Effect of Rashba spin-orbit coupling on magnetotransport in InGaAs/InP quantum wire structures

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The Rashba spin-orbit coupling in InGaAs/InP quantum wire structures with a width varying between 1 μm and 400 nm is investigated. For all quantum wire structures a clear beating pattern in the oscillations of the magnetoresistance owing to the presence of Rashba spin-orbit coupling is observed. By applying a bias voltage to a gate electrode covering the wires it was possible to control the magnitude of the spin-orbit coupling. For the narrowest wire the effect of the confining potential on the sublevel spectrum could be resolved in the magnetoresistance oscillations. It is found that the node of the beating pattern shifts towards larger magnetic fields with decreasing wire width. The corresponding increase of the Rashba spin-orbit coupling parameter is explained by the effect of the confining potential of the wire.

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I. INTRODUCTION

In the rapidly growing field of semiconductor spintronics the spin degree of freedom is used for information processing instead of its charge.[1–4] Device concepts have been proposed which offer lower power consumption and a higher degree of functionality. An example often referred to is the spin transistor proposed by Datta and Das, which can be used to explain the ingredients of a typical spintronic device.[5] The first unit which is required for a spin transistor is an injector as a source of well aligned electron spins. In the initial proposal of Datta and Das the electrons are injected by means of a metallic ferromagnetic electrode. However, in the light of recent progress on magnetic materials, dilute ferromagnetic semiconductors might also offer a promising alternative.[1] After successful spin injection into the semiconductor the spin orientation is manipulated by means of a gate electrode. For this purpose the Rashba effect is used,[6,7] where the spin precession in a semiconducting channel can be controlled by means of a gate voltage. At the final step the spin orientation has to be read out. This can be achieved by means of a second ferromagnetic electrode. Only if the spin orientation of the incoming electrons is aligned parallel to the spins in the ferromagnetic electrode a current can flow from source to drain contact.

In this work we will focus on the Rashba effect, the mechanism which allows to manipulate the spin orientation in a semiconductor. The Rashba effect is based on the spin-orbit coupling originating from a macroscopic electric field in a two-dimensional electron gas (2DEG). The spin-orbit coupling results in a spin splitting of the electron subbands in the 2DEG according to

$$E = E_z^{\mathrm{sub}} + \frac{\hbar^2 k^2}{2m^*} \pm \alpha|\mathbf{k}|, \tag{1}$$

where, E_z^{sub} is the subband energy of the 2DEG electron gas, m^* is the effective electron mass and $\mathbf{k}$ is the wave vector within the plane of the 2DEG. The strength of the Rashba effect is expressed by the coupling constant α. The presence of the Rashba effect can experimentally be verified by observing a characteristic beating pattern in the magnetoresitance.[8–12] By changing the macroscopic electric field in the 2DEG by using a gate electrode it is possible to control the Rashba coupling constant and, hence, the spin precession.[13–17]

The transport properties of one-dimensional systems taking Rashba spin-orbit coupling into account were studied theoretically by Moroz and Barnes[18] and Mireles and Kirczenow.[19] Experimentally it was shown that for wire structures with an InGaAs channel layer a characteristic beating pattern appears in the magnetoresistance similar to the case of a two-dimensional electron gas.[20,21] On the basis of specific features in the energy spectrum of one-dimensional structures, originating from the interplay between the confinement energy and the Rashba spin-orbit coupling, effects are predicted, e.g., spin filtering in a T-shape structure[22] or in coupled quantum wires.[23–25] Ultimately, the Rashba effect in one-dimensional systems might be employed in structures for quantum information processing.[26]

Here, we report the results on the Rashba effect in InGaAs/InP quantum wire structures. Magnetotransport measurements were performed on wire structures with a width ranging from 400 nm to 1μm. The transport takes place in the diffusive regime. Owing to the moderate width of the wires compared to the Fermi wavelength, many subbands are occupied at zero magnetic field. All wires showed a distinct beating pattern in the magnetoresistance which can be attributed to the presence of Rashba spin-orbit coupling. By using a gate electrode the magnitude of the Rashba coupling constant in the wires could be controlled. The position of the highest order node in the beating pattern shifted towards higher magnetic fields if the wire width is reduced. We attribute this shift to the effect of the carrier confinement potential. For wires as narrow as 400 nm a clear deviation of the $1/B$ periodicity due to carrier confinement was observed.

