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Citation for the original published paper (version of record):
Harrysson Rodrigues, I., Niepce, D., Pourkabirian, A. et al (2019). On the angular dependence of InP high electron mobility transistors for cryogenic low noise amplifiers in a magnetic field. AIP Advances, 9(8). http://dx.doi.org/10.1063/1.5107493

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Cite as: AIP Advances 9, 085004 (2019); https://doi.org/10.1063/1.5107493
Submitted: 29 April 2019 . Accepted: 26 July 2019 . Published Online: 02 August 2019

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Submitted: 29 April 2019 • Accepted: 26 July 2019 •
Published Online: 2 August 2019

View Online Export Citation CrossMark

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ABSTRACT

The InGaAs-InAlAs-InP high electron mobility transistor (InP HEMT) is the preferred active device used in a cryogenic low noise amplifier (LNA) for sensitive detection of microwave signals. We have investigated the angular dependence of the InP HEMT when oriented in a magnetic field at 2 K ambient temperature up to 14 T. A sharp angular dependence as a function of the magnetic field was measured for the output current of the InP HEMT. This was accurately described by a geometrical magnetoresistance expression for all angles and magnetic field strengths. Key device parameters such as transconductance and on-resistance were significantly affected at small angles and magnetic fields. The strong angular dependence of the InP HEMT output current in a magnetic field has important implications for the alignment of cryogenic LNAs in microwave detection experiments involving magnetic fields.

In many sensitive detection systems, high electron mobility transistor (HEMT) low-noise amplifiers (LNAs) at cryogenic temperatures (1-10 K) are used to read out tiny microwave signals. Some of these systems rely on the presence of a strong magnetic field, *e.g.* in mass spectrometry[1] or detection of dark matter.[2,3] A potential application for cryogenic LNAs in a magnetic field is magnetic resonance imaging.[4] A problem prevalent in these detectors is that amplifier properties such as gain and noise figure are negatively affected by the magnetic field. The situation is most unfavorable for the LNA oriented perpendicular to the magnetic field (because of the Lorentz force acting on the current). As a result, scientists always strive to mount the LNA away from the magnetic field using coaxial cables alternatively to align the LNA parallel to the magnetic field lines. While the former solution is not preferable because of losses and reduced sensitivity, the latter gives rise to the issue on the degree of alignment of the LNA in the field. This is related to the orientation of the HEMT (and the 2DEG transport current) in a magnetic field. Here we report the angular dependence of the output current for the cryogenic InGaAs-InAlAs-InP (InP) HEMT in a magnetic field. It is shown that the InP HEMT output current is limited by a strong geometrical magnetoresistance effect (gMR) as a function of angle and magnetic field. We also confirm that the gain and noise properties for the cryogenic InP HEMT LNA are very prone for degradation when exposed to a magnetic field. The strong angular field dependence demonstrated for the cryogenic InP HEMT output current suggests that even small misalignment of the cryogenic InP HEMT LNA in a magnetic environment is detrimental to read-out sensitivity.

We first examined the sensitivity of the cryogenic InP HEMT LNA in a magnetic field using a 10 T superconducting magnet. The LNA was a monolithic microwave integrated circuit (MMIC) chip consisting of three InP HEMT stages and passive components mounted in a gold-plated aluminum module. Neither the LNA module nor in-going passives exhibited any magnetic-field dependence as verified by additional experiments. The amplifier was a broadband design ranging from 0.3 to 14 GHz with a gain of 42 dB and average noise temperature of 4.2 K (0.06 dB) at 6 K ambient temperature.[5] The LNA was mounted at the centre of the magnet on the 2 K stage of an Oxford Instruments Triton 200 dilution refrigerator. The setup only permitted the LNA module to be oriented perpendicular to the magnetic field. In Fig. 1 the gain and noise temperature at 3, 5 and 8 GHz are presented for the cryogenic InP HEMT LNA at 2 K when exposed to static magnetic fields up to 1.5 T. For all three measured frequencies, the LNA gain and noise temperature started to be affected around 0.25 T. Compared to an earlier study for a GaAs HEMT LNA,[6] the degradation for the InP HEMT LNA in the presence of a magnetic field is much stronger. This is connected to the higher electron mobility and sheet density of the two-dimensional electron gas (2DEG) in the InP HEMT compared to the GaAs HEMT used in Ref. 6.

