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Plasmonic effect for photoluminescence enhancement in graphene/Au/ZnO hybrid structures: dependence on the surface lateral period of the Au layer

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Abstract

The basic physics of the plasmonic effect of graphene in the UV region is fascinating but is not well understood. In this work, the influence of surface lateral period on the plasmonic effect of graphene for photoluminescence (PL) enhancement in graphene/Au/ZnO hybrid structures at a laser excitation wavelength of 325 nm is studied. In graphene/Au/ZnO hybrid structures, the Au layers act as corrugated surfaces, and their lateral period varies with the layer thickness. A reduction in PL intensity due to graphene was observed in the graphene/ZnO hybrid structure, and this was attributed to electron transfer from the ZnO to the graphene. The electron transfer was confirmed by a 10 cm −1 redshift for the 2D Raman peak of graphene in graphene/ZnO in comparison to that for graphene/SiO2(300 nm)/Si. In contrast, an enhancement in PL intensity by the graphene was observed when an Au layer was inserted between the graphene and the ZnO, and the enhancement ratio strongly depended on the surface lateral period of the Au layer. This enhancement is explained by effective excitation of the plasmon in the graphene at the momentum matching condition while the corrugated Au surface provides effective momentum compensation for excitation of the plasmon by the incident light in the graphene.

Introduction

Graphene has many unique and excellent properties arising from its strictly 2D structure, such as high carrier mobility, high mechanical strength, tunable band gap, and efficient and wide range of plasmonic characteristics [1–3]. It is an important component for fabrication of various functional hybrid structures with semiconductor materials, which exhibit excellent photoelectric properties and unique physical mechanisms [4–8]. Recently, rapidly increasing interest is focused on the plasmonic effect of graphene similar to that induced by metal.

Zinc oxide (ZnO) can be a strong candidate material for UV optoelectronic devices due to its wide direct bandgap (3.37 eV), strong exciton binding energy (60 meV), and high thermal ionization energy at room temperature (RT) [9]. Several studies have been concerned with seeking to improve the emission efficiency of ZnO [10–12]. Hwang et al showed that covering the corrugated ZnO film with graphene can dramatically enhance the luminescence of ZnO under 325 nm laser excitation [13]. These workers attributed the enhancement effect to the resonant coupling of the plasmon in the graphene with the emitted photons of the ZnO. Thereafter, the enhancements of PL in graphene-coated ZnO nanorods and ZnO microbelts [14–17], ZnO nanorods grown on graphene [18, 19], and ZnO on reduced graphene oxide [20] have been reported with the same interpretation of the phenomena, namely, that the plasmonic effect of the graphene enhances the PL. However, an opposite effect has also been reported in several studies. Reductions in PL were observed in ZnO
nanostructure/reduced graphene oxide [21, 22], graphene/ZnO nanocomposites [23, 24], and other graphene-based hybrid structures, such as PbS QDs/graphene [8], graphene/GaN [25], and CdSe/ZnS QDs/graphene [26]. The reduction in PL was explained in terms of electron transfer or energy transfer from the semiconductor materials to the graphene [26].

The above observations pose several questions. Why does graphene exhibit contrasting effects regarding the PL properties of the hybrid structures? Do the above effects coexist in the same hybrid structures? What are the key factors affecting the PL properties of the hybrid structures? Clarifying these points would have great significance for the application of graphene in hybrid structures. Additionally, the proposed plasmonic effect of graphene for PL enhancement in graphene/ZnO structures is subject to ongoing debate, due to a paucity of experimental and theoretical verification studies for the plasmonic effect of graphene in the UV region. It is well known that plasmon-photon coupling requires suitable matching conditions for both energy and momentum [27]. In a previous study, the plasmons of graphene were resonantly excited by the 325 nm laser which achieved energy matching in the graphene/GeSi QDs hybrid structure [28]. However, few studies have been reported and offered profound insight on the momentum matching for plasmon excitation under UV light for a graphene/semiconductor structure. Liu et al have observed the enhanced PL from the graphene/Au nanoparticles (NPs)/ZnO microwire structure and stated that the Au NPs with 1–2 nm diameter act as a corrugated surface on ZnO microwire for momentum modulating [29]. Moreover, Raman spectroscopic measurement is an integral part of graphene research [30]. The intensity and position of the G and 2D Raman peaks may provide valuable information on defects, doping, and the number of layers [31]. Also, it has been reported that the positions of the G and the 2D peaks vary as a function of the dopant concentration [31–33]. Thus, the electron transfer from the ZnO to the graphene, which results in PL reduction, would be confirmed directly by a change in the Raman peak positions.

