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# Quantized Majorana Conductance

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33 **Majorana zero-modes hold great promise for topological quantum computing. Tunnelling**  
34 **spectroscopy in electrical transport is the primary tool to identify the presence of Majorana**  
35 **zero-modes, for instance as a zero-bias peak (ZBP) in differential-conductance. The**  
36 **Majorana ZBP-height is predicted to be quantized at the universal conductance value of**  
37  **$2e^2/h$  at zero temperature.** Interestingly, this quantization is a direct consequence of the  
38 famous Majorana symmetry, “particle equals antiparticle”. The Majorana symmetry  
39 protects the quantization against disorder, interactions, and variations in the tunnel  
40 coupling. Previous experiments, however, have shown ZBPs much smaller than  $2e^2/h$ , with  
41 a recent observation of a peak-height close to  $2e^2/h$ . Here, we report a quantized  
42 conductance *plateau* at  $2e^2/h$  in the zero-bias conductance measured in InSb  
43 semiconductor nanowires covered with an Al superconducting shell. Our ZBP-height  
44 remains constant despite changing parameters such as the magnetic field and tunnel  
45 coupling, i.e. a quantized conductance plateau. We distinguish this quantized Majorana  
46 peak from possible non-Majorana origins, by investigating its robustness on electric and  
47 magnetic fields as well as its temperature dependence. A fully-developed quantized  
48 plateau is a necessary step towards demonstrating non-Abelian braiding statistics with  
49 **Majorana zero-modes.**

50 A semiconductor nanowire coupled to a superconductor can be tuned into a topological  
51 superconductor with two Majorana zero-modes localized at the wire ends<sup>1-3</sup>. Tunnelling into a  
52 Majorana mode will show a zero-energy state in the tunnelling density-of-states, i.e. a zero-bias  
53 peak (ZBP) in the differential conductance  $(dI/dV)^{4,5}$ . This tunnelling process is a so-called  
54 Andreev reflection, where an incoming electron is reflected as a hole. Particle-hole symmetry  
55 dictates that the zero-energy tunnelling amplitudes of electrons and holes are equal, resulting in  
56 a perfect resonant transmission with a ZBP-height quantized at  $2e^2/h^{6-8}$ , irrespective of the precise

57 tunnelling strength<sup>9</sup>. The Majorana-nature of this perfect Andreev reflection is a direct result of the  
58 well-known Majorana symmetry property “particle equals antiparticle”<sup>10,11</sup>.

59 Such a predicted robust conductance quantization has not yet been observed<sup>4,5,12-14</sup>.  
60 Instead, most of the ZBPs have a height significantly less than  $2e^2/h$ . This discrepancy was first  
61 explained by thermal averaging<sup>15-18</sup>. This explanation, however, does not hold when the peak-  
62 width exceeds the thermal broadening ( $\sim 3.5k_B T$ )<sup>12,13</sup>. In that case, other averaging mechanisms,  
63 such as dissipation<sup>19</sup>, have been invoked. The main source of dissipation is a finite quasi-particle  
64 density-of-states within the superconducting gap, often referred to as a ‘soft gap’. Substantial  
65 advances have been achieved in ‘hardening’ the gap by improving materials quality, eliminating  
66 disorder and interface roughness<sup>20,21</sup>, and better control during device processing<sup>22,23</sup>, all guided  
67 by a more detailed theoretical understanding<sup>24</sup>. We have recently solved all these dissipation and  
68 disorder issues<sup>21</sup>, and here we report the resulting improvements in electrical transport leading to  
69 the so-far elusive quantization of the Majorana ZBP.

70 Fig.1a shows a micrograph of a fabricated device and schematics of the measurement  
71 set-up. An InSb nanowire (grey) is partially covered (two out of six facets) by a thin  
72 superconducting Al shell (green)<sup>21</sup>. The ‘tunnel-gates’ (coral red) are used to induce a tunnel  
73 barrier in the non-covered segment between the left electrical contact (yellow) and the Al shell.  
74 The right contact is used to drain the current to ground. The chemical potential in the segment  
75 proximitized by Al can be tuned by applying voltages to the two long ‘super-gates’ (purple).

76 Transport spectroscopy is shown in Fig.1b displaying  $dI/dV$  as a function of voltage bias,  
77  $V$ , and magnetic field,  $B$  (aligned with the nanowire axis), while applying fixed voltages to the  
78 tunnel- and super-gates. As  $B$  increases, two levels detach from the gap edge (at  $\sim 0.2$  meV),  
79 merge at zero bias, and form a robust ZBP. This is consistent with the Majorana theory: a ZBP is  
80 formed after the Zeeman energy closes the trivial superconducting gap and re-opens a topological



81 gap<sup>2,3</sup>. The gap re-opening is not visible in a measurement of the local density-of-states since the  
82 tunnel coupling to these bulk states is small<sup>25</sup>. Moreover, the finite length of the proximitized  
83 segment ( $\sim 1.2 \mu\text{m}$ ) results in discrete energy states, turning the trivial-to-topological phase  
84 transition into a smooth cross-over<sup>26</sup>. Fig.1c shows two line-cuts from Fig.1b extracted at 0 and  
85 0.88 T. Importantly, the height of the ZBP reaches the quantized value of  $2e^2/h$ . The line-cut at  
86 zero-bias in the lower panel of Fig.1b shows that the ZBP-height remains close to  $2e^2/h$  over a  
87 sizable range in  $B$ -field (0.75 - 0.92 T). Beyond this range, the height drops, most likely caused  
88 by a closure of the superconducting gap in the bulk Al contact.

89 We note that the sub-gap conductance at  $B = 0$  (black curve, left panel, Fig.1c) is not  
90 completely suppressed down to zero, reminiscent of a soft gap. In this case, this finite sub-gap  
91 conductance, however, does not reflect any finite sub-gap density-of-states in the proximitized  
92 wire. It arises from Andreev reflection (i.e. transport by dissipationless Cooper pairs) due to a high  
93 tunnelling transmission, which is evident from the above-gap conductance ( $dI/dV$  for  $V > 0.2 \text{ V}$ )  
94 being larger than  $e^2/h$ . Since this softness does not result from dissipation, the Majorana peak-  
95 height should still reach the quantized value<sup>27</sup>. In Extended Data Fig. 1, we show that this device  
96 tuned into a low transmission regime, where  $dI/dV$  does reflect the density-of-states, indeed  
97 displays a hard gap. For further understanding we use experimental parameters in a theoretical  
98 Majorana nanowire model<sup>28</sup> (see Methods for more information). Fig. 1d shows a simulation with  
99 two line-cuts in Fig. 1c (right panel). Besides the ZBP, other discrete sub-gap states are visible,  
100 which are due to the finite wire length. Such discrete lines are only faintly resolved in the  
101 experimental panels of Fig. 1b. Overall, we find good qualitative agreement between the  
102 experimental and simulation panels in Fig. 1b and 1d. We note that an exact quantitative  
103 agreement is not feasible since the precise experimental values for the parameters going into the  
104 theory (e.g. chemical potential, tunnel coupling, Zeeman splitting, spin-orbit coupling, etc.) are  
105 unknown for our hybrid wire-superconductor structure.

106 Next, we fix  $B$  at 0.8 T and investigate the robustness of the quantized ZBP against  
107 variations in the transmission by varying the voltage on the tunnel-gate. Fig. 2a shows  $dI/dV$  while  
108 varying  $V$  and tunnel-gate voltage. Fig. 2b shows that the ZBP-height remains close to the  
109 quantized value. Importantly, the above-gap conductance measured at  $|V| = 0.2$  meV varies by  
110 more than 50% (Fig. 2c and 2d), implying that the transmission is changing significantly over this  
111 range while the ZBP remains quantized. Note that the minor conductance switches in Fig. 2a-c  
112 are due to unstable jumps of trapped charges in the surroundings.

113 Fig. 2d (red curves) shows several line-cuts of the quantized ZBP. The extracted height  
114 and width are plotted in Fig. 2e (upper panel) as a function of above-gap conductance  $G_N = Txe^2/h$   
115 where  $T$  is the transmission probability for a spin-resolved channel. While the ZBP-width does  
116 change with  $G_N$ , the quantized height remains unaffected. Note that the ZBP-width ranges from  
117  $\sim 50$  to  $\sim 100$   $\mu\text{eV}$ , which is significantly wider than the thermal width  $\sim 6$   $\mu\text{eV}$  at 20 mK. The ZBP-  
118 width is thus broadened by tunnel coupling, instead of thermal broadening, i.e. fulfilling a  
119 necessary condition to observe a quantized Majorana peak. In Extended Data Fig. 2, we show  
120 that in the low transmission regime where thermal broadening dominates over tunnel broadening,  
121 the ZBP-height drops below  $2e^2/h$ <sup>15-18</sup>. We emphasize that the robustness of the ZBP quantization  
122 to a variation in the tunnel barrier is an important finding of our work.

