Flicker Noise in Graphene-based Hall Sensors

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***Abstract*—We present an investigation of shot noise in graphene-based Hall sensors, with the purpose of evaluating their detection limit and of developing strategies to improve their characteristics. We perform measurements on two devices, one with a defective contact that could however be used as a gate to control the carrier density in the device and the other with all contacts working. We discuss the results in terms of the dependence of the noise power spectral density on the carrier density and on the DC bias current. Finally, we provide an estimate of the detection limit, pointing out that the approach commonly used in the literature for its evaluation is flawed.**

***Keywords*—Hall sensor; flicker noise; Allan variance; graphene**

I. INTRODUCTION

Graphene, a two-dimensional hexagonal lattice of carbon atoms with sp^2 hybridization, has received a lot of attention in the last decade as a result of its very peculiar material properties. In particular, the very high value of the mobility at room temperature (up to 200000 cm^2 V^{-1} s^{-1} for a suspended sheet) makes it a very interesting material from the point of view of the Hall effect. In principle, Hall sensors with a sensitivity much better than the ones that are currently available (based on silicon and on III-V semiconductors) could be obtained with graphene technology. However the actual performance of a Hall sensor depends on two fundamental parameters: the sensitivity, expressed as the Hall voltage that can be obtained for a given bias current and a given magnetic field, and the signal-to-noise ratio, which depends on the noise power spectral density at the output terminals where the Hall voltage is measured. While the high mobility of graphene implies a good Hall sensitivity, the relatively large flicker noise power spectral density has an opposite effect on the achievable detection limit. In order to evaluate the actual detection limit, it is therefore essential to measure both the sensitivity and the effect of noise on the standard deviation of the measurement results. Indeed, there are frequent misconceptions in the literature [1]–[3] concerning the evaluation of the signal-to-noise ratio for a Hall sensor in the presence of flicker noise. In particular the noise contribution is erroneously assumed as infinite at zero frequency (even with a finite observation time) [1] or the flicker noise measured with DC bias is incorrectly assumed as valid for the evaluation of the signal-to-noise ratio at a nonzero frequency [2], [3]. As we will discuss in the following, it is possible to obtain a valid estimate using the so-called "Allan variance" [4], [5], which provides a good estimate of the expected standard deviation while performing a measurement with a finite observation time.

II. DEVICES

Our measurements have been performed on two devices, with different characteristics, from two different process runs. In both of them the active material was CVD (Chemical Vapor Deposition) grown graphene. The first device (device A in the following) had a glass substrate, nickel contacts, and no passivation, while the second device (device B in the following) had a sapphire substrate, gold-chromium contacts, and was passivated with alumina. In Fig. 1 we report two pictures (taken with an optical microscope), at different magnification, of devices from the same run as device A, while in Fig. 2 we report two SEM (Scanning Electron Microscope) pictures of devices from the same run as device B. The active area is a square with a side of about 2 μm. The bonding pads of the device in Fig. 1 appear to be severely damaged because of the limited adhesion of nickel on glass and repeated bonding attempts. In Fig. 3 cross sections of the two devices are shown, device A to the left and device B to the right, with an

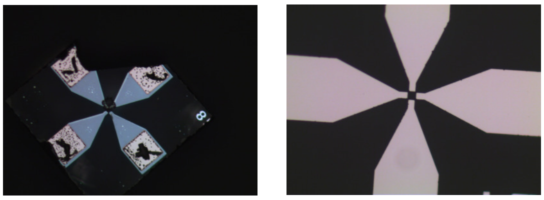

Fig. 1. Pictures of devices from the A batch, at two different magnifications.

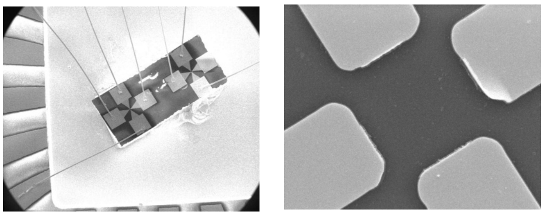

Fig. 2. SEM images of devices from the B batch, at two different magnifications.

