Topological superconductivity in metallic nanowires fabricated with a scanning tunneling microscope

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Abstract. We report on several low-temperature experiments supporting the presence of Majorana fermions in superconducting lead nanowires fabricated with a scanning tunneling microscope (STM). These nanowires are the connecting bridges between the STM tip and the sample resulting from indentation–retraction processes. We show here that by a controlled tuning of the nanowire region, in which superconductivity is confined by applied magnetic fields, the conductance curves obtained in these situations are indicative of topological superconductivity and Majorana fermions. The most prominent feature of this behavior is the emergence of a zero bias peak in the conductance curves, superimposed on a background characteristic of the conductance between a normal metal and a superconductor in the Andreev regime. The zero bias peak emerges in some nanowires when a magnetic field larger than the lead bulk critical field is applied. This field drives one of the electrodes into the normal state while the other, the tip, remains superconducting on its apex. Meanwhile a topological superconducting state appears in the connecting nanowire of nanometric size.
Since Kitaev’s proposal [1] in 2001 that Majorana fermions could be found in condensed matter systems, several efforts, both theoretical and experimental, have been addressed to establish the conditions and requirements to detect such elusive particles. It was realized that topological insulators were a platform for Majorana states [2]. Most of these activities involve the use of the superconducting state, because of the close similarity between a Majorana fermion (a particle that is its own antiparticle) and the quasiparticles of a p-wave spinless superconducting condensate that could be found close to (or at) its ground energy state (i.e. Fermi level) under some specific conditions and requirements. The different possibilities, requisites and conditions to be fulfilled by a superconducting system in order to present Majorana fermions have been extensively discussed in recent years [3–9]. One of the ‘easiest’ ways to obtain such p-wave spinless superconducting condensate consists of using a standard s-wave superconductor, whose electronic bands are split depending on the spin polarization by means of a spin–orbit coupling, and an external magnetic field which opens a Zeeman gap and a region without spin degeneracy. The effective spinless regime, where the standard superconducting states become a topological one, will be strongly dependent on the values of the superconducting energy gap, the Zeeman gap, the spin–orbit coupling and the filling of the bands (i.e. Fermi level). The existence of well-defined energy bands and levels will favor the fulfilment of the required conditions. Therefore, one-dimensional (1D) or quasi-1D systems with a small number of quantum modes will be more suited to the emergence of Majorana fermions.

Experimental efforts toward the realization of these requirements have focused mainly on the use of quasi-1D semiconducting nanowires [10–13], which present a strong spin–orbit coupling, and where superconductivity is induced by proximity to an s-wave superconductor. Mourik et al [11] have recently reported experiments on such a system, showing evidence of the detection of Majorana fermions in a semiconducting nanowire by means of tunneling spectroscopy measurements.

In a recent publication [14] we have shown a different approach to the experimental realization of the above-mentioned ‘recipe’. Instead of using a semiconductor as the ‘source’ of the spin–orbit coupling, we use lead, a metallic s-wave superconductor below 7 K, which presents a moderate spin–orbit coupling.

Indeed, there are several differences between the superconducting state developed in a semiconductor and the one present in a metal, mainly related to the characteristic energy...
and length scales of the superconducting condensate which are closely related to the Fermi wavelength in each type of material.

Another important aspect is related to the requirement of a small number of quantum electronic modes involved in the experimental object. In the case of semiconductors, due to the low electronic density of states, this is quite easily achieved by using quasi-1D nanowires, with diameter in the range of 100 nm and 1 µm length. Such nanowires may be gated in order to move the Fermi level so that the above-mentioned requirements are achieved. However, if we use a metal, the condition of having a small number (of the order of one) of quantum modes, or channels, is only achieved if the diameter of the nanowire where topological superconductivity will be induced is of the order of a few atoms [15]. This small (atomic) dimension of the nanowire implies that the effective superconducting coherence length will also be strongly reduced. Random scattering at the boundaries implies that the elastic mean free path, \( \ell \), will be of the order of the sample width, which, for a small number of channels within the nanowire, cannot be larger than a few nanometers. Then, the superconducting coherence length \( \xi \approx \sqrt{\xi_0 \ell} \) will be significantly reduced. For \( \xi_0 \approx 80 \text{ nm} \) and \( \ell \approx 1 \text{ nm} \), we find \( \xi \approx 9 \text{ nm} \), which is comparable with typical nanowire lengths.

