Turning randomly distributed 1D and 2D material into functional devices with the help of SEM mapping and innovative offline data preparation for direct write lithography

Andre Linden, Raith America Inc.
Andres Trucco and Dr. Brent P. Gila, Nanoscale Research Facility, University of Florida.

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Abstract:

“2D materials” are attracting more and more researchers to develop future electronic devices and sensors. Such 2D materials can be flakes or growing islands of CVD materials. Typically their distribution on the chosen substrate is random. An innovative workflow including offline data preparation is required to efficiently use the electron beam lithography (EBL) direct write tool resource, rather than completing data preparation on the EBL/SEM instrument.

This application note describes how data preparation is performed on a mosaic of SEM images, which has automatically mapped a large area of the sample containing the 2D materials. In a second step, GDSII CAD layout data are overlaid to the SEM image mosaic, thus generating a jobfile (positionlist) for the EBL to expose.

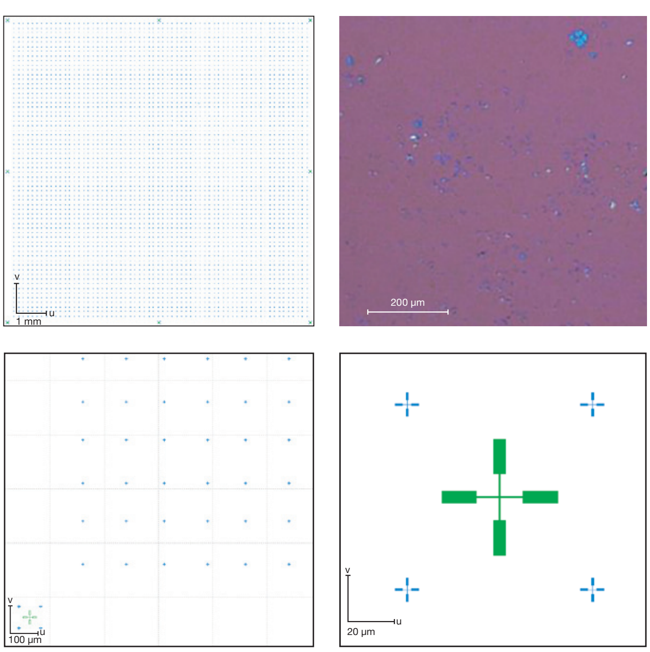

Figure 1 Fiducial marks on substrate with randomly distributed graphene flakes

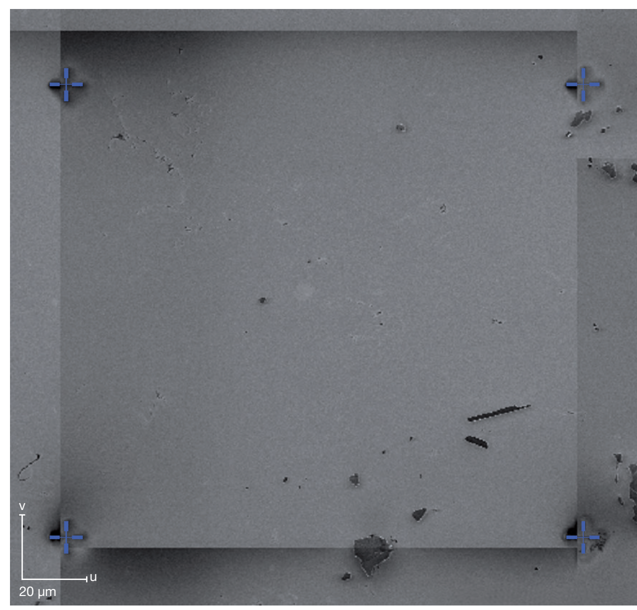

Figure 2 SEM image of fiducial marks and graphene flakes

At the University of Florida, a unique toolset containing a RAITH150 (EBL, SEM), and an ionLINE (FIB nanofabrication) is available which allows multiple strategies for sample preparation including imaging, milling and exposure, e.g. for adding reference markers.

