Efficient Modulation of 1.55 μm Radiation with Gated Graphene on a Silicon Micro-ring Resonator

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Abstract

The gate-controllability of the Fermi-edge onset of interband absorption in graphene can be utilized to modulate near-infrared radiation in the telecommunication band. However, a high modulation efficiency has not been demonstrated to date, because of the small amount of light absorption in graphene. Here, we demonstrate a ~40% amplitude modulation of 1.55 μm radiation with gated single-layer graphene that is coupled with a silicon micro-ring resonator. Both the quality factor and resonance wavelength of the silicon micro-ring resonator were strongly modulated through gate tuning of the Fermi level in graphene. These results promise an efficient electro-optic modulator, ideal for applications in large-scale on-chip optical interconnects that are compatible with complementary metal-oxide-semiconductor technology.

Keywords: graphene photonics, NIR modulator, silicon micro-ring resonator, high on/off ratio.

Large-scale integration of nanoscale electro-optic modulators with high efficiencies and speeds is a key technology required for future optical communications and computing.¹ Achieving high efficiencies is a challenging goal because of the inherently short light-matter interaction lengths in nanoscale photonic circuits. Therefore, there are currently worldwide efforts in finding new materials with ultrastrong electro-optic effects or novel schemes for effectively enhancing light intensities within a small volume.²

Graphene, a sheet of carbon atoms in a hexagonal lattice with photon-like massless and gapless electrons,³⁻⁵ strongly couples with light with universal, wavelength-independent interband absorption ($\sim 2.3\%$ per layer) in the visible range.⁶⁻⁸ This universal absorption can be suppressed, or Pauli blocked, when $2E_f > E_p$, where E_f is the Fermi energy and $E_p = \hbar\omega$ is the photon energy.^{4, 9, 10} In the communication band, the wavelength, λ , of light used is $1.55 \mu\text{m}$ (or 0.86 eV in the photon energy $\sim 0.86 \text{ eV}$); thus, interband absorption in graphene is blocked if $E_f > 0.43 \text{ eV}$ and can be tuned through electric gating.^{4, 10} Such ultrawideband tunability makes graphene a promising platform on which to build active optoelectronic devices for high-speed communications.^{2, 11, 12} Graphene-silicon hybrids have been used recently for electro-optic modulators operating in the telecommunication band, including a silicon waveguide structure¹² and a photonic crystal cavity.² However, they either have a low switching contrast ratio ($0.1 \text{ dB}/\mu\text{m}$)¹² or a relatively low quality factor, which limits their applicability to large-scale on-chip interconnections.²

Here, we combine graphene with a silicon micro-ring resonator to demonstrate a high-efficiency electro-optic modulation through the evanescent mode coupling between graphene and silicon. Micro-ring resonators have been used in various optoelectronic devices, including electro-optic modulators,^{13, 14} filters,¹⁵⁻¹⁷ buffers,^{18, 19} and sensors.^{20, 21} Electro-optic modulation is usually achieved by tuning the resonance wavelength, λ_0 , through free carrier plasma effects in silicon.⁵ It has a small footprint,²² large extinction ratios,^{13, 23} and a very high quality factor^{13, 24} and is suitable for large-scale optical interconnections,²⁵ providing a good platform for integrating graphene. Even with a single atomic layer, graphene can exhibit strong light-matter interaction^{26, 27} and have a significant effect on the resonator due to the great tunability of the Fermi level. We developed a highly efficient electro-optic modulator with a modulation depth of about 40%, which will be useful in large-scale on-chip optical interconnects for optical communications, logic computing, and sensing.

Results

Figures 1a and 1b show schematic diagrams of the graphene-silicon hybrid structure that we fabricated. The Fermi level of graphene and thus the effective index of the hybrid structure is tuned by applying a voltage between the electrodes on graphene and the doped-region electrodes with Al_2O_3 gating dielectrics, as shown in the cross-section of the device (Figure 1b). Figure 1c shows a scanning electron micrograph of the fabricated micro-ring resonator after graphene transfer (see Methods). The graphene layer was characterized using Raman spectroscopy, as shown in Figure 1d. The locations of the G and 2D peaks, the single Lorentzian shape of the 2D peak, the 2D/G intensity ratio, and the near absence of the D peak all indicate a high-quality single layer graphene sample after the transfer and fabrication processes.

