Thermal stability of thin metallic nanowires

E. B. Gordon

Institute of Problems of Chemical Physics RAS,
Chernogolovka 142432 Russia
gordon.eb@gmail.com

Буревестник – 2014

Туапсе, 17 сентября

Our idea that

the quantized vortex in superfluid helium

for any particles represents

a rigid 1D template

submerged

in supersoft, super-heat-removing

low temperature matrix

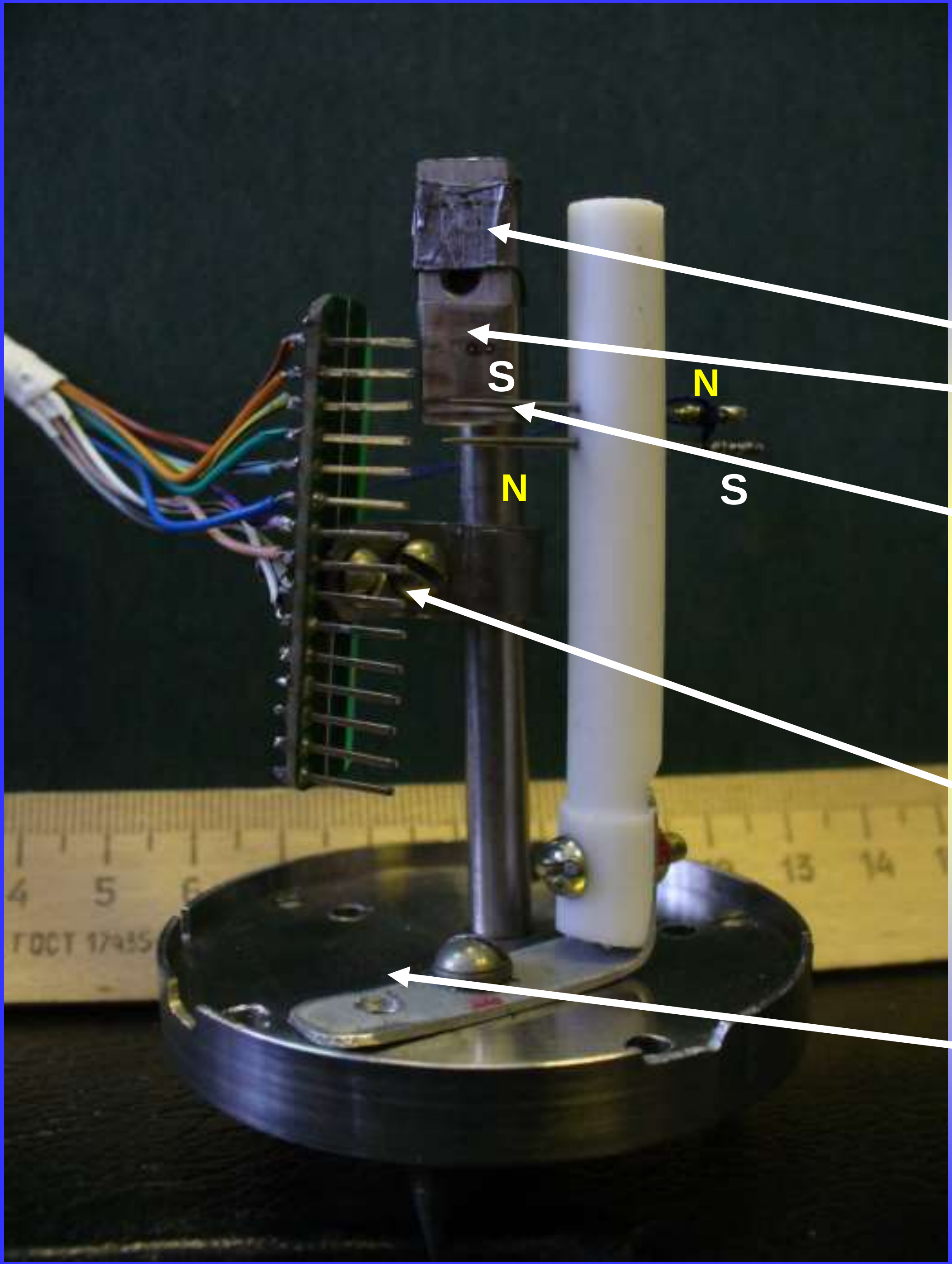
was rather fruitful

By using **the modest techniques** we produced the nanowires from a dozen metals, more than everybody else in the world.

Electron microscope and the **lithography facilities** are in other rooms

We **can fabricate** a nanowire from **everything**, even including mercury

Experimental cell



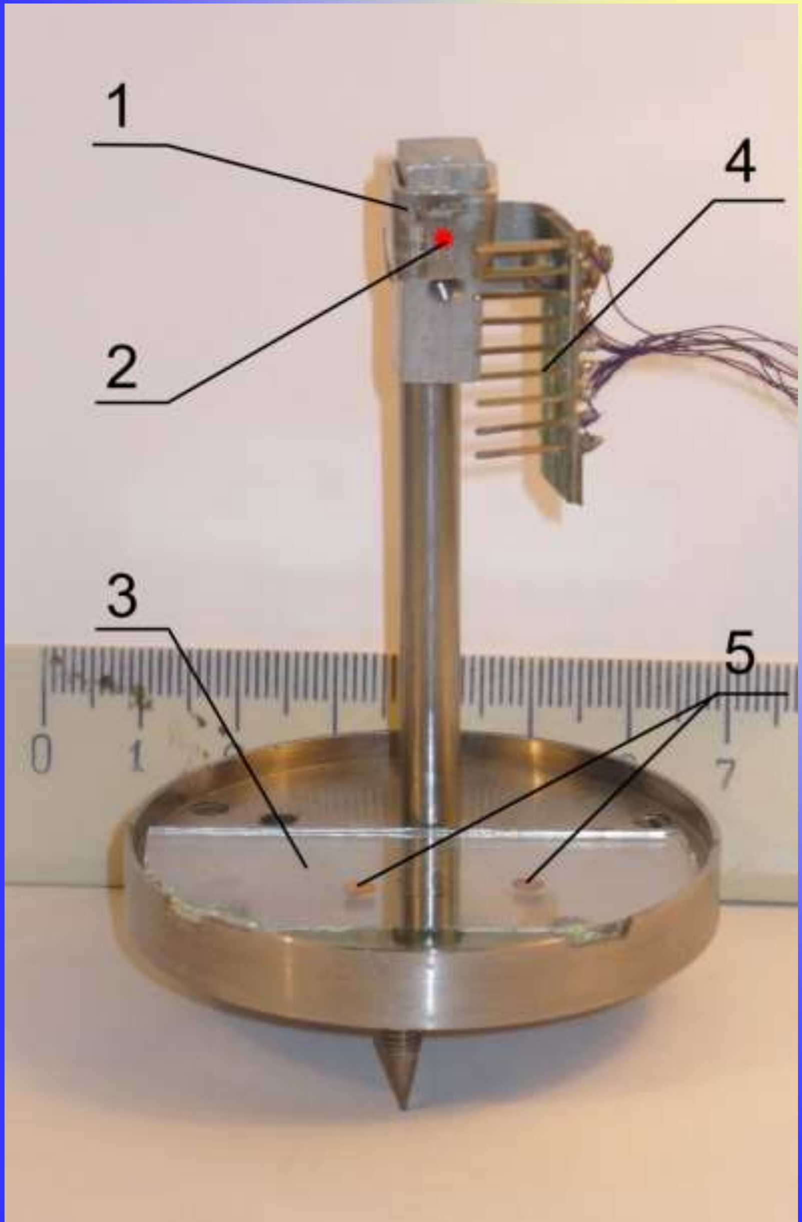
Metallic targets, the craters in laser focuses are seen

The pair of oppositely magnetized sewing needles are seen

Vertical row of gilded contacts, interelectrode distances are 1.4 mm each

Bottom, where nanowires where collected

Exprerimental cell



1 – metallic target

2 – focus of low-power pulse-repetition laser with 500 ps pulse duration

3 – glass slide

4 – the electrode array

5 – TEM grids

1. The nanowires grown between electrodes were subjected to electrical measurements in 1.6 – 300K temperature range.

2. The nanowires deposited on TEM grids were investigated by electron microscopy at 300K

To be honest we were simply lucky:

1. For some fundamental reasons the nanowires are **rather thick – 3-8 nm** – though they are much thinner than the most of known from literature.

2. They are formed through the **molten** nanoclusters and as a result they posses **regular** (not fractal) structure and rather **perfect shape (B. Halperin)**.

3. The productivity of our setup is sufficient to produce the nanoweb with total surface **up to 10 cm^2.**

4. All nanowires in nanoweb are of the **same size**

$\longrightarrow$

serious drawback:
we can't change the diameter

A lot of possible applications

Nanocatalysis - Gold, Silver, Platinum … nanoclusters displayed unusual and strong catalytic activity (one of the largest achievements in modern chemistry) but only being of 2 – 5 nm in size!!!

Nanoweb instead of clusters →

- Any support for immobilization (revealing mechanism)
- Convenient topology
- Electrocatalysis – applying electrical voltage of 10 -100 V is sufficient even for electron field emission from the nanowire's side surface

Nobody could produce so thin nanowires

A lot of possible applications

Quantum devices - "**For a superconductor, charge and phase are dual quantum variables. A phase-slip event in a nanowire changes the phase difference over the wire by 2π; it is the dual process to Cooper-pair tunnelling in a Josephson junction."** J.E. Mooij***** and Yu.V. Nazarov, Superconducting nanowires as quantum phase-slip junctions, *Nature physics v 2, p.169 (2006)*

Promises: →

- nanocomputer qubit (Shapiro steps),
- point SQUID, etc
- superconductivity suppression and Coulomb blockade has already observed in Niobium 3 nm – nanowire

Are So Thin Nanowires (regardless to the way of their production) stable at Ambient Conditions ???

Probably, YES

Theoretical evidences -

The natural upper limit of temperature stability of nano-objects is their melting point, which is different from the bulk MP. Good estimate gives the evaluation formula for the nanowires

$$T_{mw} = T_{mb}\left(1 - \frac{4}{3}\frac{d}{D}\right)$$

where T_{mw} and T_{mb} are melting points for nanowire and bulk, d and D – are the diameters of atom and wire.

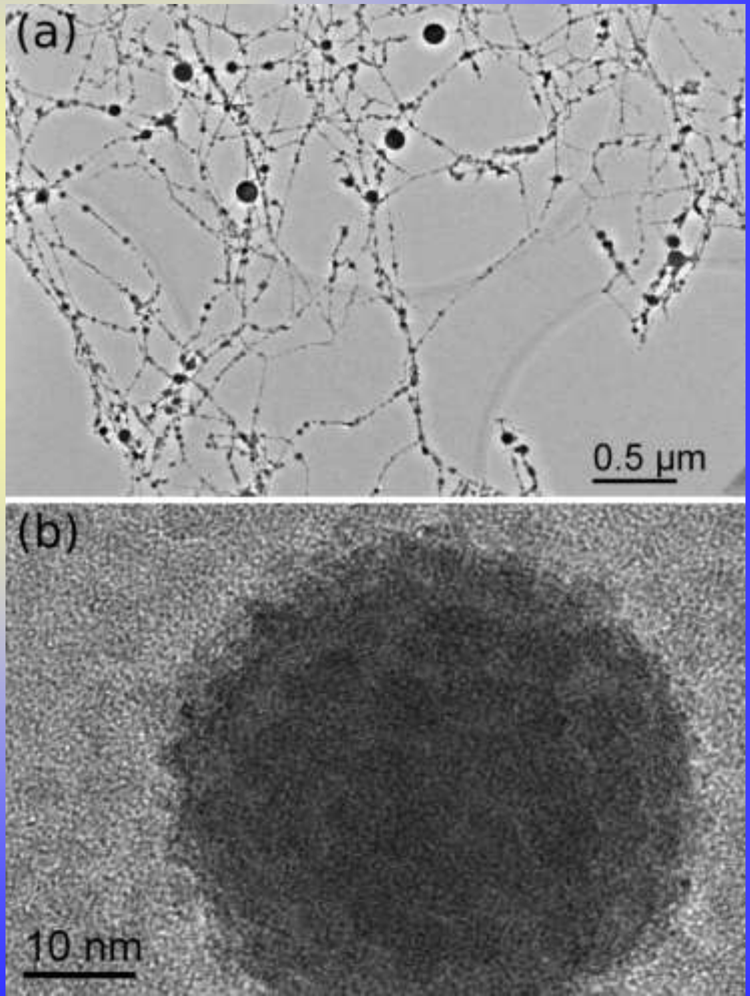
W.H. Qi , Size effect on melting temperature of nanosolids, Physica B 368 (2005) 46–50

For a nanowire with D = 3 nm it gives 15% diminishing

Are So Thin Nanowires (regardless to the way of their production) stable at Ambient Conditions ???

Probably, YES

Experimental evidences -



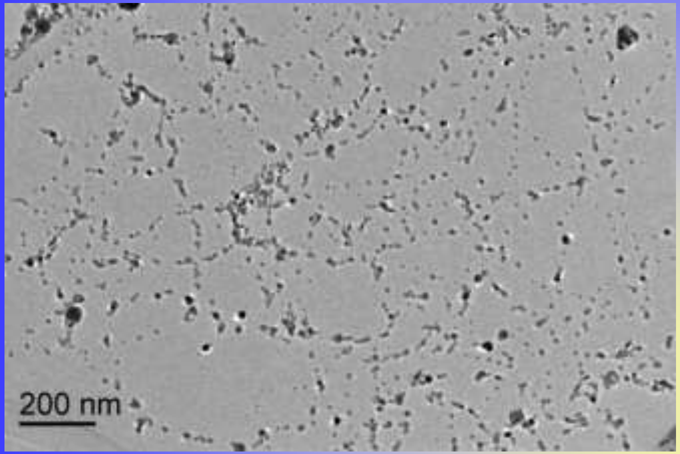
The Indium nanostructures after 6 month-long storage at 300 K:

(a) – nanowires;

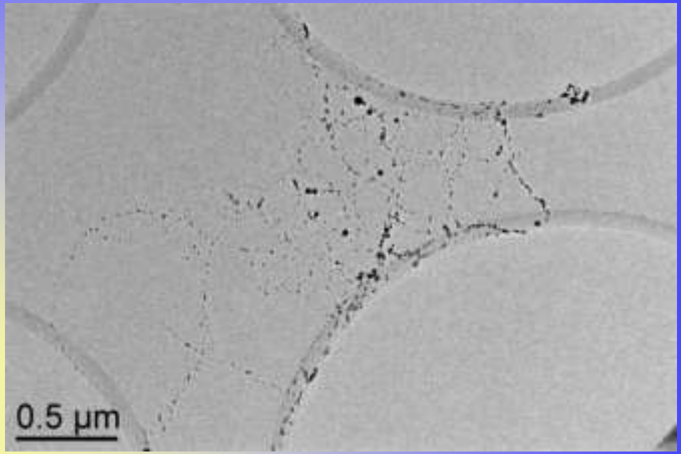
(b) – clot of the bound but not fused nanoclusters with 6 nm diameter.

Indium melting point 157^{0}C !!!

The instability of silver nanowires at room temperature

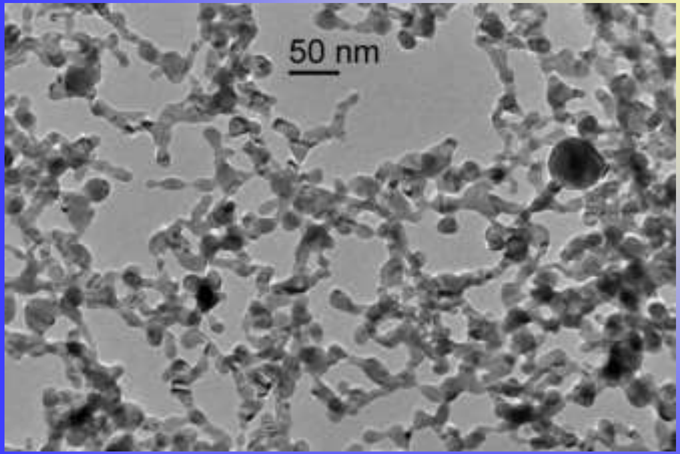


Silver melting temperature is 961 ^{0}C

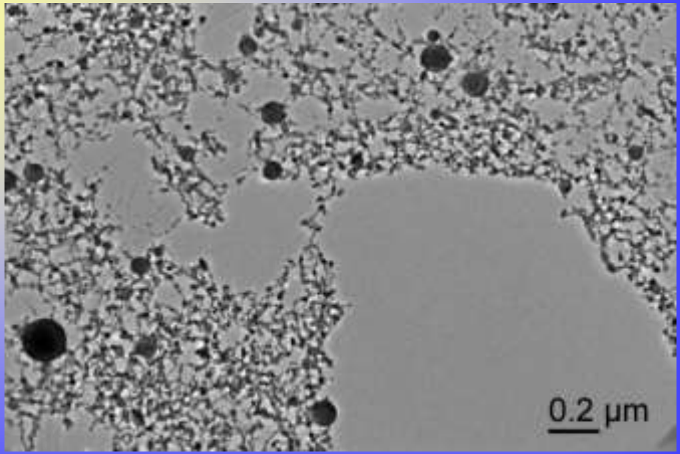


Only traces of wires as dotted lines

No sample in the holes

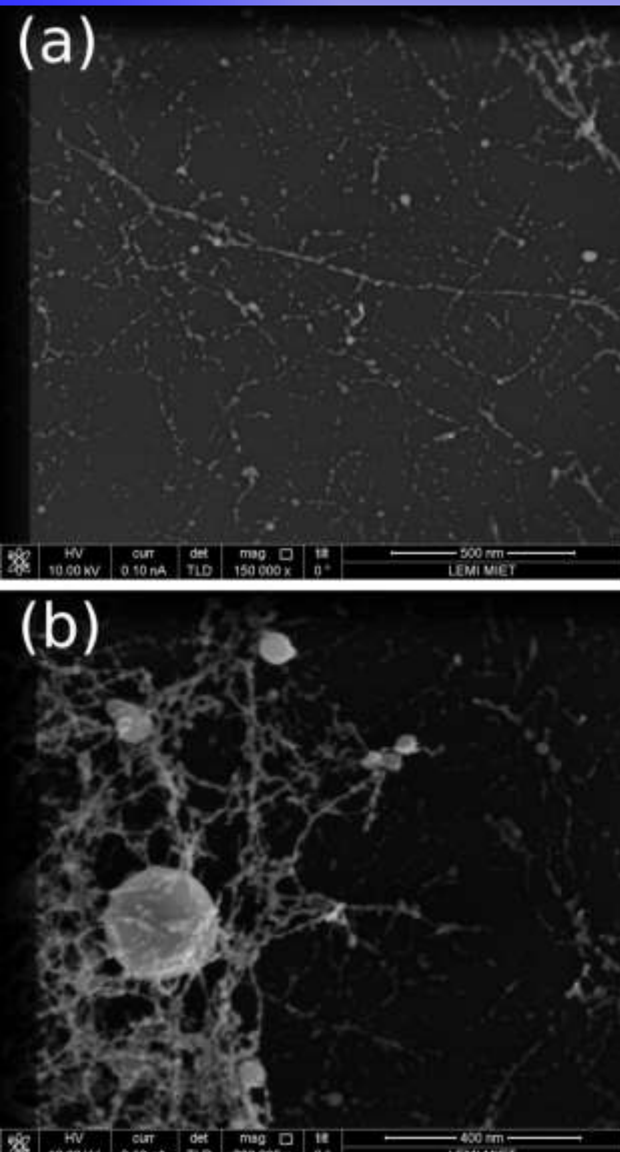


If you would bring the sample into TEM quickly



You can find the pieces of peapod web on the surface and in the holes

Decay of golden nanowires deposited on the glass



Au melting point $T_M = 1064\ ^0C$

Nanowires disintegrate into separate clusters, such as clusters of silver, in few days keeping at standard conditions

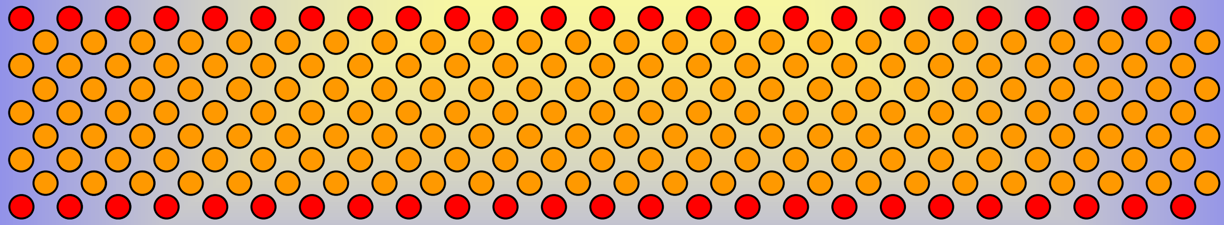
In the left side of (b) the number of deposited nanowires is so large, that they do not adhere tightly to the glass surface, and these nanowires **remain intact** (the same was observed for the fresh silver nanoweb).

