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Characterization of Optical Absorption and Polarization Dependence of Single-Layer Graphene Integrated on a Silicon Wire Waveguide

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Optical absorption efficiency of graphene integrated onto a silicon photonic platform was characterized at around 1.55-μm optical telecommunications wavelength. Micro-Raman spectroscopy performed after the completion of all fabrication processes confirmed that transferred chemical-vapor-deposited graphene is a single layer (>90% coverage) without any significant damage. Absorption efficiencies of the single-layer graphene (SLG) on a silicon wire waveguide, obtained by measuring different lengths (cutback method) of the SLG from 2.5 to 200 μm, were 0.09 and 0.05 dB/μm for TE- and TM-polarized light. The unusual relationship in the polarization dependency can be explained by strong surface-plasmon-polariton support in the TM mode.

Graphene, a carbon-based two-dimensional material, has attracted much attention since the discovery of exfoliation from bulk graphite. Several years after this discovery, graphene research spread to photonics fields, and many fruitful experimental results with a solid theoretical background have been reported, such as graphene photodetectors, polarizers, and modulators. Graphene has been chosen for such research because of its amazing electrical and optical features, such as extremely high mobility, tunable band gap (with bilayer), huge optical absorption, perfect independence from wavelength, and high nonlinearity. Very recently, graphene has been integrated on optical waveguides made of poly(methyl methacrylate) (PMMA). The key advantage of such integration is that the propagation along the direction of dielectric waveguide tremendously enhances the interaction between electromagnetic waves and one-atom-thick graphene. However, with the micrometer-order polymer core (5–9 μm) in that study, the evanescent electrical field was not strong enough to achieve this aim. Indeed, a 7-mm-long PMMA waveguide was required in order to obtain an extinction of 10–50 dB, even with multilayer graphene (approximately 10 layers). To solve the problem, Liu et al. proposed the new concept of integrating a graphene modulator on a silicon waveguide. An extremely small (40 μm) electro-absorption optical modulator was achieved by controlling the Fermi level in graphene, indicating that the combination of silicon photonics technology and graphene material would pave the way to ultrahigh-bandwidth and compact optical links. However, they did not cover the fundamental optical characteristics of graphene on a silicon photonic platform, such as the dependence of absorption on graphene length (known as the cutback method) and polarization mode. In this paper, we investigate them in detail as a step toward future device designs with graphene.

The fabrication process is illustrated in Fig. 1. The device fabrication started from a 4-in. silicon-on-insulator (SOI) wafer with SOI and buried oxide (BOX) thicknesses of 250 nm and 3 μm. After 50-nm-thick oxidation and 100-nm-thick plasma-enhanced chemical CVD (PECVD) of SiO2 as a hard mask on the SOI layer, a resist masked pattern was formed by electron-beam (EB) lithography. Precisely, silicon wire (also called “channel”) waveguides were fabricated by electro cyclotron resonance-reactive ion etching (ECR-RIE). The wire-type silicon waveguide has a width of 400 nm, and a height of 200 nm. These dimensions were selected because they satisfy the single-mode propagation condition, as well as yield very strong evanescent electrical fields at TE and TM polarizations. To enhance the fields further, we didn’t form an overclad layer on the top in order to make a refractive index difference large. The An value reaches about 2–2.5 around the silicon core. Calculated electrical optical mode profiles for each polarization are shown in Fig. 2. As an example of a simple estimation without integrated graphene, the filling factors (percentages of the optical intensity in Si core) are 65% in the TE mode and only 21% in the TM mode. These profiles and values are obtained from a mode solver in FIMMWAVE (Photon Design).

After replacing the acetone with isopropyl alcohol, we baked PMMA on the top layer was dissolved with acetone. After several times with deionized water, and then directly transferred them two times side by side to cover whole the silicon waveguides pattern on the wafer. After PMMA had been spin coated and soft baked at 170 °C, the Cu substrate was etched in 34–36% ferric chloride (FeCl3) solution for over 12 h at room temperature. The samples were rinsed several times with deionized water, and then directly transferred in the deionized water onto the 4-in. wafer. The residual PMMA on the top layer was dissolved with acetone. After replacing the acetone with isopropyl alcohol, we baked the wafer on a hotplate at 100 °C. Finally, we formed a 1.5-μm-thick photosresist and then used photolithography and RIE with an O2 gas flow to define graphene patterns. Figure 1 also shows a cross-sectional schematic and micrograph of the device after all of the fabrication steps mentioned above were completed.

