Tailoring reflection of graphene plasmons by focused ion beams

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Graphene plasmons are of remarkable features that make graphene plasmon elements promising for applications to integrated photonic devices. The fabrication of graphene plasmon components and control over plasmon propagating are of fundamental important. Through near-field plasmon imaging, we demonstrate controllable modifying of the reflection of graphene plasmon at boundaries etched by ion beams. Moreover, by varying ion dose at a proper value, nature like reflection boundary can be obtained. We also investigate the influence of ion beam incident angle on plasmon reflection. To illustrate the application of ion beam etching, a simple graphene wedge-shape plasmon structure is fabricated and performs excellently, proving this technology as a simple and efficient tool for controlling graphene plasmons.

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I. INTRODUCTION

Graphene plasmons, possessing unique and fascinating properties [1–4], like electrostatic tunability, extremely high field confinement and less intrinsic loss, are promising in integrated photonic applications [5–8], such as sensors, waveguides or modulators. Various aspects of graphene plasmons, ranging from methods of launching and detecting [9–11] to reducing the propagation loss [12] have been studied experimentally with the aid of near-field optical microscope. Moreover, the control over the propagation of graphene plasmons [7, 11] is of particular importance in integrated device applications, wherein the ability to manage reflection of plasmon waves is fundamental. Graphene plasmons have been proved to reflect efficiently at graphene edges [9, 10], grain boundaries [13] and nano gaps between SiC terraces [14]. Solving how to realize guided plasmon reflection at any required nanozone of graphene is essential, while all the present acquired reflection boundaries emerge naturally. Therefore, the introduction of controllable artificial defects on graphene for plasmon reflection is necessary.

Electron beam lithography (EBL) followed by plasma etching is widely used for patterning graphene nanostructures [8, 15–18] with spatial resolution of tens of nanometers. Nevertheless, the fabrication process is onerous and commonly results in resists remain [19]. Besides, the etching of graphene relying on plasma results in totally removed of carbon atoms. Plasmon structures of different reflection characteristics are unachievable.

In this letter, we prove the controllable plasmon reflection boundaries fabricated by focused ion beams (FIB). FIB has been proposed as an efficient tool for graphene modification [20–24], with the advantages of process-simple and high spatial resolution. However, the plasmon properties of FIB etched graphene are still unrevealed. In this work, through scattering-type scanning near-field optical microscope (s-SNOM), plasmon reflection is observed near graphene boundaries formed by FIB. By controlling the exposure dose, graphene defect structures with varied plasmon reflection properties are obtained, and fabricated reflection boundary comparable to natural one can be realized. A simple wedge-shape graphene structure is manufactured and exhibits well-behaved plasmon properties, demonstrating FIB as a flexible and powerful tool for the realization of graphene plasmonic devices. At last, we exhibit that optimized results can be achieved by varying ion beam incident direction.

II. EXPERIMENT AND RESULTS

A single graphene layer was obtained by mechanical cleavage from bulk graphite and transferred to Si substrate with 300 nm thick SiO2 layer. The layer of graphene was discerned under optical microscope and confirmed by micro-Raman spectrum. FIB etching was completed with FEI Helios Nanolab 600i system, employing 30 kV Ga+ with an ion current of 2.56 pA. To investigate the influence of exposure dose on etching results, varied ion dwell times were adopted, ranging from 100 µs to 1 µs. Infrared near-field measurements were performed with s-SNOM (Neaspec). The principle of s-SNOM is illustrated in Fig. 1(a). To probe the properties of graphene plasmons, the free-space wavelength of incident infrared laser λ0 was tuned from 10.195 to 10.653 µm. The metallic AFM tip oscillated at 266 kHz with an amplitude of about 60 nm, then near-field images were acquired by demodulating the backscattering signals at higher harmonics. The fourth harmonics scattering signal s4 is adopted in the study.

Fig. 1(b) and (c) exhibit the simultaneously obtained AFM topographies and near-field images near graphene defect lines, which were etched at different ion beam

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(c) AFM topography (left) and near-field optical images (right, at $\lambda_0$ of 10.653 $\mu$m) of FIB etched graphene. Ion dwell times are (b) 100 $\mu$s and (c) 5 $\mu$s. Bottom curves in (b) and (c) show line profiles taken along the corresponding dashed lines. Scale bars, 100 nm.

FIG. 2. The plasmon dispersion and near-field imaging of etched graphene at dwell time of 5 $\mu$s. (a) AFM (left) and near-field imaging (right) of FIB etched line defect and natural defect. (b) Line profiles of $s_4$ along the dashed line in (a) at different incident wavelengths. (c) Dispersion of graphene plasmon waves at the Fermi energy of 0.5 eV. Black crosses show the experimental extracted data. (d) Near-field imaging of graphene with two tilted line defects etched by FIB at 10.653 $\mu$m. The two dashed lines indicate the location of etched lines. Scale bars, 100 nm.

To illustrate the properties of plasmon reflection at ion etched graphene boundaries, two tilted line defects were drawn by ion beams, indicated by dashed lines in the near-field image in Fig. 2 (d). Similar phenomenon is observed as that of tapered graphene ribbon [9]. In the wider part, plasmon waves reflected from both sides interfere with each other, and the overlapping of two second plasmon peaks can be observed. Then in the nar-
row part, localized plasmon resonances arise, exhibiting enhanced near-field signals at the center of the gap, indicating enhanced local density of optical states. The lowest mode where field maxima at boundaries can also be distinguished, indicated by green arrow in Fig. 2(d), demonstrating excellent plasmon properties of ion beam etched graphene structure.