123 A more negative tunnel-gate voltage ( $< -8$  V) eventually splits the ZBP, which may be  
124 explained by an overlapping of the two localized Majorana wave-functions from the two wire ends.  
125 The tunnel-gate not only tunes the transmission of the barrier, but also influences the potential  
126 profile in the proximitized wire part near the tunnel barrier. A more negative gate voltage  
127 effectively pushes the nearby Majorana mode away, towards the remote Majorana on the other  
128 end of the wire, thus reducing the length of the effective topological wire. This leads to the wave-  
129 function overlap between the two Majoranas, causing the ZBP to split<sup>16</sup> (black curves in Fig. 2d).  
130 This splitting is also captured in our simulations shown in Fig. 2f, where we have checked that the

131 splitting originates from Majorana wave-function overlap. Note that the simulated ZBP-height (red  
132 curve in middle panel in Fig. 2f) remains close to the  $2e^2/h$  plateau over a large range, while the  
133 above-gap conductance (black curve in lower panel in Fig. 2f) changes substantially. Also, the  
134 height and width dependence in the simulation is in qualitative agreement with our experimental  
135 observation (Fig. 2e). To complete the comparison, we show in Fig. 2g the simulated line-cuts of  
136 several quantized ZBP's (red curves) and split peaks (black curves), consistent with the  
137 experimental data in Fig. 2d.

138 Pushing Majoranas toward each other is one mechanism for splitting. Another way is by  
139 changing the chemical potential through the transition from a topological to a trivial phase<sup>2,3</sup>—the  
140 topological quantum phase transition from the trivial to the topological phase can be equivalently  
141 caused by tuning either the Zeeman energy (i.e. the magnetic field) or the chemical potential.  
142 Splitting at the phase transition occurs since the Majorana wave-functions start to spread out over  
143 the entire wire length. For long wires the transition is abrupt, whereas in shorter wires a smooth  
144 transition is expected<sup>26</sup>. We investigate the dependence of the quantized ZBP on chemical  
145 potential by varying the voltage on the super-gate. Fig. 3a shows a nearly-quantized ZBP that  
146 remains non-split over a large range in super-gate voltage. More positive voltage applied to the  
147 super-gates corresponds to a higher chemical potential, and eventually we find a ZBP-splitting (>  
148 -5 V) and consequently a suppression of the zero-bias conductance below the quantized value.  
149 Although the relation between gate voltage and chemical potential is unknown in our devices, this  
150 splitting suggests a transition to the trivial phase caused by a tuning of the chemical potential  
151 induced by the changing super-gate voltage.

152 In a lower  $B$ -field and different gate settings (Fig. 3b), the splitting of the quantized ZBP  
153 shows oscillatory behaviour as a function of the super-gate voltage. The five line-cuts on the right  
154 panel highlight this back-and-forth behaviour between quantized and suppressed ZBPs.

155 Remarkably, the ZBP-height comes back up to the quantized value and, importantly, does not  
156 cross through it.

157 We find similar behaviour in the theoretical simulations of Fig. 3c. In these simulations we  
158 have confirmed that for the chosen parameters, the Majorana wave-functions oscillate in their  
159 overlap, thus giving rise to the back-and-forth behaviour of quantized and split ZBPs<sup>29</sup>. In the  
160 experiment it may also be that non-homogeneity, possibly somewhere in the middle of the wire,  
161 causes overlap of Majorana wave-functions. Again, we note that the conversion from gate voltage  
162 to chemical potential is unknown, preventing a direct quantitative comparison between  
163 experiment and simulation.

164 To demonstrate the reproducibility of ZBP quantization, we show in Fig. 4a the quantized  
165 ZBP data from a second device. In this second device the length of the proximitized section is  
166  $\sim 0.9 \mu\text{m}$ , which is  $\sim 0.3 \mu\text{m}$  shorter than the previous device. This second device allows to transmit  
167 more than one channel through the tunnel barrier, which we deduce from the above-gap  
168 conductance value (Fig. 4b, lower panel, black curve) exceeding  $e^2/h$  for voltages larger than  
169  $\sim -0.55 \text{ V}$  on the tunnel-gates. Correspondingly, the zero-bias conductance can now exceed  $2e^2/h$   
170 (Fig. 4b, middle panel) for such an open tunnel barrier<sup>9</sup>. We note that tunnelling through the  
171 second channel in the barrier region results in an additional background conductance, thus  
172 leading to the zero-bias conductance rising above  $2e^2/h$ . We find, however, from a rough estimate  
173 of this background contribution that the net ZBP-height (above background) never exceeds  $2e^2/h$ ,  
174 consistent with Majorana theory<sup>9</sup>.

175 We next fix the  $B$ -field and study temperature dependence. Fig. 4c shows a line-cut of this  
176 quantized ZBP from Fig. 4a. First, the base temperature trace in Fig. 4c (red data points) fits well  
177 to a Lorentzian line-shape with 20 mK thermal broadening, expected for Majoranas as well as for  
178 any type of resonant transmission. The ZBP temperature dependence is shown in line traces in

179 Fig. 4d and in colour scale in Fig. 4e (with the corresponding simulation in the lower panel of 4e).  
180 Fig. 4f shows the extracted ZBP-height and ZBP-width (i.e. full-width-half-maximum, FWHM) from  
181 both the experimental and simulational traces. At low temperatures, the ZBP-width (red data  
182 points) exceeds the thermal width defined as  $3.5k_B T$  (blue line). In agreement with theory<sup>15,17,30</sup>,  
183 the ZBP-height (black data points) reaches and saturates at  $2e^2/h$  when the FWHM exceeds  
184  $3.5k_B T$ . For higher temperatures, thermal averaging starts suppressing the ZBP-height below the  
185 quantized value. We note that the simulated data is calculated by a convolution integration of the  
186 derivative of the Fermi distribution function and the  $dI/dV$  trace at base temperature of 20 mK.  
187 This procedure of incorporating thermal effects holds if the temperature of the calculated  $dI/dV$   
188 curve is significantly larger than base temperature (which can then be assumed to be the effective  
189 zero-temperature conductance value). Indeed, we find excellent agreement between experiment  
190 and simulation for  $T > 50$  mK (Fig. 4f). See Extended Data Fig. 3 for detailed temperature  
191 dependence.

192         Recent theoretical work<sup>28</sup> has shown numerically for experimentally relevant parameters  
193 that ZBPs can also arise from local and non-topological Andreev bound states (ABS)<sup>16,31-34</sup>. These  
194 local ABS appear remarkably similar in tunnelling spectroscopy as the ZBPs arising from  
195 Majorana zero-modes. In a third device, we have been able to find such non-topological states  
196 by fine-tuning gate voltages. Figure 5 shows the similarities and differences between ABS and  
197 Majorana ZBPs. First of all, Fig. 5a shows a ZBP in tunnelling spectroscopy versus  $B$ -field. At a  
198 particular  $B$ -field (0.7 T, red bar) the ZBP-height reaches  $2e^2/h$ . In this device, we next vary the  
199 chemical potential via a voltage applied to a back-gate, showing a fairly stable (non-split) ZBP in  
200 Fig. 5b. In contrast, the ZBP is unstable against variations in tunnel-gate voltage. Fig. 5c shows  
201 that now the ZBP appears as level crossings instead of being rigidly bound to zero bias. The two  
202 different behaviours between back-gate and tunnel-gate are expected for ABSs that are localized  
203 near the tunnel barrier, as was modelled explicitly in Ref. 28 (see also Extended Data Fig. 5). Liu

204 et al.<sup>28</sup> show that local ABSs can have near-zero energy, which in a  $B$ -field is remarkably robust  
205 against variations in chemical potential; in our experiment tuned by the back-gate. However, this  
206 is only the case for the tunnel-gate voltage fine-tuned to level crossing points at zero bias. The  
207 local tunnel-gate and the global back-gate thus have distinguishably different effects. For the  
208 Majorana case, instead of level crossing, the ZBP should remain non-split over sizable changes  
209 in tunnel-gate voltage<sup>13</sup>, as shown in Fig. 2a and Fig. 4b.