The metal wetting of surface stimulates the nanowire decay.

How the nanowire could disintegrate without melting?

For the melting one needs to unfreeze the bulk mobility.

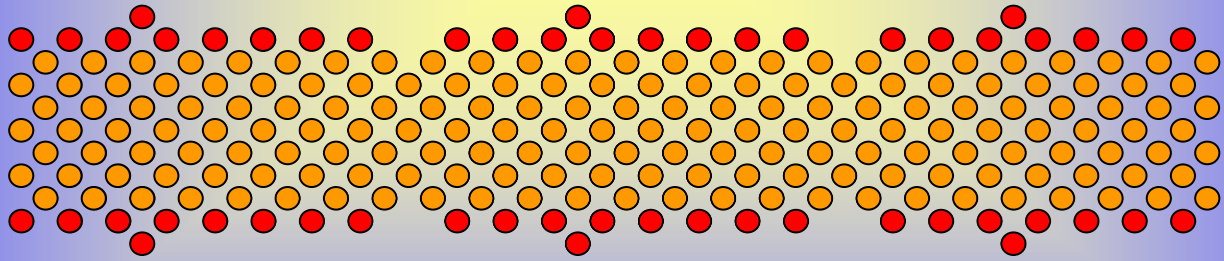
1. The atom motion along the metal surface required **2 - 3 times less** energy.
2. **Significant portion** of all the atoms **are on the surface** in nanowires.
3. In order to **change significantly the shape** of thin nanowire it is sufficient to replace **one layer of atoms** for the distance of **few nanometers**.



How the nanowire could disintegrate without melting?

For the melting one needs to unfreeze the bulk mobility.

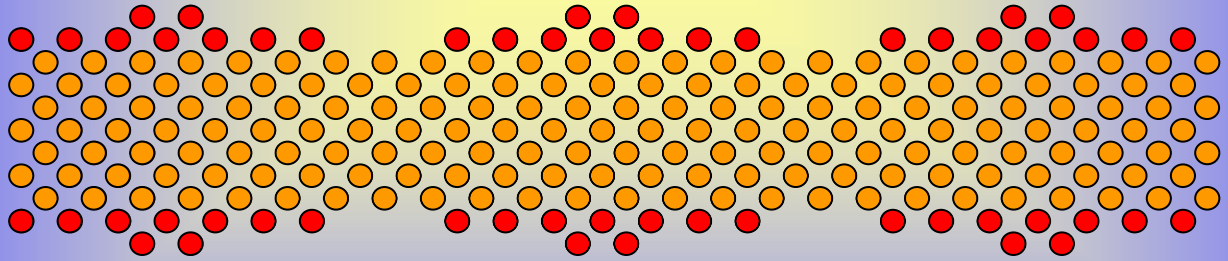
1. The atom motion along the metal surface required **2 - 3 times less** energy.
2. **Significant portion** of all the atoms **are on the surface** in nanowires.
3. In order to **change significantly the shape** of thin nanowire it is sufficient to replace **one layer of atoms** for the distance of **few nanometers**.



How the nanowire could disintegrate without melting?

For the melting one needs to unfreeze the bulk mobility.

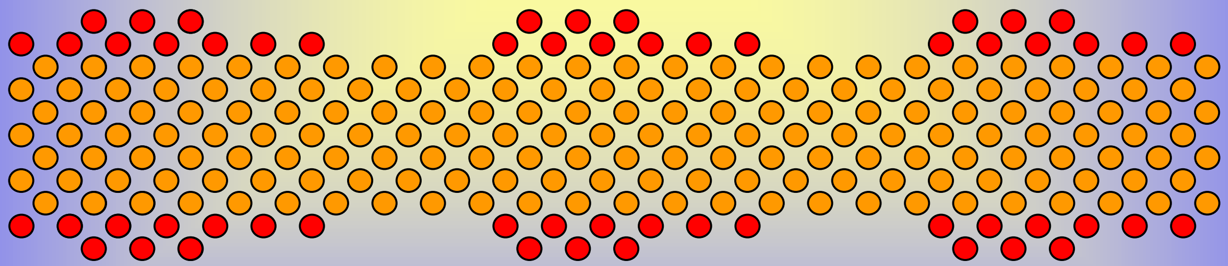
1. The atom motion along the metal surface required **2 - 3 times less** energy.
2. **Significant portion** of all the atoms **are on the surface** in nanowires.
3. In order to **change significantly the shape** of thin nanowire it is sufficient to replace **one layer of atoms** for the distance of **few nanometers**.



How the nanowire could disintegrate without melting?

For the melting one needs to unfreeze the bulk mobility.

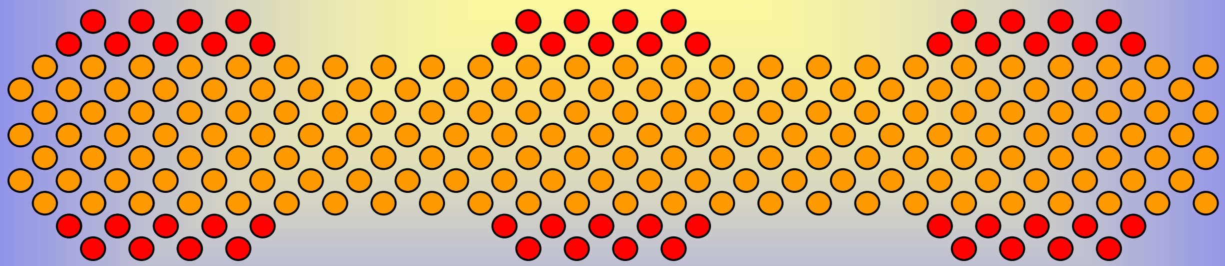
1. The atom motion along the metal surface required **2 - 3 times less** energy.
2. **Significant portion** of all the atoms **are on the surface** in nanowires.
3. In order to **change significantly the shape** of thin nanowire it is sufficient to replace **one layer of atoms** for the distance of **few nanometers**.



How the nanowire could disintegrate without melting?

For the melting one needs to unfreeze the bulk mobility.

1. The atom motion along the metal surface required **2 - 3 times less** energy.
2. **Significant portion** of all the atoms **are on the surface** in nanowires.
3. In order to **change significantly the shape** of thin nanowire it is sufficient to replace **one layer of atoms** for the distance of **few nanometers**.



It may happen at much less T than melting, but only provided the surface atom mobility **is not stochastic**; for instance, when this motion is the **relaxation to equilibrium** shape of wire.

Could the peapod structure of nanowire be equilibrium one?

Usually not, because:

1. **Surface tension** of thin nanowires makes a **major contribution** to its energy.
2. If **surface tension** coefficient **is independent** on wire diameter, the equilibrium shape of wire with fixed length is **cylindrical.**
3. Thus the **surface mobility** itself **is unable** to form a peapod structure of the nanowire which can result in **its break.**

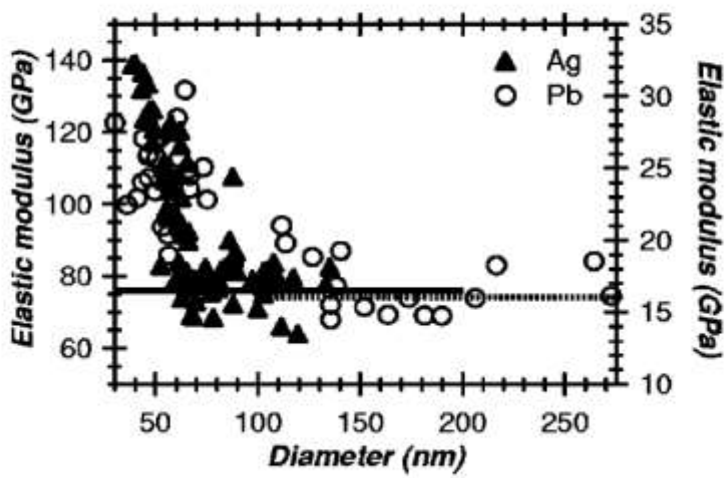


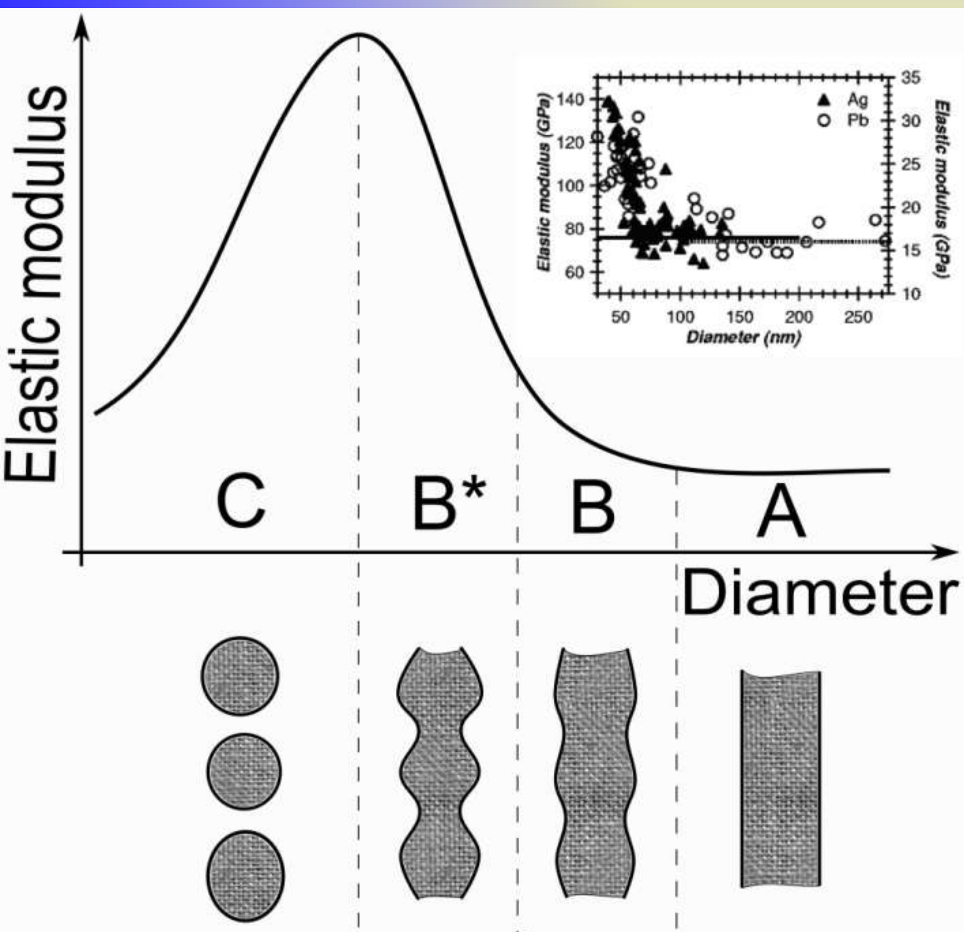
FIG. 1. Variation of the measured elastic modulus for Ag (left scale) and Pb (right scale) nanowires as a function of the diameter. The solid line corresponds to the elastic modulus of bulk silver and the dotted line to the elastic modulus of bulk Pb.

However,
just for silver (and lead) nanowires!!!

*S. Cuenot, C. Fretigny, S. Demoustier-Champagne, and B. Nysten,**
Surface tension effect on the mechanical properties of nanomaterials measured by atomic force microscopy
*PHYSICAL REVIEW B **69, 165410 (2004)***

Model of thin nanowire low-temperature decay

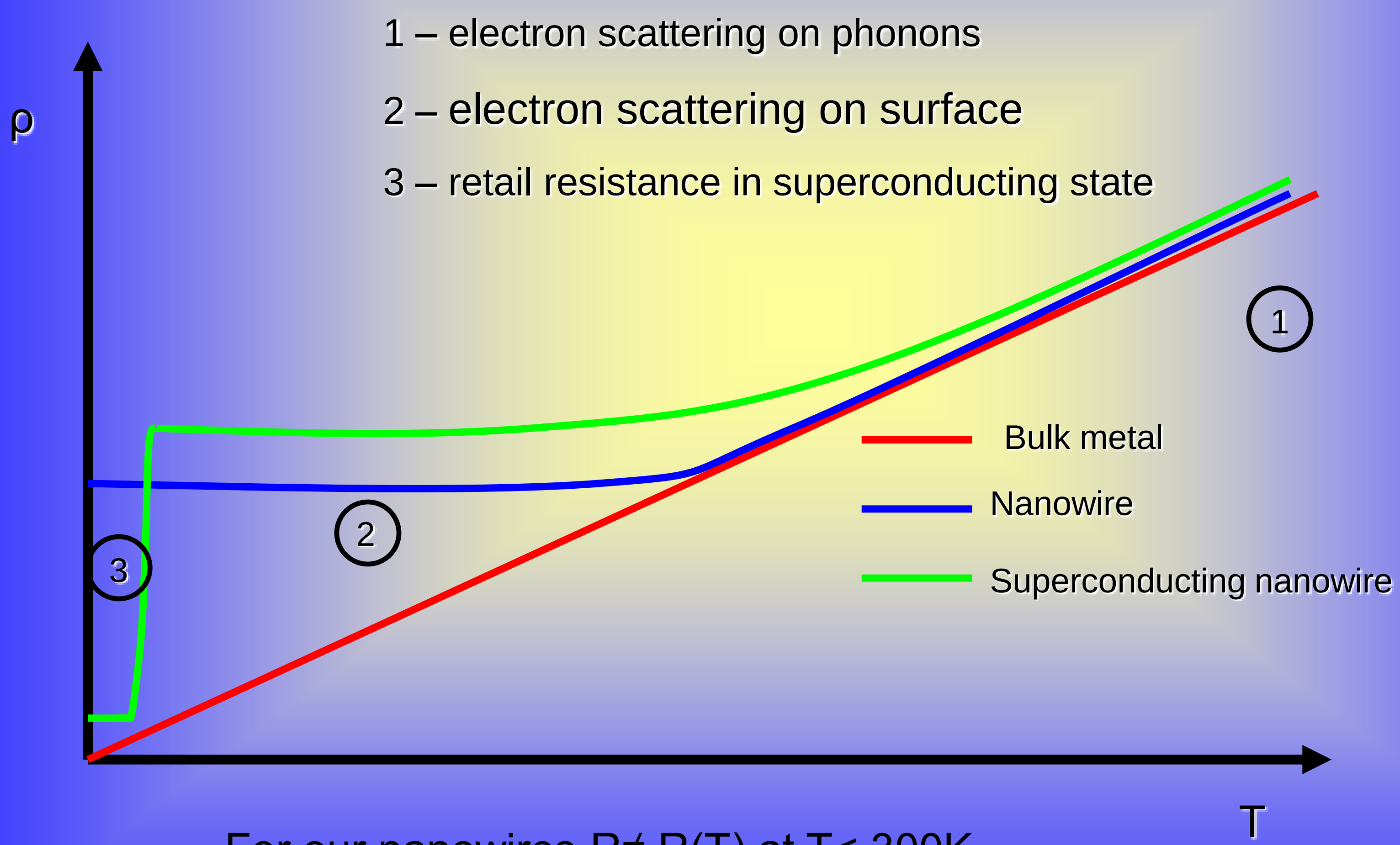
Let us assume that the dependence of ξ on D is really as shown



1. For the A region, where $\xi \neq \xi(D)$, a cylindrical shape has the lowest energy.
2. For the B region, where ξ increases with diameter decreasing, the peapod shape with a period of about wire caliber becomes equilibrium one.
3. In the C region, the increase both in the ξ value and in the wire perimeter, while D increasing, always contribute to the surface atoms motion from the areas of nodes to the antinodes. In equilibrium ⟶ the chain of individual clusters

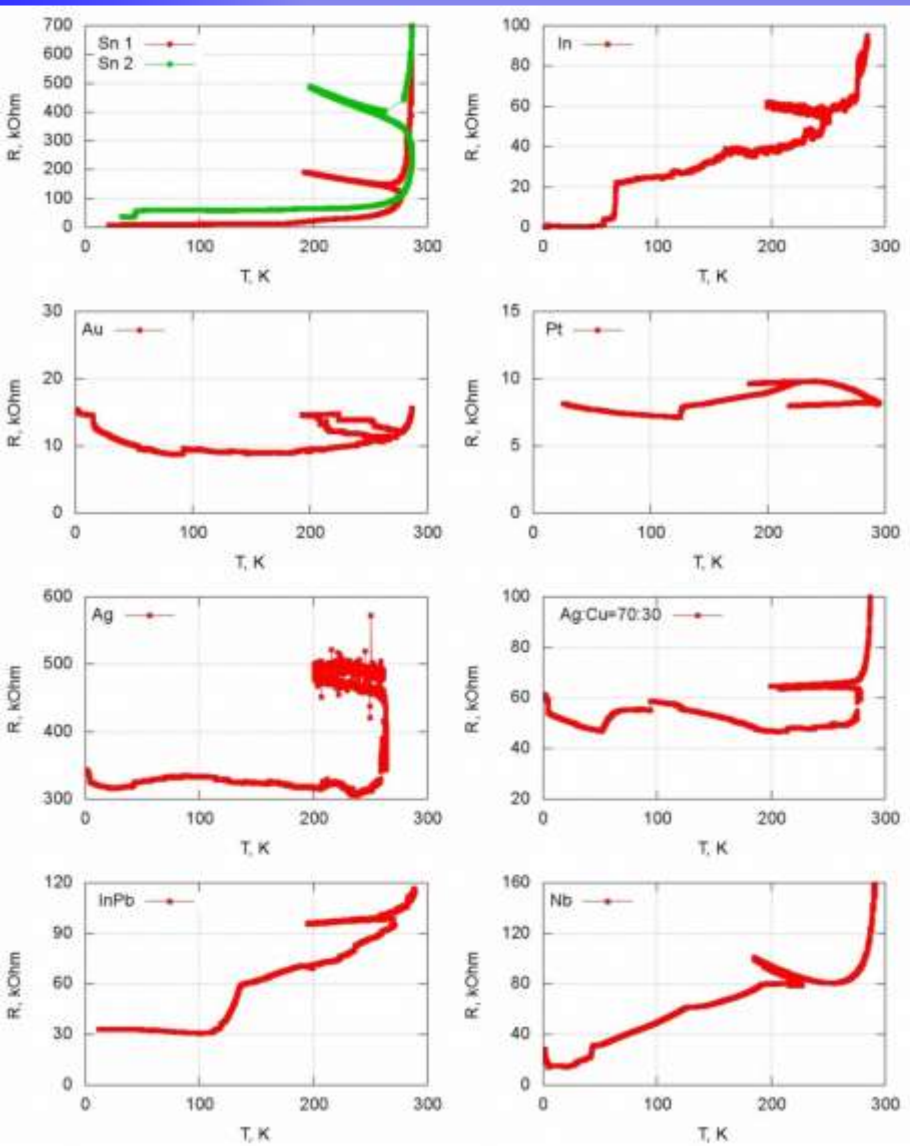
Let we apply to the experiments for evidences

