Highly Sensitive InGaAs-AlGaAs-GaAs 2DEG Quantum Well Hall Effect Integrated Circuits

Mohammadreza SADEGHI and Mohamed MISSOUS

School of Electrical & Electronic Engineering, Sackville Building, Sackville Street, University of Manchester, Manchester, M13 9PL England, UK, Phone: +44-1613064782, E-mail: Mohammadreza.Sadeghi@Manchester.ac.uk, Mohamed.Missous@Manchester.ac.uk

Abstract
GaAs-InGaAs-AlGaAs Hall sensor, current source, differential amplifier, comparator and source follower were integrated to form the first highly sensitive, low power (~18 mW) III-V DC unipolar Hall integrated circuit. This is a three terminal device which utilises 2 µm gate length technology, offering very high yields, at least ~50% higher switching sensitivity (~ 6 mT) compared to existing commercial unipolar ICs. In addition, the first low power (10.4 mW) and ultra-sensitive Linear Hall Effect Integrated Circuits (LHEIC) using the same GaAs-InGaAs-AlGaAs 2DEG technology have also been developed. These LHEIC have a state-of-the-art sensitivity of 533 µV/µT and are capable of detecting magnetic fields as low as 177 nT (in a 10 Hz bandwidth), at frequencies from 500 Hz to 200 kHz.

Keywords: Digital Hall Effect Integrated Circuit, Linear Hall Effect Integrated Circuit, pHEMT.

1. Introduction

Hall Effect integrated circuits are widely used in applications such as automation, medical, electronic and electrical industries [1]. These ICs are divided into two categories of digital and linear (dependant on the type of output they generate in the presence of magnetic field), to cover a vast number of applications. Commercially available Hall Effect ICs are all based on silicon CMOS technology mainly due to their small dimension and low cost [2-5]. However, shortcomings of these ICs include low magnetic field sensitivity, limited operating frequency range and high power consumption. Due to the inherently poor silicon Hall sensor material properties, devices made of III–V semiconductors have attracted a great deal of interest by virtue of their high electron mobility combined with moderate sheet carrier densities, low temperature dependences of the output Hall voltage and large signal-to-noise ratios (S/N) [6-10]. However, the majority of this work to date has been concerned with single Hall elements with no reports of fully integrated Hall Effect circuit using the III–V semiconductors apart from [11-12] describing a hybrid circuit using ion implanted GaAs for which the performances were less than ideal due to the difficulties of the technologies used at the time. In order to provide a higher sensitivity and lower power consumption, a new type of AC linear and DC unipolar integrated circuits have been developed in this work which utilise a two Dimensional Electron Gas (2DEG) system. These Hall integrated circuits are based on GaAs-InGaAs-AlGaAs system, which is a reasonably mature technology allowing accurate modelling and simulation of transistors for the development of Process Development Kits (PDK). Every individual elements required for successful integration have been developed in this work in order to design and fabricate highly sensitive and low power Hall integrated circuits.

2. Fabrication of GaAs pHEMTs and Hall sensor

All wafers used in these studies were grown in-house using a solid-source Molecular Beam Epitaxy (MBE) in a RIBER V100 system. The epitaxial profile of a typical 4” wafer (XMBE303) grown on a (100) GaAs semi-insulating substrate is shown in Figure 1.
The pseudomorphic high electron mobility transistor structure consists of a GaAs buffer layer, a channel/active layer of strained In$_{0.15}$Ga$_{0.85}$As cladded by an Al$_{0.35}$Ga$_{0.65}$As spacer and supply layers, a Si delta doped layer and finally a GaAs cap layer. The as-grown sheet carrier density and mobility values were obtained using Hall Effect measurements and determined to be $1.57 \times 10^{12}$ cm$^{-2}$ and 6447 cm$^2$/V.s respectively.

The 2 µm gate length pHEMTs, fabricated on the structure shown in Figure 1, with trans-conductance of 140 mS/mm, threshold voltage of -0.4 V and output conductance as low as 0.04 mS/mm (Figure 2) were perfectly suitable for the design of the Integrated Circuits as they provide ample gain and bandwidth ($f_T = 5.2$ GHz (Figure 3) and $f_{max}=11.4$ GHz).

![Figure 1. GaAs-InGaAs-AlGaAs Structure](image1.png)

![Figure 2. The pHEMTs IDS Vs VDS for VGS from -0.5V to +0.5V](image2.png)
The design of the pHEMT structure can easily be adapted to form Hall plates. Using this pHEMT-like structure, two Greek cross Hall structures, denoted as P2A and P15A, using AlGaAs/InGaAs/GaAs materials and having resolutions of 1 µT at DC and 100 nT at higher frequencies have been reported previously [13]. The design of the XMBE303 Hall sensors relied on the same principles as the designs of the P2A and P15A sensors. Figure 4 illustrates the top view of the Greek cross sensor used in the final linear integrated circuit.