We have addressed the realization of such atomic scale nanowires by using a scanning tunneling microscope (STM), which allows one to establish atomic scale contacts between metallic electrodes (usually called ‘tip’ and ‘sample’) [16, 17]. By using the different capabilities and features of the STM system, it is possible to control and modify this atomic scale contact, detecting the addition of individual atoms to the contact [18]. As an example, it has been possible to create gold nanowires consisting of a chain of single atoms between the tip and sample gold electrodes, where the electric conductance involves a single quantum channel [19].

The low value of the spin–orbit coupling in lead, compared with the value in some semiconducting materials, is an added difficulty in order to accomplish the requirements to create a topological superconducting phase in the nanowire. Lead is a type-I superconductor, with a superconducting gap of 1.35 meV at zero field and zero temperature, and a rather low bulk critical field (75 mT at 300 mK). However, the nanoscopic apex of the tip, and sharp elongated nanostructures, may remain superconducting well above the bulk critical field [17]. The estimated values of the Landé \( g \) factor for bulk lead are in the range \( g \approx 4–6 \) [20, 21], which can be enhanced by interaction effects in nanoscopic samples [22]. A magnetic field, \( B \), in the range of 100 mT leads to a Zeeman energy, \( E_Z = g \mu_B B / 2 \), in the range 0.04–0.06 meV and, as the gap is expected to go smoothly to zero as the magnetic field increases, it is possible that a regime where the Zeeman coupling is larger than the superconducting gap is present in some of these lead nanowires. The position of the Fermi energy at the nanowire will depend on details of the electrostatic potential which, in turn, is determined by the geometry of the contact and the voltage distribution within it. Therefore, it is possible that some of such Pb nanowires present a Fermi energy level located within the Zeeman gap, due to random fluctuations in the electrostatic potential. It might be possible to tune the parameters of the device by changing the bias voltage, although a detailed analysis of this topic lies outside the scope of this work.

Our experimental configuration, shown schematically in figure 1, presents another peculiarity that poses a relevant difference compared with the above-mentioned experiments involving semiconductors. The lead nanowire, which will become a topological superconductor
Figure 1. Schematics of the experimental configuration. An STM tip, with an atomically sharp nanotip, is brought into contact with a sample of the same material, lead in our case (a, b). The STM control system can be used to adjust the tunneling current, control the size of the contact established between tip and sample and eventually create a nanostructure between tip and sample by means of indentation–retraction cycles.

under an external magnetic field, is created by indenting the STM Pb tip (which in the end is of nanoscopic dimensions) into a Pb surface (which can be considered ‘flat’ compared to the tip).

We have shown in previous work [17, 23–25] that sharp and elongated nanotips or nanoprotusions on the sample surface resulting from the tip–sample indentations remain superconducting for magnetic fields much larger than the bulk critical field of lead, depending on their sharpness and dimensions compared with the bulk coherence length and penetration depth, while the larger bulk, flat or blunt parts of the Pb tip and sample have become normal.

Thus, we have a system where the topological superconducting Pb nanowire, which may present Majorana fermions, is in direct contact with (has emerged from) a bulk of the same material in normal state, and it is probed by a superconducting electrode (the nanotip) using and involving a very small number of quantum channels (typically between three and ten).

The probe, the nanotip, is in direct contact with the nanowire. The spectroscopic measurements will take place in a transmission regime where Andreev reflections play a key role [26, 27]. The shape and features of the spectroscopic curves (IV curves) in this Andreev regime are strongly dependent on the coupling and transmission probability of each individual quantum channel [25, 28–30], thus providing a detailed quantification of the number of quantum channels involved in the conduction process (and at the nanowire), and their individual transmission.

