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Magnetoresistance of a lateral contact to a two-dimensional electron gas

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Abstract

Lateral Nb contacts to a high-mobility two-dimensional electron gas (2DEG) in InGaAs heterostructures are studied. Below T_c of Nb a pronounced non-linearity due to the superconducting energy gap is observed in the differential resistance. The Nb/2DEG interface reveals an enhanced zero-bias resistance. In normal state, a drastic decrease of the resistance with increasing magnetic field perpendicular to the plane of the structure is observed. It is explained in terms of a confinement of electron trajectories near the interface with increasing magnetic field yielding an enhanced number of transmitted carriers. The suggested model shows good agreement with experiment. We conclude that the magnetic field strongly influences the effective conductance of weakly transparent contacts.

A highly transmissive ohmic contact of a 3D metal to a two-dimensional electron gas (2DEG) is usually considered as a thermal reservoir acting as an electronic "black body" [1]: all incident electrons are absorbed by the contact. In high enough magnetic field, a 2DEG is conceptually divided into the regions of nondissipative transport (such as the Landau states in the bulk and the edge states near the boundaries) and the contact regions where electrons are completely thermalized. Due to the difficulty of realizing well-defined edge contacts with a finite transparency, the crossover between these two regimes has not yet been identified in experiments. For diffusive regions, this problem has been recently addressed by Geim et al [2].

Recently, contacts between superconductors and 2DEG attracted much interest [3–7]. In contrast to the cited papers, here we study well-defined *lateral* niobium contacts to high-mobility InGaAs heterostructures (Fig. 1). We investigate the *I–V* characteristics in the superconducting and the normal state, as well as the contact magnetoresistance in normal state. A strong decrease of the boundary resistance with magnetic field is observed. Such a negative magnetoresistance is known to exist in ballistic constrictions [8], where it is attributed to a reduction of backscattering by the magnetic field. In that case the magnetic field suppresses the geometrical constriction resistance in the ballistic regime. The lateral Nb-2DEG contacts studied in the present paper are no geometrical constrictions in the 2DEG plane but heterocontacts with a potential barrier located at a sharp interface.

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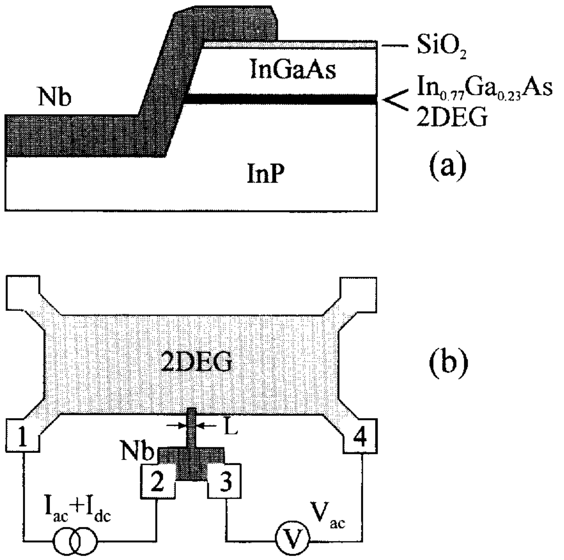

Fig. 1. (a) Schematic cross section of the investigated lateral contact to the two-dimensional electron gas layer and (b) top view of the sample layout.

Therefore, a reduction of backscattering by magnetic field cannot completely explain the observed negative magnetoresistance. We will show that for a hetero-contact an additional mechanism for this negative magnetoresistance is provided by multiple collisions of ballistic electrons with the contact.

Experiments have been performed with InGaAs/InP heterostructures schematically shown in Fig. 1. The 2DEG is formed in a strained $In_{0.77}Ga_{0.23}As$ conduction channel [9, 10]. The In-rich layer allows to obtain a very low Schottky barrier and a vanishing depletion region at the boundary [10, 11]. The conduction channel is placed under a 150 nm thick $In_{0.53}Ga_{0.47}As$ barrier layer. The top surface of the structure has been covered with an insulating layer of SiO_2. Transport measurements yield a mobility of about 3.7×10^5 $cm^2/(V\,s)$ and a sheet carrier concentration of $n_e = 6 \times 10^{11}$ cm^{-2} in the first subband. Lateral contacts to the 10 nm-thick $In_{0.77}Ga_{0.23}As$ layer were prepared by etching the heterostructure and depositing niobium from the side. Prior to the deposition, the surface was cleaned in situ by Ar sputtering. In Fig. 1(a) the cross section of the contact, and in Fig. 1(b) the sample lay out are shown schematically.

