Inherent Resistivity of Graphene to Strong THz Fields

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Abstract: The nonlinear THz conductivity of graphene is characterized using nonlinear ultrafast THz spectroscopy. Efficient carrier heating by the THz field reduces carrier scattering, yet, counter-intuitively, simultaneously suppresses the high-frequency conductivity of graphene.

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1. Introduction

In graphene the electrons can be described as massless fermions, which results in very high dc conductivity of the material. Combined with the presence of the field effect [1], the high dc conductivity implies great promise of graphene for ultra-high-speed electronics applications such as THz-rate transistors [2]. In such devices with gates as short as 70-250 nm [2], the charge transport is driven by ultrafast electric fields with strengths exceeding 100 kV/cm. In this work, we use nonlinear THz spectroscopy as a contact-free ultrafast frequency-resolved current-voltage characterization tool, to study the performance of graphene under the typical THz transistor operation conditions. Remarkably, we find that graphene possesses an inherent resistivity mechanism towards THz strong-field modulation, in that the typical conditions present in a graphene transistor cause a dramatic reduction of the material conductivity. This is the result of extremely efficient carrier heating in THz fields, revealing intrinsic, material-imposed limitations for the use of graphene in ultra-high speed electronics.

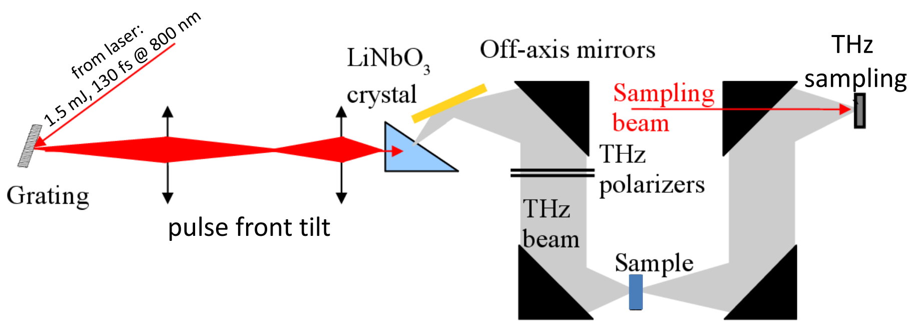

Fig. 1. : The schematic of the nonlinear THz spectroscopy setup used for contact-free ultrafast frequency-resolved current-voltage characterization of graphene.

2. Measurement

Our graphene sample was grown by chemical vapor deposition, and was transferred onto a fused silica substrate which caused *p*-doping of graphene. The Fermi level of graphene was determined by linear THz spectroscopy, and independently confirmed by Raman spectroscopy [3], to be at ~ 300 meV with respect to the Dirac point. In the nonlinear THz time-domain spectroscopy (THz TDS) arrangement based on tilted pulse front – pumped $LiNbO_3$ [4,5] (see Fig. 1), we have measured the peak-field dependent broadband conductivity of graphene in the peak THz field range 7.5 – 180 kV/cm and in the spectral range 0.4 – 1.6 THz. We control the peak field strength in the single-cycle THz pulses using crossed wire-grid polarizers, which leaves the temporal shape of the THz waveforms unaffected [4,5]. The THz pulses were detected by free-space electro-optic sampling in a 0.5 mm thick (110)-cut ZnTe crystal. The THz field before the sampling crystal was attenuated by multiple intrinsic silicon wafers, in order to ensure linear detection of the THz field. All our measurements were performed at room temperature.

3. Results

In Fig. 2 we present the spectral shape of the (real-valued) THz conductivity of graphene as function of THz field strength. The conductivity decreases with both increasing THz frequency and field strength. For frequencies exceeding 1 THz, the strong-field conductivity of graphene is only a small fraction of its conductivity probed in the linear regime (at fields below 10 kV/cm). In the same Figure we present the results of the thermodynamic modeling of graphene conductivity, incorporating both the carrier heating [5-7] *and* the decrease of carrier scattering rate for high-energy electrons [8] as the THz driving field increases. The latter is in direct contrast to standard semiconducting materials such as e.g. GaAs, where hot carriers experience higher scattering rates [9]. It is apparent, that our model adequately describes the results of our measurements, fully reproducing all the key experimental features, i.e. the frequency- and THz peak field – induced suppression of graphene conductivity. Within our experiments, at strongest THz excitation the electron temperature of graphene was found to approach 5000 K. The key to efficient carrier heating is graphene is extremely efficient electron population thermalization via hot-carrier multiplication mechanism [10-12], while it can be shown that the reduction of the scattering rates for hotter carriers counter-intuitively leads to the suppression of high-frequency conductivity of graphene [13]. Interestingly, the carrier heating does not affect the dc conductivity of graphene (see Fig. 2).

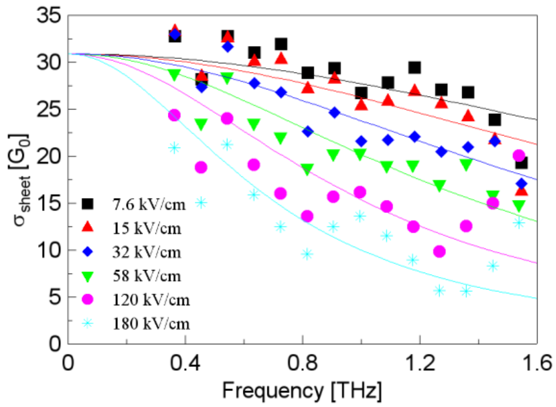

Fig. 2. Symbols: Measured (real-valued) conductivity spectra of graphene at different THz peak field strengths. Lines: fits of the measured THz conductivity to our thermodynamic model, taking into account reduced scattering for hot electrons. The conductivity is shown in quantum units of $G_0=e_0^2/(4\hbar)$.

4. Conclusions

In conclusion, the nonlinear THz conductivity of graphene was studied with ultrafast nonlinear THz spectroscopy. We find that carrier heating by the THz fields suppresses the high-frequency conductivity of graphene, in spite of the reduced scattering rate for higher-energy carriers. At the same time the dc conductivity of graphene is not affected by charge carrier heating. A thermodynamic model of the graphene conductivity was developed [13], which provides quantitative agreement with our measurements.

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