The fabrication process:

To start off, Andres Trucco and Brent P. Gila from the Nanoscale Research Facility at University of Florida use a substrate that includes randomly distributed 2D material, and place fiducial marks on it by means of direct milling or the lift-off process (fig. 1). Once the fiducial marks are in place, the entire substrate is mapped via SEM with the RAITH150 and the resulting images are tilted together. The GDSII design, underlaid with fiducial marks, is then overlaid over the SEM tiled image (fig. 2). Once the areas of interest are identified, the GDSII designs are placed over the material image using GDSII/Image overlay (fig. 3). The sample is then coated with e-beam resist (300 nm) and the GDSII file calibrated to the existing milled fiducial marks. Once the writing process is completed, the sample is developed and ready for metalization (fig.4). The metal deposition is done via e-beam evaporation. In this case, 20 nm of Ti and 50 nm of Ni are deposited and lifted using standard lift-off techniques (fig. 5).

The basic principle

The basic principle of the workflow described has been successfully applied by Prof. Joerg Appenzeller and Dr. Hong-Yan Chen from the School of Electrical and Computer Engineering and Birck Nanotechnology Center, Purdue University, turning a novel device idea into reality. Here, the ambipolar device properties of graphene have been utilized to construct a frequency tripler in a compact two-FET configuration (patent pending) with spectral purity at an output frequency of 600 Hz - more than 4 times higher compared to conventional FET triplers[1].

With regard to device fabrication, one of the biggest challenges was the accurate placement of multiple process steps onto the randomly oriented exfoliated graphene flakes. However, smart offline data prepa-

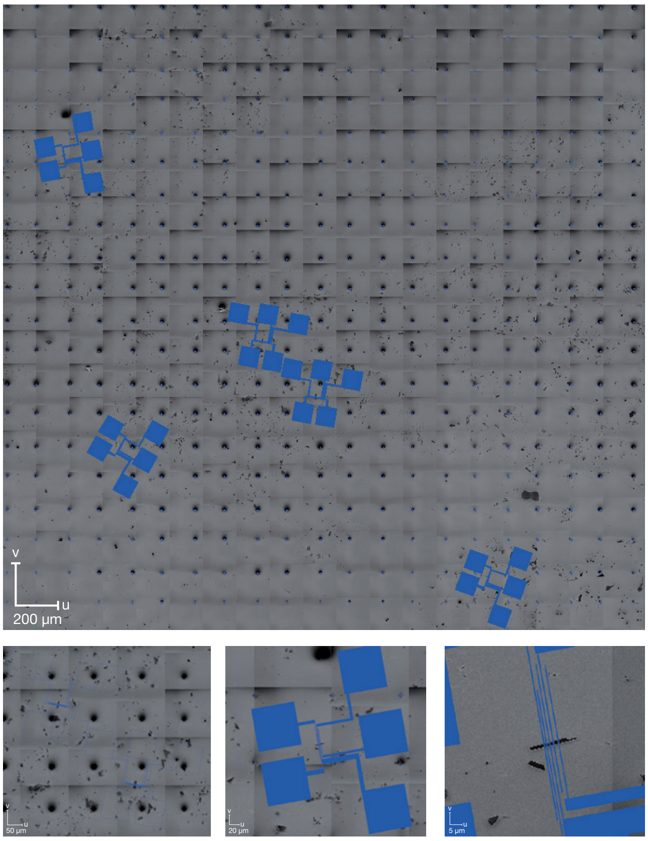

Figure 3 Aligning electrode patterns onto large area SEM image to functionalize selected graphene flakes