II. EXPERIMENT

The quantum wire structures are based on a strained InGaAs/InP heterostructure grown by metalorganic vapor

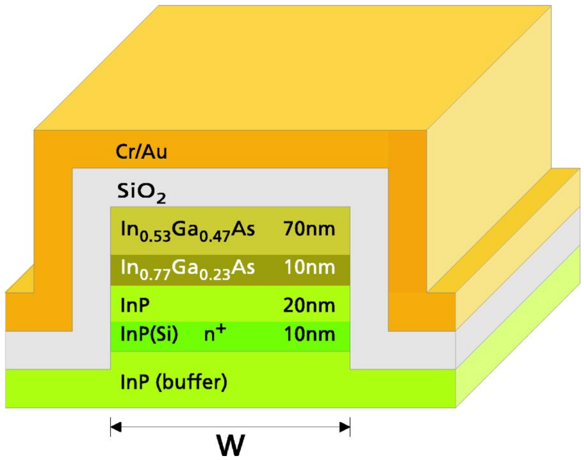

FIG. 1. (Color online) Schematic illustration of the wire structure. The two-dimensional electron gas is located in the strained $In_{0.77}Ga_{0.23}As$ layer. The widths w of the wires were 400, 600 nm, and 1 μm, respectively.

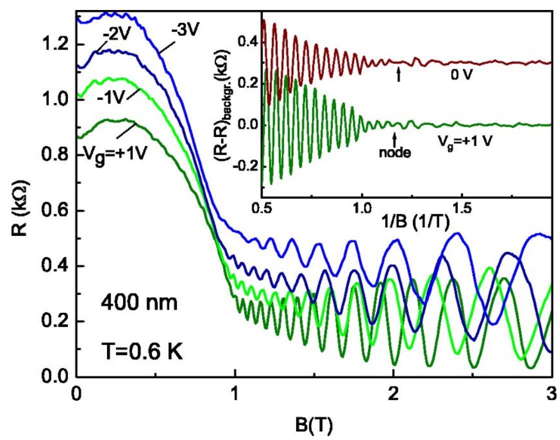

FIG. 2. (Color online) Magnetoresistance of a 400 nm wide wire structure. The gate voltage V_g was set to +1.0, −1.0, −2.0, and −3.0 V. The inset shows the magnetoresistance as a function of the inverse magnetic field for a gate voltage of +1.0 and 0 V. Here, the slowly varying background resistance was subtracted. The upper curve was shifted by 0.3 $k\Omega$. The node positions are indicated by arrows.

phase epitaxy. The corresponding layer sequence can be found in Fig. 1. The two-dimensional electron gas is located in a 10-nm-thick strained $In_{0.77}Ga_{0.23}As$ layer. The electrons in the 2DEG are supplied by an InP(Si) doping layer, which is separated by a 20-nm-thick InP barrier layer from the $In_{0.77}Ga_{0.23}As$ channel. For the upper barrier of the quantum well an $In_{0.53}Ga_{0.47}As$ layer, lattice-matched to InP, is used. From Shubnikov-de Haas effect measurements on Hall bar samples a sheet electron concentration of 8.5×10^{11} cm^{-2} and a mobility of 200 000 cm^2/Vs was extracted. Temperature dependent measurements of the Shubnikov-de Haas oscillation amplitude revealed an effective electron mass of 0.037 m_e.

