Epitaxial interfaces between superconductors and semiconductors

- P. Krogstrup, N. L. B. Ziino, W. Chang, S. M. Albrecht, M. H. Madsen, E. Johnson, J. Nygard, C. M. Marcus and T. S. Jespersen, *Epitaxy of SemiconductorSuperconductor nanowires* arXiv 1411.6254, Nature Materials
- W. Chang, S. M. Albrecht, T. S. Jespersen, F. Kuemmeth, P. Krogstrup, J. Nygard, and C. M. Marcus, *Hard Gap in Epitaxial Superconductor-Semiconductor Nanowires*, arXiv 1411.6255, Nature Nanotechnology

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Condensed matter physics is heavily dependent on the discovery of new materials, but also on new developments in materials control. A tremendously successful story is the Si/SiO_2 interface, which was driven by the desire to use the field-effect transistor, and also led to the discovery of the Quantum Hall effect. Similarly, the "Great Crystallographic Accident" of the near identical lattice constants of GaAs and AlAs, led to materials-possibilities enabling quantum well lasers and together with modulation-doping to further studies of the Quantum Hall effect and the discovery of the Fractional Quantum Hall effect. The key word became epitaxial growth and molecular beam epitaxy.

In comparison, the materials control of superconducting device-structures is immature. The discovery of superconductive tunneling by Giaever in 1960 was based on thermal oxidation of aluminum, not very different from the technology now used for quantum computation. Major innovations in materials control are very much driven by genuine industrial interest. This happened with the Josephson-computer in the 60-ies and 70-ies, leading to the discovery of the niobium tri-layer technology[1, 2], which uses very effectively the superconducting proximity-effect between niobium and aluminum[3], and in use in many practical applications. Nevertheless it uses polycrystalline and amorphous materials.

In principle, taking the heterogeneous semiconductors as a yardstick, it would be ideal to have an epitaxial technology available for superconducting devices. Unfortunately, after the demise of the Josephson digital computer in the early 80-ies, the subsequent applications pressure did not have the strength to fuel investments in materials control. In contrast, such a development has occurred with magnetic tunnel junctions, discovered in 1995, after which materials-experts were drawn into the field leading towards epitaxial tunnel barriers[5] of MgO(001) between Fe(001) layers. Interestingly, it shows to the best of my knowledge for the first time the exponential dependence of the tunnel resistance on thicknesses. By changing the thickness of the MgO from 1 nm to 3 nm the resistance for a unit area changes by 6 orders of magnitudes. Such a nice textbook dependence is normally absent in tunnel-experiments, due to the emergence of a lateral variation in tunnel-transmission. For superconductive tunneling, which is also much more sensitive to spatial variations, such a systematic exponential dependence has never been observed.

In the past 10 to 15 years superconducting hetero- and nano-hybrids have moved to center stage. They combine a semiconducting conductor with superconducting electrodes, or they use a nano-object contacted with a superconductor. In both cases the superconducting proximity-effect, or, microscopically, the Andreev reflection plays a key role. The challenge is to understand and control the interface between a superconductor and the nano-object, such as graphene and carbon nanotubes, or the semiconductor. These interfaces are at the heart of the search for zero-energy states and the associated topological superconductivity. In the absence of a strong push from a technological application exploratory-minded physicists are now forced to make the step to develop their own materials control to a level, previously only known from semiconductor physics. Obviously, this creates also a methodological risk of reaching too soon for the physics, while the materials control is not yet in sight.

The present challenge is to make epitaxial interfaces between a superconductor and a semiconductor. Early approaches relied on the well-studied and well-developed metal-semiconductor contact technology. One version was $CoSi_2$ on $Si(111)$. $CoSi_2$ is the first known metal-alloy, with an atom with a magnetic moment, which becomes superconducting[7]. It has a relatively convenient T_c of about 1.4 K. At the same time the silicides have been studied extensively as epitaxial model-interfaces to understand the Schottky-barriers[8]. Badoz et al[9] studied the superconducting properties of these epitaxial $CoSi_2$ thin films, whereas Hilbrandie et al[10] developed a Josephson-junction with heavily doped silicon as the weak link between two $CoSi_2$ films made by rapid thermal annealing. The more common superconductor lead (Pb) has been used in an epitaxial way with silicon by Heslinga et al[11]. From the point of view of superconducting devices these results were of very limited interest. However, the very important contribution has been the insight into the formation of the Schottky barrier. It has become abundantly clear that the Schottky barriers depend very strongly on the local atomic arrangement at the metal-semiconductor interfaces. It has led to extensive modeling of the Schottky-barriers as reviewed recently by Tung[12]. An important concept for the contact between a metal and a semiconductor is a so-called Interface-specific region (ISR). The ISR is unique for different arrangements of atoms and may contain the statistical distribution over the area of the interface or contact edge. It unavoidably enters a proper description of the Schottky barriers. Unfortunately the ISR is not universal, which makes it a nuisance in interpreting experiments, but critically for understanding the interface-properties.

The two new papers highlighted here focus on an epitaxial metal-semiconductor contact, specifically aluminum and InAs. They are clearly superior in comparison to older work on interfaces between superconductors and semiconductors. In addition they use an InAs surface, which is known to have a 'negative' Schottky barrier *i.e.* no barrier for electron transport. The phenomenon, which drives this experimental work, is the proximity-effect or the process of Andreev reflection at the interface and the pair-correlation in the InAs. With these experiments we are at the threshold of a very much needed systematic control and analysis of the superconductor-semiconductor interface.

