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Geometric factors in the magnetoresistance of n-doped InAs epilayers

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We investigate the magnetoresistance (MR) effect in n-doped InAs and InAs/metal hybrid devices with geometries tailored to elucidate the physical mechanism and the role of geometry in the MR. Despite the isotropic Fermi surface in InAs, we observe a strong intrinsic MR in the InAs epilayer due to the existence of a surface conducting layer. Experimental comparison confirms that the extraordinary MR in the InAs/metal hybrids outperforms the orbital MR in the Corbino disk in terms of both the MR ratio and the magnetic field resolution. The results also indicate the advantage of a two-contact configuration in the hybrid devices over a four-contact one with respect to the magnetic field resolution. This is in contrast to previously reported results, where performance was evaluated in terms of the MR ratio and a four-contact configuration was found to be optimal. By applying Kohler's rule, we find that at temperatures above 75 K the extraordinary MR violates Kohler's rule, due to multiple relaxation rates, whereas the orbital MR obeys it. This finding can be used to distinguish the two geometric effects, the extraordinary MR and the orbital MR, from each other. © 2013 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4834518>]

I. INTRODUCTION

The magnetoresistance (MR) of semiconductors has been known for decades and is commonly utilized in magnetic sensing applications. There is a list of factors that can bring about an MR effect. One is the physical or intrinsic contribution from the energy-band structure.^{1,2} In a system with a single carrier and spherical Fermi surface, no MR is expected. However, once the Fermi surface is more complicated and deviates from a spherical shape or more than one type of carriers are present, MR is predicted.

In addition, the magnetotransport property shows dependence on the geometry, e.g., the shape of the device and the placements of the electric contacts,^{3–5} resulting in the so-called geometric MR. This physical phenomenon arises from the Lorentz force exerted by the magnetic field, which points perpendicular to the direction of the moving charge carriers and deflects them by the Hall angle of $\arctan(\mu B)$, where μ denotes mobility. As a consequence, it changes the current path, thereby, the resistance. However, this effect is accompanied with a side product, the Hall effect. As the deflected current hits the edge of the bar and builds up charge accumulation (measured as the Hall voltage), the electric force generated from the accumulated charge counteracts the Lorentz force, eliminating the current deflection. In this case, no MR shows up after a transient period for charge accumulation. However, when the length of the semiconductor bar is much smaller than its width, the deflected current will flow out of the conducting region before it reaches the edge. Therefore, the Hall voltage is not fully developed allowing the current flow to keep a transverse component, thereby increasing the resistance. This is called the geometric MR effect, or

specifically, orbital MR. This is basically due to the orbital motion of the carriers induced by the Lorentz force and could be modeled using an anisotropic magneto-conductivity tensor. The Corbino disk is the quintessential geometry showing geometric MR, which is proven to be equivalent to an infinitely wide rectangular bar using the conformal mapping transformation.⁶ The Hall voltage is completely shorted in the Corbino geometry and a maximal geometric MR is observed. In practice, the Corbino disk is rarely employed, due to its low resistance. The MR can be effectively enhanced using geometric manipulation in narrow-gap, high-mobility semiconductors, such as InAs and InSb, since the Hall angle is very large even at moderate magnetic fields due to the large mobility in these systems. Such materials usually have electrons as dominant carriers.

Another approach to bring about geometric MR is by introducing inhomogeneities. For instance, geometric MR has been reported in an InSb bar with needle-like NiSb inhomogeneities.⁷ Moreover, the linear MR observed in $\text{Ag}_{2+\delta}\text{Te}$ and $\text{Ag}_{2+\delta}\text{Se}$ has also been attributed to inhomogeneities.^{8,9}

In the last decade, a massively enhanced geometric MR, the so-called extraordinary MR, has been observed at room temperature in a hybrid structure, which consists of a semiconductor bulk with a metal inhomogeneity.¹⁰ Similar to the orbital MR, the orbital motion of the carriers is also the origin of this effect. The magnetic field applied perpendicularly to the current causes a current deflection, resulting in a redistribution of the current from the metal inhomogeneity into the semiconductor and a resistance increase. The extraordinary MR has been found to have a much stronger effect (or MR ratio) than the orbital MR in Corbino disk. The fundamental principle of extraordinary MR is the change of the current path in the hybrid structure upon application of a magnetic field rather than the anisotropy of the magneto-conductivity of either the semiconductor or the metal. It has

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been demonstrated theoretically that the extraordinary MR is essentially an interfacial effect.¹¹

There are other origins for MR in systems involving ferromagnetic materials, such as in multilayers consisting of alternating ferromagnetic and non-ferromagnetic layers,^{12,13} or in colossal magnetoresistive materials,^{14,15} and in these cases, the MR is strongly linked to the scattering being dependent on the spin of the carrier.