The very strong degradation of the cryogenic InP HEMT LNA illustrated in Fig. 1 motivated the investigation of the InP HEMT as a function of angle and magnetic field. DC measurements were conducted on individual transistors at low temperature. The discrete InP HEMTs were fabricated in the same transistor technology[7] used for the cryogenic InP HEMT LNA measured in Fig. 1. We have fabricated two-finger device layouts with gate width W_g ranging from 10 to 100 μm and gate length L_g from 60 to 250 nm. The DC-characterization was carried out in a Quantum Design Physical Property Measurement System (PPMS). The transistor was electrically connected through wire bonding and mounted in a matched LC-network on a sample holder in the vacuum chamber of the cryostat and cooled down to 2 K. A static magnetic field ranging up to 14 T was then applied and DC measurements were performed using a Keithley 2604B source meter.

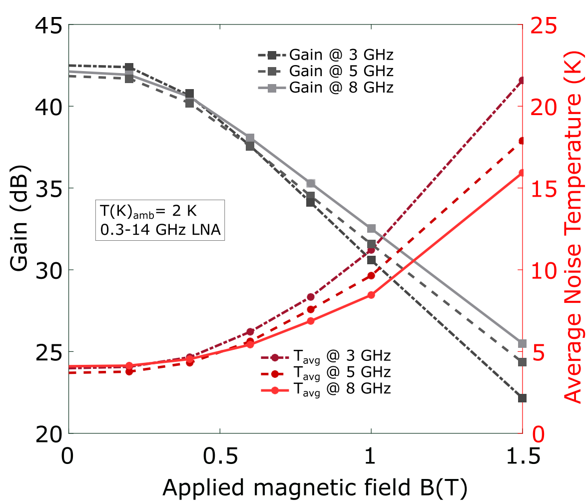

FIG. 1. Gain and average noise temperature for the cryogenic InP HEMT MMIC LNA, measured at 2 K, for three different frequencies as a function of applied magnetic field. The LNA was aligned perpendicular to the magnetic field.

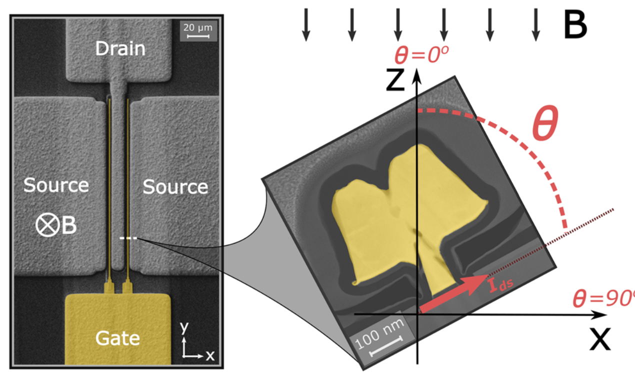

FIG. 2. The two-finger InP HEMT shown in top view (by scanning electron microscopy) and side view (by cross-sectional transmission electron microscopy) perspective. The T-shaped gate is marked in yellow. The static magnetic field was applied in z-direction. The device was rotated from $\theta = 0°(180°)$ to 90° corresponding to parallel and perpendicular orientation, respectively, of the HEMT output current with respect to the magnetic field.

The measurement setup in PPMS allows for sample rotation in the *B*-field. In Fig. 2, the geometry of the DC experiment is shown. A static magnetic field was applied in the z-direction. Fig. 2 presents a top view and side view of the two-finger InP HEMT where an angle of rotation θ is defined with respect to the magnetic field. θ could be varied between 0° and 180° degrees where 0° (180°) and 90° corresponded to measurements of the InP HEMT oriented parallel and perpendicular to the magnetic field, respectively.

The cryogenic InP HEMT output current was first measured for $\theta = 90°$. Figure 3 shows the source-drain current I_{ds} versus source-drain voltage V_{ds} for different gate-source voltage V_{gs} under a magnetic field of 0 T and 10 T. The device was a 2x50 μm InP HEMT with L_g=100 nm. Figure 3(a) illustrates a typical InP HEMT measured under cryogenic conditions in the absence of a magnetic field.

