Enhanced spin-orbit scattering length in narrow Al_{x}Ga_{1-x}N/GaN wires

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The magnetotransport in a set of identical parallel Al_{x}Ga_{1-x}N/GaN quantum wire structures is investigated. The width of the wires ranges between 1110 and 340 nm. For all sets of wires, clear Shubnikov–de Haas oscillations are observed. We find that the electron concentration and mobility are approximately the same for all wires, confirming that the electron gas in the Al_{x}Ga_{1-x}N/GaN heterostructure is not deteriorated by the fabrication procedure of the wire structures. For the wider quantum wires, the weak antilocalization effect is clearly observed, indicating the presence of spin-orbit coupling. For narrow quantum wires with an effective electrical width below 250 nm, the weak antilocalization effect is suppressed. By comparing the experimental data to a theoretical model for quasi-one-dimensional structures, we come to the conclusion that the spin-orbit scattering length is enhanced in narrow wires.

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I. INTRODUCTION

The Al_{x}Ga_{1-x}N/GaN material system is a very promising candidate for future spin electronic applications. The reason is that two important requirements for the realization of spin electronic devices are fulfilled in this material class. First, transition-metal-doped GaN diluted magnetic semiconductors have been shown to have high Curie temperatures for injection and detection of spin polarized carriers (see, e.g., Ref. 1 and references therein). Second, spin-orbit coupling for spin control in nonmagnetic Al_{x}Ga_{1-x}N/GaN heterostructures was observed.2–11

Spin-orbit coupling in Al_{x}Ga_{1-x}N/GaN two-dimensional electron gases (2DEGs) can be investigated by analyzing the characteristic beating pattern in Shubnikov–de Haas oscillations,2–5 by measuring the circular photogalvanic effect,9 or by studying weak antilocalization.4,7,9–11 The latter is an electron interference effect where the random deviations of the spin orientations between time-reversed paths result in an enhanced conductance.12–14 From weak antilocalization measurements, information on characteristic length scales, i.e., the spin-orbit scattering length $l_{so}$ and the phase coherence length $l_{ph}$, can be obtained.

For quasi-one-dimensional systems, it was predicted theoretically15–18 and shown experimentally19–22 that $l_{so}$ can be considerably enhanced compared to the value of the 2DEG. This has important implications for the performance of spin electronic devices, e.g., the spin field-effect transistor,23 since an enhanced value of $l_{so}$ results in a larger degree of spin polarization in the channel and thus in larger signal modulation.15,23 In addition, many of the recently proposed novel spin electronic device structures explicitly make use of one-dimensional channels because the restriction to only one dimension allows new switching schemes.24–27

Very recently, transport measurements on AlGaN/GaN -based one-dimensional structures, i.e., quantum point contacts, have been reported.1,28 With respect to possible spin electronic applications, it is of great interest how the spin transport takes place in AlGaN/GaN quasi-one-dimensional structures. Since an enhanced value of $l_{so}$ is very advanta-

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II. EXPERIMENT

The AlGaN/GaN heterostructures were grown by metal organic vapor phase epitaxy on a (0001) Al_{2}O_{3} substrate. Two different samples were investigated. Sample 1 consisted of a 3-μm-thick GaN layer followed by a 35-nm-thick Al_{0.20}Ga_{0.80}N top layer, while in sample 2 a 40-nm-thick Al_{0.10}Ga_{0.90}N layer was used as a top layer. The quantum wire structures were prepared by first defining a Ti etching mask using electron beam lithography and lift-off. Subsequently, the AlGaN/GaN wires were formed by Ar$^+$ ion beam etching. The etching depth of 95 nm was well below the depth of the AlGaN/GaN interface. The electron beam lithography pattern was chosen so that a number of 160 identical wires, each 620 μm long, were connected in parallel. A schematic cross section of the parallel wires is shown in Fig. 1 (inset).

Different sets of wires were prepared, comprising a geometrical width $W$ ranging from 1110 down to 340 nm (see Table I). The geometrical widths of the wires were determined by means of scanning electron microscopy. The sample geometry with quantum wires connected in parallel
was chosen in order to suppress universal conductance fluctuations. After removing the Ti mask by HF, Ti/Al/Ni/Au Ohmic contacts were defined by optical lithography. The Ohmic contacts were alloyed at 900 °C for 30 s.