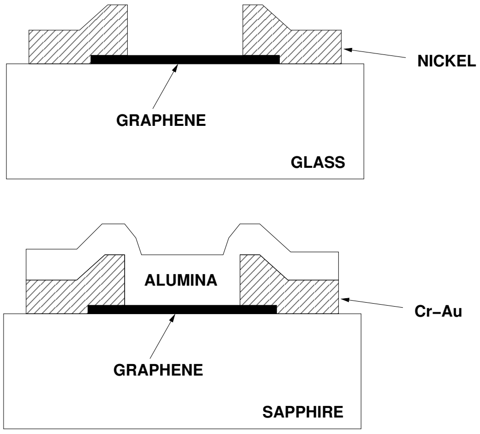

Fig. 3. Cross section of device A (top panel) and of device B (bottom panel).

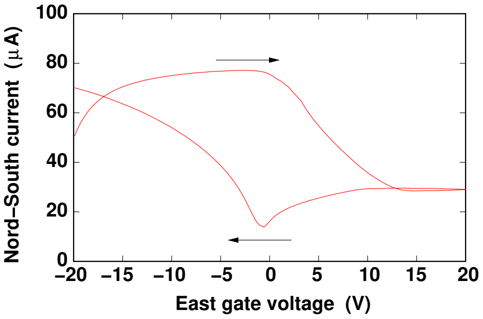

Fig. 4. Current between the North and South electrodes as a function of the East gate voltage; both the forward (top curve) and the backward (bottom curve) are reported.

indication of the materials used. While the B device was in perfect working order, with all 4 contacts operational, device A had a non working contact, probably because the metal had detached from the graphene. There was, however, a good capacitive coupling between such a contact and graphene, which made it possible to tune the carrier density in the graphene sheet by adjusting the bias voltage applied to such gate.

III. MEASUREMENTS

In the following we will define the 4 contacts of a Hall device with the names of the cardinal points, based on their position. Our first measurement was the characterization of the dependence of the current between the North and South current as a function of the voltage applied to East (defective) contact.

All measurements were performed both in air and in a vacuum, with outcomes that were very similar, in particular for the device with alumina passivation. Results are reported in Fig. 4, where the upper curve is relative to the forward scan of the East gate voltage from -20 V to $+20$ V, as indicated by the arrow, while the lower curve is relative to the backward scan, from $+20$ V to -20 V. The voltage applied between the North and the South gate was 0.1 V. It is apparent from Fig. 4 that a very strong hysteresis is present, which can be attributed to charge storage phenomena. The shape of the hysteresis also depends on the rate of change of the East gate bias, which hints at the existence of charge traps with nonnegligible time constants. We also observe that a large modulation of the North-South current is achievable through the East gate, by a factor of about 5, which is often the best that can be achieved in a field-effect device based on unconfined graphene. This hints at a rather good capacitive coupling of the East gate to the graphene sheet.

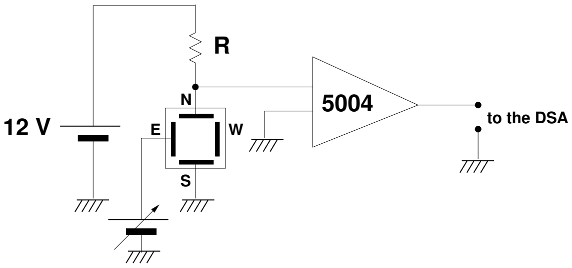

Fig. 5. Circuit diagram for the measurement of flicker noise due to the North-South channel as a function of the carrier density and of the bias current.

We have then performed noise measurements on device A, with the main purpose of determining the dependence of the $1/f$ noise (which is the prevalent form of noise within our measurement range, extending up to 100 kHz) power spectral density on the DC bias current and on carrier density, for the North-South channel.

Due to the large value of the flicker noise power spectral density, measurements did not require specialized equipment, such as correlation amplifiers, and were performed with the setup shown in Fig. 5, using an ultra-low-noise EG&G 5004 amplifier with a 60 dB gain. The graphene channel is biased via a resistor of the order of 1 MΩ (the exact value depended on the specific chosen bias point), which is much larger than the channel resistance and therefore represents, in parallel with the 5 M Ω input impedance of the amplifier, a negligible load (which is however considered while processing the data to obtain the current noise power spectral density).

The output of the 5004 amplifier is connected to the input of a Digital Signal Analyzer, which samples the signal and computes the voltage noise power spectral density S_V, which is then converted into the current noise power spectral density $S_{I_{NS}}$ of the North-South channel.

