Graphene-Based Ultrafast Electro-Optical Modulators

Seiya Suzuki
Graduate School of Engineering, Toyota Technological Institute, Tempaku-ku, Nagoya, Japan

NNIN iREG Site: Colorado Nanofabrication Laboratory (CNL), University of Colorado, Boulder, CO
NNIN iREG Principal Investigator: Prof. Thomas Schibli, Physics, University of Colorado at Boulder
NNIN iREG Mentor: Chien-Chung Lee, Physics, University of Colorado, at Boulder
Contact: sd11502@toyota-ti.ac.jp, trs@colorado.edu, chienchung.lee@colorado.edu

Abstract:

Monolayer graphene exhibits many incredible physical properties such its ultrahigh electron mobility and ultrafast relaxation time for photo-excited carriers. This fast relaxation, on the order of eight femtoseconds [1], enables ultrashort pulse generation from mode-locked lasers. Because of graphene's unique band structure, the optical absorption in graphene is controllable by applying an electric field that changes its carrier density, thus graphene can be exploited as an electro-optic modulator that actively controls optical loss in mode-locked lasers to avoid gain instabilities. In this work, we demonstrated graphene-based electro-optical modulators in a reflective geometry, which consisted of a thin-film structure consisting of a Cu/Al top-electrode on transferred graphene sheet prepared by chemical vapor deposition, and a 185 nm thick Ta_2O_5 dielectric layer on a reflective Al bottom electrode. The Ta_2O_5 film thickness was optimized to enhance the electric field of the 1.5 μm light at the location of the graphene. The optical loss of graphene was controlled by an electric field between top and bottom electrodes. The modulator showed a modulation depth close to the theoretical maximum, excellent high-frequency response, and a large active area.

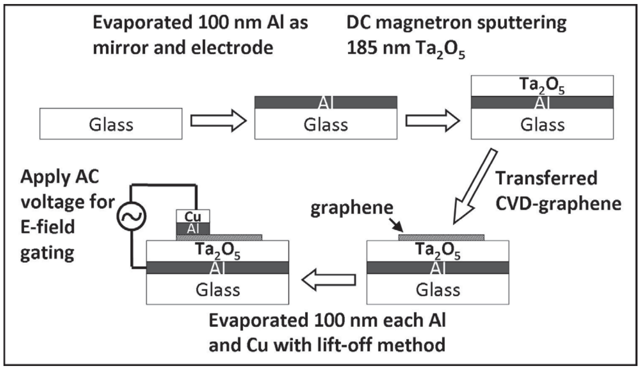

Figure 1: Schematic diagram of the modulator fabrication.

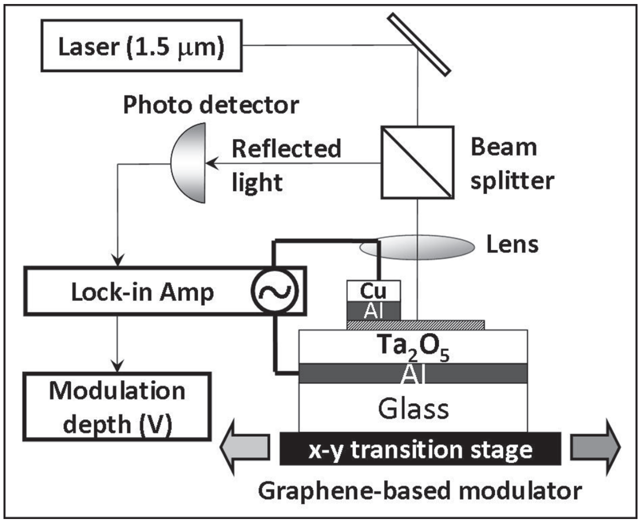

Figure 2: Schematic diagram of the measurement setup for the modulation depth.

Experimental Procedure:

Figure 1 shows the fabrication procedures for the graphene-based electro-optical modulator. A 100 nm thick aluminum (Al) film, as mirror and bottom electrode, was deposited by vacuum evaporator on a microscope glass slide. A tantalum pentoxide (Ta_2O_5) film was then deposited by DC reactive magnetron sputtering.

The deposited Ta_2O_5 showed no electrical breakdown for electric fields as high as 1 MV/cm, leading to a large tunable range in the optical absorption of graphene. The optical thickness of Ta_2O_5 (185 nm) was adjusted to be quarter wavelength of the incident laser (1.5 μm) light, such that the graphene film on top interacted with the maximum electric field. Monolayer graphene sheets were then prepared by chemical vapor deposition (CVD) and transferred onto the Ta_2O_5 film. The growth and transferring methods are described in [2]. Patterned Al and Copper (Cu) top electrodes, 100 nm thick each, were then deposited by vacuum evaporator using a lift-off method.