For reference purposes, a 100-μm-wide Hall bar structure with voltage probes separated by a distance of 410 μm was prepared on the same chip.

The measurements were performed in a He^3 cryostat at temperatures ranging from 0.4 to 4.0 K. The resistances were measured by employing a current-driven lock-in technique with an ac excitation current of 100 nA and 1 μA for samples 1 and 2, respectively.

![Diagram](image)

**FIG. 1.** (Color online) Conductance $G$ as a function of the geometrical width $W$. The conductance of a single wire is plotted, which was determined by dividing the total conductance by the number of wires connected in parallel. The full lines represent the corresponding linear fits. The arrows indicate the total width of the depletion zones $W_{\text{depl}}$. The inset shows a schematics of the cross section of the wires. Here, $W$ corresponds to the geometrical width, while $W_{\text{eff}}$ indicates the effective electrical width.

III. RESULTS AND DISCUSSION

In order to gain information on the transport properties of the Al_{x}Ga_{1-x}N/GaN layer systems, Shubnikov–de Haas oscillations were measured on the Hall bar samples. At a temperature of 0.5 K, sheet electron concentrations $n_{2D}$ of 5.1 \times 10^{12} and 2.2 \times 10^{12} cm$^{-2}$ were determined for samples 1 and 2, respectively. The Fermi energies calculated from $n_{2D}$ are 55 meV for sample 1 and 24 meV for sample 2. Here, an effective electron mass of $m^* = 0.22 m_e$ was taken into account. The mobilities $\mu$ were 9150 and 3930 cm$^2$/V s for samples 1 and 2, respectively, resulting in elastic mean free paths $l_{\text{el}}$ of 314 and 95 nm. The smaller electron concentration compared to sample 2 can be attributed to the lower Al content of the Al_{x}Ga_{1-x}N barrier layer, resulting in smaller polarization doping. The lower mobility found in sample 2 compared to sample 1 can be explained by the reduced screening at lower electron concentrations.

Owing to the large surface potential of GaN, which has been determined to be between 0.5 and 0.6 eV, a considerable surface carrier depletion can be expected. For our wires, the carrier depletion at the mesa edges will result in an effective electrical width $W_{\text{eff}}$, which is smaller than the measured geometrical width $W$. In order to gain information on the lateral width of the depletion zone, the wire conductance at zero magnetic field was determined for different wire widths. In Fig. 1, the single-wire conductance $G$ is shown as a function of the wire width for both samples. It can be seen that for both samples, $G$ scales linearly with $W$. The total width of the depletion zone was determined from the linear extrapolation to $G=0$, indicated by $W_{\text{depl}}$ in Fig. 1. The depletion zone width for sample 1 is 210 nm, while for sample 2 a value of 240 nm was determined. The larger value of $W_{\text{depl}}$ for sample 2 can be attributed to the lower electron concentration compared to sample 1. The corresponding effective electrical width $W_{\text{eff}}$ defined by $W - W_{\text{depl}}$ is listed in Table I. The two-dimensional resistivity $\rho$ of the wires at $B=0$ was calculated based on $W_{\text{eff}}$.

### TABLE I. Summary of characteristic parameters of both samples: The sample number, geometrical wire width $W$, effective electrical wire width $W_{\text{eff}}$, resistivity $\rho$, sheet electron concentration $n_{2D}$, mobility $\mu$, and elastic mean free path $l_{\phi}$. The spin-orbit scattering length $l_{\text{so}}$, and phase coherence length $l_{\phi}$ were extracted from the fit using the Kettemann model.

<table>
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<th>#</th>
<th>W (nm)</th>
<th>$W_{\text{eff}}$ (nm)</th>
<th>$\rho$ (Ω)</th>
<th>$n_{2D}$ (10^{12} cm$^{-2}$)</th>
<th>$\mu$ (cm$^2$/V s)</th>
<th>$l_{\text{el}}$ (nm)</th>
<th>$l_{\text{so}}$ (nm)</th>
<th>$l_{\phi}$ (nm)</th>
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seen by the values of $\rho$ given in Table I, for sample 1 the resistivity remains at approximately the same value if the wire width is reduced. A similar behavior is observed for sample 2, although the variations are somewhat larger. In any case, no systematic change of $\rho$ is found for both samples.