In this paper, we report the magnetotransport properties in n-doped InAs epilayer devices with comparable dimensions but different geometries to elucidate the role of the geometry. Four different microscopic structures are fabricated in comparable dimensions and in the same batch, i.e., Corbino disks, hybrid van der Pauw (vdP) disks, hybrid bars with two-contact and four-contact configurations, to compare the mechanism and performance of the orbital and extraordinary MR. We address this discussion from both a physical (mechanism for MR) and technical (output performance) point of view. At last, we test Kohler’s rule, which applies to the MR based on orbital motion, to the intrinsic, orbital, and extraordinary MR and discover another essential difference between them. The intrinsic and orbital MR obey Kohler’s rule in the case of a single temperature dependence of the relaxation rate in the semiconductor, whereas the extraordinary MR always violates it, indicating that the extraordinary MR is not only geometrically induced, but multiple scattering mechanisms are involved.

II. EXPERIMENTAL METHODS

The semiconductor wafer is grown on a (100) oriented semi-insulating GaAs substrate using solid-source molecular beam epitaxy. The growth is started with, first, a 1 μm thick $\text{In}_x\text{Ga}_{1-x}\text{As}$ metamorphic buffer to accommodate the large lattice mismatch between InAs and GaAs, and followed by a 0.2 μm thick undoped InAs stabilizing buffer (Fig. 1). The 1.5 μm -thick Si-doped active InAs epilayer is deposited on top with an impurity concentration of the order of 10^{16} cm^{-3} .

Photolithographic techniques are employed to fabricate devices with different geometries from the InAs wafer in the same batch. The devices are patterned using wet etching in a 2 : 1 citric acid (1g in 1ml of water)/ H_2O_2 solution

Si-doped InAs active layer ($n = 10^{16}\text{ cm}^{-3}$)	1.5 μm
InAs stabilizing buffer	0.2 μm
$\text{In}_x\text{Ga}_{1-x}\text{As}$ metaphoric buffer	1 μm
GaAs(100) substrate	

FIG. 1. Layer diagram showing the n-doped InAs epitaxial structure.

exploiting the semi-insulating GaAs as an etch stop. The shunts and electrodes are metallized with a Ti (50 nm)/Au (250 nm) stack by magnetron sputtering. A rapid thermal annealing process at 250 $^\circ\text{C}$ is employed to realize ohmic contacts with a low contact resistivity of $\sim 10^{-7}\Omega\text{ cm}^2$. Fig. 2 shows the microscopic pictures of the devices: (a) the orbital MR device, which is a Corbino disk, and (b),(c) the extraordinary MR devices, where (b) is an internally shunted hybrid vdP disk and (c) is an externally shunted hybrid bar. The devices in Figs. 2(a) and 2(b) consist of the same InAs annuli with inner and outer radii of 120 μm and 160 μm , respectively. The concentric holes are filled with metal and act as electrode in (a) and as internal metal shunt in (b). The Corbino disk has its second electrode surrounding the InAs annulus, while the shunted vdP disk has its four electrodes symmetrically located on the quartering points of the InAs annulus. The device in Fig. 2(c) is an InAs rectangular bar with the dimension of 40 $\mu\text{m} \times 1000\text{ }\mu\text{m}$. The external shunt is placed on one side of the bar while the electrodes are on the other side.

For a two-contact configuration, the voltage is measured between the two corner electrodes, whereas for a four-contact configuration, the voltage is measured between two inner electrodes, which are symmetrically placed about the center of the bar with a spacing of 500 μm . For both the hybrid vdP disk and hybrid bar, the optimum geometries for obtaining highest MR ratio are chosen.^{16,17} In the case of the Corbino disk, the MR ratio is independent of the radius of the annulus,⁶ and the dimension is the same as for the hybrid vdP disk.

The magnetotransport measurements and device characterizations are carried out using a Quantum Design physical property measurement system (PPMS). Electric connections are formed using wire bonding. The resistance contribution

FIG. 2. Microscopic images (a) of Corbino disk, (b) of hybrid van der Pauw disk, and (c) of hybrid bar. The InAs regions are artificially coloured in blue for clarity. I_+ and I_- denote the electrodes used as current leads; V_+ and V_- denote the electrodes used as voltage probes. In (c), if the current leads and voltage probes coincide, it is a two-contact configuration; if the voltage is measured at the two electrodes in the middle, it is a four-contact configuration. The solid arrows indicate the directions of current flow. The scale bars are 100 μm .

from the wires including the contact resistance between the wires and the sample is eliminated as much as possible by employing a four-probe measuring technique. A constant current of 1 mA (in the linear current-voltage range) is applied to the devices via current leads throughout the measurements. Homogeneous external magnetic fields B ranging from -1 to 1 T are applied perpendicularly to the film surfaces in steps of 0.01 T to measure the magnetotransport behaviour in all geometries. The transport properties of the “as-grown” InAs wafer are characterized using the standard vdP technique¹⁸ on a macroscopic $1\text{ cm} \times 1\text{ cm}$ square-shaped vdP disk directly sliced from the wafer, in which the growth-induced petty inhomogeneity is averaged out. The temperature dependence of the transverse MR and Hall resistance is investigated in the temperature T range from 300 to 5 K with 1 K steps at a magnetic field of 0.1 T.

