Rashba effect in strained InGaAs/InP quantum wire structures

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Abstract

We investigated the effect of the Rashba spin–orbit coupling in two-dimensional electron gases and quasi one-dimensional wire structures based on a strained InGaAs/InP heterostructure. For the two-dimensional electron gas structure it is demonstrated that the Rashba effect can be controlled by using a gate electrode. By a detailed discussion it is shown that our heterostructure can be employed for a spin transistor based on the Rashba effect [Appl. Phys. Lett. 56 (1990) 665]. The Rashba effect in quantum wire structures is studied by means of magnetotransport measurements. As for the two-dimensional case characteristic beating patterns were found for wire structures having a width down to 600 nm. Our results clearly show that Rashba spin–orbit coupling can directly be observed in quasi one-dimensional structures.

Keywords: Two-dimensional electron gas; InGaAs/InP heterostructure; Rashba effect; Spin–orbit coupling magnetotransport; Quantum wire

1. Introduction

In spintronics the electron spin is employed as a unit of information instead of its charge. This rapidly developing field promises electronic circuits with higher speed and lower power consumption. A well-known example is the spin transistor proposed by Datta and Das [1]. Above that, the additional degree of freedom which is gained by using the spin information can add new functionalities to electronic devices. On a longer time scale, the spin state in solid-state materials might even be crucial to the quantum information technology age.

A successful realization of spintronic circuits depends on the tailoring of appropriate material systems. With respect to semiconductor materials, dilute ferromagnetic semiconductors [2] and semiconductor layer systems showing a large spin–orbit coupling [3–6] are of outmost importance. In this report, we will focus on the latter class of materials and we will show that especially in narrow gap semiconductor heterostructures a large spin-splitting can be achieved by utilizing Rashba spin–orbit coupling [7]. Here, the macroscopic electric field in the confining quantum well of a two-dimensional electron gas (2DEG) structure causes a splitting of the subbands according to

\[
E = E_{\text{sub}} + \frac{\hbar^2 k_{\parallel}^2}{2m^*} \pm \alpha |k_{\parallel}|, \tag{1}
\]

where \(E_{\text{sub}}\) is the confinement energy of the quantum well. The second term represents the kinetic energy of the electrons in the \(xy\) plane of the 2DEG, with \(k_{\parallel}\) the wave vector within the plane and \(m^*\) the effective electron mass. The third term is due to the Rashba effect and leads to the above-mentioned spin-splitting into two subbands. The parameter \(\alpha\) is a measure of the strength of the Rashba spin–orbit coupling. The resulting \(E(k)\) dispersion is schematically shown in Fig. 1. As can be seen here, the Rashba effect leads to an energy splitting of \(\Delta_R = 2\alpha k_{\parallel}\), if a fixed \(k_{\parallel}\) vector is chosen, while for a fixed energy, i.e. the Fermi energy, the Rashba effect results in a difference of the wave vectors, e.g. \(\Delta k_{\parallel}\) in Fig. 1, depending on the two spin orientations. As pointed out by Datta and Das [1], this difference leads to a spin precession if the initial state is constituted by a superposition of both spin eigenstates. In the transistor based on the Rashba effect the spins in the semiconductor are aligned by a ferromagnetic injector electrode (source). While travelling through the semiconductor, the spin precedes owing to the Rashba effect. When the electrons reach the opposite ferromagnetic electrode (drain) they can only enter if the spin orientation...
is aligned parallel to the spins in the drain electrode. The operation of the spin transistor relies on the fact that the spin precession and thus the spin orientation at the drain electrode can be controlled by a gate electrode.