Quantum wire structures were fabricated by using electron beam lithography and reactive ion etching (CH_4/H_2). The widths of the 25 μm long wires were 400, 600 nm, and 1 μm, respectively. The carrier concentration of the wires was controlled by a Cr/Au gate electrode. In order to prevent any leakage current, the gate electrode was isolated by a 200-nm-thick SiO_2 layer from the semiconductor surface (Fig. 1). The quantum wire structures were measured in a He-3 cryostat at a temperature of 0.6 K. Standard lock-in technique with an excitation current of 100 nA was used.

III. RESULTS AND DISCUSSION

Before analyzing the effect of the Rashba spin-orbit coupling in detail, we will first address some general features of the transport properties of our wire structures. In Fig. 2 a set of characteristic magnetoresistance curves of a 400 nm wide wire is shown. Clear Shubnikov-de Haas oscillations are observed. By changing the gate voltage from +1.0 to −3.0 V the electron concentration in the wire can be decreased, as indicated by the higher resistance and the increased oscillation period. At higher magnetic fields (>1 T) the oscillations are periodic in $1/B$, as can be seen in Fig. 2 (inset). Owing to the large Landau quantization energy compared to the confinement energy of the wire, the magnetoresistance oscillations at higher magnetic fields effectively correspond to the oscillations of a two-dimensional system. By performing a fast Fourier transform in $1/B$ in the high magnetic field range the sheet electron concentration can be determined. If the gate voltage is changed from +1 to −3 V the sheet electron concentration is reduced from 1.01×10^{12} cm^{-2} to 6.2×10^{11} cm^{-2}. As can be seen in Fig. 2 at low magnetic fields of ≈0.25 T a broad resistance maximum is observed which can be attributed to diffusive boundary scattering in the wire structures.[27] The position of this peak is directly related to the width of the wires. For wires with a larger width the maximum shifts towards smaller magnetic fields in accordance to the theoretical predictions.[28]

For two-dimensional electron gas structures it is well-known that the presence of Rashba effect results in a characteristic beating pattern in the Shubnikov-de Haas oscillations. However, in the measurement of the 400 nm wide quantum wire, shown in Fig. 2, a beating pattern is difficult to resolve, owing to the steep decrease of the magnetoresistance for magnetic fields below 1 T due to diffusive boundary scattering. In order to resolve the beating pattern more clearly, the slowly varying background resistance was subtracted. The resulting curves for gate voltages of +1 and 0 V are shown in Fig. 2 (inset). For both curves a node in the beating pattern is observed at about 0.87 T. In addition to the experiments at 0.6 K some of the magnetoresistance measurements were also repeated at a lower temperature of 0.3 K. However, no significant improvement of the oscillation amplitude in the beating pattern was found. This observance can be explained by the fact that at low temperatures the carrier scattering is governed by the temperature independent alloy scattering.

Subtracting the slowly varying background resistance allows one to clearly identify the node position of the beating pattern. Therefore, we generally applied this procedure to the measured magnetoresistance data when the effect of the gate voltage on the Rashba coupling parameter is analyzed. In

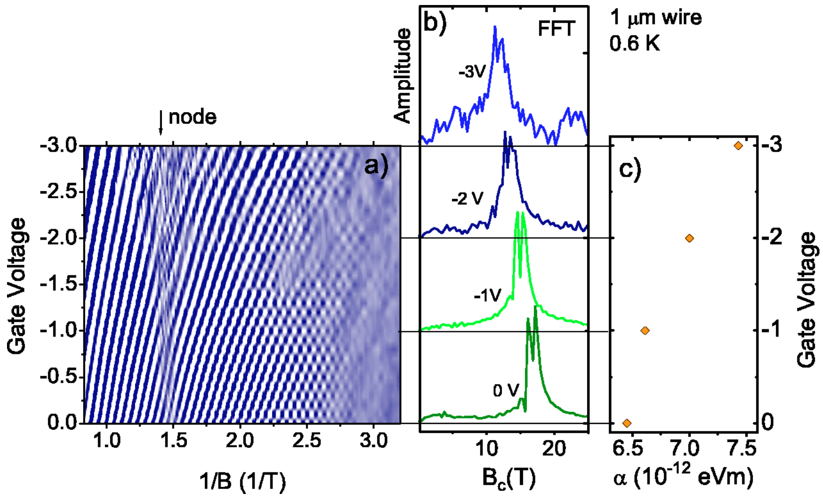

FIG. 3. (Color online) (a) Magnetoresistance as a function of the magnetic field and the gate voltage. Lighter areas correspond to higher resistance values. (b) Fast Fourier transform in $1/B$ of the magnetoresistance at 0, −1, −2, and −3 V as a function of the characteristic field B_c. (c) Rashba coupling parameter α extracted from the fast Fourier transform spectra shown in (b).

