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Dual-Drain GaN Magnetic Sensor Compatible with GaN RF Power Technology

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***Abstract*— This letter presents first–ever fabricated GaN split-current magnetic sensor device. Device operation and key manufacturing steps are also presented. The measured relative current sensitivity is constant at 14 % T^{-1} for wide mT range of the magnetic field. Constant sensitivity of a fabricated sensor can be attributed to device's 2DEG nature, i.e. its high electron concentration and mobility, and very small layer thickness.**

***Index Terms* — GaN, HEMT, MagFET, Magnetic Sensor, Split-Current, Dual Drain**

I. Introduction

The potential for superior performance of Gallium Nitride (GaN) Wide-Band-Gap (WBG) power devices in medium and high-voltage applications (600V – 1.2kV) is well recognised [1]. However, if this technology is to be used at its full potential, i.e. to switch faster at the higher power density at elevated temperatures, then real-time in-situ performance and condition monitoring is of crucial importance. One way of achieving this is to employ current monitoring techniques comprising of a magnetic sensor monolithically integrated with the power devices [2], [3], [4].

Magnetic sensing techniques exploit an extensive range of ideas and phenomena from the physics and material science fields [2], [3], [4]. The widely used magnetic sensors based on integrated circuit (IC) compatible sensing devices, such as the one based on complementary metal-oxide-semiconductor (CMOS) [5] and bipolar technologies [6] have modest sensitivity in the range of few mT comparing with the non-IC compatible magnetic sensors such as giant magnetoresistors and/or superconducting quantum interference device (SQUID) having a sensitivity bellow nT. The CMOS compatible Hall-effect sensors mostly rely on using either the p-n junction isolated diffused Hall plates or the split-drain magnetic sensitive (MS) metal-oxide-semiconductor field-effect transistors (MagFETs) as magnetic sensitive elements [7], [8]. Both sensitive devices exploit a physical phenomenon that an electron moving through a magnetic field experiences a force, known as the Lorentz force, perpendicular to its direction of motion and to the direction of the field. It is the response to this force that creates the Hall voltage in semiconductor plates or a variation in electron current distribution detected as the current or voltage difference between two drain outputs of MagFETs.

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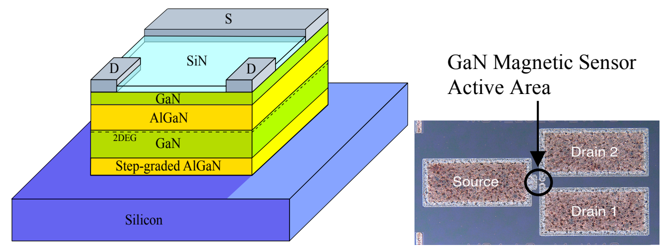

(a) (b)

Fig. 1. (a) The 3D schematics of novel split-current GaN magnetic sensor with 2nm GaN cap, 25nm $Al_{0.25}Ga_{0.75}N$ barrier and 2μm GaN buffer and (b) Microphotograph of a fabricated sensor showing the Ohmic contact pads and fabricated sensor in the middle.

Nowadays, most of the semiconductor sensor technologies are silicon based [8], [9], [10]. Obviously, to fully unlock GaN technology potential, the GaN current sensing devices are needed [11]. In this letter we described operation, manufactured and tested first-ever GaN dual-drain magnetic sensitive device fully compatible with the current RF Power GaN HEMT technology. Device concept has been confirmed by employing industrial standard SILVACO TCAD toolbox [12]. Finally, this novel dual-drain split-current magnetic sensor is suitable for the employment within the very advanced current monitoring technique, i.e. Galvanic-SenseFET current monitoring technique [13] comprising of a magnetic sensor monolithically integrated with the power devices.

II. Device Fabrication and Operation Principle

Microphotograph and 3D schematic of a fabricated magnetic sensor are shown in Fig. 1. A custom defined five-mask process was used. Starting material was 6-inch GaN on silicon-substrate wafer. Firstly, to configure device's active region, device mesas were etched using a dry etch process in an inductively coupled plasma (ICP) system. A lift-off process was used to pattern Ti/Al/Au metal stack Ohmic contacts, which were sputtered deposited and then rapidly annealed at temperatures above 750^{O}C for a short period of time under N_2 ambient. Next, a standard SiN passivation layer was deposited via plasma enhanced chemical vapor deposition (PECVD). Finally, the passivation was removed from the contact areas using a fluorine based ICP etch.