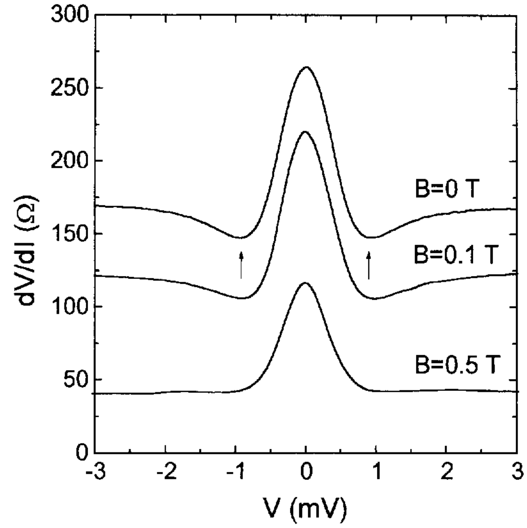

Fig. 2. Differential resistance of a 2.4 μm long contact for various magnetic fields B applied perpendicular to the plane of the 2DEG. The measurements have been carried out at 1.2 K with an AC-current of 100 nA.

The differential resistance of the contacts has been measured in the temperature range between 0.05 and 10 K. A DC-current I_{DC} superimposed by a small AC-current I_{AC} was applied between the contacts 1 and 2 while the AC-voltage drop V_{AC} was detected by lock-in technique between the contacts 3 and 4 [see Fig. 1(b)]. Contacts 2 and 3 made on superconducting Nb had the same potential resulting in a (quasi) 3-terminal measurement configuration.

A pronounced nonlinearity in the differential resistance $R = dV/dI$ of the contacts due to the superconducting energy gap of Nb has been observed below the transition temperature of Nb (about 9 K). The ratio of the zero-bias resistance R_0 to the normal state resistance R_N (measured at high bias above the gap voltage) of about 1.5 indicates the presence of a well-defined barrier at the lateral interface between the 2DEG and niobium. Fig. 2 shows measurements of the resistance versus voltage for a 2.4 μm long Nb contact taken at 1.2 K. Three measured curves at different magnetic fields B applied perpendicular to the plane of the 2DEG are plotted. Increasing the magnetic field from 0 to 0.5 T leads to a strong decrease of the resistance of the contact. It is important to note that not only the zero-bias resistance, but also the normal state resistance is suppressed.

The gap voltages V_{gap} of both polarities indicated by arrows in Fig. 2 are smaller than the Nb bulk gap $\Delta_{Nb} \simeq 1.3$ meV. This can be explained by a thin nonsuperconducting layer which may exist at the Nb/2DEG interface. Additional contribution to the gap suppression is intrinsic and originates from proximity effect between Nb and 2DEG. To account for these effects a generalization of the BTK model [12] has been done recently for the case of N-constriction-N′S structures consisting of a clean normal metal N and a disordered N′S bilayer [13]. In our case, N and N′ denote the normally conducting 2DEG and the nonsuperconducting layer on the surface of Nb, respectively, and S is the Nb film. Both the gap suppression in zero field, and the strong smearing of the conductance maximum at V_{gap} are explained in Ref. [13].

In the following, we concentrate on the discussion of the normal state properties of our contacts. We analyze possible contributions to the measured resistance and develop a model which qualitatively describes its dependence upon the magnetic field.

In order to determine the boundary resistance, the series resistance of the 2DEG has to be excluded from the data. The used 3-terminal measurement configuration contains a Hall contribution of the 2DEG for one magnetic field direction. For this reason, in our measurements we have chosen the opposite field direction without Hall contribution. Except for the Shubnikov de Haas oscillations at high fields, the 2DEG has a specific sheet resistance of about 25 Ω. Thus, at low fields the series resistance of the 2DEG is definitely smaller than the contact resistance. The zero field resistance might be influenced by an asymmetric current distribution in the 2DEG which is changed in small magnetic fields. We investigated this effect by performing measurements with different contact configurations. The relative change of the resistance for $B = 0$ was in all cases less than 20%. Thus, we conclude that the series resistance of the 2DEG plays a minor role here. Further, two-dimensional weak localization could be excluded as a possible reason of the negative magnetoresistance: varying the temperature between 50 mK and 10 K had very little influence on the observed $R(B)$ behavior.

Fig. 3 shows the experimentally measured resistance (points) of a 0.6 μm long contact as a function of the applied magnetic field B. We observe a strong decrease of the resistance with increasing magnetic field. The measurements have been carried out at a temperature of 50 mK with an AC-current of $I_{AC} = 50$ nA. In order to detect solely the normal state resistance variation, a DC-current of $I_{DC} = 5$ μA has been drawn through the Nb-2DEG contact. This current corresponds to a voltage drop at the contact larger than the superconducting gap voltage. At fields above 1 T small Shubnikov de Haas oscillations occur which indicate the influence of the 2DEG measured in series with the contact.

