Suppression of superconductivity in thin Nb nanowires fabricated in the vortex cores of superfluid helium

Eugene B. Gordon^{*a}, Alexey V. Bezryadin^b, Alexander V. Karabulin^{a,c}, Vladimir I. Matyushenko^d, Igor. I. Khodos^e.

^aInstitute of Problems of Chemical Physics RAS, Semenov avenue 1, 142432, Chernogolovka, Moscow Region, Russia.

^bDepartment of Physics, University of Illinois at Urbana-Champaign, Urbana, IL 61874, USA.

^cNational Research Nuclear University MEPhI (Moscow Engineering Physics Institute), Kashirskoe highway 31, 115409, Moscow, Russia.

^dThe Branch of Talrose Institute for Energy Problems of Chemical Physics RAS, Semenov avenue 1/10, 142432, Chernogolovka, Moscow Region, Russia.

^eInstitute of Microelectronics Technology and High Purity Materials RAS, Institutskaya Street 6, 142432, Chernogolovka, Moscow Region, Russia.

*Email: Gordon.eb@gmail.com

Keywords

Superconductivity, Thin nanowires, Superfluid helium, Vortices

Abstract

Nanowires of niobium, platinum and indium-lead $\text{In}_{88}\text{Pb}_{12}$ alloy with diameters of 4.2, 3.6 and 8 nm, respectively, were grown in quantized vortices of superfluid helium, and the dependences of their resistance on temperature have been studied. Through a detailed comparison of these dependences we present evidence that superconducting niobium wires allow a high rate of quantum phase slip. This phase slippage leads to a phase transition to an insulating state at $T \rightarrow 0$.

Introduction

Quasi-one-dimensional metals, namely nanowires, are one of the most interesting objects in nanoscale science. Naturally, the size effects are mainly the fingerprints of quantum behavior. However even such a promising and unusual chemical property as high catalytic activity of noble metals is also observed only for diameters of particles in a range of 3-5 nm [1-3], the same scale can be of relevance for nanowires, which can also turn to be catalytic if made sufficiently thin. From the point of view of physics the most attractive properties of nanowires are the size effects in their electrical conductivity and first of all in superconductivity [4-9]. If the wire diameter is made smaller and smaller the critical temperature of the wire approaches zero [10]. However, superconductivity may disappear well before the critical temperature, T_c , becomes zero. In particular, a quantum Kosterlitz-Thoulesse transition, involving a quantum depairing of phase slips and anti-phase-slips, has been predicted to occur in superconducting wires with diameters of just a few nanometers [11]. Such transition should induce a dielectric behavior in a nanowire made of a superconducting metal or alloy. The quantum phase slips (QPS), which is the main reason for the occurrence of the insulating state in nominally superconducting wires, has been discussed in numerous publications [5,6,11,12]. Typically it is accepted to distinguish two types of them: thermally activated phase slips (TAPS) [4] and quantum phase slips [5,7-9,13,14]. The QPS can make a thin wire acts like a weak insulator, even if it is made of a superconducting material [5,6]. It has been suggested that nanowires which support quantum phase slips can be used to make novel logical quantum devices. A proof-of-principle qubit based on a nanowire has been demonstrated recently [14].

The main focus of the present work is the experimental study of thin superconducting nanowires aimed to revealing the quantum size effects in their electrical conductivity. Here we present an observation of an insulating behavior in pure-metal elemental nanowires (Nb), having a surface which is clean and not oxidized. We explain the observation in terms of proliferation of quantum phase slips [11]. It is worthy to remind that other factors, besides QPS, can act as strong suppressants of the superconducting order in ultrathin nanowires. It is well known, since the pioneering works of Abrikosov and Gor'kov [15], that magnetic impurities, if their concentration increases, first reduce the critical temperature, then make superconductivity gapless and finally completely suppresses the critical temperature to zero. In other words, if the concentration of uncompensated spins in the superconductor is sufficient, they can eliminate completely all the superconducting effects including the Meissner effect. Since the surface-to-volume ratio

becomes especially large in nanowires having diameters of just a few nanometers, contamination of the surface with unpaired spins, of any origin, can have a strong impact on superconductivity. In particular, it was suggested [16] that the nanowire surface, if subjected to oxidation, can develop unpaired spins due to disorder. If unpaired spins are present at the boundary between the metal and the oxide, they can act, effectively, as magnetic impurities on the surface of the nanowire. Of course no actual impurity is present in this case [15], simply the boundary between the metal and its oxide is typically so disordered that unpaired and single-occupied localized electronic states can occur. These “free radicals” or “dangling bonds” potentially may have spins and so they may be qualified as magnetic depairing agents. In order to rule out the surface spin effect with complete certainty one has to perform experiments with nanowires prepared in extremely clean conditions. Also, nanowires should not be exposed to air, even briefly. The method of nanowires production and measurements which we used here conforms to these requirements.

