Preparation of transparent Nb/two-dimensional electron gas contacts by using electron cyclotron resonance plasma cleaning

Th. Schäpers,[a)] R. P. Müller, G. Crecelius, H. Hardtdegen, and H. Lüth
Institut für Schicht- und Ionentechnik, Forschungszentrum Jülich GmbH, 52425 Jülich, Germany

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The effect of electron cyclotron resonance plasma cleaning on the contact resistance between a superconducting Nb layer and a two-dimensional electron gas in a strained $In_xGa_{1-x}As/InP$ heterostructure is investigated. Cleaning by a He/H plasma results in a rough semiconductor surface and a high interface resistance. In contrast, by using a pure He plasma a smooth semiconductor surface with a considerably lower interface resistance is obtained. © *2000 American Institute of Physics.* [S0021-8979(00)10119-7]

Initiated by the discovery of novel quantum effects, e.g., the quantized supercurrent or Fabry–Pérot-interference effects,[1,2] superconductor/semiconductor hybrid structures have attracted considerable interest recently. In order to observe these effects a two-dimensional electron gas (2DEG) in a semiconductor heterostructure is used because of its high mobility. The latter property ensures that the quantum effects are not destroyed by scattering processes. With regard to a maximum mobility a 2DEG in an AlGaAs/GaAs heterostructure is the material system of choice.[3] However, the high Schottky barrier at the superconductor/semiconductor interface hinders carrier transfer through the interface. A better material system in this respect is an InAs-based heterostructure, i.e., AlGaAs/InAs/InP, AlGaSb/InAs or a pseudomorphic $In_xGa_{1-x}As/InP$ layer system.[4–6]

In heterostructure systems the channel layer is usually covered by a cap layer. The first possible way to contact the superconductor to this channel layer is to remove only the cap layer in order to deposit the superconductor layer, e.g., a niobium layer, directly on top.[5,7] The second choice, which leads to a better geometrical definition of the structure, is to etch the semiconductor beyond the channel layer and to contact the superconductor layer at the side wall of the mesa.[6,8] However, for most sample fabrication procedures the geometry of the semiconductor structure is defined *ex situ* before the superconductor layer is deposited. Therefore, a cleaning procedure prior to the deposition of the superconductor is necessary, since the coupling of the superconductor to the semiconductor is strongly suppressed by surface contamination. A well-established cleaning method is Ar^+ sputtering, where residual molecules and oxides at the surface are removed by the bombardment of Ar^+ ions. However, a serious drawback of the Ar^+ sputtering technique is that the semiconductor surface is deteriorated by the impact of heavy Ar^+ ions.[9]

In this communication a different approach for the fabrication of superconductor/2DEG hybrid structures is presented. Based on the well-established cleaning method prior to the re-growth of semiconductor layers by molecular beam epitaxy an electron cyclotron resonance (ECR) plasma source is employed for the cleaning of the semiconductor layers.[10–12] In most cases a hydrogen plasma is used, which removes surface oxides, hydrocarbons and other contaminants. However, it was shown for phosphorus-based III–V semiconductors, i.e., InP, that a hydrogen ECR plasma can lead to a group III enriched surface due to the formation of P hydrids.[12] In order to weaken this effect a mixture of He/H or even pure He is used in our experiments. We will show that in particular by using a He plasma very transparent Nb/2DEG interfaces can be prepared. In our structures the 2DEG is located in a strained $In_xGa_{1-x}As/InP$ layer system.

For the cleaning procedure a WAVEMAT MPDR 610 ECR source operating at 2.45 GHz was employed. As gas sources either a mixture of He/H (50:50) or pure He was used. All cleaning procedures were carried out in an ultrahigh vacuum (UHV) chamber at room temperature.

