Single-pixel camera with one graphene photodetector

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Abstract: Consumer cameras in the megapixel range are ubiquitous, but the improvement of them is hindered by the poor performance and high cost of traditional photodetectors. Graphene, a two-dimensional micro-/nano-material, recently has exhibited exceptional properties as a sensing element in a photodetector over traditional materials. However, it is difficult to fabricate a large-scale array of graphene photodetectors to replace the traditional photodetector array. To take full advantage of the unique characteristics of the graphene photodetector, in this study we integrated a graphene photodetector in a single-pixel camera based on compressive sensing. To begin with, we introduced a method called laser scribing for fabrication the graphene. It produces the graphene components in arbitrary patterns more quickly without photoresist contamination as do traditional methods. Next, we proposed a system for calibrating the optoelectrical properties of micro/nano photodetectors based on a digital micromirror device (DMD), which changes the light intensity by controlling the number of individual micromirrors positioned at +12°. The calibration sensitivity is driven by the sum of all micromirrors of the DMD and can be as high as $10^{-5}$ A/W. Finally, the single-pixel camera integrated with one graphene photodetector was used to recover a static image to demonstrate the feasibility of the single-pixel imaging system with the graphene photodetector. A high-resolution image can be recovered with the camera at a sampling rate much less than Nyquist rate. The study was the first demonstration for ever record of a macroscopic camera with a graphene photodetector. The camera has the potential for high-speed and high-resolution imaging at much less cost than traditional megapixel cameras.

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References and links

1. Introduction

As an extension of human vision, digital consumer cameras in the megapixel range have become ubiquitous owing to the dramatic improvement of photodetector technology using planar materials as a sensing element. There are mainly two types of photodetectors for traditional digital cameras: the charge-coupled device (CCD) and the complementary metal-oxide-semiconductor (CMOS). The large-scale array of photodetector comprising CCD or CMOS has been successfully manufactured and integrated into conventional cameras for high-resolution imaging. However, both CCD and CMOS have their own limitations: the equipment used to manufacture CCD is unique and cannot be utilized in the production of other devices, making CCD very expensive; while the CMOS has weak ability to absorb light due to its small sensitive area, making it very insensitive.
The poor performance of conventional photodetectors has hindered the development of cameras and has spurred the search for new high-performance and low-cost photodetectors. Recently, graphene, a single layer of carbon atoms in a honeycomb lattice, has attracted considerable attention due to its unique physical properties. For example, graphene monolayer has a large specific surface area of 2630 m²/g [1], thermal conductivity up to 5 × 10³ W/(m⋅K) [2], and breaking strength of 42 N/m [3]. In particular, its electronic structure has properties superior to those of conventional semiconductor materials, such as room-temperature in-plane carrier mobility up to 1.5 × 10⁴ cm²/(V⋅s) [4], and it also has a strong photo response near metal-graphene interfaces [5, 6]. Therefore, these excellent electronic properties and the high optical transmittance provide graphene a great potential for development in photodetectors [7]. There have been reports about graphene photodetector with surprising photoelectric effectiveness in an optical data link more than 10 Gb/s [8–10] and photo responsivity of 10³ A/W [11]. The mechanism for the light-to-current conversion of graphene is still in debate and there exist at least two mainstream viewpoints on the photocurrent conversion. One is that, upon the light illumination on the graphene, the photocurrent is generated by the electron-hole pairs which are separated and transported to the opposite directions due to the strong electric field near metal-graphene contacts [12]. And the other is that the photocurrent is generated due to the photothermoelectric effect [13], by which the electrons are excited from the valence band to the conduction band and then ultrafast relax back to the Fermi level by the photon emission and form a hot Fermion distribution [13, 14]. However, these two explanations have the same physical foundation that a p-n junction is created close to the metal-graphene contacts due to the different work functions between metal and graphene [15]. The photocurrent conversion of graphene implies that a graphene-based photodetector can be used as a sensing part in a camera system.

However, there still exist some problems that need to be solved for graphene photodetectors to be integrated into cameras. Firstly, to our knowledge, a large-scale array of graphene photodetectors cannot be fabricated because the technology to do so is not mature and efficient yet. Secondly, it is difficult to fabricate a high-performance and low-cost graphene photodetector by conventional fabrication methods, including mechanical exfoliation [16], chemical vapor deposition (CVD) [17], graphitization of carbon-containing [18], and reduction of graphing oxide [19]. CVD, the main method of photodetector fabrication, requires hours for graphene growing, transferring and patterning, and therefore it is very time consuming and often results in photoresist contamination [20] due to its complicated procedures. In addition, it is difficult to accurately calibrate the optical-electrical characteristics of the photodetector at the micro-/nano-scale. The conventional method, for calibrating photocurrent of a photodetector utilizing a light source with adjustable light intensity (power) is very expensive to perform and, on the other hand, its accuracy is low for its inaccurate regulation of light power.