In the following sections we present our recent experiments on these topological nanowires. We discuss the experimental evidence of the emergence of a topological superconducting phase at the nanowire/nanocontact region; the comparison of this type of result with those that could be considered ‘expected’ or ‘normal’ for standard S–S or S–N situations; the observability of such ‘unexpected’ results, which we assign to the presence of Majorana fermions, depending on the number of quantum channels involved and their transmissions; and the analysis of the zero bias current detected in the different superconducting regimes of the nanowire. The evolution of this zero bias current may be of key importance in the study and detection of Majorana fermions, as it would be a direct indication of the splitting of Cooper pairs injected from the superconducting nanotip into pairs of Majorana bound states in a topological superconducting nanowire with an extremely small superconducting gap.
Figure 2. STM topographic image of a Pb surface where a nanometer size protusion, created after a tip–sample indentation process, is clearly visible. The nanostructure is 35 nm wide at its base, and 25 nm high. The actual lateral dimensions of the nanostructure will be smaller, as it is scanned by an equivalent protusion at the tip apex. The image was taken at 0.3 K, for a tunneling resistance of 10 MΩ and a voltage bias of 10 mV.

2. Experiments

2.1. Sample fabrication

The experiments were performed at 0.3 K, with the STM installed in a 3He cryostat equipped with a superconducting solenoid. The STM was used to produce indentations, in the range of a few tens of nanometers, of a Pb tip on a Pb sample, in order to fabricate sharp elongated nanotips and nano-protrusions on the sample surface. Bulk Pb tip and sample pieces were cut from a high-purity lead bar (Goodfellow, purity 99.999%) just prior to being installed in the vacuum chamber of the STM cryostat system. Along the indentation processes we recorded the variation of the current across the contact as a function of the relative displacement between tip and sample, for a fixed bias voltage (typically in the range of 10 mV). The analysis of the current versus displacement curves allows one to extract information about the sharpness and dimensions of the nanostructures resulting from the indentation process [16]. When the contact is broken (by receding the tip), it is possible to scan and visualize the part of the nanostructure remaining on the sample surface (figure 2). An equivalent nanostructure remains at the tip apex. This kind of process allows us to create sharp elongated nanotips, with a cone-like apex with typical dimensions ranging from 20 to 100 nm in length and 20 to 100 nm in diameter [17].

Once a sharp Pb nanotip has been created, we move to a ‘flat’ region of the sample (far from the nanoprotusion) and we proceed with the spectroscopic characterization of the nanotip. Making use of the STM feedback control loop we go from tunneling conditions toward atomic scale contact between tip and sample. This process is followed in detail by recording the current versus displacement variations and the acquisition of current versus voltage curves along the process. The $IV$ (and conductance, $dI/dV$ versus $V$) curves evolve from the usual gapped structure in tunneling to a much richer structure (the subharmonic gap structure) as the contact is established, due to the increasing contribution of Andreev reflection processes.
As mentioned above, the subharmonic gap structure in the spectroscopic curves allows us to determine precisely the number of quantum channels and their individual coupling or transmission (figure 3). It was shown that in atomic scale contacts the individual channel transmissions, $\{\tau_n\}$, can be obtained from the experimental current–voltage, $IV$, curve by fitting to the sum of $N$ one-channel $IV$ curves, $I(V) = \sum_{n=1}^{N} f(\tau_n, V)$ [30, 31], which have been calculated elsewhere for arbitrary transmission $\tau$ [32, 33].

A zero bias current is easily observed in the curves, signature of transmission of Cooper pairs between the electrodes (dc Josephson effect). Typically, voltage bias is ramped between ±10 mV, and the conductance is obtained by the numerical derivative of the $IV$ data.

Once the atomic scale contact is created, by indenting the sharp elongated nanotip onto the Pb sample, we can perform small indentation–elongation cycles, with nominal displacements smaller than 10 nm. This leads, in each cycle, to atomic scale rearrangements in the nanocontact region (figure 4). Eventually, these mechanical processes result in a nanometric length wire, a nanowire, whose cross section is made up of a small number of atoms, as extracted from the quantum channel analysis of the conductance curves. These nanowires are expected to present a topological superconducting state, and eventually Majorana fermions, when a magnetic field is applied [14].

In these experiments, different nanostructures, with conductance values at the constriction ranging from $2G_0$ to $50G_0$ ($G_0 = 2e^2/h$ is the conductance quantum), were created, and we
Figure 4. (a) Experimental curves obtained in a series of eight consecutive indentation–elongation cycles of a Pb tip into a Pb sample. From cycle to cycle, it can be seen that the nanocontact (i.e. the nanowire) between tip and sample may be elongated in different ways before breaking it and entering the tunneling regime (see the exponential variation of the conductance versus electrode displacement in the logarithmic plot (b)). Curves are labelled with numbers to indicate the acquisition sequence (odd numbers: breaking the contact; even numbers: going back to contact).

have analyzed the evolution of their spectroscopic characteristics versus magnetic field in order to investigate the presence of Majorana fermions. The high quality of the fittings of the experimental curves to the theoretical modelizations (figure 3(a)), and the high barrier value (∼3 eV) extracted from the exponential tunneling regime in figure 4(b), indicate that the experiments actually involve clean lead nanostructures.