The effect of the ECR plasma on the surface morphology was investigated by using an atomic force microscope (AFM). Since InP is known to be the less stable material the surface of a semi-insulating InP wafer was exposed to the plasma. InP is used as the lower barrier for the 2DEG located in the strained $In_{0.77}Ga_{0.23}As$ layer. Damage of the InP at the surface is expected to have a strong effect on the property of this barrier and will thus deteriorate the 2DEG. In order to investigate the transparency of the interface between the superconductor and the semiconductor an $In_{0.53}Ga_{0.47}As/In_{0.77}Ga_{0.23}As/InP$ heterostructure was grown by metalorganic vapor phase epitaxy. The layer system consists of a 350-nm-thick InP buffer layer followed by a 10-nm-thick dopant layer ($n_D = 7\times10^{17}$ cm^{-3}) and a 20-nm-thick InP spacer layer. Subsequently, a strained 10-nm-thick $In_{0.77}Ga_{0.23}As$ channel layer was grown. The layer system is finally capped by a 115-nm-thick $In_{0.53}Ga_{0.47}As$ layer lattice matched to InP. Shubnikov–de Haas measurements at 0.6 K revealed a sheet electron concentration of 7.68×10^{11} cm^{-2} and a mobility of 363 600 cm^2/V s.

The Nb/2DEG contacts are fabricated by first preparing Au:Ge ohmic contacts to the channel layer. Subsequently, the mesa is defined by reactive ion etching (RIE) using CH_4/H_2. Before the sample is covered completely by a 100-nm-thick Nb layer the surface is cleaned by the ECR-plasma.

a)Electronic mail: th.schaepers@fz-juelich.de

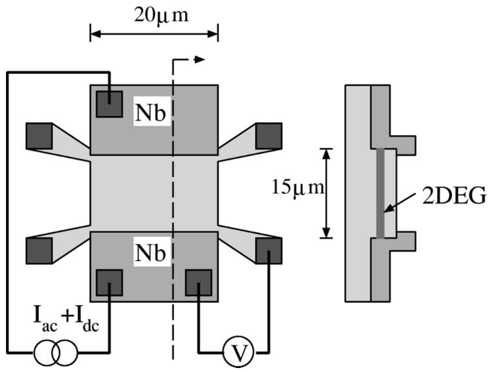

FIG. 1. Schematic of the sample layout. The two-dimensional electron gas is contacted to the Nb layer at the side wall of the mesa.

The Nb layer is deposited *in situ* in the UHV chamber. The geometry of the Nb pads is finally defined by a SF_6 RIE process. A schematic of the sample layout and measurement configuration is shown in Fig. 1. The width of the contact is 20 μm. The electrical measurements are performed in a He-3 cryostat.

The effect of the ECR-plasma cleaning procedure on the morphology of a InP surface is shown in Fig. 2. As mentioned above, it is known from preceding studies that InP is susceptible to losing its phosphorus component during exposure to a hydrogen plasma.[10,12] In order to weaken or even suppress this unwanted effect, chemically inert helium gas was added to hydrogen (50:50). Using this gas mixture the InP wafer was exposed for 30 min to an ECR plasma with a microwave power of 200 W at a chamber pressure of 2.8×10^{-4} mbar. However, the resulting surface topology measured by an AFM reveals the formation of droplets with a size of the order of 50 nm [see Fig. 2(a)]. Even reducing the plasma exposure time to 10 min, with the aim of reducing the surface damage, leads to a similar morphology. Our results show the same effect as that reported in the studies on InP surfaces exposed to a pure H plasma.[10,12] Here, the exposure of an InP surface to hydrogen led to the formation of volatile PH_3 and to an indium rich surface covered with In droplets.