Fig. 3(a) a grayscale plot of the magnetoresistance of a 1 μm wide wire is shown as a function of the gate voltage and of the inverse magnetic field. If the gate voltage is increased to larger negative values the oscillation period increases, owing to the decreasing sheet electron concentration. For the range shown here, the electron concentration is reduced from $8.17\times10^{-11}\mathrm{cm}^{-2}$ to $5.43\times10^{-11}\mathrm{cm}^{-2}$. For the 1 μm wide wire the node position is found at 1.5 T^{-1} at zero gate voltage. If the gate voltage is increase to −3 V the node slightly shifts to 1.4 T^{-1}. It can be seen in Fig. 3(a) that the magnetoresistance oscillations are periodic in $1/B$. Therefore, in this case the 1 μm wide wire can still be treated as a two-dimensional system.

For a two-dimensional system the Rashba coupling constant α can be obtained from the difference of the electron concentrations Δn of the two spin-split subbands. In order to extract these values from the oscillations of magnetoresistance, a fast Fourier transform of the magnetoresistance was performed, as shown in Fig. 3(b) for a gate voltage of 0, −1, −2, and −3 V. From the positions of the two maxima of the double peak structure the difference of the electron concentration Δn as well as the average sheet electron concentration n was determined. The Rashba coupling constant was then calculated from[14,15]

$$\alpha=\frac{\Delta n}{\sqrt{2(n-\Delta n)}}\frac{\sqrt{\pi}\hbar^2}{m^*}. \tag{2}$$

The resulting values of α are plotted in Fig. 3(c). It can be seen that despite the fact that the node position shifts only slightly, if the gate voltage is varied from 0 to −3 V, the Rashba coupling constant increases by more than 15% from 6.45×10^{-12}eV m to 7.43×10^{-12}eV m. The increase of the Rashba coupling constant can be explained by the increase of the effective electric field in the quantum well if a negative voltage is applied.[15] The node positions in the magnetoresistance 1 μm wide wire as well as the values of α of the correspond to the values obtained from Shubnikov-de Haas measurements on large-size Hall bars. This confirms that for the magnetic field range considered here, the 1 μm wide wire behaves as a two-dimensional system. However, in contrast to Shubnikov-de Haas measurements on Hall bar samples only a single node of the beating could be resolved for the wire structure. For the latter the nodes at lower magnetic fields are masked by the mesoscopic resistance fluctuations.

If the width of the wires is reduced to 600 or 400 nm a significant modification of the beating pattern is found compared to the 1 μm wire. In Fig. 4 a grayscale plot of the magnetoresistance is shown for the different widths of the quantum wires. Obviously, for narrower wires the oscillations are suppressed at higher values of the inverse magnetic field. This can be attributed to the increased contribution of the diffusive boundary scattering. At the same time the amplitude of the mesoscopic resistance fluctuations is increased if the width of the wire is reduced. Compared to the node of the beating pattern of the 1 μm wide wire at zero gate voltage the node is shifted to 1.27 and 1.13 T^{-1} for the 600 and 400 nm wide wire, respectively. For the 600 nm wire it was possible to obtain a value for the Rashba coupling parameter α by using Eq. (2). Here, a value of 9.94×10^{-12} eV m was