2.2. Sample characterization

As shown in figure 5, different types of conductance curves (i.e. $dI/dV$ versus $V$) can be obtained depending on the geometry of the electrodes at the nanoscale close to the contact, and the values of the external magnetic field [24, 34]. Figure 5(a) shows the typical result obtained at zero field, and for $H < H_c$ bulk. The full subharmonic gap structure due to multiple Andreev reflections, and a sharp zero bias peak due to Josephson current are obtained, the exact features depending on the transmissions of the different quantum channels involved in the process. The other panels show the more representative types of conductance curves that can be obtained for $H > H_c$ bulk. We also show a sketch of the geometry of the nanostructure leading to each observed result.
Figure 5. Different types of conductance curves that can be obtained in the studied nanostructures and nanocontacts. The left panel shows the different types of conductance curves: (a) S–S type: for $H < H_c$, and for $H > H_c$ if there are sharp protusions at nanotip and sample that remain in superconducting state; (b) S–S’ type: for $H > H_c$, corresponding to a sharp nanotip and a blunt nanostructure at the sample, which presents superconductivity with strong pair breaking; (c) S–N type: for $H > H_c$, the sharp nanotip remains superconducting, and the flat sample is in normal state; (d) in this type, a zero bias peak appears for $H > H_c$, and we consider that a nanowire is created between the sharp S nanotip and the N sample. In the right panel we sketch the geometries corresponding to the different types of curves.

If the contact is established between similar sharp protusions in the tip and sample, both remain superconducting at $H > H_c$, showing results similar to the ones at zero field. If the sample side of the nanostructure is more rounded or blunt than the nanotip, S–S features are still present, but very rounded due to pair-breaking effects at the sample, now more sensitive to the effect of the applied magnetic field (figure 5(b)). When the nanotip contacts a flat region of the sample, we obtain results like the one in figure 5(c), corresponding to a situation involving NS Andreev reflections, where only the nanotip remains superconducting, and all the samples are in normal state. Finally, in figure 5(d) we show a type of conductance curve that can be obtained after modifying situations like the ones shown in figure 5(c) by means of indentation–retraction cycles. The new feature is a zero bias peak in the conductance, corresponding to a finite zero bias current, which is superimposed on the NS Andreev-like conductance for finite bias. We consider that, in this case, a nanowire is created between the tip and sample.

In the following, we will describe the evolution with magnetic field of the conductance curves in the different nanostructures presented above.
Figure 6. Examples of typical evolution of the spectroscopic conductance curves of different nanowires as the applied magnetic field is varied across its bulk critical value ($H_c = 75$ mT). The panels show curves obtained at magnetic fields from 30 mT (bottom) to 120 mT (top), in 10 mT increments. Curves in green correspond to $H < H_c$, while magenta is used for $H > H_c$. In (a) there is a clear and sharp transition from well-defined curves showing standard SS multiple Andreev reflections features below $H_c$, to NS Andreev curves for $H > H_c$, corresponding to a sharp tip contacting a flat region on the sample. In (b), the tip was located on a bump on the surface, resulting in rounded spectra for $H > H_c$, due to the bump being still in superconducting state, but under strong pair breaking effects due to the field. Panel (c) shows the conductance curves that we consider due to the presence of Majorana states at the constriction: for $H > H_c$ a zero bias peak appears, superimposed on a conductance background corresponding to an apparent NS situation, similar to those in (a). Curves are normalized at their high-voltage value, and shifted vertically for clarity.

3. Experimental results and discussion

In figure 6(a) we show the evolution of the conductance curves versus magnetic field in a situation where no ‘anomalous’ or topological superconducting state is expected to happen. The conductance of this nanostructure is $6G_0$. The atomically sharp nanotip is contacting a ‘flat’ region of the sample and no indentation–elongation cycles were performed. In this situation, as we increase the external magnetic field, once the bulk critical field of lead is crossed, we observe a sharp transition from SS spectroscopic curves (showing a very rich subharmonic gap structure and Josephson current) below $H_c$, to NS like curves, with no indication of zero bias current. Obviously, for $H > H_c$ only the nanotip remains superconducting, and the bulk parts of both electrodes have become normal.