As can be seen in Fig. 2, clear Shubnikov–de Haas oscillations in the magnetoresistivity $\rho(B) - \rho_0(B)$ are resolved for different sets of wires of sample 1. For a better comparison, the slowly varying field-dependent background resistivity $\rho_0(B)$ was subtracted. In order to get an impression on the relation between the amplitude of the Shubnikov–de Haas oscillations and the background resistivity, the total resistivity $\rho(B)$ is shown exemplarily for the 1090-nm-wide wires in Fig. 2 (inset). As can be seen here, the oscillation amplitude turns out to be small compared to $\rho_0(B)$ because of the relatively low mobility. From the oscillation period of $\rho(B) - \rho_0(B)$ vs $1/B$, the sheet electron concentration $n_{2D}$ was determined for the different sets of wires. As can be seen in Fig. 2, the oscillation period, and thus $n_{2D}$, is approximately the same for all sets of wires (Table I). The values of $n_{2D}$ are comparable to the value found for the 2DEG. As given in Table I, for sample 2 the values of $n_{2D}$ for the different sets of wires were also found to be close to the value extracted from the corresponding Hall bar structure.

The mobility $\mu$ and elastic mean free path $l_{el}$ was determined from $n_{2D}$ and $\rho(B=0)$. As can be inferred from the values of $\mu$ and $l_{el}$ given in Table I, both quantities are similar for all sets of wires for a given heterostructure. For sample 2, $l_{el}$ is always smaller than $W_{eff}$; therefore, no significant deviation from the 2DEG conductivity is expected. However, for the 440- and 340-nm-wide wires of sample 1, $l_{el}$ exceeds $W_{eff}$ so that a boundary scattering contribution is expected. However, since the mobility is not decreased, we can conclude that the boundary scattering is predominately specular. Probably, the smooth potential from the depletion zone favors specular reflection.

![FIG. 2. (Color online) Magnetoresistivity as a function of the inverse magnetic field for a set of wires of different widths (sample 1). The slowly varying background resistivity $\rho_0(B)$ was subtracted. For clarity, the curves are offset by 2 $\Omega$. The resistance of the sets of wires was measured at a temperature of 0.5 K. The inset shows the resistivity of the 1090-nm-wide wires before the background resistivity $\rho_0(B)$ was subtracted.](image1)

The mobility $\mu$ and elastic mean free path $l_{el}$ was determined from $n_{2D}$ and $\rho(B=0)$.

![FIG. 3. (Color online) (a) Experimental magnetoconductivity $\sigma(B) - \sigma(0)$ normalized to $e^2/h$ for different sets of wires of sample 1. The measurement temperature was 0.4 K. Sets of wires with a geometrical width ranging from 1090 down to 340 nm were measured. The full lines show the calculated values using the Kettellmann model (Ref. 30). (b) Corresponding measurements of $\sigma(B) - \sigma(0)$ for sets of wires of sample 2 with widths in the range from 1110 to 360 nm. The full lines show the calculated magnetoconductivity.](image2)

We now turn to the investigation of spin-related effects in the electron transport. In Fig. 3(a), the normalized magnetoconductivity $\sigma(B) - \sigma(0)$ is shown for different sets of wires of sample 1. For the narrow wires with a width up to 440 nm, the magnetoconductivity monotonously increases for increasing values of $|B|$, which can be attributed to weak localization. The weak localization effect originates from the constructive interference of time-reversed paths for the case when spin-orbit scattering can be neglected. In contrast, for the 1090-, 880-, and 790-nm-wide wires, a peak is found in the magnetoconductivity at $B=0$, which is due to weak antilocalization. The slope of the magnetoconductivity changes sign at $|B| \approx 2.2$ mT. This value corresponds well to the position of the minima found in the weak antilocalization measurements on the Hall bars of sample 1. For magnetic fields beyond 2.2 mT, the transport is governed by weak localization, where the magnetoconductivity increases with $|B|$. As can be seen in Fig. 3(b), a similar behavior is found for sample 2. For wire widths up to 470 nm, weak localization is observed, whereas for the 1110-, 930-, and 720-nm-wide wires, weak antilocalization is found. In contrast to sample 1, the width of the weak antilocalization peak depends on the...
widths of the wires. For the first two sets of wires, minima in \( \sigma(B) - \sigma(0) \) are found at \( B = \pm2.2\, \text{mT} \), whereas for the 720-nm-wide wires, minima are observed at \( \pm1.5\, \text{mT} \). The peak height due to weak antilocalization decreases with increasing wire width. In general, the modulations of \( \sigma(B) - \sigma(0) \) are found to be considerably smaller for sample 2 compared to sample 1, which can be attributed to the smaller elastic mean free path and, as it will be shown later, to the smaller phase coherence length.