Figure 3 shows a schematic of the graphene integrated on a silicon wire waveguide. We used an S-shape design to form an offset of 127 μm, which makes the optical alignment process clear. The silicon wire waveguide length was set to 6 mm, including 3-μm-wide tapers at the input and output surfaces. The tapers are 300 μm long. For graphene patterns,
the width \((W)\) was fixed at 15\(\mu m\), and the lengths \((L)\) were 2.5, 5, 10, 20, 30, 50, 80, and 200\(\mu m\). A microscope image of the silicon wire waveguide and integrated SLG is shown in Fig. 4. Here, we selected the shortest graphene length of 2.5\(\mu m\) to demonstrate that our fabrication process enables us to define sufficiently narrow patterns with precision. The expanded image on the right shows the micro-Raman spectroscopy with a pump light of 532 nm. Dashed white lines correspond to the waveguide’s edges.

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G and 2D bands were observed at Raman shifts of 1592 and 2695 \(cm^{-1}\), and little D band was observed around 1350 \(cm^{-1}\). The \(I(G)/I(2D)\) intensity ratio is approximately 0.25, which suggests that the graphene is a single layer.\(^{13,14}\) At point 2, the spectrum indicates that the transferred graphene is perfectly etched in the unmasked region. Additionally, we also confirmed that the coverage of the SLG is over 90%.

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**Fig. 1.** (Color online) Fabrication processes, cross-sectional schematic and microphotograph after all fabrication processes for integrated graphene on a silicon photonics platform.

**Fig. 2.** (Color online) Calculated optical mode profiles for (a) TE and (b) TM polarization modes in a simple silicon wire waveguide core of 400\(\mu m\) (width) \(\times\) 200\(\mu m\) (height).

**Fig. 3.** (Color online) Schematic of the top view of SLG integrated on a silicon wire waveguide. The waveguide is connected to 3-\(\mu m\)-wide tapers at the input and output surfaces.

**Fig. 4.** (Color online) Microscope image of the silicon wire waveguide and integrated SLG. The shortest graphene length of 2.5\(\mu m\) is shown here.

**Fig. 5.** (Color online) Measured micro-Raman spectra at each point in Fig. 4. At measurement point 1, the peaks of G and 2D band were measured at a Raman shift of 1592 and 2695 \(cm^{-1}\). Little peak of D band is observed around 1350 \(cm^{-1}\).
A schematic of the optical measurement setup for the absorption efficiency is shown in Fig. 6. The efficiency was characterized with a C-band amplified spontaneous emission (ASE) light source (1530–1565 nm), which was used to avoid reflection and resonance between input and output surfaces. We employed a lensed fiber pair, which has a 3.3-\(\mu\m\) mode field in diameter, to couple the 3-\(\mu\m\)-wide tapered waveguides at each surface. After polarization filtering of the ASE light source with an in-line polarizer, the polarization state at the input surface was adjusted with a polarization controller. A high-input intensity may cause saturable absorption in graphene\(^\text{15,16}\) as well as two-photon-absorption-induced free-carrier absorption in a silicon wire waveguide.\(^\text{17,18}\) We therefore set the power at the input surface at around or lower than 10 mW to avoid undesired nonlinear optical effects. Before measuring the graphene absorption, we checked the propagation and coupling losses of reference silicon wire waveguides (without graphene integration) for the two polarization modes. The results were 9.0 dB/cm and 7.5 dB/facet for the TE mode and 7.0 dB/cm and 15.5 dB/facet for the TM mode.

Figure 7 plots the measured absorption efficiencies at each graphene length in TE (blue squares) and TM (red circles) polarizations. All plotted values in Fig. 7 have already been subtracted by intercepts of the two polarization modes (which is equivalent to normalization by 6-mm propagation and coupling losses in the silicon wire waveguides). Note that the measurements of both the TE and TM modes were performed in the same waveguides, so that very obvious correlation between the two polarization modes can be found in the absorption efficiencies in the plots of Fig. 7. The linear fitting lines correspond to 0.09 dB/\(\mu\m\) for the TE mode (blue line) and 0.05 dB/\(\mu\m\) for the TM mode (red line). The measurement wavelength was around 1.55 m\(\mu\m\) (C-band ASE light).

![Fig. 6.](image1) (Color online) Schematic of absorption efficiency measurement setup.

