The band gap of graphene nanoribbons (GNR) makes them suitable candidates for sensor devices. Their dimensions (one-atom thickness and widths of tens of nanometers or less) make it difficult to experimentally correlate their electrical properties with changes in their width, edge structure or defect concentration. In this context, we discuss two examples in which GNR-based devices were characterized and also modified within a TEM with the electron beam while an electrical bias was applied.

In the first example, we describe how to fabricate GNR-nanopore devices, which are promising candidates for next-generation DNA sequencing, with the converged electron beam of a TEM [1]. Such devices normally comprise a 2-10 nm diameter pore formed with the beam at the edge or in the center of a 100 nm-wide GNR on a 50 nm-thick silicon nitride membrane. We discuss the changes on GNR conductance when such devices are irradiated with a 200 keV beam and the differences between irradiating with a homogenous (TEM mode) versus a scanned condensed beam (STEM mode). By minimizing the electron dose at 200 kV in STEM mode we were able to prevent electron beam-induced damage and make nanopores in highly conducting GNR. The resulting devices, with unchanged resistances after nanopore formation, can sustain micro ampere currents at low voltages (~50 mV) in buffered electrolyte solution and exhibit high sensitivity, with a large relative change of resistance upon changes of gate voltage, similar to pristine GNR without nanopores (see Figure 1).

It is a truism that before characterizing GNR one must fabricate them, and this is a challenge by itself. In the second example, we describe how to use the condensed beam of a TEM with corrected spherical-aberrations to sputter carbon atoms from predefined areas in electrically-connected free-standing graphene sheets to obtain GNR with sub-10 nm widths [2]. This approach allows us to correlate the lattice and edge structure of sub-10 nm wide GNR with their electrical properties (see Figure 2).

These two examples illustrate the advantages of combining standard TEM observation of GNR-based devices with their electrical biasing as well as the challenges involved in this type of in situ TEM experiment, where chips fabricated with standard lithographic techniques are coupled to TEM sample holders through electrical contacts.


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Fig. 1: (a) Chip-carrier and (b) detail of 200 um-wide SiNx window containing 4 GNR. (c) GNR-nanopore device. (d) HAADF STEM image of a nanopore next to a GNR. (e) HAADF STEM image of a 100 nm-wide GNR. Inset: positioning of the beam at the edge of the GNR with a precision of ~ 4 nm. (f) Resistance of a GNR during nanopore formation.

Fig. 2: (a) Sample holder with mounted chip and (b) detail of 500 nm-wide free-standing GNR. (c) Reduction of GNR width by carbon sputtering with the condensed electron beam. (d) HRTEM image of biased sub-10 nm GNR. (e) Resistance changes as a function of GNR width reduction.