Supplementary Information: MBE Growth of Al/InAs and Nb/InAs Superconducting Hybrid Nanowire Structures

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Aluminum shell

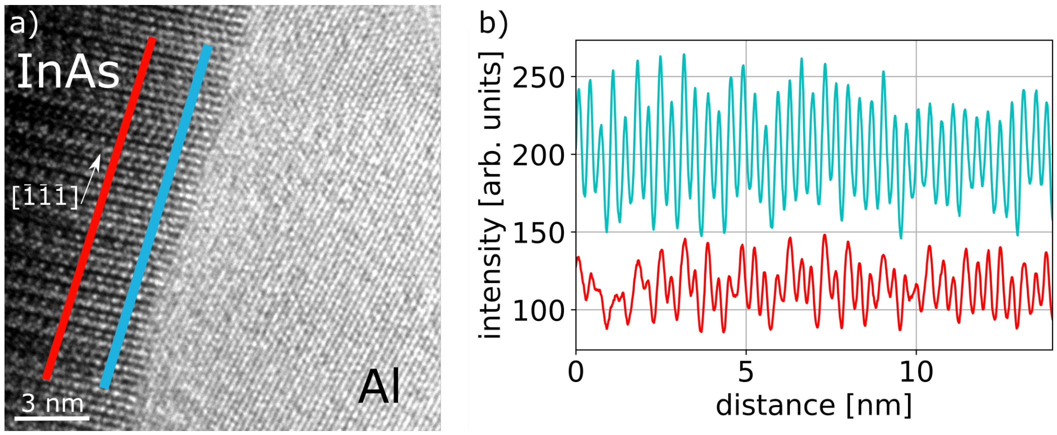

Figure S1: a) TEM image of an InAs NW showing the InAs/Al interface after As evaporation as explained in the main text and line cuts along the growth direction. b) Exemplary line profiles according to the red (InAs) and blue (interface) line cuts displayed in a).

The average lattice plane distances in the growth direction $\mathrm{d}_{\mathrm{InAs},[\bar{1}\bar{1}\bar{1}]} = 0.338 \pm 0.007\,\mathrm{nm}$ and $\mathrm{d}_{\mathrm{interface},[\bar{1}\bar{1}\bar{1}]} = 0.336 \pm 0.005\,\mathrm{nm}$ were extracted by averaging line profiles as shown exemplary in Figure S1 b). The lattice averaged mismatch was determined to $\mathrm{m}_{\mathrm{InAs/interface}} = (\mathrm{d}_{\mathrm{InAs},[\bar{1}\bar{1}\bar{1}]} - \mathrm{d}_{\mathrm{interface},[\bar{1}\bar{1}\bar{1}]})/\mathrm{d}_{\mathrm{interface},[\bar{1}\bar{1}\bar{1}]} \approx 0.6\%$. The extracted value lays within the accuracy of the method. Hence, no mismatch between the sections close to the interface and closer to the wire core is observed.

Al/InAs-nanowire/Al junction

In order to create an Al/InAs-nanowire/Al junction, as shown in Figure S2, the surrounding Al shell has to be partially removed by means of wet chemical etching using tetramethylammonium hydroxide (TMAH)-containing developer MF-CD 26. To remove the $26\,\mathrm{nm}$-thick Al shell completely, an etching time of $90\,\mathrm{s}$ was used. This resulted in a typical lateral junction length of $200 - 300\,\mathrm{nm}$. To obtain a clean interface between the superconducting Nb contacts and the Al shell, Ar sputtering was employed to remove the native $\mathrm{Al_2O_x}$ surface layer. Subsequently,

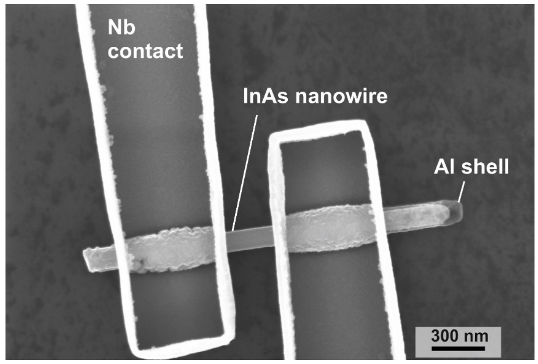

Figure S2: Scanning electron microscopy image of an Al/InAs-nanowire/Al junction. The Al shell was removed in the center part by wet chemical etching. The Al electrodes on both sides are contacted by Nb contacts.

a $300\,\mathrm{nm}$-thick Nb layer was deposited by sputtering followed by a lift-off process to define the superconducting leads. It was made sure that the Nb leads do not exceed the Al contact region. However, future works will aim to optimize this contacting procedure.

