Extended Abstracts of the 2019 International Conference on Solid State Devices and Materials, Nagoya, 2019, pp173-174

Dynamical Studies of Hot Carriers in 2D Semiconductors: Intrinsic vs. Extrinsic Processes

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Abstract

We describe the use of short (nanosecond-duration) electrical pulsing to investigate hot carrier action in graphene. We discuss how this strategy allows us to suppress the influence of self-heating (heating of the substrate by the graphene channel) and of carrier capture (injection of hot carriers from graphene into its underlying dielectric), allowing the true characteristics of hot-carrier action to be identified.

1. Introduction

In emergent devices based on two-dimensional (2D) materials, such as graphene, electrical performance can be negatively impacted by a number of undesirable extrinsic effects. Prominent among these is hot-carrier trapping, in which energetic carriers driven by the drain bias are injected into traps in the gate dielectric. This behavior is responsible for the hysteresis found in many experiments, in which electrical conduction through a 2D can be strongly sensitive on the gate- and drain-biasing history. Another problem in 2D transistors is self-heating, or Joule heating of the overall device through a process in which heat generated in the 2D channel is transmitted to its surrounding dielectric layers. This activates energetic phonons in these layers, which in turn may serve as an effective source of remote scattering of the 2D carriers.

To realize the superior electrical performance promised by many 2D materials, it is necessary to study their hot-carrier action, without the influence of the trapping and heating processes described above. In this presentation, we report a case study of this problem, in which we use graphene as the 2D material of interest. By investigating the hot-carrier action in this material with isolated pulses as short as a few nanoseconds, we demonstrate [1-3] how it is possible to suppress the influence of self-heating and hot-carrier trapping. In this way we are able to investigate the intrinsic factors that limit the current-carrying capacity of this material, and to reveal its truly impressive electrical characteristics.

2. Experimental Details

Rapid pulsing of graphene field-effect transistors (FETs) was performed at room temperature, under vacuum, in an impedance-matched setup (for details see [1]), in which electrical contact to Kish graphene flakes, exfoliated onto 300-nm thick SiO_2 substrates, was provided by an on-chip coplanar waveguide architecture. The carrier density in these devices was varied by means of a top-gate, which was isolated from the graphene using either hardened PMMA [1,2] or a transferred flake of hexagonal boron nitride (h-BN) [3]. Various devices have been investigated, using either monolayer or bilayer graphene on SiO_2 [1,2] or with full h-BN encapsulation [3]. Channel length (L) and width (W) of these devices was in the range of 0.5 – 2 μm and of 2 – 8 μm, respectively.

3. Experimental Results

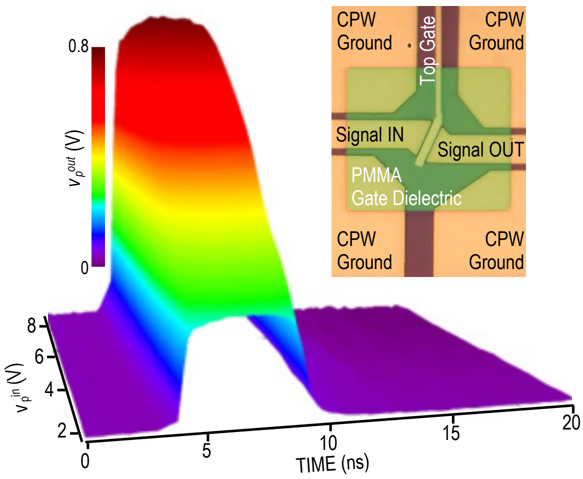

Fig. 1 The main panel shows the output pulse (v_p^{out}) measured at the oscilloscope of our fast-measurement setup, on the output side of the device. The variation is plotted as a function of time and amplitude (v_p^{in}) of the input pulse. The output faithfully follows the form of the input, even at the sub-ns time scale. The inset is an optical image of a device consisting of graphene on SiO2, with a top gate separated from the graphene layer by hardened PMMA. See [1,2] for details.

To illustrate the capabilities of our measurement setup, in the main panel of Fig. 1 we plot a color contour to show the variation of the output pulse amplitude, measured at the oscilloscope of our fast-measurement setup, as a function of the input-pulse amplitude. The duration of the pulses is approximately 4 ns, and their lineshape reproduces faithfully the form of the input pulses (not shown here). Using this setup, we are able to vary the nature of the applied pulses over a wide parameter space; the applied pulse amplitude may be varied in the range of ±10 V, while its duration may span from the ns to the ms range. Pulses may be applied in single-shot fashion, or repetitively over a range from 10 kHz – 1 MHz. As we discuss below, control of this parameter space allows us to explore a number of aspects of hot-carrier transport in graphene FETs, including charge injection from graphene into its surrounding dielectrics, self-heating of the device (involving the transfer of heat from the graphene channel to the dielectric layers), as well as intrinsic process arising from the heating of carriers in the graphene layer itself. In the following subsections, we describe these aspects in more detail.

