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### ► To cite this version:

Jérémy Brun-Picard, Rebeca Ribeiro-Palau, Fabien Lafont, Dimitrios Kazazis, Adrien Michon, et al.. Convenient Graphene-Based Quantum Hall Resistance Standards. 2016 Conference on Precision Electromagnetic Measurements (CPEM 2016), Jul 2016, Ottawa, Canada. <10.1109/CPEM.2016.7540650>. <hal-03037516>

**HAL Id: hal-03037516**

**<https://hal.science/hal-03037516v1>**

Submitted on 2 Dec 2024

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# Convenient Graphene-Based Quantum Hall Resistance Standards

J. Brun-Picard<sup>1</sup>, R. Ribeiro-Palau<sup>1</sup>, F. Lafont<sup>1</sup>, D. Kazazis<sup>2</sup>, A. Michon<sup>3</sup>, F. Cheynis<sup>4</sup>, O. Couturaud<sup>5</sup>, C. Consejo<sup>5</sup>, B. Jouault<sup>5</sup>, W. Poirier<sup>1</sup> and F. Schopfer<sup>1</sup>

<sup>1</sup>Laboratoire National de Métrologie et d'Essais, Trappes, France

<sup>2</sup>Laboratoire de Photonique et de Nanostructures, CNRS, Marcoussis, France

<sup>3</sup>Centre de Recherche sur l'Hétéroépitaxie et ses Applications, CNRS, Valbonne, France

<sup>4</sup>CINaM, CNRS/Aix-Marseille Université, Marseille, France

<sup>5</sup>Laboratoire Charles Coulomb, CNRS/Université de Montpellier, Montpellier, France  
wilfrid.poirier@lne.fr

**Abstract**—We report on measurements in large quantum Hall devices, made of high-quality graphene grown by propane/hydrogen chemical vapor deposition on SiC. These devices, having all the properties of an ideal quantum electrical resistance standard, surpass state-of-the-art GaAs/AlGaAs devices by considerable margins in their operational conditions. The Hall resistance can be found accurately quantized within one part in  $10^9$  over a 10-T range of magnetic fields with a lower bound at 3.5 T, temperatures as high as 10 K, or currents as high as 0.5 mA. This simplification sets the superiority of graphene for accessible and low-cost primary resistance standards.

**Index Terms**—Graphene, materials science and technology, measurement standards, metrology, quantum Hall effect devices.

## I. INTRODUCTION

One hallmark of the graphene Dirac physics is a quantum Hall effect (QHE) which is exceptionally robust. This comes from an energy gap between the first two Landau levels of  $36\sqrt{B}$  meVT<sup>-1/2</sup> larger than the gap of  $1.7B$  meVT<sup>-1</sup> in GaAs/AlGaAs for accessible  $B$  magnetic inductions. An ongoing goal of metrologists is to exploit this robustness to develop graphene-based quantum resistance standards (G-QHRS) operating in more convenient experimental conditions than the usual standards made of GaAs/AlGaAs heterostructures, which require high magnetic inductions ( $B \sim 10$  T), low temperatures ( $T \sim 1.3$  K) and currents ( $I \sim 40$   $\mu$ A) to be accurate to within  $10^{-9}$ , in relative value. Making the quantum resistance standards compatible with simple helium-free experimental setups will reduce the operating cost of the ohm maintaining and would improve the ohm dissemination towards industrial end-users. Although the accurate quantization of the Hall resistance ( $R_H$ ) was demonstrated in a few graphene devices, mainly made of graphene grown by thermal decomposition of silicon carbide (SiC), the best accuracy of  $1 \times 10^{-9}$  required for the primary resistance standard was obtained at still high and non competitive operating magnetic fields[1]. In fact, achieving such accuracies at low  $B$  indeed requires the availability of high-quality large graphene monolayers of low and very homogeneous carrier densities (a few  $10^{11}$  cm<sup>-2</sup>). Here, we report on measurements performed in Hall bar devices, made of graphene grown using the chemical vapor deposition (CVD) of propane/hydrogen on SiC, that can

