution of $V_{bias}$ spectra with $B$ in Figs. 3(a) and 4(a) show a gap to the lowest excited state that nearly closes then reopens at the same value of $B$ where the zero-bias peak appears, a characteristic feature of a topological phase transition [26, 28]. The residual gap at the phase transition in both devices is more than twice as small as the induced pairing potential. This implies a small topological coherence and nanowire length ratio, indicating a high quality MBS [29]. At lower densities [Figs. 3(c), 4(c)], magnetic field sweeps show a single ABS coalescing into a zero-bias peak, however, the gap closing-reopening feature is not visible in tunneling conductance. This is presumably due to the change in nanowire parameters, such as Rashba spin-orbit coupling, as the electric field generated by the gate voltage is increased.

A topological phase transition can also be induced by modifying density in the nanowire—controlled by gate voltage—at large fixed $B$ [29, 30]. The oscillatory subgap dependence [Fig. 4(c)] on gate voltage is a distinctive feature of spatially overlapping MBSs. The zero-bias peak sticking at zero seen in Fig. 4(e) is characteristic of a MBS rather than a trivial ABS. Noteworthy is the height of the zero-bias peak [Fig. 4(f)] approaching the theoretically predicted value of $2 \, e^2/\hbar$ [31, 32].

The tunneling spectrum for Device 6 further illustrates the closing and reopening of the gap in greater detail [Fig. 5]. Evolution of the subgap states can be followed rather clearly: A low energy ABS with $|g^*| = 5.0$ gives rise to a zero-bias peak at 0.8 T, which persists beyond 2 T; The first excited state reaches its minimum at 1 T, then rises in energy and merges with the higher energy ABS. A second excited state appears around $B = 1$ T.

In summary, we have measured the effective $g$-factor of subgap states in InAs nanowires with epitaxial Al as a function of density of carriers in the wire, controlled by
gate voltages, in a number of device geometries. Signatures of Majorana bound states are detected at different charge carrier densities. The observations are reproduced with multiple devices. We provide a qualitative interpretation of the data. In order to understand the experimental findings in more detail, a refined electrostatic modeling considering both Zeeman and orbital contributions is desired.

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FIG. 5: (a) Evolution of subgap states in B-field for Device 6 taken at $V_g = -5.5$ V. (b) Line-cuts from (a) at various magnetic fields. The low-energy subgap-states split at low field, the inner branches of ABS with $|g'| = 5.0$ merge around $B = 0.8$ T and stick to zero-bias. A pair of low-conductance excited states resembling gap closing-reopening are visible around $B = 0.8$ T.