Extraordinary Magnetoresistance Effect in Semiconductor/Metal Hybrid Structures

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ABSTRACT

Extraordinary Magnetoresistance Effect in Semiconductor/Metal Hybrid Structures

Jian Sun

In this dissertation, the extraordinary magnetoresistance (EMR) effect in semiconductor/metal hybrid structures is studied to improve the performance in sensing applications.

Using two-dimensional finite element simulations, the geometric dependence of the output sensitivity, which is a more relevant parameter for EMR sensors than the magnetoresistance (MR), is studied. The results show that the optimal geometry in this case is different from the geometry reported before, where the MR ratio was optimized. A device consisting of a semiconductor bar with length/width ratio of 5~10 and having only 2 contacts is found to exhibit the highest sensitivity.

A newly developed three-dimensional finite element model is employed to investigate parameters that have been neglected with the two dimensional simulations utilized so far, i.e., thickness of metal shunt and arbitrary semiconductor/metal interface. The simulations show the influence of those parameters on the sensitivity is up to 10 %. The model also enables exploring the EMR effect in planar magnetic fields. In case of a bar device, the sensitivity to planar fields is about 15 % to 20 % of the one to perpendicular fields.
A “top-contacted” structure is proposed to reduce the complexity of fabrication, where neither patterning of the semiconductor nor precise alignment is required. A comparison of the new structure with a conventionally fabricated device shows that a similar magnetic field resolution of 24 nT/√Hz is obtained.

A new 3-contact device is developed improving the poor low-field sensitivity observed in conventional EMR devices, resulting from its parabolic magnetoresistance response. The 3-contact device provides a considerable boost of the low field response by combining the Hall effect with the EMR effect, resulting in an increase of the output sensitivity by 5 times at 0.01 T compared to a 2-contact device.

The results of this dissertation provide new insights into the optimization of EMR devices for sensor applications. Two novel concepts are presented, which are promising for realizing EMR devices with high spatial resolution and for opening new applications for EMR sensors in the low-field regime.
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<td>MR</td>
<td>magnetoresistance</td>
</tr>
<tr>
<td>EMR</td>
<td>extraordinary magnetoresistance</td>
</tr>
<tr>
<td>AMR</td>
<td>anisotropic magnetoresistance</td>
</tr>
<tr>
<td>GMR</td>
<td>giant magnetoresistance</td>
</tr>
<tr>
<td>TMR</td>
<td>tunneling magnetoresistance</td>
</tr>
<tr>
<td>2D</td>
<td>2-dimensional</td>
</tr>
<tr>
<td>3D</td>
<td>3-dimensional</td>
</tr>
<tr>
<td>FEA</td>
<td>finite element analysis</td>
</tr>
<tr>
<td>vdP</td>
<td>van der Pauw</td>
</tr>
<tr>
<td>2DEG</td>
<td>2-dimensional electron gas</td>
</tr>
<tr>
<td>AlSb</td>
<td>aluminum antimonide</td>
</tr>
<tr>
<td>InAs</td>
<td>indium arsenide</td>
</tr>
<tr>
<td>Ti</td>
<td>titanium</td>
</tr>
<tr>
<td>Au</td>
<td>gold</td>
</tr>
<tr>
<td>Cr</td>
<td>chromium</td>
</tr>
<tr>
<td>GaAs</td>
<td>gallium arsenide</td>
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Chapter 1

Introduction

Magnetic sensors have become important electronic components in contemporary life and technologies with applications in various fields like consumer electronics, medical devices, industry or national defense. From the applications’ perspective, the need for improved sensors is ubiquitous. Generally, the trends are toward smaller size, faster response, higher sensitivity, lower cost, and lower power consumption. In practice, each application requires to make a trade-off between some properties [1]. For example, the widely used Hall sensor has the advantages of low power consumption, small size, and low cost, but suffers from a rather low sensitivity and poor temperature stability. In contrast, anisotropic magnetoresistance (AMR) sensors show a high temperature stability and a high sensitivity; however they normally have a large size, high power consumption and high price.

<table>
<thead>
<tr>
<th>Sensor(Model)</th>
<th>Sensitivity @ 5V (V/T)</th>
<th>Resolution @ 10 Hz (nT)</th>
<th>Linear Range (µT)</th>
<th>Price (USD)</th>
<th>Power (mW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hall (CSA1VG) [2]</td>
<td>280</td>
<td>&lt; 400</td>
<td>5000</td>
<td>~ 3</td>
<td>5</td>
</tr>
<tr>
<td>AMR (HMC1001) [3]</td>
<td>50</td>
<td>20</td>
<td>300</td>
<td>~ 15</td>
<td>30</td>
</tr>
<tr>
<td>GMR (AAL002) [4]</td>
<td>150</td>
<td>15</td>
<td>50</td>
<td>~ 8</td>
<td>5</td>
</tr>
</tbody>
</table>

1The data is for the sensors operated with driven voltage is 5V
2The data is for the sensors operated with a bandwidth of 10 Hz
Important properties of the some typical, commercial sensors, i.e., Hall sensor, AMR sensor, and giant magnetoresistance (GMR) sensor, are listed in TABLE 1.1.

In the last decades, magnetoresistance (MR) devices, which have a resistance value that depends on the state of magnetization, have become increasingly important in magnetic sensing. They are now critical components in technologies such as high-density information storage [5-7], bio-chips [8,9], space applications [10] and position monitoring [1].

There are several factors influencing the MR effect. One of them is the physical or intrinsic contribution stemming from the magnetic field dependence of carrier mobility, energy-band structure, or spin-spin interactions [10-12]. In a system with a single carrier and spherical Fermi surface, no magnetoresistance is expected. However, once the Fermi surface is more complicated and deviates from a spherical shape or more than one type of carrier are present, a magnetoresistance effect can be expected. In this case, the dependence of the resistivity on the magnetic field is due to the energy-band structure, which determines the Fermi surface and the types of carriers present. The majority of MR sensors utilize physical contributions such as GMR [13] and tunneling magnetoresistance (TMR) [14]. The GMR and TMR effects are observed in stacks of magnetic thin films separated by conducting and insulating layers, respectively. The resistance of those devices is a function of the magnetic field, due to the dependence of the spin-polarized current on the magnetization direction of the magnetic layers. GMR and TMR sensors have a huge technological and economic impact, e.g., in form of read-
head sensors in modern computer hard disk drives [6,7]. Currently, current-perpendicular-to-plane GMR sensor types are considered as promising candidates for next-generation read-head devices [15].

In addition, the magnetotransport property (the term magnetotransport refers to the transport of electrons through a semiconductor by a magnetic field) also shows a dependence on geometrical parameters, e.g., the shape of the device, the placements of the electric contacts, and any inhomogeneities [16-19], resulting in the so-called geometric MR. This physical phenomenon arises from the Lorentz force exerted on moving charge carriers by a magnetic field, which points perpendicularly to the direction of the moving charge carriers and deflects them by the Hall angle. As a consequence, it changes the current path, thereby, the resistance. However, this effect always produces a “side product”, the Hall effect. When the deflected current hits the structural boundary of a device, charges accumulate (generating the Hall voltage) until the electric force generated from the accumulated charges balances the Lorentz force, eliminating the current deflection. In this case, MR is a transient effect that last only until charge accumulation is completed. However, when the length of the structure is much smaller than its width, the current will flow through the structure before reaching the edge. Therefore, the Hall voltage will not fully develop, and the current flow will keep a transverse component, increasing the resistance. This effect is called geometric MR or, specifically, orbital MR. It is caused by the orbital motion of the carriers, induced by the Lorentz force, and can be modeled using an anisotropic magnetoconductivity tensor.
The Corbino disc is a typical structure showing geometric MR. It has been shown to be equivalent to an infinitely wide rectangular bar using a conformal mapping transformation [20]. The Hall voltage is completely shorted in the Corbino disc geometry, and the highest possible geometric MR effect is observed. In practice, the Corbino disc is rarely employed, due to its low resistance. The geometric MR effect is enhanced 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 the dominant carriers. Another approach to create a geometric MR effect is to introduce inhomogeneities. For instance, the geometric MR has been reported in an InSb bar with needle-like NiSb inhomogeneities [21]. Moreover, a linear MR, observed in Ag_{2+δ}Te and Ag_{2+δ}Se, has also been attributed to inhomogeneities [22].

In the last decade, a largely enhanced, geometric MR effect, the so-called extraordinary magnetoresistance (EMR), has been observed in hybrid structures, which consist of a high-mobility semiconductor and a metal shunt [23]. As in the case of the orbital MR effect, the orbital motion of carriers is the origin of the EMR effect. This effect, which has shown MR values of more than one million percent over a magnetic field range of several Tesla, has drawn much attention, due to its potential advantages over other solid-state magnetic field sensors. One advantage is that noise is rather low in EMR devices. Since they are made of nonmagnetic materials, there is no contribution from magnetic noise, as it is in contemporary TMR or GMR devices [24,25]. Compared to
Hall sensors, they show less thermal noise, due to the lower resistance resulting from the highly conductive metal shunt. Despite their favorable properties, EMR devices have no relevance in the magnetic sensor market so far, due to several disadvantages; e.g., the intrinsically nonlinear response and a low output signal in the low-field range.

1.1 Background

1.1.1 Basic Principle

If a carrier of charge $q$ moves with velocity $v$ in the presence of an electric field $E$ and a magnetic field $B$, it will experience a force $F$, the so-call Lorentz force [26],

$$F = q(E + (v \times B)),$$

where $F$ is the force vector, $q$ is the charge of the carrier, $E$ is the vector of the applied electric field, $v = \mu E$ is the instantaneous drift velocity vector of the moving carrier, $\mu$ denotes the carrier mobility and $B$ is the magnetic field vector. The term $qE$ is called the electric force, while the term $qv \times B$ is called the magnetic force $F_m$.

For the following, we will assume a single carrier transport system with electrons as the type of carrier. Upon application of a perpendicular magnetic field, the magnetic component of the Lorentz force causes a deflection of the current to one side of the semiconductor (Figure 1.1(a)). As a consequence, charges of opposite sign accumulate at the two surfaces of the conductor orthogonal to the current flow, creating a potential difference, the Hall voltage $V_H$.
\[ V_H = -\frac{IB}{ned} = \frac{IB}{R_n d} \]

where \( B \) is the magnitude of \( B \), \( e \) is the electron charge, \( d \) denotes the thickness of the semiconductor and \( R_n \) is the so-called Hall coefficient,

\[ R_n = -\frac{1}{ne} \]

**Figure 1.1** (a) Sketch of an n-type semiconductor exposed to a constant magnetic field, \( B \), perpendicular to the surface. Applying a constant current \( I \) will cause an accumulation of charge carriers transverse to the current direction and a Hall voltage, \( V_H \). \( F_m \) and \( F_e \) indicate magnetic force and electric force, respectively. Note, the direction of the current \( I \) in the diagram is that of a conventional current; hence, the motion of electrons is in the opposite direction. (b) Hall field \( E_H \) generated in an n-type semiconductor at field \( B \). \( j \) is the current density. \( \theta_H \) is the Hall angle indicating the difference between the total electric field \( E_t \) and the applied electric field \( E \).
The Hall voltage causes an electric field, the Hall field $E_H$. The direction of the current is collinear with the applied electric field $E$, but not collinear with the total electric field $E_t$, because of the contribution from the Hall electric field $E_H$. The angle between $E_t$ and $E$ is called the Hall angle (Figure 1.1(b)) [27]

$$\theta_H = \arctan \left( \frac{E_H}{E} \right) = \arctan \left( \mu |B| \right). \quad (1.4)$$

Let us consider a semiconductor with a metallic inclusion as an inhomogeneity embedded in it, as shown in Figure 1.2. The conductivities of the semiconductor and the metal are denoted as $\sigma_s$ and $\sigma_m$, respectively, and $\sigma_m \gg \sigma_s$. In low magnetic fields ($\theta_H$ is negligible), the current flowing through the conductor is concentrated into the metallic region, since the metal is acting as a short circuit, and the current density $j$ is parallel to $E$. The metal inhomogeneity is essentially an equi-potential body, due to its high conductivity. Thus, the direction of $E$ and $j$ at the semiconductor/metal interface are normal to the interface (Figure 1.2(a)). In high magnetic fields, the current is deflected by the Lorentz force, which results in a directional difference between $j$ and $E$ described by the Hall angle. In sufficiently high fields, the Hall angle approaches 90°, in which case $j$ is parallel to the semiconductor/metal interface, and the current is deflected around the metal inhomogeneity, which acts as an open circuit (Figure 1.2 (b)). The crossover of the metal from a short circuit at low fields to an open circuit at high fields brings about a large increase in resistance, the EMR effect. The principle of this phenomenon is the change of the current path in the hybrid structure, upon the application of a magnetic field, rather than the change of the magnetoconductivity $\sigma$ of either the semiconductor.
Rowe and Solin have theoretically demonstrated that the EMR effect in semiconductor/metal hybrid structures is essentially a geometric interfacial phenomena, using an analytical calculation with resistivity weighting functions [28]. However, there are also contributions from intrinsic effects in the hybrid structure; for example, the magnetic field depend carrier mobility [16].

![Figure 1.2 Current density distribution in a semiconductor/metal hybrid structure.](image)

(a) $\sigma_S$  
(b) $\sigma_m$

**Figure 1.2** Current density distribution in a semiconductor/metal hybrid structure. The gray and yellow areas are the semiconductor and metal, respectively. The dark lines show the paths of current density. (a) At low magnetic fields, the current density is parallel to the electric field and the metal acts as a short circuit. (b) At high field, the current is mainly flowing in the semiconductor, the hybrid acts as an open circuit.

### 1.1.2 Diffusive Transport Model in Hybrid Structures

Because of the costs of high-mobility semiconductor samples, it is of great interest to develop reliable models for studying the EMR effect in devices. Owing to the complexity of the hybrid geometry, analytical models used to describe the EMR effect are complicated and are only found for symmetric structures. In the last section, it has been pointed out that the EMR effect is a phenomenon based on diffusive transport. Typically, devices utilizing the EMR effect are based on thin film technology, and their
thickness in the axial direction is very small compared to their planar dimensions. Therefore, in most models the thickness is neglected and the device is considered to be 2-dimensional (2D). Moussa et al. were the first to introduce a reduced, 2D, diffusive transport model [29], and, since then, most of the simulation results were obtained by employing only 2D models [30,31].

According to Ohm’s law, the vector of the current density $j$ is expressed as

$$ j = \sigma(B) \cdot E, \quad (1.5) $$

where $E$ is the applied electrical field, and $\sigma(B)$ represents the 2D conductivity tensor in the presence of a homogenous external magnetic field $B$ perpendicular to the 2D plane, given by

$$ \sigma(B) = \frac{\sigma_0}{1 + (\mu B)^2} \begin{bmatrix} 1 & -\mu B \\ \mu B & 1 \end{bmatrix}, \quad (1.6) $$

where $\mu$ is the mobility of the carriers in the 2D plane and $\sigma_0$ denotes the Drude conductivity without magnetic field,

$$ \sigma_0 = ne\mu, \quad (1.7) $$

which depends on $\mu$, the carrier density $n$ and the electron charge $e$.

In a steady state condition, the problem of determining the quantity of the electrical potential $\varphi(x,y,z)$ in the hybrid structure reduces to the solution of Laplace’s equation:

$$ \nabla \left[ \sigma \cdot \nabla \varphi(x,y,z) \right] = 0. \quad (1.8) $$

The finite element analysis (FEA) has been utilized previously to solve Equation (1.8) under specific boundary and initial conditions [29]. However, in some cases, especially when the 3-dimensional (3D) current distribution needs to be considered, the reduced
2D model is no longer applicable. In chapter 3 (Section 3.2.2), the 2D FEA model is compared to experimental results, and considerable deviations between the two are found, showing limited accuracy of the 2D FEA. Thus, in chapter 3, a 3D model for the EMR effect is developed to provide higher accuracy and insight to, e.g., in-plane field effects.

1.1.3 Device Characterization

The EMR effect is typically quantified by the MR ratio, i.e., the change of resistance in the presence of a magnetic field with respect to the resistance at zero-field

\[ MR \text{ ratio} = \frac{R(B) - R(0)}{R(0)}, \]  

(1.9)

with \( R(B) \) being the resistance at magnetic field \( B \), and \( R(0) \) being the resistance at zero magnetic field \( (R(0) = R(B = 0)) \), and

\[ R(B) = \frac{V(B)}{I}, \]  

(1.10)

where \( V(B) \) is the output voltage measured at magnetic field \( B \), and \( I \) is the drive current.