In the paper by Krogstrup et al the *in situ* growth of aluminum on InAs nanowires is reported. A recipe is developed to grow InAs wires in MBE conditions followed by coverage of the wires by aluminum, partially or on all sides. Subsequently in a number of *ex situ* processing-steps such as lithography, chemical etching, ion milling and deposition, devices are made to determine the electrical properties of the interfaces. As usual with superconducting nano-hybrids the proof of the pudding is in the eating: electrical transport measurements. They serve two roles. The preparation of the device is focused on getting or removing the atoms at certain positions of the material. Only the electrical measurements are capable of revealing what one has actually made from a transport-perspective. But the electrical transport-measurements should also provide the information on the physics that one would like to discover or identify. At the current level of materials control for superconducting nano-hybrids this "signal-to-noise ratio", makes the "noise" most of the time a very important "signal" in order to determine what one has accomplished in the clean room.

The present papers are making a one-to-one correspondence between devices made by *in situ* growth of the aluminum on InAs in an UHV-MBE system, what they label 'epi', and *ex situ* evaporated aluminum on separately grown InAs wires, labeled 'evap'. Upon closer inspection there are more differences. The *ex situ* samples have to be exposed to air, which may lead to oxidation on the surface, which is then, hopefully, removed prior to evaporating aluminum in a conventional evaporator by a 'modest ion milling'. Its influence on the mobility and carrier density has been documented before by Magnée et al[13]. The consequence is that in the 'evaporated' devices an interfacial layer may exist and the surface of the InAs may have electrically active defects, both will contribute to the 'induced superconductivity'.

The central claim of the 2nd paper is that a quantum point contact with tunable transmission, due to the back gate, is used to probe the spectral density of the superconducting correlations in the InAs induced by the neighboring aluminum. There are two questions to be answered. 1; Why do the authors claim that the electrical transport is limited by a gate-tunable quantum point contact, which then can serve as a spectroscopic tool of the 'induced superconducting gap'. 2; Furthermore what is the evidence to call the spectroscopic pattern an 'induced gap', more precisely a 'hard gap' induced in the InAs, as known from standard BCS superconductors, to be compared to a 'soft gap', which is a convenient shorthand for an apparent non-textbook BCS density of states.

In principle the claim is that the experiment should be interpreted as an N-S point contact tunneling experiment. The N-part is a Au/Ti layer on pre-sputtered InAs, contacted by an uncovered piece of InAs, going over to a piece which is covered on all sides by epitaxial aluminum, which in a separate step is connected to an aluminum contact. To the first question I see two answers. Most of the wire is covered by a normal metal or by a superconductor and there is only one section of InAs, which is uncovered. Such a configuration makes it likely that the effect of the back-gate voltage is strongest on the short uncovered part (Note that the side-gate in Fig. 1b,d is not used in the experiment). The experimental proof that this piece is acting as a tunnel-barrier is contained in Fig.2d. It shows that the zero-voltage conductance scales with the square of the normal-state conductance as expected for the 2nd order nature of an Andreev-process. These data have been taken at the -12 to -10 voltage range of the back-gate. In Fig.2e they show some data slightly reminiscent of conductance steps but in a regime of back-gate voltages very far away from the range used in Fig.2d (and can be ignored for this argument).

The 2nd question is about the actual interpretation of the data as an 'induced gap' which is 'hard'. In principle, if the above is true, the results can be compared to an experiment carried out by Wolz et al[14]. A bilayer of a normal metal and a superconductor is studied with an STM used as a tunnel-probe. There are two differences: 1; the STM-probe is measuring exclusively the normal metal film, and therefore it is a measure of the induced superconducting density of states at the surface of the normal metal film, and 2; the materials are in the diffusive limit, meaning that the superconducting density of states is an impurity-averaged quantity. In the experiment reported by Chang et al, where the transport is primarily ballistic, it is a bit confusing to call the spectral information an 'induced gap'. It may easily be confused with a local density of states. In that sense a consistent interpretation in the range from -12 to -10 gate-voltage does not mean that the results, with their interpretation, can be carried over to the full back-gate voltage range from -10 V to +12 V. Nevertheless, it is striking that over the full range of back-gate voltages a peak in the conductance remains visible at the same location, which is most likely the aluminum gap itself. The spectral properties entering the voltage-dependent source-drain conductance are controlled by the full scattering environment, which in this case is changed by the back-gate and also by the opening up of the tunnel-contact. A detailed analysis of this part of the experiment, would need concepts such as used, for example, by Fagas et al[15], aided by more information about the experimental system.

In summary, the important step forward reported by Krogstrup et al and Chang et al is technological: the use of a clean, *in situ*, deposition of the superconductor on the surface of the semiconductor nanowires without the need to expose the surface to air and the need to apply an ion-milling step to 'clean' the surface. In addition, the spectroscopic demonstration that this step is beneficial for the electronic properties. These experiments on InAs wires will also be a very helpful stepping stone in combination with the recent developments in the growth of InAs/GaSb heterostructures[16].

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