Niobium shell

The NWs have partly dissolved at $200\,^{\circ}\mathrm{C}$, leaving empty Nb shells, as depicted in Figure S3 a1). The morphology of the Nb has changed, exhibiting a dotted surface. The EDX spectra depicted in Figure S3 a2), a3) show that In is still present in the NW tip, but diminished in the body of the wire. The different atomic percentages of the respective species, i.e. As, In and Nb, between NW tip and body are listed in Table S1. The high intensity Cu and Al peaks within the spectra stem from the TEM grid and the sample holder, respectively but are not of importance for the analysis. EDX linescans (normal to the wire axis) of Nb/InAs half shell structures for which Nb was deposited at $40\,^{\circ}\mathrm{C}$ and $200\,^{\circ}\mathrm{C}$ are depicted in Figure S3 a4) and a5), respectively. Note that the shift of the peak positions is merely due to a flip of the wires. At a deposition temperature of $40\,^{\circ}\mathrm{C}$ the As and In signal strongly overlap and the Nb shell signal is clearly distinct. At $200\,^{\circ}\mathrm{C}$ in contrast, the In and As signal do not overlap anymore but a strong correlation between Nb

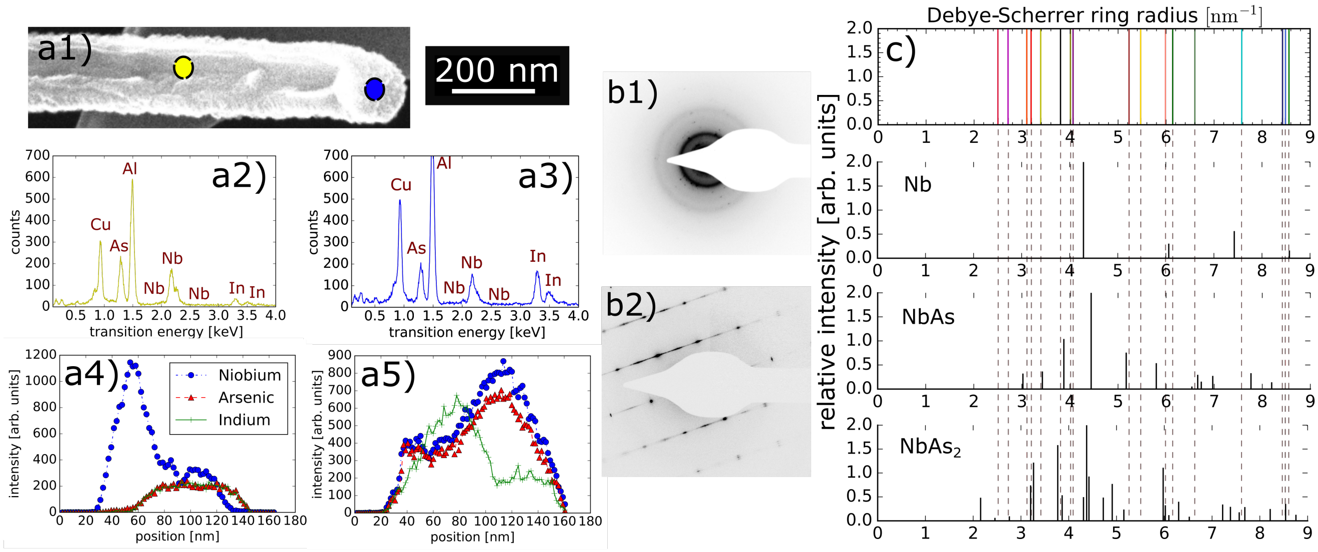

Figure S3: a1) Empty Nb shell stemming from Nb deposition on an InAs NW at 200 °C (scalebar on the right). a2), a3) EDX spectra recorded at the yellow dot (body) and blue dot (tip) in a1). The quantized atomic percentages of the tip spectrum shown in a2) as well as the body spectrum depicted in a3) are listed in Table S1. a4, a5) EDX linescan (perpendicular to the wire axis) of a Nb/InAs half shell structure where the shell was deposited at 40 °C (a4)) and 200 °C (a5)). The legend for both plots is depicted in a4). b1)-b2) Electron diffractogram (inverted colors) from a Nb shell and an InAs NW, respectively. c) Debye-Scherrer ring radii extracted from b1). Nb compound patterns listed below for comparison .[1]

and As is observed. This finding shows clearly that a chemical reaction between Nb and As was triggered at 200 °C during the deposition. Figure S3 b1) shows the electron diffraction pattern

