Journal of Visualized Experiments

Scalable quantum integrated circuits on superconducting two-dimensional electron gas platform

--Manuscript Draft--

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Editorial Office,

Journal of Visualized Experiment (JoVE),

Dear Dr. Bing Wu,

Please find the revised version of our invited methods article entitled 'Scalable quantum integrated circuits on superconducting two-dimensional electron gas platform' by '*K. Delfanazari, P. Ma, R. Puddy,T. Yi, M. Cao, Y. Gul, C. L. Richardson, I. Farrer, D. Ritchie, H. J. Joyce, M. J. Kelly, C. G. Smith*' for reconsideration and publication in Journal of Journal of Visualized Experiment (JoVE).

   In this revised version, we have followed all the editorial and reviewers comments.

Sincerely Yours,

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1　**TITLE:**
2　Scalable Quantum Integrated Circuits on Superconducting Two-Dimensional Electron Gas
3　Platform
4
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19　**KEYWORDS:**
20　two-dimensional Josephson junctions, quantum processing, quantum integrated circuits, hybrid
21　superconductor-semiconductor devices, topological superconductivity, Majorana devices
22

23　**SHORT ABSTRACT:**
24　Quantum integrated circuits (QICs) consisting of array of planar and ballistic Josephson junctions
25　(JJs) based on $In_{0.75}Ga_{0.25}As$ two-dimensional electron gas (2DEG) is demonstrated. Two different
26　methods for fabrication of the two-dimensional (2D) JJs and QICs are discussed followed by the
27　demonstration of quantum transport measurements in sub-Kelvin temperatures.
28

29　**LONG ABSTRACT:**
30　To form a coherent quantum transport in hybrid superconductor-semiconductor (S-Sm)
31　junctions, the formation of a homogeneous and barrier-free interface between two different
32　materials is necessary. The S-Sm junction with high interface transparency will then facilitate the
33　observation of the induced hard superconducting gap, which is the key requirement to access
34　the topological phases (TPs) and observation of exotic quasiparticles such as Majorana zero
35　modes (MZM) in hybrid systems. A material platform that can support observation of TPs and
36　allows the realization of complex and branched geometries is therefore highly demanding in
37　quantum processing and computing science and technology. Here, we introduce a two-
38　dimensional material system and study the proximity induced superconductivity in
39　semiconducting two-dimensional electron gas (2DEG) that is the basis of a hybrid quantum
40　integrated circuit (QIC). The 2DEG is a 30 nm thick $In_{0.75}Ga_{0.25}As$ quantum well that is buried
41　between two $In_{0.75}Al_{0.25}As$ barriers in a heterostructure. Niobium (Nb) films are used as the
42　superconducting electrodes to form Nb- $In_{0.75}Ga_{0.25}As$ -Nb Josephson junctions (JJs) that are
43　symmetric, planar and ballistic. Two different approaches were used to form the JJs and QICs.
44　The long junctions were fabricated photolithographically, but e-beam lithography was used for

45 short junctions' fabrication. The coherent quantum transport measurements as a function of
46 temperature in the presence/absence of magnetic field B are discussed. In both device
47 fabrication approaches, the proximity induced superconducting properties were observed in the
48 $In_{0.75}Ga_{0.25}As$ 2DEG. It was found that e-beam lithographically patterned JJs of shorter lengths
49 result in observation of induced superconducting gap at much higher temperature ranges. The
50 results that are reproducible and clean suggesting that the hybrid 2D JJs and QICs based on
51 $In_{0.75}Ga_{0.25}As$ quantum wells could be a promising material platform to realize the real complex
52 and scalable electronic and photonic quantum circuitry and devices.
53
54 **INTRODUCTION:**
55 A Josephson junction (JJ) is formed by sandwiching a thin layer of a non-superconducting
56 (normal) material between two superconductors[1]. Various novel quantum electronic and
57 photonic circuits and devices can be built based on JJs[2-16]. Among them, the JJs with
58 semiconductor as their non-superconducting (normal) part, or superconductor-semiconductor-
59 superconductor (S-Sm-S) JJs, have received much attention in recent years after the purported
60 detection of exotic Majorana particles with zero electrical charges at the interface of a
61 superconductor and a semiconducting one-dimensional (1D) nanowire[17-22]. Nanowire-based
62 hybrid devices are limited to the 1D geometry of the nanowire and fabrication of Y and/or T-
63 structures out of them - a necessary requirement for Majorana braiding- is challenging[22]. The fine
64 tuning of nanowire's chemical potential, for accessing topological phases, requires JJs with
65 several electrostatically gates which causes quite a lot of issues in complex device fabrication out
66 of nanowires. To overcome the scalability issues of 1D wires, two-dimensional (2D) material
67 platforms are highly desirable[19,22].
68
69 Among 2D materials, the two-dimensional electron gas (2DEG) platform -forms when electrons
70 are confined to an interface between two different materials in a semiconductor
71 heterostructure- is the most promising candidate[22]. The combination of 2DEG with
72 superconductors and forming hybrid 2D JJs opens a new avenue towards development of next
73 generation scalable quantum system such as topological quantum processing and computing.
74 They can support phase coherent quantum transport, and proximity induced superconductivity
75 with high transmission probability, which are fundamental requirement for topological phase
76 observation. In this regard, we demonstrate a QIC on a chip which consists of array of ballistic 2D
77 JJs that can be controlled by 20 wires. Each junction has two Nb electrodes as the
78 superconducting part and $In_{0.75}Ga_{0.25}As$ quantum wells in a semiconducting heterojunction as the
79 normal part. The wafer can be easily patterned to form complex structures and networked QICs.
80
81 The advantages of $In_{0.75}Ga_{0.25}As$ 2DEG include: (i) relatively large g-factor, (ii) strong Rashba spin-
82 orbit coupling, (iii) the low electron effective mass, and (iv) that the indium composition can be
83 tuned allowing the formation of JJs with high interface transparency[23-25]. The wafer can be grown
84 as a disk of up to 10 cm dimeter, allowing fabrication of thousands of hybrid 2D JJs and complex
85 QICs networks so overcoming the scalability challenges of these quantum devices.
86
87 We discuss two different approaches for device fabrications: For device 1, a circuit which includes
88 eight identical and symmetric JJs of 850 nm length and 4 µm widths are patterned by

89   photolithography[23,24]. The device 2 includes eight junctions with different lengths. They all have
90   the same width of 3 μm. The JJs are patterned by e-bam lithography[25]. The transport
91   measurements at sub-Kelvin temperature ranges in absence/presence of magnetic field will be
92   presented. The on-chip QICs consists of array of 2D Nb- $In_{0.75}Ga_{0.25}As$ -Nb JJs. The long and short
93   junctions are measured in a dilution fridge with a base temperature of 40 mK and liquid ^3He
94   cooled cryostat with a base temperature of 300 mK, respectively. Devices are biased with an *ac*-
95   signal of 5 μV at 70 Hz which is superimposed to the junction *dc* voltage bias. A two-terminal
96   standard lock-in technique is used to measure the device output *ac*-current[23-25].

