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Xuetao Gan,[2] Ren-Jye Shiue,[1] YuandaGao,[3] Kin Fai Mak,[4] Xinwen Yao,[2] Luozhou Li,[2] Attila Szep,[5] Dennis Walker, Jr.,[5] James Hone,[3] Tony F. Heinz,[2,4] and Dirk Englund[1]

1. Department of Electrical Engineering & Computer Science, Massachusetts Institute of Technology, Cambridge, MA 02138, United States
2. Department of Electrical Engineering, Columbia University, New York, New York 10027, United States
3. Department of Mechanical Engineering, Columbia University, New York, New York 10027, United States
4. Department of Physics, Columbia University, New York, New York 10027, United States
5. Air Force Research Laboratory, Sensors Directorate, WPAFB, Dayton, Ohio 45433, United States
tedshiue@mit.edu

Abstract: We demonstrate high-contrast electro-optic modulation in a graphene integrated photonic crystal nanocavity, providing a modulation depth of more than 10 dB at telecom wavelengths. This work shows the feasibility of high-performance electro-optical modulators in graphene-based nanophotonics.

The exotic optical properties of graphene enable a wide range of promising devices for light manipulation and photodetection [1,2]. In order to enhance the light-matter interaction in graphene, several schemes have been employed, including an integrated optical waveguides [3] and cavities [4,5] with graphene, and the coupling of graphene to plasmonic nanostructures [6,7]. In this work, we integrate a silicon air-slot planar photonic crystal (PPC) nanocavity with a monolayer graphene sheet. By tuning the Fermi energy of graphene with electrical gating, we obtain a modulation of the cavity reflection in excess of 10 dB with a voltage swing of only 1.5 V. This strong interaction is attributed to the substantial overlapping of the resonant optical field of the cavity and the graphene layer. Furthermore, we observe a shift of 2 nm in the resonant wavelength of the cavity, together with a 3-fold increase in the quality factor, allowing us to determine the complex optical conductivity of graphene with enhanced accuracy.

Fig. 1a shows the scheme of our device. An air-slot PPC nanocavity is fabricated on a silicon-on-insulator wafer with a 220 nm thick silicon membrane using a series of electron-beam lithography and dry/wet etching steps. After graphene is transferred on top of the PPC nanocavity, source, drain and gate metal electrodes are defined by e-beam lithography, metal deposition and lift-off. Finally, an electrolyte (PEO plus $LiClO_4$) is spun on the entire wafer, allowing us to induce high electrical fields and carrier densities in graphene. The optical transmission of the monolayer graphene can be modulated by electrostatistically tuning the Fermi energy (E_F) of graphene, as illustrated in Fig. 1b. The interband transition will be Pauli blocked when the photon energy is lower than twice of the Fermi energy away from the Dirac point. In this regime, the absorption of graphene is reduced and the reflectivity and the Q factor of the cavity can be effectively controlled.
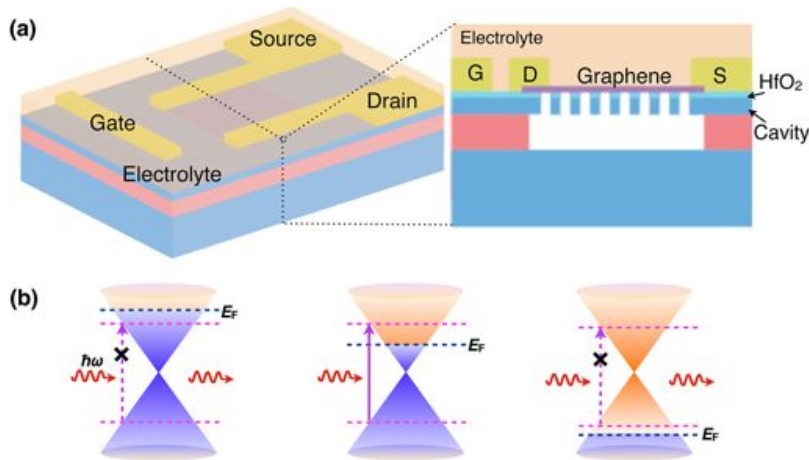

Fig. 1. (a) Schematic of the graphene integrated PPC nanocavity modulator. (b) Band structure of graphene. The interband transitions are suppressed at high doping level and the graphene becomes more transparent as a result of Pauli blocking.