If the contact is established with the nanotip located onto a ‘bumpy’ spot of the sample, this region may remain superconducting above $H_c$, but showing strong pair breaking effects...
Figure 7. (Left) Schematics of the experimental system, indicating the different basic components and their state under $H > H_c$: the nanotip, superconducting; the nanowire, topological superconducting with Majorana fermions; and the sample, in normal state. (Right) Schematics of the transport process at $V = 0$, leading to finite current, mediated by the Majorana fermions (MFs) (‘$e/h$’ indicates the presence of electrons and holes in the normal metal).

(rounding and shift of the peaks corresponding to the subharmonic gap structure, accompanied by a progressive decrease of the signal at zero bias), and eventually becomes normal. An example of this case is shown in figure 6(b), corresponding to a nanostructure with conductance $4G_0$, and it is also considered as an expected one [24].

As we showed in recent work [14], some nanostructures present peculiar behavior at magnetic fields above $H_c$. The corresponding spectroscopic curves show, for $V \neq 0$, clear and well-defined NS features, which can be fitted in terms of quantum channels and NS Andreev reflections (indicating that only one electrode remains superconducting, the nanotip), while a finite current at zero bias, like the one corresponding to the dc Josephson effect in the S–S case, can still be clearly detected (figure 6(c)). We have observed that, under $H > H_c$, the zero bias feature may disappear, and eventually reappear, after performing small indentation–elongation cycles.

We consider this behavior, the emergence of a zero peak, superimposed onto a standard NS Andreev-like quasiparticle curve, as a signature of Majorana fermions in the nanowire that has been created between tip and sample. As discussed earlier, we describe the wire as a dirty superconductor, with the mean free path, $\ell$, limited by the width of the wire. The effective coherence length within the wire is reduced to $\xi \approx 9$ nm. Hence, the two ends of a sufficiently long wire are decoupled, and the Andreev states pinned at them can be considered independently, see figure 7, left, where we also sketch the process needed to obtain zero bias current between a superconductor and a normal electrode, mediated by the presence of a topological superconductor with Majorana fermions. In the standard N–S case, when the topological superconducting nanowire is not present, no current can be obtained at zero bias, because of the presence of the energy gap in the superconductor, and the requirement of finite difference between the Fermi levels in N and S for Andreev reflection processes to be allowed.

Next, we investigate the experimental conditions that allow us to observe the phenomena that we ascribe to the presence of a topological superconducting nanowire with Majorana fermions. As was mentioned in the introduction, it is possible to extract the number of quantum channels and their transmissions involved in the transmission processes leading to the different spectroscopic curves. This can be done both in the low-field regime ($H < H_c$) bulk, SS
Figure 8. Calculated conductance curves corresponding to different values of the transmission probability of a single quantum channel. We show the SS situation (top) and the NS case (bottom). The curves are calculated for a single channel, with transmissions from 0.02 to 1. The NS case was calculated introducing a small value for the magnetic-induced pair breaking, $\Gamma = 0.005 - \Delta$

characteristics) and in the topological situation ($H > H_c$ bulk, NS quasiparticle characteristics). In figure 8 we show calculated one-channel conductance curves corresponding to different values of the transmission probability. The NS conductance curves (bottom panels in figure 8) are calculated following the BTK formalism [27] while the SS curves (top panels in figure 8) are calculated following [32, 33].

The actual conductance curve corresponding to a given experimental situation will be the result of the addition of the conductance from different channels with different transmissions, thus resulting in a unique type and shape of the conductance curve in each case.