With increasing temperature, the weak antilocalization peak decreases. This can be seen in Fig. 4(a), where \( \sigma(B) - \sigma(0) \) is shown at different temperatures for the 930-nm-wide wires of sample 2. Above 2 K, no signature of weak antilocalization is found anymore. Furthermore, the weak localization contribution to \( \sigma(B) - \sigma(0) \) successively decreases with increasing temperature. This effect can be attributed to the decreasing phase coherence length with increasing temperature.\(^{36,37}\) As can be seen in Fig. 4(b), for the 360-nm-wide wires, only weak localization was observed. Similar to the wider sets of wires, the weak localization effect is damped with increasing temperatures.

From weak antilocalization measurements, the characteristic length scales, i.e., \( l_\phi \) and \( l_{\text{so}} \), can be estimated. In order to get some reference value for the 2DEG, the model developed by Iordanskii, Lyanda-Geller and Pikus\(^{38}\) (ILP model) was fitted to the weak antilocalization measurements of the Hall bar structures. Only the Rashba contribution was considered, here. For sample 1, \( l_\phi \) and \( l_{\text{so}} \) were found to be 1980 and 300 nm at 0.5 K, respectively, whereas for sample 2, the corresponding values were 1220 and 295 nm at 0.4 K. For both samples, the effective spin-orbit coupling parameter \( \alpha = h^2/2m^*l_{\text{so}} \) is approximately \( 5.8 \times 10^{-13} \) eV m. The zero-field spin-splitting energy can be estimated by using the expression \( \Delta_{\text{so}} = 2k_F\alpha \), with the Fermi wave number \( k_F \) given by \( \sqrt{2m^*E_F} \). For sample 1 one obtains a value of \( \Delta_{\text{so}} = 0.66 \) meV, while for sample 2 one finds 0.43 meV. The values of \( \Delta_{\text{so}} \) are relatively large compared to their corresponding Fermi energies, which confirms the presence of a pronounced spin-orbit coupling in Al\(_{0.5}\)Ga\(_{1-x}\)N/GaN 2DEGs.\(^{7,9-11}\)

The ILP model is only valid for 2DEGs with \( l_\phi \ll W \); thus, it cannot be applied to our wire structures. Very recently, a model appropriate for wire structures was developed by Kettemann,\(^{30}\) which covers the case \( W < l_\phi \). Here, the quantum correction to the conductivity is given by

\[
\sigma(B) - \sigma(0) = \frac{e^2}{\hbar} \left( \frac{\sqrt{H_W}}{H_\phi + B'/4} - \frac{\sqrt{H_W}}{H_\phi + B'/4 + H_{\text{so}}} \right) - 2 \frac{\sqrt{H_W}}{H_\phi + B'/4 + H_{\text{so}}/2},
\]

with \( H_\phi = \hbar/(4eW_{\text{eff}}^2) \) and \( H_W \) given by \( \hbar/(4eW_{\text{eff}}^2) \). The effective external magnetic field \( B' \) is defined by

\[
B' = B \left( 1 - \frac{1}{1 + W_{\text{eff}}^2/(2\hbar^2)} \right),
\]

with \( l_\phi = \hbar/eB \) as the magnetic length. The spin-orbit scattering length \( l_{\text{so}} \) in the wire can be obtained from the characteristic spin-orbit field \( H_{\text{so}} = \hbar/(4e l_{\text{so}}^2) \).