In this paper, we propose a single-pixel camera integrated with a graphene photodetector based on compressive sensing (CS). The camera takes full advantage of the properties of graphene and overcomes the first issue mentioned above, i.e., the large-scale array, by utilizing only one photodetector. Rather than acquiring a pixel sample of the signal, the single-pixel camera uses the inner products between a measurement matrix and the testing signal. In particular, the single-pixel camera, with its simple and inexpensive hardware structure and one photodetector, can recover high-resolution images using smaller sampling rate than the Nyquist rate. It breakthroughs the limitation on the hardware imposed by the conventional camera to produce high-resolution images. For the second issue mentioned above, i.e., efficient fabrication of graphene photodetector, we have introduced a fabrication method called laser scribing, which converts stacked graphene oxide (GO) into graphene by using a DVD burner. The method can be used to produce graphene photodetectors at arbitrary pattern without any photoresist contamination. To solve the last problem mentioned above, i.e., accurate calibration, we propose a calibration strategy and system based on a DMD. The light intensity can be precisely controlled by changing the number of micromirrors positioned
at + 12°, by which the light can be reflected into the photodetector. The calibration system has many unique advantages, including its simple structure, low cost and high sensitivity.

The rest of the paper is organized as follows. Section 2 presents the fabrication and the structure of the graphene photodetector. The characteristics and calibration of the sensing-element are discussed in Section 3. Section 4 describes the principle and structure of single-pixel camera based on CS with a graphene photodetector, followed by the experiments using the imaging system. We present our conclusions in Section 5.

2. Graphene photodetector: fabrication and structure

The applications of graphene photodetector are essentially driven by the progress of graphene production with well-matching properties for the specific purposes. However, the conventional fabrication methods have some problems, which have stimulated researchers to seek other methods to fabricate high-performance and low-cost graphene photodetectors. Recently, one-step laser scribing to integrate wafer-scale graphene photodetectors was proposed, and it was able to quickly convert stacked GO into graphene via a DVD burner [11, 21] or a CO2 laser [22].

A schematic diagram of laser scribing fabrication of graphene photodetectors is shown in Fig. 1(a). The laser engraver (Liaocheng Hengchunyuan Machinery Equipment Co., Ltd., Liaocheng, Shandong, Chain), consisting of a 850 nm laser with power of no more than 10 mW, is used to convert the stacked GO into graphene. Some reports have concluded indirectly...
that, with this fabrication method, the graphene produced by local thermal reduction of GO [23]. The fabrication procedure is summarized as follows. Firstly, GO in water at a concentration of 2 mg/ml (Nanjing XFNANO Materials Tech Co., Ltd, Nanjing, China) is coated uniformly onto the surface of a Polyethylene Terephthalate (PET) plate, and then dried overnight at room temperature in the dark. Next, the in-plane detector pattern is designed and the processing parameters are set via computer software, including processing speed and laser power. Finally, the designed graphene structure is produced by the laser engraver and the graphene photodetector is completed by attaching two platinum poles to the two ends of the scribed graphene block, and the structure of graphene photodetector is shown in Fig. 1(b).

To observe the structure of the graphene photodetector, a scanning electron microscopy (SEM) is used to acquire the morphology of the GO after laser scribing. The morphology of the 3 mm × 0.5 mm graphene photodetector on the PET film, as depicted in Fig. 2(a), shows that the graphene clustered in the rectangular block. As shown in Figs. 2(b) and 2(c), the graphene is significantly distinguishable from the GO. The distribution of the scribed graphene on the surface is patchy and its thickness is inversely proportional to the scribing speed if the laser power is constant, as shown in Fig. 2(b). On the other hand, the surface of the GO is very wrinkly, as shown in 2(c), and the GO film is considered an insulator [11].

3. Photodetector characteristics and calibration of the sensing elements

It is crucial to clarify the characteristics of graphene photodetector, including electrical resistance tunability and optoelectrical characteristics. A 380 nm light source was used as a testing light. As shown in Fig. 3(a), the $I-V$ curves of the graphene photodetector (Fig. 3(b)) with the light on and off imply that the electrical resistance of the photodetector is tunable under the light since the variations in the current due to the light are significantly distinguishable. The resistances of the photodetector with the light on and off calculated using the curves in Fig. 3(a) are 10 kΩ and 15.2 kΩ respectively, and the current with the light on is about 0.596 times greater than that with the light off. Figure 3(c) shows the photo response of the graphene photodetector with the light being switched on and off periodically, under the 1 V input voltage. The current increases and reaches its saturate level in approximately 30 s after the light is switched on, and, on the other hand, it decreases to its original state in approximately 30 s after the light is switched off.