98   **PROTOCOL:**

100   NOTE: Semiconductor heterostructure and hybrid S-Sm Josephson junction fabrication is
101   presented.

103   **1.   Semiconducting heterostructure fabrication**

105   NOTE: The molecular beam epitaxy (MBE) grown $In_{0.75}Ga_{0.25}As$ quantum wells are used in this
106   study[23-26]. **Figure 1** depicts the sequence of distinct layers:

108   1.1 Clean a 500 μm thick, 3-inch semi-insulating (001) GaAs substrate and remove the oxide layer
109   in high temperature (above 200 °C)[26].

111   1.2 Adjust the growth temperature at 580 °C and grow the buffer layer of GaAs/AlAs/GaAs films
112   with thicknesses of 50/75/250 nm[26].

114   1.3 Ramp down the substrate temperature for 20 min and then grow a step-graded buffer layer
115   of InAlAs with a 1300 nm thickness at starting substrate temperatures of T = 416, 390, 360, 341,
116   331 and 337 °C[26].

118   1.4 Grow a 30 nm thick $In_{0.75}Ga_{0.25}As$ quantum well 2DEG at slightly higher substrate
119   temperature[26].

121   1.5 Cover the 2DEG quantum well with a 60 nm $In_{0.75}Al_{0.25}As$ spacer, and then modulation dope
122   the wafer by a 15 nm thick of a n-type $In_{0.75}Al_{0.25}As$. This will assure the conductance in the dark[26].

124   1.6 Grow a 45 nm $In_{0.75}Al_{0.25}As$ layer followed by a cap layer of InGaAs with thickness of 2 nm[26].

126   1.7 Perform the measurement of the Shubnikov–de Haas oscillations and Hall effect to find the
127   electron density (n_s) and mobility (μ_e) at temperature T= 1.5 K[26]. From the transport
128   measurements, it was inferred that the n_s= 2.24×10^{11} (cm^{-2}) and μ_e= 2.5×10^5 (cm^2/Vs) in the dark
129   but n_s= 2.28×10^{11} (cm^{-2}) and μ_e= 2.58×10^5 (cm^2/Vs) after illumination.

131   **2.   Two-dimensional Josephson junction fabrication**

133 NOTE: Here, the fabrication process of the hybrid QICs with two different approaches are
134 discussed[23-25]. Device 1 with eight identical long Josephson junctions was fabricated only with a
135 few steps of photolithography processing. The second device fabrication procedure was similar
136 to device 1 up to formation of JJs which step the e-beam- lithography was used.

138 2.1 Sketch the JJs and QIC device layout, including mesa and ohmic patterns by using AutoCad
139 software[25]. Start the drawing by selecting appropriate layers form the layer selector menu.
140 Create a new layer from **Format | Layer** in the AutoCad software.

142 2.2 Design and fabricate the photolithography mask. Choose desired shapes and geometries from
143 the panel menu in the software. Click on the desire shape of JJs (i.e., rectangles, squares) and
144 push the drawing window to initiate the shape (click in the Autocad software help menu for more
145 details).

147 2.3 Pattern the JJs and QICs designs, after developing the photoresist on the wafer, and fabricate
148 the mesa structures to act as the active region (the raised area in **Figure 1**) by wet-etch in acid
149 solution of H_2SO_4: H_2O_2: (1:8:1000)[23-25]. Rinse the device in DI water for 30 s and then dry with
150 nitrogen gas.

152 2.4 Ensure an etch depth of $\sim$ 150 nm by the DEKTAK surface profiler[23-25].

154 2.5 Form ohmic contacts, to make electrical contact between the metal and 2DEG, by spinning
155 photoresist on top of the wafer and then exposure to UV light through a photo-mask. Develop
156 the resist in MF-319 for 1 min. Deposit a thin layer, between 50 nm and 100 nm of
157 gold/germanium/nickel (AuGeNi) alloy over the resist-patterned sample[23-25].

159 2.6 Etch a $\sim$ 140 nm deep trench on top of the active region to form 2D JJs by either
160 photolithographically (device 1) or e- beam lithographically (device 2) pattering and wet-etching
161 in acid described above (the JJs should be formed far from the ohmic contacts, a distance of >
162 100 µm, to ensure that the normal electrons from this part do not influence to the junction's
163 interfaces)[23-25].

165 2.7 Sputter a $\sim$ 130 nm superconducting Nb film to form Nb-$In_{0.75}Ga_{0.25}As$-Nb JJs (by DC
166 magnetron sputtering in Ar plasma),

168 2.8 Deposit 10/50 nm thick Ti/Au films for electrical contacts and transport measurement
169 purposes.

171 2.9 Transfer and load the device on the standard leadless chip carrier (LCC) by using GE varnish,
172 and make the electrical contacts between the device and LCC pads by using gold wires.

174 2.10 Load the devices into a ^{3}He cryostat or dilution refrigerator for transport measurements.

176 **REPRESENTATIVE RESULTS:**

177

178 **Figure 2a** shows the scanning electron microscope (SEM) image of the device 1. A quantum circuit
179 with 20 electrical wires can be seen. The design allows the measurement of one or series of JJs
180 on a chip in one fridge cool-down. The SEM image of one junction on the circuit of Device 2, that
181 was fabricated by e-beam lithography, is shown in **Figure 2b**. The distance between two Nb films
182 in each side of the Nb-In$_{0.75}$Ga$_{0.25}$As-Nb junction is L= 550 nm at the shortest path. **Figure 2c** shows
183 the SEM image of one junction of Device 1- which is photolithographically fabricated. Here, the
184 two Nb electrodes are separated by a distance of L= 850 nm.