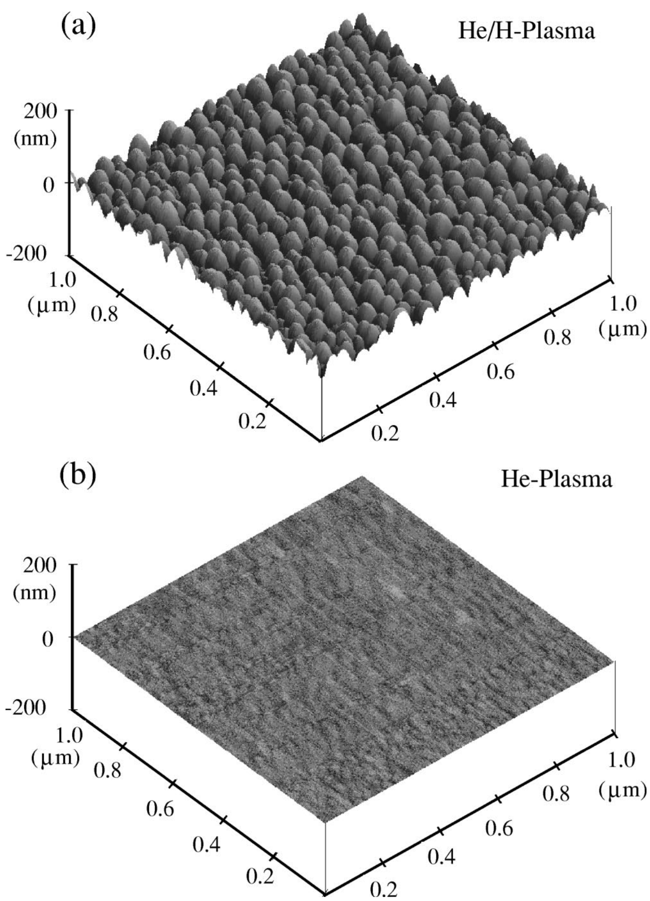

FIG. 2. (a) Atomic force microscopy picture of an InP surface treated by a He/H ECR plasma. The effect of He plasma is shown in (b).

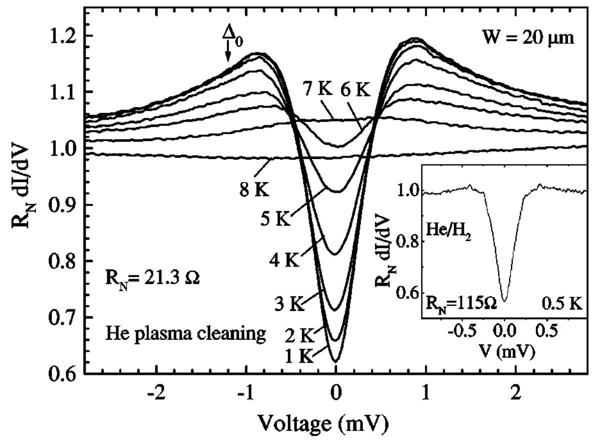

FIG. 3. Normalized differential conductance at various temperatures as a function of the voltage drop at the Nb/2DEG interface. The sample was cleaned by a He plasma. The inset shows the differential conductance for a He/H plasma cleaned sample.

The formation of indium droplets is prevented if pure He gas is used for the plasma source [Fig. 2(b)]. Here, a process pressure of 2×10^{-4} mbar with a microwave power of 250 W was used. The exposure time was 60 min in this case. The AFM picture shows that the InP surface remains smooth after the He-plasma treatment. In contrast to hydrogen, helium does not chemically react with the InP surface. The only possible mechanism is a sputtering effect of the accelerated He ions. However, in contrast to Ar^+ sputtering[6] as a cleaning method no indium droplets are formed at the surface due to the lower impact of the lighter helium ions.

The quality of surface morphology alone does not guarantee a sufficiently high transparency of the Nb/2DEG interface. Therefore, the electronic properties of Nb/2DEG structures cleaned by the ECR plasma were investigated, in addition. The normalized differential conductance $R_N dI/dV$ as a function of the voltage drop for a sample cleaned for 30 min by a He/H plasma is plotted in Fig. 3 (inset). Here, the microwave power was set to 200 W and chamber pressure was kept at 3.4×10^{-4} mbar. The normal state resistance R_N measured at bias voltages well above the superconducting gap had a value of 115 Ω at 0.5 K. The Nb layer for this sample had a critical temperature of $T_c = 7.5$ K leading to a gap of $\Delta_0 = 1.1$ meV. Several Nb/2DEG interfaces prepared in the same run were measured. All resistances were found to be between 115 and 200 Ω. Additional experiments on samples exposed for a shorter duration to the He/H plasma showed in general resistances above 200 Ω.

