Micrometer-Scale Graphene-Based Hall Sensors with Tunable Sensitivity

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Primary CNF Tools Used: Veeco Icon AFM, Zeiss Supra SEM/Nabity, Trion etcher, 5x stepper, Oxford 81, Plasma-Therm VersaLine, odd-hour evaporator

Abstract:

We have fabricated high-quality graphene-based Hall sensors that can be tuned to maintain high magnetic field sensitivity at cryogenic temperatures, at room temperature, and in high background magnetic field. At best, we achieve a sensitivity of 80 nT Hz$^{-1/2}$, outperforming existing Hall sensor technologies. We will soon fabricate these devices into scanning probes to study magnetism and superconductivity via micrometer-scale magnetic imaging.

Summary of Research:

In a Hall-effect sensor, the deflection of current in a small magnetic field *B* produces a voltage response that is linear in *B* and large at low carrier density. The noise in the Hall voltage measurement ultimately determines the magnetic field sensitivity and is typically limited by instrumentation, Johnson, and low-frequency charge noise [1,2]. The requirements for large voltage response and low noise suggest a material with low carrier density and high mobility [1,3]. Whereas mobility decreases at low carrier density in most two-dimensional electron systems, in graphene the mobility is enhanced in the absence of long-range impurity scattering [4]. We exploit tuning the carrier density in graphene through electrostatic gating to maintain sensitivity in a wide range of temperature and magnetic field conditions.

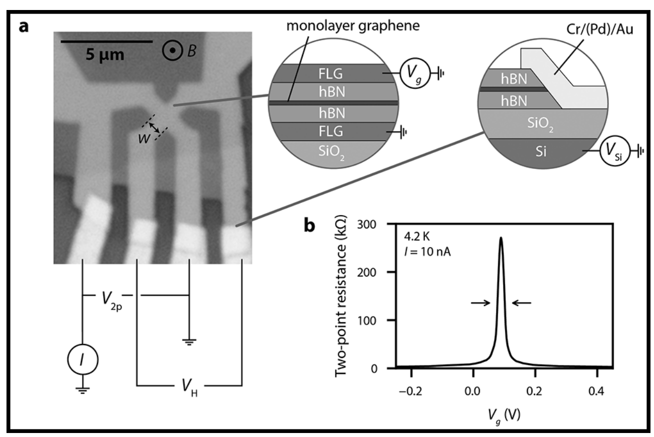

Figure 1: (a) Optical micrograph of a w = 1 *µm Hall sensor. Upper inset: Layer structure consisting of graphene encapsulated with hexagonal boron nitride (hBN) and few-layer graphite (FLG). Lower inset: Edge contacts to part of the graphene extending outside of the FLG-gated region. (b) Top gate dependence of the two-point resistance* $R_{2p} = V_{2p}/I$.

To obtain the cleanest possible graphene devices (Figure 1), we adopt recently developed strategies to achieve record-low charge inhomogeneity in graphene: encapsulation in hexagonal boron nitride (hBN) gate dielectrics [5] and few-layer graphite (FLG) gate electrodes [6]. The low charged defect density in hBN and FLG [6] improve carrier mobility [5] and have the potential to reduce noise [7]. We use electron-beam lithography (Zeiss Supra, Nabity), plasma etching (Trion), and electron-beam evaporation to define the device shape and deposit metal (Cr/Au) contacts. The two-point resistance of the device increases sharply as we apply top gate voltage V_g to tune the carrier density through charge neutrality point (Figure 1b).

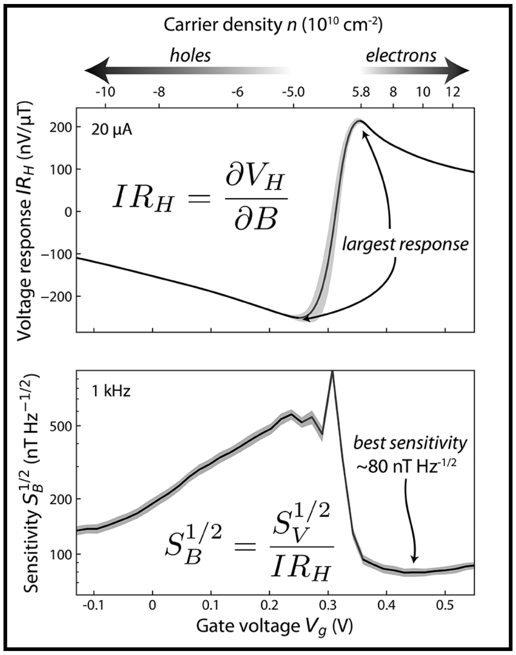

Figure 2: Gate voltage dependence of the Hall coefficient (top panel) and magnetic field sensitivity (bottom panel).

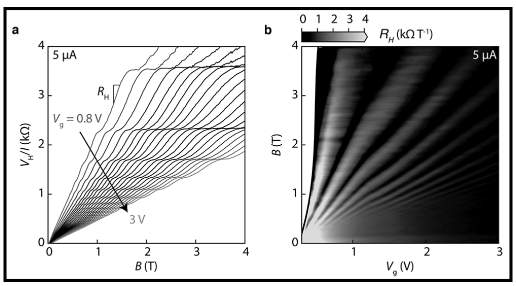

Figure 3: (a) Magnetic field dependence of the Hall resistance in the quantum Hall regime for a series of gate voltages. (b) Map of the Hall coefficient versus magnetic field and gate voltage.