Experimental

The difficulties in the experimental study of size effects in superconductivity suppression are associated as well with the fact that these effects should appear for wires with very small diameter, and the production of such a superconductor wire, possessing desirably regular structure, perfect shape and containing no impurities represents rather sophisticated problem. The method of nanowire formation in the cores of quantum vortices in superfluid helium helps to eliminate the concerns listed above.

Our method of nanowires production, using quantized vortices of superfluid helium as a template, allowed us to grow nanowires from virtually every metal and alloy [17]. The quality of the nanowires is quite reasonable, as they are formed by fusion in the quantized vortex core of nanoclusters being molten at the moment of their nucleation by the atom condensation [18]. The diameter of the nanowires formed by this technique is determined mainly by the thermal characteristics of the metal [17] and it ranges from about 7-8 nm for fusible metals to as small as 3-4 nm for refractory metals [17,19,20]. It is therefore can be expected that, at least for refractory metals, the diameter of the nanowires would be sufficiently small for certain size effects to become pronounced. As we will discuss in detail below, this expectation is true and our ultrathin Nb nanowires exhibit, indeed, a dielectric behavior, which we associated with proliferation of quantum phase slips [11].

When growing in superfluid helium the nanowires prefer to pin to various protuberances present in the zone of the growth. Indeed, the quantized vortices in superfluid helium tend to connect to sharp pins, in particular to the specifically installed pins ("electrodes") connected to the measurement leads. As a result, the bundles of nanowires were grown between the tips of the electrodes intentionally placed vertically with few millimeters distance between them. Finally the nanowires closed the electrical circuit acting as a bridge connecting the tips of the electrodes. Thus, it was possible to measure the resistance of the nanowire bundles directly in the cryostat, without exposing the nanowires to ambient air. Consequently, both the process of the wires growth and the process of their electrical transport measurements were performed in uniquely clean and inert conditions of liquid helium-4. It is well known that no contaminants and chemical reactions can be present in liquid helium. Therefore the surface of the wires was perfectly clean. As it has been shown in [19], the resistance of a bundle quite reasonably reflects the resistivity of single wire.

Our experimental technique was described elsewhere [17,19]. Atoms and small clusters of the metal are introduced into superfluid helium by laser ablation of a metal targets immersed into liquid. Foils of chemically pure (99.99%) metals were used as targets. Indium-lead alloy has been prepared by heating the pieces of individual metals together in a sealed bulb to a temperature of 350°C, well exceeded their melting points. After keeping at this temperature for 2 hours the bulb was slowly cooled to 300 K. The quantized vortices nucleate at the focus of the pulsed laser beam as a result of the media heating, i.e., in the same place and at the same time as metal nanoparticles appeared. The product of the metal coalescence in the quantized vortex cores are the bundles of parallel-series of interconnected metallic nanowires attached to the tips of electrodes inserted into the condensation zone. By connecting the tips of neighboring electrodes the bundles closed the electrical circuit; distances between electrodes were 1.4 mm. Such a way the measurements of the electrical resistance were performed inside of cryostat. Part of the nanowires bundles were deposited on a carbon-coated copper grid placed on the bottom of the cell. After heating the cryostat up to 300 K, they were replaced to vacuum chamber of TEM electron microscope (JEOL JEM-2100) for studies of nanowire structure and morphology.

On heating, the relaxation of nanowire shape, which leads to their shortening, takes place at temperatures above 100 K [20]. This causes the breaks in the web formed by the nanowires, and, due to diminishing the percolation, the irreversible changes of the total resistance of the web of nanowires connecting the electrodes. For this reason we annealed the web by its heating up to a certain temperature T_{an} and subsequently cooled it down again. As a result the resistance value

became reproducible for the temperatures below the annealing temperature, $T < T_{an}$. Typically, the temperature growth was achieved by a slow self-heating of whole cryostat. At low temperatures, reversible cycle "heating-cooling" was produced, under constant pumping of helium vapor, by a temporal irradiation of the sample immersed in liquid helium by thermal emission of incandescent lamps through the cryostat windows.

