Top-Gated Graphene-Based Ultrafast Electro-Optic Modulators

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Abstract:

Graphene's universal linear optical absorption, extraordinary carrier mobility, and zero-gap band structure motivate its use as an electro-optic modulator. The optical absorption of graphene can be altered via electrostatic doping. This electrostatic doping is achieved by applying a gate voltage between graphene and a gate electrode in a thin film structure. Improving on a previously achieved back-gated model, a top-gated geometry was investigated due to its ability to accommodate applications requiring both transmissive and reflective modulators, including utilization in low-loss Bragg reflectors and monolithic fiber lasers. In return for this enhanced versatility, the top-gated device required direct deposition of the dielectric material on graphene, which can lead to destruction of the graphene. Dielectric media that can be deposited on graphene with minimal damage were explored, including alumina and silicon monoxide. In this work, a top-gated modulator using alumina as a gate dielectric was successfully fabricated. Alumina was effective in preserving graphene while also exhibiting strong dielectric properties.

Introduction:

Electro-optic modulators are a fundamental component of most modern opto-electronic systems, ranging from telecommunications to solid-state lasers. The operating principle of these modulators is the electro-optic effect, which is a change of a material's optical properties under the presence of an electric field. While many materials exhibit this effect, graphene is of particular interest due to its electrical properties, including extraordinary electron mobility. These properties mean that the electro-optic effect occurs at very high speeds in graphene, resulting in ultra-fast modulation. These extraordinary modulation speeds, coupled with the absence of phase distortion due to graphene's two-dimensional structure are in essence the motivation for graphene's use in electro-optic modulators.

Experimental Procedure:

The fabrication process is outlined in Figure 1. Monolayer graphene grown by chemical vapor deposition (CVD) was transferred onto glass microscope slides by a wet transfer process. Metal electrodes were then deposited by thermal evaporation (20 nm Ti and 80 nm Al), and patterned using a positive photoresist and lift-off method. Titanium (Ti) was used to assist the adhesion of the aluminum (Al) layer on graphene and to reduce the contact resistance of the electrode on graphene. The graphene outside the ring-electrodes was removed by reactive-ion etching to minimize the device capacitance. A 220 nm thick aluminum oxide (Al_2O_3) dielectric layer was deposited onto the graphene by electron-beam evaporation. A 200 nm silver layer was then grown by thermal evaporation, giving the device a reflective geometry. The silver film acted as both

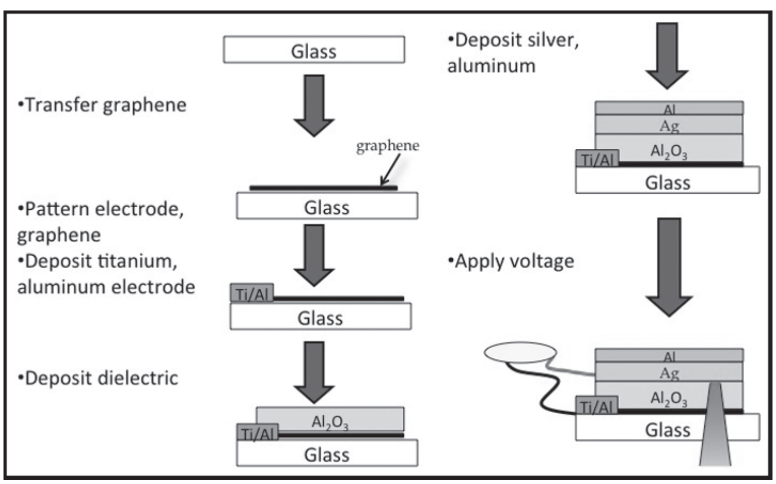

Figure 1: Major fabrication steps.

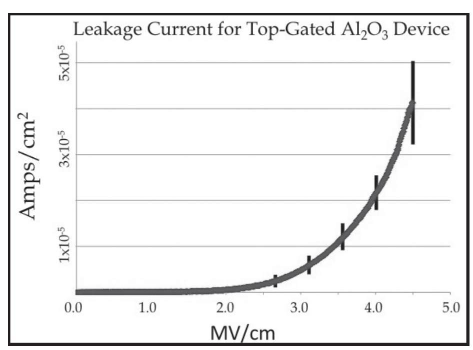

Figure 2: Typical behavior for the dependence of leakage current density on applied electric field for top-gated Al_2O_3 devices.

a mirror and top-gate electrode. An additional Al layer was deposited to serve as a protective layer.