210 The second fundamental difference is that the non-topological ABS ZBP-height is not  
211 expected to be robustly quantized at  $2e^2/h^{9,28}$ . Fig. 5d and 5e show that the ZBP-height varies  
212 smoothly as a function of the back-gate voltage without any particular feature at  $2e^2/h$ . Also, the  
213 ZBP-height in Fig. 5a at  $2e^2/h$  is just a tuned coincidence (see Extended Data Fig. 6). Note that  
214 the ZBP line-shape or temperature dependence does not discriminate between topological and  
215 non-topological cases. Both fit a Lorentzian line-shape as shown explicitly for the non-topological  
216 ABS in Fig. 5f. Thus, the temperature dependence alone cannot distinguish a Majorana origin  
217 from ABS<sup>14,30,31</sup>. Only a stable quantized tunnel-conductance plateau, robust against variations in  
218 all gate voltages and magnetic field strength, can uniquely identify a topological Majorana zero-  
219 mode.

## 220 References

- 222 1 Kitaev, A. Y. Unpaired Majorana fermions in quantum wires. *Physics-Uspekhi* **44**, 131 (2001).
- 223 2 Lutchyn, R. M., Sau, J. D. & Das Sarma, S. Majorana Fermions and a Topological Phase Transition  
224 in Semiconductor-Superconductor Heterostructures. *Physical Review Letters* **105**, 077001 (2010).
- 225 3 Oreg, Y., Refael, G. & von Oppen, F. Helical Liquids and Majorana Bound States in Quantum  
226 Wires. *Physical Review Letters* **105**, 177002 (2010).
- 227 4 Mourik, V. *et al.* Signatures of Majorana Fermions in Hybrid Superconductor-Semiconductor  
228 Nanowire Devices. *Science* **336**, 1003-1007 (2012).
- 229 5 Lutchyn, R. M. *et al.* Realizing Majorana zero modes in superconductor-semiconductor  
230 heterostructures. *arXiv:1707.04899* (2017).
- 231 6 Sengupta, K., Žutić, I., Kwon, H.-J., Yakovenko, V. M. & Das Sarma, S. Midgap edge states and  
232 pairing symmetry of quasi-one-dimensional organic superconductors. *Physical Review B* **63**,  
233 144531 (2001).
- 234 7 Law, K. T., Lee, P. A. & Ng, T. K. Majorana Fermion Induced Resonant Andreev Reflection.  
235 *Physical Review Letters* **103**, 237001 (2009).

236 8 Flensberg, K. Tunneling characteristics of a chain of Majorana bound states. *Physical Review B* **82**,  
237 180516 (2010).

238 9 Wimmer, M., Akhmerov, A. R., Dahlhaus, J. P. & Beenakker, C. W. J. Quantum point contact as  
239 a probe of a topological superconductor. *New Journal of Physics* **13**, 053016 (2011).

240 10 Majorana, E. A symmetric theory of electrons and positrons. *Soryushiron Kenkyu (English*  
241 *translation)* **63**, 149, doi:[translation from Nuovo Cimento 14, 171 (1937)] (1981).

242 11 Read, N. & Green, D. Paired states of fermions in two dimensions with breaking of parity and time-  
243 reversal symmetries and the fractional quantum Hall effect. *Physical Review B* **61**, 10267-10297  
244 (2000).

245 12 Deng, M. T. *et al.* Majorana bound state in a coupled quantum-dot hybrid-nanowire system. *Science*  
246 **354**, 1557 (2016).

247 13 Gül, Ö. *et al.* Ballistic Majorana Nanowire Devices. *Nature Nanotechnology (in Press)* (2017).

248 14 Nichele, F. *et al.* Scaling of Majorana Zero-Bias Conductance Peaks. *Physical Review Letters* **119**,  
249 136803 (2017).

250 15 Pientka, F., Kells, G., Romito, A., Brouwer, P. W. & von Oppen, F. Enhanced Zero-Bias Majorana  
251 Peak in the Differential Tunneling Conductance of Disordered Multisubband Quantum-  
252 Wire/Superconductor Junctions. *Physical Review Letters* **109**, 227006 (2012).

253 16 Prada, E., San-Jose, P. & Aguado, R. Transport spectroscopy of  $\text{NSN}$  nanowire junctions with  
254 Majorana fermions. *Physical Review B* **86**, 180503 (2012).

255 17 Lin, C.-H., Sau, J. D. & Das Sarma, S. Zero-bias conductance peak in Majorana wires made of  
256 semiconductor/superconductor hybrid structures. *Physical Review B* **86**, 224511 (2012).

257 18 Rainis, D., Trifunovic, L., Klinovaja, J. & Loss, D. Towards a realistic transport modeling in a  
258 superconducting nanowire with Majorana fermions. *Physical Review B* **87**, 024515 (2013).

259 19 Liu, C.-X., Sau, J. D. & Das Sarma, S. Role of dissipation in realistic Majorana nanowires. *Physical*  
260 *Review B* **95**, 054502 (2017).

261 20 Krogstrup, P. *et al.* Epitaxy of semiconductor–superconductor nanowires. *Nat Mater* **14**, 400-406  
262 (2015).

263 21 Gazibegovic, S. *et al.* Epitaxy of advanced nanowire quantum devices. *Nature* **548**, 434-438 (2017).

264 22 Gül, Ö. *et al.* Hard Superconducting Gap in InSb Nanowires. *Nano Letters* **17**, 2690-2696 (2017).

265 23 Zhang, H. *et al.* Ballistic superconductivity in semiconductor nanowires. *Nature Communications*  
266 **8**, 16025 (2017).

267 24 Takei, S., Fregoso, B. M., Hui, H.-Y., Lobos, A. M. & Das Sarma, S. Soft Superconducting Gap in  
268 Semiconductor Majorana Nanowires. *Physical Review Letters* **110**, 186803 (2013).

269 25 Stanescu, T. D., Tewari, S., Sau, J. D. & Das Sarma, S. To Close or Not to Close: The Fate of the  
270 Superconducting Gap Across the Topological Quantum Phase Transition in Majorana-Carrying  
271 Semiconductor Nanowires. *Physical Review Letters* **109**, 266402 (2012).

272 26 Mishmash, R. V., Aasen, D., Higginbotham, A. P. & Alicea, J. Approaching a topological phase  
273 transition in Majorana nanowires. *Physical Review B* **93**, 245404 (2016).

274 27 Liu, C.-X., Setiawan, F., Sau, J. D. & Das Sarma, S. Phenomenology of the soft gap, zero-bias  
275 peak, and zero-mode splitting in ideal Majorana nanowires. *Physical Review B* **96**, 054520 (2017).

276 28 Liu, C.-X., Sau, J. D., Stanescu, T. D. & Das Sarma, S. Andreev bound states versus Majorana  
277 bound states in quantum dot-nanowire-superconductor hybrid structures: Trivial versus topological  
278 zero-bias conductance peaks. *Physical Review B* **96**, 075161 (2017).

279 29 Das Sarma, S., Sau, J. D. & Stanescu, T. D. Splitting of the zero-bias conductance peak as smoking  
280 gun evidence for the existence of the Majorana mode in a superconductor-semiconductor nanowire.  
281 *Physical Review B* **86**, 220506 (2012).

282 30 Setiawan, F., Liu, C.-X., Sau, J. D. & Das Sarma, S. Electron temperature and tunnel coupling  
283 dependence of zero-bias and almost-zero-bias conductance peaks in Majorana nanowires.  
284 *arXiv:1708.09039* (2017).

- 285 31 Kells, G., Meidan, D. & Brouwer, P. W. Near-zero-energy end states in topologically trivial spin-orbit coupled superconducting nanowires with a smooth confinement. *Physical Review B* **86**, 100503 (2012).  
286  
287  
288 32 Lee, E. J. H. *et al.* Zero-Bias Anomaly in a Nanowire Quantum Dot Coupled to Superconductors. *Physical Review Letters* **109**, 186802 (2012).  
289  
290 33 Pikulin, D. I., Dahlhaus, J. P., Wimmer, M., Schomerus, H. & Beenakker, C. W. J. A zero-voltage conductance peak from weak antilocalization in a Majorana nanowire. *New Journal of Physics* **14**, 125011 (2012).  
291  
292  
293 34 Stanescu, T. D. & Tewari, S. Disentangling Majorana fermions from topologically trivial low-energy states in semiconductor Majorana wires. *Physical Review B* **87**, 140504 (2013).  
294

295

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299

### 300 **Author Contributions**

301 The teams in Eindhoven and Santa Barbara have grown the nanowires with epitaxial Al and  
302 performed the nanowire deposition. The team in Delft fabricated the devices, performed electrical  
303 measurements, and analysed the experimental data. The Maryland team performed the numerical  
304 simulations. The manuscript was written by HZ and LPK with comments from all authors.