Metal resistance *vs temperature*



For our nanowires R≠ R(T) at T< 300K

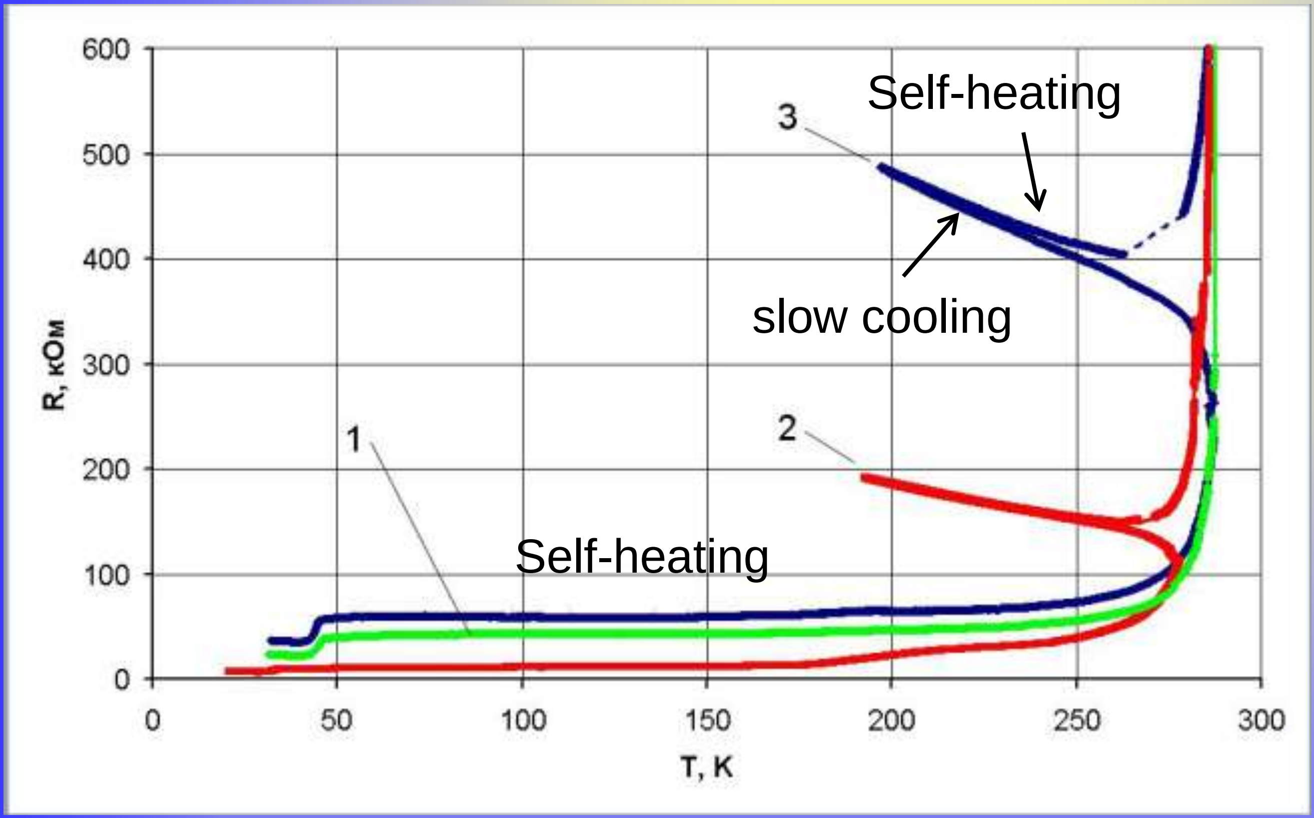
The 1.4 mm-long nanowire bundles resistance dependence on T



Irreversible increase of the resistance was explained by **partial breakage** of nanowires in the web due to **their increasing tension** (shortening).

At T≥ 250K the slow cooling gives weak and reversible dependence of reflecting the real dependence of the individual nanowires resistivity on T

R(T) for tin nanowire



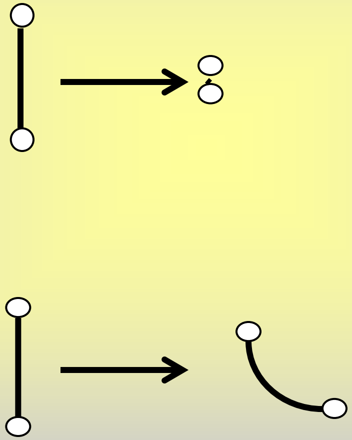
- Slow cooling of the cryostat by pouring LN into jacket .
- The heating and cooling were very slow (more than 10 hours per every step).
- R(T) reflects the real dependence of the individual nanowires resistivity on T.

Surprisingly, the nanoweb “remembers” exactly annealing temperature. It seems that for every individual nanowire exists the well-defined temperature, possibly dependent on its thickness, shape, beads inclusion and length, at which it breaks.

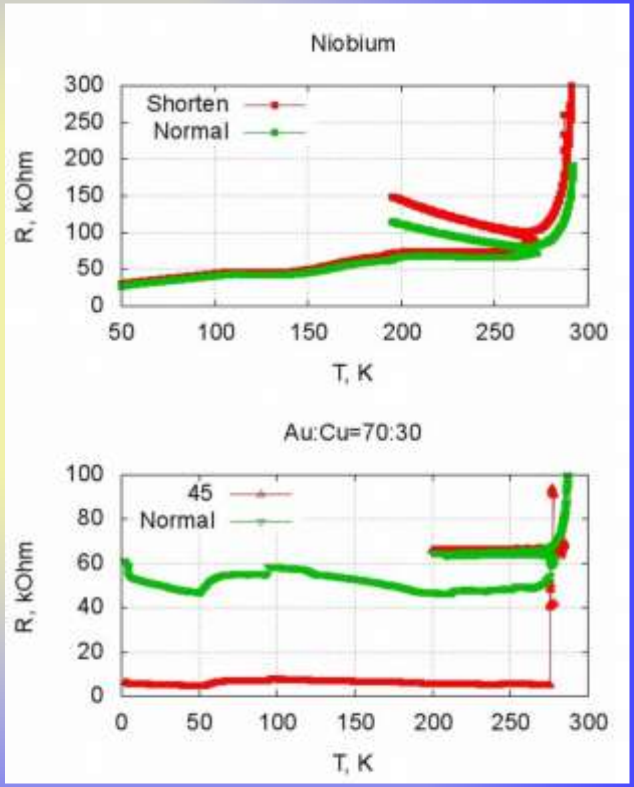
Special experiments revealing the nature of the break – either tension accumulated along total web length, or each individual nanowire breaks independently

The photo of the bundles of silver nanowires grown in the cryostat after 5 min-long laser ablation, the distances between electrodes are 1.4 mm

1.4 mm→0.07mm



0 ° ⟶ 45 °



Both gap reducing to 70 microns and transition to "catenary" shape of web have no visible influence on the losses of percolation under heating → local nature of the breakage

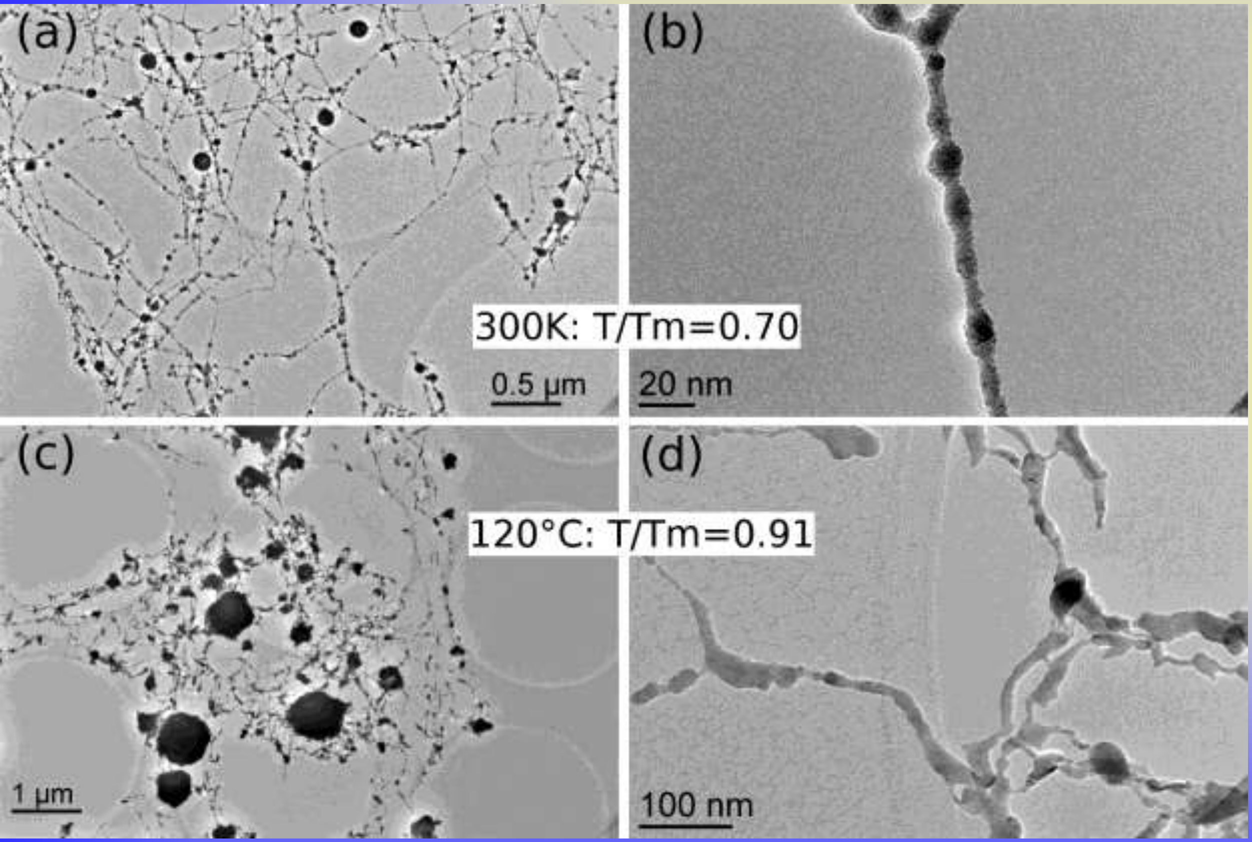
1. Our electron microscope works at 300K

2. Thus we don’t know how the nanowires look like at low temperature

3. But we can anneal them at T > 300K and then cool them down to ambient temperature

Evolution of the nanowebs morphology and structure under heating above T = 300 K

Indium



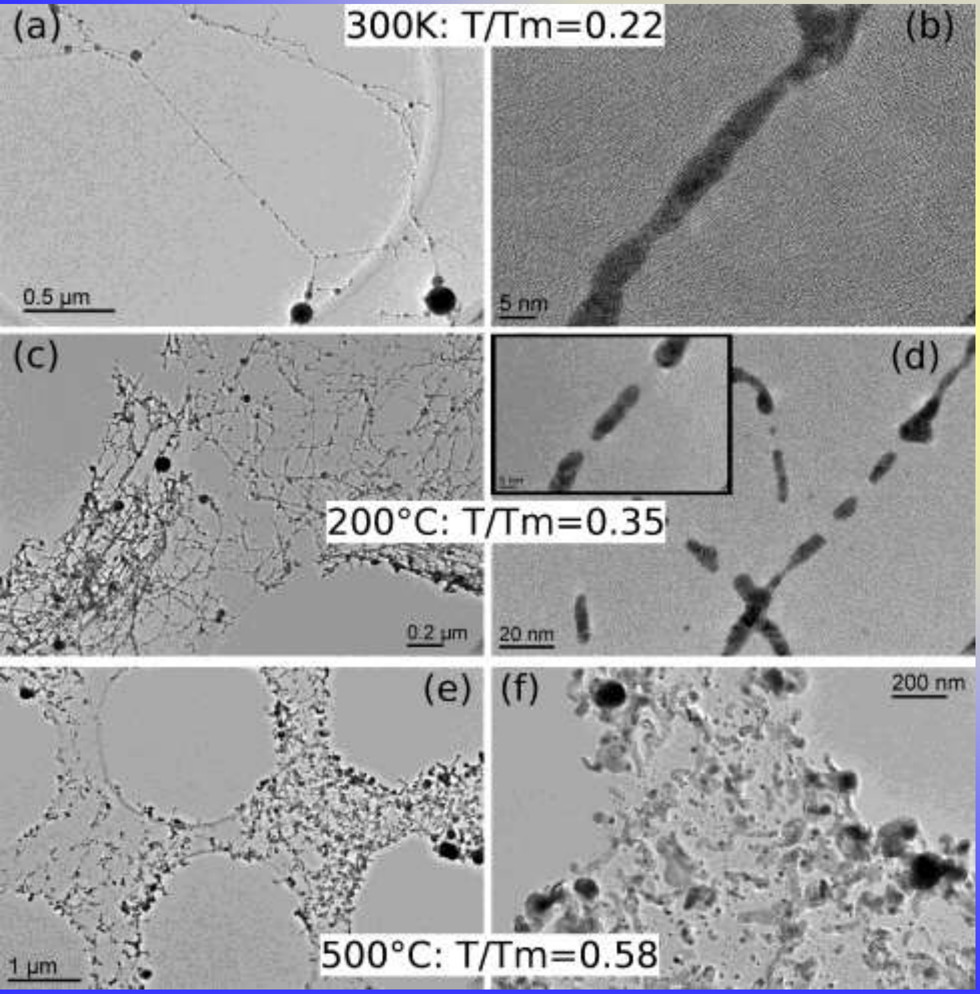
Indium nanowires at 300K are stable for many days.

Notable metamorphoses occur only at 120° C.

The shape of the nanowires becomes distorted, but no antinodes appeared. They are still cross-linked to the web and remain strained for the holes in the grids.

Evolution of the nanowebs morphology and structure under heating above T = 300 K

Gold



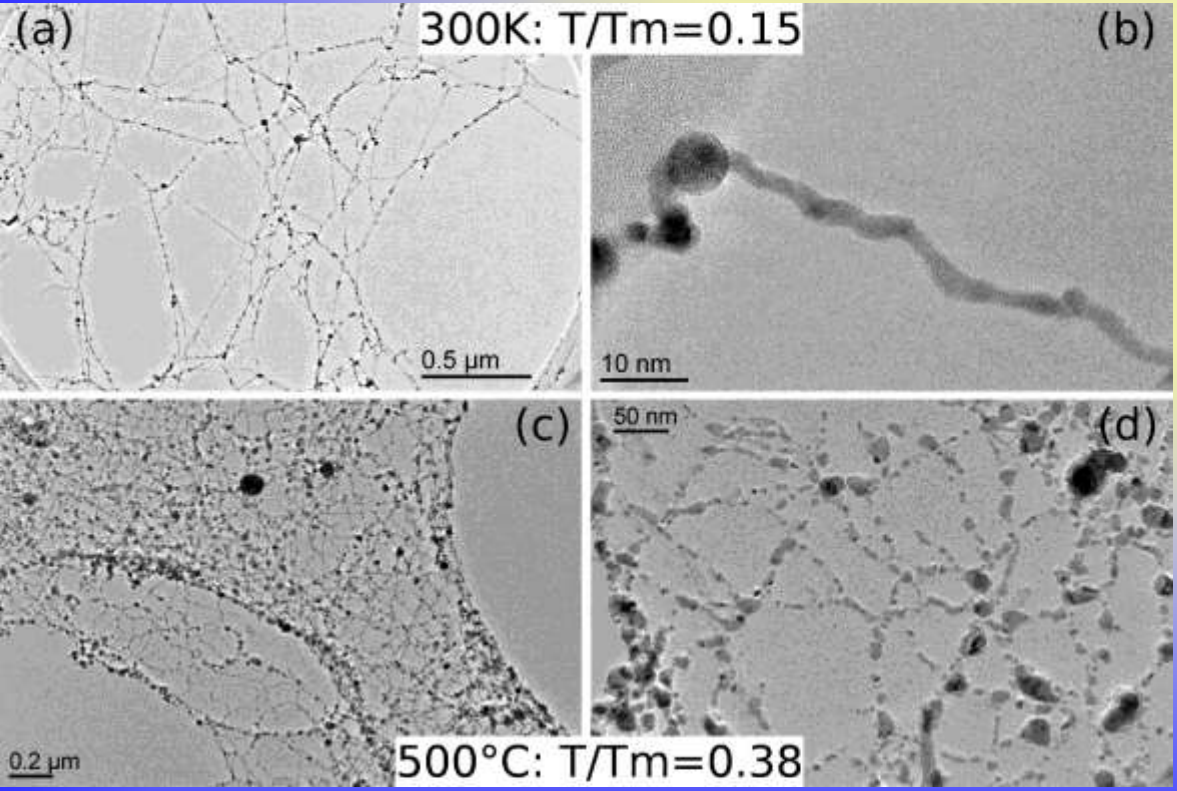
Gold nanowires were stable on the carbon film at 300K for many days/

Annealing up to 200°C; causes the numerous breaks, the resulting clusters were similar to those formed in the TEM vacuum chamber under irradiation with focused electron beam. Nanowires in holes collapsed, but only partially.

Only heating up to 500° C, i.e. to the absolute temperature being 58% of the melting temperature, led to the complete disintegration

Evolution of the nanowebs morphology and structure under heating above T = 300 K

Platinum



Platinum nanoweb at 300K is perfectly stable both on the grid surface, and being tightened in the holes.

Annealing the sample at 500^{0}C caused the practically complete disappearance of a nanowires stretched over the holes, and a significant decay of nanowires deposited on the surface of the grid.