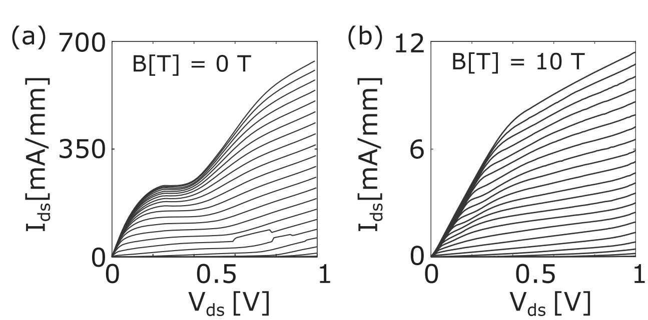

FIG. 3. I_{ds} versus V_{ds} for the InP HEMT at 2 K oriented $\theta = 90°$ in a static magnetic field of (a) 0 T and (b) 10 T. V_{gs} was varied from -0.4 to 0.4 V in steps on 0.1 V. W_g =2x50 μm and L_g=100 nm. Note difference in y-axis scale for (a) and (b).

The kink behavior at high current level around V_{ds}=0.4 V originates from electron traps in the interface layers of the heterostructure and is characteristic for these type of devices measured at low temperature.[8] Since the LC network in the sample holder did not provide a perfect 50 Ω impedance environment for the transistor, oscillations occurred for lower I_{ds} showing up as small current jumps at V_{gs} < -0.2 V, which do not influence the interpretations in this study. In Fig. 3(b), the same measurement was repeated under a magnetic field of 10 T. It stands clear that I_{ds} is extremely suppressed for $\theta = 90^\circ$ when exposed to the magnetic field. Comparing Fig. 3(a) and (b), the maximum I_{ds} (V_{ds}=1 V) was reduced by almost a factor of 100. The device still behaves as a transistor but with a much larger on-resistance and strongly reduced transconductance.

Measurements for the InP HEMT shown in Fig. 3 for $\theta = 0^\circ$ and $\theta = 90^\circ$ in a magnetic field up to 14 T are summarized in Fig. 4. I_{ds} was measured under saturation for two biases V_{ds}=0.4 and 0.6 V and normalized with respect to zero field. The strong suppression in output current for $\theta = 90^\circ$ is visualized in Fig. 4. As comparison, the effect in I_{ds} from the magnetic field for $\theta = 0^\circ$ is almost negligible (a minor reduction beyond 10 T may be due to a slight mis-orientation of the HEMT in the field). No difference with regard to V_{ds} is noted in Fig. 4.

We also observe in Fig. 4 that for $\theta = 90^\circ$, the normalized I_{ds} varies as B^2.

Moreover, it was confirmed that this dependence was the same for a range of various device sizes L_g (60, 100, 250 nm) and W_g (2x10, 2x50, 2x100 μm), see Fig. 5. In our experimental setup, the Hall effect (voltage) is negligible because of the device geometry with $W_g >> L_g$.[9] The output current transport in the InP HEMT is therefore limited by gMR,[10] which occurs due to the effect of the Lorentz force on the 2DEG in devices where $W_g >> L_g$. gMR is expected to be large under the experimental circumstances here, *i.e.* high channel mobility in the 2DEG and a strong magnetic field.

The angular dependence of the cryogenic InP HEMT output current in a magnetic field was investigated by rotating the transistor in the magnetic field. θ was increased from 0° to 180° using a step size of 1°. In Fig. 6, I_{ds} is plotted as a function of θ up to 10 T. It is noted that the I_{ds} is clearly dependent on θ and that this dependence becomes larger with higher magnetic field. Irrespectively of the applied field strength, we observe no change in the output current when (the 2DEG channel of) the transistor has a 0° or 180° rotation. A significant reduction (~ 20%) in I_{ds} for rotations as small as 15° occurs at an applied field of 3 T. With increasing magnetic field, the alignment of the InP HEMT becomes even more crucial and the I_{ds} is reduced by a minor tilt in θ of a few degrees.