185

186 The Blonder–Tinkham–Klapwijk (BTK) theory is an acceptable model to describe the quantum
187 transport in hybrid S-Sm junctions[27]. The influence of the superconductor order parameters in
188 semiconducting 2DEG results in a nonlinear differential conductance. At low temperatures, there
189 are two possible reflection mechanisms at the Nb-In$_{0.75}$Ga$_{0.25}$As interfaces: normal reflection
190 which causes no charge transmission through the interface and the Andreev reflections, which
191 transmits two charge quanta $2e$, with the retroreflection of a hole[23-25]. As the superconducting
192 condensate consists of spin singlet Cooper pairs, the reflected hole has the opposite spin as the
193 incoming electron. The cartoon diagram of these two processes are shown in **Figure 3a,b**,
194 respectively[28].

195

196 If the interface between the Nb and In$_{0.75}$Ga$_{0.25}$As contact is not transparent, there is coexistence
197 of both normal and Andreev reflected electrons. Thus, the resistance increases and a zero-bias
198 peak within the gap is formed. Such an in-gap peak in the dV/dI (V_{SD}) is not observed in our
199 junctions. However, for a homogeneous and barrier free (Z=0) interface between the Nb film and
200 In$_{0.75}$Ga$_{0.25}$As contact, all incident electrons undergo Andreev reflection. In such condition, an
201 excess current I_{exc} is formed in the junction due to correlations of electron- and hole-like
202 quasiparticles. Therefore, the differential resistance within the gap is reduced and a flat U-shape
203 dip in dV/dI (V_{SD}) is observed. According to BTK model, it can be inferred that no tunneling barrier
204 formed at the Nb-In$_{0.75}$Ga$_{0.25}$As interfaces of both devices. Therefore, the barrier strength is
205 estimated to be Z < 0.2 in our junctions[23-25].

206

207 Because of the proximity effect, induced gap of approximately $\Delta_{ind} \approx$ 100 µeV, and 650 µeV are
208 measured in the devices 1 and 2, respectively. The temperature dependence induced
209 superconducting gap with pronounced subharmonic energy gap structures (SGS) peaks and dips
210 for device 1 are shown in **Figure 4a**. The multiple Andreev reflections (MAR) at the interfaces of
211 the Nb-In$_{0.75}$Ga$_{0.25}$As junction result in the observation of SGS in the differential conductance. At
212 the lowest measured temperature T= 50 mK (red curve), the SGS appears with three peaks
213 (named as P1, P2 and P3) and three dips (named as d1, d2 and d3). The temperature evolution
214 of the peaks and dips due to the suppression of the induced superconductivity with temperature
215 increase are shown in **Figure 4b**. The SGS peak positions obey the expression $V = 2\Delta/ne$ (Δ is the
216 Nb gap energy, n = 1, 2, 3, … is an integer, and e is the electron charge): P1, P2, P3 and P4 positions
217 approximately correspond to $2\Delta/3e$, $2\Delta/4e$, $2\Delta/6e$ and the induced gap edge but the dip positions
218 do not follow the expression. All features are significantly temperature dependent, and the
219 strongest (weakest) SGS peaks (dips) are observed at T= 50 mK (800 mK). It is worth mentioning
220 that even at temperatures above T= 500 mK where the supercurrent can no longer be seen, the

221 SGS is observed but it disappears at $T>$ 800 mK- when induced superconductivity is washed out.
222 For this device with array of eight 2D JJs, in 4 out of 7 junctions, a hard-induced superconducting
223 gap in $In_{0.75}Ga_{0.25}As$ 2DEG was found[23,24]. However, three junctions showed a soft gap signature
224 and neither a hard- nor a soft-gap structure was observed for the last junction because of a wire
225 contact failure between the device and pad.

226

227 The superconducting gap as a function of applied V_{SD} voltage and temperature of device 2 is
228 shown in **Figure 5a**. This device was measured at a ^{3}He cryostat with base temperature of $T=$ 280
229 mK. The temperature and magnetic field dependences transport measurements of device 2 do
230 not show any sign of in-gap or sub-gap oscillations which are observed for device 1 (see **Figure**
231 **5a, b**). This could be due to the arrow-shaped geometry of the junction which may cause
232 destructive interreference of the MAR. Such features might appear in the differential
233 conductance if the device is measured at much lower temperatures (dilution fridge base
234 temperature). The induced gap is suppressed and moved toward zero voltage bias and their
235 amplitudes diminish with further increasing of the applied temperature and magnetic field.

236

237 **FIGURE AND TABLE LEGENDS:**
238 **Figure 1. $In_{0.75}Ga_{0.25}As/In_{0.75}Al_{0.25}As/GaAs$ heterostructure.** The schematic view of the
239 heterojunction where an $In_{0.75}Ga_{0.25}As$ quantum well with 30 nm thickness is formed $\sim$ 120 nm
240 below the wafer surface. Nb was used as the superconducting contacts (shown in black) to form
241 a hybrid and ballistic Nb–$In_{0.75}Ga_{0.25}As$ 2DEG–Nb Josephson junction.

242

243 **Figure 2: On-chip hybrid superconducting-semiconducting quantum circuits.** (**a**) SEM image of
244 the QICs device showing a top view of a quantum circuit with 20 control wires, and 8 planar and
245 symmetric JJs on a chip. The SEM image of Nb-$In_{0.75}Ga_{0.25}As$-Nb JJs with an $In_{0.75}Ga_{0.25}As$ 2DEG
246 gap of length $L=$ 550 nm and 850 nm for e-beam lithographically (**b**) and photolithographically (**c**)
247 fabricated junctions.

248

249 **Figure 3. Normal and Andreev Reflections in hybrid superconducting-semiconducting junctions.**
250 (**a**) Specular quasiparticle reflection with no charge transmission through the interface. (**b**)
251 Andreev reflection whereas the incoming electron is reflected as a hole in the opposite spin sub-
252 band and transfer 2e charge into superconducting electrode.