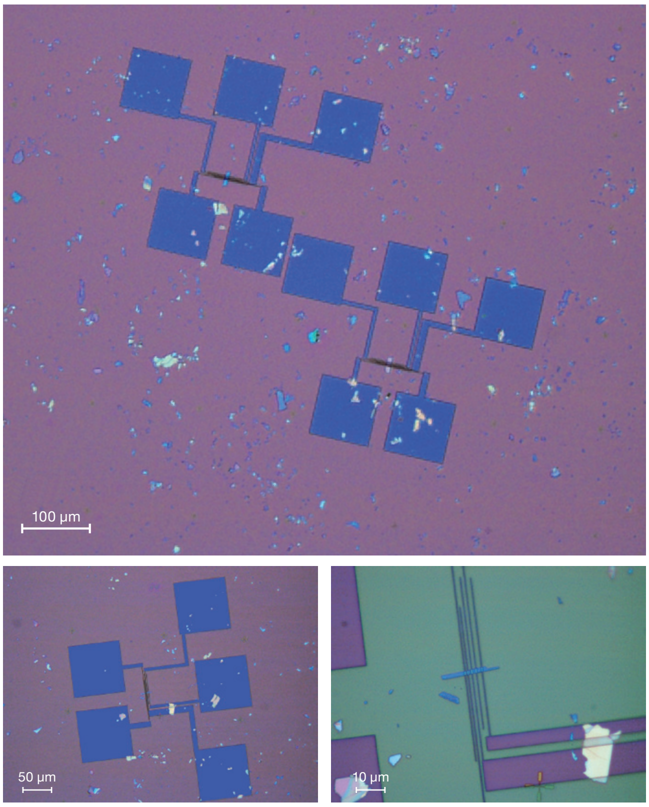

Figure 4 Lift-off mask for electrodes defined by electron beam lithography with precise placement

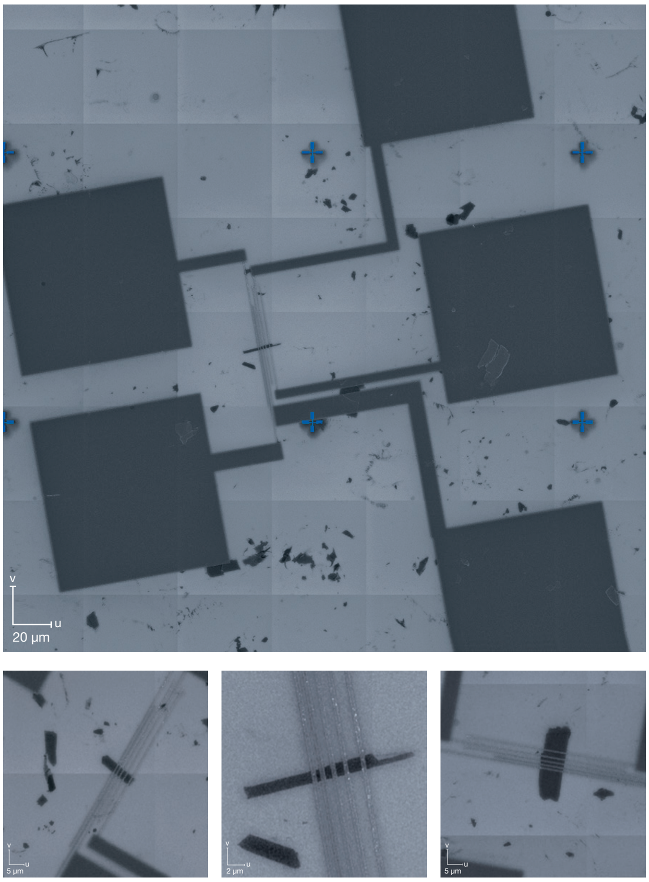

Figure 5 Metalized electrodes functionalizing selected graphene flakes

ration based on optical imaging for coarse localization of the graphene flakes and SEM imaging for accurate localization in combination with GDSII-based direct alignment of patterns to imported images have enabled this nanofabrication challenge to be outstandingly mastered a splendid mastering of this nanofabrication challenge. The details of the applied workflow are as follows:

Figure 6 Coarse optical localization of flakes

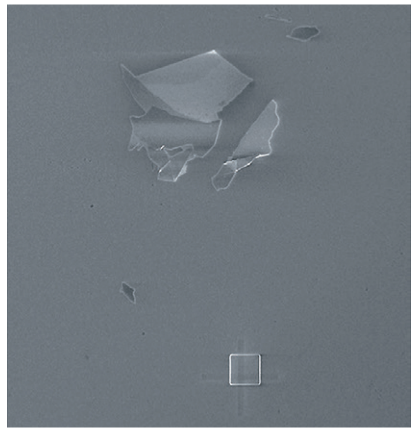

Figure 7: Fine SEM-based localization of flakes

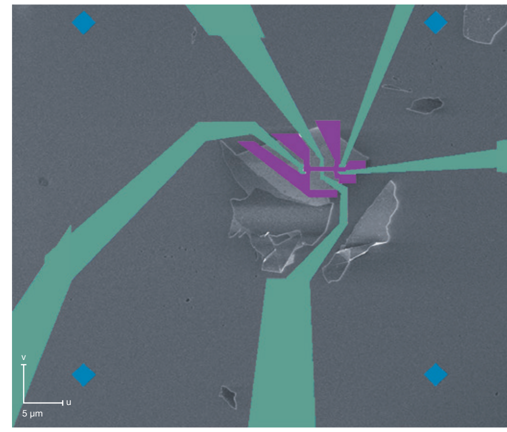

Figure 8: Electrodes and etch mask definition

Step 1: Coarse optical localization of flakes

Optical localization of mechanically exfoliated graphene flakes on 90 nm SiO_2 on top of highly doped Si substrate. The substrate has been pre-patterned with squared marks for easy relocation (fig. 6).