The discrepant near-field images for two different ion doses in Fig. 1 indicate that ion dose is a key factor that determines properties of plasmon reflection. Fig. 3(a) compares plasmon profiles of varied dwell times, where all near-field signals are normalized to that of graphene far from the reflectors. As shown, the appearances of plasmon interference profiles among dwell times of 100, 5 and 1 µs are different. Near-field signals of the first peak change with varied doses. The peak height of plasmon interference profiles, which is defined as visibility $M$, is an important parameter related to plasmon reflection from graphene boundary. For large $M$, plasmon reflection should be strong and additionally the damping of plasmon waves cannot be heavy. Moreover, varied damping tendencies imply different plasmon damping near the etched boundaries.

To extract plasmon damping information with different exposure dose, the near-field signals are fitted. The metallic tip launches plasmon waves propagating around with wave vector of $q = q_1 + iq_2$, where the imaginary part $q_2$ stands for plasmon damping. The ratio between $q_2$ and $q_1$ defines plasmon damping ratio $\gamma = q_2/q_1$. Propagating plasmon waves reflect at ion etched boundaries then are scattered by the AFM tip and collected by detector. The field can be fitted as
\[
\Psi = \Psi_G + a \frac{\exp(iq \cdot 2x)}{\sqrt{X}},
\]
where $\Psi_G$ is the near-field contribution from graphene itself, $a$ is a complex parameter and $x$ is the distance from the detection position to the reflection boundary. In order to account for the finite size of the tip which generates a spatial averaged near-field response, the weight function $\Theta$ convolved with the spatially varying response $\Psi$ yields $s$-SNOM near-field signal $s(x) = (\Psi \ast \Theta)(x)$. $\Theta$ is adopted as Gaussian function peak at $x$ with a width of 10 nm.

Affected by inhomogeneous dopings, near-field signals near the first plasmon peaks vary unpredicted by Eq. 1. Thus signals away from the first peak were fitted. The fitted result for plasmon reflected from a natural boundary is shown in Fig. 3(b), with the damping ratio valued $\gamma = 0.28$ when the fitted curve and experimental profile show identical oscillation and damping tendency. Similar fittings are processed for ion dwell times not larger than 20 µs where the second plasmon peaks can be distinguished. The acquired damping ratios for different ion doses are plotted in Fig. 3(c), together with the $M$ values. Moreover, the damping ratios for larger dwell times can be deduced from the trend indicated by the red line. With decreased dwell times, as shown, plasmon waves decay weaker near etched boundaries, to a damping ratio of $\gamma = 0.27$ when dwell time is 1 µs. This is nearly identical with that from natural graphene boundaries, implying little graphene degeneration occurs near the etched boundaries. The relation of decreased damping ratio with less ion dose is apparent, as fewer defects are introduced to graphene near etched boundaries at decreased ion dose.

Another parameter in Fig. 3(c) is the fringe visibility $M$, which experiences a rise than drop with more ions irradiating. The rise is easy to understand, as more ions strengthen the reflection boundaries with introduc-
ing more reflection components. When the ion dose is large enough that the graphene layer is cutted into two pieces, the reflection ratio of plasmon waves should tend to saturate. Increasing ion dose can barely contribute to the reflection of plasmon waves, but introduces more defects near reflection boundary. This results in increased damping to plasmon waves propagating towards and away from the boundary, thus the drop of plasmon wave amplitude at interference peak.

The fixed damping ratios in fitting of Fig. 3 reveal averaged graphene qualities over the distance of one plasmon wavelength. The influence of ion etching on graphene further away is unrevealed. Former research on the spatial influence of ion beam on etched graphene relies on Raman spectrum characterization [32–34], which, restricted to diffraction limit, cannot reach the spatial resolution of smaller than 400 nm. Here, the influence of ion etching can be identified through near-field plasmon imaging.

![Fig. 4](image)

**Fig. 4.** Influence of FIB etching on nearby graphene plasmon propagation. (a) Near-field imaging of graphene with crossed FIB etched defect and natural defect. Incident wavelength is 10.616 μm. Scale bar, 100 nm. (b) Line profiles near the dashed lines in (a).

Fig. 4 shows the near-field image at the cross connection zone between a natural line defect and the FIB induced defect at dwell time of 5 μs. Line profiles near the natural defect along lines of different distance to the ion etched area are plotted in Fig. 4(b). Line 2 is 420 nm away to the irradiated area and line 1 is about 170 nm away to that. As can be seen, the near-field signals exhibit almost coincident distributions, revealing that no deprivation of graphene plasmon properties occur for 170 nm away from ion irradiated area. Therefore negligible change to graphene optical properties occur for separation larger than 170 nm far from ion etched zone, guaranteeing the availability of graphene away from the etched plasmon reflector in integrated applications. Moreover, profile taken along the ion etched boundary reveals a slightly larger damping compared to those from the natural one, in coincidence with the damping ratios shown in Fig. 3.

Our works above employ the configuration of perpendicular irradiation. Ion beam direction was proposed as an important factor for improving graphene modification quality [35]. Here, ion beam is tilted 30°, and correspond-
fect [21, 22]. Our study shows that FIB is an simple and efficient tool for engineering graphene functional plasmon elements of varied properties, which is promising for applications in integrated photonic devices.

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