III. TRANSPORT PROPERTIES IN InAs EPILAYERS

A. Magnetic field dependence

As is well known, materials with a spherical Fermi surface do not exhibit MR. However, as Figs. 3(a) and 3(b) show, strong magnetic field dependences of transport properties are observed in our InAs samples, i.e., a significant variation of the Hall coefficient and a strong MR ratio, even though an isotropic mobility tensor and Fermi surface are expected in an InAs crystal.³ The Hall coefficient shows an anomalous behaviour, decreasing with increasing magnetic field and tending to saturate at higher fields, instead of maintaining a constant value expected in a single conducting layer.

The intrinsic MR ($\Delta\rho/\rho_0$) data are obtained from the transverse MR measurement which has shown to provide an excellent approximation of ($\Delta\rho/\rho_0$) at low field.⁴ We attribute the observed anomalous magnetic field dependences in the InAs epilayers to the surface state property of InAs, which tends to form a strong charge accumulation with a sheet density of $\sim 10^{12}\text{ cm}^{-2}$ on the free surface, independent of doping, caused by native surface defects.^{19,20} Hence, the surface accumulation layer with high carrier concentration

acts as a parallel transport channel, and therefore, a multi-layer conducting model needs to be employed.²¹ This gives rise to a strong magnetic field dependence of the Hall coefficient and resistivity.¹ It is worth to notice that the impact of the $0.2\text{ }\mu\text{m}$ undoped InAs stabilizing buffer layer on the conduction is negligible. The sheet conductance is defined as

$$G = \sigma \cdot d = en\mu d, \quad (1)$$

where $\sigma = 1/\rho = en\mu$ is the conductivity, e is the electron charge, n is the carrier density, μ is the electron mobility, and d is the thickness of the conductive layer. The contribution from holes is ignored owing to the small concentration in both n-doped and undoped InAs layers. For the undoped InAs buffer layer, the carrier concentration is of the order of 10^{14} cm^{-3} and the electron mobility is around $2 \sim 3 \times 10^4\text{ cm}^2/\text{V} \cdot \text{s}$ at room temperature. In contrast, the $1.5\text{ }\mu\text{m}$ thick bulk InAs is doped at 10^{16} cm^{-3} and has an electron mobility of $8160\text{ cm}^2/\text{V} \cdot \text{s}$ based on our vdP measurements. The sheet conductance of the doped top InAs layer is dominant, since it is more than two orders of magnitude higher than that of the undoped InAs buffer layer. Thus, the transport process can be reduced and described in terms of a bulk/surface two-layer model¹ for the doped InAs layer. The measured conductivity is

$$\sigma_0 = (G_b + G_s)/d, \quad (2)$$

where the subscripts b and s indicate the bulk-like and surface-like layer, respectively. The Hall coefficient and intrinsic MR are described as

$$R_h(B) = d \frac{\mu_s G_s + \mu_b G_b + B^2(\mu_b^2 \mu_s G_s + \mu_s^2 \mu_b G_b)}{(G_s + G_b)^2 + B^2(\mu_s G_b + \mu_b G_s)^2}, \quad (3)$$

$$\frac{\Delta\rho}{\rho_0} = \frac{(\mu_b - \mu_s)^2 G_s G_b B^2}{(G_b - G_s)^2 + B^2(\mu_s G_b + \mu_b G_s)^2}. \quad (4)$$

At low fields, the terms that do not include B^2 dominate in both the numerator and denominator of Eqs. (3) and (4) which can be approximated by the simplified forms

$$R_h(B) = \frac{d(\mu_s G_s + \mu_b G_b)}{(G_s + G_b)^2}, \quad (5)$$

$$\frac{\Delta\rho}{\rho_0} = \frac{(\mu_b - \mu_s)^2 G_s G_b B^2}{(G_b - G_s)^2}. \quad (6)$$

This explains the flat behaviour in the Hall coefficient curves and the quadratic behaviour in the MR curves observed at very low fields. At ultra-high fields, the terms including B^2 dominate, and both the Hall coefficient and intrinsic MR display constant values independent of magnetic field, indicating the tendency to saturate at high field.

The thickness of the surface accumulation layer d_s is estimated by the Debye length L_D , which is defined as

$$L_D = \sqrt{\frac{\epsilon_0 \kappa k_b T}{e^2 n_b}}, \quad (7)$$

FIG. 3. Magnetic field-dependence (a) of the Hall coefficient, and (b) of the intrinsic MR at various temperatures measured using standard van der Pauw technique. The solid lines show the theoretical data obtained from Eqs. (3) and (4).

where ϵ_0 is the permittivity of free space, κ is the static dielectric constant of InAs, k_b is Boltzmann's constant, and n_b is the carrier concentration in the bulk-like layer. The thickness of the bulk-like layer d_b is calculated as $d - d_s$. Besides d_s , another two fitting parameters μ_b and n_b are estimated from light-doped single crystal bulk InAs published data and ionized impurity concentration.