253

254 **Figure 4. Induced superconductivity and SGS in $In_{0.75}Ga_{0.25}As$ quantum wells in**
255 **photolithographically fabricated junction.** (**a**) Temperature dependence induced
256 superconducting gap with pronounced SGS peaks due to multiple Andreev reflections. The SGS
257 and the induced gap edge peaks, are marked by P1 to P4 while the SGS dips are marked by d1 to
258 d3. (**b**) The SGS peaks and dips shown in (a) as a function of temperature. SGS are suppressed
259 significantly at $T>$ 400 mK leading to a shift toward zero bias.

260

261 **Figure 5. The temperature and magnetic field dependence of induced superconductivity in e-**
262 **beam lithographically fabricated junctions.** (a) Induced superconducting gap vs. applied source-
263 drain voltage V_{SD} at temperatures between 300 mK and 1.5 K. The curves are vertically offset for
264 clarity. (**b**) Color-coded differential resistance as a function of V_{SD} and perpendicular magnetic

265 field at $T = 300$ mK.
266
267 **DISCUSION:**
268 On-chip QICs comprising an array of JJs based on superconducting indium gallium arsenide
269 (In$_{0.75}$Ga$_{0.25}$As) quantum wells were demonstrated. Two important challenges of hybrid S-Sm
270 material systems such as the scalability and interface transparency were addressed. Two critical
271 steps whining the protocol including the growth of high quality and high mobility In$_{0.75}$Ga$_{0.25}$As
272 two-dimensional electron gas in semiconducting heterostructures and proximity induced
273 superconductivity into 2DEG were discussed[23-25].
274
275 Growth of In$_{0.75}$Ga$_{0.25}$As with step-graded buffer layers in GaAs substrate and also the formation
276 of homogeneous and barrier-free interfaces between the superconductor and semiconductor is
277 a crucial step in such hybrid 2D quantum circuit development. It was demonstrated that with
278 careful etching the sputtered superconducting film can make highly transparent contacts to
279 In$_{0.75}$Ga$_{0.25}$As quantum wells resulting in detection of induced superconducting gap in
280 semiconductors[23-25].
281
282 The significance with respect to existing methods is that the presented technique for 2D hybrid
283 JJs and circuit realization does not require the insitu deposition of superconductor on
284 semiconductors in an MBE chamber after the semiconductor growth has been completed[23-25].
285 The other significance is that the heterostructure wafer can be grown as a desk of up to 10 cm
286 dimeter, allowing the fabrication of thousands of hybrid 2D junctions and circuits, so overcoming
287 the scalability challenges of the hybrid S-Sm quantum circuits and devices[22-25].
288
289 The induced superconductivity in quantum wells, SGS on differential conductance of the 2D
290 junctions, and the phase coherent ballistic quantum transport measured in our junctions strongly
291 suggest that hybrid 2D junctions and circuits based on superconducting In$_{0.75}$Ga$_{0.25}$As 2DEG afford
292 promising material system for scalable quantum processing and computing technologies. Our
293 approach may open a new road toward quantum technology and helps pave the way for the
294 development of on-chip topological quantum circuits for realizing the next generation of
295 quantum processors[23-25].
296