For a transistor layout with $W_g >> L_g$, the gMR in the channel is expected to vary as $1 + \mu^2 B^2$, where μ is the electron mobility in the channel.[9,10] Taking the angular dependence in Fig. 2 into account for a transistor output current in an electrical field subject to a Lorentz force leads to

$$I_{ds}(B,\theta) = \frac{V_{ds}}{R_0(1 + \mu^2 B^2 \sin^2\theta)} \tag{1}$$

where R_0 is a resistance term (including channel and access resistance contributions in the InP HEMT). Fitting the data to Eq. 1 gives $R_0 = 11\ \Omega$ and $\mu = 10,500\ \mathrm{cm^2/Vs}$, which is in excellent agreement for the full range of measured θ and B in Fig. 6 reflecting the symmetrical angular dependence in I_{ds} around $\theta = 90^\circ$.

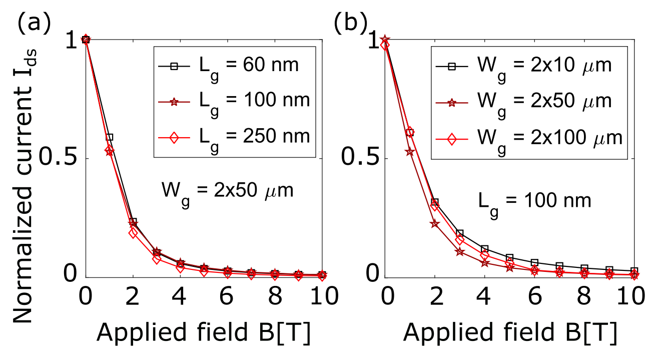

FIG. 5. Normalized I_{ds} versus magnetic field up to 10 T for InP HEMTs oriented $\theta = 90^\circ$ with (a) L_g = 60, 100 and 250 nm and (b) W_g = 2x10, 2x50 and 2x100 μm. A fix V_{gs} and V_{ds} of 0.4 V were applied in an ambient temperature of 2 K.

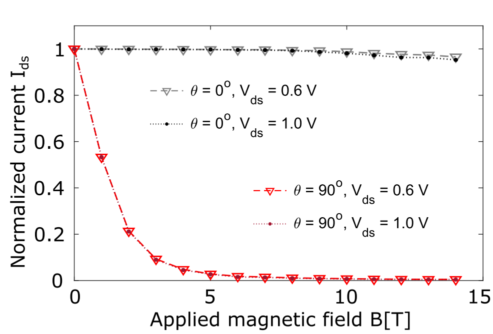

FIG. 4. Normalized maximum I_{ds} versus magnetic field ranging from 0 to 14 T in steps of 1 T with $\theta = 0^\circ$ (black) and $\theta = 90^\circ$ (red), at V_{gs} = 0.4 V. Values for V_{ds} = 0.6 V (triangle) and 1.0 V (dot) are plotted. Device size: W_g = 2x50 μm and L_g = 100 nm, measured at 2 K.

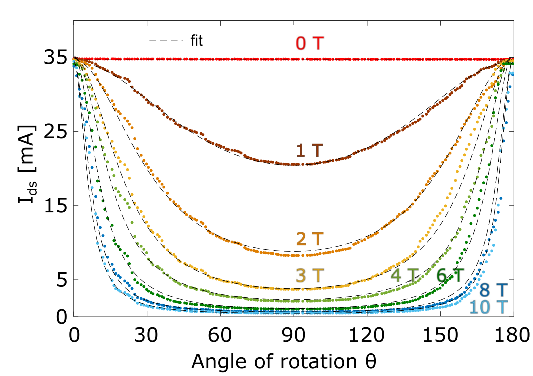

FIG. 6. Rotation sweep (θ from 0 to 180°) showing I_{ds} (absolute values) for various externally applied magnetic fields 0, 1, 2, 3, 4, 6, 8 and 10 T at a fix V_{gs} and V_{ds} of 0.4 V in an ambient temperature of 2 K. The dashed lines (black) are fitting of Eq.(1) to the experimental data points (colored). Device size W_g=2x50 μm and L_g = 100 nm.