For normal metal nanowires as well as for superconducting nanowires, the diameter is one of the key factors defining the strength of all kinds of quantum size effects (QSE). But the origins of QSE for normal and superconducting metals are different: In normal metals the resistance is determined by the scattering of the conduction electrons on the surface of the wire or on the grain boundaries whereas in superconductors QSE may be due to a variety of reasons, including quantum phase slips and Coulomb suppression of superconductivity. Unfortunately, in experiment we cannot change the diameters of the nanowires because, for our nanofabrication method, the diameter is fixed for a given material. Instead we can produce nanowires out of different metals and alloys and compare them.

Results and Discussions

We compare the temperature dependence of the resistance of the nanowire bundles made of three materials - niobium, platinum and indium-lead alloy. Figure 1 shows the morphology and structure of the nanowires grown from niobium (a,b), indium-lead alloy (c,d) and platinum (e,f). All nanowires were of good quality, that is, without significant nodes and antinodes; their structure was close to being crystalline. It is seen from Figure 1b, d, and f that the diameter of the nanowires for refractory niobium is about 4 nm, for the indium-lead alloy the diameter is about 8 nm, and the diameter of the platinum wire is 3 nm. The nanowire made of indium-lead alloy has no noticeable spatial inhomogeneity of the elemental composition, which is a consequence of the well-known fact that the alloy of these elements always forms a solid solution [21].

Niobium superconducting nanowire is a favorite object in searches for size suppression of superconductivity [22]. However, the nanowires used previously have always been subjected to the contact with the ambient air. Thus some effect of surface spins could not have been ruled out. The diameter of our Nb wires is about 4 nm (Figure 1), i.e. our Nb nanowires are thinner than in all previous studies. For the purpose of comparison, we have made nanowires out of a noble metal, which is not expected to be superconducting, namely Pt. The nanowires made of Pt exhibit even somewhat smaller diameters, namely about 3 nm. We also have grown the bundles of nanowires made of the indium-lead alloy. The diameter of these wires was much thicker,

namely, about 8 nm and such diameters were typical for nanowires used in the most previous studies of the size effects in 1D systems [8]. The alloy composition was In:Pb = 88:12; the reasons will be discussed below.

Figure.1 Structure and morphology of the bundles of nanowires heated up to 300 K: (a,b) – Nb; (c,d) – In:Pb = 88:12; (e,f) – Pt. All images are made using a transmission electron microscope (TEM).

For all types of wires the electrical characteristics were measured in situ, in the cryostat, on the bundles of interconnected nanowires grown vertically between the tips of gold-plated

electrodes, arranged in an array and positioned near the condensation zone. The electrical signals were recorded simultaneously from the three bundles. Measurements were performed during the cryostat self-heating first in the liquid helium, and then in helium gas. The measurement results are shown in Figure 2, 3 and 4.

Figure.2. Temperature dependence of the resistance of bundle of nanowires grown from the indium-lead $\text{In}_{88}\text{Pb}_{12}$ alloy. The left inset (a) shows in more detail the resistance behavior measured for nanowire bundles submerged in liquid helium. On the right (b) - the results of bundle annealing; in the point A the jacket of the cryostat was filled by liquid nitrogen and therefore the specimen temperature dropped slowly until the point B, wherein liquid nitrogen is removed from the jacket and the self-heating restarts.

The temperature dependence for the resistance of the indium-lead nanowires (Figure 2) was close to those of nanowires of other fusible superconductors studied earlier [19]. At temperatures below the superconducting transition the resistance did not depend on temperature T . In view of the fact that in our two-probe measurement method the resistance of the nanowires registered together with the resistance of the contacts and the outer measurement leads, we cannot make a definite about the origin of the residual resistance observed at $T < 2.5$ K. It is also possible that at $T < 2.5$ K the residual resistance is due to a non-zero rate of quantum phase slips. Yet this rate is not sufficient to put our In-Pb nanowires into the insulating regime. The observed

superconducting transition has a width of about 0.5 K, and its center occurred at $T = 5.0$ K, i.e., at temperatures close to T_c for a bulk alloy of this composition [23]. When heated above a transition the measured resistance is mainly determined by the resistance of nanowires themselves, and it weakly decreases with temperature according to dependence

$$R/R_0 = 1 - \rho T, \quad (1)$$

where $\rho = 3 \times 10^{-3} \text{ K}^{-1}$. The weak temperature dependence of resistance is common to all nanowires grown by our technique, because at least at $T < 300$ K, the resistance R is determined by electrons scattering on the surface of wires, which causes a weak localization of the electronic wave functions [20]. The negative slope of the resistance versus temperature dependence (observed at $T < 45$ K) could also be caused by a weak Coulomb blockade, which might occur due to the small size of the wires and due to a rather high total resistance of the nanowire bundle network.