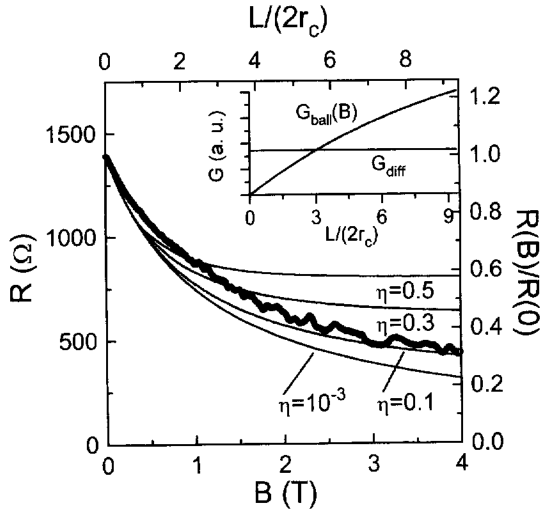

Fig. 3. Normal state resistance of a 0.6 μm long contact (points) as a function of the applied magnetic field. The lines show the calculation results using Eq. (3) for values of the barrier transmission coefficient η indicated in the plot. The inset shows G_{diff} and $G_{ball}(B)$ in arbitrary units.

All electrons in the 2DEG near the Nb-2DEG interface can be explicitly divided into nonequilibrium current-carrying electrons ("effective electrons" EE) [14–16] and those in equilibrium which do not contribute to the current. The ballistic mean free path for electron transport in the considered 2DEG is of the order of the contact length L. Therefore, some of the EE move to the contact ballistically while others are scattered in the vicinity of the interface and give rise to a field-independent, diffusive contribution to the current. For the case of a finite transparency of the interface, $\eta < 1$, relevant for our Nb-2DEG contacts, all EE are partly reflected. Depending on the field strength the ballistic EE may return to the contact

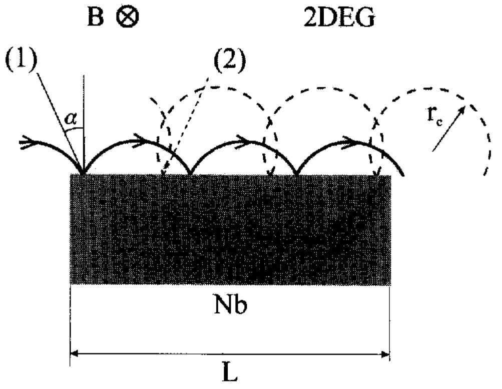

Fig. 4. Ballistic electron trajectories at the tunnel barrier interface in the applied magnetic field B for positive (1) and negative (2) angles α.

following cyclotron orbits and give rise to the observed negative magnetoresistance.

The diffusive contribution to the conductance $G(B)$ is given by a modification of the 2D analogue of Sharvin's formula [8, 14, 16]:

$$G_{\text{diff}} = M\frac{2e^2}{h}\frac{k_{\text{F}}L}{\pi}\int_0^{\pi/2}\cos(\alpha)D(\alpha)\,\mathrm{d}\alpha, \qquad (1)$$

where $M \leqslant 1$ is the fraction of diffusive EE relative to the total number of initial EE; k_{F} denotes the Fermi wave vector of the 2DEG electrons and $D(\alpha)$ is the angle-dependent transmission coefficient which may be approximated by $D(\alpha) \approx \eta\cos(\alpha)$ for $\eta \ll 1$; η depends on the Fermi velocities and the interface barrier strength; α is the angle between the normal to the boundary and the velocity of the electron (see Fig. 4).

To calculate the ballistic contribution $G_{\text{ball}}(B)$ to the conductance we extend the classical analogy to edge state transport namely skipping orbits [17] to very low fields (5 mT). Accordingly, the ballistic EE follow cyclotron orbits with a Larmor radius of $r_{\text{c}} = \hbar k_{\text{F}}/(\text{eB})$. We assume further that these electrons are reflected specularly [18] by the sample edge as well as by the contact, as shown in Fig. 4. The angle distribution of the initial ballistic EE is assumed to be homogeneous within the interval $-\pi/2 < \alpha < \pi/2$.