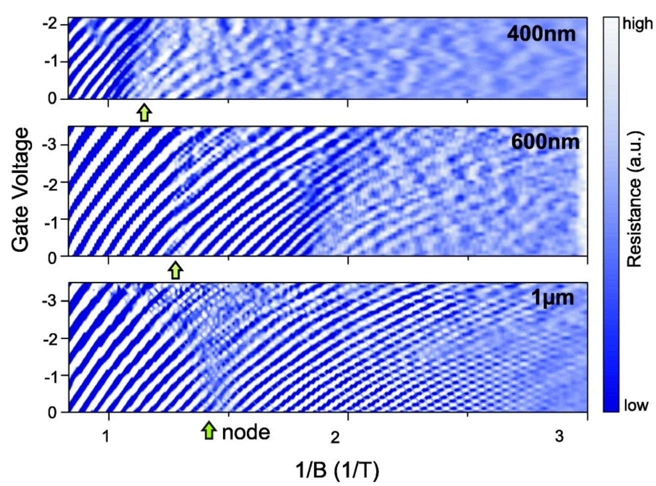

FIG. 4. (Color online) Magnetoresistance oscillations of the 400, 600 nm, and 1 μm wide wires as a function of the inverse magnetic field and of the gate voltage. Lighter areas correspond to higher resistance values. The position of the node of the beating pattern is indicated by an arrow. The measurement temperature was 0.6 K. The slowly varying background resistance was subtracted.

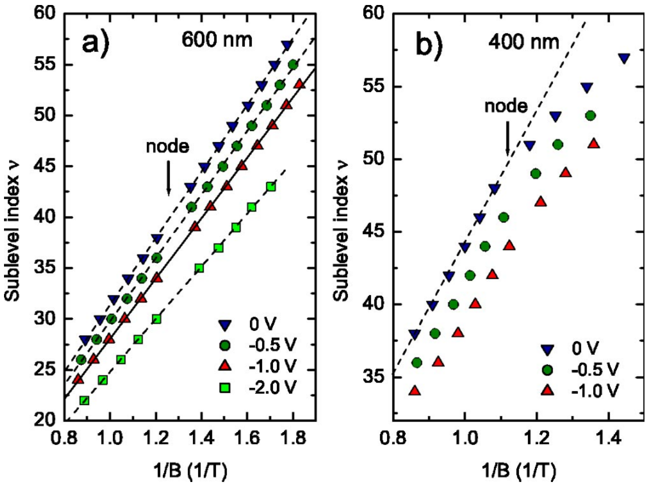

FIG. 5. (Color online) Sublevel index vs inverse magnetic fields of the 600 (a) and 400 nm wide (b) quantum wires at various gate voltages. The node position is indicated by an arrow.

extracted. For the 400 nm wide wire it was not possible to obtain a value for α, because of the the strong suppression of the oscillation amplitude at low magnetic fields.

In order to analyze the effect of the confinement potential on the sublevel spectrum in the quantum wires, the number of occupied sublevels, the sublevel index ν, was determined as a function of the inverse magnetic field. As can be seen in Fig. 5(a), up to an inverse magnetic field of 1.8 T^{-1} the sublevel index shows a linear dependence on $1/B$ for the 600 nm wide wire indicating that this wire can still be regarded as a two-dimensional system. If the sublevel index is reduced by increasing the gate voltage the linear dependence is preserved. If the node of the beating pattern is crossed, the oscillation acquires a phase shift of π. Since the sublevel index was determined for a nondegenerate spin system, ν changes from an even to an odd number after crossing the node of the beating pattern. At zero gate voltage a sheet electron concentration of 7.3×10^{-11} cm^{-2} was determined, resulting in a Fermi wavelength of 28 nm. As was shown in a previous investigation on InGaAs/InP wires structures, the electrical width basically corresponds to the geometrical width, owing to the small depletion region at the edge of the wire.[29] If we assume a rectangular shape of the confining potential, which is a good approximation for large electron concentrations,[30] a number of 86 sublevels are occupied in the wire. The highest sublevel index which could be determined from the measurements is well below this value, therefore a deviation from a linear increase cannot be expected. This observation agrees well to our simulations of the magnetosublevels for a 600 nm wide wire with a rectangular potential profile and infinitively high barriers.[31] Here, effects of the confinement on the level separation are only found for inverse magnetic fields larger than 2 T^{-1}.