In order to calculate theoretical values for the Hall coefficient and MR ratios, using Eqs. (2)–(4) and (7), the values for the parameters of the surface-like layer, μ_s and n_s , still need to be found. They can be deduced by fitting theoretical curves to the experimental results. First, Eq. (3) is fitted to the Hall coefficient data, while the goodness of fit is evaluated using a chi-squared test. The fitted curves are plotted in Fig. 3(a) as solid lines, and the values of all parameters are listed in Table I. The prediction of MR ratios from Eq. (4) using the fitted parameters are plotted in Fig. 3(b) as solid lines; a good agreement is found with the experimental data. At lower temperatures larger deviations exist between the experimental and theoretical values. We ascribe this to the small value of d_s estimated using Eq. (7) at lower temperature. From the deduced data, the sheet density of the surface-like layer is 12.9×10^{12} , 8.1×10^{12} , 5.8×10^{12} , and $1.6 \times 10^{12} \text{ cm}^{-2}$ at 300, 200, 100, and 5 K, respectively. These values are in accordance with those reported for the sheet density of InAs surfaces of $\sim 10^{12} \text{ cm}^{-2}$. As conclusion, the experimental data can be well approximated by the two-layer theoretical model, which provides an explanation for the anomalous magnetotransport behaviour observed in the InAs epilayer samples.

B. Temperature dependences

The temperature dependences of the transport properties in the InAs samples are shown in Fig. 4. The mobility and carrier density values in Fig. 4 are directly obtained from the vdP measurement with n via the Hall measurements at 0.1 T and μ calculated from the Hall coefficient and resistivity data. Their values at 300 K and zero field can be calculated theoretically as $\mu(0) = 0.99 \times 10^4 \text{ cm}^2/\text{V} \cdot \text{s}$ and $n(0) = 6.0 \times 10^{16} \text{ cm}^{-3}$, using the following equations derived from Eqs. (1)–(3) and the parameters listed in Table I:

$$\mu(0) = \frac{\mu_b^2 n_b d_b + \mu_s^2 n_s d_s}{\mu_b n_b d_b + \mu_s n_s d_s},$$

$$n(0) = \frac{(\mu_b n_b d_b + \mu_s n_s d_s)^2}{d(\mu_b^2 n_b d_b + \mu_s^2 n_s d_s)}. \quad (8)$$

TABLE I. Fitting parameters μ_b , n_b , and d_s and deduced parameters μ_s and n_s at different temperatures in the InAs samples.

T (K)	μ_b ($10^4 \text{ cm}^2/\text{V} \cdot \text{s}$)	n_b (10^{16} cm^{-3})	μ_s ($10^4 \text{ cm}^2/\text{V} \cdot \text{s}$)	n_s (10^{18} cm^{-3})	d_s (nm)
300	1.6	2.00	0.336	3.93	32.88
200	2.5	1.92	0.529	2.69	30.10
100	4.8	1.47	1.007	2.35	24.63
5	2.0	0.48	0.420	1.80	8.70

FIG. 4. (a) Mobility μ and carrier concentration n , and (b) resistivity ρ_0 as a function of temperature in the InAs epilayer samples directly measured using the van der Pauw technique at 0.1 T. The solid line shows the best-fit of Matthiessen's rule to mobility data.

A moderate *nominal* mobility μ of $8160 \text{ cm}^2/\text{V} \cdot \text{s}$ and carrier density n of $5.6 \times 10^{16} \text{ cm}^{-3}$ have been measured at room temperature $T = 300 \text{ K}$ and a magnetic field $B = 0.1 \text{ T}$. The mobility shows its maximum value of $25000 \text{ cm}^2/\text{V} \cdot \text{s}$ at around 75 K. The mobility can be determined from the relaxation rate approximation as

$$\mu = \frac{e\tau}{m^*}, \quad (9)$$

where τ is the relaxation rate of the free electron and m^* is the effective mass of the electron. The scattering processes influence the relaxation rate, thereby, limiting the mobility value.

The experimental data obtained are fitted with the combined mobility model using Matthiessen's rule. Above 75 K, the mobility decreases with increasing temperature and is proportional to T^a with an exponent $a \sim -1.55$, which is in good agreement with the theoretical model of bulk InAs ($\mu \propto T^{-1.5}$) dominated by lattice vibration scattering. Below 75 K, the mobility decreases with decreasing temperature and becomes proportional to T^b with an exponent $b \sim 0.8$, as the manifestation of a different scattering mechanism, which is usually ionized impurity scattering. However, there are discrepancies between the model obtained from fitting the experimental data ($\mu \propto T^{0.8}$) and the impurity scattering model ($\mu \propto T^{1.5}$). Similar anomalous temperature dependence of mobility at low temperature with an exponent of 0.8 has been reported in InAs epilayers before,²² which is attributed to scattering due to dislocations. The smaller value of the exponent (or slope) suggests the presence of additional scattering processes in this temperature range. One reasonable explanation is that, even at low temperature, the thermal vibration of the lattice cannot be neglected, due to the large carrier density in the surface layer.