The magnitude of the Rashba effect $\alpha$ is determined by the electric field affecting the electronic state in the two-dimensional electron gas. By a careful design of the heterostructure, concerning the choice of the material system and the layer sequence, a very large spin-splitting can be achieved [8,9]. For the successful implementation of a spin transistor, it is furthermore necessary that the Rashba parameter $\alpha$ can be tuned by a gate electrode. This mechanism has been demonstrated in various material systems [8–13]. However, in order to obtain a sufficiently large signal modulation, it is furthermore necessary that the carrier transport is restricted to a quantum wire structure [1]. In one-dimensional structures the carriers propagate only along one direction, so that signal lowering due to averaging over a wide range of emission angles is suppressed. Only few experimental investigations on the Rashba effect, i.e. the pioneering work of Sato et al. [14] dealt with the experimental realization of wire structures. Concerning theoretical investigations, very recently, a number of publications were devoted to the spin transport properties of one-dimensional systems [15–17].

In this paper we report on our investigations on the Rashba effect in low-dimensional systems. Our studies are based on a strained InGaAs/InP heterostructure. In contrast to many heterojunctions fabricated for investigations on the Rashba effect grown on a GaAs substrate [8,9,18,19], our structures are grown on an InP substrate. We will first demonstrate how the Rashba effect manifests itself in a two-dimensional electron gas containing a strained InGaAs layer as the conducting channel. It will also be shown, that the Rashba coupling constant can be tuned by applying a gate voltage. In the last part, we focus on quantum wire structures. It will be discussed in which manner the additional confinement affects the manifestation of the Rashba effect in magnetotransport measurements.

2. Experimental

Our strained InGaAs/InP layer systems were grown by metal-organic vapor phase epitaxy (MOVPE) on a semi-insulating InP substrate at a temperature of 670 °C. The first three InP layers of our heterostructure consist of a 350 nm thick InP buffer layer, a 10 nm thick InP (Si) n-doped layer, and a 20 nm thick InP spacer layer. The channel layer is formed by a 10 nm thick strained In$_{0.77}$Ga$_{0.23}$As layer which is finally capped by a 150 nm and a 70 nm thick In$_{0.53}$Ga$_{0.47}$As layer for the Hall bar and wire structures, respectively. A schematic illustration of the complete layer sequence with the corresponding conduction band profile is shown in Fig. 2.

A mesa structure was defined by using reactive ion etching (CH$_4$/H$_2$). For the large area Hall bar samples (400 x 200 µm$^2$) optical lithography was employed to
define the geometry of the mesa while electron beam lithography was used for the quantum wire structures (Fig. 3). For the latter, the wire width varied between 400 nm and 1 \( \mu \)m. The length of the wire structure was either 5 or 30 \( \mu \)m. A 30 nm thick Ti layer defined by lift-off served as a mask for the reactive ion etching process. The Hall bar samples were covered by a gate electrode. For gate isolation a 100 nm thick SiO\(_2\) layer was deposited by using plasma-enhanced chemical vapor deposition. A Cr/Au (5 nm/90 nm) layer was used for the gate electrode.

The samples were measured in a He-3/He-4 dilution refrigerator at a temperature of 30 mK and in a He-3 cryostat at temperatures between 0.3 and 1.0 K. Standard a lock-in technique was used for the measurement of the magnetoresistance.

3. Results and discussion

In the first part of this section we will briefly show how the Rashba effect manifests itself in a two-dimensional electron gas and by which means a gate control of the coupling constant is achieved. In the second part we will discuss the case, when the carriers are confined in a quasi one-dimensional wire structure.

3.1. Two-dimensional structures

The resistance \( R_{xx} \) of a two-dimensional electron gas in a InGaAs/InP heterostructure is plotted in Fig. 4 as a function of the magnetic field \( B \) for different voltages applied to the gate electrode. The measurements were performed at a temperature of 30 mK.

The magnetoresistance shows pronounced oscillations due to the Shubnikov–de Haas effect. For the single subband case Shubnikov–de Haas oscillations in \( 1/B \) with only a single frequency are expected, when the frequency is directly proportional to the carrier concentration. However, the measurements shown in Fig. 4 show a characteristic beating pattern, which indicates a superposition of two oscillations with slightly different frequencies. The beating pattern is thus a direct consequence of the Rashba effect, since effectively two subbands are formed, as shown in Fig. 1.