To operate the magnetic sensor device, source contact is kept at $0V$. When positive voltage is applied at D1 and D2 contacts, the drain electric field spreads throughout the device eventually reaching the source, thus allowing for the electric currents to flow between the source and the drains D1 and D2, I_{DS1} and I_{DS2} respectively. When no magnetic field is present, these two currents are identical (I_{DS1}–I_{DS2}=0). The presence of magnetic field will cause a deflection of electrons in the currents leading to current differences, I_{DS1}–I_{DS2} = ΔI. By measuring ΔI one can determine the magnetic field value.

III. Magnetic Sensitivity Test, Results and Discussion

The probe station LA-150 bench-top system by INSETO was used to test the magnetic sensor sensitivity. It has a 150mm chuck with full x-y-z movement and dual-mode optics for both microscope and digital video viewing. The probe station connects the device under-test to a Keithley 4200-SCS semiconductor characterisation system with 200V/1A DC, pulse and CV measurement capability.

The magnetic field $\overrightarrow{B_y}$ perpendicular to a chuck surface was produced by the coil embedded backside through the hole of chuck plate. By a precise control of coil supply current, the different field intensities $|\overrightarrow{B_y}|$ from 0 to 30mT in 1.25mT steps were generated in-situ which was verified using a precise digital magnetometer. Owning to a coil diameter (2cm) that is much larger than sensor dimension (35x20μm), it is justified to assume that the homogenous magnetic field $\overrightarrow{B_y}$ was applied over the device area.

A common figure of merit of split-current magnetic sensors' performance is current relative sensitivity S_r defined as $S_r = \Delta I_D \cdot \left(I_D|\overrightarrow{B_y}|\right)^{-1} \cdot 100\%$, where $I_D = I_{DS1} + I_{DS2}$ is the total drain current [2]. Fig. 2 shows the measured S_r versus $|\overrightarrow{B_y}|$ extracted from testing a number of devices on the same GaN wafer, as well as simulated S_r. A split-current magnetic sensor (Fig. 1) is simulated in this paper using drift-diffusion transport model. The magnetic field effect is modelled using 3D MAGNETIC module of Silvaco Atlas [12]. The Fermi level at the surface of structure is pinned at E_C=1.65eV. The unintentional oxygen and carbon impurity dopants resulting from precursor and carrier gases during the epitaxial growth are included into the GaN buffer layer at $E_C - E_T$ = 0.11eV and $E_C - E_T$ = 3.28eV, respectively [14]. The capture cross sections of electrons and holes are set to $\sigma_{n,p} = 1 \times 10^{-15}$ cm^2. The Shockley-Read-Hall (SRH) and Fermi-Dirac statistics are activated for all models. Nitrides mobility for low and high

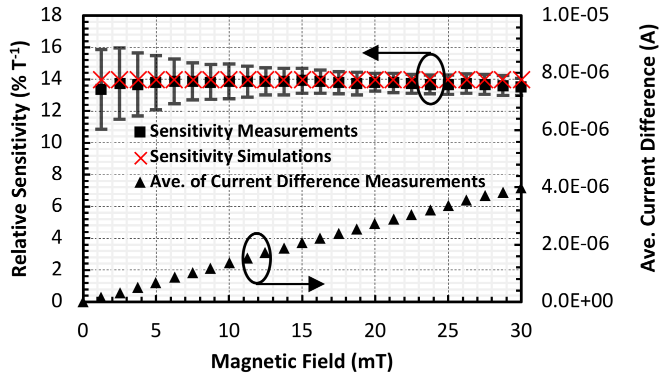

Fig. 2. Measured and simulated dependences of S_r versus $|\overrightarrow{B_y}|$ at total drain current $I_D = I_{DS1} + I_{DS2}$=1mA. Squares are sensitivity results obtained from measurements, crosses are sensitivity calculations from simulation results and triangles are average of current imbalance in 12 fabricated GaN split-current magnetic sensors for various applied magnetic fields. The error bars are standard deviations of sensitivities calculated for 12 fabricated devices.

fields are employed in the 3D simulations. Nitride parameters used in this paper are extracted from the literature [15]. Self-heating effects are neglected.