305

### 306 **Method**

307 **Theory model.** We use the theoretical model from reference 28 to perform numerical simulations  
308 with experimentally relevant parameters, such as the effective mass  $m^* = 0.015 m_e$ , the spin-orbit  
309 coupling  $\alpha = 0.5 \text{ eV}\text{\AA}$ , the chemical potential of the lead  $\mu_{\text{lead}} = 25 \text{ meV}$ , the Landé  $g$ -factor  
310  $g = 20$  such that the Zeeman energy  $V_z [\text{meV}] = 1.2 B [\text{T}]$ , and the length of the nanowire  $L = 1.0$   
311  $\mu\text{m}$ . Note that the collapse of the bulk Al superconducting gap is included explicitly in the theory  
312 to be consistent with the experimental situation where the bulk gap collapses  $\sim 1\text{T}$ .



313 **Lorentzian fit.** We fit our ZBP line-shape with the Lorentzian formula:  $G(V) = \frac{2e^2}{h} \times \frac{\Gamma^2}{\Gamma^2 + (eV)^2}$ ,  
314 where  $\Gamma$  defines the tunnel coupling and FWHM of the peak, i.e.  $2\Gamma$ . Then we do convolution  
315 integration with the derivative of the Fermi distribution function (at 20 mK) to fit our ZBP shape.  
316 Since the FWHM of our ZBP is much larger than the thermal width, we took  $\Gamma$  to be roughly equal  
317 to half of the FWHM for all the fittings in Fig. 4c and Fig. 5f.

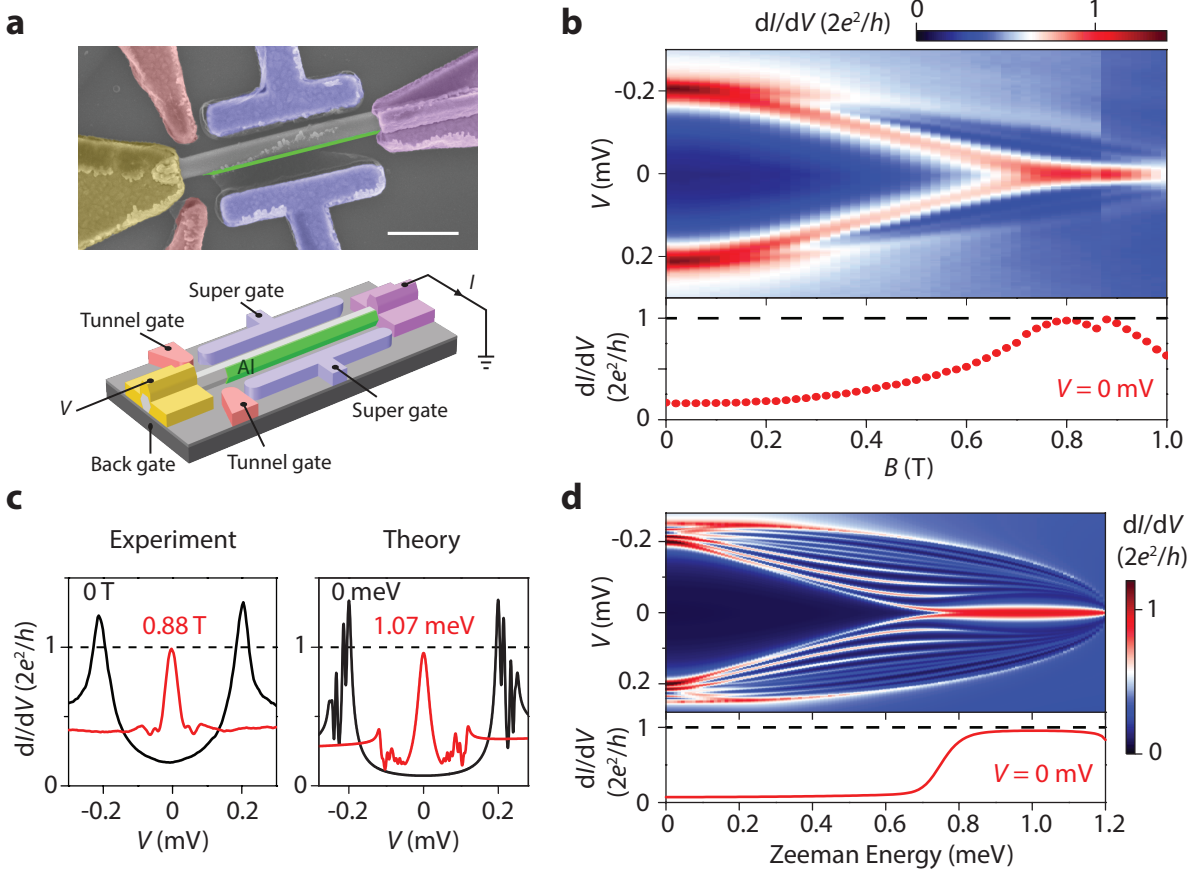


Figure 1: **Quantized Majorana zero bias peak.** **a** False-color scanning electron micrograph of device A (upper panel) and its schematics (lower panel). The scale bar is 500nm. Side gates and contacts are Cr/Au (10nm/100nm), labeled by different colors. The substrate is p-doped Si, acting as a global back gate, covered by 285nm SiO<sub>2</sub>. The two tunnel (super) gates are short externally as one tunnel (super) gate. **b** Magnetic field dependence of the quantized ZBP with the zero bias line-cut in the lower panel. Magnetic field direction is aligned with the nanowire axis for all the measurement. Super (tunnel) gate voltage is fixed at -6.5V (-7.7V), while back gate is kept grounded. Temperature is 20mK unless specified. **c** Comparison between experiment and theory. Left (right) panel is the vertical line-cuts from **b** (**d**) at 0T and 0.88T (1.07meV). **d** Majorana simulation of Device A, qualitative agreeing with the experiment data. A small dissipation term ( $\sim 30mK$ ) is introduced to account for the effect of finite temperature and small lock-in excitation voltage ( $8\mu V$ ).