In case of magnetic sensors, the output sensitivity \( \delta \) is an important specification characterizing the sensor’s performance. It is defined as the change of resistance with respect to a small variation \( \Delta B \) of the field \( B \). For constant values of \( I \), the sensitivity can be expressed in terms of the output voltage sensitivity

\[ \delta(B) = \frac{R(B + \Delta B) - R(B)}{\Delta B} \overset{I=\text{Const.}}{\rightarrow} \frac{V(B + \Delta B) - V(B)}{\Delta B}. \]  

(1.11)
The sensitivity together with the noise determines the magnetic field resolution $B_{\text{min}}$, which describes the minimal detectable field, using the sensing device, and is of high relevance from a practical point of view. It is defined as

$$B_{\text{min}} = \frac{V_N}{I \cdot \delta},$$

where $V_N$ is the noise voltage.

### 1.2 EMR Device Review

The EMR effect was first discovered using an internally shunted van der Pauw (vdP) disk by Solin and his co-workers in the year 2000 [23]. This device consists of a semiconductor disc of radius $a$ and a concentric, metallic, circular inhomogeneity of radius $b$, as shown in Figure 1.3(a).

**Figure 1.3** Sketches of the EMR devices with different geometries. (a) Van der Pauw disc geometry, (b) symmetric bar geometry, and (c) asymmetric bar geometry. The dark lines labeled with $I_+$, $I_-$, $V_+$, and $V_-$ represent the current leads and voltage probes, respectively. The dashed lines show the central axes of the bar-type devices. The gray blocks indicate semiconductor bulk material, and the yellow blocks indicate metal shunts.
The ratio of the radii, $\alpha = \frac{b}{a}$, is called filling factor, and it has been shown that $\alpha$ is the most critical geometric parameter, changing the MR ratio within two orders of magnitude [23]. In order to obtain the maximum EMR effect, the optimum value is between $12/16 \sim 13/16$ (Figure 1.4). In this case, MR ratios as high as 100 % and 9100 % at fields of 0.05 T and 0.25 T, respectively, were obtained. The geometry dependence and filling factor have also been investigated in other studies [29,32,33].

![Figure 1.4](image.png)

**Figure 1.4** The MR versus filling factor $\alpha$ of an internally shunted vdP disk made of InSb and Au at magnetic fields of 0.05 T, 0.1 T, 0.25 T, 1.0 T, and 5.0 T. Reprinted with permission from [17]. Copyright © 2000, American Association for the Advancement of Science.

In case of the optimized filling factor, the hybrid structure shows neither “semiconductor-like” nor “metal-like” behavior. Instead, a flat resistance versus temperature curve (demarcation line between semiconducting and metallic behavior curves) has been observed experimentally for optimized geometries. The optimized
geometry of the hybrid structure has also been found in a numerical study utilizing a resistivity weighting function. With this method, the optimized geometry was identified by the maximum sampling value of the applied current at the semiconductor/metal interface [28].

Recently, Hewett and Kusmartsev investigated a vdP disk with a multi-branched, metallic shunt and obtained an EMR effect two orders of magnitude greater than with a vdP disk with concentric, circular, metallic shunt [30]. By extending the inhomogeneity further into random, metallic islands, using a random branch model, the large MR effect found in silver chalcogenides was identified as an EMR effect [22].

It is worth to note that independent of the geometry, the MR curves change from a quadratic dependence at low field values to a quasi-linear one at high field values and eventually saturate [23,30]. Branford et. al. compared the EMR effect in the hybrid vdP disk with the MR effect in another disk-type geometry, the Corbino disk, with the same dimension. The EMR effect in the vdP disk was found to produce a higher MR ratio except for very high fields, where the EMR effect saturates [16]. However, the huge MR ratio achieved in the hybrid vdP structure is attributed to its small value of $R(0)$. For instance, $R(0)$ values of 1 to $10^{-2}$ Ω were reported for different $\alpha$ ratios in Solin’s work [23]. As a consequence, even though the MR ratios are very high, the output signal is small and low output sensitivities (Equation (1.9)) can be expected from this geometry in case of sensor applications.

Besides its low sensitivity, the hybrid vdP structure suffers from another obvious
drawback. For many applications, such as bio-chip sensors, devices of small dimensions are required, in order to achieve the necessary spatial resolution. However, difficulties might be encountered during fabrication of nanoscopic, shunted vdP disks, which are mostly caused by the etching of the concentric hole in the semiconductor disk and the subsequent metallization requiring a good electrical contact. The first vdP disk reported had dimensions in the millimeter range [23], which was reduced to several hundred microns in the experimental studies that followed.

Using the concept of bilinear conformal mapping, a bar-type geometry, having a semiconductor bar shunted by a metal stack along one sidewall, has been derived from the vdP configuration (Figure 1.3(b)) [34]. The bar-type configuration is much simpler in terms of fabrication; a nanoscopic EMR device could be realized employing standard fabrication processes [35]. Meanwhile, a large MR value, reaching up to 60 % at 0.05 T, is still retained. Consequently, most studies of the EMR effect were conducted using bar-type geometries. The length/width ($L/W$) ratio of the semiconductor bar was found to be a critical geometric parameter for the EMR effect in the bar-type device. Regarding the MR ratio, the optimal $L/W$ has been found to be around ~20 [31,36,37]. Increasing the value of $L$ further causes a weak reduction in the MR ratio. However, as the value of $L/W$ decreases below 20, especially at higher fields, the MR ratio drops drastically.

With respect to the placements of the two current leads (I) and the two voltage probes (V), two major kinds of configurations can be distinguished: symmetric and asymmetric (Figure 1.3(b) and (c)), where the placements of electrodes are symmetric...
about the central axis of the bar-type device or asymmetric, respectively. In the symmetric configuration, the maximum MR ratio is obtained with a separation between the two voltage probes of around \( L/2 \) \cite{36}. When the two probes move closer to or further away from each other, the MR ratio decreases. An enhanced MR ratio in the low-field region was observed for the asymmetric configuration \cite{31,38}.

**Figure 1.5** (a) SEM micrographs of a mesoscopic EMR device with IVIV configuration. 2DEG indicates an AlSb (2 nm)/InAs (12.5 nm)/AlSb (2 nm) heterostructure. (b) Output voltage versus applied current for IVIV EMR devices at a field of 0.09 T. Inset A: Output voltage in IVIV device as a function of applied field using a bias current of 1 mA. Inset B: Comparison between the signals measured with the IVIV configuration and with the IVVI configuration. Reprinted with permission from \cite{39}. Copyright © 2009, IEEE

A modified configuration, using an IVIV electrode arrangement, in which the EMR effect cooperates with the Hall effect, was reported, having a sensitivity higher than the
asymmetric configuration (Figure 1.5) [39,40]. A five-contact configuration IVVI was also developed, in which current splitting is utilized through three current leads. This device showed a 3 times enhancement of the MR ratio to a four-contact IVIV configuration [41].

![Diagram of InSb/In\textsubscript{1-x}Al\textsubscript{x}Sb heterostructure](image1)

**Figure 1.6** (a) InSb/In\textsubscript{1-x}Al\textsubscript{x}Sb heterostructure used to prepare the device shown in (b). The active region is the 25 nm thick InSb quantum well. (b) SEM photo of the mesoscopic bar-type EMR device. Reprinted with permission from [35]. Copyright © 2003, American Vacuum Society.

Even though the EMR effect is strongly geometry dependent, there is still a large influence by the material parameters and their complex interplay. The mobility of the semiconductor $\mu_s$ was demonstrated to be the most critical parameter [42]. The EMR rises with increasing values of $\mu_s$ in the regime of low mobility, owing to the increased dimensionless field $\mu_s B$, i.e., the current redistribution between the semiconductor and
the metal shunt becomes more pronounced, due to a larger Hall angle in the semiconductor (Equation (1.2)). As $\mu_s$ increases to very high values, the conductivity of the semiconductor approaches that of the metal shunt. As a result, the current redistribution caused by the magnetic field does not cause much change in the resistance of the hybrid. However, in practice, when $\mu_s$ increases, the carrier density $n_s$ drops, keeping the change of the conductivity small. In general, semiconductors with a high mobility have shown to exhibit a strong EMR effect and are preferred.

For instance, silicon-based devices exhibit a weak EMR effect because of the low carrier mobility. Troup et. al. measured an EMR of 15.3 % at 10 T in a device built with n-doped silicon ($\mu_s = 0.0065 \text{ m}^2/\text{Vs}$) [43]. Narrow-gap III-V compound semiconductors, such as InSb or InAs, display a high mobility. A large EMR of 1000 % at 5 T has been measured with a polycrystalline InSb sample, prepared by thermal evaporation, having a mobility of 1.22 m$^2$/Vs [33]. An even higher mobility can be achieved with single crystalline III-V thin films, grown by epitaxy technology [44]. Mobility values of $\sim$7 m$^2$/Vs and $\sim$3 m$^2$/Vs have been observed in single crystalline InSb and InAs, respectively. An MR ratio of 750000 % at 4 T and room temperature was reported in a 1.3 $\mu$m thick InSb thin film with a mobility of 4.55 m$^2$/Vs [23]. Typically, the thin films of III-V semiconductors need to exceed 1 $\mu$m in thickness to provide a large mobility value; for example, the mobility of bulk InSb drops drastically reaching a value of 0.01 m$^2$/Vs in a 0.1 $\mu$m thick film [45]. This prevents III-V thin films from being used for mesoscopic devices having sub-micron dimensions.
In order to overcome the problem of low mobility in thin bulk material layers, III-V semiconductor-based heterostructures are employed, which have very thin layers of about 100 nm. For instance, a high mobility two-dimensional electron gas (2DEG) can be achieved with an aluminum antimonide/indium arsenide (AlSb/InAs) system (the so-called “6.0 Å material systems”) grown using epitaxy. Such systems show large room temperature electron mobility values exceeding 2 m²/V·s [46]. With 2DEG layers, mesoscopic devices have been realized. In 2003, Solin et. al. firstly reported an EMR device with an active region of 35 nm by 30 nm, fabricated from an InSb/In₁₋ₓAlₓSb heterostructure containing a 25 nm thick quantum well with a mobility of 2.3 m²/Vs (Figure 1.6) [35]. They observed a high MR ratio of 35 % at 0.05 T and a large output sensitivity of 528 Ω/T at a bias field of 0.2 T. The power signal to noise ratio was found to be ~43 dB, which is an impressive value for a magnetic sensors with such high spatial resolution. Boone et. al. found a sensitivity of 67 Ω/T at a very low bias field of 0.09 T in a mesoscopic IVIV EMR device consisting of an AlSb/InAs 2DEG heterostructure (Figure 1.5) [39]. This performance was pointed out to be comparable to a GMR device of the same size. Further, the minimized device dimensions provide an enhanced spatial resolution. However, as the device size decreases to a value smaller than the mean free path, ballistic transport phenomena are gaining relevance, having an impact on the device performance. It has been shown that the EMR effect still persists in such a case, albeit the MR ratio is expected to be smaller than in case of the diffusive transport regime.
In practice, in order to ensure a good electric contact and simplify the fabrication, the semiconductor and metal shunt have different thicknesses, and the metal overlaps the semiconductor to some extent, resulting in additional contact surfaces between them. This causes a vertical current component, which is negligible in case of an EMR device made from a 2DEG but not in case of an EMR device made from a bulk material. Using 2DEG results in devices representing two-dimensional transport systems; hence, the geometry of the semiconductor/metal interface has little influence.

Recently, graphene attracted attention as a material for EMR devices because of its potentially large mobility and two-dimensional structure. Pisanska et. al. designed and fabricated a mesoscopic IVIV EMR device using mechanically exfoliated graphene samples [47,48]. The sensitivity of this device can reach values as high as 1000 $\Omega$/T, which is much larger than the one achieved in 2DEG devices with a comparable size. The performance can be tuned via changing the mobility and carrier density in the graphene layer by an electric field applied with a back gate voltage. Similarly, a gate-tunable linear MR ratio of 600 % at 12 T was observed in an EMR device fabricated with graphene grown by chemical vapor deposition [49].

The property of the metal shunt is also important for the performance of EMR devices. The shunt needs to have a high conductivity, in order to short the semiconductor at zero-field. An FEA showed the conductivity ratio between metal and semiconductor is required to be larger than $10^6$ for a significant EMR effect. The EMR effect drops quickly as the ratio becomes lower than $10^5$ [36]. The conductivity of the
metal is not the only concern, when selecting the metal. The contact achieved at the interface needs to be of ohmic type. Typically, titanium/gold (Ti/Au) and Ti/platinum (Pt)/Au metal stacks provide good contact to many III-V semiconductors and very high conductivity. However, in some special cases, such as AlSb/InAs 2DEG heterostructures, metal structures like AuGe/nickel (Ni)/Au or palladium (Pd)/Pt/Au are required to achieve good contact conditions [50]. For graphene based devices, Ni and chromium (Cr)/Au may be employed.

1.3 Dissertation Objectives and Outline

The geometric EMR effect, which has shown MR ratios of more than one million percent over a magnetic field range of several Tesla, has drawn much attention, due to its potential advantages over other solid-state magnetic field sensors. Most of the pervious investigations on EMR effect and optimization of EMR devices were done using simplified 2D finite element analysis, where only the 2D electron transport was considered. However, in order to obtain results that can reflect the real devices with higher accuracy, and for cases where 3D transport has to be considered, e.g., in EMR devices with arbitrary semiconductor/metal interfaces, the reduced 2D model is not sufficient. Thus, there is a need for a model, which simulates EMR devices in the 3D space. Previously, the parameter that has mainly been taken into account for device optimization was the EMR ratio. Another relevant performance factor, output sensitivity, has been ignored in many cases so far, even though it is of critical importance in many
sensor applications. Optimization of EMR devices in terms of output sensitivity could provide new insight into the influence of geometrical parameters on the performance and result in new rules for device design.

Furthermore, EMR devices suffer from several critical drawbacks when utilized as magnetic sensors, i.e., a weak low-field sensitivity and a complex fabrication process especially in case of miniaturized dimensions.

The aim of this dissertation is to achieve enhanced output performance of EMR-based magnetic field sensing devices through geometric optimization, simplified fabrication, and physical contribution.

The expected outputs from this dissertation are:

- Development of a full 3D model describing the transport in the EMR device;
- Geometric optimization of EMR devices for high output performance, taking into account the output sensitivity;
- Development of a simplified fabrication process for EMR devices;
- Development of EMR sensors with enhanced low-field performance.

The dissertation will be presented as following: In Chapter 2, the MR effects in devices with different geometries fabricated from n-doped InAs epilayers are investigated and compared experimentally. In Chapter 3, the EMR effect is investigated using 2D and 3D finite element models to address the geometric optimization of the output performance of the devices. In Chapter 4, the improvements achieved in the
EMR devices for sample fabrication method and enhanced output performance will be described. Finally, the conclusion and an outlook are presented in Chapter 5.
Chapter 2

Magnetoresistance Effects in n-doped InAs Epilayer Structures

As mentioned in chapter 1, the EMR effect and the orbital MR effect share a similar origin, which is ascribed to Lorentz force and orbital motion of carriers. The EMR effect in hybrid structures has been shown to be much stronger than the intrinsic MR and orbital MR effects in Corbino structures. However, no comparison has been conducted between the performances of the geometric MR in different geometries.

In this chapter, the magnetotransport properties in n-doped InAs epilayers will be investigated for devices of 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 discs, hybrid vdP discs, hybrid bars with 2-contact and 4-contact configuration, to compare the mechanism and performance of the MR effect. Characterizations are exploited to compare between intrinsic, orbital, and extraordinary MR effects. The discussion addresses both a physical (MR ratio) and technical (output performance) point of view.

2.1 Experimental Details
The semiconductor material used in this work is an n-doped InAs epilayer sample. The structure of the epilayer is showed in Figure 2.1 (details are provided in Appendix A). 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 citric acid solution exploiting the semi-insulating gallium arsenide (GaAs) as an etch stop. The shunts and electrode metal structures are made of a Ti (50 nm)/Au (250 nm) stack deposited by magnetron sputtering. A rapid thermal annealing process at 250 °C is employed to realize an ohmic contact with a low contact resistivity of \( \sim 10^{-7} \) Ωcm\(^2\). The details about the fabrication process can be found in Appendix A.

![Layer diagram showing the n-doped InAs epitaxial structure.](image)

**Figure 2.1** Layer diagram showing the n-doped InAs epitaxial structure.

Figure 2.2 shows the microscopic pictures of the devices: the orbital MR device: (a) Corbino disc; and EMR devices: (b) internally shunted hybrid vdP disc and (c) externally shunted hybrid bar. The Corbino disc and the hybrid vdP disc consist of the same InAs rings with inner and outer radii of 120 μm and 160 μm, respectively. The concentric holes are filled with metal and act as an electrode in case of the Corbino disc and as an
internal metal shunt in case of the hybrid vdP disc. The Corbino disc has its second electrode surrounding the InAs ring, while the shunted vdP disc has its four electrodes symmetrically located on the InAs ring. Figure 2.2(c) shows an InAs rectangular bar with the dimension of 40 μm × 1000 μm with a shunt on one side of the bar and the electrodes on the other side.

