Bessel-Beam Nano-patterning of Graphene

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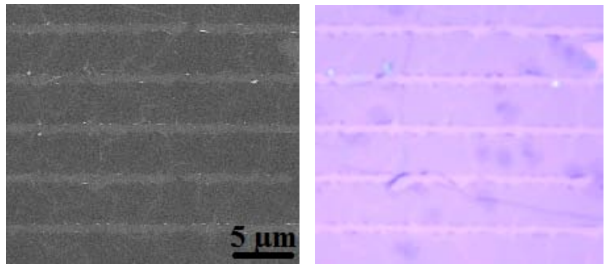
Since its invention, graphene has attracted attention for variety of applications. Most of the optical applications especially in IR and THz regimes require its surface to be patterned at micro and nanoscale [1], [2]. Although lithographical techniques can yield such structures, direct laser structuring of graphene on different substrates is still challenging. Laser ablation in ultrafast regime can provide easier and faster alternative. Recent studies show that femtosecond (fs) pulsed lasers can yield sub-wavelength resolution by working near the ablation threshold [3]. Recently, we show that femtosecond laser pulses with Bessel Beam profile provide further advantages (especially considering alignment requirements) and make the process ablation on thin films much simpler [4], [5].

In this study, we focus on patterning of graphene at nanoscale without any damage to substrate by using fs laser Bessel beams. Since it provides visibility of graphene layers even in optical microscope (OM), SiO_2/Si is commonly used as a substrate for graphene, and we also use this setting for our experiments. We use chirped-pulse amplification system, producing 550-fs pulses at 1 kHz repetition rate at a central wavelength of 1030 nm. For improving the resolution, third harmonic (343 nm) of the laser output is generated through consequent second harmonic and sum-frequency generations. Output of laser is Gaussian and it is converted to Bessel Beam with a 40^0-base angle axicon.

In the visible part of the electromagnetic spectrum, Si has more linear absorption and lower ablation threshold than graphene. Therefore, one expects Si-substrate damage before graphene removal. Our experimental results indicate that substrate damage after graphene removal can be mitigated or even completely avoided by nonlinear shielding of graphene, at appropriate scan speed and laser fluence values. We conduct systematic experiments and find an optimal window for energy and scan speed values in order not to damage the substrate.

Fig. 1 shows ablated channels on single layer graphene with the explained method. Laser energy and scan speed of sample are 120 nJ and 330 μm/sec, respectively. Under these conditions, no detectable substrate damage is observed. When the scan speed is reduced within this energy regime, the substrate starts to be damaged. Similarly, at fixed scan speed when the energy is increased the substrate starts to be damaged. The status of the substrate (whether damaged or not) is also verified through micro-RAMAN microscopy measurements.



(a) (b)

Figure 1: Fs-laser written graphene stripes: (a) SEM Image of a fabricated structure (bright lines are ablated parts), (b) OM Image of the same region

In order to determine the limit (smallest ablation width) in our setup, we gradually decrease average power of laser while observing ablated channel widths. For 90 nJ pulse energy we could reach 400 nm-widths in ablated channels [6]. During these experiments scan speed of sample is kept constant at 330 µm/sec. In addition to obtaining smallest width, we try to bring graphene stripes as closer as possible. We could fabricate structures with periodicities of 1.8 µm and channel width of 0.9 µm.

Fabricated structures are also characterized with a RAMAN microscope in order to verify the complete graphene removal. Measurements indicate that characteristic RAMAN peaks of graphene disappear on ablated channels. On the other hand, small increase is observed in single layer graphene D-band at the edge of graphene stripes because of oxidation during ablation. OM, SEM and Raman 2D images of fabricated structures confirm the graphene removal.

In conclusion, we show that fs-pulses with Bessel beam profile can be used in nano-structuring graphene. Our maskless fabrication process does not require any special environment making the method straightforward. Nanometer-size structures are obtained even at ambient conditions. We also optimize the laser fluence and scan speed of sample to keep substrate intact. Similar processes can also be applicable to other graphene like atomically thin layered materials on various substrates.

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