The growth of the nanowire bundle resistance at $T > 160$ K is, as it has already been mentioned, the consequence of the breakage of some part of nanowire web connecting the tips of the electrodes. The resistance of the annealed bundle represents, as it is seen from Figure 2 (right inset), the reversible quasilinear dependence with slope $\rho = -3 \times 10^{-4} \text{ K}^{-1}$ (ρ is negative because in Eq.1 it appears with the sign minus). In other words, at these higher temperatures the resistance increases with warming, as it should be for a metallic sample.

The temperature behavior of the resistance of the bundle of niobium nanowires is completely different (Figure 3). The most characteristic feature of this dependence is a steep increase in resistance at $T \rightarrow 0$. As can be seen from the left inset, it corresponds to a proportional increase of the conductivity on temperature ($1/R \propto T$). What is even more impressive is that the conductivity value extrapolated to zero conductivity at $T = 0$. This fact is a strong indicator of a dielectric or insulating behavior of our Nb wires.

Figure 3. The temperature dependence of the resistance of the bundle of niobium nanowires. The left inset (a) presents a low-temperature behavior of the conductivity (linear extrapolation gives zero conductivity at $T = 0$). On the right (b) - the results of the annealing; at the moment A the jacket of the cryostat filled with liquid nitrogen and the resulting specimen temperature dropped slowly until the moment B, wherein liquid nitrogen is removed from the jacket of the cryostat, which reversed the temperature evolution and restarted the warming-up process.

The observed minimal resistance, realized at $T = 3.5$ K, and its subsequent steep growth with temperature may be interpreted as a degenerate superconducting transition at $T \approx 4$ K, by analogy with the temperature dependence for thicker nanowires of fusible superconductors [19]. This temperature is close to the superconducting transition temperature in the indium-lead nanowires (Figure 2). By the way, the $\text{In}_{88}\text{Pb}_{12}$ composition of the alloy was chosen from these considerations, i.e., to make the T_c similar to the indicated transition in Nb wires. The T_c of our Nb wires ($T \sim 4$ K) is significantly lower than the value of T_c for bulk niobium, which is equal to 9 K.

Figure 4. Temperature dependence of the resistance of the platinum nanowire bundle. The annealing procedure was as for other nanowires: at the moment A the jacket of the cryostat filled with liquid nitrogen and the specimen temperature dropped slowly until the moment B, wherein liquid nitrogen is removed from the jacket of the cryostat. In this test $T_{an} = 275$ K. The inset presents the low-temperature behavior of the conductivity of Pt nanowires bundle (linear extrapolation gives a non-zero conductivity at $T = 0$).

At temperatures above this "transition" a slight drop in resistance with increasing temperature was observed with slope $\rho = 3 \times 10^{-3} \text{ K}^{-1}$, both in the range of 10-60 K and (for annealed wires) in the range of 200-260 K. It should be noted that such smooth temperature dependence is typical for nanowires made of all poor metals (both normal and superconducting) [20].

For platinum nanowires, as for other noble metals [20], annealed samples demonstrated a much weaker dependence of R on T : As shown in Figure 4 its slope, at least in the range $T = 200\text{--}300$ K, was $\rho = -3 \times 10^{-4} \text{ K}^{-1}$. Apparent resistivity jump in λ point, $T_\lambda = 2.17$ K, took place for any nanowire and it was associated with changes in the morphology of the web suspended in liquid helium due to the loss of the superfluidity of liquid helium [20]. The jump near $T = 60$ K we associate with the restructuring that takes place in the bulk platinum at this temperature [24]. There was also a decrease in conductivity at $T \rightarrow 0$, but the effect is much weaker than in niobium and the conductivity extrapolated to $T = 0$ is not equal to zero, as seen in Figure.4(inset).