**Figure 2.2** Microscopic images of (a) Corbino disc, (b) hybrid van der Pauw disc and (c) hybrid bar. I+ and I- denote the electrodes used as current leads, V+ and V- denote the electrodes used as voltage probes. In (c), if the same electrodes are utilized as current leads and voltage probes, the device is denoted a 2-contact configuration; if the voltage is measured with the two electrodes in the middle, the device is a 4-contact configuration. The solid arrows indicate the directions of current flow. The scale bars show 100 μm.

For a 2-contact configuration, voltage is measured between the corner electrodes, whereas for a 4-contact configuration, voltage is measured between the two inner electrodes, which are symmetrically placed about the center of the Hall bar with a
spacing of 500 μm. For both hybrid structures, the vP disc and the bar, the optimum geometries for obtaining the highest MR ratios are chosen [29,51]. Another hybrid bar with a non-optimized semiconductor dimension of 40 μm × 220 μm is also prepared for comparison.

The device characterizations are carried out using a Quantum Design physical property measurement system (Appendix B). Constant current of 1 mA (in the linear current-voltage range) is applied to the devices via current leads throughout the measurements. Homogenous external fields \( B \) ranging from -1 T to 1 T are applied in a direction perpendicular to the film surfaces in steps of 0.01 T to measure the magnetotransport behaviors in all geometries. The transport properties in the “as-grown” InAs sample are measured using the standard van der Pauw technique (Appendix B). The temperature dependence of the transverse MR and Hall resistance is investigated in the temperature \( T \) range from 5 K to 300 K with 1 K step at magnetic field of 0.1 T.

### 2.2 Transport Properties in InAs Epilayers

#### 2.2.1 Magnetic field dependence

As mentioned in chapter 1, materials with a spherical Fermi surface do not exhibit magnetoresistance. However, as presented in Figures 2.3(a) and (b) strong magnetic field dependences of the transport properties are observed in the n-doped InAs epilayer samples, i.e., a significant variation of the Hall coefficient and a strong MR ratio, even
though an isotropic Fermi surface is expected in an InAs crystal [52]. The intrinsic MR ratio \((\Delta \rho/\rho_0)\) data is obtained from the transverse MR measurement (see Appendix B.2) which is shown to provide an excellent approximation of \((\Delta \rho/\rho_0)\) at low field [53]. The Hall coefficient shows an anomalous behavior of decreasing with increasing magnetic field and tending to saturate at higher field, instead of maintaining a constant value expected in a single semiconductor conductance, indicating increased carrier density \(n\).

![Figure 2.3](image)

**Figure 2.3** Magnetic field-dependence of (a) Hall coefficient and (b) intrinsic MR ratio measured in InAs at different temperatures. The solid lines show the fitted data obtained from Equations (2.3) – (2.4).

The observed anomalous magnetic field dependence in the InAs epilayers is addressed quantitatively as following: InAs is known for its unique surface charge property, i.e., a charge accumulation with a sheet density of \(\sim 10^{12} \text{ cm}^{-2}\) is formed on the
free surfaces, independent of doping, caused by native surface defects [54, 55]. Note, the sheet density is the product of the carrier density and film thickness. Hence, the surface accumulation layer with high carrier concentration acts as a parallel transport channel, and therefore, a multi-layer conduction model needs to be employed [56].

![Figure 2.4](image.png)

**Figure 2.4** (a) Sketch and (b) equivalent electric circuit of the two-layer transport model the InAs epilayer.

It is worth to note that the impact of the 0.2 μm undoped InAs stabilizing buffer layer on conduction is negligible. The sheet conductance is defined as

\[ G = \sigma_0 \cdot d = en\mu d, \]

where \( \sigma_0 \) is the conductivity (Equation 1.7), \( e \) is the electron charge, \( n \) is the carrier density, \( \mu \) 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 \( 2 \times 10^4 \) cm\(^2\)/V·s to \( 3 \times 10^4 \) cm\(^2\)/V·s at room temperature [57]. In contrast, the 1.5 μm thick bulk InAs is doped and
has a concentration of $10^{16}$ cm$^{-3}$ and an electron mobility of $\sim 0.8160$ m$^2$/V·s based on results from the vdp measurement. 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 model [13] for the doped InAs layer (see Figure 2.4(a)).

From Figure 2.4(b), the measured conductivity can be found as

$$\sigma_0 = \frac{(\sigma_b d_b + \sigma_s d_s)}{d_s + d_b} = \frac{(G_b + G_s)}{d_s + d_b},$$  \hspace{1cm} (2.2)

Where $d$ is the thickness and the subscripts $b$ and $s$ indicate the bulk-like and surface-like layer, respectively. The Hall voltage of the epilayer is the superposition of that in each layer; hence, using Figure 2.4(b),

$$V_H = \frac{(V_{hb} G_b + V_{hs} G_s)}{G_b + G_s}.$$  \hspace{1cm} (2.3)

In Wieder’s paper [12], the derivation of $R_h$ and $(\Delta \rho/\rho_0)$ of the InAs epilayer in terms of the parameters of each layer is shown. The correlations between the electric fields and current densities in the InAs epilayer and each layer the along x and y axes are

$$E_b = \frac{J_{xb}}{\sigma_b} - (R_{hb}B)J_{yb} = \frac{J_{xs}}{\sigma_s} - (R_{hs}B)J_{ys} = E_s,$$  \hspace{1cm} (2.4)

$$E_{hb} = \frac{J_{yb}}{\sigma_b} + (R_{hb}B)J_{xb} = \frac{J_{ys}}{\sigma_s} + (R_{hs}B)J_{xs} = E_{hs},$$  \hspace{1cm} (2.5)

$$J_x = \frac{(d_b J_{xb} + d_s J_{xs})}{d},$$  \hspace{1cm} (2.6)

$$0 = d_b J_{yb} + d_s J_{ys},$$  \hspace{1cm} (2.7)
where $E$ is the electric field in the direction of the applied current (x-axis) of density $J_x$, $E_H$ and $J_y$ are the Hall electric field and current density along the y-axis. From Equations (2.2)-(2.7), the Hall coefficient and the intrinsic MR ratio can be derived as

$$ R_{H}(B) = \frac{E_H}{J_x B} = d \left( \frac{\mu_s G_s + \mu_b G_b + B^2 (\mu_b^2 \mu_s G_s + \mu_s^2 \mu_b G_b)}{(G_s + G_b)^2 + B^2 (\mu_s G_b + \mu_b G_s)^2} \right), \quad (2.8) $$

$$ \frac{\Delta \rho}{\rho_0} = \frac{(\mu_b - \mu_s)^2 G_s G_b B^2}{(G_s + G_b)^2 + B^2 (\mu_s G_b + \mu_b G_s)^2}. \quad (2.9) $$

At low fields, the terms that do not include $B^2$ dominate in both the numerator and denominator in Equations (2.8) and (2.9) and can be approximated to the simplified forms:

$$ R_{H}(B) = \frac{d (\mu_s G_s + \mu_b G_b)}{(G_s + G_b)^2}, \quad (2.10) $$

$$ \frac{\Delta \rho}{\rho_0} = \frac{(\mu_b - \mu_s)^2 G_s G_b}{(G_s + G_b)^2}. \quad (2.11) $$

This explains the flat behavior of the Hall coefficient curves and quadratic behavior of the magnetoresistance curves observed at low fields (Figure 2.3). At very high fields, the terms including $B$ dominate and both the Hall coefficient and intrinsic MR ratio display constant values independent of the magnetic field, indicating the tendency to saturate at high field.

$$ R_{H}(B) = \frac{\mu_b^2 \mu_s G_s + \mu_s^2 \mu_b G_b}{(\mu_s G_s + \mu_b G_b)^2}, \quad (2.12) $$

$$ \frac{\Delta \rho}{\rho_0} = \frac{(\mu_b - \mu_s)^2 G_s G_b}{(\mu_b G_s + \mu_s G_b)^2}. \quad (2.13) $$
The thickness of the surface accumulation layer $d_s$ is estimated by the Debye length $L_D$. It is the distance over which significant charge separation can occur, and defined as

$$L_D = \left(\frac{\epsilon_0 \kappa k_b T}{e^2 n_b}\right)^{1/2},$$

(2.14)

where $\epsilon_0$ is the permittivity of free space, $\kappa$ 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. Besides $d_s$, another two fitting parameters $\mu_b$ and $n_b$ are required. They are estimated from published data for lightly-doped, single crystal, bulk InAs material with ionized impurity concentration [57].

**TABLE 2.1.** The fitting parameters $\mu_b$, $n_b$, and $d_s$ and deduced parameters $\mu_s$ and $n_s$ at different temperatures in the InAs samples.

<table>
<thead>
<tr>
<th>$T$ (K)</th>
<th>$\mu_b$ ($10^4$ cm$^2$/Vs)</th>
<th>$n_b$ ($10^{16}$ cm$^{-3}$)</th>
<th>$\mu_s$ ($10^4$ cm$^2$/Vs)</th>
<th>$n_s$ ($10^{18}$ cm$^{-3}$)</th>
<th>$d_s$ (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>1.6</td>
<td>2.00</td>
<td>0.336</td>
<td>3.93</td>
<td>32.88</td>
</tr>
<tr>
<td>200</td>
<td>2.5</td>
<td>1.92</td>
<td>0.529</td>
<td>2.69</td>
<td>30.10</td>
</tr>
<tr>
<td>100</td>
<td>4.8</td>
<td>1.47</td>
<td>1.007</td>
<td>2.35</td>
<td>24.63</td>
</tr>
<tr>
<td>5</td>
<td>2.0</td>
<td>0.48</td>
<td>0.420</td>
<td>1.80</td>
<td>8.70</td>
</tr>
</tbody>
</table>

In order to calculate theoretical values for the Hall coefficient and the MR ratio, using Equations (2.8) and (2.9), the values for the parameters of the surface-like layer, $\mu_s$ and $n_s$, still need to be found. They can be deduced by fitting theoretical curves to the experimental results. This is done in an iterative way using commercial software (OriginPro8) and the goodness of fit is evaluated using a chi-squared test [58]. The fitted curves are plotted in Figure 2.2 as solid lines, and the values of all parameters are listed
in TABLE 2.1. At lower temperature, larger deviations exist between the experimental and theoretical values. These can be ascribed to the small value of \( d_s \) calculated at low temperature with Equation (2.14), which causes larger error when estimating the surface layer thickness. From the deduced data, the sheet density of the surface-like layer is 12.9×10^{12} \text{ cm}^{-2}, 8.1×10^{12} \text{ cm}^{-2}, 5.8×10^{12} \text{ cm}^{-2}, \text{ and } 1.6×10^{12} \text{ cm}^{-2} \text{ at } 300 \text{ K, 200 K, 100 K, and 5 K, respectively. These values are in accordance with the reported sheet density of InAs of } \sim 10^{12} \text{ cm}^{-2}. \text{ As conclusion, the experimental data can be well approximated by the two-layer theoretical model, which provides an explanation for the anomalous magnetotransport behaviors observed in the InAs epilayer.}

2.2.2 Temperature dependence

The temperature dependences of the transport properties in the InAs samples are shown in Figure 2.5. The mobility and carrier density values are directly obtained from the vdP measurement with \( n \) obtained from the Hall measurements at 0.1 T and \( \mu \) calculated from the Hall coefficient and resistivity data (Appendix B.2 and Equation (B.1)). The Hall measurement at 0.1 T provides a good approximation of the value of \( n \) at zero-field (see Figure 2.3 and Equation (2.10)). The accurate values at zero-field can be calculated theoretically with the following equations derived from Equations (2.8) and (2.9) using the parameters listed in TABLE 2.1

\[
\mu(0) = \frac{\mu_b^2 n_b d_b + \mu_s^2 n_s d_s}{\mu_b n_b d_b + \mu_s n_s d_s}. \tag{2.15}
\]
Figure 2.5 (a) Mobility $\mu$ and carrier concentration $n$ measured as a function of temperature $T$ in the InAs epilayer samples measured using the van der Pauw technique at 0.1 T. The solid line in (a) shows the theoretical prediction for the mobility. (b) Temperature dependence of resistivity.

The measurement shows a moderate mobility $\mu$ of 8160 cm$^2$/V·s and carrier density $n$ of 5.6×10$^{16}$ cm$^{-3}$ at temperature $T$ of 300 K and magnetic field $B$ of 0.1 T. The mobility shows its maximum value of 25000 cm$^2$/V·s at around 75 K. Above 75 K, the mobility is proportional to $T^a$ with an exponent $a \sim -1.55$ and decreases with increasing temperature, due to the stronger influence of lattice scattering. At lower temperatures, the ionized impurity scattering is dominant. The mobility decreases with decreasing temperature, and becomes proportional to $T^b$ with an exponent $b \sim 0.8$. These
exponents are obtained from data fitting with the combined mobility model using Matthiessen’s rule. When more than one source of scattering is present, the approximation of mobility values needs to consider the influence of all kinds of scattering by

\[ \frac{1}{\mu} = \sum \frac{1}{\mu_{\text{scattering}}}, \quad (2.17) \]

Where \( \mu \) is the actual mobility and \( \mu_{\text{scattering}} \) is the mobility value the material would have, if only one specific type of scattering would be taken into account.

In the high temperature region (> 100 K), the experimental data is in good agreement with the theoretical lattice vibration scattering limiting mobility model of the bulk InAs, which indicates that the mobility is proportional to \( T^{-1.5} \). However, at lower temperatures, there are discrepancies between the experimental data (\( \mu \propto T^{0.8} \)) and the lattice scattering model (\( \mu \propto T^{1.5} \)). Similar anomalous temperature dependence of mobility with an exponent of 0.8 has been reported in InAs epilayers before [59]. The smaller exponent value (or slope) suggests the presence of additional scattering processes in this temperature range. One reasonable explanation might be that, even at low temperature, the thermal vibration of lattice does not vanish due to the large carrier density in the surface layer; and the lattice scattering maintains the comparable strength to that of ionized impurity scattering.
2.3 Magnetoresistance Effects in Structures of Different Geometries

2.3.1 Resistances at Zero-field

From Equation (1.9), it is known that the resistance at zero-field $R(0)$ has a critical impact on the MR ratio. Therefore, at first, zero-field resistances in different geometries are investigated. Considerably small values of zero-field resistance, i.e., 4.84 Ω, 3.9 Ω, 2.99 Ω, and 4.38 Ω at 300 K, 200 K, 100 K, and 5 K, respectively, are measured in the Corbino disc. The current flow is in the radial direction in the ring-shaped semiconductor (Figure 2.2 (a)), which produces a short and wide channel (the length of the channel $L$ is given by the thickness of the ring, 40 μm, and the width of the channel $W$ is given by the mid-circumference of the ring, ~750 μm), thereby, a large cross-section area compared to the length of the channel.

In contrast, large resistance values are measured for the 2-contact hybrid bar, i.e., 156 Ω, 127 Ω, 99 Ω, and 118 Ω at 300 K, 200 K, 100 K, and 5 K, respectively, even if a short circuit is formed for the semiconductor bar by the metal shunt. This can be understood using the equivalent electric circuit of the hybrid bar provided in Figure 2.6. 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 $R_{sr}$) (Figure 2.2(c)).

This is due to the high resistance $R_{sp}$ of the semiconductor bar. The resistance of the metal $R_m$ is negligible owing to the low resistivity of gold ($2.42 \times 10^{-6} \ \Omega \cdot \text{cm}$, $1.61 \times 10^{-6} \ \Omega \cdot \text{cm}$, $8.05 \times 10^{-7} \ \Omega \cdot \text{cm}$, and $5.10 \times 10^{-8} \ \Omega \cdot \text{cm}$ at 300 K, 200 K, 100 K, and 5 K, respectively) compared to the resistivity of InAs (lower plot in Figure 2.5). Thus, the resistance of the entire hybrid bar can be approximated by two InAs resistors $R_{sl}$ and $R_{sr}$ in series. It is worth to mention that at zero-field, $R_{sl} = R_{sr}$, while under a magnetic field, the values of $R_{sl}$, $R_{sr}$ and $R_{sp}$ are modulated through current redistribution.

![Figure 2.6](image)

**Figure 2.6** Equivalent electric circuit of the hybrid bar. $V_2$ and $V_4$ denote the voltage probes used in 2-contact and 4-contact configurations, respectively.

Remarkably small values of $R(0)$ are observed in the two 4-contact hybrid geometries, the hybrid vdP disc and 4-contact hybrid bar, e.g. 0.22 $\Omega$ and 0.69 $\Omega$ at 300 K,
respectively. $R(0)$ is calculated from $V_4$ divided by the applied current (Equation (1.10)). Since $R_{sp}$ is in parallel to $R_m$ (Figure 2.6), the value of $V_4$ is small and so is $R(0)$.