Figure 1. (a) Schematic diagram of graphene-modulated silicon micro-ring modulator. (b) Cross-sectional diagram of the modulator corresponding to the red dashed line in (a). Al_2O_3 works as the gate dielectric material. The gate voltage is applied between the bottom n^+ doped silicon slab and graphene layer. (c) Top-view scanning electron microscope picture of the modulator after graphene is transferred on top of the micro-ring area. (d) Raman spectrum of transferred graphene.

Figure 2a shows transmission spectra for devices without graphene (solid lines) and with graphene (dashed lines) with different gap distances between the waveguide and ring resonator. The smallest gap we can get is limited by the fabrication process to be 200 nm. Without graphene, the device with a gap of ~ 200 nm is close to the critical coupling condition and has an extinction ratio greater than 10 dB. The other two devices with larger gaps are under-coupled, and the extinction ratio becomes smaller as the gap increases. With monolayer graphene integrated, the linewidth is significantly broadened and the extinction ratio is decreased. It shows that the photon lifetime in the cavity significantly decreases due to interband absorption in graphene.

Based on the classical photonic circuit model, the transmission spectra can be fit with

$$T(\lambda) = |(t - e^{-r+i\phi(\lambda)}) / (1 - te^{-r+i\phi(\lambda)})|^2, \quad (1)$$

where $t = \sqrt{1 - \kappa^2}$, κ is the coupling coefficient between the straight waveguide and the ring resonator, and e^{-r} and $\phi(\lambda)$ are the loss and phase delay, respectively, in the cavity per round; the loss is determined by the imaginary part and the phase delay is determined by the real part of the effective index, n_{eff} . From this model, together with the coupled mode theory,²⁸ we determined the intrinsic quality factor ($Q_i = 2\pi^2 n_g R / \lambda_0 r$) to be ~ 5000 and the coupling quality factor ($Q_c = 4\pi^2 n_g R / \lambda_0 \kappa^2$) to range from ~ 7500 to ~ 25000 , as plotted versus gap value in Figure 2b and Figure 2c, respectively. Here, λ_0 is the resonance wavelength, R is the ring radius, and n_g is the group index of the cavity. After graphene integration, Q_i is decreased to ~ 1300 , suggesting that the loss from graphene dominates the photon lifetime in the cavity while the coupling quality factor does not change much as expected. Also, from the difference in loss in the ring cavity between before and after graphene integration, we estimated the loss in graphene to be ~ 200 dB/cm for all three devices, which is two orders of magnitude higher than the intrinsic loss of a typical silicon waveguide.

Figure 2. (a) Transmission spectra for devices with different gaps. The solid lines show the spectra without graphene and dash lines show the spectra with graphene. (b) Calculated intrinsic quality factors. (c) Calculated coupling quality factors.

Figure 3a shows transmission spectra at different gate voltages, V_g , for a micro-ring resonator with graphene with a gap width equal to 200 nm. Figure 3b shows the corresponding transmission spectra change $\Delta T / T_0$ at different V_g where T_0 is transmission when gate voltage is 0V and ΔT is the transmission difference between transmission spectrum under certain gate voltage and that without gate voltage *i.e.* $\Delta T = T(V_g) - T_0$. With increasing V_g , the resonance width decreases, and the extinction ratio increases. When the resonance blue-shifts as the gate voltage rises, light with wavelength larger than the resonance will couple lower power into the cavity thus experience lower loss from graphene. Actually, the more blue shift of the resonant wavelength, the lower loss from graphene and the higher transmission will be at the longer wavelength. Thus ΔT is positive at the longer-wavelength side of the resonance, and peaks on the differential transmission spectra of Figure 3b will rise as the V_g increases. The V_g

dependence of transmission at a wavelength of 1555.97 nm is shown in Figure 3c. The transmission at $V_g = 6$ V is about 60% of that at $V_g = 0$ V, corresponding to a modulation depth of $\sim 40\%$. Here the modulation depth is defined as $\Delta T / T_0$ at the wavelength of 1555.97 nm. The measured spectra were fit with Equation 1 to extract the λ_0 and Q_i values while the Q_c value did not change with V_g . Figures 3d and 3e show, respectively, Q_i and λ_0 (compared with the 0 V resonance wavelength) as a function of V_g . An increasing V_g elevates the E_F of graphene to lower interband absorption through Pauli blocking, which in turn increases the photon lifetime in the cavity and the quality factor. As shown in Figure 3e, either an increase or decrease in V_g blue-shifts the resonance wavelength, suggesting that the real part of the dielectric constant of graphene peaks around $V_g = 0$ V and thus any bias lowers the effective index of the waveguide.¹¹ However, limited by the quality of dielectric oxide, the Fermi level of graphene could not be shifted to a higher value to make the graphene almost transparent which is similar as the condition before the graphene transfer shown in solid lines in Figure 2a. Meanwhile, when the graphene was removed by oxygen plasma, the resonance will be shifted back from dashed lines to solid lines shown as in Figure 2 in the experiment.