Since the value of the biasing resistor R is much larger than the device resistance R_d, the current is substantially determined by R. Considering that the 5004 amplifier has a gain $A_v = 1000$ and an input impedance much larger than R_d, we can obtain $S_{I_{NS}}$ as

$$S_{I_{NS}} = \frac{S_V}{A_v^2 (R//R_d)^2} \tag{1}$$

We have varied the East gate voltage between 0 and 12 V, with a resistor $R = 1$ MΩ. Therefore, the current was substantially constant around 12 μA, while the voltage drop on the device varied with the electron density. From the voltage drop across the device and the current through it, we

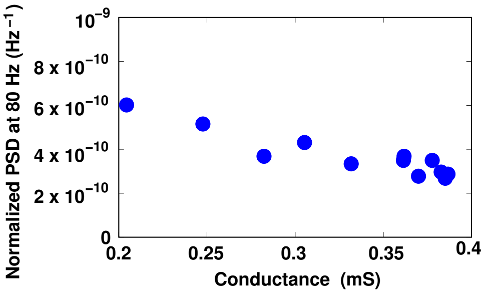

Fig. 6. Normalized power spectral density at 80 Hz as a function of the channel conductance.

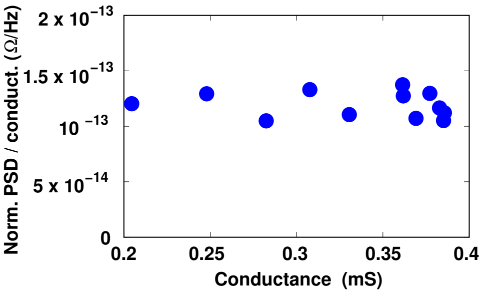

Fig. 7. Normalized power spectral density at 80 Hz divided by the device conductance as a function of the device conductance.

have determined its conductance, which can be assumed as proportional to the electron density.

In Fig. 6 we report $S_{I_{NS}}$ at 80 Hz normalized to the square of the bias current, as a function of the device conductance and therefore of the electron density. We notice that the normalized power spectral density is substantially inversely proportional to the carrier density, which is consistent with Hooge type noise.

This is confirmed by the content of Fig. 7, where we report the normalized power spectral density divided by the device conductance as a function of the device conductance: the result is almost constant, further confirming that the flicker noise of the device under investigation follows Hooge's law.

We have then moved on to the measurement of device B, which was a fully functional Hall cross. Measurements were performed both in air and in vacuum, at three different values of the orthogonal magnetic field: 0, 5, and 10 mT. The magnetic field has been obtained by means of two coils, each with 750 turns of 0.3 mm copper wire, wound on aluminum reels (in order to improve heat dissipation, in particular during the vacuum operation). The magnetic field at the device location was measured with a Hirst GM-07 magnetometer.

The measurement setup for device B is shown in Fig. 8: the Hall voltage is available between the East and West contacts and is amplified with a differential amplifier based on the INA110 (instrumentation amplifier). Therefore in this case we have to study also the noise power spectral density that appears superimposed to the Hall voltage. In Fig. 9 we report the current noise power spectral density of the North-South channel for two values of the bias current, 7.2 and 13.7 μA. Also in this case, the quadratic dependence of the flicker noise power spectral density on the bias current is confirmed. In Fig. 10 we plot the voltage noise power spectra at the East-West contacts: they, too, exhibit a $1/f$ behavior, although a few interferences are present, due to the vacuum equipment and other sources. Furthermore, we notice that also in this case the noise power spectral density is proportional to the square of the bias current.

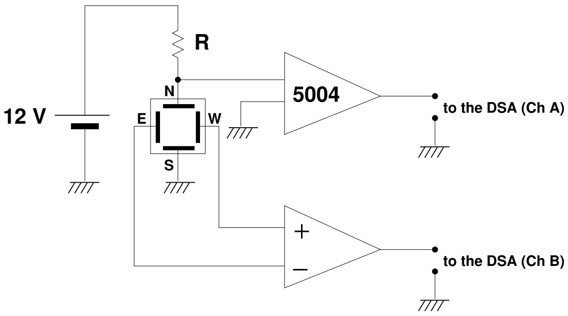

Fig. 8. Schematic diagram of the setup for noise measurements on device B.