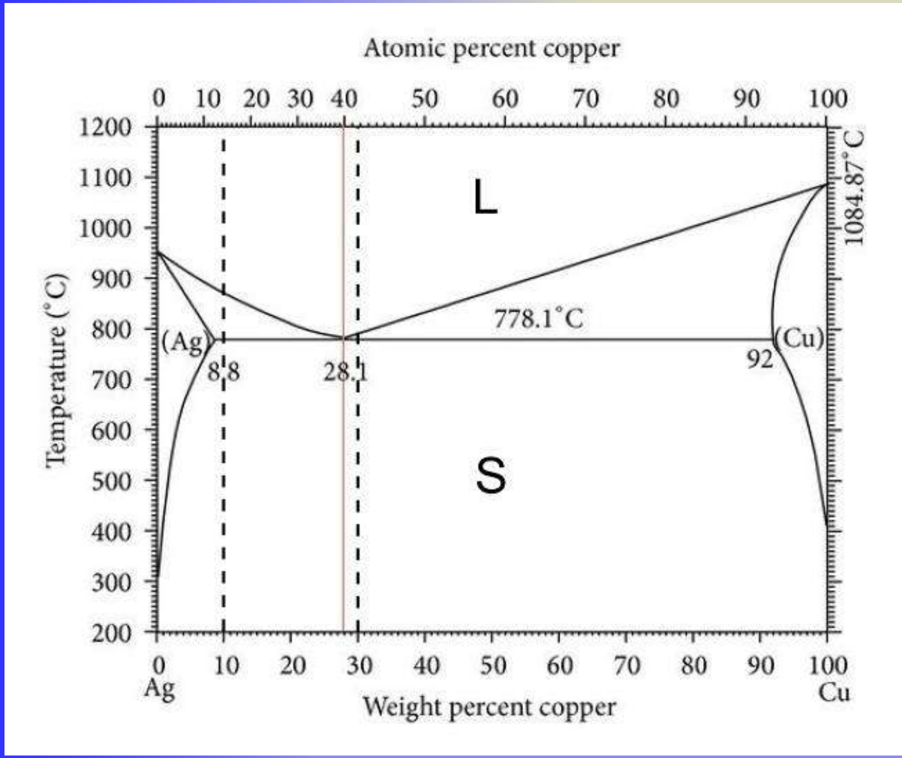
Summary

	Indium	Silver	Gold	Platinum
Diameter, nm	**8**	**5**	**4**	**3**
$T_{melting}$, K	**430**	**1235**	**1337**	**2041**
T_{mw}/T_m , equation (1)	**0.95**	**0.92**	**0.92**	**0.87**
T_d/T_m , experiment	**0.9**	**0.24**	**<0.5**	**0.4**

For nanowires with diameter **less than 5 nm**, there is a specific channel of decay realized at temperatures **2 - 3 times lower their melting**. According to our experiments, this channel is implemented by **unfreezing the atom surface mobility** with the proviso that **peapod shape is energetically favorable structure**

Could we suppress the surface mobility by its covering with less movable atoms ???

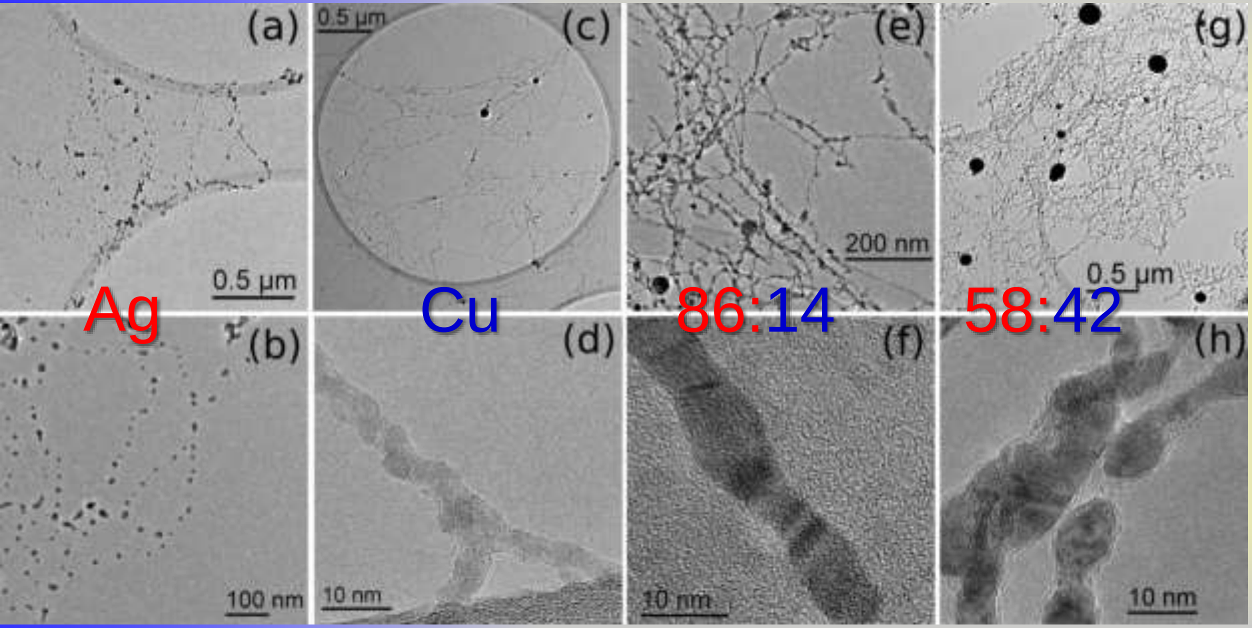
Nanowires from the silver-copper alloys



Ag - Cu phase diagram, solid vertical line marks the eutectics, the dashed lines correspond to the alloys

For **α (Ag:Cu ≥ 88:12)** or **β (Ag: Cu ≤ 8:92)** phases a solid solution is formed after cooling. Outside these regions precursor must disintegrate upon solidification to crystallites rich by silver (α phase) or copper (β phase).

Nanowires from the silver, copper and their alloys



Addition copper to silver improves the thermal stability of the nanowires made of alloy

Morphology and structure of sediments on the grid under laser ablation in superfluid helium of various targets: Light halo around the nanowires corresponds to copper oxide formed during the contact with air. The diameter of holes are 2 μm.

The nanowires made of alloys - promises

Phase diagram for the surface layers, the energy of which is determined mainly by the surface tension is different from that for the bulk. As a result, the surface of the nanowire is enriched by one of the components atoms compared with the bulk. → The surface covering by motionless or oxidized atoms

For alloys with compositions close to the eutectic, the separation of α and β phases nanocrystals in the axial direction. The specific length of different composition alternation should be close to the caliber, i.e. wire diameter. →The nanowire heterostructures for various purposes could be created in this way.

Conclusion

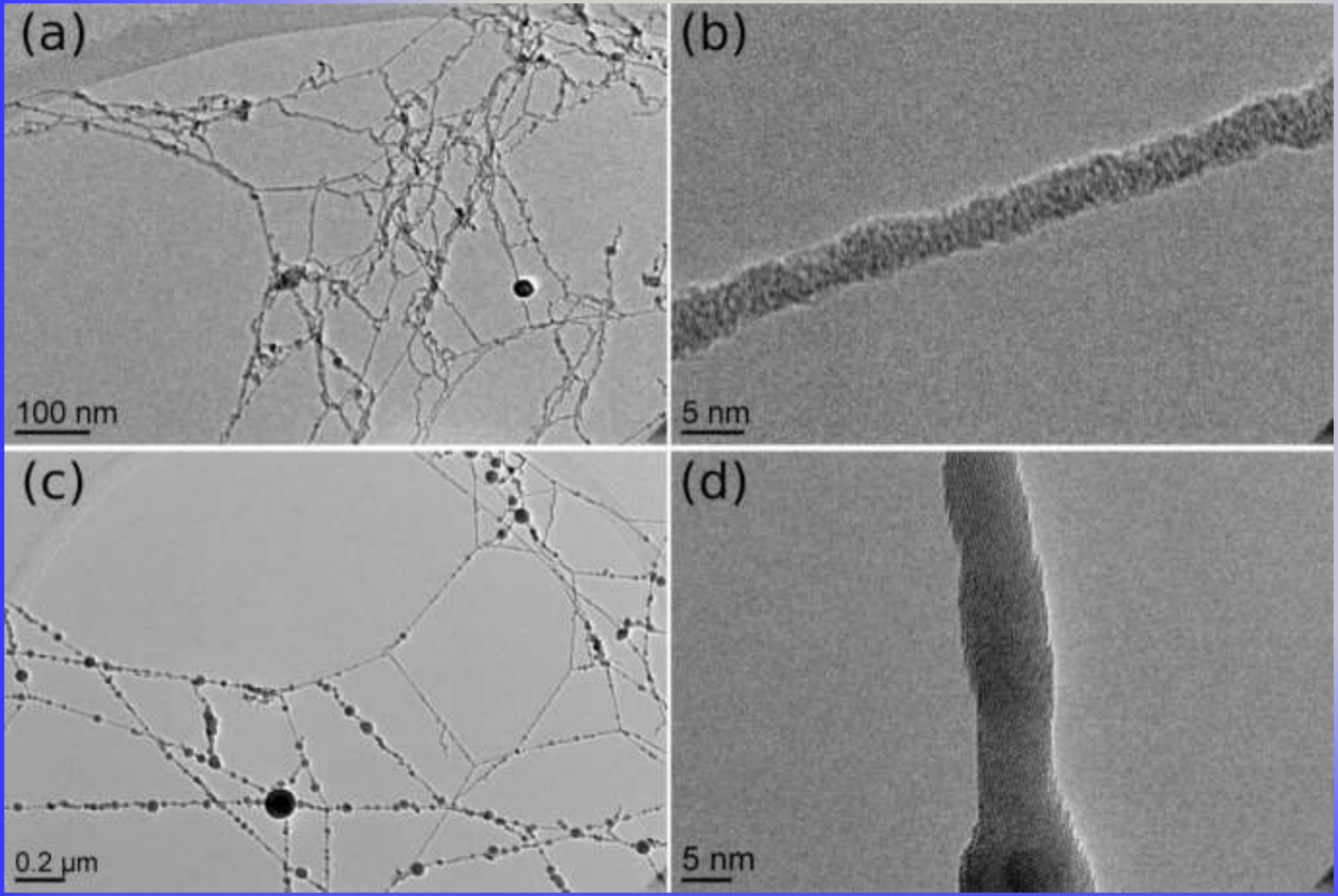
.

1. **Thin (<5 nm) nanowires have drastically reduced thermal stability in comparison with other nano-objects - nanoclusters and nanofilms.**

2. **Their thermal stability can be significantly improved by doping the basic metal with either less movable or able to be passivated atoms the metals.**

3. **By using as a material for nanowires production the alloys with compositions close to their eutectics the nanowire heterostructures for different purposes can be created.**

Size effect in thin nanowires. The suppression of superconductivity. Two superconductors with equal Tc , but with different diameters