The analysis of tens of nanowires showed that, for similar values of the total conductance, typically in the range of 3–10$G_0$, only those that presented high transparency channels (with transmission probability very close to one) showed a well-defined zero bias current together with an NS quasiparticle Andreev regime, independently of the channel distribution in the SS low-field regime. In figure 9 we show two examples illustrating the different situations that we have found regarding the conductance characteristics of the nanowires under a magnetic field.
Figure 9. Conductance curves, and their corresponding fittings in terms of quantum channels and Andreev reflections, for two different nanocontacts, showing curves taken below $H_c$ (green) and above $H_c$ (magenta). The left panel shows a ‘standard’ SS to NS transition in a contact with conductance $8G_0$, while for the contact shown in the right panel, with conductance $7G_0$, a sharp peak at zero bias appears superimposed on an NS conductance for $H > H_c$, corresponding to a finite zero bias current. These two types of behavior could be achieved and tuned by modifications of the atomic arrangement in the nanowire by means of indentation–elongation cycles in the range of 1 nm. Panels (a) and (d) show the conductance curves. Panels (b) and (e) show a zoom of the region of the IV curves close to zero bias. Panels (c) and (f) show the distributions of transmissions of the quantum channels used to generate the corresponding calculated fitting curves, shown in black in panels (a) and (d). (Conductance curves in the low-field regime (green) are shifted vertically for clarity.)

The value of the zero bias current in the topological regime (magenta curves, in figures 9(d)–(f)) was in these cases always in the range of 1/4–1/5 of the value obtained at zero field (or for $H < H_c$ bulk). This observation can be taken as a proof to rule out the possibility that this zero bias current in the topological regime is just Josephson current between the superconducting tip (with a gap value equal to the one at zero field, $\Delta_0$) and a superconducting region of the sample with a very reduced gap. In the conductance curve no signature of a second gap is detected. We can estimate that the second gap, $\Delta_2$, would be less than 2% of $\Delta_0$, while the gap at the tip, $\Delta_1$, equals $\Delta_0$. Josephson current in such an $S_1$–$S_2$ situation would be of the order of $\Delta_1\Delta_2/{(\Delta_1 + \Delta_2)}$, leading to a value of the order of $\Delta_0/50$, a quantity 25 times smaller than $\Delta_0/2$, the value corresponding to identical gaps. Note that in our experiments, the zero bias current is reduced by just a factor of 4 or 5, not 25, with respect to the case when both electrodes are in the superconducting state.

Let us note that the topological superconductor, with a reduced gap value and Majorana zero modes, is probed by a superconductor (the nanotip). In this situation, the zero bias
conductance should not present the typical limiting value of $2e^2/h$ per channel due to Majorana-induced resonant Andreev reflection, as obtained when the topological superconductor is probed by a normal metal [35]. In our experiment, due to the superconducting probe, multiple Andreev reflections should be present, leading to a larger zero bias conductance arising from these Majorana-induced multiple resonant Andreev reflections.

This is a situation equivalent to the one present in the ‘standard’ NS versus SS cases. For a high transparency ($\tau = 1$) barrier, the zero bias conductance is $2G_0$ ($4e^2/h$) per channel in the NS case, while it diverges in the SS case (see the black curves in the left panels of figure 8).

The relevance of the presence of high transmission channels in order to observe the zero bias feature (i.e. Majorana fermions) has been addressed by studying nanowires whose total conductance is slightly modified in a controlled way. With the nanowire in the topological regime ($H > H_c$ bulk), we vary the conductance by a value equivalent to $1G_0$ or less. The example in figure 10(a) shows that the curve with larger total conductance presents a slightly smaller zero bias peak. This behavior is very similar to the one observed in S–S nanocontacts [36], where it was seen that the value of the zero bias current depends mainly on the individual transmissions of the quantum channels, and not on the total conductance of the nanocontact. These observations are compatible with the analysis in [37], where the robustness of the Majorana signatures in high transparency situations was studied.

Finally, we show an example of the evolution of the zero bias current with temperature. We wish to note that different nanowires could present slightly different behaviors, but the overall behavior is the one depicted in figure 11. We prepare a nanostructure with a conductance value

**Figure 10.** Example of a situation where a slightly increased conductance of the nanowire (blue curves, (a)) is not accompanied by an increase of the zero bias current, as can be seen in (b) and the zoomed zero bias region (c).
of $5G_0$, and apply a magnetic field of 200 mT. As temperature increases, the Andreev-gap-related features in the conductance curves are rounded and move toward zero bias (i.e. the gap at the nanotip decreases as temperature increases), disappearing at about 6 K in this case, while the signature corresponding to zero bias current was observed to disappear at a much lower $T$, between 1.5 and 2 K. This is an indication of a critical temperature for the topological superconducting nanowire lower, between 25 and 33%, than that of the ‘parent’ superconducting material.

