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Broadband Conductivity of Graphene from DC to THz

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Abstract — **In this paper for the first time we have studied the broadband sheet conductance of few-layer graphene on single-crystal quartz substrate. Few-layer graphene was grown on Nickel coated Si wafers and transferred to the target substrate, which is single crystal quartz. High frequency measurements at X-band (8-12 GHz), using WR90 waveguide were performed. In addition, sheet resistance at W-band (75-100 GHz) and 1 THz range is also measured providing a comprehensive frequency sheet conductance calculation. The sheet resistance is extracted form the transmission coefficient (S_{21}). The results present small variation at different frequency bands, and are quite stable within the bands.**

***Index Terms* – Few-Layer Graphene, Sheet Conductance, Radio Frequency, S-parameters**

I. Introduction

Radio frequency characteristics of 1D and 2D nanomaterials have always been a fundamental source in defining their electronic applications. Moreover, the broadband frequency response of devices based on such materials is not clear especially for graphene sheets. Graphene is known as a semi-metallic 2D material, which shows a great performance in DC and sensor applications. In addition, graphene exhibits a favourable optical response due to inter-band and intra-band transitions [1]. However, the performance of graphene-based devices in radio frequency and Terahertz regime has rarely been explored in detail [2-7].

In this work, we are presenting the sheet conductance measurement of few-layer graphene for a wide range of frequency spectrum from DC to terahertz and more detailed in the X-band (8-12 GHz), W-band (75-110 GHz), and THz regime. The presented results demonstrate small variation at different frequency bands, which verifies the stability of few-layer graphene sheet conductance in broadband applications.

II. Fabrication

To measure the radio frequency sheet conductance of graphene we transferred/deposited clean graphene sheets onto single-crystal transparent quartz wafer. Graphene sheets are grown on Nickel using Chemical Vapor Deposition method (CVD). Graphene grown on Ni are mostly few-layer sheets of graphene.

Polymethyl-methacrylate (PMMA) is spin coated on top of Ni/Graphene sample. Then the Ni is etched leaving the graphene/PMMA stack floating on the liquid. After transferring the graphene on the desired area on single-crystal quartz substrate the PMMA is washed away with Acetone. The Raman spectroscopy of the graphene sheets (shown in Fig. 1) confirms the few-layer graphene deposited on top of the quartz substrate.

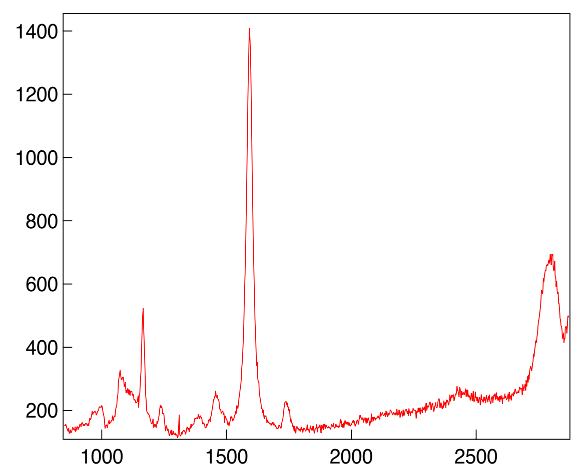

Fig. 1. Raman spectrum of few-layer graphene

As shown in the Raman data, the 2D band at around 2780 cm^{-1} is smaller than the G band at 1600 cm^{-1} which confirms the few-layer structure in transferred graphene. The D band (around 1300 cm^{-1}) represents the defects from both the growth and transfer process.

III. Technical Results

A. Formulation

Traditionally there have been two methods generally used for characterization of thin conductors (thin films). Resonant methods which rely on the measurement of the shift in frequency and the variation of the quality factor , and transmission methods, which perform the characterization through the variations in the transmission coefficient, S_{21} . This paper presents results in the calculation of graphene sheet conductance through transmission measurements.

For thin films, usually the transmission expression can be simplified as (for normal incidence, $\theta_0 = 0$)

$$\frac{E_2}{E_1} = T \approx \frac{2}{\cos(k_1 d_1)\left[2 + \eta_0 \sigma_S\right] + \sin(k_1 d_1)\left[\frac{\eta_1}{\eta_0} + \frac{\eta_0}{\eta_1} + \eta_1 \sigma_s\right]} \quad (1)$$

where E_2 and E_1 are the transmitted and incident electric fields, σ_S the sheet conductance, η_i the wave impedance of free-space and the substrate respectively. For an oblique incidence, the previous expression would be modified by changing η_i with $\eta_i / \cos\theta_i$ with θ_i the angle at each media.

B. Experimental results.

Two different measurements are investigated; the first measures a bare quartz substrate that is used as a reference measurement, to obtain a characterization of the permittivity of the quartz. The second measurement consists of a quartz substrate from the same wafer with a few-layer graphene on top of it. Both are then post-processed using (1) to obtain the sheet conductance of the graphene sheets. Three different frequency bands have been measured which are discussed below. All DC data are extracted using 4-probe measurement therefore, the effect of the contact resistance has been suppressed.