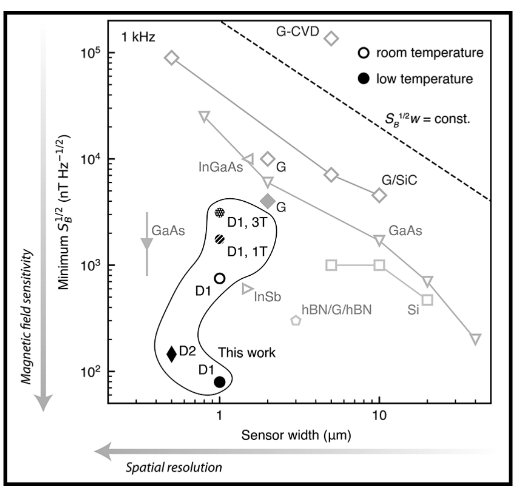

Figure 4: Magnetic field sensitivity $S_B^{½}$ at 1 kHz compared against the width w of Hall sensors reported here and in the literature. Filled (open) markers correspond to liquid-helium (room) temperature. The outlined group of markers shows the best performance of our devices, and the other markers are estimates of the best performance of devices made from graphene and conventional semiconductor materials.

To properly characterize the sensitivity of the devices to small changes in magnetic field [1,3], we apply a DC bias current and determine the Hall coefficient $R_H = I^{-1} [\partial V_H/\partial B]_{B=0}$ and Hall voltage noise spectral density $S_V^{½}$. The latter is dominated by flicker noise, which is pervasive in graphene-based microdevices [2] and decreases as $1/f^{½}$ with frequency f. The noise at 1 kHz is largest at low carrier density, at which charge fluctuations are poorly screened and the device resistance is large.

Dividing the Hall voltage noise by the Hall coefficient, we estimate the magnetic field sensitivity $S_B^{½} = S_V^{½}/IR_H$ (Figure 2, bottom panel). This quantity, when multiplied by the square root of the bandwidth of the measurement, represents the minimum detectable magnetic field. The best sensitivity — ~ 80 nT Hz$^{-½}$ — is found at an intermediate carrier density, indicating that the reduction in $S_V^{½}$ from tuning away from charge neutrality is more important than tuning to the largest R_H.

We also demonstrate for the first time that magnetic field response can be maintained in a large background magnetic field. While at low magnetic field, the Hall voltage grows linearly with magnetic field, above ~ 500 mT (at 5 μA bias) the Hall voltage begins to develop plateaus, indicating a transition into the quantum Hall regime (Figure 3a). At each (B, V_g), we calculate the effective Hall coefficient $R_H = I^{-1}(\partial V_H/\partial B)$ and plot as a map in Figure 3b, in which dark bands indicate suppressed Hall coefficient due to the plateaus. At a fixed magnetic field, tuning the gate voltage into one of the white bands enables the sensor to maintain sensitivity in high magnetic field.

Finally, in Figure 4 we compare the noise measurements for our devices at low temperature and room temperature against similar measurements on leading micrometer-scale Hall sensors reported in the literature. Our devices, which combine high magnetic field sensitivity with small sensor size, lie towards the lower left corner of the plot, outperforming all other reported materials. Our work establishes a new standard for fabricating Hall sensors to engineer superior device performance. We anticipate that scanning graphene-based magnetic field probes will enable the first high-resolution, high-sensitivity imaging of localized magnetic fields under high temperature and magnetic field conditions.

References:

[1] Dauber, J., et al. Ultra-sensitive Hall sensors based on graphene encapsulated in hexagonal boron nitride. Appl. Phys. Lett. 106, 193501 (2015).

[2] Balandin, A. A. Low-frequency 1/*f* noise in graphene devices. Nat. Nanotechnol. 8, 549-555 (2013).

[3] Hicks, C. W., Luan, L., Moler, K. A., Zeldov, E., and Shtrikman, H. Noise characteristics of 100 nm scale GaAs/Al_xGa_{1-x}As scanning Hall probes. Appl. Phys. Lett. 90, 133512 (2007).

[4] Das Sarma, S., Adam, S., Hwang, E. H., and Rossi, E. Electronic transport in two-dimensional graphene. Rev. Mod. Phys. 83, 407-470 (2011).

[5] Wang, L., et al. One-dimensional electrical contact to a two-dimensional material. Science 342, 614-617 (2013).

[6] Zibrov, A. A., et al. Tunable interacting composite fermion phases in a half-filled bilayer-graphene Landau level. Nature 549, 360-364 (2017).

[7] Stolyarov, M. A., Liu, G., Rumyantsev, S. L., Shur, M., and Balandin, A. A. Suppression of 1/*f* noise in near-ballistic *h*-BN-graphene-*h*-BN heterostructure field-effect transistors. Appl. Phys. Lett. 107, 023106 (2015).