Hot Carrier Injection into Dielectric Traps

The use of large drain voltages in CMOS devices is known to result in current degradation, which arises when hot carriers in the FET channel are injected into the gate oxide. Similar problems may arise for graphene FETs, especially those supported on a SiO_2 substrate. This problem can be studied by applying the drain voltage to the device in a pulsed fashion, while using a variation of the pulse amplitude, duration, and repetition frequency to explore a wide parameter space. In our original work performed for graphene-on-SiO_2 FETs, we found increasing evidence of current degradation due to hot-carrier trapping as the pulse amplitude and duration were increased [1,2]. The trapping was manifested as a region of negative differential conductance, which onset for pulse durations in excess of ~10 ns and for average fields in the channel of 20 – 30 kV/cm (Fig. 2, inset).

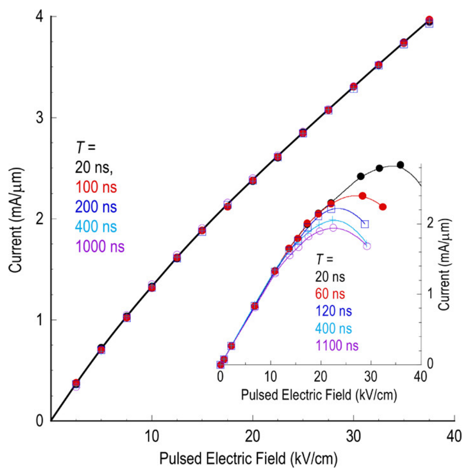

Fig. 2 Main panel plots the results of pulsed current–voltage measurements of an h-BN-encapsulated monolayer graphene FET. Results are shown for various pulse durations (T, indicated), and the solid line is a guide to the eye. Inset: corresponding measurements for a (bilayer) graphene-on-SiO_2 device. Figure from Ref. 3. Copyright 2019 American Chemical Society.

In contrast to the situation for graphene on SiO_2, in h-BN encapsulated devices we find that the pulsed *I-V* characteristic can remain independent of pulse duration up to time scales as long as μs [3]. This behavior is shown in the main panel of Fig. 2, which plots the results of measurements of one of our encapsulated devices over a similar field range to that in the inset. There is no apparent negative differential current observed, and the data also show no noticeable dependence on pulse duration. Clearly, these results indicate that h-BN is a better dielectric than SiO_2 when considering the hot-electron applications of graphene. We attribute this to the good lattice matching of h-BN to graphene, and to the much lower density of native traps of h-BN compared to SiO_2.

Self-Heating of Graphene FETs

When the channel of a graphene FET is subjected to a large drain bias, Joule heat generated through electron-phonon coupling in graphene is transmitted to the surrounding dielectric layers (i.e. SiO_2 or h-BN). For graphene on SiO_2, the thermal mismatch between these layers is large, meaning that heating of the oxide does not occur rapidly, but rather takes place over tens of nanoseconds or more. This allows the application of short (<10 ns) electrical pulses to be used to probe the internal dynamics of heating within graphene, separate from the influence of the substrate. In Ref. 1, we showed how this approach can be used to address the long-standing mystery of the unexpectedly low saturation velocity for hot carriers in graphene. In prior experiments, measurements of the drift velocity in graphene were made by DC, or quasi-DC approaches, resulting in significant self-heating that reduced the carrier velocity in graphene, via remote scattering from optical phonons in SiO_2. In this way we were able to demonstrate measurement of the true saturation velocity of graphene for the first time [1].

3. Conclusions

Transient measurements of two-dimensional semiconductors provide a powerful means to probe the dynamics of their hot carriers, allowing intrinsic and extrinsic processes of energy relaxation to be studied. We have discussed this here for the representative case of graphene on SiO_2 and on h-BN.

Acknowledgements

This work was supported by the US Department of Energy, Office of Basic Energy Sciences, Division of Materials Sciences and Engineering (Award DE-FG02-04ER46180). R.S. received support from King Mongkut's Institute of Technology Ladkrabang Research Fund (KREF046102 & Thep-61-EQP-KMITL3) and from its Faculty of Science.

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