Results:

The breakdown voltage of the devices was characterized by a two-point probe setup. Figure 2 shows the results from a fabricated device, which was durable under fields up to 4.5 MV/cm. Combined with the measured dielectric constant of $\varepsilon \approx 10.9$ of our Al_2O_3 films, which was in agreement with earlier studies [1], this high breakdown field strength enabled substantial electrostatic doping, and hence, strong optical modulation. Devices fabricated using silicon monoxide (SiO) as a dielectric layer showed breakdown under fields of 0.5 MV/cm and a measured dielectric constant of $\varepsilon \approx 5.5$. The superior dielectric properties of Al_2O_3 over SiO made it clear that Al_2O_3 was a more favorable dielectric for this device.

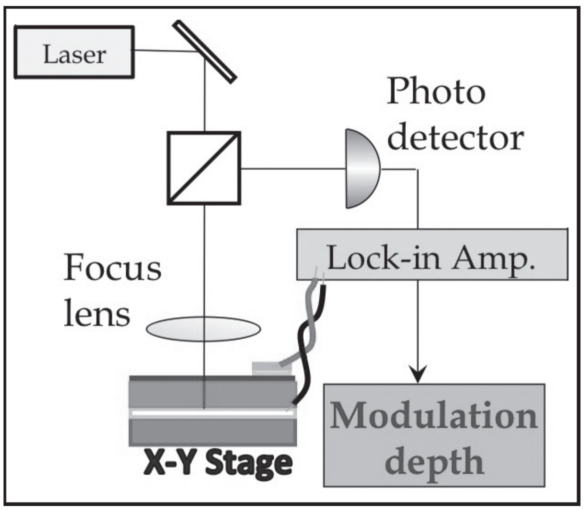

Figure 3: Setup used to measure modulation depth.

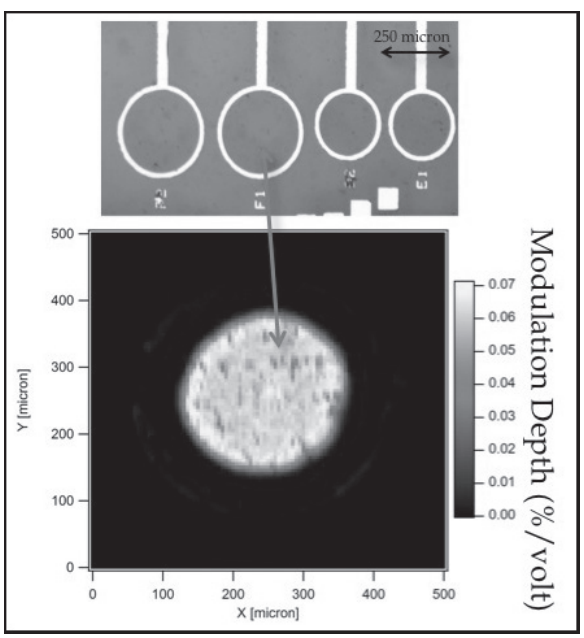

Figure 4: Top: SEM of several modulators on a chip. Bottom: 2D scan of modulation depth across one ring electrode.

The setup used to characterize the modulation depth is shown in Figure 3: A continuous-wave laser at 1.55 μm wavelength was reflected off the sample, which was placed on a translational XY-stage. For each location on the sample the reflectivity change versus applied AC voltage was recorded. A resulting 2D modulation map is shown in Figure 4.

We observed uniform modulation across the active area, besides small processing defects that likely originated from the transfer of the graphene to the substrate. These defects were small enough so that they did not have a significant impact on the performance of the device. The consistent modulation depth across the graphene verified that the fabrication process did not substantially alter the electronic and optical properties of the graphene layer.

Conclusions:

We have fabricated a top-gated graphene-based modulator. We found that Al_2O_3 was a suitable dielectric due to its transmissivity, benign interaction with graphene during deposition, and strong dielectric properties. Most notably of these dielectric properties was the high breakdown voltage, which allowed for a considerable shift of graphene's Fermi level and large achievable modulation depths. We also saw uniform modulation across the active area, which confirmed that graphene remained intact during the fabrication process.

Future Work:

More characterization, including a measurement of the modulation speed, is needed to further understand the effectiveness of this device. In addition, more work needs to be done to allow this device to be transmissive. This could be achieved by replacing the silver mirror with another layer of graphene, for example. A transmissive geometry has exciting applications including use in low-loss Bragg reflectors and monolithic fiber lasers.

Acknowledgments:

I would like to thank the National Nanotechnology Infrastructure Network Research Experience for Undergraduates Program and the University of Colorado at Boulder for funding this project. Special thanks go to Chien-Chung Lee and Thomas Schibli for the invaluable guidance. I would also like to thank Bart Van Zeghbroeck, Jan Van Zeghbroeck, Tomoko Borsa, Bounkheana Chhun, Ian Haygood, Tzu-Min Ou, and Zefram Marks.

References:

[1] M.Y. Seo, et al., "Characterization of Al_2O_3 films grown by electron beam evaporator on Si substrates"; Nanoelectronics Conference Publications 3rd International (3-8 Jan. 2010): 238-239.