For a more detailed analysis, let us first focus on the measurement corresponding to a gate voltage of +2 V. A total sheet electron concentration of \( n = 8.07 \times 10^{11} \times \text{cm}^{-2} \) was extracted from the average value of the two frequencies of the Shubnikov–de Haas oscillations. By taking the specific conductance into account a mobility of 332 600 cm\(^2\)/V s was determined. This results in an elastic mean free path of \( l_\text{el} = 4.9 \mu \text{m} \).

The electron concentration of the two-dimensional electron gas is gradually depleted by changing the gate voltage towards negative values. At a gate voltage of -2 V the sheet electron concentration \( n \) is reduced by 22% to a value of \( 6.47 \times 10^{11} \text{cm}^{-2} \). The decreased electron concentration also leads to a lower electron mobility of 285 500 cm\(^2\)/V s and to a shorter elastic mean free path of 3.8 \( \mu \)m.

The Rashba coupling constant was extracted for the different gate voltages by analyzing the node sequence of the beating patterns. As can be seen in Fig. 5(a), the coupling constant \( \alpha \) is increased if a more negative gate voltage is applied. At a gate voltage of -10 V a value of \( 5.2 \times 10^{-12} \text{eV m} \) was obtained. This increase can be explained by the fact that for more negative gate voltages the semiconductor becomes increasingly depleted at the metal/semiconductor interface. This leads to an increase of the conduction band energy at the upper side of the quantum well and consequently to a more triangular-like shape of the quantum well potential. As a result the effective electric
field in the quantum well is increased leading to a more pronounced Rashba effect. For completeness the dependence of $\alpha$ on the electron concentration is shown in Fig. 5(b).

We will now briefly discuss if the modulation of the Rashba coupling constant obtained by applying a gate voltage is sufficiently large for the operation of a spin transistor [1]. The requirement for a successful implementation is that the precession angle is altered by $\pi$ so that the spin orientation is reversed. For a fixed coupling constant $\alpha$ the spin precession along a distance $L$ is determined by the difference of the wave vectors $\Delta k_x$ at the Fermi energy. By using Eq. (1) the following equation for the precession angle can be deduced [1]:

$$\theta = \Delta k_x L = 2m^* \alpha L / h^2.$$  

(2)

In order to reverse the spin orientation, the difference in the coupling constant $\Delta \alpha$ by tuning the gate voltage must be so large that the difference in the precession angle $\Delta \theta = 2m^* \Delta \alpha L / h^2$ is at least $\pi$. We can assume a typical modulation of the coupling constant of about $\Delta \alpha = 10^{-12}$ eV m from the experimental results presented above. The gate length $L$ which is required to obtain a phase shift of $\pi$ is then given by 3.2 $\mu$m. A comparison with the values of the elastic mean free path $l_{el}$ confirms that we can indeed expect the electrons to propagate without significant scattering underneath the gate electrode of a length determined above.

In the discussion given above it was shown that it is in principle possible to find a set of parameters which fit the requirements of the spin transistor proposed by Datta and Das [1]. However, for a technological realization some parameters can be optimized. It was shown recently by Grundler [9] and Sato et al. [8] that the Rashba coupling constant $\alpha$ can be increased by about a factor of 10 compared to the values reported here. This larger value would allow a reduction of the required gate length and thus leads to a smaller dimension of the device. By placing the dopant layer on top of the channel layer it is also possible to obtain an effectively reversed electric field in the quantum well. Consequently, this results in a reversed dependence of $\alpha$ on the gate voltage compared to our case. By using a front and a back gate it was shown by Grundler [9] that $\alpha$ can be altered by changing the symmetry of the quantum well while keeping the electron concentration in the quantum well constant. If the electron concentration is increased above a certain value, the second subband of the quantum well can be occupied, in addition. It was shown by Hu et al. [20,21] that the Rashba coupling constant of the second subband differs from the coupling constant of the first subband. This might result in a weakening of the output signal of the spin transistor.