As it was already mentioned the Niobium nanowires were the favorite object for studying the size effects. The suppression of superconductivity in them has been studied by several groups. For example, in [22] the Nb nanowires having diameters 7-15 nm have been prepared by a sputter-deposition of a thin layer of Nb on the surface of a suspended single wall carbon nanotube. Nanowire resistance measured by pseudo-4-probe technique vs temperature, $R(T)$, showed a good agreement with the model of thermally activated phase slips (TAPS) [7].

In another study [25] the "nanowire" was an ion-milled strip formed from the rather thick (100 nm) niobium film grown on a silicon substrate. The jet of gallium ions served as a cutter and Ga ions partially embedding into the Nb strip suppressed its superconductivity. However, while observing the section of ion-milled "wires" by an electron microscope the authors observed a dark region in the core of them, having a diameter of a few nanometers. It was interpreted as an area free from gallium impurities and that spot was accepted as pure niobium "nanowire" responsible for the transition to the superconducting state observed through transport measurements. The authors concluded that the temperature dependence of the resistance near the superconducting transition may be described in terms of TAPS, and at temperatures below 5.4 K it fits better using QPS models.

Engel in his comment [26] to the paper [25] suggests that their results can be described by the proximity effect in the two-layer system "superconductor - normal metal" without involving phase slip phenomenon. In response to this comment [27] the authors provided additional experimental information in favor of the existence of the phase slip, in particular, QPS, in their samples.

In Reference [28] the authors examine bundles of 30 interconnected nanowires, grown through a porous silicon substrate. The authors estimate the diameter of the individual nanowires as 17-20 nm. The main effect they observed was a shift of the superconducting transition to lower T and some unusual shape of low-temperature tail of this transition. The authors of [28] believe that their results were in good agreement with theoretical models describing QPS.

The brief analysis presented above shows that various research groups do not come to a common conclusion. Moreover, the predicted insulating regime [11] has not been observed in pure metal nanowires having a non-oxidized clean surface. The samples used in many previous studies have a more complex shape and structure than the cylindrical crystalline nanowire. The surface of the nanowires studied by the research groups cited above was oxidized and/or was in contact with some extraneous materials. Finally, the diameters of the wires in the previous

studies were probably not sufficiently small for a pronounced superconductivity suppression through the proliferation of quantum phase slips [11].

Our central result is the observation of an insulating regime in the oxide-free ultrathin Nb nanowires. The conductance in such insulating wires scales approximately linearly with the temperature. Moreover, the conductance approaches zero if it is extrapolated down to zero temperature. This is in agreement with the theory of quantum phase slips advanced by Zaikin and co-workers [11] which predicts an insulating state at $T = 0$. It should be emphasized also that according to the Zaikin et al. theory [11] the conductance of the wire in the insulating state should be proportional to the temperature to some power. The power is positive and it can be equal to unity or not equal to unity. Thus our observation that the conductance is linearly proportional to the temperature is in agreement with the theoretical predictions [11].

The rapid decline of the wire conductance with cooling, observed in Nb nanowires, is qualitatively different from normal, i.e., non-superconducting metals. The behavior of platinum nanowires which have been formed in the exact same manner demonstrates this conclusion very clear. It is important that superconductor-insulator transition was observed only for very thin nanowires - for twice as thick superconducting wires of lead-indium alloy such effect is absent. Our results clearly show that the insulating regime on thin superconducting wires can occur even if the surface is perfectly clean and not oxidized.

To confidently discard other, different from quantum phase slips, possible causes of the observed insulating behavior in Nb, let us analyze them in more detail. One possible line of argument could be to say that the superconductivity on the Nb wires is suppressed due to the magnetic spins present on the surface of the Nb wires, similar to the magnetic spins found in other experiments. Then one can claim that once the superconductivity is suppressed the resistance might increase due to Anderson localization of the electrons. Yet, as explained above, the localization physics is ruled out by the experiment on Pt nanowires, which actually have even smaller diameters than our Nb nanowires but they do not show any significant growth of the resistance with cooling.

Now let us discuss the magnetic spins. The first obvious step to avoid unpaired spins is to make the wire very pure. Thus high purity Nb was chosen as the target material. Yet this is not enough. As was shown in a couple of previous publications, unpaired spins can occur on the surface due to the oxidation of nanowires. Again, in our present experiment this issue is reliably eliminated since absolutely no oxidation can occur in the liquid helium environment. Thus we

conclude that unpaired spins cannot be the pair-breakers in our Nb nanowires and cannot be responsible for the observed insulating regime.