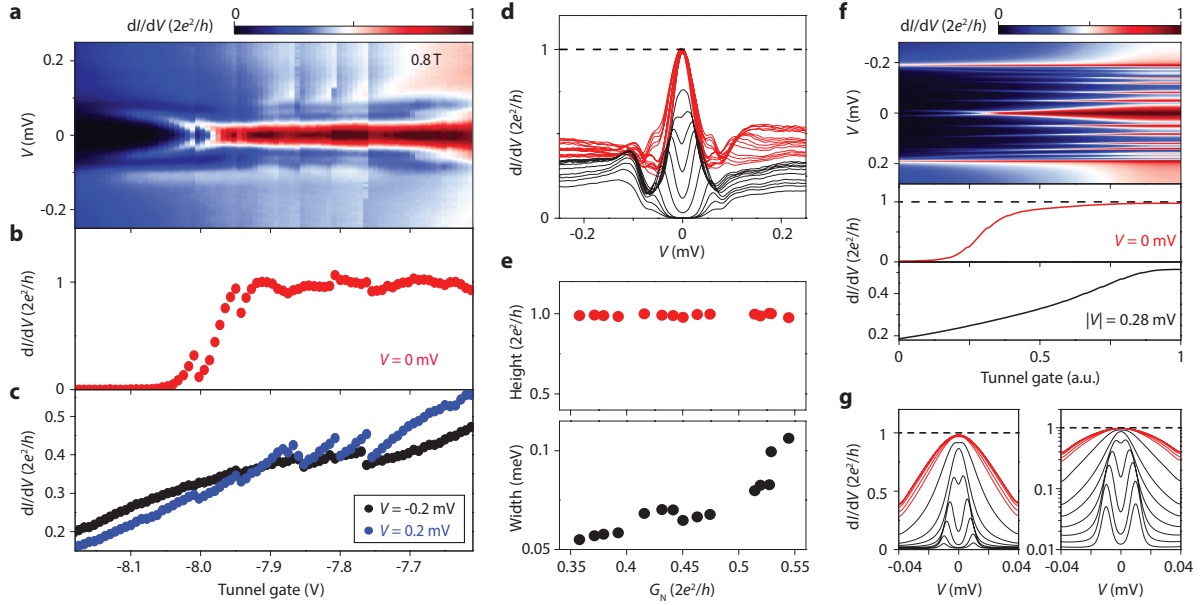
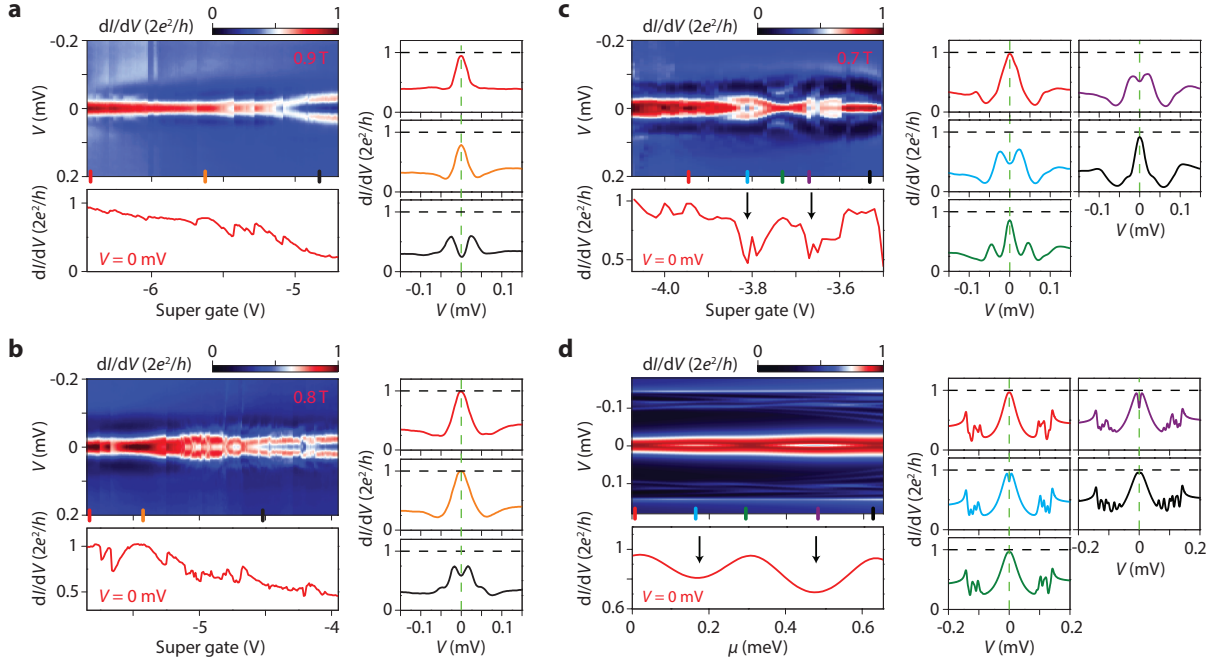
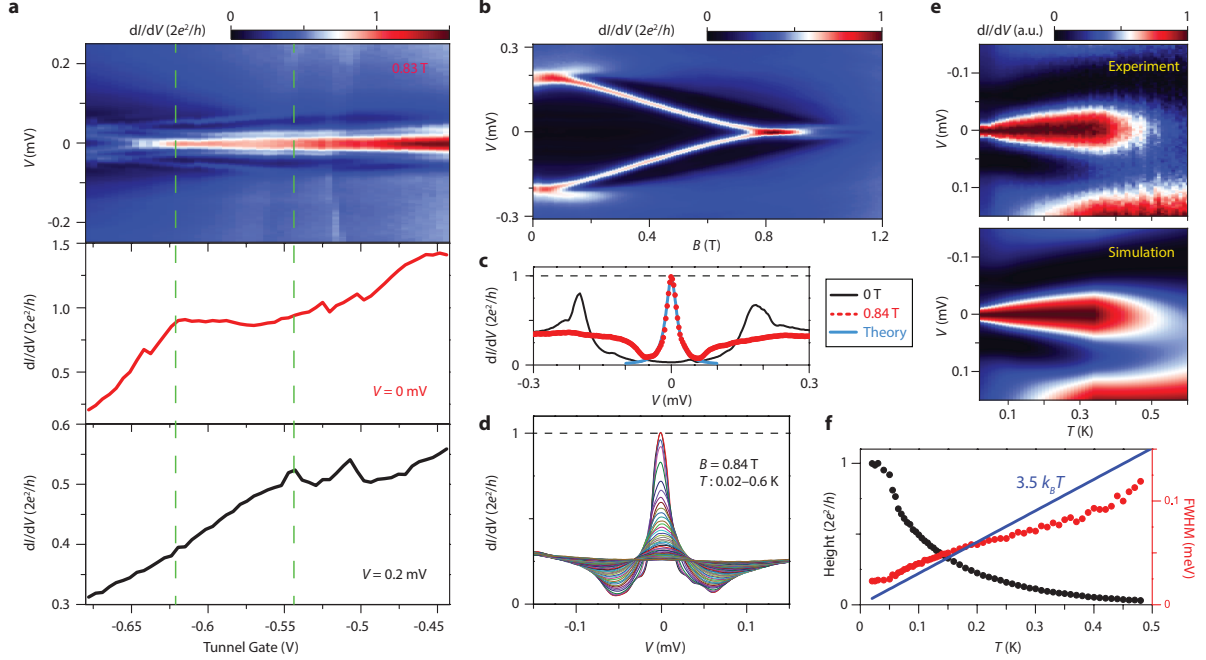


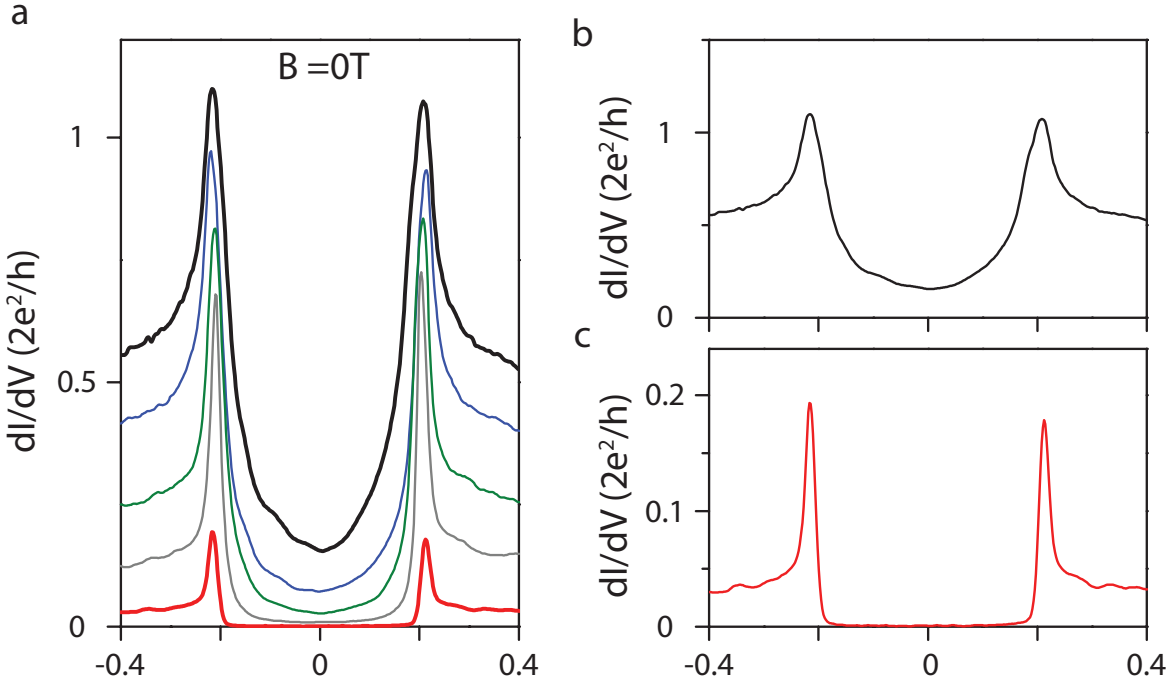
Figure 2: **Quantized Majorana conductance plateau.** **a** Tunnel gate dependence of the quantized ZBP at  $B=0.8\text{T}$ . Super (back) gate voltage is fixed at  $-6.5\text{V}$  ( $0\text{V}$ ). The ZBP remains robust (un-split) with the tunnel gate voltage changing from  $-7.6\text{V}$  to  $-7.95\text{V}$ . Until the more negative tunnel gate voltage splits the ZBP. **b,c** Horizontal line-cuts from **a**, showing zero bias conductance and above-gap conductance, respectively. The above-gap conductance (transmission) changes from  $0.35 \times 2e^2/h$  to  $0.55 \times 2e^2/h$ , while the ZBP height remains close to  $2e^2/h$ , i.e. a quantized plateau. **d** Several vertical line-cuts from **a**, showing quantized ZBP curves (red). The above-gap conductance is changed by more than 50%, while the ZBP height sticks at  $2e^2/h$ . The black curves show the zero bias conductance drops from the quantized value when the ZBP starts to split. **e** The ZBP peak height (red dots) and width (black dots) extracted from **d** (red curves), as a function of above-gap conductance ( $G_N$ ). The width is defined by the bias voltage value at which the  $dI/dV$  is  $e^2/h$ . **f** Majorana simulation on the tunnel gate dependence, qualitatively agrees with the experiment data. **g** Vertical line-cuts from **f** in both linear and log scale showing the quantized ZBP (red) and split-peaks (black).