In this paper, graphene/ZnO hybrid structures containing different thicknesses of Au insertion layers were fabricated, where the Au layers act as corrugated surfaces for modulating the momentum matching for excitation of plasmon in graphene [34], since the surface lateral period of the Au layer varies with thickness. Systematic studies on the PL properties of the graphene/Au/ZnO hybrid structures under 325 nm laser excitation were performed. A reduction in the PL intensity due to graphene was observed in the graphene/ZnO hybrid structure, which was attributed to electron transfer from the ZnO to the graphene. The electron transfer was confirmed by a 10 cm\(^{-1}\) redshift for the 2D Raman peak of graphene/ZnO in comparison with graphene/SiO\(_2\)(300.0 nm)/Si. In contrast, an enhancement in PL intensity by the graphene was observed when an Au layer was introduced to the structure. Also, the enhancement ratio strongly depended on the surface lateral period of the Au layer, providing evidence that the PL enhancement results were derived from the effective excitation of plasmon in the graphene by momentum matching while the corrugated Au surface provides an effective momentum compensation for the excitation of the plasmon by the incident light in the graphene.

**Experimental section**

**Materials preparation and processes**

Uniform ZnO single crystal (SC) wafers with thickness about 0.5 mm were used as substrates. Thin film Au layers of varying thicknesses (1.0, 2.0, 2.5, 3.0, 5.0, and 10.0 nm) were fabricated on the ZnO by electron beam evaporation at RT with a deposition rate of 0.03 Å s\(^{-1}\). And the vacuum is lower than 5 × 10\(^{-7}\) Torr during the evaporation. High-quality uniform monolayer graphene was grown on a thick (25 μm) Cu foil by a chemical vapor deposition method. The grown graphene was cleaved into small pieces which were then transferred onto the surfaces of SiO\(_2\)(300.0 nm)/Si, ZnO, Au/ZnO, and SiO\(_2\)(2.0 nm)/ZnO by a conventional PMMA-mediated method, respectively. As shown in figure S1 (available online at stacks.iop.org/MRX/8/055902/mmedia), the transfer process consisted of the following steps. A PMMA solution was spin-coated onto the graphene/Cu foil and then allowed to dry at 120 °C for 15 min. Then, to etch the Cu substrate, the PMMA/graphene/Cu construct was immersed in 0.4 g ml\(^{-1}\) FeCl\(_3\) solution. After the Cu foil had been completely removed, the PMMA/graphene was rinsed repeatedly with deionized (DI) water, then transferred onto the target substrate. The sample was dried at 70 °C for 20 min to remove the residual water sandwiched between the PMMA/graphene and the target substrate. Subsequently, the PMMA layer was removed by acetone, and the sample was rinsed with methanol and DI water, and drying with blowing nitrogen gas. After the sample underwent the last few steps, the graphene firmly remained on the target substrate, confirming a high-quality interface between the graphene and the target substrate.
Measurements
Structure and charge doping of the graphene were characterized by Raman spectrometry under 532 nm laser excitation. The surface morphologies of the samples were characterized by atomic force microscopy (AFM) in tapping mode. The PL spectra were measured at RT with a 325 nm He-Cd laser as the excitation source. The transmission spectra of the graphene and the Au layer were obtained by coating a graphene or an Au layer on a quartz glass substrate.