The number of tunneling attempts n for a ballistic EE depends on the ratio $L/(2r_{\text{c}})$ and directly enters the effective transmission probability $D_{\text{eff}}(\alpha, n) = \sum_{i=1}^{n} D(\alpha)(1 - D(\alpha))^{i-1} \equiv 1 - [1 - D(\alpha)]^n$. Therefore, reducing r_{c} by an increase of the magnetic field leads to an increase of n and consequently of $D_{\text{eff}}(\alpha, n)$. The effective transmission probability has to be averaged over angles and starting points of the ballistic trajectories leading to the following expression for the ballistic contribution to $G(B)$:

$$G_{\text{ball}}(B) = N\frac{2e^2}{h}\frac{k_{\text{F}}L}{\pi}\int_0^{\pi/2}\mathrm{d}\alpha\left\{\cos(\alpha)\frac{1}{s(\alpha)}\right.$$
$$\left.\times\int_0^{s(\alpha)} D_{\text{eff}}\left(\alpha, \text{Int}\left(\frac{L+x}{s(\alpha)}\right)\right)\mathrm{d}x\right\}, \qquad (2)$$

where $\text{Int}(Y)$ denotes the integer part of Y representing the number of tunneling attempts, and $s(\alpha) = 2r_{\text{c}}\cos(\alpha)$ is the distance between two collisions with the boundary. The constant $N \leqslant 1$ defines the relative contribution of G_{diff} and $G_{\text{ball}}(B)$. As the total number of initial modes is given by $k_{\text{F}}L/\pi$, the normalization condition requires $M + N = 1$. A possible field dependence of the coefficients M and N is neglected in the model. This should be considered as the simplest approximation to take into account both contributions to $G(B)$. Therefore, the approach can be compared with experiment only qualitatively.

As follows from Eq. (2), $G_{\text{ball}}(B \to 0)$ vanishes and $G(0)$ can be approximated by G_{diff} [19]. Therefore, the normalized magnetoresistance can be written as

$$\frac{R(B)}{R(0)} = \frac{G(0)}{G(B)} = \frac{G_{\text{diff}}}{G_{\text{ball}}(B) + G_{\text{diff}}}. \qquad (3)$$

In the considered case of strongly different electronic concentrations of the contacting metals the increased transparency which enters $G_{\text{ball}}(B)$ is not compensated by backflow processes from Nb to 2DEG. Since the Larmor radius in Nb is much larger than the contact length and the mean free path in Nb, the electrons in Nb diffuse from the boundary into the bulk. Therefore, they do not give rise to multiple tunneling attempts back into the 2DEG. This means that the backflow current contribution is independent of magnetic field.

The above discussion of increasing $D_{\text{eff}}(\alpha, n)$ by magnetic field in the same way holds for unoccupied states (holes [20]) in the 2DEG: a collision of a hole with the contact interface results in an enhanced probability for an electron to tunnel from Nb to 2DEG. This leads to the symmetry of the magnetoresistance with respect to the polarity of the DC-voltage drop V (Fig. 2).

$R(B)/R(0)$ has been calculated numerically from Eqs. (2) and (3) and is shown in Fig. 3. The upper x-axis is directly related to the magnetic field axis taking the geometrical width $L = 0.6$ µm and the known value $B \times r_c = 0.13$ T µm for our 2DEG. A rather good agreement between experiment and theory can be achieved for the fitting parameters $\eta = 0.1$ and $M/N = 3.4$. The inset shows the corresponding contributions $G_{\rm ball}(B)$ and $G_{\rm diff}$ which add to the total conductance.

For $L/(2r_c) < 1$ the decrease of magnetoresistance is mainly due to the enhancement of the probability for ballistic EE to interact with the contact at all. This effect is comparable to the suppression of backscattering by magnetic field for a geometrical constriction in a 2DEG discussed for the ballistic regime in Ref. [8]. For $L/(2r_c) > 1$ all ballistic EE which do not tunnel at their first attempt have more than one tunneling attempt, further decreasing the magnetoresistance. In the limit of low transparency, $\eta \ll 1$, and for intermediate fields Eq. (2) can be rewritten as

$$G_{\rm ball}(B) = N\frac{2e^2}{h}\frac{k_{\rm F}L}{\pi}\frac{\eta L}{r_c}, \quad 1 \ll \frac{L}{r_c} \ll \eta^{-1} \tag{4}$$

using $1 - [1 - D(\alpha)]^n \approx nD(\alpha)$. This means that $R(B)/R(0)$ becomes independent of η in this field range as it cancels out in Eq. (3). A corresponding curve for $\eta = 10^{-3}$ is also plotted in Fig. 2. At very high fields when $L/r_c \gg \eta^{-1}$ the magnetoresistance starts to saturate at the level $R(B)/R(0) = M\eta/(M\eta + 2N)$ as $D_{\rm eff}(\alpha, n)$ approaches unity.

We measured more than ten contacts of various dimensions (between 0.6 and 100 µm) at different temperatures below and above the critical temperature of Nb. Fair agreement between theory and experiment was found with η values between 0.1 and 0.3.

In summary, we report that Nb contacts to the edge of a high-mobility two-dimensional electron gas in InGaAs heterostructures show the gap structure of Nb and a large negative magnetoresistance. The latter is explained in terms of a confinement of electron trajectories near the contact boundary with increasing magnetic field. The suggested model shows good agreement with experiment and can be used to characterize the contacts.

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