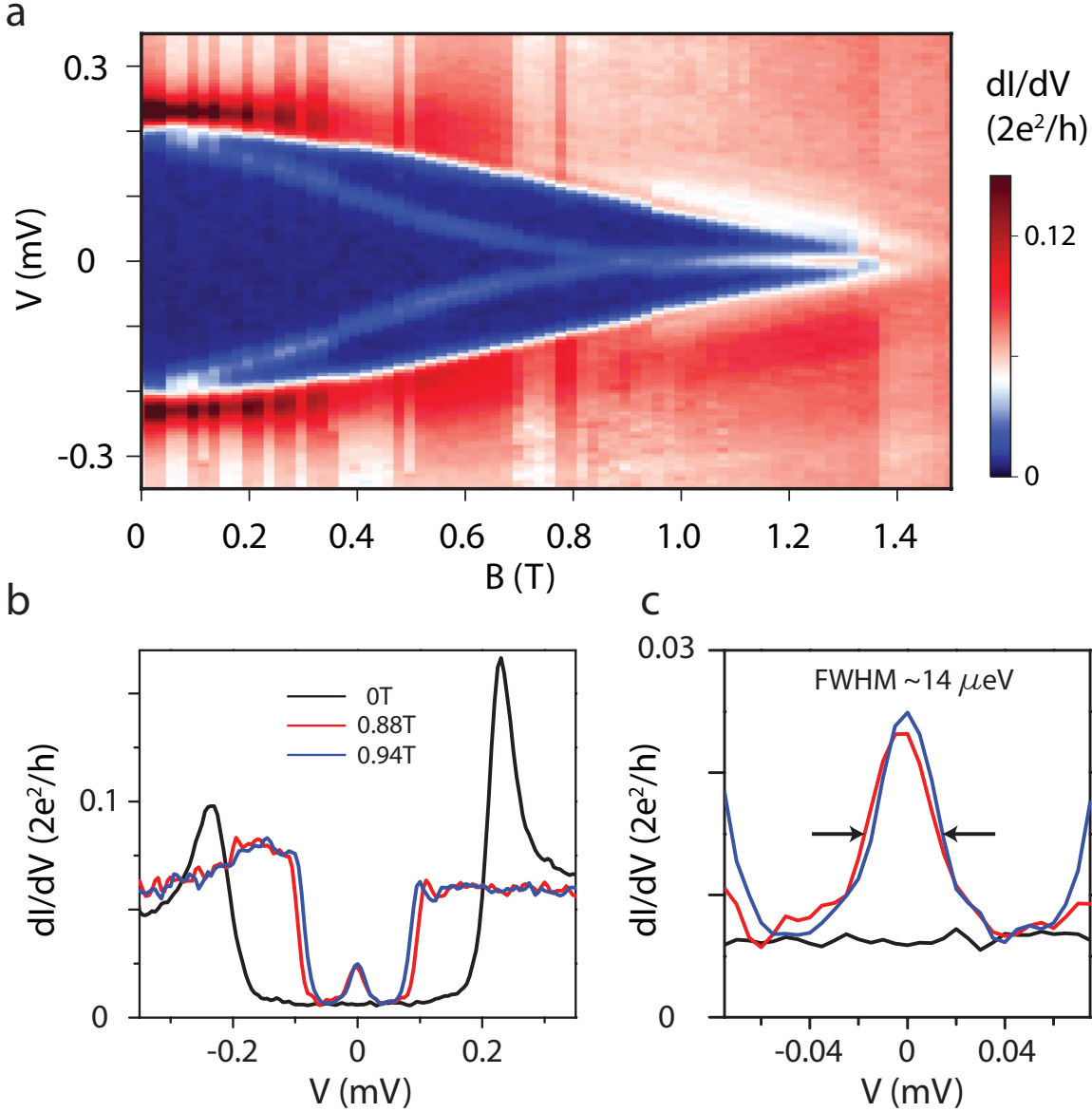
**Figure 3: Majorana splitting and oscillations.** **a-c** Super gate dependence of the quantized ZBP at difference fixed magnetic fields: 0.9T, 0.8T and 0.7T respectively. The tunnel gate voltage is adjusted simultaneously when sweeping the super gate voltage, to compensate for the cross coupling between the two gates. The transmission (above-gap conductance) is kept roughly as a constant. The super gate mainly tunes the chemical potential in the proximitized nanowire part. Lower panel is the zero bias line-cut, while the right panel shows vertical line-cuts at gate voltages indicated by the corresponding color bars. The ZBP remains unsplit over a large super gate voltage range, with its peak height close to  $2e^2/h$ . More positive super gate voltage increases the chemical potential, which splits the ZBP by driving the system from topological into trivial regime. Switches in the color maps are due to charge jumps in the gate dielectric. **c** shows oscillatory behavior of the ZBP, i.e. increasing the super gate voltage gives a ZBP-split peak-ZBP-split peak-ZBP pattern, as clearly shown in the line-cuts. The two split peak regions correspond to the two valleys in the zero bias line-cut (indicated by the back arrows). This could be explained by the oscillation of Majorana wavefunction overlapping, as shown in **d**. **d** Theory simulation of Majorana conductance showing oscillatory splitting behavior as a function of chemical potential.



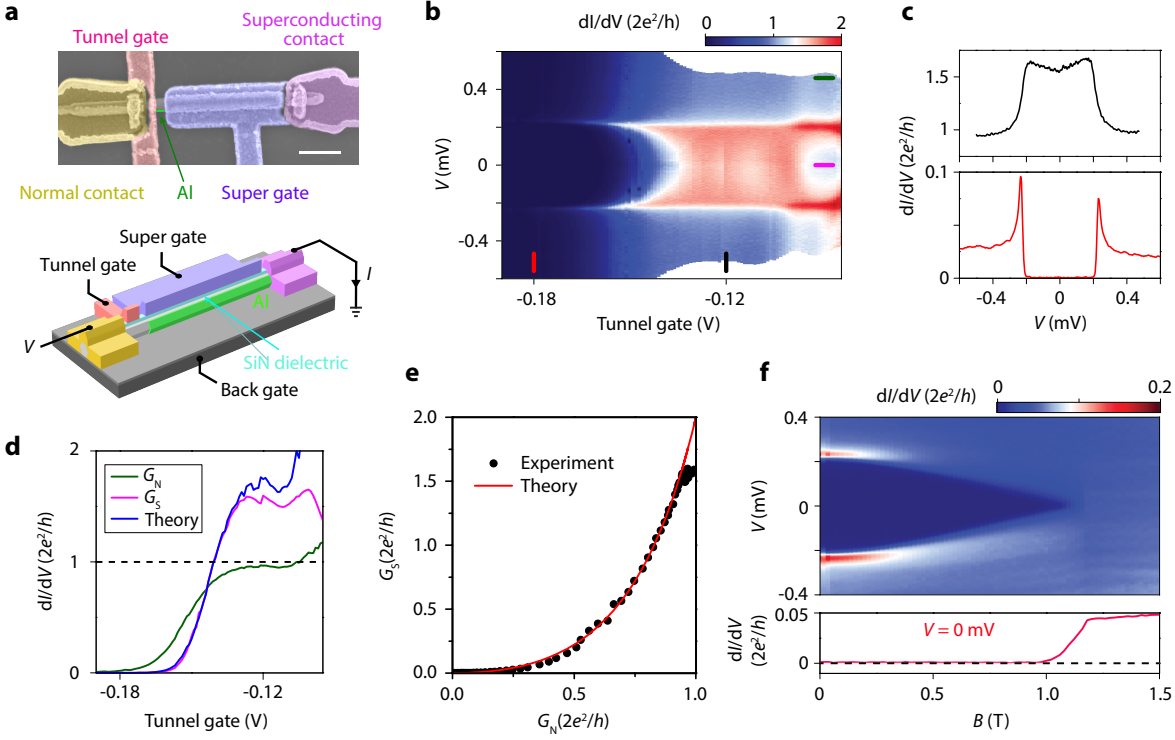
**Figure 4: Majorana plateau reproduced, and its temperature dependence.** **a** Tunnel gate dependence of the ZBP in Device B at  $B=0.83\text{T}$ . For tunnel gate voltage between  $-0.62\text{V}$  and  $-0.54\text{V}$  (the two green dashed lines), the above-gap conductance changes from  $0.8 \times e^2/h$  to  $1.06 \times e^2/h$ , by 33%. In the meantime, the ZBP height remains constant at  $\sim 0.9 \times 2e^2/h$ , resolving a plateau close to the quantized value. More positive gate voltage pushes the zero bias conductance exceeding  $2e^2/h$ , due to the increase of background, contributed by other populated channels. After the right green dashed line, the above-gap conductance is larger than  $e^2/h$ , meaning more than one channel is populated. The net ZBP height (after subtracting background) never exceeds  $2e^2/h$ . **b** Magnetic field dependence of the quantized ZBP. **c** Vertical line-cuts from **b** at  $0\text{T}$  and  $0.84\text{T}$ . The ZBP line-shape fits quite well with the Majorana theory (blue line), by assuming a tunnel coupling  $\Gamma = 13.7\mu\text{eV}$  and temperature of  $20\text{mK}$ . **d** Temperature dependence of this quantized ZBP with temperature varies from  $20\text{mK}$  to  $600\text{mK}$  with  $10\text{mK}$  step. **e** Color plot of the temperature dependence in **d**. At each temperature the conductance is renormalized for clarity by setting the minimum 0 and maximum 1. As the temperature increases, the ZBP is thermal broadened and smeared out at  $\sim 500\text{mK}$ . Lower panel is the theory simulation, agreeing perfectly well with the experiment. **f** ZBP height and FWHM as a function of temperature (extracted from **e**). As the temperature decreases, the ZBP height saturates at  $2e^2/h$ , while the ZBP width becomes wider than thermal broadening (above the  $3.5k_B T$  blue line). See Extended data for more information.