3.2. Wire structures

In Section 3.1 it was shown that in an InGaAs/InP heterostructure the modulation of the Rashba coupling constant by a gate electrode is sufficiently strong to inverse the spin orientation. However, in a two-dimensional spin transistor structure the electrons are injected at various angles from the ferromagnetic electrode into the two-dimensional electrode. Since the precession angle depends on the injection angle this effect causes a decrease of the output modulation [1]. In order to restrict the electron transport to a smaller angle, we fabricated wire structures of various width. For the spin transistor proposed by Datta and Das ballistic transport is assumed [1]. Nevertheless, in our investigations long wire structures are used, where the transport takes place in the diffusive regime. This allowed us to use Shubnikov–de Haas oscillations to analyze the Rashba effect. In contrast, for shorter wire structures where the transport takes place in the ballistic regime quantized conductance is expected [22,23], as was indeed observed in point contacts based on an InGaAs/InP heterostructures [24, 25]. However, extracting the effect of the Rashba spin–orbit coupling was so far not possible for these point contact structures.

The magnetoresistance of a 400 and 800 nm wide wire is shown in Fig. 6(a). These wires had a length of 5 $\mu$m. The measurements were performed at a temperature of 0.5 K. As for the Hall bar samples, pronounced Shubnikov–de Haas oscillations are observed. For the 800 nm wide wire the oscillations are periodic in $1/B$. This shows that the magnetoresistance effectively follows a two-dimensional behavior. From the oscillation frequency an electron concentration of $n = 6.46 \times 10^{11}$ cm$^{-2}$ was extracted.

In order to observe confinement effects in the quantum wire, the energy spacing owing to the spacial quantization has to be compared to the energy separation by the Landau quantization. The latter is proportional to the magnetic field $B$. In a two-dimensional structure only the Landau quantization is relevant, which leads to the periodic oscillations in $1/B$. If in a one-dimensional structure...
the confinement energy level separation is comparable to the Landau level spacing a mixing of both contributions into magnetosubbands is expected. As a result, a deviation of the periodicity in $1/B$ occurs at low magnetic fields [26–28].

The fact that for the 800 nm wide wire only a $1/B$ periodicity is found, can be explained by estimating the number of sublevels. For simplicity, we approximate the confining potential by a rectangular 800 nm wide quantum well. Since our wires are defined by etching, sidewalls of infinite high potential can be assumed. From the value of the electron concentration a Fermi wave length of 31.2 nm is determined which results in approximately 51 sublevels. The largest energy spacing is expected between the two uppermost levels which is about 1.6 meV if an effective mass of 0.037 $m_e$ is assumed [29]. This corresponds to the Landau level separation $v_c$ present at a magnetic field of 0.5 T. The quantity $v_c = eB/m^*$ is the cyclotron frequency. Since the energy spacing in the quantum well is even smaller between lower levels it can be expected that at magnetic fields above 0.5 T, where clear Shubnikov–de Haas oscillations start to appear, effects originating from the carrier confinement are difficult to identify.

If the oscillations of the 400 nm wide wire are compared to the measurement of the 800 nm wide wire at fields around 1 T it can clearly be seen that for the previous one the separation of the peaks is considerably larger (Fig. 6(a)). Whereas at higher field the peak positions of the resistance of both samples coincide. This clearly shows that for the narrower wire confinement effects are directly observed in the magnetoresistance. The deviation from the periodicity in $1/B$ can also be seen in Fig. 6(b). Here, the position of the oscillation minima in $1/B$ is plotted as a function of the Landau level index $\nu$ (filling factor). At larger numbers of $\nu$ a clear deviation from the linear dependence due to the effect of the one-dimensional confinement is found in accordance to theoretical predictions [26–28]. For the 400 nm wide wire the estimated number of sublevels due to the one-dimensional confinement is 26, resulting in an energy separation of the uppermost levels of 3.2 meV. Since this value is twice as large as the corresponding level separation of the wider wire, confinement effects are experimentally observed at higher magnetic fields.

