Graphene, which is composed of a hexagonal lattice of sp2 carbon atoms arranged in a single sheet and exhibits extraordinary electrical and optical properties,6,7 was previously proposed as a novel platform for integrated optoelectronics and terahertz devices.3

Indeed, electrical control of resonances has been demonstrated at infrared frequencies using large-area graphene. Plasmonic structures fabricated on graphene enhance the interaction of the incident optical field with the graphene sheet, and the impact of graphene is much stronger at mid-infrared wavelengths. Full-wave simulations, where graphene is modeled as a 1 nm thick effective medium, show excellent agreement with experimental results.12

Graphene exhibits a unique linear dispersion relation as shown recently, a closely related approach was applied to electrically control plasmonic resonances in gold nanorods.20

Here we show that it is indeed possible to electrically tune the loss of a plasmonic resonance wavelength, preferably by applying an electrical bias. This is achieved by employing metal nanostructures that are resonant at a particular optical wavelength. Dynamic switching of a plasmonic resonance may become large and makes graphene unattractive as a plasmonic material.18,19 Alternatively, the optical loss in graphene could instead be used as an advantage in order to vary the loss of a plasmonic resonance. Here we demonstrate electrical control of a plasmonic resonance at infrared frequencies using large-area graphene. Plasmonic structures fabricated on graphene enhance the interaction of the incident optical field with the graphene sheet, and the impact of graphene is much stronger at mid-infrared wavelengths. Full-wave simulations, where graphene is modeled as a 1 nm thick effective medium, show excellent agreement with experimental results.12

The resonance wavelength of the nanostructure can be tuned by varying the size, shape, and material properties of the structure. However, in some applications like integrated modulators, switches, and sensors, it is desirable to have the ability to dynamically tune the resonance. Here we show that it is indeed possible to electrically tune a plasmonic resonance wavelength, preferably by applying an electrical bias. This is achieved by employing metal nanostructures that are resonant at a particular optical wavelength. Dynamic switching of a plasmonic resonance may become large and makes graphene unattractive as a plasmonic material.18,19 Alternatively, the optical loss in graphene could instead be used as an advantage in order to vary the loss of a plasmonic resonance. Here we demonstrate electrical control of a plasmonic resonance at infrared frequencies using large-area graphene. Plasmonic structures fabricated on graphene enhance the interaction of the incident optical field with the graphene sheet, and the impact of graphene is much stronger at mid-infrared wavelengths. Full-wave simulations, where graphene is modeled as a 1 nm thick effective medium, show excellent agreement with experimental results.12

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Supporting Information

* * *

grown, a 100 nm layer of dry thermal oxide. A large-area graphene
60 nm Au strips on a lightly doped Si substrate with a previously
contacts were deposited by e-beam evaporation of 10 nm Ti/

generate an electron
captures the response from interband transitions, which exhibit a
carrier (intraband) response of graphene. The second term
Boltzmann constant. The
T
Drude relaxation rate,
the graphene thickness,
then the resonance decays by direct emission of e
resonance frequency is above the graphene interband threshold,
interaction with the graphene sheet. Hence, if the plasmonic

accompanied by a local
e
field enhancement that causes enhanced

Fl
Fl
ff
ff
Information Figure S1). The calculated e
functions at three di
ergetic dielectric
interband losses at 0 K. The predicted optical conductivity is
consistent with experimental measurements. 22

demonstrating plasmonic resonance tuning. A gate voltage (

is applied through the silicon back-gate. The resistance between

dr"

−
dr"

fi
fi

G
G

−
−
1013 cm
1013 cm

source
source

drain
drain

dr"
dr"

nanostructures. We observed changes in the graphene carrier

concentration caused by additional electron doping due to the

metal (see Figure 2b). At the same time, the electrical char-

acteristics remained qualitatively similar to those of bare

graphene except for a shift in the Dirac point.

Figures 1a and 2b show a

domain discontinuities can be observed. A Fourier transform

different carrier concentrations are shown in

Figure 1.

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2012, 12, 5202

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Figure 2.

 Nano Lett.
2012, 12, 5206
infrared (FTIR) spectrometer with a microscope was used to optically characterize the plasmonic resonance behavior. All the optical measurements were performed in ambient air at room temperature. The experimentally measured optical transmission spectra of the resonant structures on top of the graphene are shown in Figure 3d. We observe a strong resonance that exhibits a red shift in resonant wavelength with increasing dimensions.

To gain further insight into the experimentally obtained spectra, we performed full-wave numerical simulations using 3D spatial harmonic analysis (SHA). The sample was modeled with four layers: silicon, silicon dioxide, graphene, and gold bowtie antennas with corresponding material properties and geometries taken from experiments. We treated graphene as an effective medium with a thickness of 1 nm, and we calculated its dielectric function using the optical conductivity of graphene (eq 1). To investigate the impact of gate voltage, we used the carrier concentration of the graphene sheet as a fitting parameter in our numerical simulations.