IV. MAGNETORESISTANCE IN DIFFERENT GEOMETRIES

A. Resistances at zero-field

The MR ratio is defined as $MR = (R(B) - R(0))/R(0)$, where $R(B)$ is the magnetoresistance with magnetic field and

FIG. 5. Sketch and the equivalent electric circuit of the hybrid bar. V_2 and V_4 denote the voltage probes used in two-contact and four-contact configurations, respectively.

$R(0)$ is the zero-field resistance. It is clear that $R(0)$ has a critical impact on the value of the MR ratio. Therefore, at first, zero-field resistances in different geometries are investigated. Considerably small values of zero-field resistances, i.e., 4.84, 3.9, 2.99, and 4.38 Ω at 300, 200, 100, and 5 K, respectively, are measured in the Corbino disk, resulting from the large cross-section area of the annulus-shaped semiconductor channel compared to the length.

Remarkably small values of $R(0)$ are observed in the four-contact hybrid geometries, the hybrid vdP disk and four-contact hybrid bar, e.g., 0.22 and 0.69 Ω at 300 K, respectively. In contrast, large resistance values are measured for the two-contact hybrid bar, i.e., 156, 127, 99, and 118 Ω at 300, 200, 100, and 5 K, respectively. The rather large differences in the resistance of these two different contact configurations can be understood using the equivalent electric circuit of the hybrid bar shown in Fig. 5.

Because of the high conductivity of the metal shunt, the majority of the current flows in a direction *perpendicular* to the long edge of the bar into the metal at the input lead (equivalent resistor R_{sl}), followed by a path in the metal shunt *parallel* to the long edge (equivalent resistor R_m), and exits the metal shunt in a direction *perpendicular* to the long edge of the bar into the output current lead (equivalent resistor R_{sr}) (Fig. 2(c)). The middle part of the InAs bar R_{sp} is effectively shorted by the negligible resistance R_m of the shunt, compared to the resistivity of InAs (Fig. 4). Thus, the resistance of the entire hybrid bar can be approximated by $R_{sl} + R_{sr}$. A finite element analysis suggests that the current flow in the InAs bar is concentrated in the narrow area near the current electrodes with a width of $\sim 50 \mu\text{m}$.²³ Based on $R = \rho_0 L / (Wd)$, the hybrid bar resistance is expected to be 30 times larger than that of the Corbino disk, which is in good agreement with the experimental data. With the optimized four-contact configuration, only the parallel circuit $R_{sp} \parallel R_m$ is measured. As a consequence, small values of $R(0)$ are measured.

B. Magnetoresistance responses

Fig. 6 shows the MR measurements at different temperatures in the Corbino disk, hybrid vdP disk, and hybrid bar devices. Symmetric MR curves with respect to the directions of the magnetic field are found in all geometries. A slight asymmetry observed in the hybrid vdP disk originates from an alignment error of the concentric metal shunt.

The MR ratios calculated from the MR data are plotted in Fig. 7. At all temperatures, the extraordinary MR effect in

the hybrid geometries produces a higher MR ratio than the orbital MR in the Corbino geometry with the intrinsic MR being the lowest (see Fig. 3(b)), which demonstrates enhancement of the MR effect in the InAs epilayers achieved by the geometric manipulations. In addition, a strong temperature dependence of the MR ratio is observed in all geometries with the MR ratio being the highest around 100 K, where the mobility is maximum. This is due to the fact that both the orbital MR in Corbino geometry and the extraordinary MR in hybrid geometries strongly depend on the mobility value of the semiconductor^{6,26,27} and are enhanced in semiconductors having larger mobility, as a result of the increased current deflection.

The response of the hybrid vdP disk resembles the one of the four-contact hybrid bar (see Figs. 6(b) and 6(c)), as expected, since the geometries of these two devices can be transformed from each other using bilinear conformal mapping.²⁵ The small distinctions observed are from the slight geometric difference, e.g., the wider current leads used in the hybrid vdP disk compared to the bar geometry (Fig. 2). As a consequence, current spreads wider into the InAs region in the hybrid vdP disk, resulting in a lower $R(0)$ (3 to 4 times). This causes enhanced MR ratios (3 to 4 times) in the hybrid vdP disk compared to the four-contact hybrid bar (Fig. 7).

FIG. 6. Resistance curves measured as a function of applied field at 300, 200, 100, and 5 K in different geometries (a) Corbino disk, (b) hybrid van der Pauw disk, (c) four-contact hybrid bar, and (d) two-contact hybrid bar.

FIG. 7. MR ratio curves measured in different geometries as a function of applied field at (a) 300 K, (b) 200 K, (c) 100 K, and (d) 5 K. Note that axis breaks are used in the MR axes.