Step 2: Fine SEM-based localization of flakes

Mark-based automatic SEM imaging of the graphene flakes selected for device fabrication (fig. 7).

Step 3: Electrodes and etch mask definition

Import of the collected SEM images into the GDSII editor and direct drawing of electrodes (“layer 1, green”) and etch mask (“layer 2, purple”) onto the imported underlying SEM images, plus incorporation of additional alignment marks (“layer 3, blue”) to accurately overlay the plasma dry-etch step onto the electrode deposition step (fig. 8).

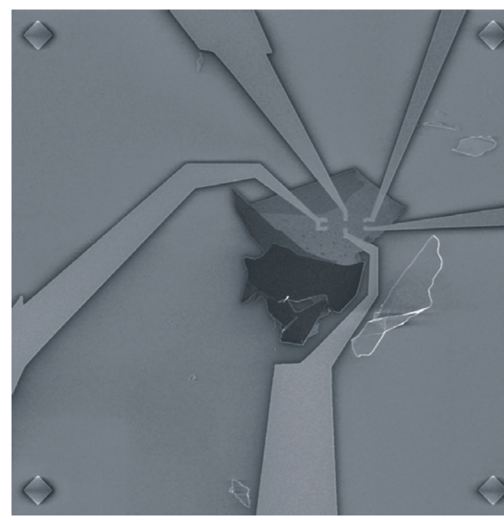

Figure 9: Electrode patterning and metallization

Step 4: Electrode patterning and metalization

The substrate including the graphene flakes were covered with PMMA 950k, followed by mark recognition for precise placement of the electrode-defining EBL pattern (“layer 1”) onto the graphene flakes and the additional diamond-shaped alignment marks (“layer 3”), followed by resist development, metal evaporation, and lift-off (fig. 9).

Step 5: Etch mask patterning and etching

Another resist layer was applied to subsequently expose the etch mask (“layer 2”) required to structure source, drain, and side gate into the graphene sheet. For accurate placement of the etch mask with regard to the electrodes, diamond-shaped marks were employed for this second exposure step (fig. 10).

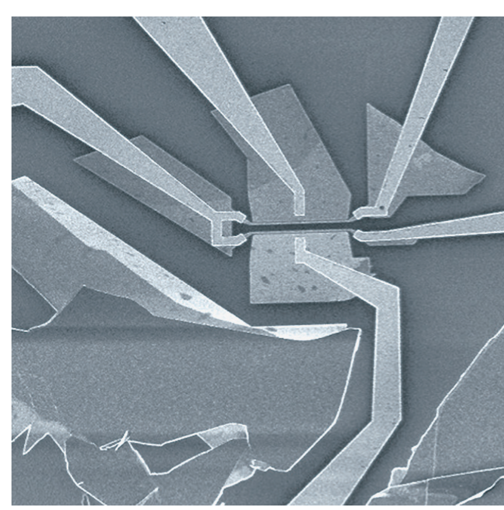

Figure 10: Completed prototype device structure

Step 6: Performance test of completed device

Figure 10 shows the completed prototype device structure of the graphene-based tripler, with clear separation between the side gates and the adjacent channels.

The fabricated graphene frequency tripler was characterized at room temperature. The graphs show the actual AC input signal of 200 Hz and the measured output waveforms in the time domain (fig. 11).