In contrast, the effect of the geometrical confinement can clearly be observed for the 400 nm wide wire. As can be seen in Fig. 5(b), the slope of the Landau plot becomes smaller for inverse fields larger than 1.2 T^{-1}. In this case the contribution of the geometrical confinement to the energy level separation is sufficiently large to result in a deviation from the $1/B$ periodicity due to Landau quantization. For a 400 nm wide quantum wire with a rectangular profile we estimated an occupation of 32 levels for zero gate voltage. This number is reasonably close to the maximum value of the sublevel index observed in the experiment so that a deviation from the linear ν vs $1/B$ dependence can be expected.

From the presence of the beating pattern in the magnetoresistance, we can directly conclude that Rashba spin-orbit coupling is present in our quantum wire structures. However, the node position is considerably shifted towards higher magnetic fields if the wire width is reduced. At least in the case of the 1 μm and 600 nm wide wires the Rashba coupling parameter α could be extracted from the double peak structure found in the fast Fourier transform. If compared to the case of the 1 μm wide wire, a considerably larger value of α was found for the 600 nm wide wire. Moroz and Barnes[18] pointed out that the lateral confinement potential of the quantum wire leads to an additional contribution to the spin-orbit coupling. In their estimate this contribution would be in the order of one tenth of the Rashba spin-orbit coupling caused by the asymmetry of the quantum well. In our experimental investigation the node position in $1/B$ shifts by about 10% if the wire width is reduced from 1 μm to 400 nm. The spin-orbit coupling contribution due to the confinement potential thus might at least partially account for this shift. In addition to this mechanism, the carrier depletion at the edges of the wires can also contribute to the shift of the node position. A reduced carrier concentration at the edges will result in a modified potential profile and thus in a different effective electric field. As was found for a carrier depletion induced by a gate bias voltage, the effective electric field in the channel and consequently the Rashba coupling constant is increased (Fig. 3). However, a quantitatively evaluation of the Rashba coupling parameter α would require a three-dimensional simulation of the potential profile of the wire, which was omitted here. From the $1/B$ periodicity of the magnetoresistance oscillations of the 600 nm and 1 μm wide wires it was concluded that these wires can effectively be regarded as a two-dimensional systems. In case of the 400 nm wide wire a significant deviation of the $1/B$ periodicity of the magnetoresistance was observed [Fig. 5(b)]. This deviation was caused by the non-negligible contribution of the lateral confining potential on the sublevel spacing. Hence, for the 400 nm wide wire it is possible that the modified sublevel spectrum also contributes to the shift of the node position in the beating pattern.

IV. CONCLUSION

In conclusion, the Rashba spin-orbit coupling in InGaAs/InP quantum wire structures was investigated. For all quantum wires, with a width ranging from 1 μm down to 400 nm, a distinct beating pattern was observed. For the 1 μm and 600 nm wide wire it was possible to extract the Rashba spin-orbit coupling parameter by performing a fast Fourier transform. A value of 6.45×10^{-12}eV m and 9.94 $\times 10^{-12}$eV m was determined for the 1 μm and 600 nm wide wire, respectively. By applying a gate voltage the Rashba coupling parameter in the wires could be controlled. The characteristic node of the beating pattern was found at larger magnetic fields for narrower wire structures. The increased coupling parameter for smaller wires was explained by the effect of the confining potential of the quantum wire.

Although many subbands are occupied in our quantum wires the measurements clearly demonstrate that the effect of the Rashba spin-orbit coupling on the magnetotransport can be observed in a confined system. For future investigations towards a possible realization of spintronic devices it is important to reduce the number of occupied subbands. However, for lower numbers of subbands probably no beating pattern will be observed in the magnetoresistance, owing to the stronger confinement energy compared to the Rashba spin splitting. A possible solution might be to investigate ballistic structures with a shorter channel, in order to gain information in the spin-orbit coupling by analyzing the quantized conductance at various magnetic fields.