The electrical current distributions at $|\overrightarrow{B_y}|$ = 0T (Fig. 3(a)) and $|\overrightarrow{B_y}|$ = 30mT (Fig. 3(b)) are obtained at V_{DS} = 0.5V where $\overrightarrow{B_y}$ is the magnetic field along the y-axis (direction perpendicular to the device surface). The simulated current distribution in presence of magnetic field is a result of the Lorentz force and asymmetrical accumulation of electrons at the device's 2DEG channel.

Different V_{DS} biasing conditions were set to find optimal device sensitivity, for this particular device layout. Results shown in Fig. 2 were obtained for $V_{DS1} = V_{DS2} = 0.5V$ (source contact is kept at $0V$). A S_r with a value around 14% T^{-1} at a wide range of magnetic fields and at 1mA of supply current is extracted from magnetic sensor measurements (Fig. 2). The outstanding constant sensitivity of a fabricated sensor across a wide range of the magnetic field values can be attributed to device's 2DEG nature, i.e. its high electron concentration and mobility, and very small layer thickness.

In split-current sensors, similar to Hall sensor devices, a sensor response time is determined by the time needed by moving electrons to spatially relocate inside the semiconductor in order to respond to a time varying magnetic field. Sensor response time is very important device parameter determining potential sensor applications. It strongly depends on the resistivity of 2DEG, while the magnetic field density has a negligible effect on the response time [16]. Since the resistivity of the 2DEG is very low, in the region of 0.2 Ω·cm [17], the response time of the GaN sensor presented in this work can be estimated to be below nano-second [16]. Its potential applications can vary from the machine control purposes (kHz range) to current monitoring in the very-high frequency (VHF) power converters (hundreds of MHz range) [1].

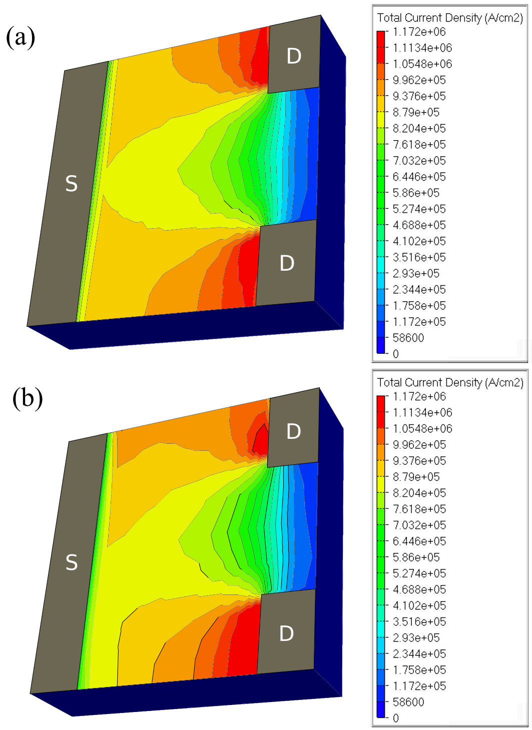

Fig. 3. Simulated current distribution of split current magnetic sensor at V_{DS}= 0.5V (a) no presence of external magnetic, 2DEG channel showing the symmetry in the current density; (b) external magnetic field perpendicular to the 2DEG channel is present, 2DEG channel showing current asymmetry.

IV. Conclusions

The operation, fabrication and sensitivity measurement results of the first-ever GaN technology-based split-current dual-drain magnetic sensor that is fully compatible (no extra materials or micromachining needed) with the GaN RF Power technology is described. Owning to high mobility of 2DEG electrons the fabricated prototype of 35µm×20µm magnetic sensing device exhibited S_r with the constant value of 14 % T^{-1} at 1mA of supply current. The constant sensitivity can be attributed to the 2DEG's nature (high electron concentration, high mobility and very small layer thickness).

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