The contact configuration is crucial for the MR ratio since the MR ratio depends on the value of $R(0)$. In the hybrid bar, the four-contact configuration exhibits a significant enhancement of the MR ratio compared to the two-contact one at all temperatures (Fig. 7). Despite the ~ 70 times reduction in the value of the resistance change ($R(B) - R(0)$) (see Fig. 6) in the four-contact configuration compared to the two-contact one, the MR ratio is still larger in the four-contact configuration due to the larger reduction of $R(0)$ (~ 250 times smaller).

In all geometries, the MR curves show a quadratic dependence at low magnetic fields that eventually evolves to a quasi-linear behavior as the field increases (Fig. 7). We attribute the crossover to the breakdown of the electron transport by diffusion in InAs at high field. As an example, we investigate the case of the Corbino disk. When the magnetic field dependence of the mobility is considered, the orbital MR ratio in a Corbino disk is⁶

$$MR = (\mu(B) \cdot B)^2, \\ \mu(B) = \frac{R_h(B)}{\rho(B)} \Rightarrow MR = \frac{(R_h \cdot B/\rho)^2}{[1 + (\Delta\rho/\rho_0)]^2}. \quad (10)$$

Hence, the orbital MR ratio can be predicted theoretically using Eq. (10) with the transport property data obtained for InAs through vdP measurement. The result is plotted in Fig. 8, which is found to have an excellent agreement with the experimental one at weak fields, where $\mu B < 1$. However, at $\mu B > 1$, the electrons start following an orbital motion, the MR curve transits from a quadratic behaviour to a quasi-linear one, and the diffusion transport model on which Eq. (10) is based is no longer tenable. For instance, at 100 K, InAs shows a mobility μ of $\sim 24\,000 \text{ cm}^2/\text{V} \cdot \text{s}$ and the crossover occurs at the field of $\sim 0.4 \text{ T}$.

FIG. 8. Open symbols show orbital MR ratios measured in Corbino disk at different temperatures; the solid lines show the theoretical predictions using Eq. (10).

V. OUTPUT PERFORMANCES OF DIFFERENT GEOMETRIES FOR SENSING APPLICATIONS

Even though very large MR ratios can be achieved with the four-contact hybrid geometry, this geometry does not guarantee a good performance in sensing applications. A similar issue has been argued for the geometrically enhanced piezoresistance in semiconductor/metal hybrids before, where large relative resistance changes were achieved, but the resolution was low.^{28,29} From a practical point of view, the magnetic field resolution B_{min} , which is the minimum detectable field change, is of great importance when evaluating the device performance. It is determined by the sensitivity together with the noise as $B_{min} = \sqrt{S}/(I \cdot \delta)$, where δ is the output sensitivity, $\sqrt{S}$ is the noise voltage, and I is the current input (in this work, we use $I = 100 \mu\text{A}$).

The output sensitivity is defined as the rate of change of the MR with respect to the magnetic field, i.e., $\delta = \partial R(B)/\partial B$. Since the hybrid vdP and four-contact hybrid bar are equivalent in terms of output behavior, only the performance of the four-contact hybrid bar is examined in this section. The dependence of δ on the magnetic field is shown in Fig. 9(a) for the Corbino disk and the two-contact and the four-contact hybrid bars. The four-contact hybrid device does not provide an improved sensitivity compared to the Corbino disk. On the other hand, as a result of the large resistance, the hybrid device with a two-contact configuration shows a sensitivity which is larger than the sensitivities of the four-contact device and the Corbino disk by two orders of magnitude. In addition, the two-contact extraordinary MR device exhibits a constant sensitivity in the range from ~ 0.2 to 1 T , which is an advantage over the four-contact device for sensing applications.

In the InAs devices, flicker noise dominates at low-frequency,³⁰ while at higher frequencies Johnson noise dominates, which is given by $\sqrt{S_J} = \sqrt{4k_b T R}$. As is known, Johnson noise is produced by thermal agitations of the electrons at equilibrium inside the entire system, regardless of any applied current. It is worth to note that in the four-contact device, the resistance R that accounts for Johnson

FIG. 9. (a) Output sensitivity, (b) measured series resistance (for Corbino disk, see Fig. 6(a)), (c) calculated Johnson noise, and (d) magnetic field resolution with respect to applied field in the Corbino disk and the hybrid bar devices with two-contact and four-contact configurations at 300 K.

noise is the so-called series resistance R_{series} , which is measured at two voltage sensing probes of a device,^{31,32} and is different from the resistance measured for the MR ratio calculations. For two-contact devices, i.e., the Corbino disk and the two-contact hybrid bar, the value of R_{series} is the same as the one relevant for the MR measurements. R_{series} measured in the hybrid devices at the sensing electrodes for both the two-contact and four-contact configurations at 300 K are plotted as a function of B in Fig. 9(b). R_{series} obtained without magnetic field for the four-contact hybrid bar is 136.9Ω at 300 K, which is close to that for the two-contact configuration (156.2Ω), even though the distance between the electrodes differs by a factor of two between the two configurations. This is due to the fact that most of R_{series} is attributed to the resistance of the semiconductor, where the current path is perpendicular to the long edge of the bar and is equivalent for both measurement configurations. Fig. 9(c) shows the Johnson noise calculated for the Corbino disk and the two-contact and four-contact hybrid as a function of B . The noise voltage values of the two-contact and four-contact hybrid devices are very similar as expected from the similar values of R_{series} . Owing to its lower value of R_{series} , the Corbino disk exhibits the advantage of lower noise voltage compared to the hybrid devices.