Results and discussion
The surface morphology of the ZnO and a schematic of the graphene/ZnO structure are presented in figure 1(a). The ZnO had a very smooth surface with a roughness of about 0.19 nm. In the hybrid structure, the region covered with graphene is referred to as the single-layer graphene (SG) region, while the region not covered with graphene is referred to as the non-graphene (NG) region. The PL spectra in both the SG and the NG regions were measured under 325 nm laser excitation, as shown in figure 1(b). From inspection of the spectra, distinct emission peaks are located at 375 nm and relatively weak visible emission bands can also be discerned, which correspond to the near-band-edge emission and the defect-related emission of ZnO substrates, respectively, indicating a high crystalline quality for ZnO. The intensity of PL in the SG region is reduced significantly, compared with that in the NG region, with reductions of about 34% for the UV emission peak and about 20% for the visible emission band. The reductions in emission in excess of 20% could not be caused by the absorption of graphene given that the transmittance of graphene in the UV-visible band is between 94% and 98%, as shown in figure 1(c).

As shown in figure 2(a), the 2D and G Raman peaks of the graphene are very sharp with an intensity ratio, $I_{2D}/I_G$, of over 2, demonstrating the monolayer nature of the graphene [35, 36]. The AFM image of the graphene on SiO$_2$(300.0 nm)/Si substrate is shown in figure S2. The height difference between the surface of the graphene and the substrate is about 0.80 nm, which is roughly close to 0.67–0.77 nm, the height of the monolayer graphene on the substrate reported in the literature [37–39]. Interestingly, the position of the 2D Raman peak for the graphene on ZnO is located at about 2680 cm$^{-1}$ (upper curve), indicating a 10 cm$^{-1}$ redshift in comparison with the 2690 cm$^{-1}$ (black vertical bar) for the pristine graphene on SiO$_2$(300.0 nm)/Si. This redshift may be

Figure 1. (a) AFM image of the ZnO and schematic of the graphene/ZnO structure. (b) PL spectra from the SG and the NG regions in the graphene/ZnO under 325 nm excitation. The insert shows the enlargement of a part of the spectra. (c) Transmittance spectrum of graphene in the UV-visible band.

Figure 2. (a) Raman spectra of graphene in the graphene/SiO$_2$(2.0 nm)/ZnO and graphene/ZnO. The black vertical bars show the position of the G (1588 cm$^{-1}$) and 2D (2690 cm$^{-1}$) peak of graphene in graphene/SiO$_2$(300.0 nm)/Si. UV band PL spectra from the SG and the NG regions in (b) graphene/SiO$_2$(2.0 nm)/ZnO and (c) graphene/ZnO under 325 nm excitation.
attributed to the unintentional electron doping in the graphene due to electron transfer from the ZnO to the graphene [31, 40]. An increase in the electron density of graphene shields ions in the lattice and weakens the interaction among the neighboring lattice ions on the one hand, and causes the expansion of the lattice on the other hand, both of which will cause phonon softening [31, 41, 42]. Thus, the reduction in PL intensity of ZnO by the graphene would be attributed to this electron transfer channel. When the hybrid structure was excited by 325 nm laser, the photoexcited electrons in the conduction band of ZnO will transfer to the graphene through this channel, resulting in a reduction in the radiation recombination in ZnO. A spacing smaller than 1.0 nm between the graphene and the ZnO is very important to making electron transfer occur [37, 43–45]. To further confirm the electron transfer mechanism, a 2.0 nm thick SiO2 layer was inserted between the graphene and the ZnO as a spacer layer. The surface morphology of the SiO2/ZnO is presented in figure S3. Its roughness is about 0.19 nm, similar to that of bare ZnO. With reference to the Raman spectrum in figure 2(a) (bottom curve), no significant Raman peak shift occurred in comparison with that for the pristine graphene on SiO2(300.0 nm)/Si (black vertical bars), implying that the electron transfer from the ZnO to the graphene was blocked by the 2.0 nm thick SiO2 layer. In this case, the PL intensity in graphene/SiO2(2.0 nm)/ZnO was slightly reduced by the graphene as shown in figure 2(b) in sharp contrast with the large reduction for the graphene/ZnO as depicted in figure 2(c). It implies that the Förster-type energy transfer mechanism could be ruled out, since the Förster-type energy transfer generally takes place within a spacing of ~10.0 nm between the interacting systems [37, 43, 44]. If there was a significant energy transfer between the graphene and the ZnO, there would be an obvious PL reduction by the graphene in graphene/SiO2(2.0 nm)/ZnO structure.