Nb –

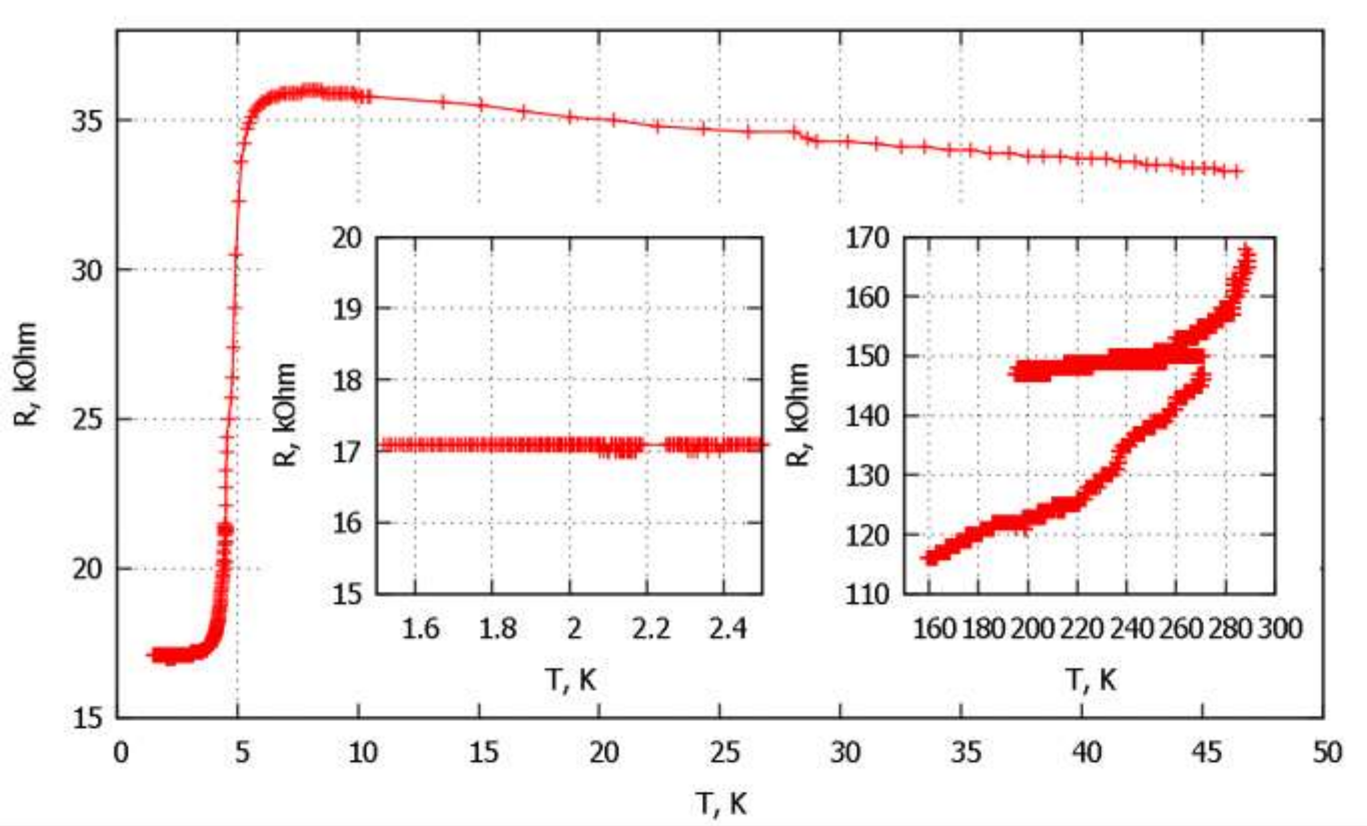
D = 3 nm

$In_{88}\,Pb_{12}$ -

D = 7 nm

“Normal” (though a little suppressed) R(T) behavior of superconducting nanowire

- $In_{88}\,Pb_{12}$, D = 7 nm

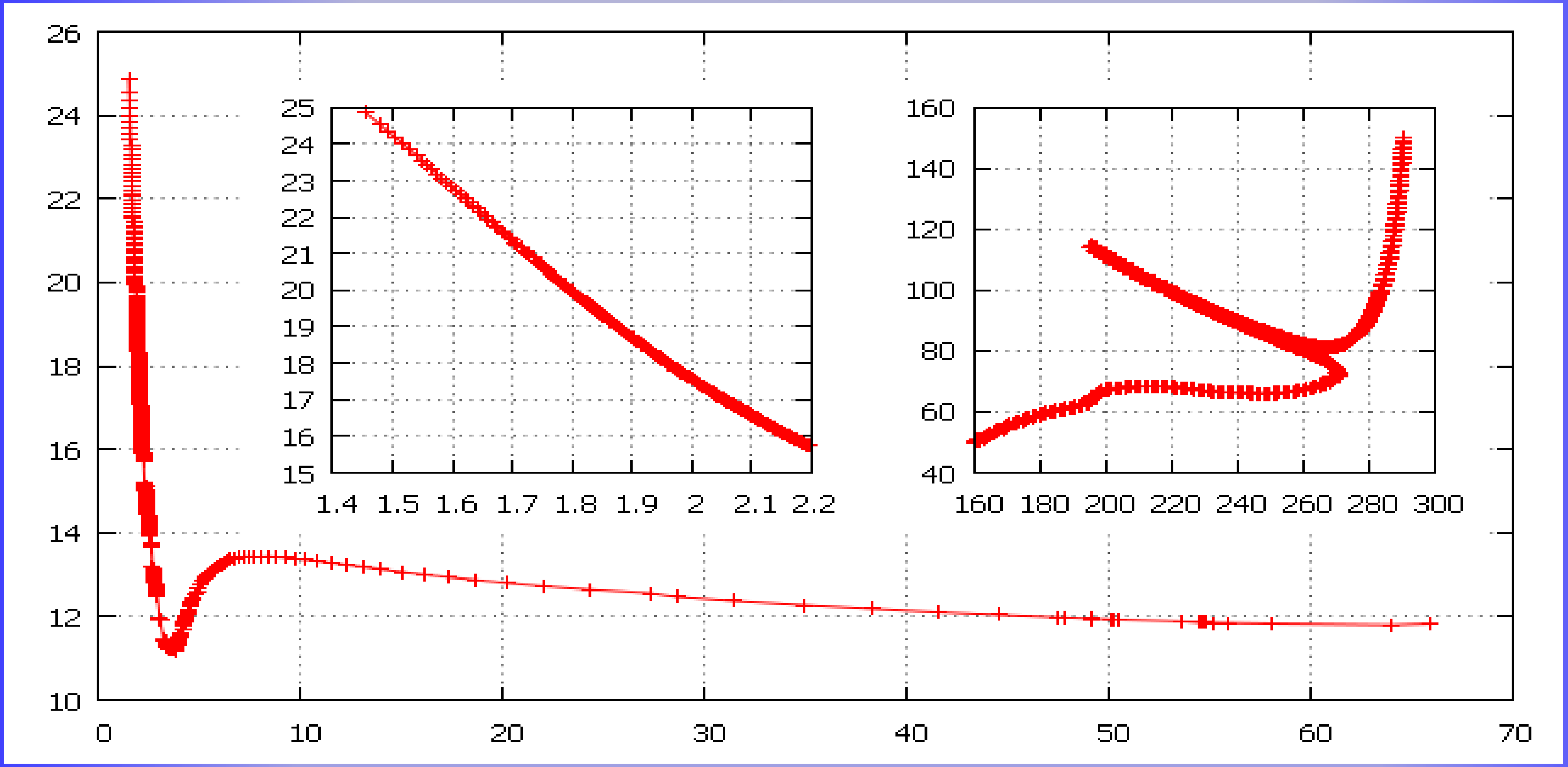


Superconductive transition at 5K

Low and “high” temperature details are shown in insets

Completely suppressed superconductivity . R(T) dependency

- Nb, d = 3 nm

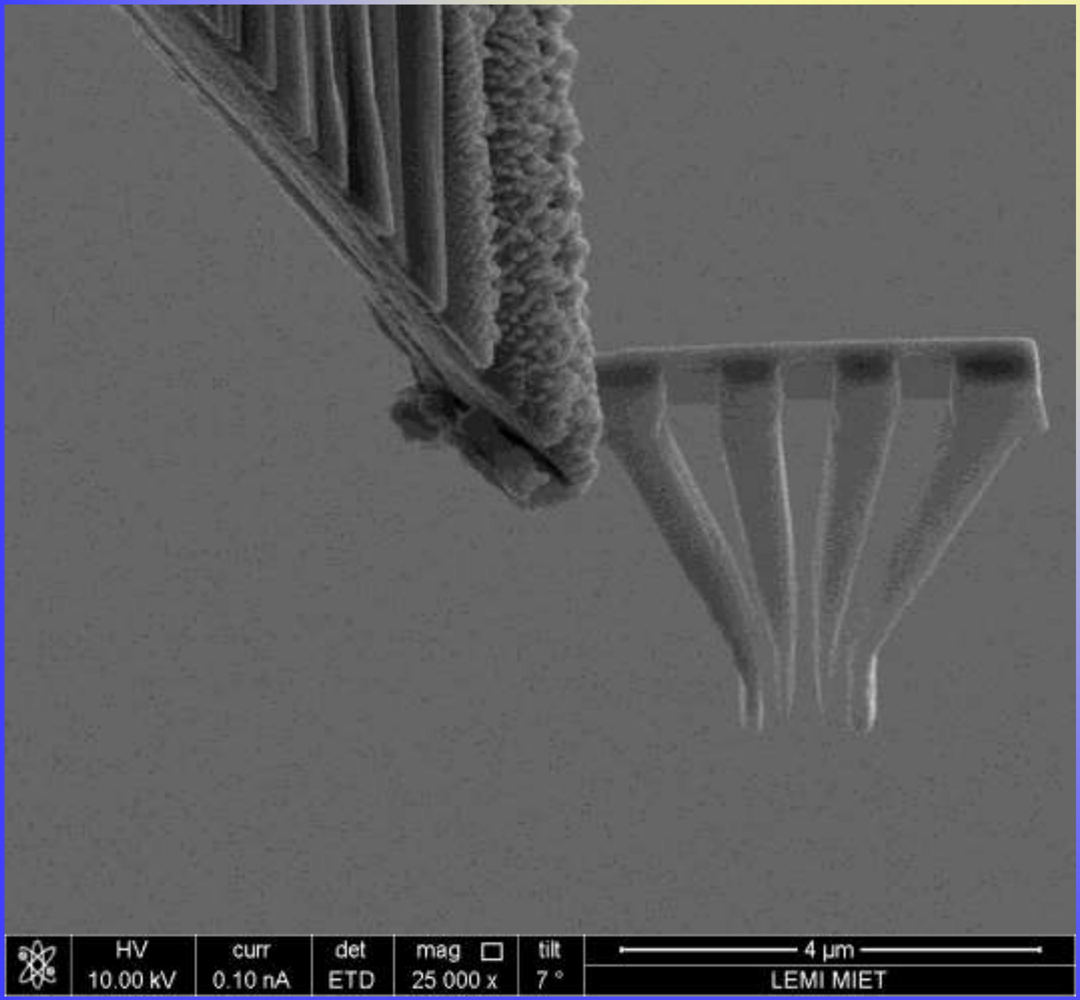


Remains of superconductive transition are seen as well as the tremendous resistance growth at T→0 due to Coulomb blockade. The specimen was preliminarily annealed.

In order to see all quantum effects we should deal with individual nanowire.

Corresponded technique is already in our possession.

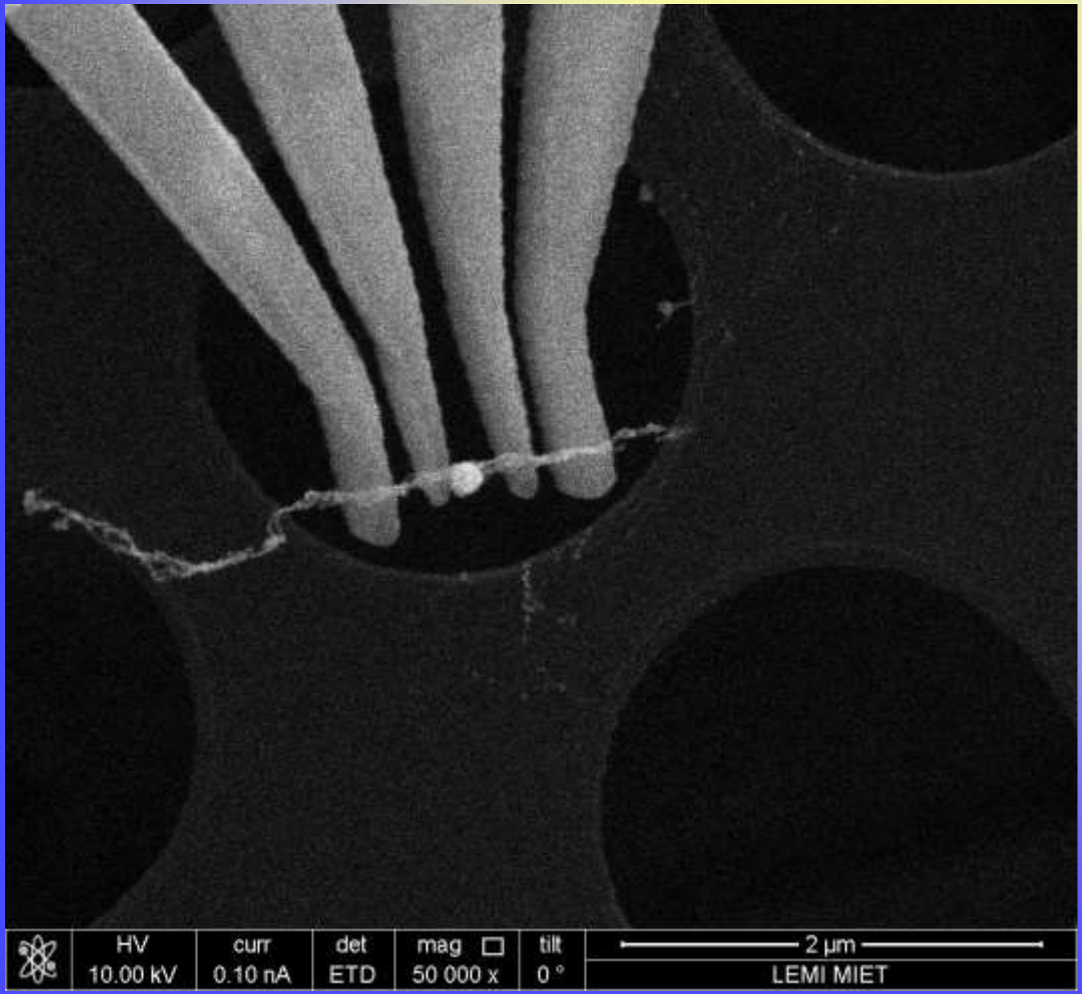
“Fork” technique



Step 1.

The "fork" with four teeth was manufactured and soldered to the cantilever

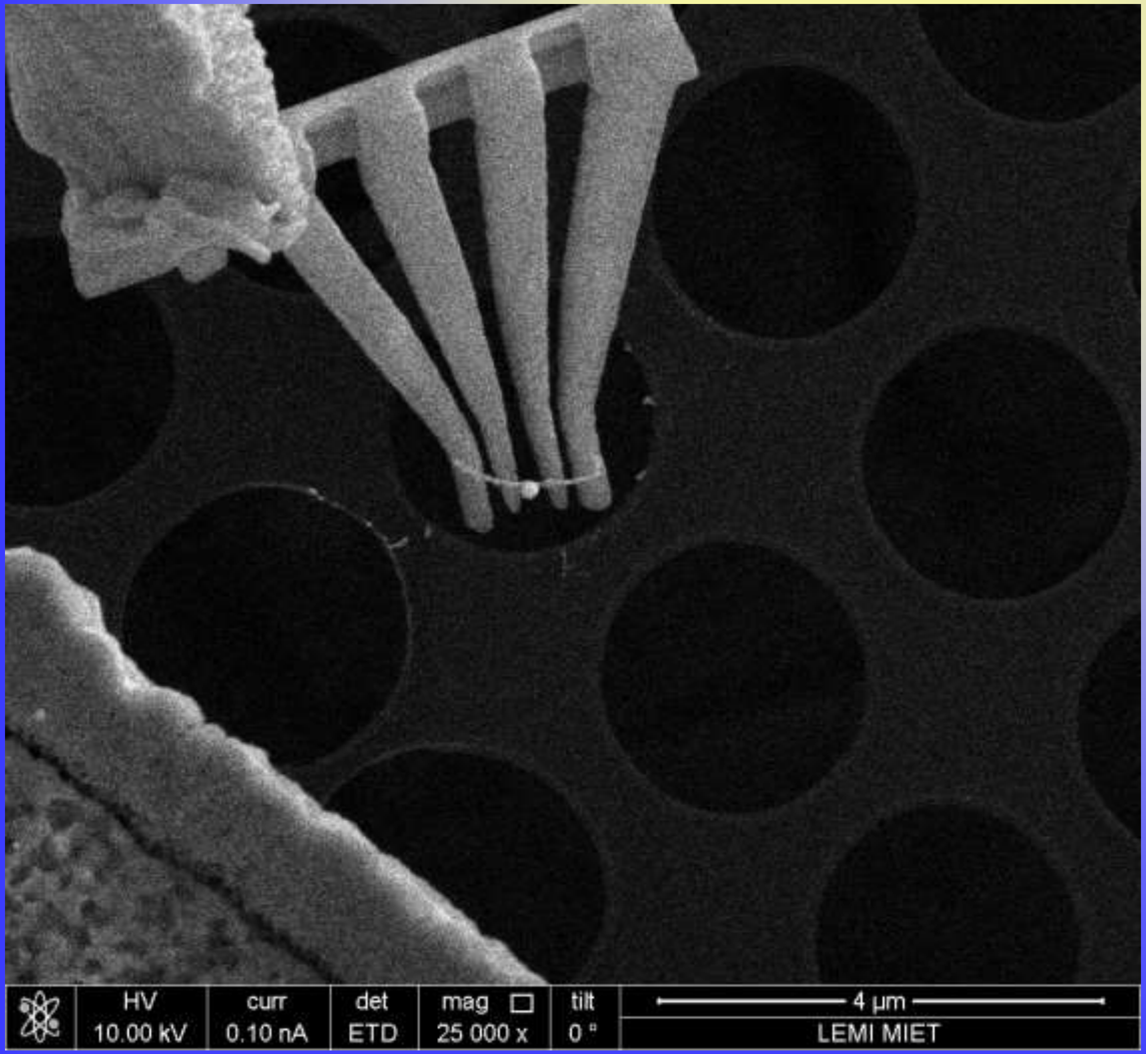
“Fork” technique



Step 2.

Fork is placed beneath of our nanowire stretched over the 2-micron diameter hole in the carbon-coated copper grid and then lifts nanowire above the plane of the grid.

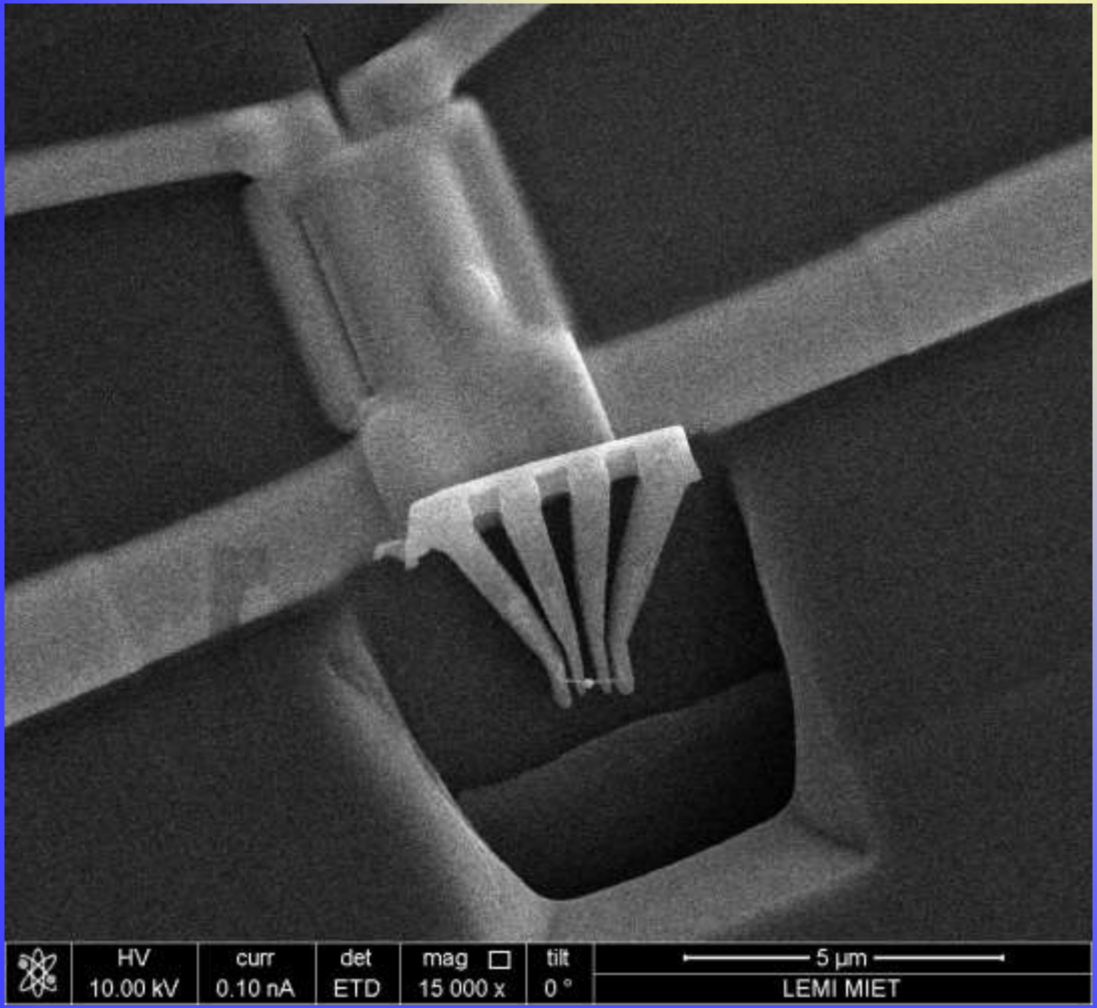
“Fork” technique



Step 3.

Nanowire ends are cut by an electron beam

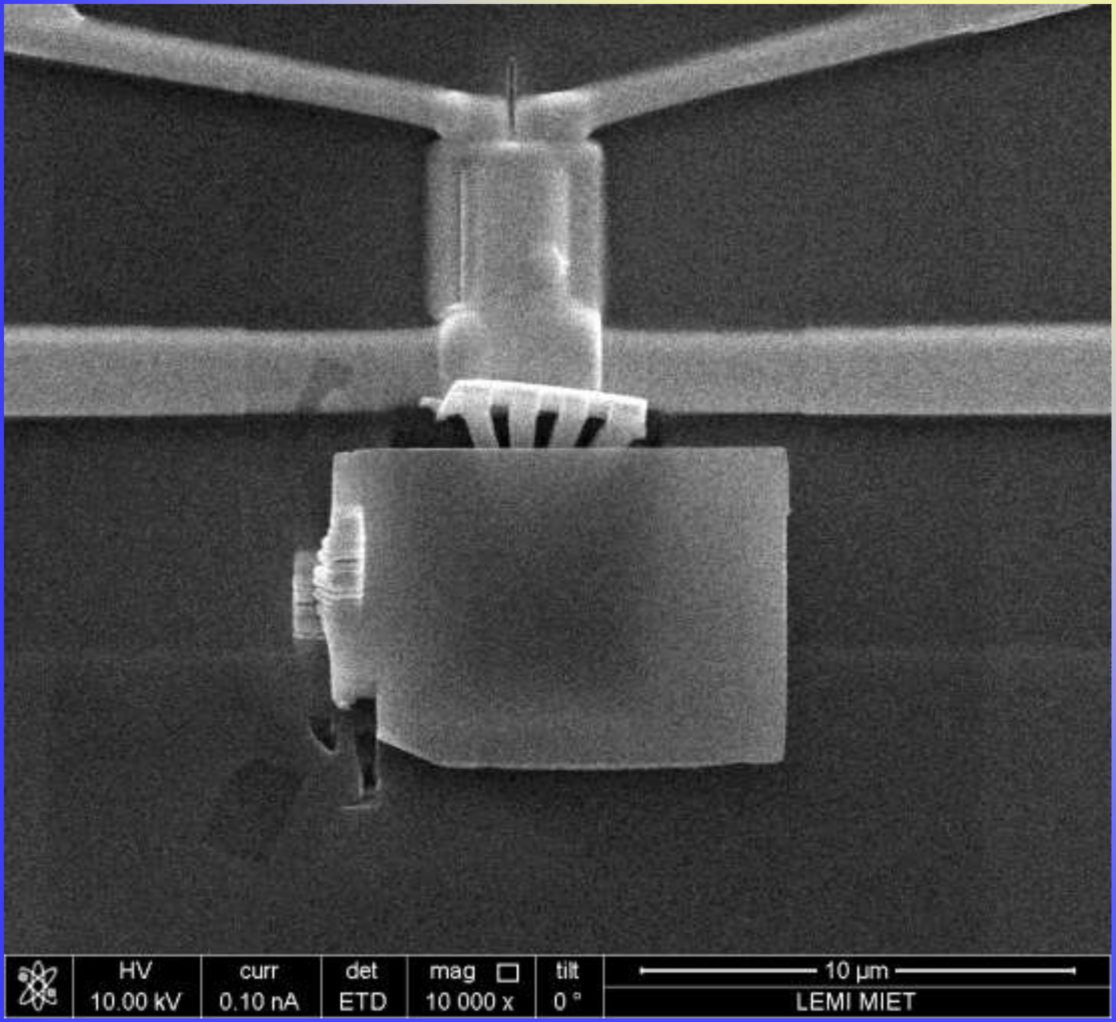
“Fork” technique



Step 4.

Fork with nanowire is transferred to the chip and fork is placed into a recess specially arranged therein. Then fork soldered to the edge of the chip and cut off cantilever.