In recent work, Potter and Lee [38] proposed a system where surface states in a metallic gold nanowire (in contact with an s-wave superconductor) may fulfill the requirements to present topological superconductivity and Majorana fermions. They suggest that Majorana fermions, arising from surface states in the metallic nanowire, could be detected by an STM tip. The nanowire would have dimensions similar to the ones used in semiconducting wires (in the range of 100 nm width and 1000 nm length), and should be grown in the (111) orientation. In our experimental realization, a metallic conducting nanowire is also considered to develop topological superconductivity and Majorana fermions. However, the nanowire itself is made up

Figure 11. Evolution of the zero bias feature with temperature in the topological superconducting regime of the nanowire. (a) Selected conductance curves (normalized and shifted vertically) obtained at 200 mT for different temperatures (temperature increases from top to bottom, from 0.4 to 1.9 K in increments of 0.25 K). The gap-like feature due to Andreev reflections was observed to disappear at 6 K. (b) Variation of the zero bias current with temperature.

Figure 12. Sketch of the experimental systems proposed by Potter and Lee involving a metallic nanowire (a) and the one proposed in this work (b).
of a superconducting material, lead, and brought to atomic scale in order to carry a few quantum channels. Moreover, in our case, the superconducting gap at the nanowire is reduced (or almost destroyed) by the external magnetic field, and it is not proximity induced by a ‘back-up’ s-wave superconductor. We consider that these differences, shown schematically in figure 12, should be considered in further theoretical work dealing with the presence and detection of Majorana fermions in topological superconducting metallic nanostructures.

4. Conclusions

We have reported on a study of metallic superconducting nanostructures and nanowires which, under given values of the external magnetic field and number and coupling of the quantum channels at the nanowire, may lead to the observation of features that can be ascribed to the presence of Majorana fermions when a topological superconducting state is induced in the nanowire. We have shown that the channel number and transparency are key elements in the detection of Majorana fermions in these systems, which appear as a zero bias current superimposed onto a standard NS quasiparticle curve in the Andreev reflection regime. Applying, using the STM capabilities, small elongation–retraction cycles of the order of 1 nm to the nanowire lead to the disappearance or appearance of the zero bias signature. When the conductance curves are analyzed, we obtain that the presence of a few high transparency channels is generally associated with the presence of the zero bias peak.

We consider that the metallic systems presented in this work can be an alternative to other systems, involving mainly semiconductors, currently under study in the search for Majorana fermions in condensed matter physics. An open question, to be considered in future work, is the fine tuning of the parameters which characterize the devices. This can be achieved by small changes in the structure once the basic features have been fixed, and by control of the region where the voltage drops, which, in turn, depends on the bias voltage.