The values of the zero-field resistance $R(0)$ in all geometries change with the variation of temperature. In the Corbino disc, since the semiconductor acts as the only conducting channel, the value of the zero-field resistance $R(0)$ of the device changes with the same tendency as the resistivity $\rho_0$ (see Figure 2.5). Interestingly, the $R(0)$ values in all hybrid geometries share similar temperature dependence, which is distinct from the InAs Corbino disc. For instance, in the 2-contact hybrid bar device, $R(0)$ is 118.4 $\Omega$ at 5 K, which is smaller than that of 126.7 $\Omega$ at 200 K even though the semiconductor sample has a larger resistivity at 5 K than at 200 K. This can be explained by the hybrid geometry, which includes a metal as a part of the conducting path, and the resistivity of a metal decreases monotonically as the temperature is decreased. This demonstrates that more current is attracted into the metal part at 5 K than at 200 K, resulting in lower resistances of the hybrids at 5 K. In addition, owing to the critical impacts of the semiconductor/metal interface condition on the transport in the hybrid structure [60], the variation of it upon the temperature change might also have an influence.

### 2.3.2 Magnetoresistance Curves

Figure 2.7 shows the magnetoresistance measurements with respect to magnetic field at different temperatures in the Corbino disc, hybrid vdP disc, and hybrid bar devices. Symmetric MR curves with respect to the directions of the magnetic field are found in all geometries. A slight asymmetry is observed in the hybrid vdP disc, which
originates from the alignment error of the concentric metal shunt. In addition, in all geometries, the resistance responses stay quadratic at low magnetic fields and eventually evolve to quasi-linear behavior as the field increases.

Figure 2.7 Magnetoresistance curves measured for (a) Corbino disc, (b) hybrid van der Pauw disc, (c) 4-contact hybrid bar, and (d) 2-contact hybrid bar as a function of magnetic field at different temperatures.

The InAs plays a very important role in all types of MR effect, since the current deflection mainly occurs in the semiconductor. This can be demonstrated from the similarity of the MR curves (shape and range) measured at 200 K and 5 K (Figure 2.7), where the transport properties of InAs, such as the mobility and carrier density, are very
similar (Figure 2.5) even though the resistivity of the metal drops dramatically from 200 K to 5 K by a factor of 30.

At each temperature, the response of the hybrid vdP disc resembles the one of the 4-contact hybrid bar. Indeed, the geometries of these two devices can be transformed from each other using bilinear conformal mapping and therefore, these two geometries are equivalent in electric properties [34]. However, in the bar geometry, narrower current leads are used compared with those in the hybrid vdP disc (Figure 2.2). Thus current spreads wider in InAs region in the hybrid vdP disc, thereby, resulting in a lower resistance in the hybrid vdP disc.

2.3.3 MR Ratios

The MR ratios calculated from the magnetoresistance data are plotted in Figure 2.8. A strong temperature dependence of the MR ratio is observed in all geometries. Both the orbital MR in the Corbino geometry and the EMR in the hybrid geometries strongly depend on the mobility value of the semiconductor [42,61]. They are enhanced in semiconductors having larger mobility, as a result of the increased current deflection.

The MR ratio of orbital MR effect in a Corbino disc is known to be [61]

\[ MR \text{ ratio } = (\mu B)^2. \]  

(2.18)

When the magnetic field dependence of the mobility is considered, Equation (2.18) is modified to

\[ MR \text{ ratio } = (\mu(B)B)^2 \left( \frac{R_n(B)}{\rho(B)} \right)^2 = \frac{R_n(B)B^2}{\rho_0} \left[ 1 + \left( \frac{\Delta \rho}{\rho_0} \right) \right]^2. \]  

(2.19)
**Figure 2.8** MR ratio curves measured in different geometries as a function of applied field (a) at 300 K, (b) at 200 K, (c) at 100 K, and (d) at 5 K. Note, axis breaks are used for the MR ratio axes. The dashed lines indicate the MR ratios in the non-optimized 2-contact hybrid bar.

Hence the orbital MR ratio can be predicted theoretically using Equation (2.19) with the transport property data obtained for InAs through vdP measurement (Figure 2.3). The predicted data is plotted in Figure 2.9 which is found to have an excellent agreement with the experimental one at weak fields, where $\mu B < 1$. However, at strong fields, where $\mu B > 1$, the electrons start following an orbital motion, and the diffusion transport model on which Equation (2.18) is based is no longer tenable. Therefore, the data deviates from the quadratic behavior. The MR ratios in the Corbino disc at 1 T are
36 %, 65 %, 107 %, and 56 % at 300 K, 200 K, 100 K, and 5 K, respectively, which are higher than intrinsic MR ratios of 21 %, 38 %, 70 %, and 35 % in the simplex InAs epilayer sample at the corresponding temperatures. This shows that the enhancement of the MR effect in the InAs sample is achieved using geometric manipulation.

**Figure 2.9** Open symbols show orbital MR ratios measured at different temperatures; the solid lines show the theoretical predictions of orbital MR ratios using Equation (2.17).

At all temperatures, the EMR effect in the hybrid geometries produces higher MR ratios than the orbital MR in the Corbino geometry with the intrinsic MR being the lowest (see Figure 2.3(b)). In the hybrid bar, the geometry plays an important role. Larger MR ratios are observed in the optimized 2-contact configuration for all temperatures compared to the non-optimized 2-contact geometry. The contact configuration is even more crucial for the MR ratio. The optimized 4-contact
configuration exhibits a significant enhancement of the MR ratio compared to the 2-contact one, which could also be considered as a non-optimized 4-contact configuration, where the current leads and the voltage probes overlap.

Although the fundamental principle of the EMR effect - the current redistribution upon the application of a magnetic field - is the same in the hybrid device independent of the measurement configuration, the measured voltage drop can be very different from one configuration to another, owing to the inhomogeneity of the current distribution. As in the foregoing discussions, $R(0)$ measured in the 4-contact configuration is not the entire resistance of the device but reflects only the voltage drop between two sensing points. The large variations of the MR ratio are due to the dramatic decrease (~a factor of 250) of $R(0)$ when a 4-contact configuration is employed. Based on the same arguments, the hybrid vdP disc geometry has larger MR ratios than the 4-contact hybrid bar due to the lower $R(0)$ value in the hybrid vdP disc despite their MR behaviors being basically the same.

2.3.4 Output Performances in EMR Devices

In order to characterize the performance of the devices for sensing applications, the sensitivity is calculated (Equation (1.11)). Figure 2.10 shows the output sensitivities in the hybrid bar with both 2-contact and 4-contact configurations at 300 K. Owing to the large output signal, the EMR device with 2-contact configuration shows around 50 times larger sensitivity than the 4-contact one using the same input current. The 2-contact EMR device also exhibits a linear sensitivity range from around 0.2 T to 1 T, while no
linear behavior is found for the 4-contact device. Thus, based on the output sensitivity, the 2-contact configuration has a better performance than the 4-contact one, which is just opposite to the conclusion drawn based on the MR ratio. Hence, for the evaluation of the performance as a sensing device, it is important to consider the relevant parameters.

![Figure 2.10](image)

Figure 2.10 Output sensitivity with respect to applied field in the hybrid bar device with 2-contact and 4-contact configurations at 300 K.

In EMR devices, flicker noise dominates at low-frequency [62]. At higher frequencies, Johnson noise $V_{NJ}$ dominates, which is given by

$$V_{NJ} = \sqrt{4k_bTR}$$

(2.18)

where $k_b$ is the Boltzmann constant.
It is worth to note that in the 4-contact hybrid device, the resistance $R$ used in Equation (2.18) is the so-called series resistance $R_{\text{series}}$, which is measured at the two voltage probes of the device [35,63] and different from the resistance measured for the MR calculations. As is known, Johnson noise is produced by thermal agitations of the electrons at equilibrium inside the entire system, regardless of any applied current.

![Graph showing series resistance at different fields measured in the hybrid bar devices with 2-contact and 4-contact configurations at 300 K.](image)

**Figure 2.11** Series resistance at different fields measured in the hybrid bar devices with 2-contact and 4-contact configurations at 300 K.

The series resistances measured in the devices at the sensing electrodes for both the 2-contact and 4-contact configurations at 300 K are plotted in Figure 2.11. The series resistance without magnetic field in the hybrid bar in the 4-contact configuration is 136.9 $\Omega$, 110.9 $\Omega$, 86.3 $\Omega$ and 100.4 $\Omega$ at 300 K, 200 K, 100 K, and 5 K, respectively, whose value is close to that in the 2-contact configuration (156.2 $\Omega$, 126.2 $\Omega$, 98.4 $\Omega$, $\ldots$).
and 118.4 Ω, respectively) even though the distance between the electrodes differs by a factor of two between the two configurations. The result suggests that a similar Johnson noise level can be expected in both cases. When measuring series resistance, only two sensing electrodes are actually used in the 4-contact device, where the equivalent electric circuit for the 2-contact configuration is applicable (Figure 2.6). Due to the geometric inhomogeneity, the values of $R_{sl}$, $R_{sr}$ and $R_{sp}$ are slightly different from these for 2-contact configuration.

As summary, at all temperatures, the EMR effect wins over the orbital MR and intrinsic MR in terms of both MR ratio and output sensitivity. The 2-contact configuration defeats the 4-contact one on output performance even though it shows lower MR ratios. The same sensitivity is expected in the 4-contact vdP device as in the 4-contact hybrid bar. However, the hybrid bar geometry is preferred, since the hybrid vdP disc is difficult to be realized in minimized dimensions. In conclusion, care must be taken, when conducting geometric optimizations, by considering which performance parameter needs to be optimized.
Chapter 3

Finite Element Analysis Study of EMR Effect

Previous studies that have investigated the geometric influence on the performance of EMR devices using 2D FEA, have mostly evaluated the MR ratio [30,31,36,37]. However, as discussed in Chapter 2, a more important parameter for sensing applications is the output sensitivity, which has not been considered so far. Moreover, in some cases, especially when the 3D current distribution needs to be considered, the 2D FEA model cannot be employed. Hence, there is a need for developing a 3D model for EMR devices.

In this Chapter, EMR devices with the hybrid bar geometry are modeled and simulations carried out by means of FEA. A 3D FEA model is developed and compared to the results obtained with a common 2D model as well as to experimental results. The purpose these simulations are to calculate quantities such as current density distribution and spatial potential, which in turn are used to investigate geometric influences on the output sensitivity of a semiconductor/metal hybrid structure. This allows finding the critical parameters, which need to be optimized for specific applications.
3.1 Two-dimensional FEA Studies

In this section, the performances of bar-type EMR devices are simulated for different device geometries, electrode configurations, and contact conditions by FEA, using the 2D model (Equations (1.5)-(1.8)). The performance is evaluated with regard to the output sensitivity of the device (Equation (1.11)), which is more relevant for potential applications ranging from reading heads to biomedical sensors.

3.1.1 Two-dimensional Finite Element Model

The model of the bar-type EMR device consists of a semiconductor bar shunted by a metal stack. The structure and geometric parameters of the device model are shown in Figure 3.1. The device is symmetric about the y-axis, and the x-axis is placed along one of the edges of the semiconductor. The widths of the semiconductor and metal and the lengths of the device are denoted $W_s$, $W_m$, and $L$, respectively. The current leads $I$ and voltage probes $V$ were placed along the edge of the semiconductor bar. Depending on their arrangement, the contact configuration can be classified into two types, namely, IVVI (Figure 3.1(a)) and VIIV (Figure 3.1(b)). While the two outer contacts are placed at the edges of the semiconductor, the locations of the inner ones are varied, whereby $\alpha_{VL}$, $\alpha_{VR}$, $\alpha_{IL}$ and $\alpha_{IR}$ are the distances of the left and right voltage probes and current leads in IVVI and VIIV configuration, respectively, from the y-axis.

The material parameters are: $\mu_s = 4.55 \text{ m}^2\text{V}^{-1}\text{s}^{-1}$ and $n_s = 2.55\times10^{22} \text{ m}^{-3}$ for the semiconductor, and $\mu_m = 5.3\times10^{-3} \text{ m}^2\text{V}^{-1}\text{s}^{-1}$ and $n_m = 5.9\times10^{28} \text{ m}^{-3}$ for the metal. The width $W_m$ is 15 $\mu$m while $W_s$ and $L$ are varied during the simulation. A width of 0.1 $\mu$m is
assigned to the current leads, while the voltage probes were considered as a point-like contact with zero width.

![Diagram of semiconductor/metal structure](image)

**Figure 3.1** Geometry of the semiconductor/metal structure with (a) IVVI and (b) VIIV configurations, where I and V represent current leads and voltage probes, respectively.

A current of 10 μA, corresponding to a density of $10^8$ A/m$^2$, is applied as the boundary conditions at $I_+$ and $I_-$, which is a feasible assumption based on the electromigration limit of the metal ($< 10^{11}$ A/m$^2$) as well as heating constraints, which are the general concerns when considering the momentum transfer between conducting electrons and diffusing metal atoms and joule heating [64]. The current lead $I_-$ is grounded. All other outer boundaries are electrically insulating ($\sigma = 0$, Neumann...
condition), while the contact resistivity at the semiconductor/metal interface is $10^{-8}$ Ω-cm$^2$, unless otherwise specified. The models are meshed with triangular elements, which conform well to a large range of model geometries, and consist of approximately $\sim10^5$ elements and degrees of freedom. The mesh density is varied adaptively. The FEA is carried out using commercial finite element software, COMSOL-Multiphysics, to calculate the output of the modeled devices with Equation (1.8). The investigations are conducted for the relationships between the output sensitivity and different semiconductor length/width ratios $L/W_s$, the placements of the voltage probes in an IVVI configuration, the placements of the current leads in a VIIV configuration, and the contact conditions at the semiconductor/metal interface as a function of the magnetic field. The output sensitivity is calculated using Equation (1.11) with $\Delta B = 1\times10^{-4}$ T.

### 3.1.2 Two-dimensional FEA results

**Width of the Metal Shunt**

In order to study the influence of the width of the metal shunt, an IVVI configuration is employed with a semiconductor of width $W_s = 5$ μm, length $L = 75$ μm, and symmetrically placed voltage probes with $\alpha_{VR} = -\alpha_{VL} = 12.5$ μm. The width of the metal shunt $W_m$ is varied from $0.01 \times W_s$ (50 nm) to $50 \times W_s$ (250 μm).

Figure 3.2 shows the sensitivity as a function of different $W_m/W_s$ ratios at 0.05 T and 1 T. As can be seen, $\delta$ increases as the width of the shunt increases up to a certain value before it saturates. When $W_m$ is thicker than $0.1 \times W_s$, the influence is rather small with
an increase of less than 1 % for strong fields and around 3 % for weak fields, indicating that the current is mainly confined to a thin layer in the metal shunt close to the semiconductor. Similar results were found for a model with a different semiconductor bar of \( W_s = 3 \mu m \) using the same values for all other parameters.

**Figure 3.2** Output sensitivity \( \delta \) of the EMR device as a function of the ratio \( W_m/W_s \) (\( W_s = 5 \mu m \)) at magnetic fields \( B = 0.05 \) and 1 T. The arrows indicate the corresponding axis.

Hence, it can be concluded that the dimension of the metal shunt should be larger than 0.1 \( x \) \( W_s \) in order to maintain a good performance of the EMR device. A thickness larger than 5 \( x \) \( W_s \) is not necessary due to its negligible influence on the device sensitivity. In the following simulations, a value of \( W_m = 5 \times W_s \) is being used, unless otherwise mentioned.
Length/Width Ratio of the Device

In order to investigate the influence of the length/width ratio $\alpha = L/W_s$, a device with symmetric IVVI configuration is studied. The length $L$ is varied from 30 μm to 105 μm with a step size of 3 μm in order to obtain different values of $L/W_s$, while $W_s$ and $\alpha_{VR}$ are 3 μm and $L/6$, respectively. The width of the metal is $W_m = 5 \times W_s = 15$ μm.

![Figure 3.3](image)

**Figure 3.3** Sensitivity $\delta$ as a function of the length/width ratio $\alpha = L/W_s$ at various external fields. The insets show the current deflection in the semiconductor bar of the EMR device with (a) low value of $\alpha$, (b) optimal value of $\alpha$, (c) large value of $\alpha$, under a constant Hall angle $\theta$. The dashes indicate the deflected current path. The dark, thick lines represent the interfaces between semiconductor and metal (metal is not shown here).

Figure 3.3 shows $\delta$ as a function of $\alpha$ at magnetic fields of 0.05 T, 0.5 T, and 1 T. The optimal value of $\alpha$ shows some dependence on the magnetic field. Values of 5, 10 and...
20 provide maximum sensitivity for magnetic fields of 0.05 T, 0.5 T and 1 T, respectively. The optimal value increases for stronger fields. This can be understood by the help of the insets in Figure 3.3, which indicate the relation between $\alpha$ and the current path in the EMR device. In very simplified terms, if no magnetic field is applied, the current flows straight through the semiconductor into the conductor shunt via the shortest possible way. Due to the Hall angle $\theta$, resulting from a magnetic field, the current path will be deflected into the semiconductor, which causes an increased resistance. It’s important to keep in mind that a given external field will result in a certain Hall angle $\theta$, independent of the geometry. In case of a low value of $\alpha$, the deflected current will be confined to the semiconductor bar (Figure 3.3 inset (a)). As $\alpha$ increases, the current path through the semiconductor becomes longer and, eventually, reaches the interface between the semiconductor and metal, leading to the optimal value of $\alpha$, at which small changes of the magnetic field cause the largest changes in resistance (Figure 3.3 inset (b)). It can be seen from Figure 3.3 inset (c) that a further increase in length only increases the path of the current flow through the conductor, which doesn’t contribute to the resistance. The sensitivity decreases as $\alpha$ increases. Since the Hall angle is larger at stronger fields, the optimal value of $\alpha$ is larger at stronger fields.