As is known, to excite the plasmon of graphene effectively, a surface periodic structure should be introduced to compensate for the large momentum mismatching between the plasmon in the graphene and the photon [13]. Given that small dense islands form at the initial growth stages of the Au film, the thin Au film could provide an effective way to modulate the surface of ZnO gradually [29, 34]. However, materials like SiO2 cannot meet this requirement for that the surface roughness has not been changed by depositing a 2.0 nm thick SiO2 layer on ZnO, as shown in figure S3. Thus, before transferring the graphene on the ZnO surface, thin Au film layers of varying thicknesses (1.0, 2.0, 2.5, 3.0, 5.0, 10.0 nm) were deposited on the ZnO substrate. AFM images after the deposition of the thin films and the corresponding height distributions of the Au islands are shown in figure S4. Partly SEM images are shown in figure S4. Based on the kinetic growth mechanism of the thin Au layer, the Au islands can be viewed roughly as consisting of half NPs connected to each other [29, 34]. The lateral period of the Au surface would be approximately equal to the height of the Au NPs. In the Au(1.0 nm)/ZnO structure, the height of the Au NPs is about 1.15 nm. Further, as the thickness of the Au layer increases, the height of the Au NPs increases at first, reaches the highest value of 1.72 nm when the thickness of the Au layer is about 2.5 nm, and then begins to decrease due to the occurrence of secondary nucleation [34]. These values of the heights were used to represent the surface lateral periods of the Au layers.

The PL properties of the graphene/Au/ZnO as a function of the Au layer thickness under 325 nm laser excitation were studied. As shown in figure 4(a), for the NG regions (blue), that is, the ZnO and the Au/ZnO without graphene, the UV (375 nm) emission intensity decreases greatly due to the presence of the Au layer, while the previously reported emission enhancement caused by the localized surface plasmon (LSP) excitation in Au was not observed. It is due to the fact that the response of the Au LSP is in visible band, whereas the visible emission intensity decreases greatly due to the presence of the Au layer, while the previously reported emission enhancement caused by the localized surface plasmon (LSP) excitation in Au was not observed. It is due to the fact that the response of the Au LSP is in visible band, whereas the visible emission intensity decreases greatly due to the presence of the Au layer, while the previously reported emission enhancement caused by the localized surface plasmon (LSP) excitation in Au was not observed. It is due to the fact that the response of the Au LSP is in visible band, whereas the visible emission intensity decreases greatly due to the presence of the Au layer, while the previously reported emission enhancement caused by the localized surface plasmon (LSP) excitation in Au was not observed.
visible emission show a significant and a slight enhancements respectively, in sharp contrast to the significant reduction as revealed in figure 1(b) for the graphene/ZnO. The uniformity of the structure is evaluated by the optical microscope image and the corresponding micro-PL mapping image as shown in figures 4(e) and (f). The underlying mechanism for the enhanced PL from the graphene/Au/ZnO would be attributed to the excitation of plasmon in the graphene by the UV incident light, which depends critically on the surface lateral period. It is also supported by the reflectance spectra as shown in figure 5. An enhanced absorption in the UV range was observed in the graphene/Au(2.5 nm)/ZnO compared with that for the Au(2.5 nm)/ZnO, indicating a plasmon response of graphene in the UV range, while this was not observed for graphene/ZnO relative to that for ZnO, indicating the importance of the lateral period for the plasmon excitation.