Table S1: Quantized atomic percentages extracted from the EDX scanned Nb shell deposited on an InAs NW at 200 °C (cf. Figure S3).

	As	In	Nb
NW-Tip	43%	30%	27%
NW-Body	48%	9%	43%

of a Nb shell deposited at 200 °C. The occurrence of Debye-Scherrer rings is characteristic for polycrystalline materials. The absence of streaks demonstrates that the reaction with Nb at 200 °C was detrimental for the InAs NW. Diffraction patterns of vapor-solid grown InAs NWs show characteristic streaks due to their high number of stacking faults, as exemplified in Figure S3 b2) for comparison .[2]

The Debye-Scherrer diffraction pattern presented Figure S3 c) reveals that the Nb has reacted with As, forming new compounds. The obtained patterns show resemblance with the signatures of NbAs and $\mathrm{NbAs_2}$ but not with pure Nb.

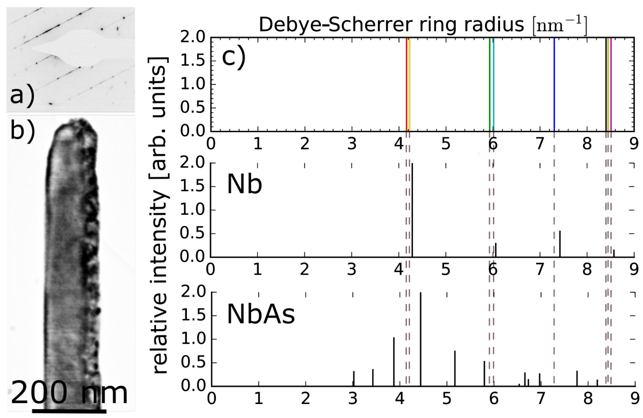

Figure S4: a) Electron diffraction pattern (inverted colors) of the Nb half shell covered InAs NW depicted in b). b) TEM[3] image of an Nb/InAs NW (wire on the left, shell on the right). The shell was deposited at $40\,^{\circ}\mathrm{C}$ under an elevation angle of $87°$. c) Extracted Debye-Scherrer ring radii for a Nb/InAs NW. Nb and NbAs Debye-Scherrer ring radii patterns are plotted for comparison .[1]

The electron diffraction pattern presented in Figure S4 a) is clearly streaked, which proves the presence of an InAs NW. The side view of a niobium covered wire, presented in Figure S4 b), discloses the homogeneous morphology of the Nb shell. The Debye-Scherrer diffraction pattern depicted in Figure S4 c), indicates no additional compounds to Nb, suggesting the absence of a chemical reaction at $40\,^{\circ}\mathrm{C}$.

References and Notes

1 F.I.Z. Karlsruhe, *Inorganic Crystal Structure Database*, https://icsd.fiz-karlsruhe.de, (accessed August 2016).

2 T. Rieger, *Phd Thesis*, RWTH Aachen University, 2015.

3 M. Luysberg, M. Heggen and K. Tillmann, *J. large-scale Res. Facil. JLSRF*, 2016, **2**, A77.