Yet one more potentially possible explanation for the destruction of superconductivity is the fermionic mechanism. It was shown previously that due to disordering the electron-electron Coulomb repulsion can be enhanced in nanowires. Thus the critical temperature should be suppressed. Although the existing theory, strictly speaking, is applicable only when the T_c suppression is low [10], it seems possible to suggest that further reduction of the wire diameter can lead to a complete suppression of the T_c to zero. Yet, even if this happens, there is no obvious reason why the conductance of the wire should show a non-fermionic and non-weak-localization behavior, such as the observed linear proportionality of the wire conductance and the temperature, $G \sim T$. Normal metals are supposed to show a much weaker temperature dependence [29], $G(T)=G_0-C(Ll/L)$ where G_0 is the conductance without weak localization, C is some constant, L_l is the phase coherence length and L is the wire length. Since the phase coherence length $L_l \sim l/T^{1/3}$ is expected to diverge at low temperatures, the conductance should decrease with cooling. Yet the effect is usually just a small correction since the coherence length L_l cannot be very large at temperatures above 1 K and in very thin wires. Thus the weak localization theory cannot account for the observed giant increase of the Nb wire resistance with cooling, in which the conductance approaches zero linearly. Another argument against weak localization is that if it would be the cause of the conductance suppression proportional to the temperature, $G \sim T$, then it should be even more pronounced in Pt wires since they are thinner. Yet this is not the case. Note also that the shape of the $R(T)$ curve suggest that there is a superconducting transition at $T \sim 4$ K in our web of Nb nanowires. This fact is in direct contradiction with the supposed complete suppression of the critical temperature to zero, made above. So we conclude that the fermionic mechanism¹⁰ is not responsible for the observed divergence of the Nb wires resistance.

Finally we see only one plausible explanation for the observed divergence of the resistance of the Nb nanowire with cooling. It is provided by the theory of quantum phase slips [11]. In this theory a superconducting to insulator transition is expected to occur. The critical point is expected to be controlled by the diameter of the nanowire. The critical diameter is estimated to be a few nanometers. The resistance is predicted to diverge in the insulating phase according to a power law, $R \sim T^{-\alpha}$. These predictions are in agreement with our results on Nb wires. In our case $\alpha = 1$.

Conclusions

Finally, the main result is the following. Thin nanowires of a pure superconducting metal, niobium, undergoes the phase transition to an insulator at $T = 0$. At the same time, pure normal metal nanowires, i.e., our Pt nanowires, remain metallic at $T \rightarrow 0$, and this is regardless the fact that their diameters are by $\sim 25\%$ smaller on average than the diameters of our Nb nanowires. The superconducting transition in a thin niobium nanowire has been found to be distorted and strongly shifted towards lower temperatures. At the same time the nanowires made of the superconducting lead-indium alloy, having twice the diameter and similar values of T_c , display the superconducting transition neither distorted nor shifted in temperature. Thus we have confirmed that even in the wires free from the surface oxide the insulating behavior is possible, providing additional strong evidence in favor of the quantum phase slips theory [11].

Another important for the traditional direction of our group result is the production of thin nanoweb from refractory niobium, which should be a promising and potent catalyst in various chemical reactions. These expectations are based on the well-established fact that niobium nanoparticles are excellent catalysts [30-32].

Acknowledgment

This work was supported by the Russian Science Foundation (RSF), Project #14-13-00574. A.B. acknowledges support from the NSF grant No. ECCS-14-08558. E.B.G. acknowledges support from RFBR, Project #13-03-00788.

References

- [1] M. Haruta, N. Yamada, T. Kobayashi, S. Iuima, J. Catal. 115 (1989) 301.
- [2] A.T. Bell, Science 299 (2003) 1688.
- [3] A. Salehi-Khojin, H.-R.M. Jhong, B.A. Rosen, W.Zhu, S. Ma, P.J.A. Kenis, R.I. Masel, J. Phys. Chem. C 117 (2013) 1627.
- [4] W.A. Little, Phys. Rev. 156 (1967) 396.
- [5] N. Giordano, Phys. Rev. Lett. 61 (1988) 2137.
- [6] A. Bezryadin, C.N. Lau, M. Tinkham, Nature 404 (2000) 971.
- [7] A. Bezryadin, Superconductivity in Nanowires: Fabrication and Quantum Transport, Wiley-VCH, 282 pages, 2012.
- [8] K.Yu. Arutyunov, D.S. Golubev, A.D. Zaikin, Phys. Rep. 464 (2008) 1.