The magnetic field resolutions of the three devices are shown in Fig. 9(d). Suffering from the low sensitivity and high noise voltage, the hybrid device with four-contact configuration shows rather poor resolution. Even though the geometric manipulation produces a high MR ratio, the four-contact hybrid device is inferior to the conventional Corbino disk in terms of the magnetic field resolution. Interestingly, in spite of the moderately enhanced MR ratio, the two-contact hybrid geometry shows the highest resolution, which is one order and two orders larger than that of the Corbino disk and the four-contact hybrid device, respectively. At zero field, the resolution is $2.7 \mu\text{T}/\sqrt{\text{Hz}}$. From zero to 0.2 T, the resolution increases dramatically, as a result of the increasing sensitivity. From 0.2 to 1 T, where the sensitivity

is constant, the resolution also is almost constant at $\sim 12 \text{ nT}/\sqrt{\text{Hz}}$. With a lock-in amplifier and a bandwidth of 1 Hz, the two-contact hybrid device has the potential to detect a magnetic field change as small as $\sim 12 \text{ nT}$ with a $100 \mu\text{A}$ current input, which is about ~ 15 and ~ 75 times better than that of the Corbino disk and four-contact hybrid device, respectively. This result demonstrates that both MR ratio and output performance are boosted in the InAs epilayer by tailoring a metallic hybridized architecture with only two electric contacts.

VI. KOHLER'S RULE: DISTINGUISHING BETWEEN GEOMETRIC MAGNETORESISTANCES

As mentioned at the beginning, the MR effects can be categorized by their origins, i.e., the intrinsic physical MR effect and geometric MR effect. In this section, we show that the MR effects can be categorized in a different way using Kohler's rule with the orbital MR and the extraordinary MR, which are geometric effects, being distinguished from each other using Kohler's rule.

According to Kohler's rule, the MR ratio curves, measured at different temperatures and fields, can be scaled onto a single curve, if there is a single temperature dependence of the relaxation rate at all points on the Fermi surface in the transport process or in other words the anisotropy of the relaxation rate is temperature independent. Thus, the violation of Kohler's rule, if any, translates into the breakdown of such an assumption, indicating the presence of different scattering mechanisms, resulting in the anisotropy of the relaxation rate being temperature dependent. Kohler's rule is not an accurate tool; however, it provides a fast track to determine the scattering processes in the system.

The Kohler's rule is expressed as

$$\frac{\Delta R}{R(0)} = f(\omega_c \tau) = f\left(\frac{B}{ne\rho_0}\right) = f\left(\frac{BR_h}{\rho_0}\right), \quad (11)$$

where $\Delta R/R(0) = f(\omega_c \tau)$ is the accurate form, f is the scaling function, and ω_c denotes the cyclotron angular frequency. One simplified form of Kohler's rule, $\Delta R/R(0) = f(B/\rho_0)$, where n and m^* are considered as constant, is frequently employed; however, a casual use of it sometimes results in an incorrect conclusion.³³ For instance, when n has a strong dependence on temperature or magnetic field, the simplified form of Kohler's rule is inaccurate. In this study, we use BR_h/ρ_0 to approximate $\omega_c \tau$ to take into account the strong temperature dependence of the carrier density.

We prepare the Kohler's diagrams for different geometries (effects) by plotting their MR ratio data versus BR_h/ρ_0 . In Fig. 10, the Kohler's diagrams are shown for MR effects in the structures without metal shunt, hereafter referred to as the simplex InAs geometries, i.e., intrinsic and orbital MR effects. For both of them, the data at temperatures of 300, 200, and 100 K share the same slope implying the obedience of Kohler's rule; however, at 5 K, Kohler's rule fails as a deviation of the MR curve from the Kohler's diagram is observed. In order to investigate this behaviour at lower

FIG. 10. Kohler's diagram for (a) intrinsic MR in InAs epilayer and (b) orbital MR in Corbino disk. The quadratic law is provided as broken lines. Insets show the detail in the dash boxes.

temperatures in more detail, the MR data at 75, 50, and 25 K are also examined, revealing that above 75 K, the curves coalesce. Deviations occur at lower temperatures and become more pronounced with decreasing temperature. As a conclusion, for both intrinsic and orbital MR effects, Kohler's rule is obeyed by the simplex InAs system at $T \geq 75$ K and violated at $T < 75$ K. This can be explained by the temperature dependence of the mobility in InAs, where at $T \geq 75$ K scattering from the lattice vibration dominates, whereas at $T < 75$ K, different scattering mechanisms (ionized impurity scattering) dominate. Deviation of the MR curves from the Kohler diagram at $T < 75$ K implies that the anisotropy of the scattering rate for ionized impurity is different from that of the lattice vibration and that there is probably more than one scattering mechanism at $T < 75$ K, which agrees with the conclusion drawn from the temperature dependence of the mobility.