299
300 **DISCLOSURES:**
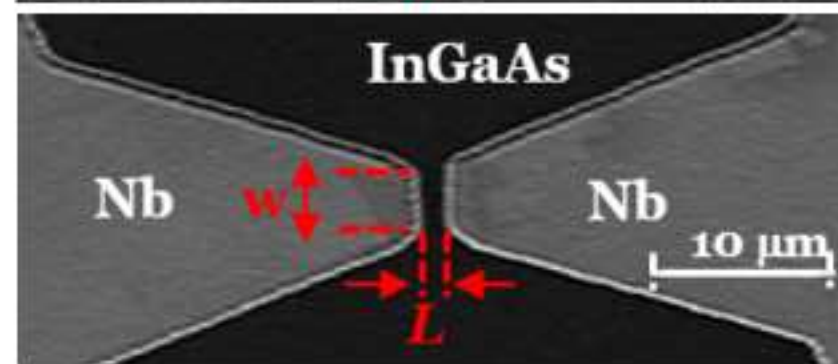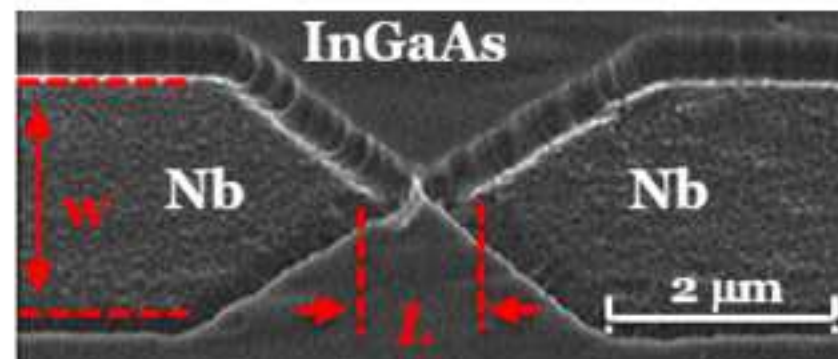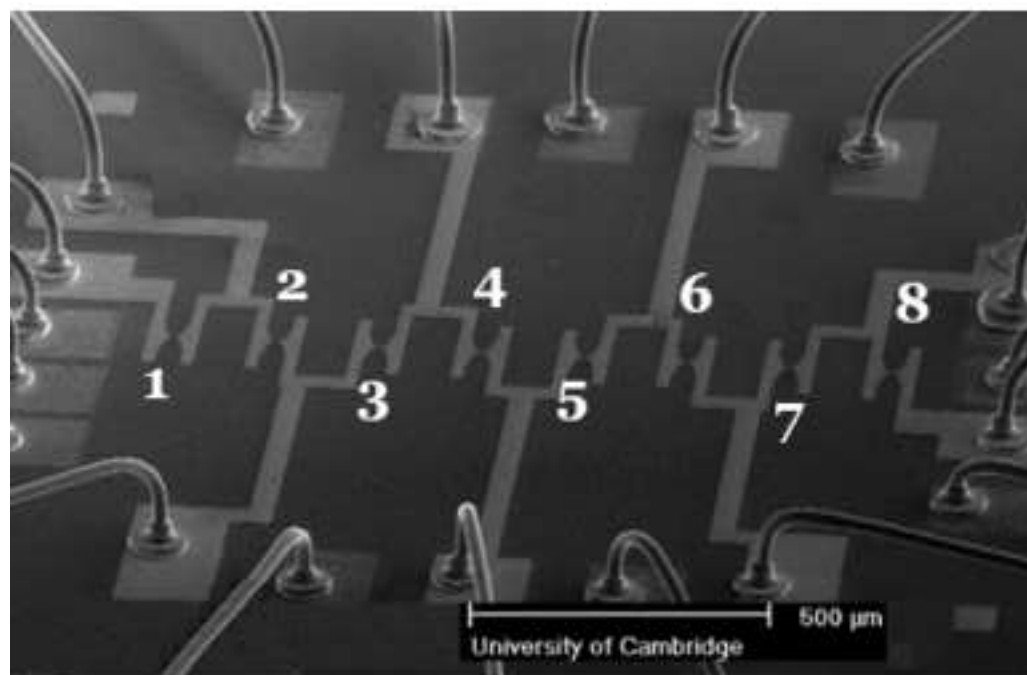301 The authors have nothing to disclose.
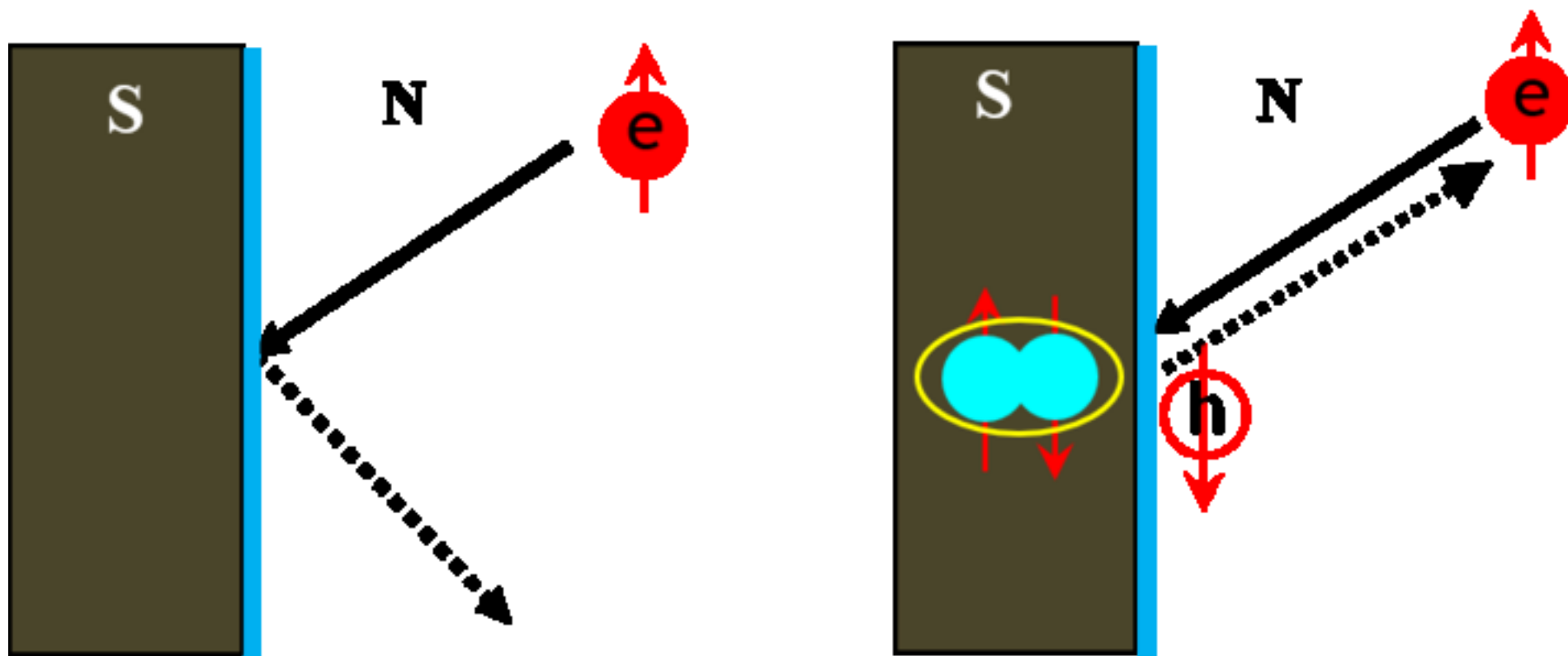302

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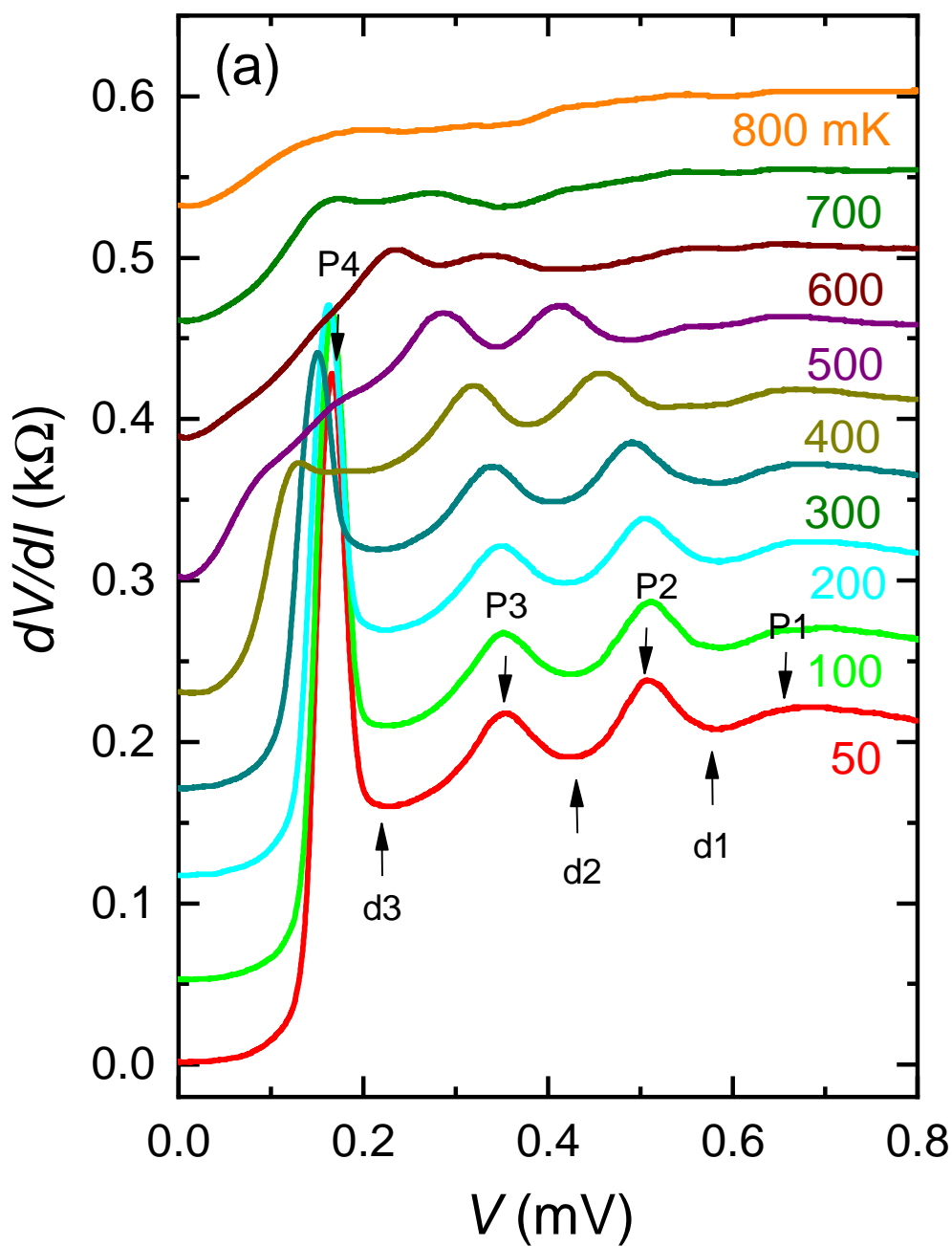307 *Applied Superconductivity* **21**, 760–9 (2011).