The differential conductance plotted in Fig. 3 (inset) shows a characteristic minimum at zero bias voltage. This feature can qualitatively be explained by the Blonder–Tinkham–Klapwijk (BTK) model where the transport through the superconductor/normal conductor interface is described by normal and Andreev reflection processes.[13] In the latter mechanism the electron is retroreflected as a hole, while a Cooper pair is formed in the superconductor.[14] Usually the Nb/2DEG interface is not ideal in the sense that surface contaminants and oxides lead to a barrier at the interface. Due to this barrier normal reflection of an incoming electron occurs, which is a detrimental process to the resistance, lowering by Andreev reflection. The barrier strength can be characterized by the dimensionless Z parameter, which is related to the barrier transparency by $D=1/\sqrt{1+Z^2}$. In a 2DEG/superconductor system the large Fermi velocity mismatch $r=v_{F,\mathrm{2DEG}}/v_{F,S}$ between the 2DEG and the superconductor is connected to an additional potential step at the interface. This step leads to an essentially larger Z factor which is given by $Z_{\mathrm{eff}}=\sqrt{Z^2+(1-r^2)/4r}=\sqrt{Z^2+Z_0^2}$.[15] Here, Z_0 represents the Z factor due to the potential step.

According to the BTK model a low Z_{eff} of 0.85 was determined from the zero bias value of $R_N dI/dV$ of the He/H plasma cleaned sample shown in Fig. 3 (inset). For our material system the Fermi velocity mismatch ($r=0.46$) leads to $Z_0=0.65$ resulting in $Z=0.55$ originating from surface contaminants and oxides. The low Z_{eff} value reflects the large Andreev contribution to the transport. With regard to the BTK model the lowering of the differential conductance should extend up to a bias voltage of $\pm\Delta_0/e$. In our measurement the width of the minimum is smaller. The He/H plasma cleaning leads to the damaged semiconductor surface as well as to the enhanced In concentration at the surface. This can be described by introducing an additional interlayer between the Nb and the 2DEG. As shown by Neurohr *et al.*[6] additional layers at the interface affect the shape of the differential conductance strongly and thus lead to deviation from ideal BTK behavior.

The normalized differential conductance versus bias voltage of a sample cleaned by a He plasma is plotted in Fig. 3 for different temperatures. For this structure a microwave power of 250 W at a pressure of 8×10^{-5} mbar was used. The semiconductor surface was cleaned for 120 min before the Nb layer was deposited. This sample has a considerably lower normal state resistance of 21.3 Ω compared to the He/H plasma cleaned structures. All other interfaces prepared in the same run show a value close to this value (21.3±2 Ω). Samples cleaned for a shorter duration of 25 min reveal larger interface resistance of the order of 100 Ω. From the zero bias value of $R_N dI/dV$, shown in Fig. 3, $Z_{\mathrm{eff}}=0.8$ is extracted resulting in $Z=0.47$ which is lower than the value for the He/H cleaned samples. The temperature dependence of the zero bias conductance fits well to the prediction of the BTK model. The general shape of the $R_N dI/dV$ vs V curve resembles more the ideal BTK curve: The width of the minimum is close to $2\Delta_0/e$ and enhancement of the differential conductance is found at bias voltages slightly below $|\Delta_0/e|$. The latter feature originates from the enhanced density of states in the superconductor near Δ_0. The occurrence of this maximum clearly indicates that the superconductor is not much affected by the semiconductor surface. The normal resistance of an S/2DEG interface is not only determined by the transparency given by the Z factor but also by the homogeneity of the interface. If a large fraction of the interface is transparent the normal state resistance is expected to be low as observed for the He-cleaned sample. In contrast, the large R_N observed for the He/H plasma cleaned sample indicates that only part of the interface is transparent. This explanation is supported by our AFM studies, showing a rough surface for the He/H treated sample.

In summary, an ECR-plasma cleaning procedure was used to prepare Nb/2DEG contacts. The He/H-plasma treatment leads to a rough semiconductor surface and to a low interface resistance. In contrast to that, the samples cleaned by a pure He plasma showed a much lower interface resistance and no indication of semiconductor surface degradation. A probable explanation might be the chemical etching effect of the atomic H which is missing in a pure He plasma.

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