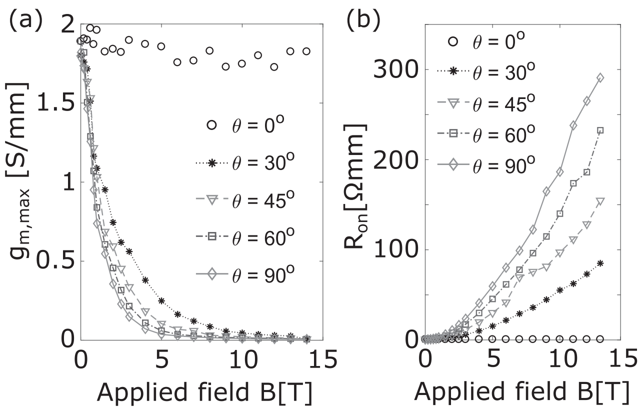

FIG. 7. (a) $g_{m,max}$ and (b) R_{on} as a function of applied magnetic field up to 14 T for $\theta = 0°$, 30°, 45°, 60° and 90°. Ambient temperature of 2 K and device size W_g = 2x50 μm, L_g = 100 nm. V_{ds} = 1.0 V, V_{gs} = 0.4 V.

The transconductance and on-resistance are two HEMT parameters fundamental for the design of a cryogenic LNA. The maximum transconductance $g_{m,max}$ at 2 K of the cryogenic InP HEMT is plotted in Fig. 7(a) as a function of the applied magnetic field up to 14 T for various angles θ. The $g_{m,max}$ is around 1.9 S/mm at zero field and strongly decreases as a function of magnetic field for $\theta = 30°$ and above. Already at 1 T, the $g_{m,max}$ is reduced with 40% (60%) for $\theta = 30°$ (90°). Field-effect transistor transconductance versus magnetic field for $\theta = 90°$ has been reported in Refs. 6 and 11 for GaAs and silicon devices at cryogenic and room-temperature conditions, respectively. The dependence on magnetic field is much stronger for the InP HEMTs investigated in this study. In contrast to Ref. 6, the $g_{m,max}$ here is directly calculated from measured I-V data for the transistor at cryogenic temperature in a magnetic field. Compared to Fig. 7(a), Ref. 11 shows a much weaker dependence which is probably related to the silicon-based transistor subject to study, a device normally not used in cryogenic LNAs. The on-resistance for the InP HEMT (at 2 K) as a function of B for various θ is presented in Fig. 7(b). For B=0 T, the R_{on} is around 0.7 Ωmm independent of B for $\theta = 0°$. As expected from Figs. 3 and 4, R_{on} increases rapidly with B for $\theta = 90°$, two orders of magnitude at 5 T. This dependence is also strong at smaller angles as illustrated for $\theta = 30°$ in Fig. 7(b). R_{on} is found to vary in a similar way as the denominator in Eq. (1): $R_{on} = R_0(1 + \mu^2 B^2 sin^2\theta)$. Fig. 7 demonstrates that transistor parameters crucial for the design of a cryogenic LNA are highly sensitive to the alignment of the InP HEMT in a magnetic field at 2 K. This explains the strong degradation of the LNA gain and average noise temperature (measured for $\theta = 90°$) observed in Fig. 1.

In conclusion, we have investigated the angular dependence of the output current of cryogenic InP HEMTs in magnetic fields up to 14 T and found that it is greatly attenuated, not only at $\theta = 90°$, but also at small θ. The physical reason is the very strong gMR occurring for I_{ds} in the cryogenic InP HEMT. This was validated by an accurate fitting of experimental I_{ds} data with an equation describing the gMR as a function of B and θ. Furthermore, we have shown the strong influence from θ for the transistor parameters $g_{m,max}$ and R_{on} when the cryogenic InP HEMT is exposed to a magnetic field. As a result, the alignment of cryogenic InP HEMT LNAs with respect to a magnetic field is critical in sensitive microwave detection systems: even small deviation from $\theta = 0°$ (180°) leads to significantly lower gain and higher average noise temperature.

This work was performed in GigaHertz Centre in a joint research project between Chalmers University of Technology, Low Noise Factory AB, Wasa Millimeter Wave AB, Omnisys Instruments AB and RISE Research Institutes of Sweden. We are grateful to Serguei Cherednichenko for valuable assistance in the noise measurements and Niklas Wadefalk for the LNA design.

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