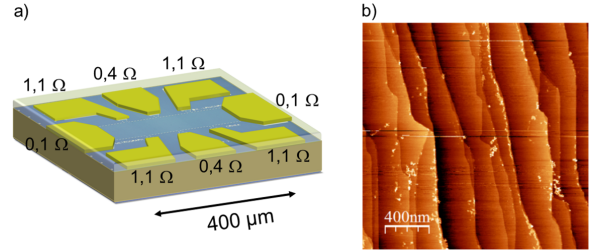


Fig. 1. a) Graphene Hall device with Pd/Ti/Au contact resistance values. b) AFM picture of the graphene after growth on top of the SiC substrate (height color scale from black to white is 2.5 nm).

demonstrate quantization of the Hall resistance within  $1 \times 10^{-9}$  under relaxed and extended experimental conditions. Filling the full set of quantization criteria, such devices constitute reliable and accurate quantum resistance standards.

## II. GROWTH METHOD AND DEVICES

Devices are large Hall bars of  $(100 \times 420 \mu\text{m}^2)$  size (Fig. 1a) made of graphene grown by propane/hydrogen CVD on the Si face of semi-insulating  $0.16^\circ$  off-axis 6H-SiC substrates. The atomic force microscopy (AFM) image (Fig. 1b) shows the substrate after graphene growth on top. SiC steps define terraces with a typical width of 300 nm. Structural characterizations demonstrates the existence of a  $(6R\sqrt{3} \times 6R\sqrt{3} - R30^\circ)$  reconstructed carbon-rich interface layer beneath the graphene and the presence of small bilayer inclusions ( $\approx 1 \mu\text{m}$  long) covering about 15 % of the sample surface. Prior to Hall bars patterning, graphene samples were annealed at  $500^\circ\text{C}$  during 1 min. Ohmic contacts were formed by depositing, a Pd/Au (60/20 nm) bilayer using an ultrathin Ti layer for adhesion, and then thicker Ti/Au (20/200 nm) bonding pads. Finally, samples were covered by a bilayer resist P(MMA-MAA)/ZEP520A (300/300 nm). The ZEP520A is photosensitive and known to reduce the electron density under UV illumination; however, no illumination was done.

## III. RESULTS

Figure 2 reports the Hall  $R_H$  and longitudinal  $R_{xx}$  resistances as a function of the magnetic induction  $B$  measured in

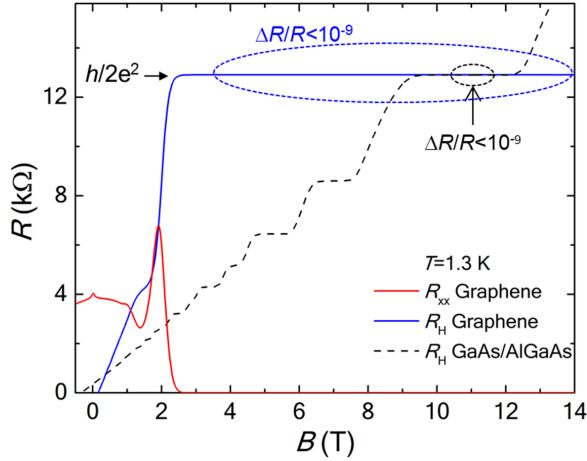


Fig. 2. Hall  $R_H$  (blue) and longitudinal  $R_{xx}$  (red) resistances as a function of  $B$  for the graphene device.  $R_H$  measured in a GaAs/AlGaAs-based standard is also reported (dashed black line). Ellipses indicate the  $B$ -ranges where  $R_H$  is quantized to  $R_K/2$  within  $1 \times 10^{-9}$ , in relative value, for the graphene (blue) and the GaAs/AlGaAs (black) devices, at 1.3 K and  $I \sim 10 \mu\text{A}$ .