Figure 3. (a) Normalized transmission spectra at different gate voltages for the ring resonator with a waveguide-ring gap of 200 nm after graphene transfer. (b) Gate-voltage-induced differential transmission spectra at different voltages. A large modulation depth about 40% is observed at $\lambda_0 = 1555.97$ nm (the resonance wavelength at $V_g = 6$ V). (c) Normalized output power change as a function of gate voltage at λ_0 . (d) Calculated intrinsic quality factor and (e) relative resonance wavelength shift defined as the resonance wavelength detuning from the original resonance wavelength at $V_g = 0$ V.

To confirm that the blue-shift of λ_0 and the increase of Q_i of the ring resonator with increasing V_g are solely due to the graphene layer, we developed a theoretical model to quantitatively explain the experimental observations. Gate-dependent complex dielectric constants of graphene have been extensively studied within the random phase approximation and using the Kramers-Kronig relations.^{11, 29, 30} The imaginary part, ϵ_g'' , is characterized by interband and intraband absorption while the real part, ϵ_g' , can be obtained from ϵ_g'' by using the Kramers-Kronig relation. The complex dielectric constant of graphene has the following form¹¹

$$\epsilon_g'(E_p) = 1 + \frac{e^2}{8\pi E_p \epsilon_0 d} \ln \frac{(E_p + 2|E_f|)^2 + \Gamma^2}{(E_p - 2|E_f|)^2 + \Gamma^2} - \frac{e^2}{\pi \epsilon_0 d} \frac{|E_f|}{E_p^2 + (1/\tau)^2}, \quad (2)$$

$$\epsilon_g''(E_p) = \frac{e^2}{4E_p \epsilon_0 d} \left[1 + \frac{1}{\pi} \left(\tan^{-1} \frac{E_p - 2|E_f|}{\Gamma} - \tan^{-1} \frac{E_p + 2|E_f|}{\Gamma} \right) \right] + \frac{e^2}{\pi \tau E_p \epsilon_0 d} \frac{|E_f|}{E_p^2 + (1/\tau)^2}, \quad (3)$$

where d is the thickness of graphene (0.5 nm),³¹ Γ is the interband linewidth broadening (set to be 160 meV through fitting the measured spectra), and the free carrier scattering rate $1/\tau$ can be neglected as it is much smaller than the incident photon frequency, ω .

By using Equations 2 and 3 above to fit the experimental data, we can get the relationship between the n_{eff} of the waveguide and graphene's E_f . Figure 4a shows spectra at different gate voltages together with fitting curves, and Figure 4b shows the extracted E_f value versus V_g . When V_g increases from 0 V to 6 V, E_f increases by ~66 meV, lowering both the real and imaginary parts of graphene's

dielectric constant so that λ_0 blue-shifts and the photon lifetime becomes longer. However, when V_g is negative, there is a noticeable blue shift (Figure 3e) but a much smaller quality factor change (Figure 3d). It indicates a much smaller shift in E_f at negative V_g which is probably due to the poor quality of dielectrics and the residual carriers from carrier puddles in the transferred graphene.^{10, 32, 33} This smaller shift in E_f also yields a tiny modulation at negative V_g as shown in Figure 3c.

Figure 4. (a) Transmission spectra at different gate voltages ($V_g = 0$ V, 2 V, 4 V, 6 V). (b) Extracted Fermi level as a function of gate voltage based on our model.