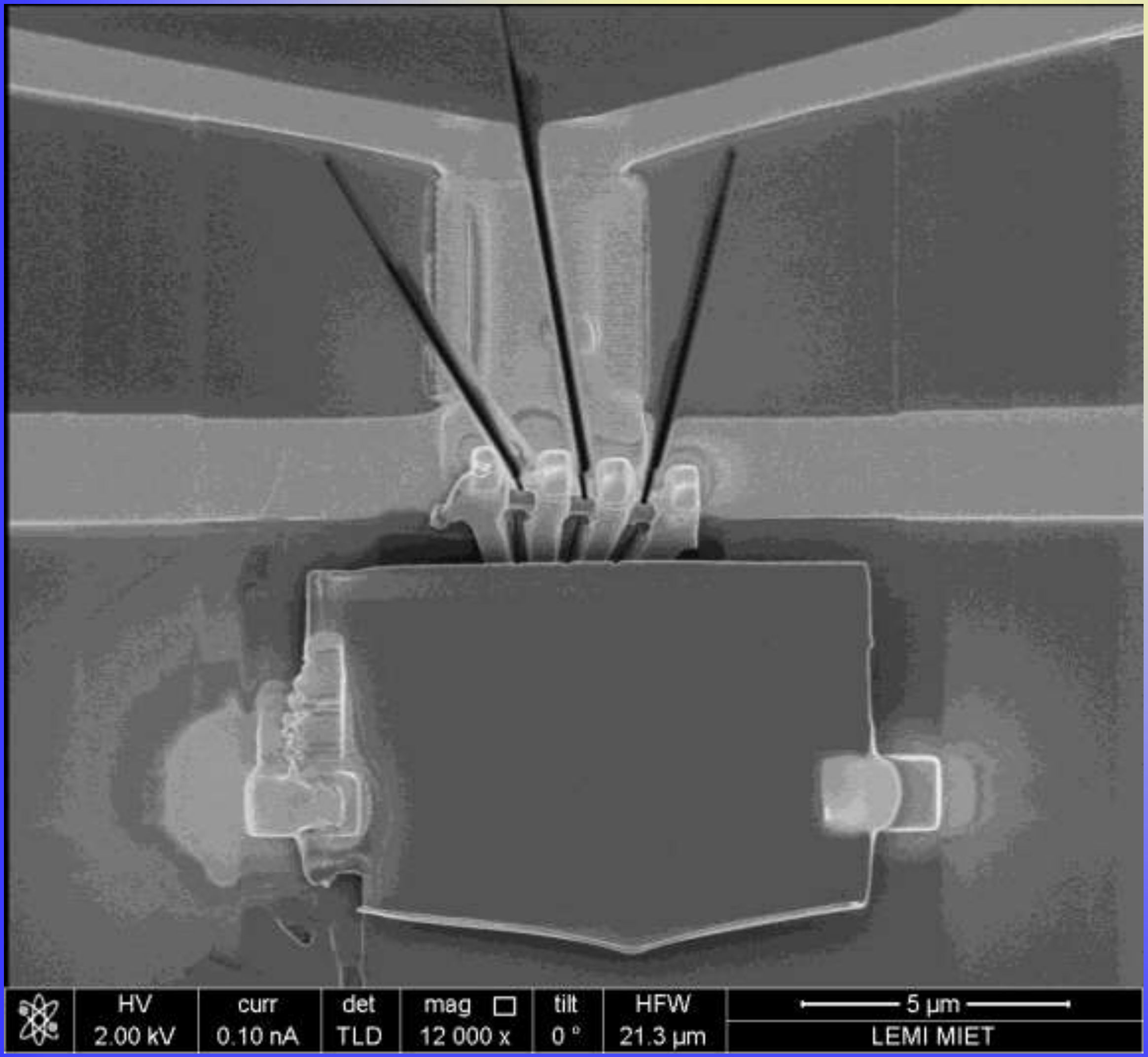
“Fork” technique



Step 5.

Fork nanowire is covered by protective shield to prevent formation of a conductive film during the subsequent proceedings.

“Fork” technique



Step 6.

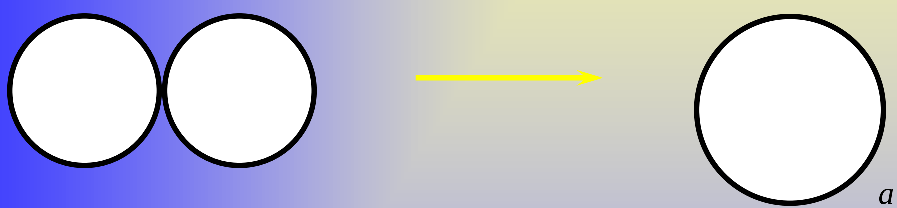
Fork is cut by electron beam into four isolated parts, thereby allowing the measurement of nanowire resistance by 4-wire method.

The measurements are now in progress.
We hope to see the Shapiro steps.

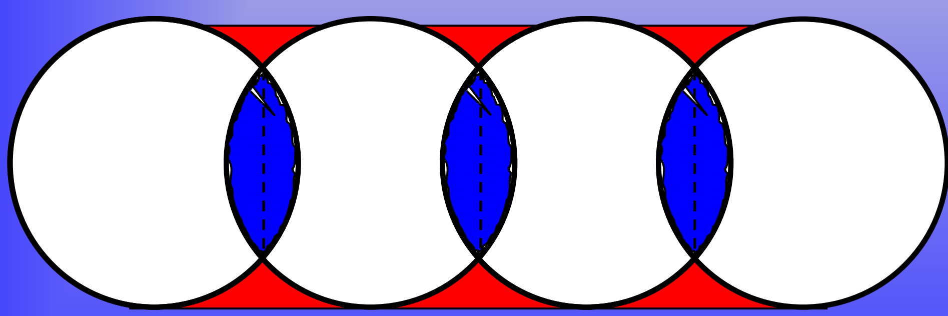
Thank you for attention!

In adiabatic conditions small cold metallic clusters are known to melt at merging

Simple model for estimating limiting radius of liquid ball and wire



a – **one-layer thickness**



$$R \le R_s^{\max} \equiv 0.78\alpha a$$

$$\boxed{\alpha \equiv Q_b / (CT_b + Q_m)}$$

$$R \le R_w^{\max} \equiv \alpha a$$

Limiting sizes for premelting spheres, R_s, and wires ,R_w

	α	R_s^{max}, nm	R_w^{max}, nm
In	7.66	1.8	2.3
Ni	3.05	0.7	0.9
Sn	7.12	1.6	2.1
Pb	4.34	1.0	1.3
Cu	3.28	0.78	1.0
Au	3.49	0.78	1.0
W	3.18	0.74	0.95
H_2	0.87	-	-
H_2O	0.77	-	-

In accordance with experimental results the radius of nanowire for casting metals is more than for refractory metals.

In hydrogen and water α <1 and melting is impossible.

Nanowires were formed for all metals and alloys

We conducted comparative studies of:

- Morphology of nanowire bundles
- Structure of nanowires
- Electrical measurements for nanowire bundles closed electrical circuit between the electrodes

Periodic Table of Elements

Atomic # / Symbol / Name / Atomic Mass

C Solid — Hg Liquid — H Gas — Rf Unknown

Metals: Alkali metals | Alkaline earth metals | Lanthanoids | Actinoids | Transition metals | Poor metals

Nonmetals: Other nonmetals | Noble gases

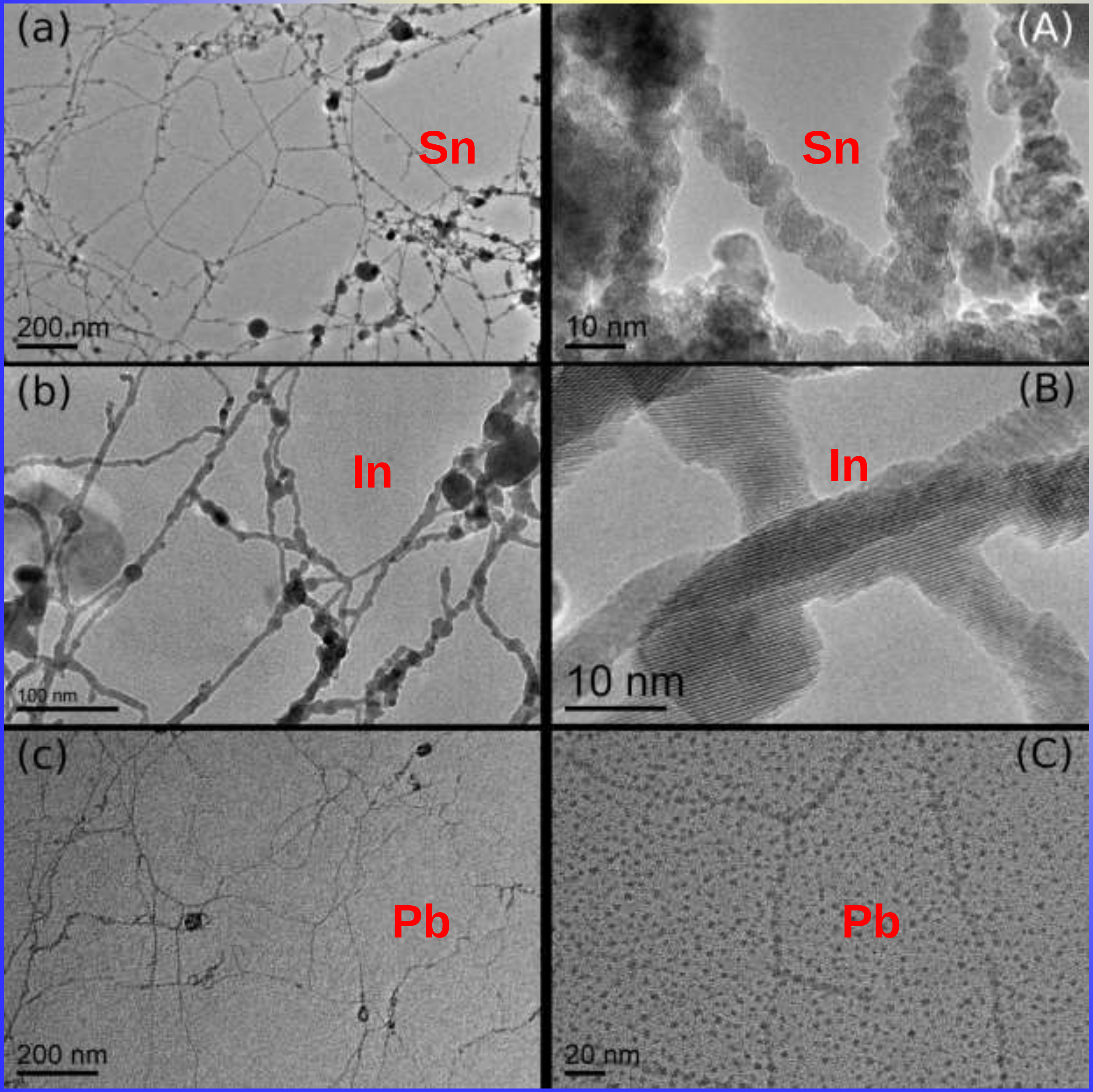
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H Hydrogen 1.00794																	2 He Helium 4.002602
2	3 Li Lithium 6.941	4 Be Beryllium 9.012182											5 B Boron 10.811	6 C Carbon 12.0107	7 N Nitrogen 14.0067	8 O Oxygen 15.9994	9 F Fluorine 18.9984032	10 Ne Neon 20.1797
3	11 Na Sodium 22.98976928	12 Mg Magnesium 24.3050											13 Al Aluminium 26.9815386	14 Si Silicon 28.0855	15 P Phosphorus 30.973762	16 S Sulfur 32.065	17 Cl Chlorine 35.453	18 Ar Argon 39.948
4	19 K Potassium 39.0983	20 Ca Calcium 40.078	21 Sc Scandium 44.955912	22 Ti Titanium 47.867	23 V Vanadium 50.9415	24 Cr Chromium 51.9961	25 Mn Manganese 54.938045	26 Fe Iron 55.845	27 Co Cobalt 58.933195	28 Ni Nickel 58.6934	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.64	33 As Arsenic 74.92160	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 83.798
5	37 Rb Rubidium 85.4678	38 Sr Strontium 87.62	39 Y Yttrium 88.90585	40 Zr Zirconium 91.224	41 Nb Niobium 92.90638	42 Mo Molybdenum 95.96	43 Tc Technetium (97.9072)	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.90550	46 Pd Palladium 106.42	47 Ag Silver 107.8682	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.760	52 Te Tellurium 127.60	53 I Iodine 126.90447	54 Xe Xenon 131.293
6	55 Cs Caesium 132.9054519	56 Ba Barium 137.327	57–71	72 Hf Hafnium 178.49	73 Ta Tantalum 180.94788	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.084	79 Au Gold 196.966569	80 Hg Mercury 200.59	81 Tl Thallium 204.3833	82 Pb Lead 207.2	83 Bi Bismuth 208.98040	84 Po Polonium (208.9824)	85 At Astatine (209.9871)	86 Rn Radon (222.0176)
7	87 Fr Francium (223)	88 Ra Radium (226)	89–103	104 Rf Rutherfordium (261)	105 Db Dubnium (262)	106 Sg Seaborgium (266)	107 Bh Bohrium (264)	108 Hs Hassium (277)	109 Mt Meitnerium (268)	110 Ds Darmstadtium (271)	111 Rg Roentgenium (272)	112 Uub Ununbium (285)	113 Uut Ununtrium (284)	114 Uuq Ununquadium (289)	115 Uup Ununpentium (288)	116 Uuh Ununhexium (292)	117 Uus Ununseptium	118 Uuo Ununoctium (294)

For elements with no stable isotopes, the mass number of the isotope with the longest half-life is in parentheses.

57 La Lanthanum 138.90547	58 Ce Cerium 140.116	59 Pr Praseodymium 140.90765	60 Nd Neodymium 144.242	61 Pm Promethium (145)	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.92535	66 Dy Dysprosium 162.500	67 Ho Holmium 164.93032	68 Er Erbium 167.259	69 Tm Thulium 168.93421	70 Yb Ytterbium 173.054	71 Lu Lutetium 174.9668
89 Ac Actinium (227)	90 Th Thorium 232.03806	91 Pa Protactinium 231.03588	92 U Uranium 238.02891	93 Np Neptunium (237)	94 Pu Plutonium (244)	95 Am Americium (243)	96 Cm Curium (247)	97 Bk Berkelium (247)	98 Cf Californium (251)	99 Es Einsteinium (252)	100 Fm Fermium (257)	101 Md Mendelevium (258)	102 No Nobelium (259)	103 Lr Lawrencium (262)

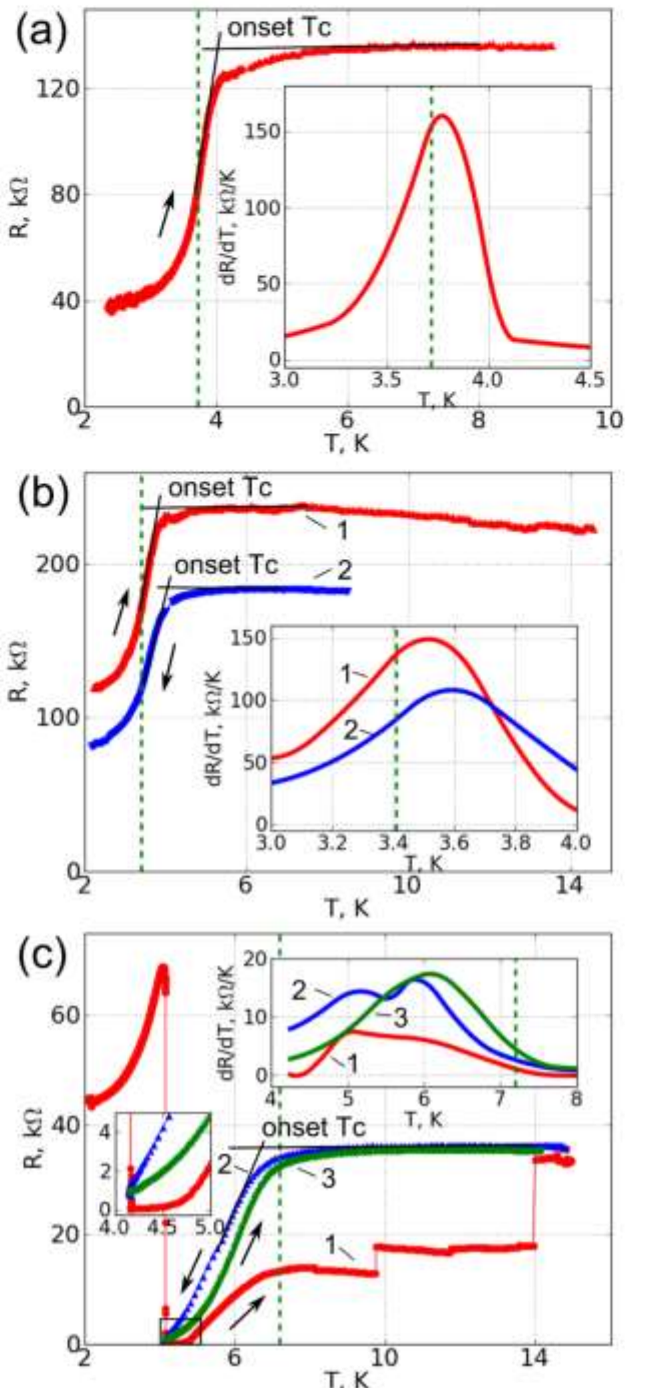
Ptable.com

Nanowire bundles morphology and structure



TEM images of fragments of nanowire bundles.

Nanowires of different metals display different structures: tin nanowires composed of sticked together polycrystals with crystallite sizes of 2 nm (A), indium wire are fused to each other monocrystals (B), lead nanowires unfortunately rapidly oxidized on air and only traces of consisting of oxide nanowires seen in the electron microscope (C).



The transition to superconducting state for the bundles of nanowires of tin (a), indium (b) and lead (c).