![Fig. 3. The optoelectrical characteristics of graphene photodetector. (a) $I-V$ curves of the photodetector with 380 nm light source on and off, respectively. (b) The current of graphene photodetector versus time with the light switched on and off periodically under the constant input voltage. The light was on 65 s and off 65 s for each cycle.](image)

Light tunability is an important characteristic of graphene photodetector, especially for imaging application with its integration into a single-pixel camera. The high-resolution imaging with such camera system is intrinsically determined by the accurate calibration of the optoelectrical characteristic of the photodetector. In the conventional calibration, the power of light source is varied and the calibration accuracy is determined by the adjustment accuracy of
light power. This method acquires expensive instruments and the light adjustment accuracy is low, which cause the calibration inefficient and ineffective. Aiming at this problem, we proposed an approach to accurately calibrating the optoelectrical characteristic of the photodetector based on the DMD, and the calibration system comprises a light source, lens 1, the DMD, lens 2, the graphene photodetector, and the source meter, as shown in Figs. 4(a) and 4(b). The DMD (top right corner in Fig. 4(b), Texas Instruments, Dallas, TX, USA) consists of an array (1024 rows and 768 columns) of square micromirrors, each of which can be positioned at two angles: $-12^\circ$ and $+12^\circ$. The positions of all the micromirrors are controlled by a control picture of $1024 \times 768$ pixels, with which each micromirror is controlled by the corresponding pixel value of either 1 or 0. A micromirror is positioned at $+12^\circ$ if the corresponding pixel value is 1, and, on the other hand, the micromirror is positioned at $-12^\circ$.

The light passing through lens 1 is focused onto the DMD, and then is reflected by the micromirrors in the DMD and is separated into two light beams along different directions, one by the micromirrors at $+12^\circ$ and another by those at $-12^\circ$. The light beam reflected by mirrors at $+12^\circ$ goes through lens 2 and is further focused on the photodetector. The variation of the light intensity on the photodetector leads to the change of the photocurrent, which is sampled by the source meter (bottom left corner in Fig. 4(b), No. 2410, Keithley Instruments, Solon, OH, USA). The light intensity on the photodetector is modulated by controlling the number of micromirrors at $+12^\circ$ and it is directly proportional to the number of micromirrors at $+12^\circ$. Therefore, the theoretical calibration accuracy is up to $I/1024 \times 768$, where $I$ is the ratio of the maximum photocurrent to the light intensity with all the micromirrors positioned at $+12^\circ$.

The calibration process comprises three steps. Firstly, the relationship between the photocurrent of the photodetector and the number of the micromirrors at $+12^\circ$ is determined using the calibration system as shown in Fig. 4(b), yielding the results as shown in Fig. 4(c). Secondly, the light intensity on the photodetector is measured by the optical beam profilers (BP209, THORLABS, Inc., Newton, NJ, USA) with incremental variation of micromirrors at $+12^\circ$. (C) 2016 OSA
$\pm 12^\circ$, yielding the relationship between the light intensity and the number of micromirrors at $\pm 12^\circ$ as shown in Fig. 4(d). Finally, based on the results achieved in the first two steps, the relationship between the photocurrent of the photodetector and the light intensity can be obtained, as shown in Fig. 4(e). The relationship is expressed by a linear regression as $y = 0.01403z$, where $y$ is the photocurrent (uA) and $z (z > 0)$ is the light intensity (uW).

The calibration method is an indirect method and its accuracy is closely dependent on optical beam profilers. The proposed calibration approach can also be used to calibrate a photodetector at nano-/micro-scale with multicolor light.

4. The graphene single-pixel camera

The graphene photodetector has many exceptional properties, including high-speed optical communication [8] and high photo responsivity [24]. However, to our knowledge, there have been no reports on a large-scale array of graphene optoelectronics that could replace the CCD or CMOS array as a sensitive part in traditional digital cameras because the current fabrication technology is not reliable. In this study, we established a CS-based single-pixel camera by integrating a single graphene photodetector as a sensitive part to demonstrate the feasibility of imaging with a graphene photodetector.

Imaging with the single-pixel camera is based on the mathematical theory and reconstruction algorithms of CS [25], which combine both sampling and compression in a linear measurement process and recover the scene using the after-treatment optimization [26]. The main point of CS is to reconstruct a sparse signal $x \in \mathbb{R}^N$ from an observation vector $y \in \mathbb{R}^M$ using the linear equation: $y = \Phi x$, where $\Phi \in \mathbb{R}^{M \times N}$ is a measurement matrix and $M < N$ [27]. The unique solution to the equation cannot be obtained by classical matrix inversion because the equation is under-determined. However, the sparse signal $x$ can be recovered using the $l_0$-norm minimization problem with large probability by linear programming if the signal $x$ is $k$-sparse (i.e., the signal $x$ contains no more than $k < M$ non-zero entries) and $\Phi$ satisfies the Restricted Isometry Property (RIP) condition [28]. In practice, many signals are not sparse in their original forms, but they can be sparsely represented in another space. Given that $\Psi \in \mathbb{R}^{N \times N}$ is a sparse representation matrix, then a signal $x$ can be expressed as $x = \Psi s$, where $s$ is a $k$-sparse vector.