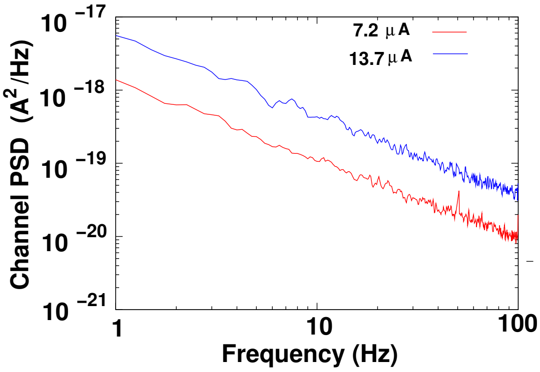

Fig. 9. Current noise power spectral density of the North-South channel as a function of frequency for two values of the bias current.

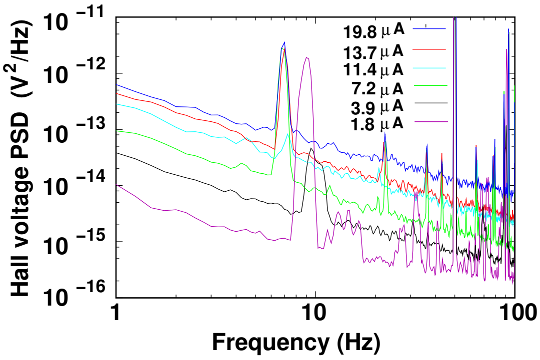

Fig. 10. Voltage noise power spectral density at the East-West contacts, as a function of frequency, for a few values of the bias current.

We have also measured the sensitivity, defined as

$$S_I = \left|\frac{V_H}{I B_\perp}\right| , \tag{2}$$

obtaining a value around 153 V/(AT). This is significantly lower than that achieved (5700 V/(AT)) with exfoliated graphene encapsulated in boron nitride [6]. Such a strong reduction in sensitivity is probably due to the reduction in mobility resulting from the usage, in the devices we have tested, of CVD graphene (which typically exhibits a lower mobility with respect to exfoliated samples). A further decrease in mobility with respect to the devices of Ref. [6] is due to lack of the encapsulation in hexagonal boron nitride, which is known to represent an important mobility booster.

Since the noise power spectral density increases with the square of the bias current, it has the same dependence on bias current as the Hall signal power, therefore the signal-to-noise ratio is independent of the bias current.

IV. DETECTION LIMIT

As we have already discussed in the Introduction, the approaches used in the literature for the evaluation of the detection limit are often incorrect, because, if a nonzero frequency bias is used, it is not appropriate to consider, in an interval around the bias frequency, the noise power spectral density measured with a DC bias. Indeed, for an AC bias the excess noise is not a stationary process any longer (most likely a cyclostationary process), and has nothing to do with the flicker noise associated with the DC bias. If, instead, we use a DC bias as is commonly done, the finite time of observation will prevent the divergence that would be expected integrating the $1/f$ power spectral density down to zero frequency. If we assume that the evaluation of the Hall voltage is performed by averaging the voltage observed over a finite time, we can estimate the standard deviation to be expected over repeated measurements with the approach of the so-called Allan variance [4], [5], [7]. The expression of the Allan variance $\sigma_{y_n}^2(\tau)$ (where τ is the observation time) in the case of $1/f$ noise is given by

$$\sigma_{y_n}^2(\tau) = 4A\int_0^{\infty} \frac{\sin^4(\pi f\tau)}{f(\pi f\tau)^2}\,df = A\cdot 2.7726 \qquad (3)$$

where $A = S_{x_n}(f)f$ and the result is substantially independent of τ. This means that there is no improvement in terms of the variance affecting the measure if we average over a longer time (this is the consequence of the particular nature of flicker noise).

On the basis of this result, if we assume that the maximum expected measurement error is twice the standard deviation, the detection limit for the present device, for a sensitivity of 153 V/(AT), is around 0.88 mT.

V. CONCLUSION

We have performed a detailed electrical and noise characterization of two graphene-based Hall sensors. From our measurements it is possible to conclude that the main limitation in terms of the minimum detectable magnetic field is represented by flicker noise. The observed flicker noise is of the Hooge type with a power spectral density proportional to the square of the DC bias current and inversely proportional to the carrier density. We can conclude that Hall sensors made with CVD graphene do not have satisfactory performances yet, due to the relatively low mobility and to the high concentration of defects, which leads to significant levels of flicker noise. We have also presented a rigorous approach to the determination of the detection limit in the presence of flicker noise, based on the Allan variance.

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