The "conductor-superconductor" transition in nanowire is always broadens;

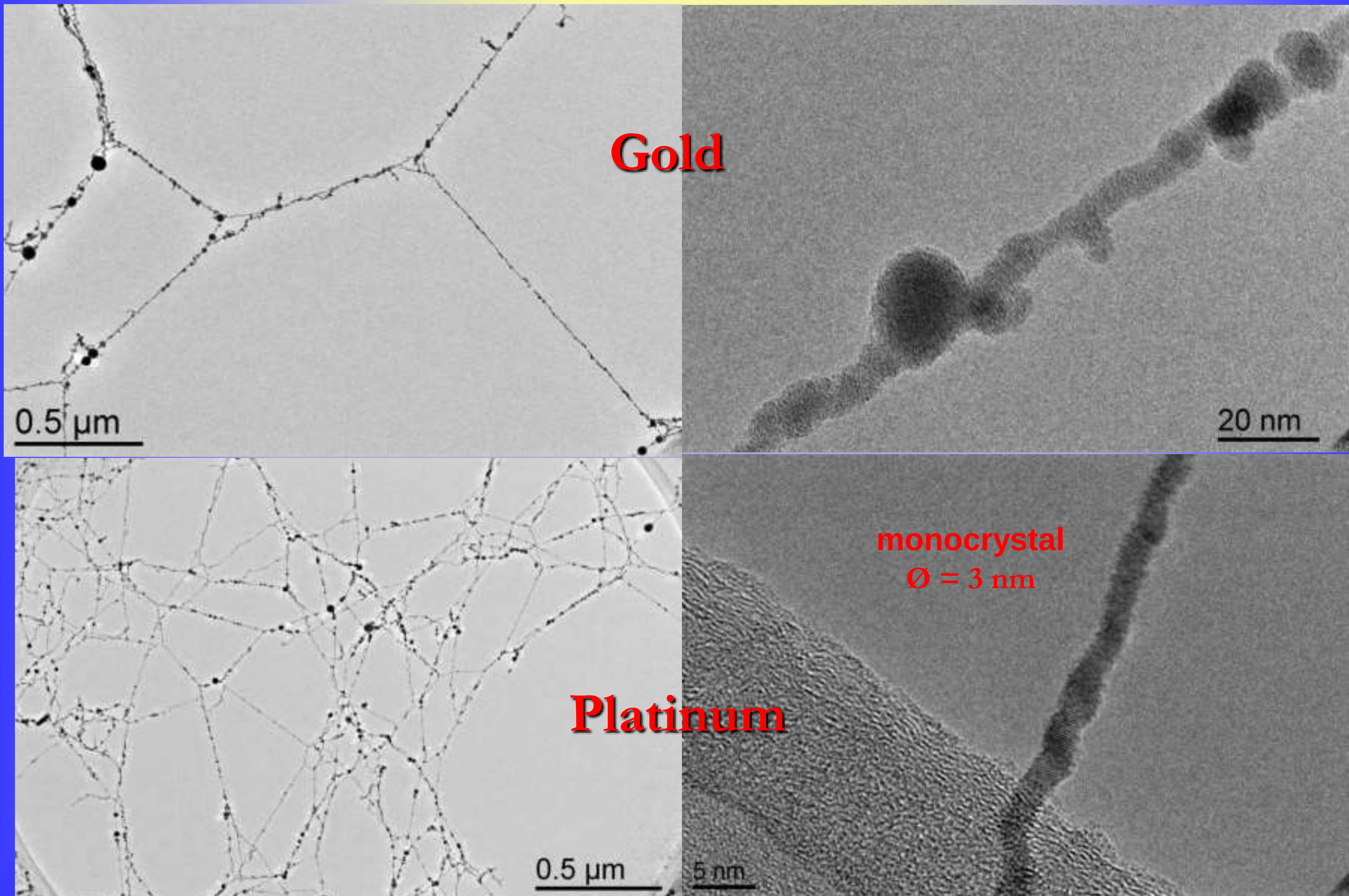
onsetT_c in nanowires can be as below T_c in a bulk - (worsen superconductivity), as above it - (improving superconductivity),

but

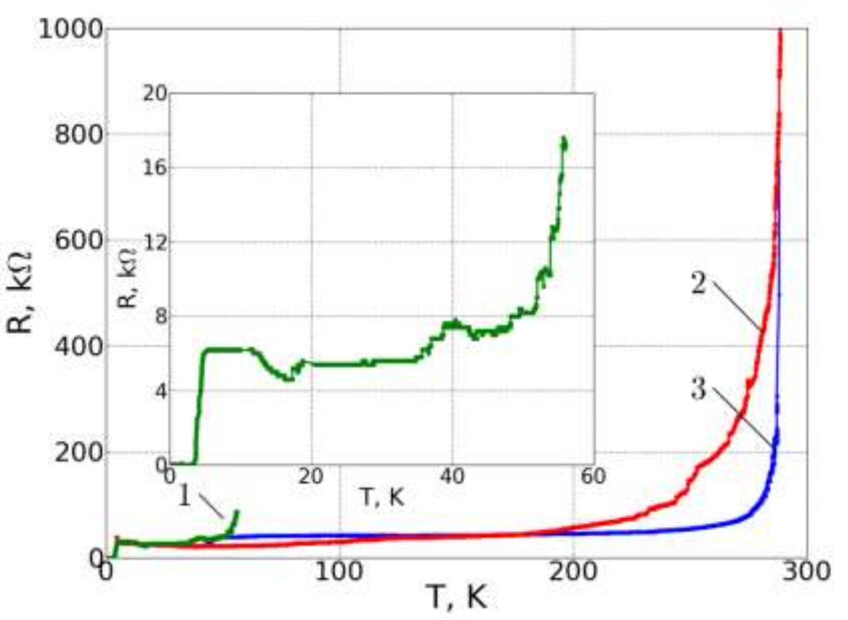
the temperature of loss of resistance (that is necessary for applications)

always falls down

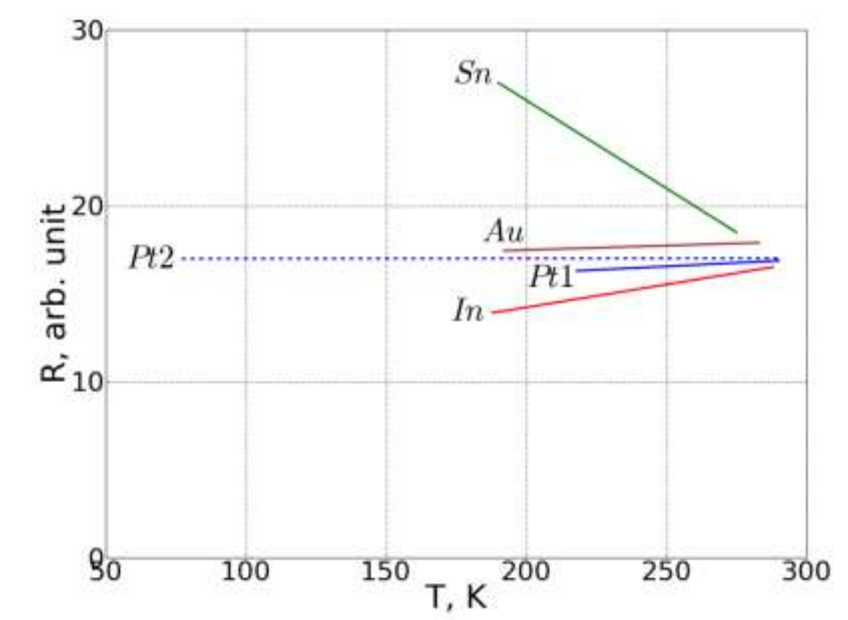
Nanowire bundles morphology and structure of individual wires



Resistance vs temperature

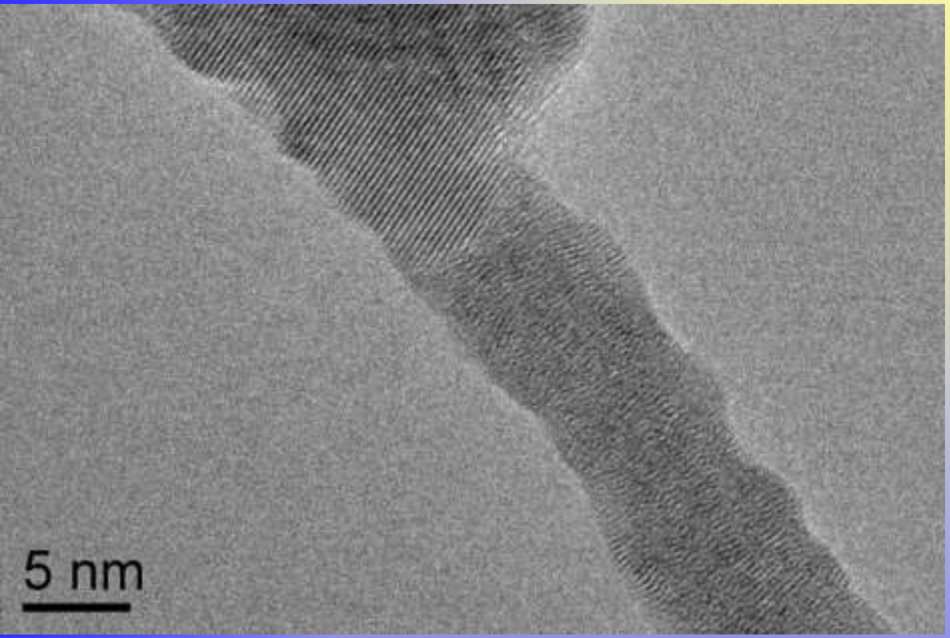


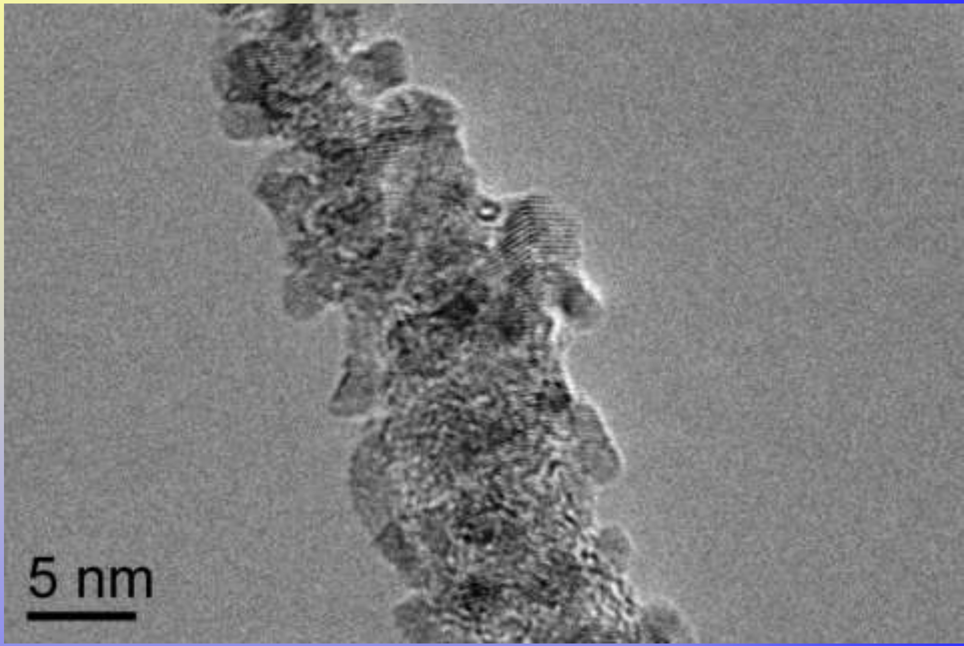
The resistance for bundles of mercury (1), gold (2) and platinum (3) nanowires. The inset shows transition from the superconducting to the normal state in mercury nanowires in more detail.



The resistances of annealed bundles

Nanowire structure



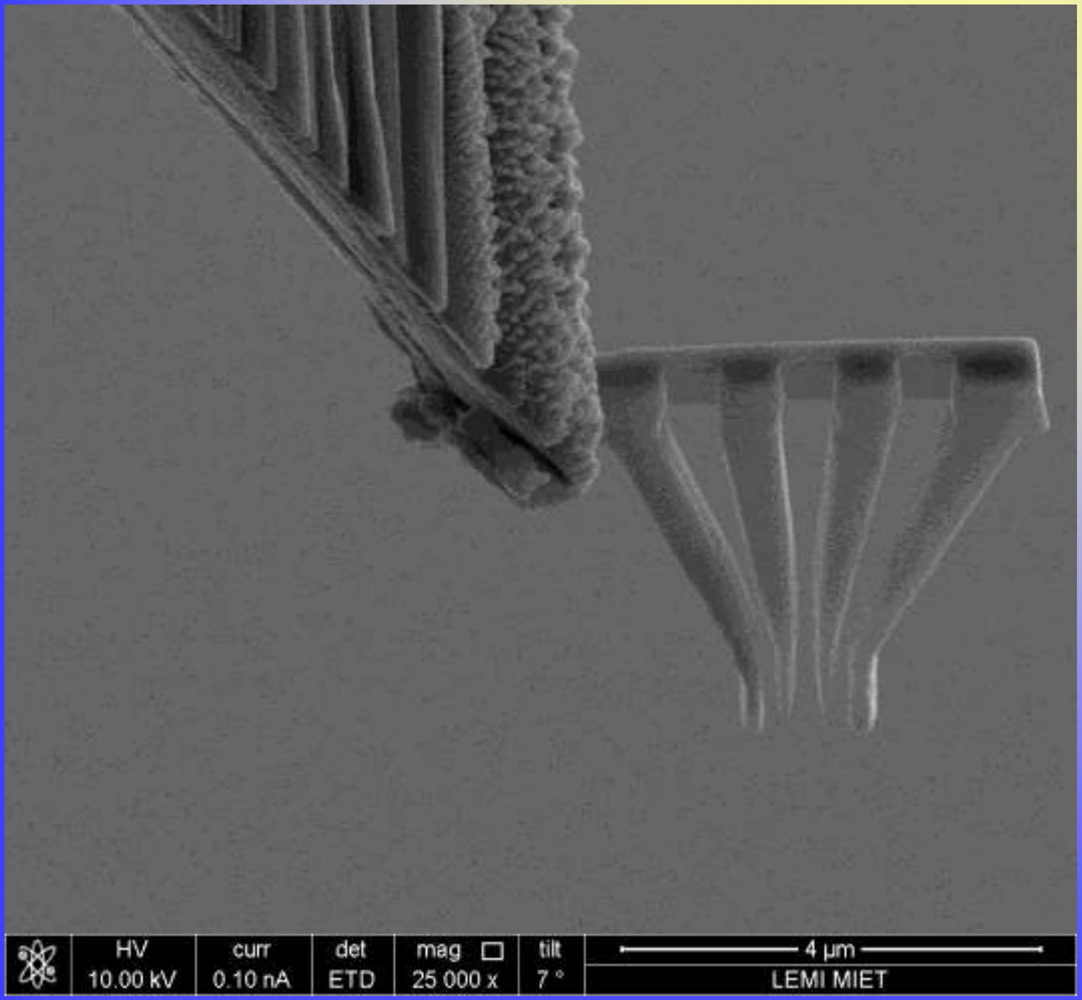


Indium

Permalloy

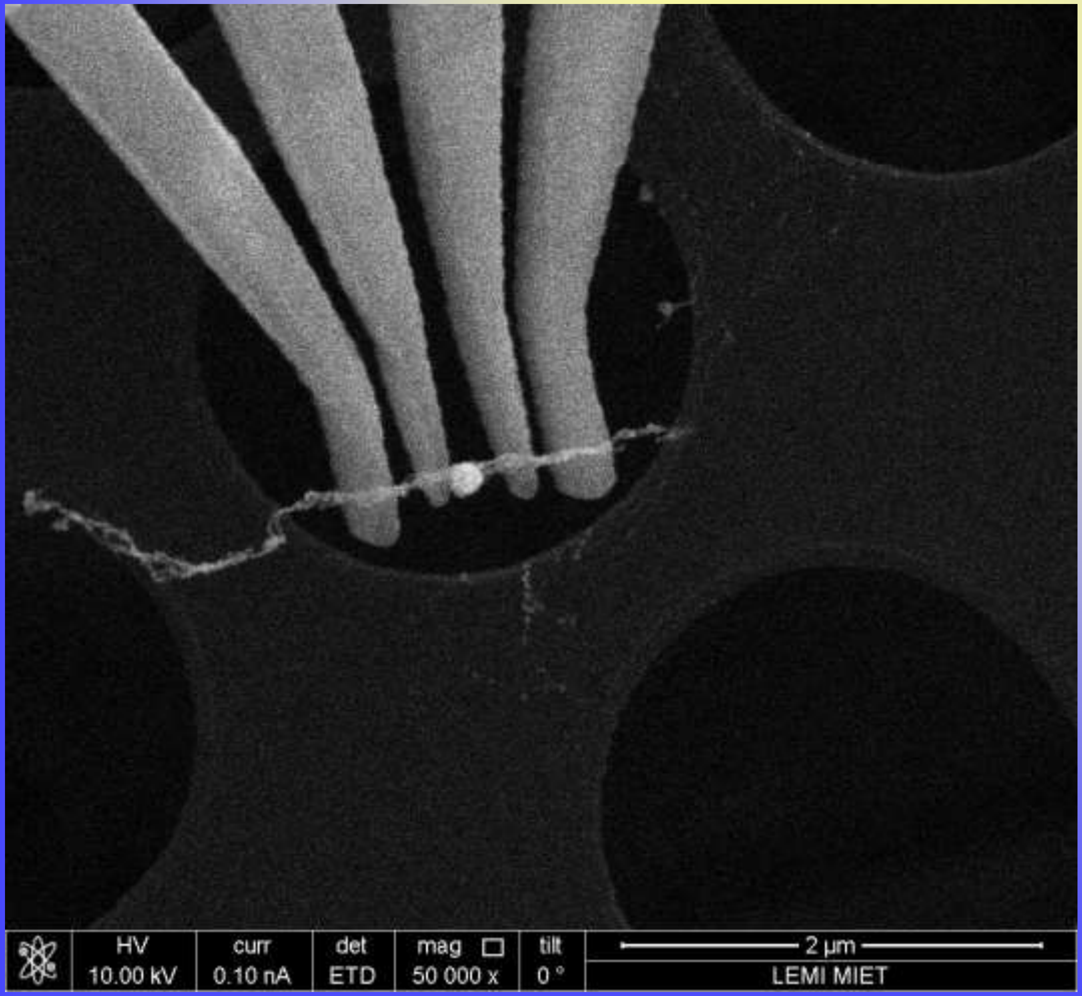
Two directions of recent research

“Fork” technique



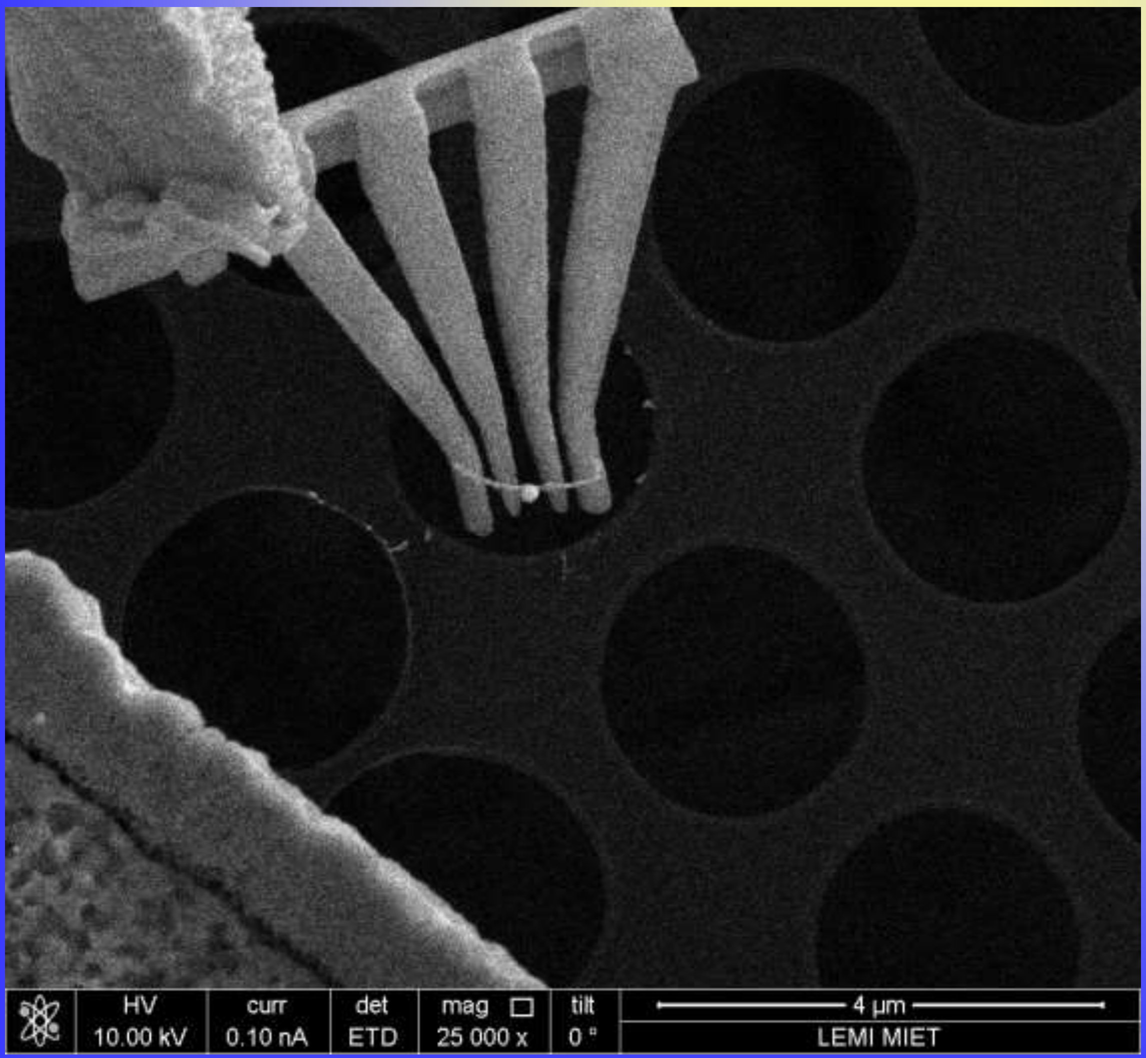
Step 1.The "fork" with four teeth was manufactured and soldered to the cantilever