A quadratic behaviour is observed at weak fields (thin solid lines), which begins to convert to a linear behaviour at $BR_h/\rho_0 \sim 0.5$, and is linear at fields where $BR_h/\rho_0 > 0.75$ (Figs. 10(a) and 10(b)). The linear MR is retained in both geometries at higher fields. The crossover from weak-field behaviour to strong-field behaviour, which determines the applicability of Eq. (10), occurs at $\omega_c\tau \sim 0.5$, a field value where the electron is substantially short from completing a cyclotron orbit before experiencing a collision.

The origin of the intrinsic MR in InAs is the existence of a two-layer conducting channel. Bending of the carrier trajectory, due to the Lorentz force, is compensated by the Hall voltage and only causes transient effects. By shorting the Hall voltage, using geometric manipulation, the enhanced orbital MR in the Corbino disk is obtained. It is important to note that, in this case, the geometric manipulation does not introduce a new scattering mechanism or alter the relaxation rate and Kohler's rule is obeyed.

Kohler's rule is strongly violated in all hybrid geometries showing the extraordinary MR effect at all temperatures (Fig. 11). In the case of the hybrid vdP geometry, at low field range, each MR ratio curve exhibits a quadratic behaviour and turns to linear at fields where $\omega_c\tau > 0.75$. The explanation of the violation is straightforward: due to the existence

FIG. 11. Kohler's diagram for extraordinary MR in (a) hybrid van der Pauw disk, (b) four-contact hybrid bar, and (c) two-contact hybrid bar. Insets show the detail in the boxes.

of a large metallic inhomogeneity, the relaxation rate for the electrons in the hybrid system consisting of a semiconductor and a metal cannot be described by a single temperature dependence. Moreover, the condition of the semiconductor/metal interface is crucial to extraordinary MR;²⁴ the scattering at the interface region is also different from that in the metal or the semiconductor. The carriers in the semiconductor, metal, and the interface region have totally different relaxation rates and temperature dependence. The hybrid geometry should exhibit, at least, three relaxation rates. In addition, the carrier density in the metal is independent of temperature, whereas the carrier density in the semiconductor is temperature dependent. Thus, the violation of Kohler's rule in extraordinary MR is an indication that current redistribution between the metal and the semiconductor (it depends on the Hall angle, conductance difference between metal and semiconductor, and the interface condition²⁴) occurs in addition to current deflection inside the semiconductor (it depends on the Hall angle) since current deflection inside the semiconductor alone does not necessarily cause violation of Kohler's rule. The current redistribution and current deflection contribute to the extraordinary MR simultaneously, differentiating the extraordinary MR from the geometric MR effect based on Lorentz force-induced current deflection only.

VII. CONCLUSION

In summary, MR effects in devices with different geometries fabricated from InAs epilayers are investigated. We study and compare two strong geometric MR effects in different geometries, i.e., the orbital MR in Corbino disks and the extraordinary MR in hybrid vdP disks and hybrid bars with two-contact and four-contact configurations. In order to isolate the contribution of the physical mechanism in the device performance, the device dimensions are kept the same where possible, such as keeping the dimension of the outer diameters of the circular devices the same. The hybrid bar is designed to conformally map to the hybrid vdP disk and their performances are compared. We observe intrinsic MR in

vdP geometry with no metal shunt, which can be explained as a result of the strong field-dependent transport property in a bi-layer conductor consisting of surface and bulk conducting channels. At all temperatures, the extraordinary MR outperforms the orbital MR and intrinsic MR, and the MR behaviours of the hybrid vdP disk and hybrid bar are essentially the same, confirming the conformal mapping. Even though the four-contact hybrid devices show the largest MR ratio, the two-contact hybrid bar shows the advantage over other geometries of a larger magnetic field resolution. The resolution of ~ 12 nT/ $\sqrt{\text{Hz}}$, found for the two-contact hybrid device in this work, is ~ 15 and ~ 75 times better than that of Corbino disk and the four-contact hybrid device, respectively. This value indicates that through geometric manipulation extraordinary MR devices might be employed for low-field applications.

The different MR effects in different geometries are described as intrinsic or geometric effects, depending on whether there is an enhancement in the MR due to the device geometry, with the Corbino and extraordinary MR being in the group of geometric effects. In this work, we demonstrate that the geometric MR effects can be distinguished based on whether they obey Kohler's rule, with the intrinsic and orbital MR obeying Kohler's rule for temperatures where a single temperature dependence of the relaxation rate is observed in the semiconductor (>75 K), whereas the extraordinary MR always violates Kohler's rule, due to different relaxation rates in the semiconductor and the metal. This shows that the extraordinary MR effect is not merely a geometric manipulation; instead, it also has physical components, since additional scattering mechanisms are involved.

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