The Kettemann model was fitted to the experimental curves by adjusting \( H_{\text{so}} \) and \( H_\phi \). The corresponding values of \( l_{\text{so}} \) and \( l_\phi \) extracted from the fit are listed in Table I and shown in Fig. 5. Even for the widest wires, \( l_{\text{so}} \) is found to be larger than the value obtained for the 2DEG from the ILP fit. The deviations are probably already due to confinement effects. In addition, different approximations made in the ILP model\(^{38}\) for the two-dimensional case and the Kettemann model\(^{30}\) for wire structures might also account partially for the deviations.

As can be seen in Fig. 5, for sample 1, the spin-orbit scattering length \( l_{\text{so}} \) monotonously increases with decreasing \( W_{\text{eff}} \), while \( l_\phi \) decreases. The latter is in accordance to theoretical predictions.\(^{36,37}\) For the wider wires with \( W = 1090, \)
880, and 790 nm, $l_\phi$ exceeds $l_\alpha$, so that weak antilocalization is expected. In contrast, for the very narrow wires with $W_{\text{eff}}=230$ and 130 nm, the values for $l_\alpha$ obtained from the fit are close to or even exceed $l_\phi$. In this case, the spin rotation caused by spin-orbit coupling is not sufficiently strong to affect the interference of time-reversed paths.\textsuperscript{39} As a consequence, the weak antilocalization effect is suppressed so that weak localization remains. For the 340-nm-wide wires, a satisfactory fit could be obtained down to a lower boundary value of $l_\alpha$, indicated by the half filled symbol shown in Fig. 5(a). In principle, one could argue that the appearance of weak localization for the very narrow wires is solely due to a strongly reduced phase coherence length, while $l_\alpha$ remains at the relatively low values found for the wider wires. However, in our fits, the suppression of the weak antilocalization effect could not be explained by simply decreasing $l_\phi$ compared to the values of the wider wires. A satisfactory fit was only obtained if $l_\alpha$ was increased to a larger value compared to the wider wires.

As can be seen in Fig. 5, for sample 2, the spin-orbit scattering length $l_\alpha$ also increases with decreasing $W_{\text{eff}}$ although with a smaller slope, compared to sample 1. Similarly to sample 1, $l_\phi$ decreases with decreasing wire width. However, due to the lower elastic mean free path of sample 2, $l_\phi$ is considerably smaller for this sample (Fig. 5). All values of $l_\alpha$ and $l_\phi$ obtained from the fit are listed in Table I. A comparison of $\sigma(B)−\sigma(0)$ for the widest wires and for the Hall bar structures reveals that the weak antilocalization peak is larger by a factor of 2. Thus, although $l_\phi$ is significantly smaller than $W_{\text{eff}}$, this clearly indicates that the additional carrier confinement already affects the interference effects.\textsuperscript{39}

By fitting the Kettemann model to the measurements shown in Fig. 4, $l_\phi$ was determined for the 930- and 360-nm-wide wires at different temperatures. For both samples, a fixed value of $l_\alpha$, corresponding to the values at 0.4 K, were assumed. As can be seen in Fig. 5(a), inset, for both samples $l_\phi$ monotonously decreases with temperature, in accordance with theoretical models.\textsuperscript{36,37} At a temperature of 4 K, $l_\phi$ is found to be close to $l_\phi$. In that regime, the interference effects are expected to be suppressed. This is confirmed by the measurements where only a weak field dependence of $\sigma(B)−\sigma(0)$ is found.