"Fork" technique



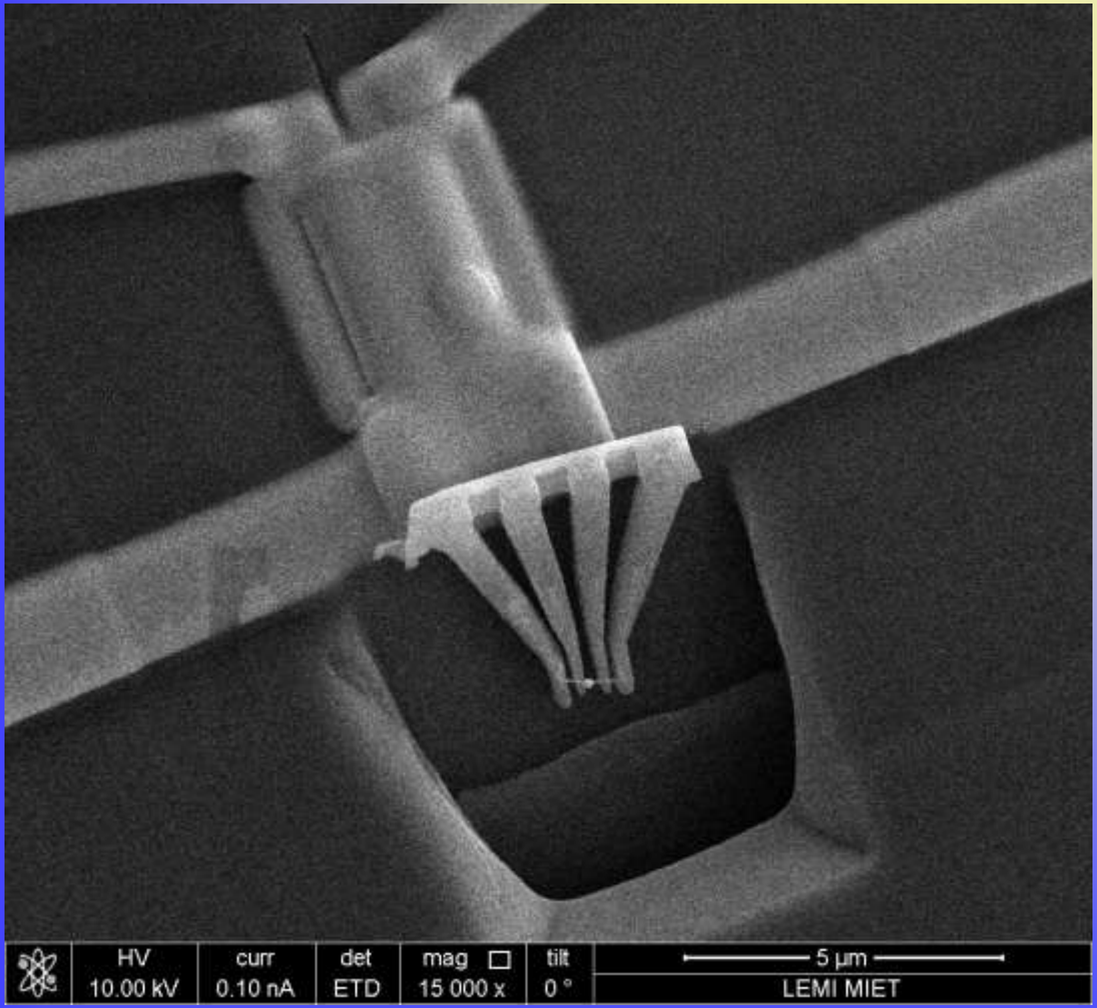
Step 2. Fork is placed beneath of our nanowire stretched over the 2-micron diameter hole in the carbon-coated copper grid and then lifts nanowire above the plane of the grid.

“Fork” technique



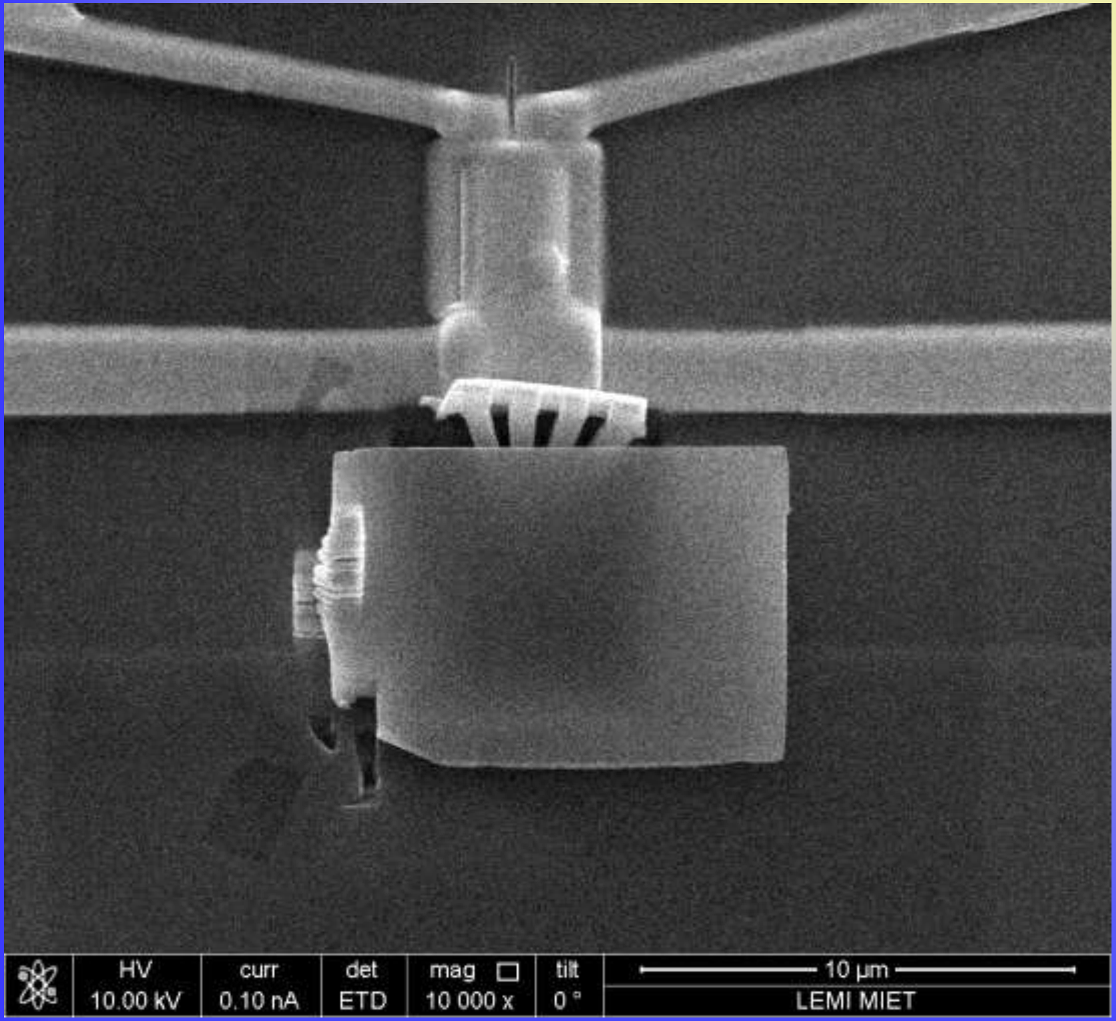
Step 3. Nanowire ends are cut by an electron beam

"Fork" technique



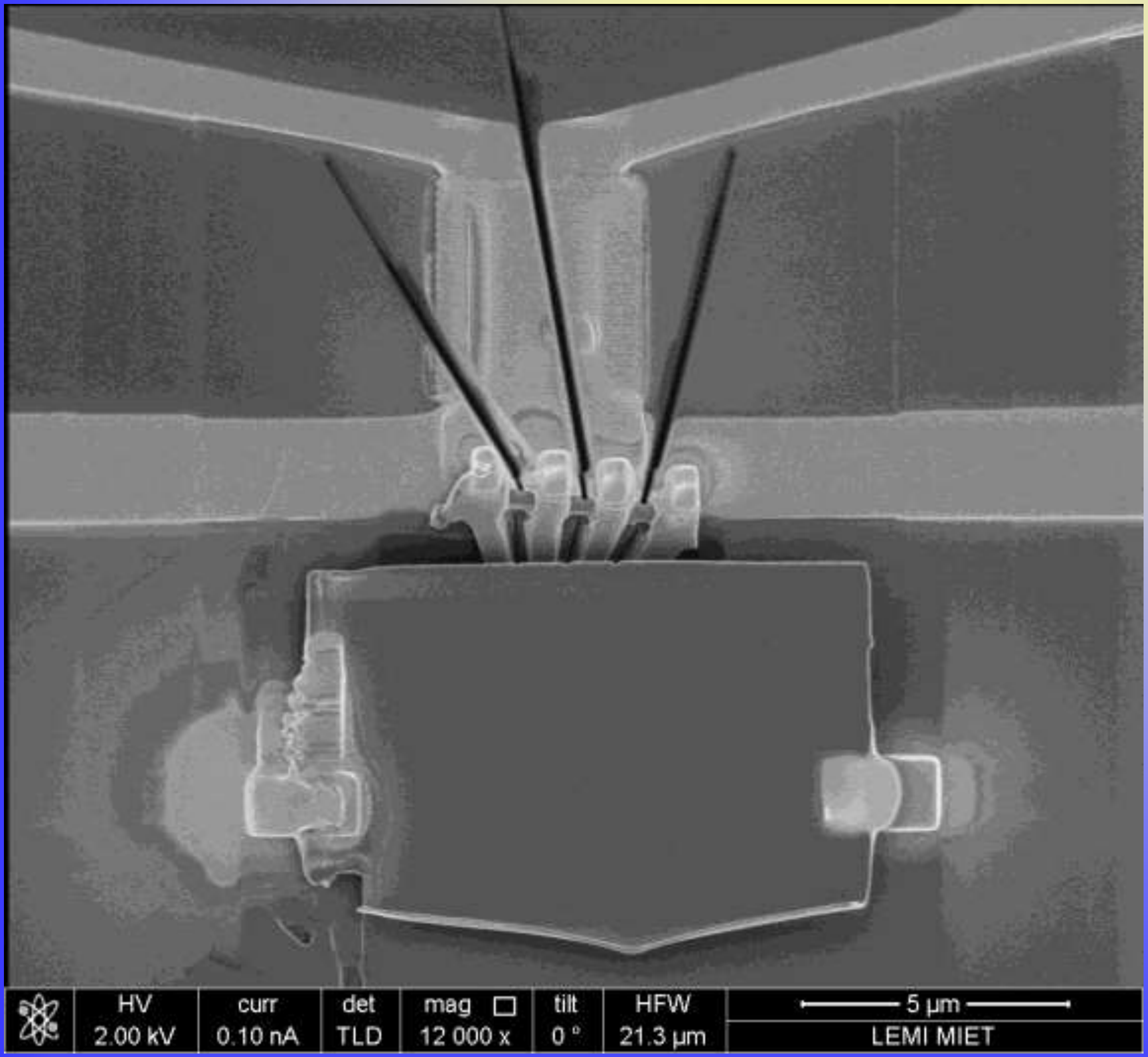
Step 4. Fork with nanowire is transferred to the chip and fork is placed into a recess specially arranged therein. Then fork soldered to the edge of the chip and cut off cantilever.

“Fork” technique



Step 5. Fork nanowire is covered by protective shield to prevent formation of a conductive film during the subsequent proceedings.

"Fork" technique



Step 6. Fork is cut by electron beam into four isolated parts, thereby allowing the measurement of nanowire resistance by 4-wire method.

Nanoweb as catalyst

- Gold nanoparticles - a wonderful catalyst, but only at a diameter of 2 - 5 nm!
- Nano-web should be much more convenient than nano-dust
- Nobody knew how to produce so thin nanowires but we could
- It was necessary to provide the electrical conductivity through the nano-web heated up to T = 300K (it is needed to maintain voltage and charge drain)
- We did that by annealing
- The collaborative with Moscow State University (Department of Chemistry) study of catalytic ability of gold, platinum, nickel, silver, etc. nanowebs are in progress now

The nanoweb total surface should be as large as 100 cm^2 – it is enough to study the catalytic conversion by Mass-spectrometer or chromatographic tools

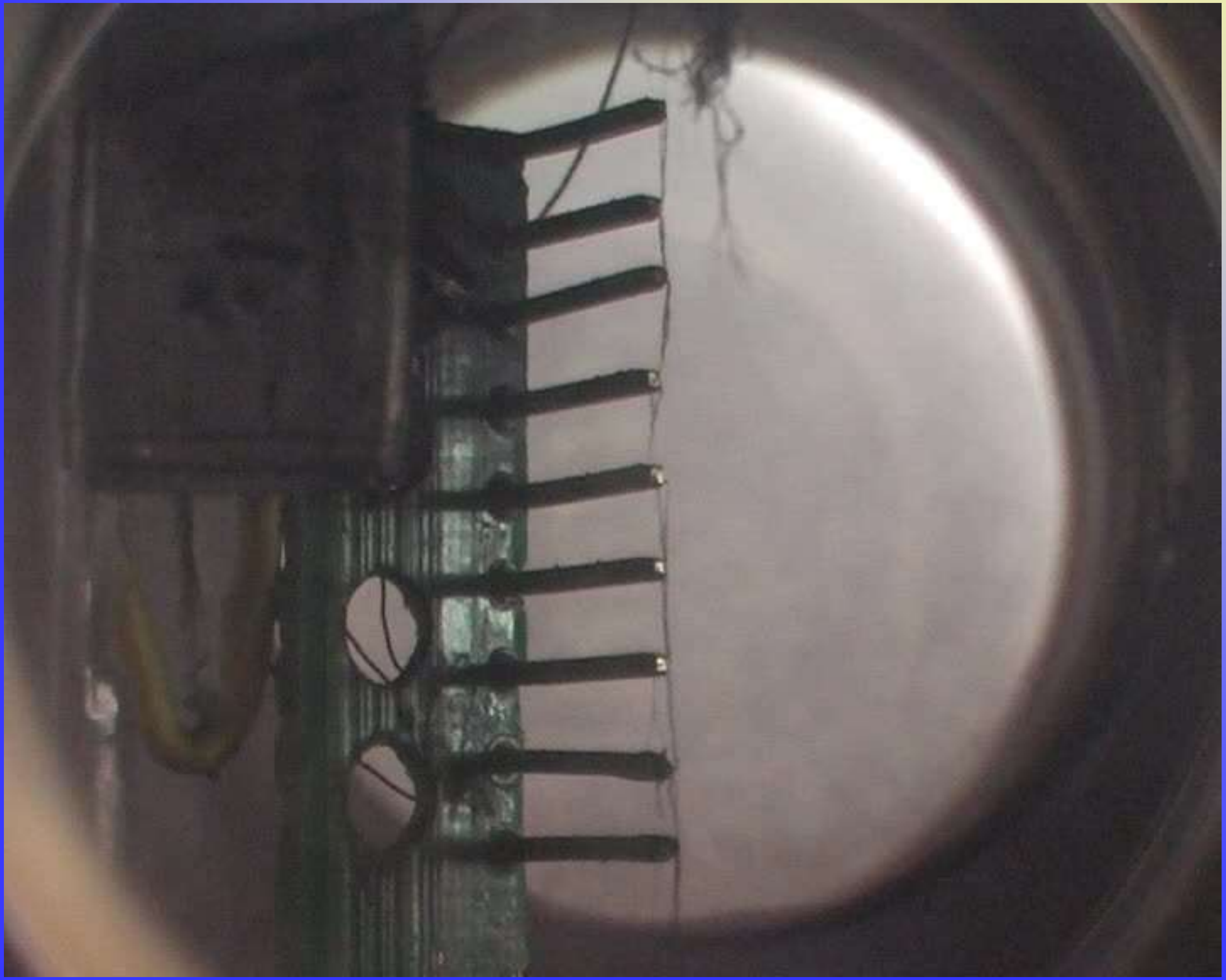


Photo made by cell phone

Report is based on papers:

1. Gordon E.B., Okuda Y., Catalysis of impurities coalescence by quantized vortices in superfluid helium with nanofilament formation. LOW TEMP. PHYS. 35(3) P: 209-213 (2009).

2. Gordon E.B., Karabulin A.V., Matyushenko V.I., et al., Electric properties of metallic nanowires obtained in quantum vortices of superfluid helium: LOW TEMP. PHYS. 36 (7) P: 590-595 (2010).

3. P. Moroshkin, V. Lebedev, B. Grobety, C. Neururer, E.B. Gordon and A. Weis. Nanowire formation by gold nano-fragment coalescence on quantized vortices in He II: EPL, 90(3), AN 34002, (2010).

4. Gordon E.B., Karabulin A.V., Matyushenko V.I., et al., Structure of metallic nanowires and nanoclusters formed in superfluid helium JETP 112(6) p: 1061-1070 (2011).

5. V. Lebedev, P. Moroshkin, B. Groberty, E. Gordon, A. Weis. Formation of Metallic Nanowires by Laser Ablation in Liquid Helium. J.Low Temp.Phys. 165(3-4), 166-176, (2011).

6. E. B. Gordon, A.V. Karabulin, V.I. Matyushenko, V.D. Sizov, I.I. Khodos. The role of vortices in the process of impurity nanoparticles coalescence in liquid helium. Chem. Phys. Lett., 519-520, 64-68, (2012).

7. E. B. Gordon, A. V. Karabulin, V. I. Matyushenko, V. D. Sizov, I. I. Khodos. The electrical conductivity of bundles of superconducting nanowires produced by laser ablation of metals in superfluid helium. Appl. Phys. Lett. 101(5) , 052605 (2012).

8. E. B. Gordon, Superfluidity Influence on Impurities Condensation in Liquid Helium, Low Temp. Phys. 38, 1043-1055 (2012).

9. E. B. Gordon, A.V. Karabulin, V.I. Matyushenko, V.D. Sizov, I.I. Khodos. The Nanostructures Produced by Laser Ablation of Metals in Superfluid Helium, J. Low Temp. Phys. 172, 94-112 (2013)