The investigation of the length/width ratio is also carried out with a model of varied width $W$, and fixed length $L = 75\mu m$. This simulation provides exactly the same results as the previous one, indicating that the scale of a device has no influence on the performance of an EMR device. Therefore, EMR devices can be fabricated according to
the spatial resolution requirements for the specific applications or restrictions due to the fabrication technology. This not only gives flexibility with respect to design but also higher accuracy for specific applications.

**Placement of Voltage Probes in IVVI Configuration**

An IVVI device with length $L = 45 \, \mu m$ and width $W = 3 \, \mu m$ ($L/W = 15$) is simulated to investigate the influence of the placement of the voltage probes. Here, $\alpha_V$ is used to denote the distance of the voltage probes from the $y$-axis (Figure 3.1(a)). Firstly, a symmetric configuration is used, i.e. $\alpha_V = \alpha_{VL} = \alpha_{VR}$. $\alpha_V$ is changed from 0.5 to 22.5 $\mu m$ in steps of 1 $\mu m$, and its influence on $\delta$ is shown in Figure 3.4.

![Graph showing sensitivity $\delta$ as function of the voltage probe placement at external fields of 0.05 T, 0.5 T, and 1 T in the EMR device with symmetric IVVI configuration.](image)

**Figure 3.4** Sensitivity $\delta$ as function of the voltage probe placement at external fields of 0.05 T, 0.5 T, and 1 T in the EMR device with symmetric IVVI configuration.
\( \delta \) increases as the probes move further away from the \( y \)-axis at both weak and strong fields, and it can be concluded that the larger the separation of the probes the higher the performance. It is interesting to note that there is a considerable increase in sensitivity as the two probes approach their respective corners.

![Figure 3.5](image)

**Figure 3.5** Potential distribution along the edge of the semiconductor bar in the EMR device at different magnetic fields.

In order to get a better understanding of this effect, Figure 3.5 shows the electric potential distribution along the edge of the semiconductor bar for different magnetic fields. Most of the potential change occurs in the semiconductor close to the current leads. This is due to the smaller cross-section available for the current to pass through, resulting in higher current densities and, consequently, larger electric fields. As the magnetic field increases, the current density along the right edge of the semiconductor
increases even further, while on the left edge of the semiconductor the opposite happens. In between, the two edges, at higher fields, the amount of current flowing through the semiconductor increases thereby facing an increased resistance and, hence, larger potential differences are observed. Since the largest changes of the potential arise around the corners, higher sensitivity can be obtained by placing the voltage probes closer to the corners (Figure 3.5). Hence, a symmetric EMR sensor with high sensitivity can be reduced to a two-contact device where the contacts are utilized for current injection as well as voltage measurement.

Figure 3.6 Sensitivity $\delta$ as a function of the placements of voltage probes at external fields of 0.05 T, 0.5 T, and 1 T in the EMR device with asymmetric IVVI configuration. The arrow indicates the location of the fixed voltage probe.
It has previously been reported that the asymmetric contact configuration increases the MR ratio in the EMR device [31,38]. In order to study the influence of an asymmetric arrangement of the voltage probes, an IVVI configuration is simulated with $\alpha_{VR}$ fixed at 7.5 $\mu$m while $\alpha_{VL}$ is varied from -22.5 $\mu$m to 22.5 $\mu$m. The current is injected at the current lead and the position of the current lead is varied. Figure 3.6 shows $\delta$ as a function of $\alpha_{VL}$. Compared to the results found for the symmetric arrangement (Figure 3.4), the maximum value of $\delta$ at a high field (1 T) has reduced. In the case of low fields, $\delta$ has slightly increased due to the asymmetric arrangement.

**Placement of Current Leads in VIIV Configuration**

The effect of the placements of the current leads $\alpha_i$ in a symmetric VIIV device is studied using the same geometric parameters for the model as employed for the IVVI device. $\alpha_i$ denotes the distance of the current leads from the midline of the device (Figure 3.1(b)). $\delta$ depends on $\alpha_i$ in a very similar way as it does on $\alpha_V$ in the case of the IVVI configuration and the same trends can be observed (Figure 3.7). Again, this result shows the high sensitivity that can be obtained by using a simple two-contact electrode arrangement.
Figure 3.7 Sensitivity $\delta$ as a function of the placement of the current leads at various external fields in the EMR device with symmetric VIIIV configuration.

A study of asymmetric current lead arrangement shows that $\delta$ can only be increased for low magnetic fields (Figure 3.8), which is also similar to what is found for the asymmetric IVVI configuration. The large change in $\delta$ as the leads are placed closer to the corners of the device can be explained in the same way as in case of the IVVI configuration. It can be concluded that VIIIV and IVVI configurations are very similar in general and optimally utilized with two electrodes at the corners of the semiconductor. This result suggests that an EMR sensor with high sensitivity can be reduced to a two-contact device with the two contacts located at the corners of the semiconductor layer. The asymmetry does not contribute significantly to the high field performance, but needs to be considered in order to improve the low field sensitivity.
Figure 3.8 Sensitivity $\delta$ as a function of the placement of current leads at various external fields in the EMR device with symmetric VIIV configuration. The arrow indicates the location of the fixed current lead.

**Contact Resistivity at Semiconductor/Metal Interface**

It has been pointed out in previous studies that the contact resistivity of the interface between the semiconductor and metal is of critical relevance for the EMR effect [42]. For the investigation of the influence of the interface, a bar-type EMR device with IVVI electrode configuration is used. The dimensions of the device model are: $W_m = 15 \, \mu m$, $W_s = 3 \, \mu m$, $L = 75 \, \mu m$, and the two voltage probes are symmetrically placed from the midline of the hybrid bar with a spacing of 50 $\mu m$. At the semiconductor/metal interface, different values ranging from $10^{-11} \, \Omega \cdot cm^2$ to $10^5 \, \Omega \cdot cm^2$ for the contact
resistivity \( \rho \) are applied. In practice, \( 10^{-8} \Omega \cdot \text{cm}^2 \) is considered a low ohmic contact resistivity. An external magnetic field \( B \) of 1 T is applied to the model.

Figure 3.9 Current density distributions in different devices with various contact resistivities: (a) ideal contact (no contact resistivity), (b) \( 10^{-8} \Omega \cdot \text{cm}^2 \), and (c) \( 10^{-5} \Omega \cdot \text{cm}^2 \). The color bar represents the strength of the current density (A/m\(^2\)). Dark streamlines show the path of current. Left column: at zero magnetic field. Right column: at magnetic field of 1 T.

Figure 3.9 shows the distribution of the current density in devices with different contact resistivities at \( B = 0 \) T and \( B = 1 \) T. The current density is symmetric in case of \( B = 0 \) T whereas it is deflected by the Lorentz force at \( B = 1 \) T, yielding increased density in the semiconductor and decreased density in the metal. With a low contact resistivity (\( 10^{-8} \Omega \cdot \text{cm}^2 \)), the current distribution in the device at zero and high fields are almost the same as in the ideal case with no contact resistivity. As the resistivity increases at the semiconductor/metal interface, it acts like a barrier and the current is increasingly inhibited to enter the metal shunt. Since the current density becomes larger in the
semiconductor region, the value of $R(0)$ increases, thereby reducing the EMR effect. These dependencies can also be seen in Figure 3.10, which shows the current density distribution at the central-line of the hybrid bar along the $y$-axis.

![Figure 3.10](image)

**Figure 3.10** Current density distributions along the symmetry axis ($y$-axis) of the EMR devices with different values of the contact resistivity of the interface between semiconductor (SC) and metal at magnetic fields of (a) 0 T and (b) 1 T.

It is worth to note that the area under each curve is identical to the total current $I$. As the contact resistivity increases, the current density in the semiconductor increases, and a similar effect is obtained by increasing the magnetic field.

Figure 3.11 shows the MR ratio and $\delta$ as a function of the contact resistivity at $B = 1$ T. Nonlinear curve fitting is applied to find the exponential functions that approximate both the EMR effect and the sensitivity. For contact resistivities between $10^{-11}$ $\Omega \cdot \text{cm}^2$ and $10^{-7}$ $\Omega \cdot \text{cm}^2$, the MR ratio is almost constant. In case of $\delta$, this range is from $10^{-11}$
Ω·cm² to 10⁻⁸ Ω·cm². As the contact resistivity increases beyond 10⁻⁷ Ω·cm² and 10⁻⁸ Ω·cm², the MR ratio and δ, respectively, decrease exponentially. In particular, the device with a contact resistivity of 10⁻¹¹ Ω·cm² shows an MR ratio of 1.1×10⁵ %. The MR ratio is 1.1×10⁶ % for the device with a contact resistivity of 10⁻⁸ Ω·cm² and it decreases to 6.0×10⁵ % and 423 % for the devices with 10⁻⁶ Ω·cm² and 10⁻⁵ Ω·cm², respectively. The MR ratio is almost reduced by 95 % compared to the ideal device (10⁻¹¹ Ω·cm²), when the contact resistivity increases to 10⁻⁶ Ω·cm². The MR ratio in the device with 10⁻⁵ Ω·cm² contact resistivity is only 0.4 % of the one of an ideal device. A similar behavior is observed for the dependence of δ on the contact resistivity. For a contact resistivity lower than 10⁻⁸ Ω·cm², the δ is app. 8.6 mV/T. It drops rapidly as the contact resistivity increases and has a value of 7.4 mV/T at 10⁻⁵ Ω·cm².

![Figure 3.11](image-url)  
**Figure 3.11** MR ratio and sensitivity δ as a function of the contact resistivity at 1 T (MR ratio and contact resistivity axes are logarithmic).
The study shows that the contact resistivity at the semiconductor/metal interface does not have a significant influence on both the MR ratio and $\delta$ until it is higher than $10^{-8}$ $\Omega\cdot$cm$^2$. This result is consistent with experimental results reported previously. Interestingly, a device with contact resistivities up to $10^{-6}$ $\Omega\cdot$cm$^2$ could still show a considerably large $\delta$, which is 95% of that in the device with contact resistivity of $10^{-8}$ $\Omega\cdot$cm$^2$. Attempts to reduce the contact resistivity below this value will not yield a relevant improvement of the performance of the device, which is often governed by the sensitivity. This is an important conclusion, since, in practice, a good ohmic contact with low resistivity requires a more complex fabrication process with carefully controlled etching for semiconductors and a rapid thermal annealing process after metal deposition.

3.2 Three-dimensional FEA Studies

As mentioned previously, the reduced 2D FEA model is based on the assumptions of negligible thickness and carrier transport in perpendicular direction [30,31], which requires the metal shunt to be of the same thickness as the semiconductor mesa, and the electrical contact between them to exist only at the vertical faces. In addition, stacks of different materials cannot be taken into account.

In practice, however, it is difficult to restrain the semiconductor/metal interfaces only to the vertical faces; the so-called cleaved metal deposition technique needs to be employed [37]. With conventional micro-fabrication processes, in order to ensure a
good electric contact and simplify the fabrication, EMR devices always have variations in thickness (Figure 3.12(a)), a multilayer shunt and an overlap between the metal shunt and semiconductor (Figure 3.12(b)), resulting in additional contact surfaces between the semiconductor and metal.

Figure 3.12 EMR devices (a) with different thicknesses for metal and semiconductor layers (b) with overlap between metal and semiconductor. The thickness of the metal and semiconductor are denoted as \( t_m \) and \( t_s \), respectively, and the width of the metal and semiconductor are denoted as \( W_m \) and \( W_s \), respectively. \( W_o \) represents the overlap between the metal and semiconductor; note \( W_d + W_o = W_s \).

In this section, a 3D model is introduced, which simulates the EMR effect in the case of fields in different directions and arbitrary semiconductor/metal interface geometries. The model is verified by experimental results and applied to study the performance of a bar-type semiconductor/metal hybrid EMR device with respect to the interface geometry.

3.2.1 Three-dimensional Finite Element Model

By direct integration of the Boltzmann equation, the current density vector due to
carriers at a single quadratic energy extremum is given by

\[ j = \sigma(E + \frac{j \times B}{ne}) \rightarrow j + \mu \cdot B \times j = \sigma \cdot E, \]  

(3.1)

where,

\[ \sigma = ne \mu, \]  

(3.2)

is the conductivity without magnetic field and \( \mu \) is the carrier mobility tensor. \( B \) is the magnetic field vector defined as

\[ B = \begin{bmatrix} B_x & B_y & B_z \end{bmatrix}^{-1}, \]  

(3.3)

where \( B_x, B_y, \) and \( B_z \) are the components of the homogenous field \( B \) in \( x, y, \) and \( z \)-directions, respectively.

The vector cross product can also be expressed as the dot product of a skew-symmetric matrix and a vector, thus

\[ B \times j = B_m \cdot j \Rightarrow \begin{bmatrix} B_x \\ B_y \\ B_z \end{bmatrix} \times j = \begin{bmatrix} 0 & -B_z & B_y \\ B_z & 0 & -B_x \\ -B_y & B_x & 0 \end{bmatrix} \cdot j, \]  

(3.4)

where \( B_m \) is the so-called magnetic field matrix. Then, Equation (3.1) can be rearranged to

\[ j + \mu \cdot (B \times j) = \sigma \cdot E \Rightarrow j + \mu \cdot B_m \cdot j = \sigma \cdot E \Rightarrow j = ne \left( \mu^{-1} + B_m \right)^{-1} E, \]  

(3.5)

and further more to:

\[ j = \sigma(B) E, \sigma(B) \equiv \begin{bmatrix} 1 & -\mu B_z & \mu B_y \\ \mu B_z & 1 & -\mu B_x \\ -\mu B_y & \mu B_x & 1 \end{bmatrix}^{-1}, \]  

(3.6)

where \( \sigma(B) \) is the magnetoconductivity tensor (note it is different from the \( \sigma \) above).
The spatial electrostatic potential $\varphi(x,y,z)$ in the EMR device can be solved using Laplace’s equation under specific boundary conditions (Equation (1.8)).

### 3.2.2 Model Validation

In order to validate the 3D FEA model, an EMR device similar to the one shown in Figure 3.12(b) was fabricated as well as simulated and the results are compared. The semiconductor used in this investigation is a 1.5 μm thick Si-doped InAs epilayer ($n = 10^{16}$ cm$^{-3}$). The details of the sample can be found in Appendix A. After growth, the semiconductor is patterned into a bar structure with 300 μm in length and 23 μm in width ($W_o + W_d$) using wet etching (Appendix A). The metal shunt with a width $W_m$ of 80 μm is fabricated by deposition of a Ti (50 nm)/Au (250 nm) stack using electron beam evaporation. Ti serves as an adhesion layer. An overlap $W_o$ of 3 μm exists between the semiconductor and metal shunt. Two metal leads with a width of 5 μm are located at the two corners of the InAs bar to apply the current and measure the voltage $V(B)$. At the semiconductor/metal interface, the device shows an ohmic contact with a resistivity of $10^{-7}$ Ωcm$^2$. This value is implemented in the model.

A constant current with a density of $6.67 \times 10^7$ A/m$^2$ (corresponding to 100 μA) is applied as the boundary conditions at the faces of the current leads. All other outer boundaries are set to be electrically insulating ($\sigma = 0$). The model is meshed with tetrahedral elements. The mesh density was varied adaptively in order to account for the large differences of the dimensions of the structural components. The material
parameters used in the simulation are $\mu = 0.82 \text{ m}^2/\text{V}\cdot\text{s}$ and $n = 5.6\times10^{22} \text{ m}^{-3}$ for the semiconductor, $\mu = 5.30\times10^{-3} \text{ m}^2/\text{V}\cdot\text{s}$ and $n = 5.90\times10^{28} \text{ m}^{-3}$ for gold, and $\mu = 2.90\times10^{-3} \text{ m}^2/\text{V}\cdot\text{s}$ and $n = 5.12\times10^{27} \text{ m}^{-3}$ for titanium. Homogenous magnetic fields in x, y, and z-directions changing from -1 to 1 T with steps of 0.1 T are applied. The result from the 2D FEA simulation is also provided for comparison, in which the width of the semiconductor bar is 20 µm and only a gold shunt without the titanium adhesion layer is considered.

It is worth to note that the mean free path in the InAs sample is around 70 nm. Thus, since our model considers only diffusive transport, the dimensions of the simulated...
structures are always larger than the mean free path in order to avoid ballistic transport phenomena [63].