We characterize the graphene-PPC nanocavity using a cross-polarization confocal microscope with a broad-band (super-continuum laser) excitation source. The cavity reflection is analyzed using a commercial spectrometer with a resolution 0.05 nm. The measured optical and electrical signal are recorded simultaneously and presented in Fig. 2. We sweep the gate voltage in a sawtooth pattern between -7 V and 6 V. The resistance peak in Fig. 2b indicates the charge neutrality point (V_{CN}) of our graphene field effect transistor (FET) is at 1 V. In Fig. 2c, three different resonant modes are evolving as the gate voltage is sweeping. At V_G = 0 to -1 V, the cavity spectra remains unchanged. Two peaks can be observed at the wavelengths of 1571.1 nm and 1593 nm, respectively (top panel of Fig. 2d). As V_G goes below -1 V, the two peaks narrow and red shift slightly. The increase of cavity reflectivity arises from the reduction of graphene absorption, where Pauli blocking starts to take effect. Decreasing V_G further, the peaks continue to grow narrow but starts to blue shift. The Q factor stabilizes when V_G is below -2.5 V, indicating a full Pauli blocking regime in graphene is achieved. At V_G = -7 V, these peaks are very narrow and a mode at 1576 nm becomes more distinguishable (third panel of Fig. 2d). The cavity spectra shows corresponding behavior when V_G is moving back from -7 V to 0 V. At positive V_G, the graphene becomes n doped when V_G is larger than V_{CN}. The evolution of the cavity spectrum has the same effect for the n and p doped side of graphene and is therefore symmetrical to V_{CN} = 1 V. In terms of the variation of the cavity reflectivity to gating, we obtain a maximum modulation of more than 10 dB at a wavelength of 1592.9 nm when V_G is between -1 V and -2.5 V, corresponding to a voltage swing as small as 1.5 V. To understand the behavior of the cavity reflectivity, we can further apply a coupled mode theory for this graphene-cavity system [4], and the complex optical conductivity of graphene can be extracted from the experimental results.
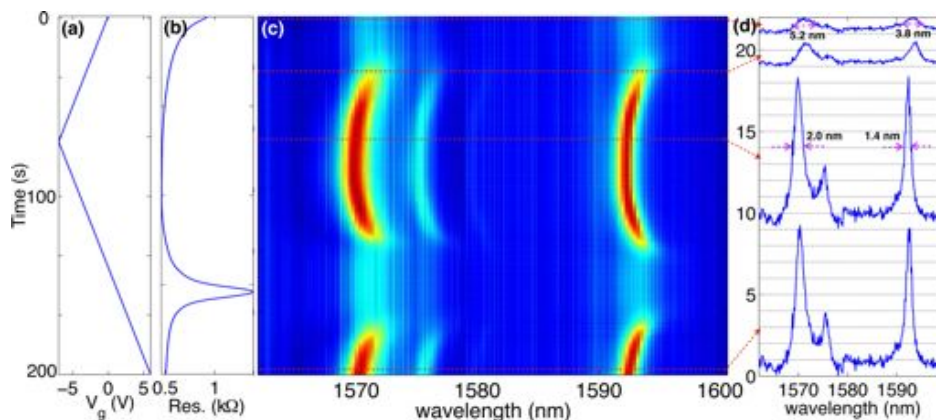

Fig. 1. Electrical and optical response of the graphene-PPC nanocavity modulator. (a) Gate voltage (V_G) as a function of time. (b) Resistance of the grpahene FET. (c) Reflection spectra of the cavity as V_G is modulated. Three resonant peaks show clear shift in wavelengths and modulation in their intensity and Q factors. (d) Normalized spectra of the cavity reflectivity in (c) at V_G = 0, -1, -7 and 6 V (top to button).

Our works shows the strong optical modulation in coupled graphene-cavity systems. While the speed of our current device is limited by the ionic mobility of the gating electrolyte, the use of dual-gated graphene layers or highly doped silicon PPC nanocavities as a back gate will permit the operation up to the GHz regime. The potential of graphene-based modulators are promising for a new generation of low power consumption, high modulation depth and high-speed applications in photonic integrated circuits.

References

[1] F. Bonaccorso, Z. Sun, T. Hasan and A. C. Ferrari, "Graphene photonics and optoelectronics," Nat. Photonics **4**, 611-612 (2010).
[2] Q. Bao and K. P. Loh, "Graphene photonics, plasmonics, and boradband optoelectronic devices," ACS Nano **6** (5), 3677-3694 (2012).
[3] M. Liu, X. Yin, E. Ulin-Avila, B. Geng, T. Zentgrad, L. Ju, F. Wang and X. Zhang, " A graphene-based broadband optical modulator," Nature **474**, 64-7 (2011).
[4] X. Gan, K. F. Mak, Y. Gao, Y You, F. Hatami, J. Hone, T. F. Heinz, D. Englund, "Strong enhancement of light-matter interaction in graphene coupled to a photonic crystal nanocivity," Nano Lett. **12**, 5626-5631 (2012).
[5] M. Furchi, A. Urich, A. Pospischil, G. Lilley, K. Unterrainer, H. Detz, P. Klang, A. M. Andrews, W. Schrenk, G. Strasser and T. Mueller, "Microcavity-integrated graphene photodetector," Nano Lett. **12**, 2773-7 (2012).
[6] F. Schedin, E. Lidorlkis, A. Lombardo, V. G. Kravets, A. K. Geim, A. N. Grigorenko, K. S. Novoselov and A. C. Ferrari, "Surface-enhanced raman spectroscopy of graphene," ACS Nano **4** (10), 5616-5626 (2010).
[7] L. Ju, B. Geng, J. Horng, C. Girit, M. Martin, Z. Hao, H. A. Bechtel, X. Liang, A. Zettl, Y. R. Shen and F. Wang, "Graphene plasmonics for tunable terahertz metamaterials," Nature Nanotechnol. **6**, 630-4 (2011).