**Extended Data Figure 1 | Dissipationless ‘soft gap’ due to large Andreev reflection.** **a**  $dI/dV$  of Device A as a function bias voltage. Different curves are for different fixed tunnel gate voltages (transmissions). In the deep tunneling regime (red curve), where the above-gap conductance ( $\sim 0.03 \times 2e^2/h$ ) is much less than  $2e^2/h$ ,  $dI/dV$  is proportional to the density of states in the proximitized wire part, resolving a hard superconducting gap. In the open regime (black curve), where the above-gap conductance (transmission) is comparable with  $2e^2/h$  (unity), the sub-gap conductance is non-zero, reminiscent of soft gap. But the finite sub-gap conductance is contributed by Andreev reflection, instead of dissipation (a real soft gap). This fake soft gap does not affect the quantized ZBP height. **b** Re-plot of the two curves from **a**.

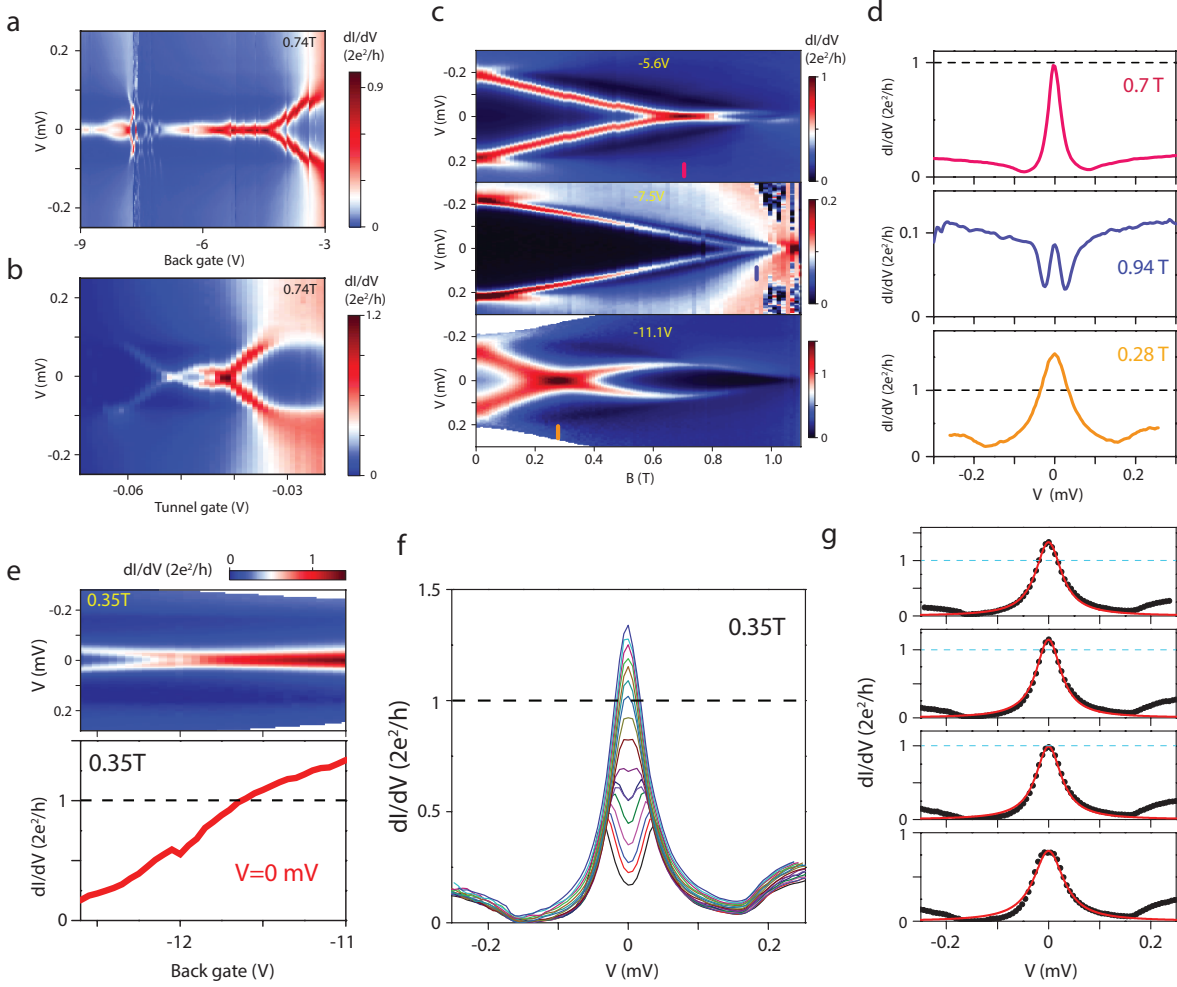


**Extended Data Figure 2 | Thermal broadened low ZBP coexists with hard gap.** **a**  $dI/dV$  of device C, as a function of magnetic field, resolving a stable ZBP. **b** Vertical line-cuts from **a**, at three different magnetic fields. At  $B=0\text{T}$ , the above-gap conductance ( $\sim 0.05 \times 2e^2/h$ ) is much less than  $2e^2/h$  (deep tunneling regime), resolving a hard gap. The residue sub-gap conductance is due to the small Andreev reflection and noise background from the measurement equipment. The small transmission leads to a narrow width of the ZBP, whose height is greatly affected (decreased) by thermal broadening. The sub-gap conductance at the finite magnetic field where ZBP exists, is the same with the sub-gap conductance at zero field, suggesting that the gap remains hard at the magnetic field where we create Majoranas. **c** A zoom-in image shows the FWHM of the ZBP is  $\sim 14\mu\text{eV}$ , consistent with the sum of the thermal broadening width ( $3.5k_B T$ ,  $6\mu\text{eV}$  at  $20\text{mK}$ ), the lock-in bias voltage excitation ( $5\mu\text{eV}$ ) and the original peak width at  $T=0\text{K}$ .