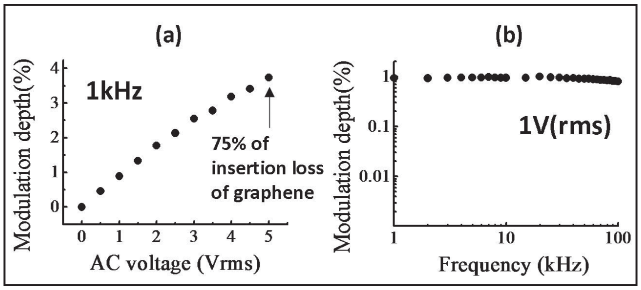

Figure 3: The dependence of the modulation depth (%) on (a) the AC voltage (in Vrms) and (b) driving frequency (kHz) at driving frequency of 1 kHz and voltage of 1 Vrms, respectively.

The modulation depth was measured in a reflective geometry with a lock-in amplifier as shown in Figure 2. The control voltage was applied between top and bottom electrodes. A continuous-wave laser (1.5 μm) illuminated the device under normal incidence and a computer-controlled x-y translation stage was used for obtaining two-dimensional images of the modulation depth.

Results and Discussion:

Figure 3(a) shows the dependence of the modulation depth (%) on the root mean square AC voltage (V_{rms}) driven at 1 kHz. Modulation depths as high as 3.7% at 5 V_{rms}, corresponding to approximately 75% of the insertion loss of graphene, were observed. This surprisingly high modulation was achieved due to the high-κ value of Ta_2O_5, and the local and enhancement of the electric field of the 1.5 μm light. Figure 3(b) shows the dependence of the modulation depth (%) on driving frequency (kHz) with a driving voltage of 1 V_{rms}. The modulation depth was nearly independent from the driving frequency at least up to 100 kHz which was our instruments limit.

Figures 4(a) and (b) show an optical microscope and a two-dimensional modulation depth image of the same region. The inner diameter of the ring electrode is 120 μm. The modulator was driven by 1 V_{rms} at 1 kHz. The measured region was entirely covered by graphene except for the cracks pointed out in Figure 4(a). As shown in Figure 4(b), the electrode and cracks did not show modulation but the inside of the ring showed large modulation depths with high uniformity corresponding to approximately 10,000 μm^2, which were clearly coincident with Figure 4(a). The regions of no modulation outside of the ring were surface impurities or defects in the graphene induced by the fabrication process. On the other hand, modulation was observed over the entire area of the graphene sheet, even 1000 μm away from the electrodes. This indicates that the transferred CVD graphene was continuous and our fabrication processes of the modulator were reproducible.

Conclusions and Future Work:

We demonstrated graphene-based electro-optical modulators in a reflective geometry. The modulators showed surprisingly high modulation depth of 3.7% at 5 V_{rms} owing to the high-κ value of Ta_2O_5, and the local enhancement of the electric field of the 1.5 μm wavelength light. The frequency response was higher than 100 kHz. The entire area of graphene, even 1,000 μm away from electrodes, showed uniform modulation, which indicates the high uniformity of the transferred CVD graphene.

With further improvements in the mirror design and patterning of graphene, and by combining this graphene-based modulator with the inherent saturable absorption of graphene, an active/passive hybrid ultra-fast pulse generator for mode-locked lasers can be achieved.

Acknowledgements:

Special thanks to Prof. Thomas Schibli and Chien-Chung Lee for guiding me throughout the project. Also, thanks to the CNL staff, including Prof. Bart Van Zeghbroeck and Tomoko Borsa for their efforts and assistance. Finally, I would like to acknowledge the generous support from the NSF through the NNIN iREG Program, and from the National Institute for Materials Science in Japan.

References:

[1] Guo, X.G. et al.; "The Physics of Ultrafast Saturable Absorption in Graphene"; Optics Express, 18, 4564 (2010).

[2] Li, X. et al.; "Graphene Films with Large Domain Size by a Two-Step Chemical Vapor Deposition Process"; Nano Lett., 10, 4328 (2010).

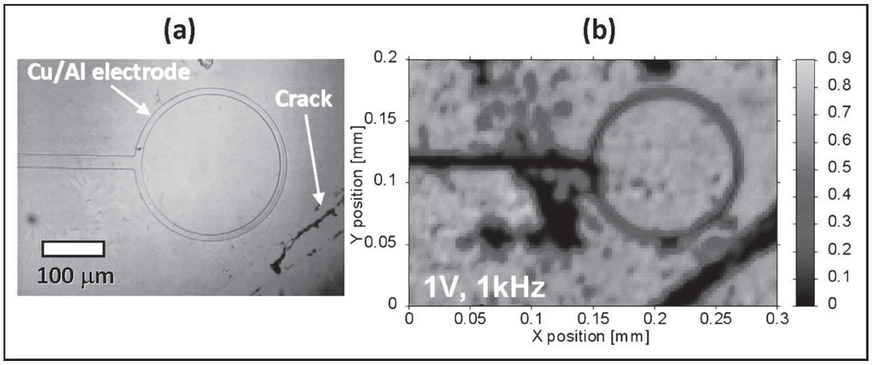

Figure 4: (a) An optical microscope image of the graphene electro-optic modulator. The inner diameter of the ring electrode is 120 µm. (b) A two-dimensional modulation depth (%) image of the same regions as in (a). The modulator was driven by 1 V_{rms} at 1 kHz.