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[1] Y. Ohno, Science **281**, 951 (1998).
[2] G. A. Prinz, Science **282**, 1660 (1998).
[3] P. Ball, Nature (London) **404**, 918 (2000).
[4] S. A. Wolf, Science **294**, 1488 (2001).
[5] S. Datta and B. Das, Appl. Phys. Lett. **56**, 665 (1990).
[6] E. I. Rashba, Fiz. Tverd. Tela (Leningrad) **2**, 1224 (1960) [Sov. Phys. Solid State **2**, 1109 (1960)].
[7] Y. Bychkov and E. I. Rashba, J. Phys. C **17**, 6039 (1984).
[8] J. Luo, H. Munekata, F. F. Fang, and P. J. Stiles, Phys. Rev. B **38**, 10142 (1988).
[9] J. Luo, H. Munekata, F. F. Fang, and P. J. Stiles, Phys. Rev. B **41**, 7685 (1990).
[10] B. Das, D. C. Miller, S. Datta, R. Reifenberger, W. P. Hong, P. K. Bhattacharya, J. Singh, and M. Jaffe, Phys. Rev. B **39**, 1411 (1989).
[11] B. Das, S. Datta, and R. Reifenberger, Phys. Rev. B **41**, 8278 (1990).
[12] Y. S. Gui, C. Hu, Z. Chen, G. Zheng, S. L. Guo, J. Chu, J. X. Chen, and A. Z. Li, Phys. Rev. B **61**, 7237 (2000).
[13] J. Nitta, T. Akazaki, H. Takayanagi, and T. Enoki, Phys. Rev. Lett. **78**, 1335 (1997).
[14] G. Engels, J. Lange, Th. Schäpers, and H. Lüth, Phys. Rev. B **55**, R1958 (1997).
[15] Th. Schäpers, G. Engels, J. Lange, Th. Klocke, M. Hollfelder, and H. Lüth, J. Appl. Phys. **83**, 4324 (1998).
[16] D. Grundler, Phys. Rev. Lett. **84**, 6074 (2000).
[17] Y. Sato, T. Kita, S. Gozu, and S. Yamada, J. Appl. Phys. **89**, 8017 (2001).
[18] A. V. Moroz and C. H. W. Barnes, Phys. Rev. B **61**, R2464 (2000).
[19] F. Mireles and G. Kirczenow, Phys. Rev. B **64**, 024426 (2001).
[20] Y. Sato, S. Gozu, T. Kikutani, and S. Yamada, Physica B **272**, 114 (1999).
[21] Th. Schäpers, J. Knobbe, A. van der Hart, and H. Hardtdegen, Sci. Technol. Adv. Materials **4**, 1925 (2003).
[22] A. A. Kiselev and K. W. Kim, Appl. Phys. Lett. **78**, 775 (2001).
[23] M. Governale and U. Zülicke, Phys. Rev. B **66**, 073311 (2002).
[24] M. Governale, D. Boese, U. Zülicke, and C. Schroll, Phys. Rev. B **65**, 140403 (2002).
[25] U. Zülicke and M. Governale, Phys. Rev. B **65**, 205304 (2002).
[26] J. C. Egues, G. Burkard, and D. Loss, Phys. Rev. Lett. **89**, 176401 (2002).
[27] T. J. Thornton, M. L. Roukes, A. Scherer, and B. P. V de Gaag, Phys. Rev. Lett. **63**, 2128 (1989).
[28] E. Ditlefsen and J. Lothe, Philos. Mag. **14**, 759 (1966).
[29] J. Appenzeller, Th. Schäpers, H. Hardtdegen, B. Lengeler, and H. Lüth, Phys. Rev. B **51**, 4336 (1995).
[30] S. E. Laux, D. J. Frank, and F. Stern, Surf. Sci. **196**, 101 (1988).
[31] The effect of the Rashba spin-orbit coupling was not included in these simulations.