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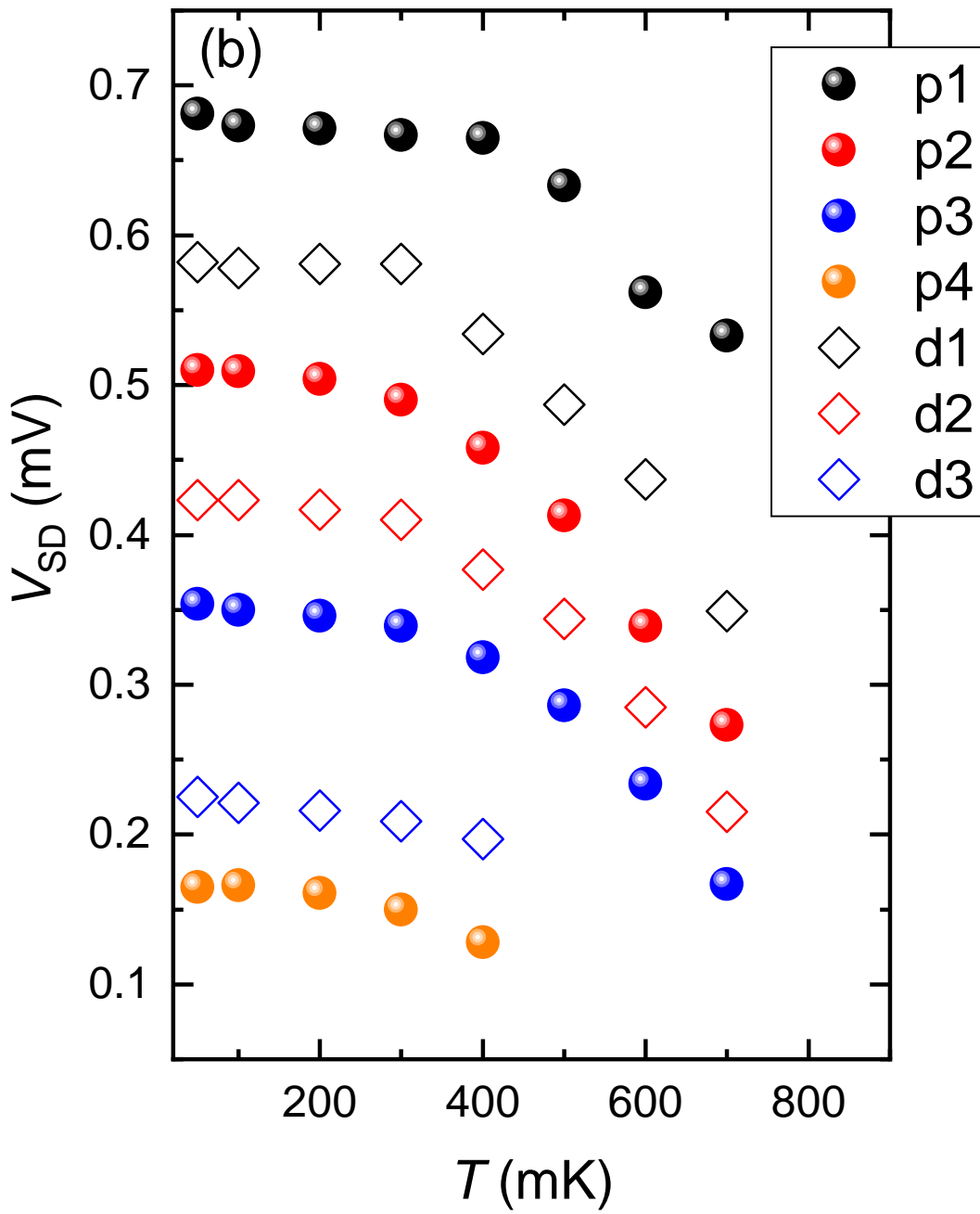350 (2017).