![Figure 3.14](image)

*Figure 3.14* MR ratios as a function of magnetic field at (a) perpendicular field $B_z$ and (b) planar fields $B_x$ and $B_y$.

Figure 3.13 shows the simulated current path distribution in the EMR device as a function of magnetic fields in different directions. (Note, different dimensions are used for the device in order to provide clear illustrations). The dark streamlines show the current flow in the device. Without an external field, the current flows from the semiconductor into the metal, whereby a portion of the current flows through the overlap between semiconductor and metal. As a magnetic field is applied, deflections of current paths occur due to the Lorentz force. It is important to note that in case of
magnetic fields applied in the x-direction (Figure 3.13 (a)), the current redistributions for positive and negative fields are asymmetric with respect to the current distribution at zero-field, which is a result of the asymmetric geometry of the structure in x-view. However, in case of magnetic fields applied in z-direction or y-direction, current redistribution is symmetric.

Figure 3.14(a) shows the EMR ratio as a function of the perpendicular magnetic field $B_z$. Both the 2D and 3D FEA models provide accurate results for smaller field values. At higher fields the 3D model is considerably more accurate than the 2D one. For example, the MR ratios obtained from measurements at $B_z = 1$ T are 59.1 % compared to 61.8 %, and 76.2 % obtained from 3D and 2D FEA calculations, respectively. The stronger EMR effect found with the 2D simulation is mainly due to neglecting the lower conductivity of the titanium layer compared to gold and the semiconductor/metal overlap, which results in a wrong estimation of the device resistance at zero-field. The dependences of the MR ratio on magnetic fields applied in planar directions are shown in Figure 3.14(b). The ratios are 11.5 % and 8.2 % at $B_x = 1$ T and 9.0 % and 7.4 % at $B_y = 1$ T in case of experimental measurements and 3D FEA, respectively. Their values are about 15 % to 20 % of those obtained at perpendicular fields. A stronger EMR effect is observed at $B_x$ than at $B_y$. This can be attributed to the difference in the strength of the Lorentz force acting on the carriers near the interface between the semiconductor and metal shunt, which is the region where the Lorentz force has the largest impact on the current redistribution. The current density at the interface is highest near the contacts, where
the current flow is mainly in y-direction. Therefore, the Lorentz force on the carriers at the interface is larger, when the magnetic field is in x-direction rather than in y-direction. The magnetoresistance curve for the fields in x-direction is asymmetric due to the asymmetric geometry.

The simulated results for planar fields are slightly smaller than the experimental ones, which, I assume, can be attributed to the defects in the semiconductor, which are more abundant in the vicinity of the interface. Since the current flow is not uniform in regions with defects, the current component in z-direction is larger as compared to the ideal case, causing planar fields to produce additional Lorentz forces, which contribute to the current redistribution. Another factor influencing this result is the precision with which the magnetic field is aligned with respect to the x-y plane. A possible slight misalignment also creates a field component in z-direction, causing larger output signals.

### 3.2.3 Three-dimensional FEA results

**Metal Shunt Thickness**

In this subsection, the influence of the thickness of the metal shunt is studied. An EMR model with the same structure as shown in Figure 3.12(a) is employed having a 6 µm long semiconductor bar with the width $W_s$ of 150 nm and the thickness $t_s$ of 50 nm. The width $W_m$ of the metal shunt is 450 nm while the thickness $t_m$ is varied from 5 nm to 100 nm (10% to 200% of $t_s$). Figure 3.15 shows $\delta$ and the MR ratio as a function of $t_m/t_s$. 

at perpendicular fields of 0.1 T and 0.5 T. δ increases as \( t_m \) increases and reaches saturation when \( t_m = t_s \). The same behavior is observed for the MR ratio. When \( t_m < t_s \), as \( t_m \) decreases, the contact area at the interface becomes smaller. Assuming an ohmic contact at the interface with a constant contact resistivity, the resistance will increase, reducing the current flow into the metal. Therefore, as \( t_m \) decreases, a larger portion of the current flows directly from the left electrode to the right one without entering the shunt (Figure 3.16 (a) and (b)), weakening the EMR effect. When \( t_m > t_s \), the area of the contact interface becomes invariant, the current density stays constant in the semiconductor region (Figure 3.16 (c) to (e)), and, as a consequence, a constant EMR effect is observed.

Figure 3.15 (a) Output sensitivity \( \delta \) and (b) MR ratio as a function of \( t_m / t_s \), the ratio of metal thickness and semiconductor thickness, at \( B_z = 0.1 \) T and 0.5 T.
Figure 3.16 Current density distributions in the y-z planes along the symmetric axes of the devices with varying \( t_m/t_s \) values of (a) 20 %, (b) 40 %, (c) 100 %, (d) 160 %, and (e) 200 %. The color bar expresses the strength of the current density. “Sc” denotes semiconductor.

In the case of \( t_m \geq t_s \), the semiconductor bar is completely shunted at the x-z contact interface by the metal. However, for smaller values of \( t_m \), current components exist in z-direction near the interface, which do not contribute to the current redistribution under a perpendicular field, reducing the EMR effect. The influence from this difference in thicknesses is rather weak with a reduction of 1.9 % and 11 % at \( B_z = 0.1 \) T, and 2.8 % and 10.8 % at \( B_z = 0.5 \) T of \( \delta \) and the MR ratio, respectively. Hence, the thickness of the metal shunt can be reduced with only a small sacrifice of sensitivity and MR ratio.
**Semiconductor/Metal Overlap**

In order to investigate the influence of the semiconductor/metal overlap, a device with the structure shown in Figure 3.12(b) is simulated. The length of the device is 6 µm. The thickness of the semiconductor and metal is 50 nm in both cases. The width of the metal shunt $W_m$ and the spacing from the semiconductor edge to the metal shunt $W_d$ are 450 nm and 150 nm, respectively, while the overlap $W_o$ is changed from 0 (no overlap) to 100 % of $W_m$ ($W_o = 450$ nm). Without overlap, the device has the optimized length/width ratio of 40 for highest MR ratio [31]. As the overlap $W_o$ increases, the contact area in the x-y plane increases while that one in the x-z plane remains constant.

**Figure 3.17** (a) Output sensitivity $\delta$ and (b) MR ratio as a function of $W_o/W_m$, the ratio of the overlap and the metal width, at $B_z = 0.1$ T and 0.5 T. ($L = 6$ µm, $L/W_d = 40$).
Figure 3.17 shows $\delta$ and the MR ratio as a function of the overlap. Both of them decrease as $W_o$ increases and take on constant values, when $W_o$ reaches about 25 % of $W_m$. The maximum reduction of $\delta$ due to the overlap is around 2 ~ 5 % while that one of MR ratio is around 6 ~ 8 %.

Figure 3.18 Current density in z-direction at the x-y semiconductor/metal interface and in y-direction at the x-z interfaces in an EMR device with (a) $W_o/W_m = 10 \%$, and (b) $W_o/W_m = 50 \%$. The dark lines indicate the edge of the interface in the x-y plane; the area above the line is the interface while that below is the surface of the semiconductor bar. The color bar indicates the strength of the current density. ($L = 300$ nm, $W_d = 100$ nm, $t_i=t_m=50$ nm).
Figure 3.18 shows the current density distributions at the semiconductor/metal interfaces with $W_o/W_m$ of 10% and 50% (Note, different dimensions are used for the device in order to provide clear illustrations. $l = 300$ nm, $W_d = 100$ nm, $t_s = t_m = 50$ nm). The current density in y-direction passing through the x-z interface is considerably lower in the device with $W_o/W_m = 50\%$ than in the device with $W_o/W_m = 10\%$, indicating that with a larger overlap, less current passes through the x-z interface and the semiconductor is “shorted” by the overlap region. From the current densities in z-direction at the x-y interfaces it is apparent that the transfer of current into the shunt happens in close proximity to the boundary of the overlap region in both cases. This shows that the z-component of the current, which is responsible for the in-plane field sensitivity and for the reduction of sensitivity and MR ratio to perpendicular fields, is mainly confined to the boundary of the overlap. It is worth to mention that in devices made of only a single atomic layer, e.g. graphene based, the influence of the x-z interface might be different.

One aspect worth to elaborate on is that the overlap influences the EMR effect by modifying the semiconductor length/width ratio. In case of no overlap, the effective width of the semiconductor bar, $W_{e}$, is equal to $W_d$, which is defined by width of the semiconductor region which carries a current (note, the majority of current flows in y-direction, parallel to the short edge of the semiconductor bar). In case of an overlap, the current spreads into the semiconductor bar underneath the overlap making the effective width larger, i.e.,
\( W_e = W_d + f W_o, \)  
\( (3.7) \)

where \( f \) is a coefficient. As a consequence, the ratio is modified from \( L/W_d \) to \( L/(W_d + f W_o) \). When \( L/W_d \leq 40 \), the overlap reduces the effective length/width ratio, which had an optimized value; hence, reducing the performance of the device (as shown in Figure 3.16). In the case of \( L/W_d \) being larger than the optimum value, the effect of an overlap, decreasing the ratio, improves the performance.

![Figure 3.19](image)

**Figure 3.19** (a) Output sensitivity \( \delta \) and (b) MR ratio as a function of \( W_o/W_m \), the ratio of overlap to the metal width, at \( B_z = 0.1 \) T and 0.5 T \( (L = 9 \mu m, \ L/W_d = 60) \).

In order to get a deeper insight into the effect of the overlap, a simulation has been conducted with a device having a length of 9 \( \mu m \) while other geometric parameters are kept the same as before. Without an overlap, the device has a sub-optimized length/width ratio of 60. The result shows the same behavior as before; the
performance reduces as the overlap increases and remains constant when the overlap reaches 25 % of \( W_m \) (Figure 3.19). The maximum sensitivity drop due to the overlap is around 2 % to 5 % and that of the MR ratio is around 6 % to 8 %. This result suggests that the influence of the overlap on the effective length/width ratio is rather small, and so is the value of the coefficient \( f \) (Equation (3.7)). Note that the width in the calculation of the effective length/width ratio is the distance between the current leads and the edge of the overlap. Since most of the current enters the overlap within a short distance from its edge, as shown in Figure 3.18, the effect of the overlap quickly diminishes with increasing length. In addition, as discussed above, the current underneath the overlap consists of a large z-component, which does not contribute to the EMR effect under a perpendicular field, and also does not have a strong effect on the effective length/width ratio (compare Figure 3.18). In summary, the main influence of the overlap is that it produces a z-component of the current flow causing the effects discussed above.

A device fabricated with a metal shunt and semiconductor of the same thickness and without any overlap between the two materials provides the best results in terms of output sensitivity. However, such a device is unreasonable from a fabrication point of view. If the thickness of the metal shunt is reduced to about 20 % of the thickness of the semiconductor, the output sensitivity is only reduced by about 2 % to 10 % for perpendicular fields. If a device is fabricated with an overlap between the metal and semiconductor, the sensitivity drops by around 4 % to 6 %. However, in a real device, the losses due to the overlap might be compensated by the benefits of a better
electrical contact between the semiconductor and shunt. Recently, an EMR device with a fully overlapping structure has been reported, which showed the great advantage of considerably reduced fabrication complexity, while maintaining a considerable performance [65]. In summary, the results show that an efficient EMR device with a reasonable compromise between costs, fabrication complexity and performance consists of a thin metal shunt with an overlap at the top of the semiconductor bar.
Chapter 4

Improved EMR Devices

4.1 Influences of the Magnetic Field Direction and Temperature

The semiconductor/metal hybrid structure shows a strong MR effect for magnetic fields applied perpendicularly to the planar device. However, the MR effect also exists in for in-plane fields (see Figure 3.14). Further, as shown in chapter 2, the EMR effect exhibits strong temperature dependence. Hence, when the operation temperature changes or the applied magnetic field deviates from the perpendicular direction, the output performance of an EMR device changes. In this section, the dependence of the output sensitivity to external fields both perpendicular and parallel to the device will be evaluated as functions of temperature.

4.1.1 Experimental Details

It has been shown in chapter 3 a highly sensitive EMR device can be obtained by simplifying the conventional 4-contact configuration into a 2-contact one with the two electrodes located at the corners of the semiconductor layer. Therefore, for the investigation in this section, a 2-contact EMR device is fabricated, which has an overlap between the semiconductor and metal shunt, is simple to pattern and is made of an n-doped InAs epilayer sample (Appendix A.2). The temperature dependent transport
properties in the unpatterned InAs samples are shown in Figure 2.4.

![Figure 4.1 Optical micrograph of the fabricated 2-contact EMR device.](image)

The InAs epilayer is patterned into a rectangular bar of 20 μm × 300 μm by wet etching (Appendix A.4). The metal shunt and electrodes are metallized with a Ti (50 nm)/Au (250 nm) stack and patterned by standard photolithography and a lift-off process (Appendix A.5). An overlap of 3 μm exists between the semiconductor bar and metal shunt. Figure 4.1 shows the optical microscope image of the fabricated device. The device is wire bonded on a printed circuit board. The measurements and characterizations are carried out using a physical property measurement system (Quantum Design). A homogenous external field $B$ ranging from -1 to 1 T with a step of 0.02 T was applied to the devices in three directions labeled $x$, $y$, and $z$ in Figure 4.1, at temperatures varying from 5 K to 300 K. A constant current $I$ of 100 μA, which is in the linear $I$-$V$ regime, is applied to the electrodes $I_+$ and $I_-$. (Figure 4.1) throughout the measurements. The output voltage $V$ was measured at the same electrodes. The
resistance and sensitivity of the device are calculated using Equations (1.10) and (1.11), respectively.

4.1.2 Results and Discussion

The magnetoresistance curves of the device at perpendicular fields and different temperatures are shown in Figure 4.2.

![Magnetoresistance curves](image)

**Figure 4.2** Magnetoresistances as a function of the perpendicular field at various temperatures.

The zero-field resistance $R(0)$ is about 340 $\Omega$ at 300 K and drops to 240 $\Omega$ as the temperature decreases to 100 K. As the temperature decreases further (< 100 K), $R(0)$ rises and reaches a value of about 340 $\Omega$ at 5 K. As discussed in Chapter 2, this phenomenon is related to the change of $\rho_0$ (Figure 2.4) of the InAs epilayer showing the semiconductor dominates the temperature dependence of $R(0)$. As the field increases,
the resistance $R$ becomes larger. At 1 T, the MR ratio is 61 % at 300 K, 99 % at 200 K, 176 % at 100 K, and 85 % at 5 K.

![Graph showing sensitivity as a function of perpendicular field and temperature](image)

**Figure 4.3** Sensitivities as a function of the perpendicular field at various temperatures.

The sensitivities as a function of the perpendicular field and temperature are shown in Figures 4.3 and 4.4, respectively. At 0.1 T the sensitivity is 85 $\Omega/T$ at 300 K and 400 $\Omega/T$ at 75 K. The output sensitivity at 75 K is enhanced by a factor of about 4.7 compared to 300 K, which is even higher than the enhancement in MR ratio of about 2.9 (177 % at 75 K). The value of the sensitivity saturates as the field strength increases beyond 0.25 T, and the device shows a linear range, whereby the saturation field is higher for lower mobility conditions. At 75 K the sensitivity reaches a peak value of 562 $\Omega/T$ at 0.26 T, while at 300 K, the device does not saturate in the field range of 0 to 1 T and has a value of 245 $\Omega/T$ at 1 T.
**Figure 4.4** Sensitivities as a function of temperature at various perpendicular fields.

**Figure 4.5** Magnetoresistances as a function of a planar field applied in (a) x-direction and (b) y-direction at various temperatures.
Figures 4.5 and 4.6 present the magnetoresistances and output sensitivities of the device for planar fields (along x and y axis). These two quantities, qualitatively, show similar behavior as observed for perpendicular fields; however, the effects are much smaller. The sensitivities to planar fields are about 20% to 25% of the ones to perpendicular fields.

Moreover, in an ideal EMR device, the electrical contact between the semiconductor layer and metal shunt is established between the contacting sidewalls only. Thus only the Lorentz force induced by a perpendicularly applied field can produce a relevant current redistribution and EMR effect. In practice, however, in order to ensure a good electric contact and simplify fabrication, EMR devices always show some overlap
between the semiconductor and the metal layer. In case of the studied device the overlap is 3 μm (Figure 4.1). The Lorentz force induced by a planar field applied in the x- or y-direction will also cause a current redistribution thereby changing the resistance of the device and influencing the output signal.

In Figure 4.7, the temperature dependences of the output sensitivity to planar fields are presented. In both cases, x and y-directions, the sensitivity shows a maximum value at 75 K, which is consistent with the result observed at perpendicular field and associated with the maximum mobility of InAs at this temperature.

**Figure 4.7** Output sensitivity as a function of temperature to planar field applied in (a) x-direction and (b) y-direction at various field strengths.