Our graphene based micro-ring modulator can potentially operate at tens of GHz. In this structure, graphene only needs to be present on top of the micro-ring resonator to have an effect. The modulation speed is limited by the R_sC of the circuit, where R_s and C are the resistance and capacitance of the device, respectively. In our scheme, the fundamental limitation of the device resistance mainly comes from the graphene resistance and the contact resistance; the former is typically several hundred kilo-ohms in our devices, and the latter is several ohms. However, one can reduce the graphene resistance by extending the electrical metal connection to the micro-ring resonator. A very tight gap about $\sim 1 \mu\text{m}$ can in principle be obtained, which will be necessary to eliminate any absorption in the metal. Furthermore, the graphene sheet resistance can be as low as $\sim 125 \Omega/\text{sq}$ in a highly doped region. Thus, the graphene serial resistance can be reduced to a few ohms. The capacitance due to the graphene layer can be calculated as

$C = \epsilon_0 \epsilon_d A_{gra} / d \approx 0.1$ pF in the tight gap configuration, where ϵ_d ($= 9.34$) is the relative permittivity of Al_2O_3 , ϵ_0 is the vacuum permittivity, and d ($= 25$ nm) is the thickness of Al_2O_3 . Hence, the speed, taken as $1/2\pi R_s C$, can be as large as ~ 80 GHz by taking $R_s \sim 20 \Omega$.

In conclusion, we have demonstrated an active micro-ring modulator based on graphene. By using this high- Q resonator, strong amplitude modulation with a depth as large as $\sim 40\%$ was achieved. With better quality gating dielectric layer, we should be able to largely tune the Fermi level of the graphene and thus significantly enlarge the modulation depth to be >10 dB. Its operation speed is also expected to be up to tens of GHz by better device fabrication and higher graphene quality. Its footprint is significantly reduced to fit large-scale on-chip interconnections, which will find applications in optical communications, imaging, signal processing, and sensing.

Methods

Device Fabrication. The micro-ring resonator was initially fabricated using the OPSIS service, through a CMOS photonics foundry at the Institute of Microelectronics of Singapore.³⁴ The fabrication process started with a silicon-on-insulator wafer, consisting of a 220-nm thick top silicon layer and a 2- μm thick buried oxide layer. Rib waveguides with a 500-nm width, 220-nm height, and 90-nm slab thickness were used to construct the photonic circuit, in which only quasi-TE mode was supported.³⁵ A micro-ring resonator with a diameter of 10- μm was side-coupled to the straight waveguide. Inverse tapers with 180-nm wide tips were integrated for input and output terminals of the waveguide to enhance the coupling between the waveguide and tapered lens fibers.³⁶ A deep-UV lithography process was used first to define the device pattern, which was then etched into the silicon layer by inductively coupled plasma etching. Following the etching process, a n^+ doping region was formed outside the ring, as illustrated in Figure 1b, by patterned ion implantation. The gap between the n^+ doping region and the ring waveguide is set to be 1.5 μm to eliminate the effect on silicon waveguide from the gate voltage. A 2.1- μm thick SiO_2 layer was then deposited onto the wafer using plasma-enhanced chemical vapor deposition. Then vias

were opened on the implanted area, and a 2- μm thick aluminum layer was sputtered and etched to form electric connections to the doping region. A 1.8 μm dry etch and 0.5 μm wet HF etch was followed to open a bare silicon area in the device region. We then deposited a 25-nm layer of Al_2O_3 in the bare silicon area as the electrostatic gating by using electron beam evaporation. Chemical vapor deposition (CVD) grown graphene from the copper foil was transferred onto this device using standard transfer techniques.³⁷ The transferred graphene layer was typically p-doped. Graphene was then patterned by electron beam lithography and oxygen plasma to avoid contact with the aluminum pad on the n^+ doping region. The perimeter of the ring is about 31.4 μm and the effective area covered by graphene is 15.7 μm^2 . Finally, a 30-nm Ti/Au electrode on graphene was deposited through electron-beam lithography and a lift-off process.

Graphene Transfer. The graphene layer was grown by chemical vapor deposition (CVD) on copper foil and then transferred onto a SiO_2/Si substrate using a Poly(methyl methacrylate) (PMMA) assisted wet-transfer technique. In this transfer process, first a PMMA layer was spin-coated on graphene on the copper foil, and the copper foil was then etched away in iron(III) chloride (FeCl_3) solution. The PMMA-graphene film floating on the etchant was moved to distilled water several times to rinse the etchant residue and then scooped by the substrate. The chip was dried in air overnight, and the PMMA was removed by acetone and the whole chip was cleaned by isopropyl alcohol (IPA).

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