![Fig. 7.](image2) (Color online) Absorption efficiencies in TE (blue squares) and TM (red circles) polarization modes. The linear fitting lines correspond to 0.09 dB/\(\mu\m\) for the TE mode (blue line), and 0.05 dB/\(\mu\m\) for the TM mode (red line). The measurement wavelength was around 1.55 m\(\mu\m\) (C-band ASE light).

![Fig. 8.](image3) (Color online) Normalized transmission spectra (left axis) of a 6-mm-long silicon wire waveguide without (Si WG only) and with 200-\(\mu\m\)-long graphene (Si WG w/graphene): (a) TE mode and (b) TM mode. The difference between them (Difference) (right axis) indicates optical absorption induced by graphene integration.
Here, we first discuss the values by comparing them with previous reports, which described absorption in SLG or few-layer graphene on a single-mode fiber (SMF) and PMMA waveguide. Our values are at least four times higher than the previous ones at each polarization mode (e.g., 0.02 dB/μm at TE and 0.01 dB/μm at TM for the SMF; 0.006 dB/μm at TE and 0.004 dB/μm at TM for the PMMA waveguide). This obviously reveals that, in our device, a very strong interaction occurred between the electric field and SLG on a silicon-based submicrometer waveguide. Since we cannot compare the absorption efficiency at each polarization mode on a silicon waveguide (modulator) at present, we only show the values for the TE mode here, which were 0.09 dB/μm for SLG, and 0.16 dB/μm for double-layer graphene. These values are very close to ours in the same conditions (polarization mode and number of layer). All previous results shown above were obtained by using 1.5-μm telecommunications-band light sources, but none of those studies used the cutback method. That is, each value was only estimated by one parameter in graphene length; therefore, the credibility of the values is not strong enough. In a new report describing concept similar to ours (but with the SLG integrated on a planar hydrogen silsesquioxane (HSQ), not on a silicon wire waveguide directly), a Mach–Zehnder interferometer and the cutback method were used to determine the absorption efficiency by changing the graphene length. The value on HSQ is 0.05–0.11 dB/μm at the TE mode. However, there is no mention of polarization dependence for the TM mode. Additionally, the p-type carrier concentration and Fermi level were estimated to be ~4 × 10^{12} cm^{-2} and ~0.23 eV; therefore, the absorption occurred with interband transition (ℏω/2 > |E_F|), which is totally different conditions from ours, as we describe below. Next we discuss the validity of the relationship between the two polarization modes. The evanescent field of light and optical overlap in the TM mode are much larger than in the TE mode due to the flattened-shaped waveguide. Therefore, the relation between the absorption efficiencies in Fig. 7 should exactly follow this in theory. However, the measurement result was the opposite, which indicates that surface plasmon polariton (SPP) in the TM mode strongly contribute to the low-absorption propagation. Under this supposition, the value for the TM mode would mainly come from the mixture of absorption and scattering loss on the surfaces. Additionally, although the graphene absorption dependence on wavelength in the TE mode [Fig. 8(a)] is reasonable for mode profile expansion as the wavelength increases, the dependence in the TM mode [Fig. 8(b)] is not the case. This reveals the existence of an unconventional propagation mode in the graphene-integrated silicon waveguide.

The theoretical mechanisms and conditions of SPP propagation in graphene are described in Refs. 21 and 22. On the basis of these analyses, we believe that the Fermi level in our integrated graphene shifts from the Dirac point and that it reached to around or over the half of photon energy of input light, which causes intraband absorption (ℏω/2 < |E_F|) in graphene. As a result, the highly doped graphene can act as a metal-loaded plasmonic waveguide in this case. The supposition can also be experimentally confirmed from the G- and 2D-band peaks in the Raman shift as shown in Fig. 5 (measurement point 1). As the peaks were observed at 1592 and 2695 cm^{-1}, the p-type concentration and Fermi level should be around 1×10^{11} cm^{-2} and over ~0.4 eV as described in Ref. 23. This is a very reasonable explanation for the opposite relationship in our measurement results, because photon energy of the input light source was 0.8 eV (∤=1.55 μm).

In summary, we investigated the absorption efficiency of SLG integrated on a silicon photonics platform. The measurement results reveal that TE-mode absorption is approximately 1.8 times higher than that of TM-mode. The unusual relationship in the polarizations dependencies can be explained by strong SPP support in the TM mode. We hope these fundamental characterizations will help in future development of integrated electrical and optical circuits as a first step, by using group-IV materials such as silicon, germanium, and carbon.

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