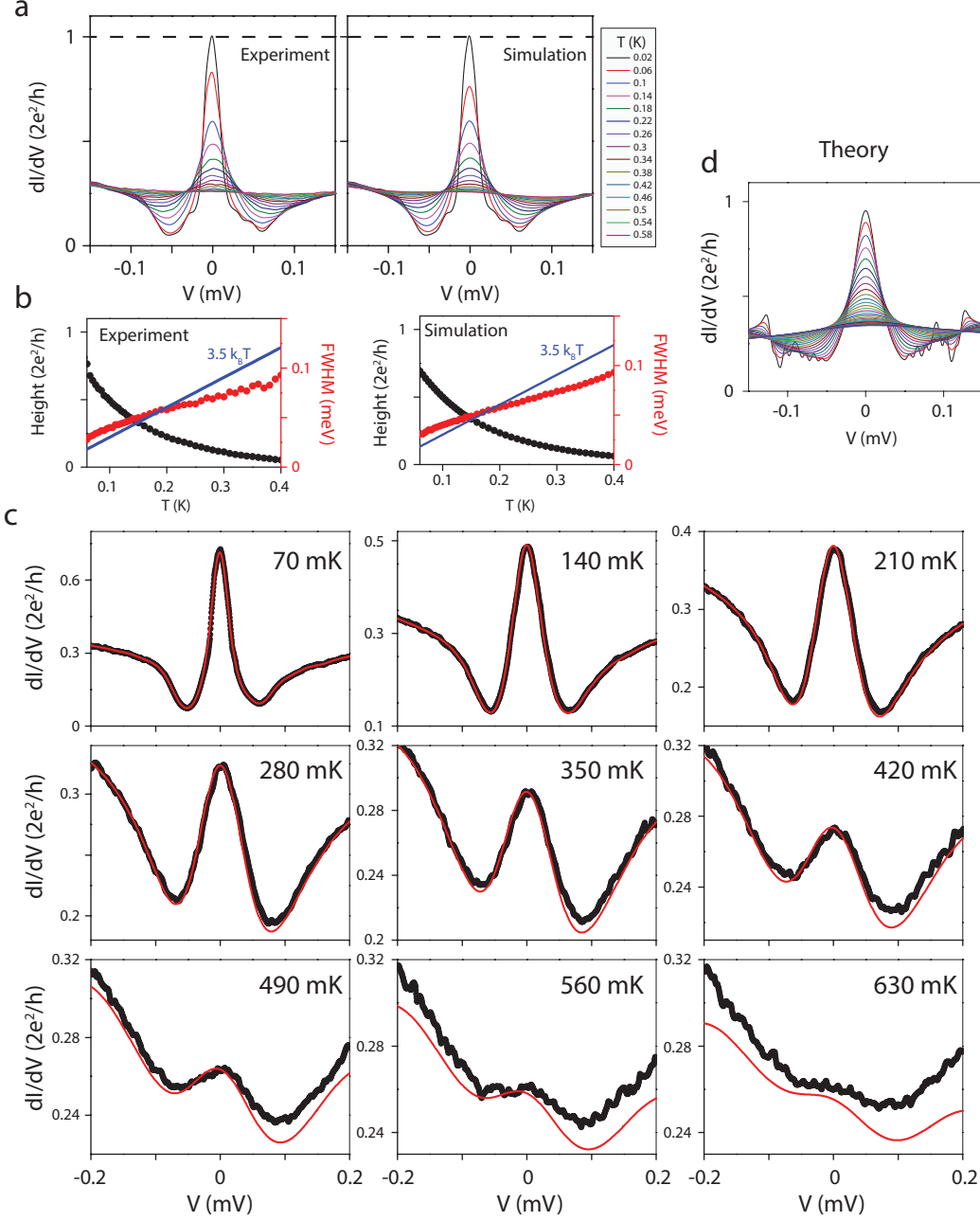


**Extended Data Figure 3 | Perfect ballistic Andreev transport in InSb-Al nanowires.** **a** False-color scanning electron micrograph of device D. The scale bar is 500nm. Electrical contacts and top gates are Cr/Au and labeled with different colors. Lower panel shows the device schematic and measurement set up. The two top gates (tunnel gate and super gate) are separated from the nanowire by 30nm thick SiN dielectric. The global back gate is p-doped Si covered by 285nm thick SiO<sub>2</sub> dielectric. **b** Differential conductance ( $dI/dV$ ) of Device D, as a function of bias voltage ( $V$ ) and tunnel gate voltage. **c** Vertical line-cuts from **b** at tunnel gate voltage = -0.18V (lower panel) and -0.12V (upper panel), resolving hard superconducting gap in the tunneling regime (lower panel) and strong Andreev enhancement on the plateau (upper panel). **d** Horizontal line-cuts from **c** for  $V=0\text{mV}$  (pink, sub-gap conductance,  $G_S$ ) and  $V=0.45\text{mV}$  (green, above-gap conductance,  $G_N$ ). The blue curve is the calculated sub-gap conductance using  $G_S = 4e^2/h \times T^2/(2-T)^2$ , where transmission  $T$  is extracted from the above-gap conductance:  $G_N = 2e^2/h \times T$ . **e**  $G_S$  as a function of  $G_N$  (black dots) and its comparison with the theory fit:  $G_S = 2 * G_N^2/(2 - G_N)^2$ , with  $G_S$  and  $G_N$  in unit of  $2e^2/h$ . **f** Magnetic field dependence of the hard gap. Lower panel shows the zero bias line-cut. The gap remains hard until 1 Tesla where the superconducting gap closes.





**Extended Data Figure 4 | Trivial zero bias peaks from Andreev bound states.** **a**  $dI/dV$  of Device D, as a function of back gate voltage which tunes the chemical potential in the proximitized wire part. Tunnel and super gate voltages are fixed at  $-0.03V$  and  $0V$ , respectively.  $B=0.74T$ . **b** Tunnel gate dependence of this ZBP. The super and back gate voltages are fixed at  $0V$  and  $-5.6V$ , respectively.  $B=0.74T$ . The zero bias peak does not remain stable (un-split) over tunnel gate voltage change, and only exists at the crossing points of the Andreev levels. This indicates that the ZBP has a trivial origin which is from Andreev bound states localized near the tunnel barrier due to the potential fluctuations there. Thus the tunnel gate voltage change can modify the potential fluctuations, changing the Andreev bound state energy. **c** Magnetic field dependence of this trivial ZBP at different back gate voltages ( $-5.6V$ ,  $-7.5V$  and  $-11.1V$ ). The tunnel (super) gate voltages are  $-0.05V$  ( $0.05V$ ),  $-0.05V$  ( $0.05V$ ) and  $0.01V$  ( $-0.44V$ ), respectively. **d** line-cuts of the ZBPs from **c**, showing the trivial ZBP height varies with different gate setting. It can be exactly at  $2e^2/h$ , or much less (larger) than this quantized value. **e** Back gate dependence of the ZBP at  $0.35T$ , for tunnel and super gate voltages fixed at  $0.01V$  and  $0V$ , respectively. Lower panel shows the zero bias line-cut, where the zero bias conductance continues to increase across  $2e^2/h$ . **f** Vertical line-cuts from **e** (with only half the lines plotted for clarity), showing a continuous change of zero bias peak height. This trivial ZBP height continuously varies with gate voltage change and does not resolve a plateau like the Majorana case (Figure 2 and Figure 4). **g** Lorentzian fit (red curve) of the trivial ZBPs (black dots) taken from **f**. We assumed a temperature broadening of  $20mK$ . This Lorentzian fit applied equally well for trivial ZBPs here and the Majorana case in Figure 4c. This means that the ZBP shape can not be used to distinguish Majoranas from ABS.



**Extended Data Figure 5 | Temperature dependence simulation of the quantized Majorana zero bias peak in Device B.** We take the  $dI/dV$  curve at 20mK as the input, and assume this as the zero temperature  $dI/dV$ . Then we perform the convolution of the derivative of Fermi distribution function to calculate the  $dI/dV = G(V, T) = \int_{-\infty}^{\infty} d\epsilon G(\epsilon, 0) \frac{df(eV - \epsilon, T)}{d\epsilon}$  at any temperature  $T$  and bias voltage  $V$ ,  $f(E, T)$  is the Fermi function. Because we use 20mK data as the zero temperature data, our model only works for  $T$  sufficiently larger than 20mK, e.g. ( $T > 50mK$ ). **a** Comparison of the experimental data (left, taken from Fig.4d) and theory simulations, for different temperatures. **b** Comparison of the extracted peak height and width as a function of temperature between experiment (left panel, taken from Fig.4f) and theory simulations (right panel). **c** Several typical curves at different temperatures, black dots are the experimental data while the red curves are the theory simulations. The perfect agreement between simulation and experiment indicates that thermal averaging effect is the dominating effect that smears out our Majorana ZBP in our temperature dependence. **d** Temperature dependence of the theory simulated zero bias peak take from Figure 1c (right panel). The temperature is from 25mK to 700mK with 23 mK step.