1) X-band measurements (8-12 GHz):

The free-space formulation (1) requires a sufficiently big sample in terms of wavelength, in order to avoid diffraction effects in the measurement. At 10 GHz the wavelength is few centimeters, to avoid the need of big samples, graphene can be introduced perpendicularly into a waveguide thus reducing the dimensions of the waveguides. The same formulation as in free space (1) can be used, provided that the angle of incidence at each frequency is properly set through the frequency dispersion relationship

$$\cos\theta = \sqrt{1 - \left(\frac{f_c}{f}\right)^2} \quad (2)$$

where f_C is the cutoff frequency of the waveguide.

In order to perform the measurement the waveguides are connected to a network analyzer through coaxial cables, and the parasitic effects are removed performing a TRL calibration. Fig. 2 presents the processed results for the sheet conductance of the sample.

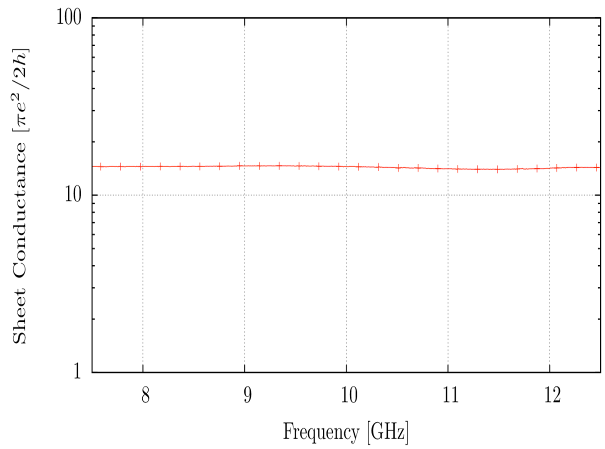

Fig. 2. Sheet conductance measurements for X-band

2) W-band measurements (75-110 GHz):

At W-band frequencies the sample is large enough and a free-space measurement can be done. In order to improve the resolution a focusing system is used to take the transmission measurements. Fig. 3 presents the processed results for the sheet conductance of the sample.

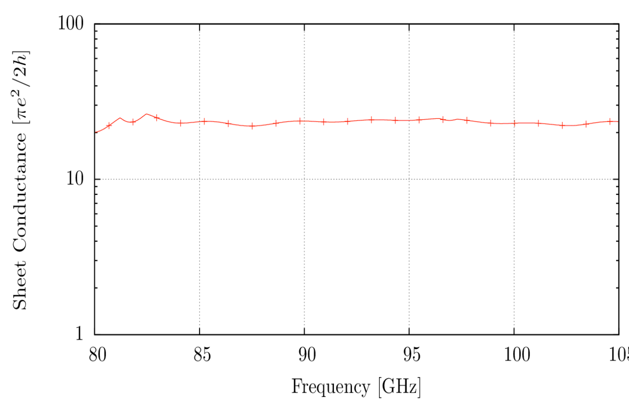

Fig. 3. Sheet conductance for W-band

3) THz measurements (100 GHz – 1 THz):

Finally, we have used a coherent photo-mixer spectrometer [8] to determine the conductance of graphene from 100 GHz to 1.1 THz. The measurements were carried out with a coherent photo-mixing spectrometer with circularly polarized radiation incident normal to the graphene film.

Modeling of the data was performed to extract the sheet conductance. The compiled data from all three methods is plotted in Fig. 4.

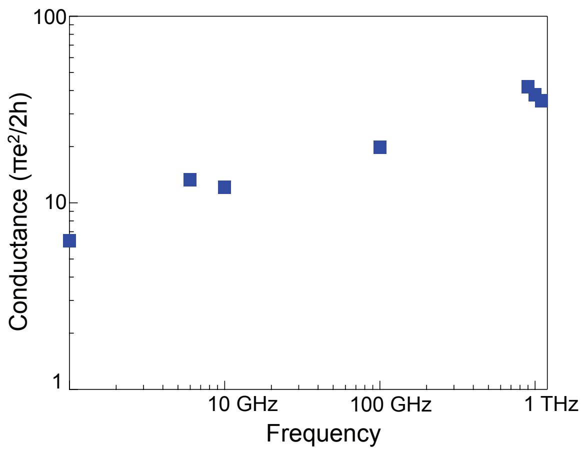

Fig. 4. Normalized sheet conductance of few-layer graphene (in Log scale) in broadband frequency range up to 1.1 THz

IV. Conclusion

Measurements of few-layer graphene sheet conductance have been carried out at three different frequency bands. The results present small variation at the different frequency bands, and are quite stable within the bands. They are also in agreement with a parallel set of single graphene layer, thus reducing the sheet resistance from a single layer with proportionality in the order of the number of layers.

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