For both samples, we found an increase of $l_\alpha$ with decreasing wire width and even a suppression of weak antilocalization for narrow wires. This observance is in accordance with weak antilocalization measurements of quantum wires based on low-band-gap materials, i.e., InGaAs or InAs.\textsuperscript{19,20} However, for these types of quantum wells, the coupling parameter $\alpha$ is usually very large. In this case, transport takes place in a different regime where $l_\alpha < l_\phi$ so that a more elaborated model had to be applied to extract $l_\alpha$.\textsuperscript{19} As discussed by Kettemann,\textsuperscript{30} the increase of $l_\alpha$ can be attributed solely to a modification of the backscattering amplitude. In an intuitive picture, the increase of $l_\alpha$ in narrow wires can be explained, by the reduced magnitude of accumulated random spin phases due to the elongated shape of relevant closed loops. Here, the spin phase accumulated in the forward direction is basically compensated by the propagation in the backward direction, so that the spin-related contribution to the interference of electrons backscattered on time-reversed paths tends to diminish. As a result, only weak localization is observed.\textsuperscript{15,19} Although the spin-orbit coupling strength in our AlGaN/GaN samples is small compared to heterostructures based on InAs and, thus, different models have to be consulted for a detailed description, the basic mechanism responsible for a suppression of the weak antilocalization effect is the same for both material systems. In our case, no decrease of spin-orbit coupling strength, quantified by $\alpha$, is required to account for the suppression of weak antilocalization in narrow wires. In fact, an estimation of the effect of the confinement potential on $\alpha$ based on the theory of Moroz and Barnes\textsuperscript{40} confirmed that for our wire structures no significant change of $\alpha$ with $W_{\text{eff}}$ is expected. As shown in Fig. 5(a), for sample 2 the increase of $l_\alpha$ with decreasing wire width is smaller than for sample 1. We attribute this to the fact that for sample 2 the larger extent of diffusive motion, quantified by the smaller value of $l_\phi$, partially masks the effect of carrier confinement. Due to the larger values of $l_\phi$ and $l_\alpha$ of sample 1 compared to sample 2, the shape of the loops responsible for the interference effect is affected more by the confinement of the wire. Thus, the enhancement of $l_\alpha$ is expected to be stronger. Indeed, theoretical calculations by Pareek and Bruno\textsuperscript{41} showed that for quasi-one-dimensional channels a strong increase of $l_\alpha$ can only be expected if $W_{\text{eff}}$ is in the order of $l_\phi$.

For narrow wires with $W_{\text{eff}}<l_\phi$, in the diffusive regime ($l_\phi<W_{\text{eff}}$), the spin-orbit scattering lengths can be estimated by\textsuperscript{30}

$$l_{\alpha,\text{diff}} = \sqrt{\frac{12}{3}} \frac{l_\alpha^{2D}}{W_{\text{eff}}} l_{\alpha,2D}. \quad (3)$$

Here, $l_{\alpha,2D}$ is the spin-orbit scattering length of the 2DEG. The calculated values of $l_{\alpha,\text{diff}}$ should only be compared to the fitted values of $l_\alpha$ of sample 2 since only for this sample is $l_\phi < W_{\text{eff}}$ fulfilled. As can be seen in Fig. 5(a), $l_\alpha$ calculated from Eq. (3) fits well to the experimental values corresponding to an intermediate effective wire width of $W_{\text{eff}}=480$ nm. However, for smaller effective wire widths, the calculated values of $l_{\alpha,\text{diff}}$ are considerably larger. Probably, spin scattering processes other than the pure Rashba contribution are responsible for this discrepancy.\textsuperscript{30}

An enhanced spin-orbit scattering length is very desirable for spin electronic devices. Providing that the strength of the spin-orbit coupling itself remains unchanged, a confinement to a quasi-one-dimensional system would result in a reduced spin randomization. A reduction of spin randomization is an advantage for the realization of spin electronic devices since it would ease the constraints regarding the size of these type of devices. In this respect, our finding that $l_\alpha$ increases with decreasing wire width is an important step toward the realization of spin electronic devices based on AlGaN/GaN heterostructures.

**IV. CONCLUSIONS**

In conclusion, the magnetotransport of AlGaN/GaN quantum wires had been investigated. Even for sets of quantum wires with a geometrical width as low as 340 nm, clear Shubnikov–de Haas oscillations were observed. Magne-
totransport measurements close to zero magnetic field revealed a suppression of the weak antilocalization effect for very narrow quantum wires. By comparing the experimental data with a theoretical model for one-dimensional structures, it was found that the spin-orbit scattering length is enhanced in narrow wires. The observed phenomena might have an important implication regarding the realization of spin electronic devices based on AlGaN/GaN heterostructures.

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