The device is more sensitive to fields along the x-axis than along the y-axis. At 0.1 T and 300 K, the sensitivity to fields along the x-axis is 12 Ω/T, whereas it is 8 Ω/T to fields
along the y-axis. This difference can be attributed to the difference in the strength of the Lorentz force acting on the carriers near the interface between the semiconductor and metal shunt, which is the region where the Lorentz force has the largest impact on the current redistribution. At zero magnetic field, the current density at the interface is maximum near the electric contacts, where the current flow is mainly in the y-direction. Therefore, the Lorentz force acting on the carriers at the interface is larger when the magnetic field is in x-direction rather than in y-direction, giving rise to a larger current redistribution and larger EMR effect.

In summary, a strong temperature dependence of the sensitivity is observed in an EMR device, which is correlated to the mobility of the semiconductor. The highest sensitivity of 562 Ω/T is measured at a temperature of 75 K and a perpendicular field of 0.26 T. An even higher value can be expected in a device based on a semiconductor epilayer with higher mobility. It was also found that the EMR device is sensitive to planar fields, whereby the sensitivity is about 20% to 25% of the one to a perpendicular field. These results show the considerable influence of planar fields on the output signal of EMR sensors and also suggest the possibility to design an EMR device sensitive to planar fields.

4.2 Top-contacted EMR device

So far, EMR devices have mainly been made by patterning a semiconductor layer, e.g., into bars, and, subsequently, depositing a metal layer on its sidewalls to attach
conductive elements. Accordingly, the fabrication requires etching processes that may cause roughness and damage to the semiconductor’s surfaces [66]. One consequence of such damage is that it is difficult to obtain a low contact resistivity at the semiconductor/metal interface, which is a critical factor for the performance (Chapter 3). Recently, an EMR device was developed with a metallic contact fully overlapping the semiconductor, a configuration that simplifies the fabrication process, especially the formation of the electric contact between the semiconductor and the metal layers [65]. Since the device employs a patterned semiconductor, careful alignment of the metal contacts and the semiconductor structure is still required. As the dimensions of the device are reduced, for example, to increase the spatial resolution, the alignment and the fabrication of the high-aspect-ratio structures become challenging. In this section, an EMR device fabricated by a simple process is introduced, which does not require patterning of the semiconductor, reducing the complexity of the fabrication process and having the potential to reduce damage to the semiconductor.

### 4.2.1 Experimental Details

Firstly, the surface of the InAs sample is covered with a 100 nm thick silicon nitride insulation layer grown by plasma-enhanced chemical vapor deposition, which is patterned by inductively coupled plasma reactive ion etching, using SF₆ gas, to open a window for the metal contacts (Appendix A.6). Then, the metal shunt and electrodes are made of Ti (10 nm)/Au (200 nm) and patterned by standard photolithography and a lift-
off process (Appendix A.5). The metal shunt (200µm × 150 µm) is placed on the InAs surface, while the electrodes are placed on the insulation layer with only their tips touching the semiconductor to provide the top contacts. The electrodes are symmetrically placed about the central line of the metal shunt with a separation of 100 µm between them. The alignment is simplified by the fact that accuracy is required only in the y-direction to ensure that the tips of the electrodes extend beyond the insulator and touch the semiconductor’s surface. The distance between each electrode’s tip and the edge of the metal shunt is 20 µm. Figures 4.8(a) and (b) show the microscopic image and 3-D sketch of the “top-contacted device,” respectively.

Figure 4.8 Optical microscopic images and 3-D sketches (a, b) of the top-contacted EMR device and (c, d) of the side-contacted EMR device, respectively. SC denotes semiconductor. The scale bars indicate 100 µm.

A reference “side-contacted device” is also fabricated conventionally by patterning the InAs sample into a rectangular bar of dimension 110 µm × 30 µm, using standard
photolithography, followed by wet etching in a citric acid solution (Appendix A). A Ti/Au stack is deposited and patterned to form the metal shunt and the electric contacts on the sidewalls. The overlap between the contacts and the semiconductor bar is 5 µm, the overlap between the shunt and the bar is ~1 µm. All other geometric parameters are the same in both devices. Figures 4.8(c) and (d) show the microscopic image and 3-D sketch of the side-contacted device, respectively.

Magnetoresistance measurements are carried out using a physical property measurement system (Quantum Design) at 300 K. The electric contacts are established using wire bonding. A homogenous magnetic field, $B$, of -1 to 1 T is applied perpendicularly to the devices in steps of 0.01 T. By means of the four-wire technique, a constant current of $I = 1$ mA was applied throughout the measurements, and the output voltage, $V$, was measured. The magnetoresistance, MR ratio, and output sensitivity are calculated with respect to the magnetic field using Equations (1.9), (1.10), and (1.11), respectively. The noise voltage $V_N$ is measured between the two electrodes inside a shielded chamber, using shielded cables and a lock-in amplifier (Stanford Research SR850) within the reference range from 1 to 200 Hz and with a bandwidth of 0.78 Hz (Appendix B) [67]. With the noise voltage and output sensitivity, the magnetic field resolution $B_{min}$ can be calculation from Equation (1.12).

4.2.2 Results and Discussion

The dependencies of the magnetoresistance and the MR ratio on the magnetic field are shown for both devices in Figure 4.9. The value of $R(0)$ of the top-contacted device is
about 40% lower than that of the side-contacted one. However, the MR ratios are found to be similar in both devices with the top-contacted device having slightly smaller (about 10%) values. At 1 T, the values are 79.6% and 88.7% in the top-contacted and the side-contacted devices, respectively.

**Figure 4.9** (a) Magnetoresistance curves and (b) MR ratios measured in the top-contacted and side-contacted devices as a function of the magnetic field.

In order to get an understanding for the smaller resistance value found experimentally, a 2D FEA simulation of the current distributions in the EMR devices is conducted using the same model described in chapter 3. The material parameters used are: $\mu = 0.816 \text{ m}^2\text{V}^{-1}\text{s}^{-1}$ and $n = 5.6 \times 10^{16} \text{ cm}^{-3}$ for the semiconductor, and $\mu = 5.3 \times 10^{-3} \text{ m}^2\text{V}^{-1}\text{s}^{-1}$ and $n_m = 5.9 \times 10^{22} \text{ cm}^{-3}$ for the metal. A current of 1 mA is applied. The upper
images in Figure 4.10 (a) and (b) show a top view of the devices with a color plot of the current density distributions.

![Figure 4.10](image)

**Figure 4.10** Current densities without field for (a) side-contacted device and (b) top-contacted device. Line plot: along the symmetric axis (y-axis). Color plot: the top view. The color bar represents the strength of the current density (red: high, blue: low). Dark arrows show the current paths. The light dashes show the locations of symmetric axis of the devices, and the dark dash in (b) indicates the edge of the insulation layer.

The lower curves in Figure 4.10 (a) and (b) show the current densities along the symmetric axes (y-axis) of the devices. Note, the areas under these curves are identical to the total current. In case of the side-contacted device, most of the current flows through the semiconductor bar into the metal shunt and, therefore, contributes to the EMR effect. Only a small portion of 9.6% of the total input current flows directly from
the left current lead to the right one without entering the metal shunt. Since it does not contribute to the EMR effect, it can be treated as a “current leakage”. In the top-contacted device, the “leakage” is 27 \%, due to the large area available for the current to pass from one electrode to the other one. For the same reason, the top-contacted device exhibits a smaller resistance value. Due to the lower value of \( R(0) \) in the top-contacted device, the MR ratios are similar for both devices. It is important to note that there is no current flow between the electrodes left of the semiconductor bar in case of the side-contacted device (Figure 4.10 (a)), since the substrate (GaAs) acts as an insulator (\( \rho = \sim 10^6 \Omega \cdot \text{m} \)). This is the main reason for the smaller current leakage in the device.

![Figure 4.11](image.png)

**Figure 4.11** Sensitivities as a function of the magnetic field, \( B \), measured in the top-contacted and side-contacted device.
The sensitivities as a function of the magnetic field are shown in Figure 4.11. The values are 28.6 $\Omega/T$ and 60.4 $\Omega/T$ at 0.1 T in the top-contacted and side-contacted devices, respectively. The sensitivities continuously increase with stronger fields and saturated at around 0.4 T. The saturation value is 87 $\Omega/T$ in the top-contacted device and 165 $\Omega/T$ in the side-contacted device. The ~2 times larger sensitivity of the latter device is mainly attributed to its higher resistance.

Figure 4.12 Voltage noise spectra of (a) top-contacted device and (b) side-contacted device. Both are measured without applying current or magnetic field. The oblique lines show the frequency-dependent $1/f$ behavior, and the horizontal lines indicate the frequency-independent white noise levels. They intersect at the corner frequencies.

As aforementioned in chapter 2, the flicker noise dominates in the EMR device in the low-frequency range, while at higher frequencies the Johnson noise dominates. Due to
the considerable difference in resistance between the top-contacted device and the
side-contacted one, the differences in Johnson noise are expected using Equation (2.18).
In order to compare the performance of the two devices it is worth to study the
frequency dependence and to determine the frequency region at which the device
exhibits low noise (in the Johnson noise range). The noise spectra are measured and are
shown in Figure 4.12(a) and (b) for the top-contacted and side-contacted devices,
respectively. Throughout the frequency range tested, the top-contacted device exhibits
less noise than the side-contacted one. The corner frequency, $f_c$, below which the flicker
or $1/f$ noise is dominant, is 8.8 Hz in (a) and 9.5 Hz in (b). The low corner frequency is
maintained in the top-contacted device, which may be beneficial to applications in the
low-frequency regime. Above $f_c$, the white noise levels are 1.69 nV/$\sqrt{\text{Hz}}$ and 2.33 nV/$\sqrt{\text{Hz}},$
in the top-contacted and the side-contacted devices, respectively, which is consistent
with the expectation.

The influence of external magnetic fields on the noise of both devices is studied
shown in Figure 4.13. The noise voltages are plotted as a function of the magnetic field in
the white noise regime. In both devices, the values increase with the magnetic field. In
general, it is expected that the magnetic field influences the noise characteristic of an
EMR device only via changing its resistance (Johnson noise) and not due to magnetic
fluctuations. To put this expectation to a test, the noise voltages of the top-contacted
and side-contacted EMR devices at similar resistance are compared. The side-contacted
device has a resistance of 156.6 $\Omega$ at 0 T and a noise voltage of 2.33 nV/$\sqrt{\text{Hz}}$. At 0 T, the
top-contacted device has a resistance of 89.6 Ω and a noise voltage of 1.69 nV/√Hz. At 0.95 T, the top-contacted device shows a resistance of 156.9 Ω and a noise voltage of 2.21 nV/√Hz. This noise voltage value is basically the same as the one obtained for the side-contacted device with the same resistance value, indicating that only the resistance caused the noise (Johnson noise). Owing to its lower resistance value, the top-contacted device always exhibits the advantage of lower noise voltage compared to the side-contacted one with at same magnetic field.

**Figure 4.13** Voltage noises of the top-contacted and side-contacted device as a function of the magnetic field.

Since sensitivity and noise are both functions of the magnetic field, the magnetic field resolution also depends on the applied field. The magnetic field resolutions of both devices are shown in Figure 4.14(b). At zero-field, the resolutions are 7.5 μT/√Hz and 4.3 μT/√Hz for the top-contacted and the side-contacted devices, respectively. From zero to
0.2 T, the resolution increases dramatically, as a result of the increasing sensitivity. From 0.4 T to 1 T, where the sensitivity is constant, the resolutions of both devices are almost constant as well, changing from 24 nT/√Hz and 18 nT/√Hz to 26 nT/√Hz and 19 nT/√Hz for the top-contacted and the side-contacted devices, respectively. This small change could be attributed to the slight increase in noise with increasing magnetic field. Even though the sensitivity of the side-contacted device is 2 times better than that of the top-contacted device, the resolution of the side-contacted device is only 30 % better, due to its larger noise voltage. With, for example, the lock-in technique and a bandwidth of 1 Hz, the top-contacted EMR device has the potential to detect a magnetic field change as small as 24 nT.

![Graph showing magnetic field resolutions of the top-contacted and side-contacted device as a function of the magnetic field.](image)

**Figure 4.14** Magnetic field resolutions of the top-contacted and side-contacted device as a function of the magnetic field.
In conclusion, a top-contacted EMR device is designed, fabricated and characterized, which does not require patterning of the epilayer. In addition, it features a simplified fabrication process in which precise alignment of the semiconductor and metal layers is required only in the $y$-direction as compared with both the $x$ and $y$-directions in other processes. The device shows a similar MR ratio as a conventional side-contacted device but a smaller sensitivity. Due to additional current paths in the semiconductor layer, we observed a lower resistance. This reduces the noise, keeping the magnetic field resolution at the same level as that one of the side-contacted device. The smallest detectable field was 24 nT/√Hz, indicating that the top-contacted EMR device can be employed for low-field applications, such as single magnetic bead detection [68]. It is worth mentioning that the top-contacted device design could also be exploited to minimize the damage incurred on the semiconductor’s surface due to fabrication. For example, using a low-temperature deposition method for the insulator followed by a lift-off process to pattern the insulation layer would render the need for etching unnecessary. At the same time, the photoresist would protect the semiconductor during the deposition of the insulator.

4.3 Hall Effect Enhanced Low-field Sensitivity in EMR devices

Since the symmetric EMR device has a parabolic magnetoresistance curve, it suffers from poor low-field sensitivity, limiting the applicability of EMR devices and being a hindrance for commercial success. At high fields, an outstanding sensitivity can be easily
achieved with the symmetric EMR devices made of III-V materials. A two-contact EMR device described in the previous section exhibits a strong sensitivity of 150 Ω/T at 0.4 T; however, at a low field of 0.05 T, the value decreases to only 20 Ω/T. Therefore, developing devices with improved low-field sensitivity would be an important contribution to further the potential of this technology. An asymmetric electrode configuration (Figure 1.3(c)) was introduced to achieve the enhanced performance in the low-field region for EMR devices. Another modified IVIV configuration, in which the EMR effect cooperates with the Hall effect, was reported by Holz et al., having a sensitivity higher than the asymmetric configuration (Figure 1.5) [40].

In this work, a device with a 3-contact configuration is described, which also combines the EMR effect and the Hall effect, to significantly enhance the low-field sensitivity.

4.3.1 Experimental Details

The fabrication process for the 3-contact device is the same as the one for the conventional two-contact device. The InAs epilayer sample is patterned into a rectangular bar by photolithography followed by wet etching. The metal shunt and electrodes are made from a Ti (10 nm)/Au (150 nm) stack. Figure 4.15 shows the optical microscopic image of a fabricated device.

The current electrodes 1 and 2 are symmetrically placed at the semiconductor bar with a separation of 50 μm from the central line. At the central line, the voltage
electrode 3 is connected to the metal shunt, while electrode 4 is connected to the semiconductor bar. The output signal is measured through electrode 3 and 2. Electrode 4 is added to the device only to measure the reference signals for the sake of comparison. The distances between each electrode on the semiconductor bar and the edge of the metal shunt are 10 μm.

Figure 4.15 Optical micrograph of the 3-contact EMR device. The current is applied through the electrodes labeled as 1 and 2, and the arrow shows the direction of current flow. The output signal is measured through electrode 3 and 2. The external magnetic field is applied perpendicularly to the illustration plane.

The device is wire bonded to a printed circuit board. The measurements and characterizations are carried out using a physical property measurement system. A homogenous external field $B$ ranging from -1 to 1 T is applied in perpendicular direction
to the devices in steps of 0.01 T. A constant current of 100 μA is applied to the device via electrodes 1 and 2 throughout the measurements.

4.3.2 Results and Discussion

The output voltage of the device can be expressed as

\[ V_{3-2} = V_{3-4} + V_{4-2}, \]  

(4.1)

where the subscripts denote the electrodes used for voltage measurement, \( V_{3-4} \) is the Hall voltage of the hybrid structure and \( V_{4-2} \) is the voltage arising from the asymmetric magnetoresistance \( R_{4-2} \). The sensitivity is calculated using Equation (1.11) and Equation (4.1) as

\[ \delta_{3-2} = \frac{\partial V_{3-2}}{\partial B} = \delta_{3-4} + \delta_{4-2}. \]  

(4.2)

Thus, in addition to a component \( \delta_{4-2} \), resulting from the response of an asymmetric EMR sensor, the output sensitivity of this device is enhanced by a component \( \delta_{3-4} \), which is caused by the Hall effect.

The voltages \( V_{i-j} \) measured between different electrodes are shown as functions of the magnetic field in Figure 4.16. The symmetric EMR voltage \( V_{1-2} \) is also measured for the sake of comparison. In the magnetic field range of ± 0.25 T, the output of the symmetric EMR \( V_{1-2} \) is approximately parabolic while the Hall voltage \( V_{3-4} \) has a linear behavior. Asymmetric curves are observed for both asymmetric EMR voltages \( V_{4-2} \) and \( V_{3-2} \), which represents the output of the 3-contact geometry. The difference between them, \( V_{3-2} - V_{4-2} \), is equivalent to the Hall voltage \( V_{3-4} \), as expected.
Figure 4.16 Voltages between different electrodes of the device shown in Figure 4.15 as functions of the homogenous magnetic field applied in perpendicular direction to the device.