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FIG1

Mesa (active region)

Niobium

Niobium

In0.75Ga0.25As Cap

In0.75Al0.25As

In0.75Al0.25As Modulation doping

In0.75Al0.25As spacer

In0.75Ga0.25As 2DEG

In0.75Al0.25As buffer

In0 → 0.85AlAs linear graded buffer

GaAs/AlAs/GaAs buffer

GaAs Substrate

FIG2

FIG3

(b)

dV/dI (kΩ)

0.1

0

V_{SD} (mV)

B (mT)
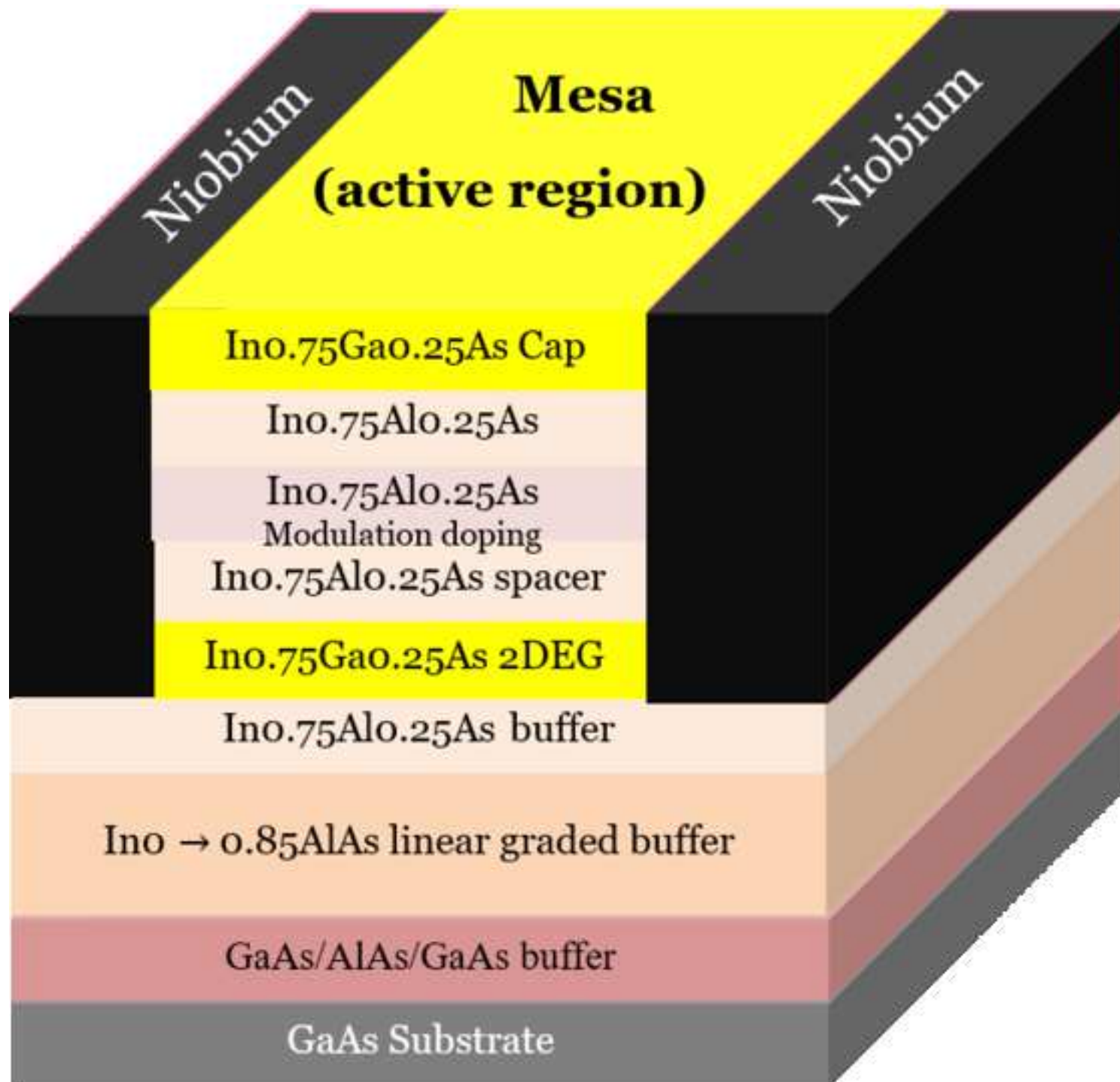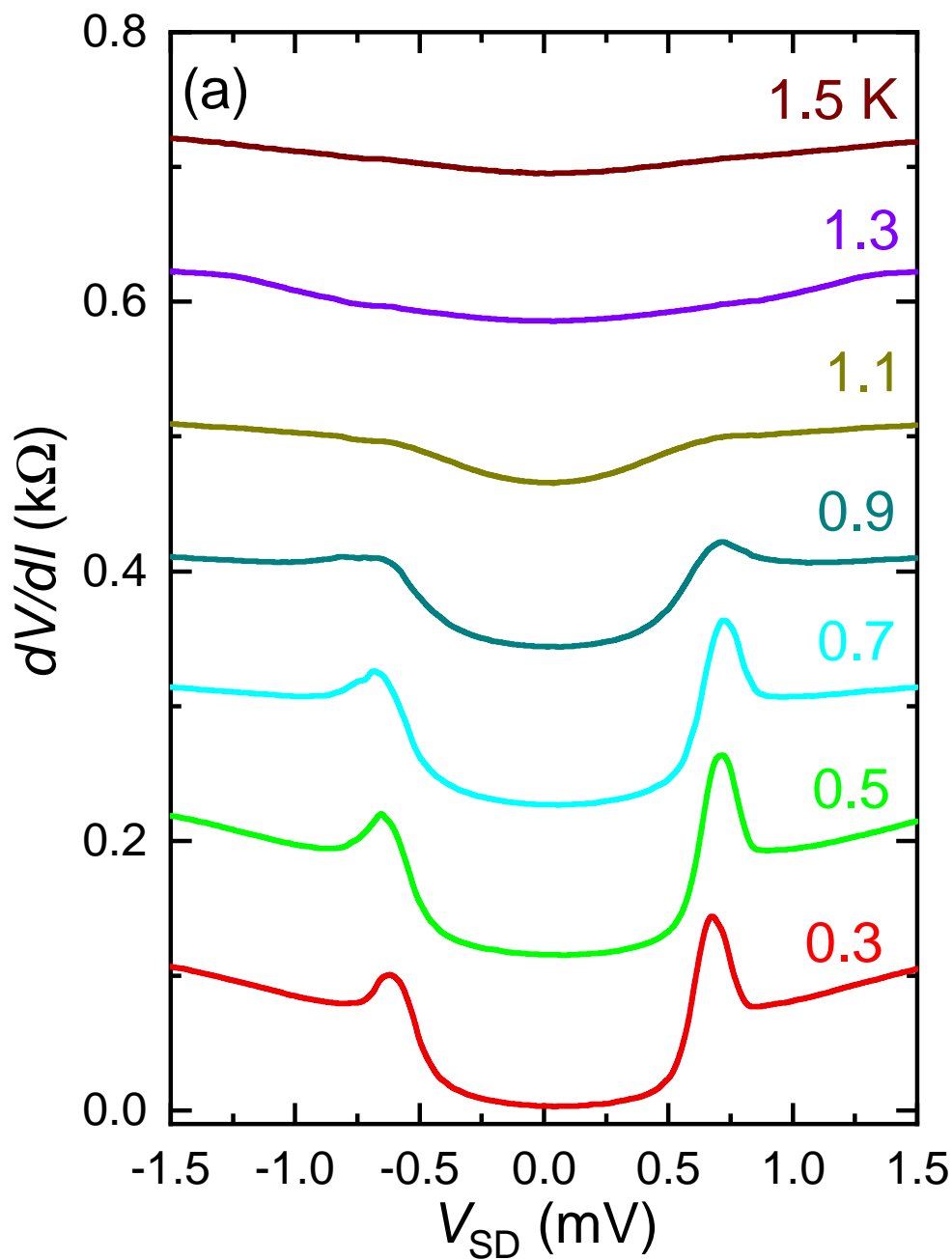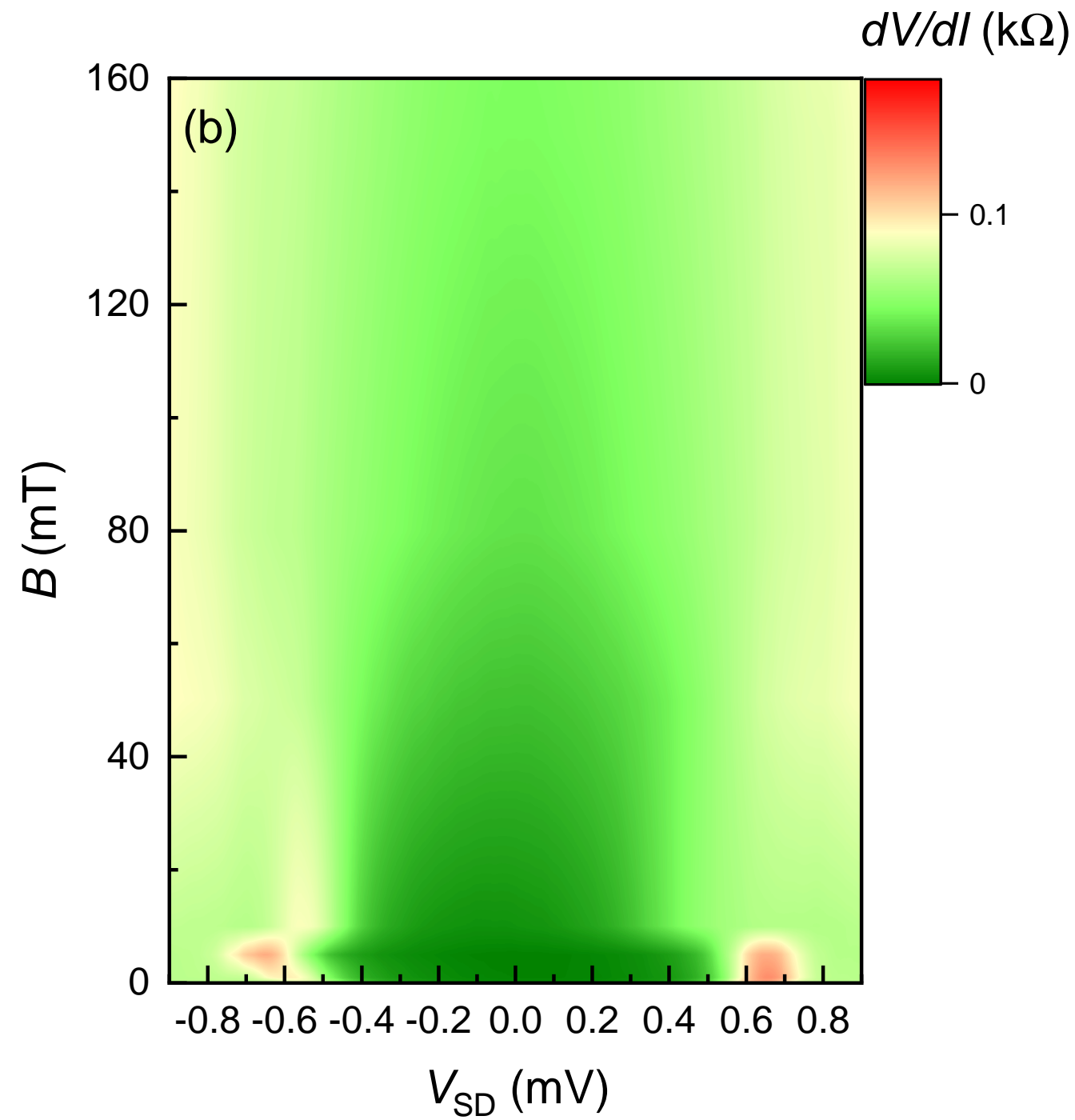
Name of Material/ Equipment	Company	Catalog Number	Comments/Description
CompactDAQ Chassis	National Instruments	NI cDAC-9178	
DSP Lock-in Amplifier	AMETEK 7265	190284-A-MNL-C	
Dilution refrigerator	Blueforce		Buttom loaded fridge
Dilution refrigerator	Oxford	KelvinoxMX40	Wet-fridge
Diamond scriber MICROTEC	Karl Suss	HR 100	
Dektak Surface Profilometer	Veeco	3ST	
Evaporator	Edwards	AUTO 306 Coating system	
Evaporator	Edwards	E306A	
^{3}He Cryostat	Oxford		
Photoresist Spinner	Headway Research Inc.	EC101DT-R790	
Matlab			
Mask Aligner	Karl Suss	MJB 3	
Source meter	Keithley	2614B	
Semiconducting heterostructure	MBE Veeco	Gen III system	MBE Grown wafers
Wire Bonder	K&S	4524	

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