Based on the literature [13, 49–52], the dispersion of the plasmon frequency of graphene ($\omega$) with in-plane momentum ($q_{sp}$) may be expressed as,

$$\omega \approx \left[ \frac{ne^2}{\varepsilon_0(\varepsilon_1 + \varepsilon_2)m^*q_{sp}^2 + \frac{3}{4}v_F^2q_{sp}^2} \right]^{1/2}$$

(1)

where $n$ is the number of electrons per unit area, $\varepsilon_0$ is the vacuum permittivity, $\varepsilon_1$ and $\varepsilon_2$ are the dielectric constants of the surrounding media, $v_F$ is the Fermi velocity, $v_F \approx 1.12 \times 10^6$ m s$^{-1}$, $m^*$=0.077$m_e$ is the effective mass of the graphene electrons, $m_e$ is electron mass, and $c$ is the speed of light. Given that the momentum of the plasmon, estimated by equation (1), is much larger than that of the photon ($q_{ph}$), the modulation period ($a$) in the graphene for momentum matching for plasmon excitation is given by,

$$a = \frac{2\pi}{|q_{sp} - q_{ph}|} \approx \frac{2\pi}{q_{sp}}$$

(2)

where the electron concentration $n$ in the graphene may be estimated by the Raman peak position of the graphene [42, 53]. As mentioned before, an increase in the electron concentration will cause phonon softening, a $\sim$7–10 cm$^{-1}$ redshift, as shown in figure S5, of the 2D Raman peak in the graphene/Au/ZnO, corresponding to
an electron concentration in the graphene of about \(2.5 \times 10^{13} \text{ cm}^{-2}\). According to equations (1) and (2), the resonant wavelength as a function of the modulation period \(a\) for \(n = (2.5 \times 2.8) \times 10^{13} \text{ cm}^{-2}\) is obtained, as shown in figure 6. Here, it is assumed that the graphene is surrounded by air \((\varepsilon_1 = \varepsilon_2 = 1)\) due to the weak interaction between the transferred graphene and the substrate \([13]\). Under 325 nm laser excitation, \(a\) is estimated to be 1.70 nm. The closer the surface lateral period is to this value of 1.70 nm, the more effective the plasmon excitation would be. The experimental results that the maximum PL enhancement induced by plasmon excitation is observed with a lateral period of 1.72 ± 0.35 nm as shown in figure 4(b) agree well with the theoretical estimation.

When the thickness of the Au layer is 10.0 nm, a reduction of PL intensity due to graphene was observed, although the surface lateral period is about 1.40 nm and larger than the 1.15 nm value for graphene/Au (1.0 nm)/ZnO which showed PL enhancement. As reported previously, the plasmons of graphene decay exponentially and the skin depth is several nm \([28, 49, 54, 55]\). When the thickness of Au is 10 nm, the plasmon of the graphene could not extend significantly to the ZnO, whereas the electron transfer would dominate, resulting in a reduction in PL intensity.

**Figure 4.** (a) UV peak-integrated intensities of the PL spectra from the SG and the NG regions of the graphene/Au(0.0, 1.0, 2.0, 2.5, 3.0, 5.0, 10.0 nm)/ZnO structures under 325 nm laser excitation. (b) The intensity ratio, \(I_{SG}/I_{NG}\), of the UV emission of the graphene/Au/ZnO and the surface lateral period of Au/ZnO as a function of the thickness of the Au layer. (c) Transmittance spectrum of the 3.0 nm thick Au layer in the UV-visible band. (d) PL spectra from the SG and the NG regions in the graphene/Au(2.5 nm)/ZnO structure under 325 nm excitation. The insert shows the enlargement of a part of the spectra. (e) Optical microscope image of the Au(2.5 nm)/ZnO partly covered with graphene. (f) The micro-PL mapping image taken from the red rectangular region marked in (e).
Conclusions

In summary, the PL properties of graphene/Au/ZnO hybrid structures with different thicknesses of Au layers inserted between the graphene and ZnO have been studied. A reduction in PL intensity by the graphene in the graphene/ZnO hybrid structures was observed, which is attributed to electron transfer from the ZnO to the graphene. This fact was confirmed by a 10 cm$^{-1}$ redshift of the 2D Raman peak of graphene. In contrast, an enhancement in PL intensity by the graphene was observed when an Au layer was introduced to the hybrid structures, and the enhancement ratio by the graphene was very dependent on the surface lateral period of the Au layer. This enhancement of PL was attributed to effective excitation of the plasmon in the graphene while the surface lateral period of the Au layer provided effective momentum compensation for the excitation of the plasmon by the incident light in the graphene. These results provide a scientific basis for utilizing graphene to improve the optical properties of semiconductors.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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References