Fig. 7 shows the magnetoresistance of four wires with different width at smaller magnetic fields up to 1 T. These wires had a length of 30 $\mu$m. For the 1 $\mu$m, 800 nm, and 600 nm wide wires a clear beating pattern due to the Rashba effect is observed. The first node is found at a magnetic field of approx. 0.7 T, in accordance to the measurement performed on a Hall bar sample fabricated on the same chip. However, the amplitude of the beating pattern is considerably weaker if compared to the two-dimensional case. Owing to the weaker oscillations, it was not possible to resolve a series of nodes in the beating patterns as seen for the Hall bar samples. However, the Rashba coupling constant can be estimated by means of a fast Fourier transform. As can be seen in Fig. 8, the beating pattern results in a double peak structure in the fast Fourier spectrum. For the 1 $\mu$m, the 800 nm and the 600 nm wide wires this double peak structure is clearly resolved, while for the 400 nm wide wire only a broad single peak is found in the spectrum.

A Rashba coupling constant of about $22 \times 10^{-12}$ eV m was extracted from the distance of the two peaks in the fast Fourier spectrum for the first three wires. This value is considerably larger than the value of the coupling constant determined for the two-dimensional structure discussed above. There are two reasons for this discrepancy. First, a heterostructure with a 70 nm thick cap layer was used for the quantum wire structures. Due to the closer distance to the surface, the potential profile of the quantum well might
be more tilted leading to a larger value of $\alpha$. Second, as pointed out in a previous publication [29], the determination of the Rashba coupling constant based on a fast Fourier transform overestimates $\alpha$; since the contribution of the Zeeman effect is included, here. Above that, a comparison with the Hall bar sample fabricated from the same heterostructure revealed the same value of $\alpha$ as for the wire structures. Therefore, it can be concluded that in our wire structures the coupling constant $\alpha$ is not modified by one-dimensional confinement.

As confirmed by Fig. 7, Rashba spin–orbit coupling can clearly be seen in wire structures of widths down to 600 nm. However, as mentioned above, the observed oscillation amplitude is lower compared to the measurements on Hall bar samples. A possible explanation for this difference is the additional scattering contribution due to diffusive boundary scattering [30]. For wire structures the roughness of the boundary, in our case caused by reactive ion etching, leads to a diffusive backscattering and consequently to an increase of the resistance. The presence of diffusive boundary scattering is also confirmed by the observed broad maximum in the magnetoresistance. In accordance to theoretical predictions [31], the position of the maximum increases linearly with the inverse magnetic field, as can be seen in Fig. 7 (circles).

As was discussed above, diffusive boundary scattering in quantum wire structures suppresses the Shubnikov–de Haas oscillations at low magnetic fields especially for narrow wire structures. However, narrow wires are of particular interest, since here one can expect deviations of the beating pattern found for two-dimensional structures due to the additional contribution of one-dimensional confinement. A possible solution to reduce the influence of diffusive boundary scattering might be to define the quantum wires by the split-gate technique [32], since an electrostatically defined boundary is supposed to be smoother than a boundary defined by etching.

4. Conclusions

In conclusion, the effect of Rashba spin–orbit coupling on the magnetotransport in two-dimensional electron gases as well as in quantum wire structures was reported. Our investigations are based on a strained InGaAs/InP heterostructure. It was explained that the Rashba spin–orbit coupling manifests itself by a characteristic beating pattern. By using a gate electrode the beating pattern and as a consequence the Rashba coupling parameter $\alpha$ can be controlled. If the transport is restricted to a quasi one-dimensional wire structure the beating pattern due to the Rashba effect was observed down to a wire width of 600 nm. However, the additional contribution of the diffusive boundary scattering results in a considerable decrease of the oscillation amplitude. Therefore, the effect of the Rashba spin–orbit coupling ultimately has to be confirmed in ballistic wire structures, with almost no scattering along the wire. In order to reach this goal a prerequisite is to achieve a large spin–orbit coupling constant $\alpha$, since this reduces the required ballistic length on which the spin orientation is rotated.

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