- [9] F. Altomare, A.M. Chang, One-Dimensional Superconductivity in Nanowires, Wiley-VCH, 240 pages, 2012.
- [10] Y. Oreg, A. M. Finkelstein, Phys. Rev. Lett. 83 (1999), 191.
- [11] A.D. Zaikin, D.S. Golubev, A. van Otterlo, G.T. Zimanyi, Phys. Rev. Lett. 78 (1997) 1552.
- [12] A. Bezryadin, J. Phys. Condens. Matter 76 (2008) 043202.
- [13] M. Sahu, M.-H. Bae, A. Rogachev, D. Pekker, T.-C. Wei, N. Shah, P.M. Goldbart, A. Bezryadin, Nat. Phys. 5 (2009) 503.
- [14] O.V. Astafiev, L.B. Ioffe, S. Kafanov, Yu.A. Pashkin, K.Yu. Arutyunov, D. Shahar, O. Cohen, S. Tsai, Nature 484 (2012) 355.
- [15] A.A. Abrikosov, L.P. Gor'kov, Zh. Sov. Phys. JETP 12 (1961) 1243.
- [16] A. Rogachev, T.-C. Wei, D. Pekker, A.T. Bollinger, P.M. Goldbart, A. Bezryadin Phys. Rev. Lett. 97 (2006) 137001.
- [17] E.B. Gordon, A.V. Karabulin, V.I. Matyushenko, V.D. Sizov, I.I. Khodos, J. Exp. Theor. Phys. 112 (2011) 1061.
- [18] E.B. Gordon, A.V. Karabulin, V.I. Matyushenko, V.D. Sizov, I.I. Khodos, Chem. Phys. Lett. 64 (2012) 519.
- [19] E.B. Gordon, A.V. Karabulin, V.I. Matyushenko, V.D. Sizov, I.I. Khodos, Appl. Phys. Lett. 101 (2012), 052605.
- [20] E.B. Gordon, A.V. Karabulin, A.A. Morozov, V.I. Matyushenko, V.D. Sizov, I.I. Khodos, J. Phys. Chem. Lett. 5 (2014) 1072.
- [21] J.P. Nabot, I. Ansara in: "Phase Diagrams of Indium Alloys and Their Engineering Applications", C.E.T. White, H. Okamoto (eds.), Indium Corporation of America, Utica, N.Y., and Materials Information Soc., Materials Park, Ohio, 1992.
- [22] A. Rogachev, A. Bezryadin, Appl. Phys. Lett. 3 (2003) 512.
- [23] G. Brändli, F.D. Enck, R. Griessen, Helvetica Physica Acta 44 (1971) 784
- [24] J. Aspeling, C.S.B. Piani, Phys. Lett. A 68 (1978) 101.
- [25] G.C. Tettamanzi, C.I. Pakes, A. Potenza, S. Rubanov, C.H. Marrows, S. Prawer, Nanotechnology 20 (2009) 465302.
- [26] A. Engel, Nanotechnology 21 (2010) 168001.
- [27] G.C. Tettamanzi, C.I. Pakes, A. Potenza, S. Rubanov, C.H. Marrows, S. Prawer, Nanotechnology 21 (2010) 168002.
- [28] M. Trezza, C. Cirillo, P. Sabatino, G. Carapella, S.L. Prischepa, C. Attanasio, Appl. Phys. Lett 103 (2013) 252601.

- [29] C.W.J. Beenakker, H. van Houten, Phys. Rev. B 38 (1988) 3232.
- [30] M. Ziolek, Catalysis Today 78 (2003) 47.
- [31] K. Tanabe, Catalysis Today 78 (2003) 65.
- [32] I.E. Wachs, J.-M. Jehng, G. Deo, H. Hu, N. Arora, Catalysis Today 28 (1996) 199.

Laser ablation in superfluid helium allows producing thin nanowires of any metal.

Nb nanowires, about 4 nm in diameter, form in the cores of superfluid vortices

Our oxide-free Nb nanowires exhibit a quantum superconductor-to-insulator transition.

The insulating behavior in Nb wires is explained in terms of quantum phase slips.

Such nanowires can be used in superconducting phase-slip qubits and transistors.