[1] Novoselov K S, Geim A K, Morozov S V, Jiang D, Zhang Y, Dubonos S V, Grigorieva I V and Firsov A A 2004 Electric field effect in atomically thin carbon films Science 306 666–9
[2] Ma Y F and Chen Y S 2015 Three-dimensional graphene networks: synthesis, properties and applications Natl Sci. Rev. 2 40–53
[3] Wang Q H, Kalantar-Zadeh K, Kis A, Coleman J N and Strano M S 2012 Electronics and optoelectronics of two-dimensional transition metal dichalcogenides Nat. Nanotechnol. 7 699–712
[4] Cong H, Yang F, Xue C, Yu K, Zhou L, Wang N, Cheng B and Wang Q 2018 Multilayer graphene-GeSn quantum well heterostructure SWIR light source Small 14 e1704414
[5] Roy K, Padmanabhan M, Goswami S, Sai T P, Ramalingam G, Raghavan S and Ghosh A 2013 Graphene-MoS2 hybrid structures for multifunctional photoresponsive memory devices Nat. Nanotechnol. 8 826–30
[6] Sun Z P, Martínez A and Wang F 2016 Optical modulators with 2D layered materials Nat. Photonics 10 227–38
[7] Wei J, Zhang Z G, Zhang Y B, Wang M, Du J H and Tang X S 2017 Enhanced performance of light-controlled conductive switching in hybrid cuprous oxide/reduced graphene oxide (Cu2O/rGO) nanocomposites Opt. Lett. 42 911–4
[8] Kim B S et al 2016 High performance PbS quantum dot/graphene hybrid solar cell with efficient charge extraction ACS Appl. Mater. Interfaces 8 13902–8
[9] Si M, Choi W J, Jeong Y J, Lee Y K, Kim J J and Lee J O 2016 Controlled doping of graphene using ZnO substrates Physica E 80 115–9
[10] Dong X, Xu C, Yang C, Chen F, Manohari A G, Zha Z, Zhang W, Wang R, You D and Chen J 2019 Photoelectrochemical response to glutathione in Au-decorated ZnO nanorod array J. Mater. Chem. C 7 5624–9
[11] Zhang Y, Yan Y, Yao L, Xing C, Zeng Y, Zhao Y and Jiang Y 2019 Ultraviolet luminescence enhancement of planar wide bandgap semiconductor film by a hybrid microsphere cavity/dual metallic nanoparticles sandwich structure Opt. Express 27 15399–412
[12] Lawrie B J, Haglund R F and Mu R 2009 Enhancement of ZnO photoluminescence by localized and propagating surface plasmons Opt. Express 17 25665–72
[13] Hwang S W et al 2010 Plasmon-enhanced ultraviolet photoluminescence from hybrid structures of graphene/ZnO films Phys. Rev. Lett. 105 127403
[14] Li J, Jiang M, Xu C, Wang Y, Lin Y, Lu J and Shi Z 2015 Plasmon coupled Fabry–Perot lasing enhancement in graphene/ZnO hybrid microcavity Sci. Rep. 5 9263
[15] Xu C, Qin F, Zhu Q, Lu J, Wang Y, Li J, Lin Y, Cui Q, Shi Z and Manohari A G 2018 Plasmon-enhanced ZnO whispering-gallery mode lasing Nano Research 11 3050–64
[16] Li et al 2014 Graphene surface plasmon induced optical field confinement and lasing enhancement in ZnO whispering-gallery microcavity ACS Appl. Mater. Interfaces 6 10469–75
[17] Jiang M, Li J, Xu C, Wang S, Shan C, Xuan B, Ding Y and Shen D 2014 Graphene induced high-Q hybridized plasmonic whispering gallery mode microcavities Opt. Express 22 23836–50
[18] Qin F F, Xu C X, Zhu Q X, Lu J F, Chen F, You D T, Zha Z and Manohari A G 2018 Optical performance improvement in hydrothermal ZnO/graphene structures for ultraviolet lasing J. Mater. Chem. C 6 5240–4