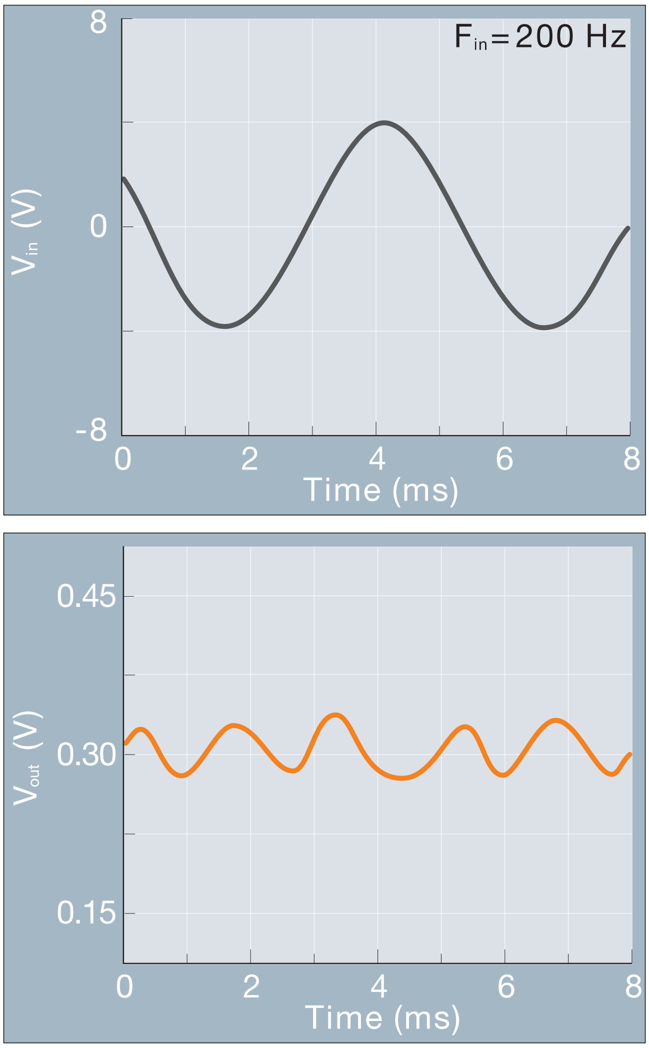

Figure 11 AC input signal (top) and measured output waveform (bottom) of the fabricated graphene frequency tripler

Outlook

Plasma etching is widely used to structure graphene sheets while employing EBL-patterned etch masks. Here, the extremely reactive graphene sheets are exposed to foreign materials such as PMMA or other electron beam resists. Effective resist removal without modifying the properties of the graphene layer still remains a challenge. Thermal annealing has been shown to preserve the distinct characteristics of graphene, but does not always allow entire removal of all resist residues. The remaining extrinsic contamination potentially influences specific properties of the graphene relevant for the device performance.

From there comes the motivation to explore alternative resistless patterning strategies that can be seamlessly incorporated into the workflow described above. Graphene patterning by focused ion beam (FIB) induced surface modification is a promising candidate. Morphology and electronic properties of local nanodefects created by ion irradiation has been demonstrated to exhibit progressive and local amorphization of the graphene monolayer [2].

Employing a dedicated FIB lithography instrument like the Raith ionLINE Plus system enables GDSII-based structuring of graphene sheets with highest precision and control. Embedded mark recognition capabilities facilitate pattern placement accuracy with regard to e.g. pre-patterned gold electrodes. Further advanced lithography features such as traxx [3] allow nanodefects to be created along a single pixel line over millimeter lengths without showing any stitching errors from write field fracturing. These unique, but not yet fully explored patterning capabilities have the potential to enable new, novel devices.

References

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Raith GmbH, Konrad-Adenauer-Allee 8, PHOENIX West, 44263 Dortmund, Germany
phone +49 231 / 95004 - 0, fax +49 231 / 95004 - 460, e-mail: sales@raith.com, website: www.raith.com

Raith America Inc., 1377 Long Island Motor Parkway, Suite 101, Islandia, New York 11749, USA
phone +1 631 738 9500, fax +1 631 738 2055, e-mail: sales@raithamerica.com

Raith Asia Ltd., Two Chinachem Exchange Square, No. 338 King‘s Road, Floor 11, Unit 03, North Point, Hong Kong
phone +852 2887 6828, fax +852 2887 6122, e-mail: sales@raithasia.com

Raith China Ltd., Room 1409, Tower B, Techart Plaza, No.30 Xue Yuan Road, Haidian District, 100083 Beijing, P.R.China
phone: +86 10 828679 22, fax: +86 10 828679 19, e-mail: sales@raithchina.com

Raith India Pvt. Ltd., Sri Krishna Complex, No 36, 2nd Floor, Opposite Mother Theresa School, M. E. S. Ring Road, Bangalore 560054, India
phone +91 80 2838 4949, Fax +91 80 2838 4949, e-mail: sales@raithindia.com