Embedded Optical Hall Effect in Terahertz Hall-Effect Amplifier Nanoscale Device (HAND)

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Abstract

A new version of a nanoscale device based on the well-known Hall Effect, and named HAND (Hall Amplifier Nanoscale Device), was designed and analytically modelled for DC and AC conditions. Analytical and numerical results were found fully matched, enabling the validation of a mathematical model for various coil geometries. Such an improved device, combining work at high frequencies, amplification, the Hall Effect and nanoscale dimensions, is capable of revolutionizing microelectronic circuitry.

Introduction

Exploitation of the macroscale Hall Effect in micro and nanoscale circuity has long been decades-long dream of researchers and engineers. As with devices relying on the macroscale effect, the device receives a current as an input and creates a voltage as an output, which means it has a low input impedance and a high output impedance. The Hall Effect can be described analytically by the anisotropic magneto-resistance tensor in expression (1):

$$\begin{pmatrix} E_x \\ E_y \\ E_z \end{pmatrix} = \begin{bmatrix} \frac{1}{\sigma_0} & -R_H B_z & R_H B_y \\ R_H B_z & \frac{1}{\sigma_0} & -R_H B_x \\ -R_H B_y & R_H B_x & \frac{1}{\sigma_0} \end{bmatrix} \begin{pmatrix} J_x \\ J_y \\ J_z \end{pmatrix} \qquad (1)$$

where σ_0 is the material conductivity, R_H is the Hall coefficient and B_i is the magnetic field in axis $i = (x, y, z)$. The HAND has two modes of operation in the classical region where $B < 1/\mu_e$: amplification mode (DC applied voltage as presented [1]) and mixer mode (AC applied voltage according to the heterodyne Hall Effect [2]). There are many potential applications of the HAND, with the main ones being the possibility of using nanotechnology to integrate extremely small devices into electronic circuits, plasmonic circuits and to enable terahertz frequencies via the Optical Hall Effect [3].

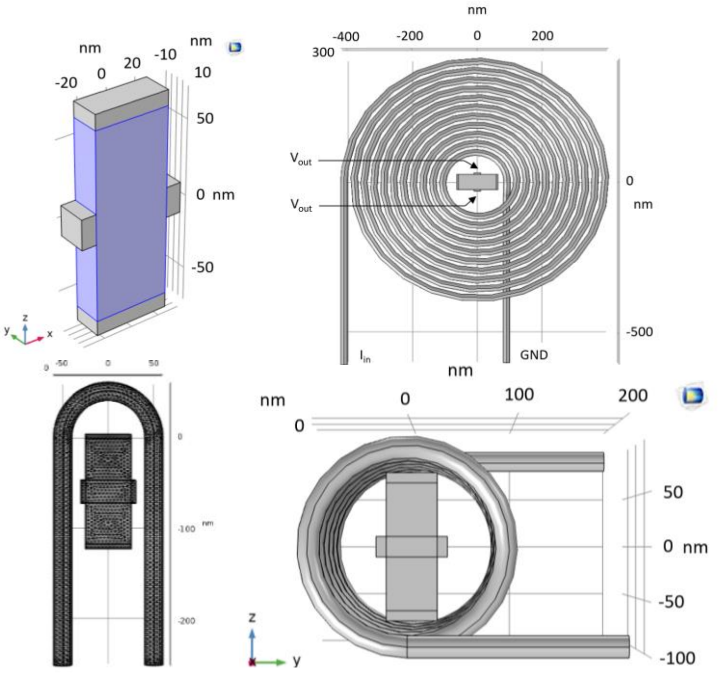

Fig. 1: The HAND coil geometries and Hall Bar.

Three coil geometries were studied in this research, as shown in Fig. 1: Single-Loop Coil (SLC), Circular Multi-Loop Coil (CMLC), and Spiral Multi-Loop Coil (SMLC).

Mathematical Models

Four mathematical models were developed for the HAND gain in the three geometries studied: The SLC model for the single loop coil, the ICS and FCS models for the circular multi loop coil and the SMLC model for the spiral multi-loop coil. The HAND gain is given by expression (2):

$$G = \frac{V_H}{I_{in}} = \frac{\mu_e V_{dd} \mu}{L_x} G_c(R, N, l, L_y) \qquad (2)$$

Where G is the HAND DC gain, V_H is the Hall voltage, I_{in} is the input electric current, μ_e is the electron mobility, V_{dd} is the applied DC voltage, μ is the magnetic permeability in the Hall bar surroundings, L_x is the Hall bar length in the X direction, R is the coil major radius (or the distance between the coil the Hall bar), N is the number of coil windings, l is the coil length, and L_y is Hall bar length in Y direction. $G_c(R, N, l, L_y)$ is the gain correction for each coil geometry:

Geometry	Model	$G_c(R, N, l, L_y)$
Single-Loop Coil	SLC	$\frac{1}{2\pi} \ln\left(\frac{R + L_y/2}{R - L_y/2}\right)$
Circular Multi-Loop Coil	ICS	$\frac{N}{l} L_y$
	FCS	$\frac{N}{2\pi} \int_0^{\frac{L_y}{2}} \sqrt{\frac{1}{Rr}} k \left(K(k) + \frac{R - r}{R + r} \Pi(h, k) \right) dr$
Spiral Multi-Loop Coil	SMLC	$\frac{N}{\pi} \int_0^{\frac{L_y}{2}} \int_R^{R+l} \frac{1}{l} \left[\frac{1}{R' - r} E(k) + \frac{1}{R' + r} K(k) \right] dR'\, dr$

where $\mathrm{K(k)}$, $\mathrm{E(k)}$ and $\Pi(\mathrm{h, k})$ are complete elliptic integrals of first, second and third kind respectively. For the FCS model the elliptic modulus are defined as $\mathrm{k = 4Rr/\left((R + r)^2 + l/2\right)}$ and $\mathrm{h = 4Rr/(R + r)^2}$, and for the SMLC model $\mathrm{k = h}$. The mathematical model for the frequency response of the HAND was developed using perturbation theory and is shown in Fig. 3. In this new equation (equation (3) not presented here), σ_{XY} is the XY component of the anisotropic magneto-conductivity tensor, ${}_1F_4(a; c; z)$ is the hypergeometric function, and $x = j\omega\tau$, where τ is the electron scattering time, ω is the angular frequency and $b = \mu_e B_z$.

Results

In order to validate the mathematical models, simulation were performed using COMSOL Multiphysics, a program which solves PDEs numerically via the finite element method (FEM). Fig.2 shows the simulated magnetic field of the SLC geometry.

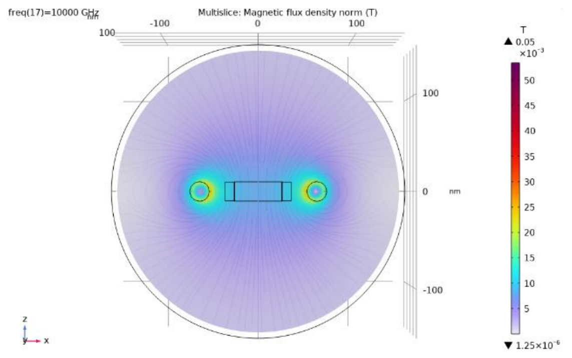

Fig. 2: The simulated magnetic flux density norm

Results

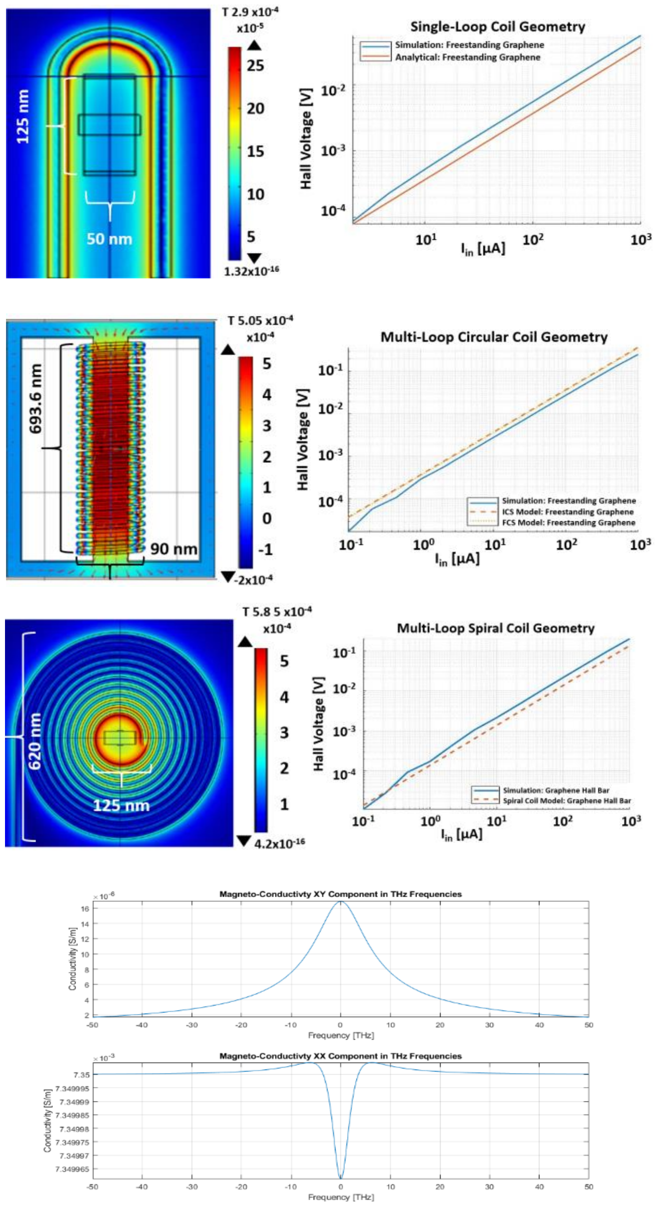

Fig 3: Simulation results for SLC, CMLC and SMLC geometries, and frequency response of Hall conductivity in Graphene Hall Bar

Conclusions

The simulation results and the mathematical models macth closely, as shown in Fig. 3. Moreover, the Hall conductivity frequency response for a graphene hall bar is in the THz region. Only when L_x is nanoscale does the HAND gain becomes relevant. Furthermore, by using materials with high μ_e such as graphene for the Hall bar, or even using a magnetic core to increase μ in the Hall bar surroundings, the HAND gain can become extremely high.

Main References

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