The carrier concentration of graphene can be realistically tuned between $1 \times 10^{12}$ and $3 \times 10^{13} \text{ cm}^{-2}$, and hence $E_F$ can be varied in the range of $0.12$ to $0.64 \text{ eV}$. Therefore, we can expect a significant impact from the gate voltage on the resonances at IR wavelengths. To investigate this dependence we compared the optical transmission spectra from three structures (Bowtie 1−3) fabricated on the same device. We found that the effect of the gate voltage on the resonance increases as the resonant frequency shifts further into IR as shown in Figure 4. We observed that the change for graphene with bowtie antennas was much higher than the approximately 1% change in a bare graphene device (shown in Supporting Information Figure S2). This is consistent with the results reported in the published literature, confirming that plasmonic structures do indeed enhance the interaction of light with graphene.

The optical transmission spectrum for a resonance at 4.5 $\mu$m is shown in Figure 5a where we see an observable variation of transmittance with gate voltage. At the Dirac point ($\Delta V = V_G - V_{DP} = 0$), the interband transitions are allowed at all frequencies, leading to a broader resonance. However, with increasing carrier concentration ($\Delta V < 0$) some of the interband transitions are forbidden, leading to narrower line width. The asymmetric influence of graphene on the line shape reflects the changes in the dielectric function plotted in Figure 1b. The full-wave numerical electromagnetic simulations show remarkable agreement with the experimental results using only the carrier concentration in graphene as a fitting parameter. We observe up to 210 nm decrease in resonance line width.
E bias shows the precise electrical control of the resonance. (c) The narrowing of the width of the resonance with gate since both real and imaginary parts of permittivity of graphene are tuned and tuning of plasmonic resonances control the damping of plasmonic resonances in the mid-infrared.

Additional information on choice of e

Figure 5.

On the basis of simulations it has been suggested previously significantly change the transmittance when the resonant electric field is parallel to the graphene sheet.31 In contrast, we observe a small blue shift in the resonance. This is not surprising as the absorption due to graphene, we also see a full-wave simulations (dashed lines) pertaining parameter produce fi

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REFERENCES

441.

N. M.; Palit, S.; Smith, D. R.; Di Ventra, M.; Basov, D. N.


F.; Hillenbrand, R.; Koppens, F. H. L.

Nanoscale 2011, 3, 1025.

458.

Bonaccorso, F.; Sun, Z.; Hasan, T.; Ferrari, A.

Nat. Mater. 2009, 8, 630.

Gorbachev, R.; Grigorenko, A.; Geim, A.; Ferrari, A.; Novoselov, K.

Science 2011, 337, 1518.

J.; Averitt, R. D.


622.

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**Supplementary Online Material**

Graphene is a 0.35-nm-thick monolayer of sp² carbon atoms. In numerical simulations, we treated graphene as an effective medium with a thickness of 1 nm. This value is reasonable considering the inhomogeneities in CVD-grown graphene, which can lead to a graphene layer that is thicker than the ideal thickness. We also performed simulations with the effective thickness as a parameter in order to verify the impact of this assumption on the final results. We found that the simulation results converged for an effective graphene thickness of 1 nm or below (see Figure S1). We also show simulations on control sample without any graphene in Fig S1. As expected and reported elsewhere, adding graphene causes the resonance to be weaker and broader (c.f. Zou Y et al., Opt. Express(2012) and Kim J et al., ArXiv(2012) which are references 32 and 21 in the paper).
Figure S1. In numerical simulations, atomically thin graphene is assumed to have an effective thickness \( t_g \). The plotted simulation results show convergence for effective thickness of graphene below 1 nm. A carrier concentration of \( 1 \times 10^{12} \text{ cm}^2 \) and Drude scattering rate of \( 1 \times 10^{-13} \text{s} \) were used in calculations.

In the main text, we discussed the enhanced interaction of light with graphene in the presence of bowtie antennas. We also performed optical transmission measurements on a device without bowtie antennas. These results revealed much smaller changes in transmittance of up to only 1\%, as shown in Figure S2. The incident photon is most sensitive to carrier concentration in graphene when its energy is around \( 2E_F \). Therefore, we see a matching peak in the normalized transmission spectrum. A gate voltage of 30V results in \( 2E_F \) peak at 0.5eV, which corresponds to a carrier density of \( 4.6 \times 10^{12} \text{ cm}^{-2} \). At low gate voltages we expect the carrier concentration to be below \( 1 \times 10^{12} \text{ cm}^{-2} \). We suspect that the peaks are not clear at low voltages because of the lower peak amplitudes and charge inhomogeneities in graphene.
Figure S2. Optical transmission measurements for a device without bowtie antennas. The change in the observed transmittance is about 1% and is far smaller than the changes observed with bowtie antennas as shown in Figures 4 and 5 of the main text.