The sensitivities as functions of the magnetic field are shown in Figure 4.17. The linear Hall response has a constant sensitivity $\delta_{3-4}$ of $\sim 0.16 \text{ mV/T}$, while the outputs of the EMR effect become more sensitive as the field gets stronger. The asymmetric EMR sensitivity $\delta_{4-2}$ is slightly increased compared to the symmetric one $\delta_{1-2}$ in the range of 0 T to 0.015 T. The highest sensitivity at zero-field is obtained between electrodes 3 and 2 with $\delta_{3-2} = 0.19 \text{ mV/T}$, which is equivalent to the one of the symmetric EMR $\delta_{1-2}$ with a bias of 0.037 T and to the one of the asymmetric EMR $\delta_{4-2}$ at 0.061 T. At $B = 0.01 \text{ T}$, which is a typical working range for low field applications like magnetic beads detection,
$\delta_{3,2}$ is as high as 0.2 mV/T compared to $\delta_{4,2} = 0.067$ mV/T and $\delta_{1,2} = 0.048$ mV/T. At the very high field regime, the device is still extremely sensitive though its performance is not quite as good as the one of a regular EMR device.

![Figure 4.17](image.png)

**Figure 4.17** Sensitivity versus magnetic field at (a) low-field region and (b) high-field region in the devices with different electrode configurations. Notice that the x-axes in (a) and (b) have different scales.

In conclusion, an EMR device with a 3-contact geometry, which combines the Hall effect and EMR effect, has been fabricated and characterized. The device shows a significant enhancement of the low-field output sensitivity. A value of 0.2 mV/T at 0.01 T has been measured, which is 5 times larger than that in a conventional symmetric EMR device. In order to achieve a similar sensitivity, the conventional EMR device needs an
external bias field of at least 0.03 T. An even higher value can be expected in a device made of a semiconductor epilayer with higher mobility and with an optimized geometry that takes into account the EMR and Hall effect. These results might extend the applicability of the EMR device into the low field region while maintaining an exceptional performance in the high field region.
Chapter 5

Conclusion

In this dissertation, the EMR effect in semiconductor/metal hybrid structures is investigated with the aim to enhance the performance of EMR-based magnetic sensors. The geometric dependence of the output sensitivity of EMR sensors is explored by FEA. Two new concepts are introduced and studied experimentally, simplifying the fabrication process and enhancing the low field sensitivity of EMR sensor devices.

At first, the different kinds of geometric MR effects in n-doped InAs epilayers are investigated. An experimental comparison is conducted between intrinsic MR effect (vdP geometry), orbital MR effect (Corbino disc) and EMR effect. Three different geometries are employed in case of the EMR effect: 4-contact hybrid vdP disc, 2-contact hybrid bar, and 4-contact hybrid bar. Overall, the EMR effect in the hybrid structures is found to be much stronger than the orbital MR effect known as the largest geometric MR effect existing in simplex semiconductor structures. Large differences of the output voltages are found for 2-contact and 4-contact configurations. Employing a simple equivalent circuit, this result can be understood by the larger resistance value of the 2-contact configuration, which causes larger output voltages for the same applied current value.

The output sensitivity is a more relevant specification parameter than the MR ratio for evaluating a sensing device’s performance, where the minimal detectable field is
critical. However, this parameter has previously not been taken into account when optimizing the geometry of EMR devices, which has been done with respect to maximizing the MR ratio. Hence, the geometric dependence of the EMR devices is investigated thoroughly by 2D simulations with the aim to maximize the output sensitivity. The findings show that for obtaining a device with large output sensitivity a considerably different geometry is required compared to a device that achieves a large MR ratio. For example, the optimal length/width ratio of the semiconductor bar for large output sensitivity is found to be 10 to 20 for strong magnetic fields and 5 for weak fields, instead of 25 required to obtain the maximal MR ratio. As it is the case with the MR ratio, the placement of the voltage probes and current leads crucially influences the output sensitivity. An asymmetric electrode configuration has previously been reported to enhance the MR ratio. In contrast, the results of this work show that it has no significant contribution with respect to the output sensitivity in the high field regime, but it requires to be considered in the low field regime. With respect to sensor applications, the 2-contact hybrid bar EMR device is found to be the best choice for its significantly enhanced output sensitivity compared to the widely used 4-contact configuration. This is in contrast to the results reported before, where, in order to optimize the MR ratio; a 4-contact configuration with two voltage electrodes separated from each other by half of the length of the bar is suggested. A potential advantage of using the 2-contact device is an improvement of the spatial resolution, since, with fewer electrodes, the dimension of the device can be further reduced.

The influence of the contact resistivity at the semiconductor/metal interface on the device performance is also studied using 2D simulation, since it has been reported to play a major role, and values of $10^8 \Omega \cdot \text{cm}^2$ should be obtained in order to achieve high
MR ratios. However, when considering the output sensitivity, the results of the 2D simulations show that the interface resistance displays only minute impact, until its value exceeds $10^{-6} \, \Omega \cdot \text{cm}^2$. From a practical point of view, a small interface resistance is challenging to fabricate and normally requires an annealing process. With this new finding, the complexity of the fabrication process can be reduced without compromising performance.

Yet another important aspect to consider from a fabrication point of view is the semiconductor/metal interface geometry. With the established 2D FEA the influence of different metal shunt thickness and overlap between metal shunt and semiconductor cannot be investigated. In order to enable a study of those as well as other parameters, which are not taken into account in the 2D FEA, a 3D model is developed in this work. The validity of the model is confirmed by comparison with experiential results. The geometry of the interface exhibits an impact on the output sensitivity of up to about 10%. From the obtained result, an EMR device with a reasonable compromise between costs, fabrication complexity and performance is proposed to have a thin metal shunt with an overlap at the top of the semiconductor. The 3D model also enables an investigation of the EMR effect in planar magnetic fields for the first time. The 2-contact hybrid bar device is found to be sensitive to planar fields with about 15% to 20% of the sensitivity obtained for a perpendicular field. This result not only shows the considerable influence of planar fields on the output signal of EMR devices, but it also suggests the possibility of designing EMR devices sensitive to planar fields.
The EMR effect in the 2-contact hybrid bar devices fabricated from the n-doped InAs is studied at different temperatures. The results show a strong dependence of the EMR effect; the highest sensitivity of $562 \: \Omega/T$ is measured at 75 K, where InAs shows its largest mobility of $2.5 \: m^2/Vs$, which is enhanced by a factor of about 4.7 compared to 300 K. The major origin of the influence of the temperature on the EMR effect is found to be the variation of the mobility of the semiconductor, while other parameters, e.g. conductivity of the metal, are found to be of less relevance.

While the 2-contact EMR device has an effective design in terms of output sensitivity and fabrication complexity compared to the other geometries, as the dimensions are reduced to nanoscopic scale, the fabrication of high-aspect-ratio semiconductor structures and the alignment still bear considerable challenges. In this work, atop-contacted EMR device, which does not require patterning of the epilayer, has been developed. It benefits from a simplified fabrication process, in which less precision during the alignment of the semiconductor and metal layers is required. The device shows a similar MR ratio as a conventional, side-contacted device and a smaller sensitivity. Due to its lower resistance, the magnetic field resolution is kept at the same level as that of the side-contacted device. The resolution obtained with the fabricated devices is $24 \: nT/\sqrt{Hz}$ when biased with 0.4 T.

The excellent performance observed in EMR devices typically requires large biasing fields, e.g., the aforementioned 0.4 T. In order to improve the EMR devices in this regard and enhance the low-field sensitivity, a novel 3-contact EMR device is proposed. It
combines the Hall effect and EMR effect. The enhancement of sensitivity in the low-field region is a result of the linear response of the Hall effect to a magnetic field. In case of the fabricated device, a significant enhancement of the low-field output sensitivity is observed with the sensitivity of 0.2 mV/T at 0.01 T, which is 5 times larger than that in the conventional, 2-contact bar-type EMR device. While, in this work only the concept of the 3-contact EMR device is demonstrated, a higher sensitivity can be expected by geometric optimization in the future.

The results obtained with the EMR devices fabricated in this work are limited by the low mobility value (0.816 m²/V·s) of the InAs epilayer sample used. While this does not affect the findings in general, the absolute values could be increased considerably by using materials with higher mobility, e.g. quantum well in heterostructures or graphene. For example, a mobility as high as 20 m²/V·s has been reported for suspended graphene [69], which would yield largely enhanced EMR effects.

The findings of this thesis opened the door for a lot of interesting work in the future. Nanoscopic EMR devices could be explored and studied using the top-contacted structure, which will be of interest for applications requiring high spatial resolution like reading heads. It could be combined with the 3-contact concept, enhancing the low-field sensitivity, to be utilized for applications in magnetic beads detection for miniaturized biosensor systems. Compared with other types of magnetic sensor devices, e.g., tunnel magnetoresistance sensor, the EMR device features simple fabrication and robust performance.
Appendix A

Fabrication Details

A.1 EMR device fabrication procedure

The fabrication of EMR devices are following the sequence listed below:

(a) Growth of InAs epilayer;
(b) Patterning of InAs epilayer into expected geometries using photolithography;
(c) Wet etching for InAs;
(d) Patterning of metal shunt and electrodes using photolithography;
(d) Metal deposition and lift-off.

A.2 InAs epilayer

The InAs epilayer used in this work is grown on a (100) oriented semi-insulating GaAs substrate using solid-source molecular beam epitaxy (Veeco Gen-930 MBE system) facility at University College London.

The growth is started with a 1 μm In$_x$Ga$_{1-x}$As metamorphic buffer to accommodate the large lattice mismatch between InAs (lattice constant of 6.06 Å) and GaAs (lattice constant of 5.65 Å), and followed by a 0.2 μm undoped InAs stabilizing buffer (Figure A.1). The 1.5 μm-thick, Si-doped, active InAs epilayer is deposited on top with an impurity concentration of $\sim 10^{16}$ cm$^{-3}$ (see Figure A.1).
A.3 Photolithography

At the very beginning, the surface of InAs sample is cleaned in solvents as following: immerse the sample in Acetone for 5 minutes; immerse the sample in isopropyl alcohol for 2 minutes; wash the surface with deionized (DI) water flow for 30 seconds, blow dry the surface with nitrogen flow.

Then, the sample is placed on a hotplate at 100 °C for 2 minutes to remove the residual moisture on the surface.

The AZ 5214E is used as the positive photoresist with a nominal thickness of 1.6 µm, which is coated on the InAs layer’s top surface using the following speed and acceleration: 500 rpm (500 rpm/s) for 3 seconds, 1500 rpm (1500 rpm/s) for 3 seconds, and 3000 rpm (3000 rpm/s) for 30 seconds.
A prebake process is conducted, using a hotplate at 110 °C for 2 minutes, to semi-harden the photoresist and make it photosensitive.

The patterns are transferred from photomask to photoresist by exposed it to broadband ultraviolet light using EVG6200 mask aligner at an intensity of 75 mJ/cm². The exposed area in photoresist is removed in developer AZ 726 for 1 minute after exposure followed by washing in DI water and blowing dry with nitrogen flow.

If the prepared sample is for etching, a post-bake process is followed using hotplate at 100 °C for 5 minutes to harden the remaining photoresist as a protective layer. Otherwise, for lift-off process, no post-bake is expected.

A.4 Wet chemical etching

Citric acid (C₆H₈O₇) based chemical etchants are found to have effective etching for III-V semiconductor [70]. In this work, all etchings are performed at room temperature using citric acid/hydrogen peroxide (H₂O₂) mixture. First, anhydrous citric acid crystals are dissolved in DI water at the ratio of 1 g C₆H₈O₇:1 ml DI H₂O. As this mixture is an almost saturated solution, the dissolution is assisted by the use of an ultrasonic bath. In order to prevent outgasing, H₂O₂ (31%) is added shortly before etching, in a volume ratio of 2 ml of citric acid solution: 1 ml H₂O₂. The etch rate is found to be ~90 nm/min for InAs, and ~10 nm/min for GaAs. In the aforementioned epilayer structure, the undoped GaAs substrate is employed as etch-stop. The etched depth (~2.7 µm) is checked with profilometer (Veeco Daktak-8).
A.5 Metal deposition and Ohmic contact formation

After photolithographic patterning, the metal shunt and electrodes are formed with the nonalloyed metal stake of Ti/Au using magnetron sputtering (ESC sputter system). The Ti layer performs as an adhesive layer. Subsequently, the sample is left in acetone for long enough time to fully lift-off the undesired metal (checked with optical microscope).

A 90 seconds rapid thermal annealing (RTA) process (Jipelec JetFirst 200) is employed at 250 °C in nitrogen environment to achieve the low contact resistivity of $< 10^{-7} \ \Omega \cdot \text{cm}^2$ at semiconductor/metal contact interfaces.
Appendix B

Characterization Details

B.1 Instrumentation and characterization of EMR device

The characterizations are carried out using a physical property measurement system (PPMS) by Quantum Design. It comprises of low temperature stage, magnetometry, and electrotransport measurement facilities. The PPMS provides the voltage measurement resolution of 1 nV, current drive amplitude from 5 nA to 100 mA, and resistance measurement ranges from 10 µΩ to 5 GΩ. Sample environment controls include fields up to ± 9 T and temperature range of 1.9 K to 400 K [71]. The measured samples or devices are wire bonded on a printed circuit board (PCB), and then electrically connected to the channels on the PPMS sample holder. The EMR device is characterized using four-terminal sensing method which is a resistance measuring technique that uses separate pairs of current-injecting and voltage-sensing electrodes to make more accurate measurements than traditional two-terminal sensing. The key advantage of four-terminal sensing is that the separation of current and voltage electrodes eliminates the resistance contribution from the wiring and contact.

B.2 Standard van der Pauw method
The transport properties, the mobility $\mu$ and the carrier density $n$, of the semiconductor sample are proved to be very important parameters in EMR effect. As known, the electron mobility $\mu$ is determined by

$$\mu = \frac{1}{en_sR_s}, \quad (B.1)$$

where $e$ is the electron charge, $n_s$ is the sheet carrier density, $R_s$ and is the sheet resistance.

The carrier density $n$ is expressed as

$$n = \frac{n_s}{d}, \quad (B.2)$$

where $d$ is the thickness of the semiconductor sample.

![Figure B.1. Rectangular device for vdP measurement. Numbers denote the electrodes.](image)

In order to determine both the mobility $\mu$ and the carrier density $n$, the van der Pauw (vdP) technique is employed, which combines resistivity and Hall measurement [72]. As originally devised by van der Pauw, one uses an arbitrarily shaped thin plate sample containing four small ohmic contacts placed on the corners of the plate. A schematic of a rectangular vdP configuration used in this work is shown in Figure B.1. The transport properties in the “as-grown” InAs samples are conducted with a
macroscopic 1 cm × 1cm square-shaped vdP disc mechanically sliced from the epilayer wafer, with which the growth-induced petty inhomogeneity is eliminated. The sheet resistance $R_s$ is determined by the transverse resistivity measurement, where the voltage is measured parallel to the current flow. There are actually two characteristic resistances $R_a$ and $R_b$ associated with the corresponding terminals. $R_a$ and $R_b$ are defined by means of the following expressions,

$$ R_a = \frac{V_{43}}{I_{12}}, R_b = \frac{V_{14}}{I_{23}}, $$

(B.3)

where $V_{ij}$ and $I_{ij}$ indicate the voltage measured and current applied at electrodes $i$ and $j$, respectively.

The sheet resistance $R_s$ could be solved numerically through the van der Pauw equation,

$$ e^{-\pi R_a R_s} R_s e^{-\pi R_b R_s} + 1 = 1. $$

(B.4)

The Hall measurement could determine the sheet density $n_s$ by measurement the Hall voltage $V_H$ which is the voltage output measured at electrodes 2 and 4 when current I is forced through an opposing pair of electrode 1 and 3 and magnetic field $B$ is applied perpendicularly to the sample surface. The sheet carrier density $n_s$ can be calculated via

$$ n_s = \frac{IB}{e|V_H|}. $$

(B.5)

The mobility, then, could be calculated using Equation (B.1) afterwards.
B.3 Noise Characterization

The setup of the noise characterization is shown in the Figure B.2. The EMR device is placed in the shielded chamber and excited by using a magnetic field generator. The noise voltage measurement is carried out using the SR850 lock-in amplifier by Stanford Research System. Its noise voltage is firstly amplified by a preamplifier and then measured by the lock-in technique at the reference frequency ranged from 1 to 200 Hz and with a bandwidth of 0.78 Hz.

Figure B.2. The schematic of noise characterization.
BIBLIOGRAPHY


PEER-REVIEWED JOURNAL ARTICLES


CONFERENCE PROCEEDING


BOOKCHAPTER CONTRIBUTION

PATENT


ORAL PRESENTATIONS


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