[19] Das S K, Pradhan G K, Singh A, Sahoo P K and Sahoo S 2018 Enhanced ultraviolet emission from self-assembled ZnO nanorods grown on graphene J. Appl. Phys. 124 235302
[20] Kim K, Min Lee S, Seon Do Y, Il Ahn S and Cheol Choi K 2013 Enhanced photoluminescence from zinc oxide by plasmonic resonance of reduced graphene oxide J. Appl. Phys. 110 074903
[21] Tian Z S, Xu C X, Li J T, Li P L, Wu J, Hao X L, Fan X M and Shi Z L 2015 Facile assembly of two-dimensional functional ZnO quantum dots/reduced graphene oxide nanocomposites Epl-Europ. Phys. Lett 109 18004
[22] Zhao Y, Liu L, Cui T, Tong G and Wu W 2017 Enhanced photocatalytic properties of ZnO/reduced graphene oxide sheets (rGO) composites with controllable morphology and composition Appl. Surf. Sci. 412 58–68
[23] Liu H, Xiang M and Xiao X 2018 Graphene/ZnO nanocomposite with seamless interface renders photoluminescence quenching and photocatalytic activity enhancement J. Mater. Sci. 53 13924–35
[24] Salem M, Akir S, Massoudi I, Litaiem Y, Gaidi M and Khirouni K 2018 Photoelectrochemical and optical properties tuning of graphene–ZnO nanocomposites J. Alloys Compd. 767 982–7
[25] Wang J, Zheng C, Ning J, Zhang L, Lin W, Ni Z, Chen Y, Wang J and Xu S 2015 Luminescence signature of free exciton dissociation and liberated electron transfer across the junction of graphene/GaN hybrid structure Sci. Rep. 5 7687
[26] Gromova Y, Alafeirov A, Rackauskas S, Ermakov V, Orlowa A, Maslov V, Moskaliev S, Baranov A and Fedorov A 2015 Photoinduced electrical response in quantum dots/graphene hybrid structure J. Appl. Phys. 118 104305
[27] Okamoto K, Funato M, Kawakami Y and Tamada K 2017 High-efficiency light emission by means of exciton-surface-plasmon coupling J. Photochem Photobiol. Sci. 84 38–77
[28] Chen Y L et al 2014 Effect of graphene on photoluminescence properties of graphene/GeSi quantum dot hybrid structures Appl. Phys. Lett. 105 021104
[29] Liu R, Fu X W, Meng J, Bie Y Q, Yu D P and Liao Z M 2013 Graphene plasmon enhanced photoluminescence in ZnO microspheres Nanoscale 5 5294–8
[30] Yuan G et al 2020 Proton-assisted growth of ultra-flat graphene films Nature 577 204–8
[31] Casiraghi C, Pisana S, Novoselov K S, Geim A K and Ferrari A C 2007 Raman fingerprint of charged impurities in graphene Appl. Phys. Lett. 91 233108
[32] Peimyoo N, Li J W, Wang J Z, Shen X N, Qiu C Y, Xie L H, Huang W and Yu T 2012 Photocontrolled molecular structural transition and doping in graphene ACS Nano 6 8878–86
Liu Y, Willis R F, Emtsev K V and Seyller T 2008 Plasmon dispersion and damping in electrically isolated two-dimensional charge
Che S, Behura S K and Berry V 2019 Photo-organometallic, nanoparticle nucleation on graphene for cascaded doping
Stern F 1967 Polarizability of a two-dimensional electron gas
Rodrigo D, Limaj O, Janner D, Etezadi D, de Abajo F J G, Pruner E and Altug H 2015 Mid-infrared plasmonic biosensing with
Bradac C, Xu Z Q and Aharonovich I 2021 Quantum energy and charge transfer at two-dimensional interfaces
Ahn K J
Das A