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References

[1] Kitaev A Y 2001 Unpaired Majorana fermions in quantum wires Phys.—Usp. 44 131–6
[2] Fu L and Kane C L 2008 Superconducting proximity effect and Majorana fermions at the surface of a topological insulator Phys. Rev. Lett. 100 096407
[3] Lutchyn R M, Sau J D and Das Sarma S 2010 Majorana fermions and a topological phase transition in semiconductor–superconductor heterostructures Phys. Rev. Lett. 105 077001
[4] Oreg Y, Refael G and von Oppen F 2010 Helical liquids and Majorana bound states in quantum wires Phys. Rev. Lett. 105 177002
[5] Sau J D et al 2010 Generic new platform for topological quantum computation using semiconductor heterostructures Phys. Rev. Lett. 104 040502
[6] Sau J D et al 2010 Non-Abelian quantum order in spin–orbit-coupled semiconductors: search for topological Majorana particles in solid-state systems Phys. Rev. B 82 214509
[7] Alicea J 2012 New directions in the pursuit of Majorana fermions in solid state systems Rep. Prog. Phys. 75 076501
[8] Leijnse M and Flensberg K 2012 Introduction to topological superconductivity and Majorana fermions Semicond. Sci. Technol. 27 124003
[9] Beenakker C W J 2013 Search for Majorana fermions in superconductors Annu. Rev. Condens. Matter Phys. 4 113–36
[10] Rokhinson L P, Liu X and Furdyna J K 2012 The fractional A.C. Josephson effect in a semiconductor–superconductor nanowire as a signature of Majorana particles Nature Phys. 8 795–9
[11] Mourik V et al 2012 Signatures of Majorana fermions in hybrid superconductor–semiconductor nanowire devices Science 336 1003–7
[12] Anindya Das Y R, Most Y, Oreg Y, Heiblum M and Shtrikman H 2012 Zero-bias peaks and splitting in an Al–InAs nanowire topological superconductor as a signature of Majorana fermions Nature Phys. 8 887–95
[13] Finck A D K et al 2013 Anomalous modulation of a zero-bias peak in a hybrid nanowire-superconductor device Phys. Rev. Lett. 110 126406
[14] Rodrigo J G et al 2012 Topological superconducting state of lead nanowires in an external magnetic field Phys. Rev. Lett. 109 237003
[15] Agrait N, Yeyati A L and van Ruitenbeek J M 2003 Quantum properties of atomic-sized conductors Phys. Rep. 377 81–279
[16] Agrait N et al 1993 Atomic-scale connective neck formation and characterization Phys. Rev. B 48 8499–501
[17] Rodrigo J G et al 2004 Superconducting nanostructures fabricated with the scanning tunnelling microscope J. Phys.: Condens. Matter 16 R1151–82
[18] Agrait N, Rodrigo J G and Vieira S 1993 Conductance steps and quantization in atomic-size contacts Phys. Rev. B 47 12345–8
[19] Yanson A I et al 1998 Formation and manipulation of a metallic wire of single gold atoms Nature 395 783–5
[20] Phillips R A and Gold A V 1969 Landau-level widths, effective masses, and magnetic-interaction effects in lead Phys. Rev. 178 932–48
[21] Everett P M and Grenier C G 1978 Phase smearing and magnetic interaction in lead Phys. Rev. B 18 4477–86
[22] Gorokhov D A and Brouwer P W 2003 Fluctuations of $g$ factors in metal nanoparticles: effects of electron–electron interaction and spin–orbit scattering Phys. Rev. Lett. 91 186602
[23] Poza M et al 1998 Nanosized superconducting constrictions Phys. Rev. B 58 11173–6
[24] Rodrigo J G, Suderow H and Vieira S 2003 Superconducting nanobridges under magnetic fields Phys. Status Solidi b 237 386–93
[25] Suderow H et al 2000 Andreev scattering in nanoscopic junctions in a magnetic field Europhys. Lett. 50 749
[26] Octavio M et al 1983 Subharmonic energy-gap structure in superconducting constrictions Phys. Rev. B 27 6739–46
[27] Blonder G E, Tinkham M and Klapwijk T M 1982 Transition from metallic to tunneling regimes in superconducting microconstrictions: excess current, charge imbalance, and supercurrent conversion Phys. Rev. B 25 4515–32
[28] Brandbyge M, Sorensen M R and Jacobsen K W 1997 Conductance eigenchannels in nanocontacts Phys. Rev. B 56 14956–9
[29] Cuevas J C, Yeyati A L and Martin-Rodero A 1998 Microscopic origin of conducting channels in metallic atomic-size contacts Phys. Rev. Lett. 80 1066–9
[30] Scheer E et al 1998 The signature of chemical valence in the electrical conduction through a single-atom contact Nature 394 154–7
[31] Scheer E et al 1997 Conduction channel transmissions of atomic-size aluminum contacts Phys. Rev. Lett. 78 3535–8

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[32] Averin D and Bardas A 1995 AC Josephson effect in a single quantum channel Phys. Rev. Lett. 75 1831–4
[33] Cuevas J C, MartinRodero A and Yeyati A L 1996 Hamiltonian approach to the transport properties of superconducting quantum point Phys. Rev. B 54 7366–79
[34] Misko V R, Fomin V M and Devreese J T 2001 Strong enhancement of superconductivity in a nanosized Pb bridge Phys. Rev. B 64 014517
[35] Law K T, Lee P A and Ng T K 2009 Majorana fermion induced resonant Andreev reflection Phys. Rev. Lett. 103 237001
[36] Rodrigo J G, Crespo V and Vieira S 2006 Josephson current at atomic scale: tunneling and nanocontacts using a STM Physica C 437–38 270–3
[37] Wimmer M et al 2011 Quantum point contact as a probe of a topological superconductor New J. Phys. 13 053016
[38] Potter A C and Lee P A 2012 Topological superconductivity and Majorana fermions in metallic surface states Phys. Rev. B 85 094516