In the single-pixel camera, the DMD is used to generate a measurement matrix $\Phi$ by simultaneously flipping all the micromirrors $M$ times, with each flip controlled by a random picture matrix, which is produced mainly by reshaping one of the row vectors of the measurement matrix onto a square matrix of $\sqrt{N} \times \sqrt{N}$, determined by the length of the sparse signal but less than the size of DMD, 1024×768. Each entry of the measurement matrix is either 0 or 1. The random picture matrix is located at the center of the DMD array as a central submatrix for sampling the sparse signal; the other entries in DMD array around the random picture matrix are always 0. One entry of the observation vector is obtained when all the micromirrors are flipped simultaneously, and $M$ times flips are performed to obtain $M$ entries of observation vector $y$. Finally, the original signal $x$ is reconstructed from $y$ and $\Phi$ by the orthogonal matching pursuit algorithm [29, 30].

The setup of single-pixel camera integrated with a graphene photodetector is similar to the calibration system, described as above. The system comprises a light source (380 nm), objective image for testing, lens 1, DMD, lens 2, graphene photodetector, Source Meter and computer, as shown in Figs. 5(a) and 5(b). The objective image is projected onto lens 1, and then converged onto the DMD by lens 1. It is then sparsely sampled by flipping DMD micromirrors under the control of random picture matrices and the sampled image is further converged onto the photodetector by lens 2, resulting in photocurrent variation. Then the optoelectrical signal of the graphene photodetector is collected by the Source Meter and transferred to the computer for image reconstruction.

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To test the effectiveness of the camera, a letter “V” was used as an objective image, as shown in Fig. 5(c) for the imaging experiment. The recovered image with a resolution of 100×100 pixels, as shown in Fig. 5(d), was reconstructed with only 5600 measurements, which is only 56% of the total number of pixels. In this study, a commercial photodiode (OPT101, Texas Instruments, USA) was also used as a sensitive part in the camera system to acquire the objective image, as shown in Fig. 5(e), to examine the imaging quality of the graphene photodetector. Although the imaging quality by the graphene photodetector is inferior to that by the commercial photodiode, the contour of the objective image can be significantly distinguished in both recovered images at the corresponding similar positions, demonstrating the imaging feasibility of a graphene photodetector. The reason is that, compared to the commercial photodiode, the fabrication technology of graphene photodetector is still immature. However, compared with the conventional photodetectors, the graphene photodetector have some attractive advantages. Graphene photodetector can potentially operate at high speeds > 500 GHz [10], and much broader spectral detection can be expected with graphene photodetector because of the graphene ultrawideband (from visible to near-infrared) absorption [8, 9]. Those merits imply that graphene-based photodetector has superior application potential, such as high-resolution and high speed imaging, and broader spectral detection.

Fig. 5. Single-pixel camera integrated with a graphene photodetector. (a) Schematic diagram of the single-pixel camera integrated with a graphene photodetector. (b) The setup of the single-pixel camera. (c) Objective image used for the imaging feasibility with a graphene photodetector. (d) The recovered image by the single-pixel camera with the graphene photodetector. (e) The recovered image by the single-pixel camera with a commercial photodiode.

5. Conclusion

In this paper, we introduced a new method for fabricating a graphene photodetector, which converts a stacked GO into graphene piece of any pattern cost-effectively without photoresist contamination by laser scribing. The photodetector fabricated with the method has high photo-responsivity up to 0.23 A/W and can quickly reach a stable photocurrent. In addition, we proposed a DMD-based approach to calibrating the optoelectrical properties of the photodetector with a sensitivity of 10⁻⁵ A/W at micro-/nano-scale. Finally, the calibrated
graphene photodetector was integrated into a single-pixel camera system to demonstrate the imaging feasibility of a single graphene photodetector. The camera not only has the essential properties of a single-pixel camera, including acquisition of an image at a sampling rate much less than the Nyquist rate and a simple hardware structure, but also has high-resolution imaging capability with more than $10^7$ pixels. This is the first exploration to apply a graphene photodetector into a macroscopic imaging system to realize high-resolution imaging. In addition, the camera has the potential for high-speed and broader spectral imaging because of the photoelectric effect of graphene.

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