a graphene device with electron density of  $1.8 \times 10^{11} \text{ cm}^{-2}$  and carrier mobility of  $9400 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ . It shows an extremely wide  $R_H$  plateau extending from 2.5 T up to 14 T, which has to be compared with the much shorter one of a GaAs/AlGaAs reference sample. Graphene/metal contact resistances are very low ( $\approx 1 \Omega$ ) (Fig. 1a), which is an asset for accurate Hall quantization. A complete set of metrological characterizations was carried out in wide ranges of magnetic induction  $B$ , temperature  $T$  and current  $I$  [2]. By comparison with a well-characterized GaAs/AlGaAs-based QHRS (LEP514), and using a cryogenic current comparator,  $R_H$  was found accurately quantized in the graphene device within  $1 \times 10^{-9}$  (or below) over a 10-T wide range of  $B$  with a remarkable lower bound at 3.5 T,  $T$  as high as 10 K, or  $I$  as high as 0.5 mA. The quantization accuracy was even tested within the ultimate measurement uncertainty of  $8.2 \times 10^{-11}$ . Such  $R_H$  accuracy is supported by measurements of very low dissipation level:  $R_{xx}$  is as low as a few  $\mu\Omega$ . The extension of the  $(B, T, I)$  parameter space ensuring a  $1 \times 10^{-9}$  quantization accuracy of  $R_H$  is found much larger in the graphene device than in the GaAs-based device. As a consequence the standard is versatile and can be used with various combinations of experimental parameters while keeping its perfect accuracy. The spatial homogeneity and the invariance of  $R_H$  against the  $B$ -field direction, both considered as quality criteria for quantum resistance standards, are demonstrated with relative measurement uncertainties of no more than  $1 \times 10^{-9}$  (Fig. 3). Besides, the robustness of the device properties against ageing and thermal cycling was demonstrated. Excellent  $R_H$  accuracy was also demonstrated in a second device, establishing the reproducibility of the device production technique. Finally, the physics of the QHE in these graphene devices was investigated through measurements of  $R_{xx}$  (versus  $T$  and  $I$ , at different  $B$ ) and its coupling with  $R_H$ . First results reveals a strong localization of electronic states between the Landau levels over a wide range of  $B$  that can be correlated with the structure of the material [3].

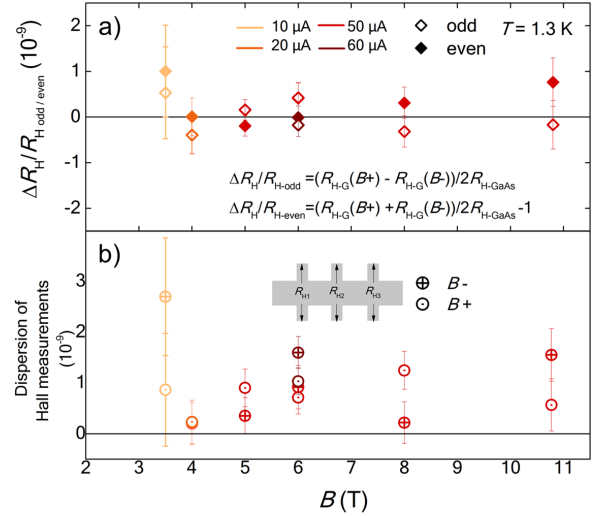


Fig. 3. a)  $\Delta R_H/R_{H\text{-odd}}$  and  $\Delta R_H/R_{H\text{-even}}$ , as defined in the figure, as a function of  $B$  for several current values. b) Relative dispersion of  $R_H$  measurements carried out using three Hall terminal pairs as a function of  $B$  for both  $B$ -field directions. Error bars represent uncertainties given with a coverage factor  $k=1$  (one standard deviation).

#### IV. CONCLUSION

We have investigated the metrological properties of large quantum Hall devices made of high-quality graphene grown by CVD on SiC. These devices can have all the properties of an ideal and convenient primary quantum resistance standard, able to supplant the GaAs/AlGaAs-based QHRS by their performances. Notably, they are fully adapted to an operation in simple cryogen-free setups, in which it was recently shown that  $R_H$  measurements can be performed with relative precision of a few  $10^{-9}$  [4]. Operation at lower magnetic fields (2 T) will be explored by a reduction of the carrier density using resist UV illumination. Further improvements of graphene devices could rely on a reduction of the bilayer coverage achieved by tuning the CVD on SiC growth parameters.

#### ACKNOWLEDGMENT

This research has received funding from the French National Research Agency (grant n° ANR-2011-NANO-004). It was partly supported within the European Metrology Research Program (EMPRP) project SIB51, GraphOhm. The EMPRP is jointly funded by the EMPRP participating countries within EURAMET (European association of national metrology institutes) and the European Union. This research has received partial funding from the European union Seventh Framework programme under grant n° 604391 Graphene Flagship.

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