Froehlicher G, Lorchat E and Berciaud S 2018 Charge versus energy transfer in atomically thin graphene-transition metal
dichalcogenide van der Waals heterostructures
Zhao L, Wang Y, Zhu X, Ji P, Zhang K, Yu X, Shi C, Li R, Ma Y and Ma L 2019 Metal-free synthesis of few-layer graphene films on
insulating SiO2 and SiC substrates by chemical vapor deposition
Mater. Res. Express 6 105604
Chun J, Guo Y, Wen Y, Huang L, Xue Y, Geng D, Wu B, Luo B, Yu G and Liu Y 2013 Two-stage metal-catalyst-free growth of high-
quality polycrystalline graphene films on silicon nitride substrates
Adv. Mater. 25 992–7
Liu H et al 2019 Plasmonic nanolasers enhanced by hybrid graphene-insulator-metal structures
Nano Lett. 19 5017–24
Liu J, Li Q, Zou Y, Qian Q, Jin Y, Li G, Jiang K and Fan S 2013 The dependence of graphene Raman D-band on carrier density
Adv. Funct. Mater. 23 3844–50
Saha S K, Waghmare U V, Krishnamurthy H R and Sood A K 2007 Probing zone-boundary optical phonons in doped graphene
Phys. Rev. B 76 201404
Bradac C, Xu Z Q and Aharonovich I 2021 Quantum energy and charge transfer at two-dimensional interfaces
Nano Lett. 21 1193–204
Gaudreau L, Tielrooij K J, Prawiroatmodjo G E, Osmond J, Garcia de Abajo F J and Koppens F H 2013 universal distance-scaling of
nonradiative energy transfer to graphene
Nano Lett. 13 2030–5
Taghinejad H et al 2020 Synthetic engineering of morphology and electronic band gap in lateral heterostructures of monolayer
transition metal dichalcogenides
ACS Nano 14 6322–30
Amendola V, Pilot R, Frasconi M, Marago O M and Iati M A 2017 Surface plasmon resonance in gold nanoparticles: a review
J. Phys. Condens. Matter 29 203002
Ye Z, Chen J, Luo J, Yi Y, Kang X, Ye X, Bi P, Gao X, Yi Y and Tang Y 2015 Surface-plasmon-enhanced band emission and enhanced
photocatalytic activity of Au nanoparticles-decorated ZnO nanorods
Plasmonics 10 1373–80
Dong Z et al 2020 Experimental realization of 1400–2100 nm broadband emission for wide-bandwidth optical communication in Er–
Tm Codoped ZnO films and devices
J. Phys. Chem. C 124 3747–55
Liu Y, Willis R F, Emtsev K V and Seyller T 2008 Plasmon dispersion and damping in electrically isolated two-dimensional charge
sheets
Phys. Rev. B 78 201403
Chugh S, Adhikari N, Lee J H, Berman D, Echegoyen L and Kaul A B 2019 Dramatic enhancement of optoelectronic properties of
electrophoretically deposited C60-graphene hybrids
ACS Appl. Mater. Interfaces 11 24349–59
Che S, Behura S K and Berry V 2019 Photo-organometallic, nanoparticle nucleation on graphene for cascaded doping
ACS Nano 13 12929–38
Stern F 1967 Polarizability of a two-dimensional electron gas
Phys. Rev. Lett. 18 546–8
Das A et al 2008 Monitoring dopants by Raman scattering in an electrochemically top-gated graphene transistor
Nat. Nanotechnol. 3 210–5
Ahn K J et al 2011 Comment on ‘plasmon-enhanced ultraviolet photoluminescence from hybrid structures of graphene/ZnO films’
reply
Phys. Rev. Lett. 107 159702
Rodrigo D, Limaj O, Janner D, Etezadi D, de Abajo F J G, Pruner E and Altug H 2015 Mid-infrared plasmonic biosensing with
graphene
Science 349 165–8