The fabricated device was fully symmetrical and thus input and output resistance were the same (~1750 Ω). The fabricated sensor had an (L/W) ratio of 3 with L = 60 µm and a sensitivity of 0.4 mV/mA.mT and was capable of detecting magnetic fields as low as 10 nT (with amplification of 40 K using off-chip components).

3. DC Digital (unipolar) Hall Effect Integrated Circuit

The GaAs-InGaAs-AlGaAs monolithic all Integrated Digital Hall Effect Circuit, which was designed, fabricated and tested in this work is illustrated in Figure 5.
This IC with a sensitivity of 8.5 mV/mT and a switching magnetic field of 6 mT operated successfully in the presence and absence of magnetic field. The output of this IC is depicted in Figure 6.

The DC unipolar Hall Effect IC developed in this work represents a first attempt at digital (unipolar) Hall Effect IC using 2DEG GaAs heterojunction material. Table 1 compares the performance of this IC and the commercial DC unipolar ICs available in the market.

Table 1. Comparison of the performance of the GaAs 2DEG IC developed in this work with the commercial DC unipolar Hall ICs

<table>
<thead>
<tr>
<th>Reference</th>
<th>Switching sensitivity (mT)</th>
<th>Power consumption (mW) at 5 V supply</th>
</tr>
</thead>
<tbody>
<tr>
<td>[14]</td>
<td>12</td>
<td>9.5</td>
</tr>
<tr>
<td>[15]</td>
<td>18</td>
<td>27.5</td>
</tr>
<tr>
<td>[16]</td>
<td>10</td>
<td>18</td>
</tr>
<tr>
<td>This work</td>
<td>6</td>
<td>18</td>
</tr>
</tbody>
</table>

As shown in Table 1, the switching sensitivity obtained in this work (despite consuming only 18 mW of power at 5 V) is at least 1.5 higher than the other commercial DC unipolar Hall ICs. This is despite the fact that the commercial Hall ICs employ multiple amplification circuitries along with current spinning technique to achieve better sensitivities.

4. AC linear Hall Effect Integrated Circuit

To take advantage of reduced 1/f noise at higher frequencies, an entire high mobility GaAs-InGaAs-AlGaAs based AC Hall Effect Integrated Circuit has also been designed, fabricated and tested. This Integrated AC Hall Effect circuit has proven to detect magnetic fields as low as 177 nT in a 10 Hz bandwidth (Figure 7) at the frequency range of 500 Hz to 200 kHz.
The overall integrated circuit’s sensitivity was 533 mV/mT and was determined by the Hall Effect sensor’s sensitivity (0.4 mV/mT biased at 1 mA) and the amplifier’s gain of 1333. This is a factor of 10, 13 and 37 higher compared with the Allegro (A1324), Melexis (MLX90242) and Honeywell (SS39ET) [14-16] devices. In addition to providing very high sensitivity, this IC had a power consumption of only 10.4 mW. Despite being the most sensitive amongst all commercial silicon ICs investigated in this study, the power consumption of the Honeywell SS39ET IC is 30 mW (at 5 V supply), which is almost 3 times higher than the GaAs Hall IC reported here. The power consumption for the Allegro A1324 and Melexis MLX90242 ICs are 34.5 mW and 12.5 mW at 5 V supply, respectively. The reason for high power consumption of these silicon ICs is because they employ complex circuitries for spinning current technique, circuit protection, signal buffering, offset and 1/f noise cancellation.

5. Conclusion

In this work, the performances of the first GaAs-InGaAs-AlGaAs 2DEG fully integrated AC linear and DC digital (unipolar) Hall Effect integrated circuit were presented. The low power (~10.4 mW) AC linear IC provides a sensitivity of 533 µV/µT at bandwidths greater than 200 kHz. This IC is capable of detecting AC magnetic fields as low as 177 nT (in a 10 Hz bandwidth), which is almost a factor of 4 lower than the best commercially available Si Hall IC. The DC digital IC offers switching sensitivity of ~6 mT and power consumption of ~18 mW which is at least 1.5 times more sensitive compared to commercial silicon DC unipolar Hall ICs. The AC linear and DC unipolar Hall Effect ICs can be employed in diverse applications such as automotive and consumer industrial, solid state switch, wiper motor, sunroof opener, seat motor adjuster and electrical power steering and especially where extreme of temperatures are encountered.

References

[9] J.S. Lee, K.H. Ahn, Y.H. Jeong, D.M. Kim, Quantum-well Hall devices with Si-delta-doped Al0.25Ga0.75As/GaAs and pseudomorphic Al0.25Ga0.75As/In0.25Ga0.75As/GaAs heterostructures grown by LP-MOCVD: performance comparisons, IEEE Trans. Electron Devices, 43 (10) (1996) 1665–1670.