Toward atomic-scale e-beam fabrication: imaging and altering graphene-based devices

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There has been increasing interest in using an electron beam in a scanning transmission electron microscope (STEM) to tailor materials at the atomic scale.[1] While scanning probe microscopy (SPM)-based techniques have revealed exquisite control over atoms on surfaces,[2] the STEM beam offers unique opportunities with regard to the achievable energy transfer and accessibility to the interior of a crystal.[3] However, it comes with its own unique set of challenges as well. Here, we discuss our efforts to leverage a STEM as a fabrication platform, connecting to traditional semiconductor fabrication workflows and providing the precision of the STEM.

A flexible device platform was developed to interface with the electrical contacting STEM holder and provide an electron transparent SiN window for viewing prototype devices. Various geometries of patterned graphene were connected to the electrical contacts and could be electrically characterized *in situ*. Graphene supported on SiN is not visible with conventional high angle annular dark field (HAADF) imaging. To image the supported devices, we used secondary electron beam induced current (SEBIC) to map electrical conductivity with pico amp-level sensitivity. A schematic of the operation is shown in Figure 1. This technique enabled imaging of a single atomic layer of graphene supported on 20 nm of SiN as well as identification of cracks. Suspended graphene was also detectable.

Many interesting properties can be obtained by doping graphene with other elements. A procedure for performing this locally *in situ* was previously developed for Si in graphene.[4] Here, we demonstrate this procedure is more generally applicable to other elements including Pt, Ag, Ni, Fe, Cr, and Ti (Figure 2). Meanwhile, it has been predicted that small pores in graphene may also exhibit interesting properties like magnetism or the anomalous quantum Hall effect.[5,6] Within this context we have developed a control platform for scanning the STEM electron beam in array patterns while simultaneously monitoring detector readout in real-time for feedback control. We demonstrate use of this platform to create nanopore arrays and comment on the possibility of using it to create dopant arrays (Figure 2).

These experiments show a pathway toward atomic-scale device fabrication in STEM. While many challenges remain, the future appears promising.

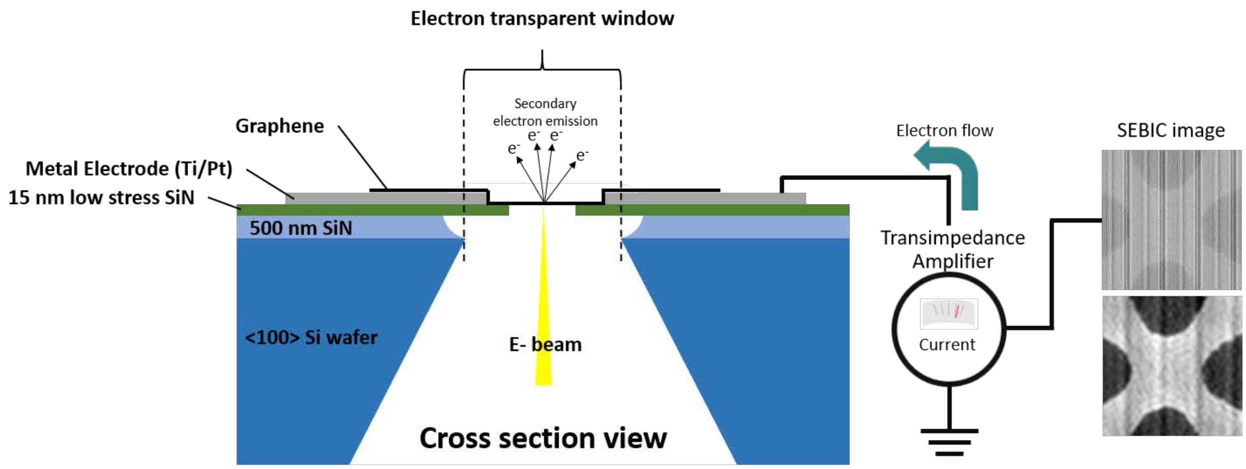

Figure 1 Schematic diagram of the proposed STEM-compatible SEBIC chip and simplified electrical circuit. The e-beam excites electrons from the sample which are emitted as secondary electrons into the STEM vacuum. The sample is grounded through a transimpedance amplifier which enables a measurement of the current flow required to passivate the positive charge building up on the sample. The beam is then scanned across the specimen to create a SEBIC image. This can be done concurrently with conventional ADF imaging to create a one-to-one correspondence between the two modes.

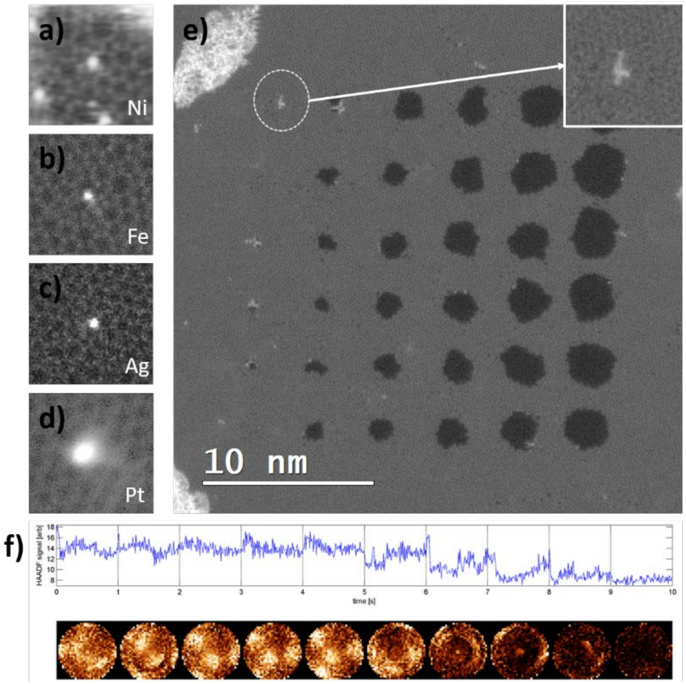

Figure 2 a)-d) example elements inserted in a graphene lattice. e) example array drilled in graphene. The smallest holes often heal incorporating dopant atoms, inset. f) bottom: images acquired during the milling process. Time increases to the right. Top: HAADF intensity measured during each frame.

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