Synthesis of Graphene Nanoribbons from Amyloid Templates by Solid-Phase Graphitization using Gallium as Catalyst and Their Electrical Properties

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Graphene shows great potential as a material for next-generation field-effect transistors (FETs), owing to its high carrier mobility [1]. Developing replicable methods for synthesizing graphene nanoribbons (GNRs) is essential for the realization of graphene-based electronic devices. This is because, owing to the quantum confinement effect, the band gap of GNRs can be controlled by changing their width, making them suitable for use in electronic devices. Researchers have attempted to synthesize GNRs using various "top-down" and "bottom-up" techniques, such as conventional electron-beam lithography [2], the chemical “scissoring” of graphene and/or carbon nanotubes [3], and using self-assembling molecules as templates [4]. However, no replicable technique for fabricating GNRs with widths of less than 10 nm has yet been developed. In this study, we synthesized GNRs by the gallium vapor-assisted solid-phase graphitization of carbonaceous amyloid fibrils, which were used as templates.

The amyloid fibrils, which had an average width of 6.5 nm and were several micrometers in length, were self-assembled from lysozyme from hen's egg albumin. To allow the fibrils to self-assemble, a 5 g/L lysozyme solution was stirred for 9 h at approximately 89–93 °C. The resulting dispersion of amyloid fibrils was dropped onto the c-plane of a sapphire substrate, and the fibrils were rinsed with distilled water and dried by nitrogen gas blow at room temperature. The fibrils, which acted as starting templates, were then transformed into GNRs by being annealed in an atmosphere of gallium vapor at 900–1050 °C. Next, to investigate the electrical properties of the synthesized GNRs, an FET was synthesized using several of the GNRs as the channel; Ti/Au electrodes for the FET were fabricated by conventional e-beam lithography and the lift-off process. The electrical characteristics of the FET were measured by applying an electrochemical gate potential via an ionic liquid (1-butyl-3-methylimidazolium hexafluorophosphate).

Figure 1 shows an atomic force microscopy (AFM) image of the amyloid fibrils before and after their graphitization at 1000 °C. It can be seen that the amyloid fibrils, which were over 1 μm in length, were arranged in line with the direction in which nitrogen gas was blown over the sapphire substrate. The typical thickness and width of the fibrils were 4 nm and less than 10 nm, respectively. After graphitization, the amyloid fibrils, which acted as templates, transformed into GNRs that were typically 1 nm thick but of the same length and

width as the fibrils. Figure 2 shows the Raman spectra of GNRs synthesized at different temperatures. With an increase in the graphitization temperature, the G and D peaks tended to drift apart. In addition, a distinct 2D peak was noticed in the spectrum of the GNRs synthesized at 1050 °C. Figures 3 (a) and (b) show a typical scanning electron microscopy (SEM) image of the FET based on the GNRs synthesized at 950 °C and its conductance as a function of the gate potential, respectively. The GNRs-based FET exhibited n-type characteristics, and the ratio of its maximum conductance to its minimum conductance was 3.7. That the FET exhibited n-type characteristics can probably be attributed to the impurities contained in the amyloid fibrils.

References

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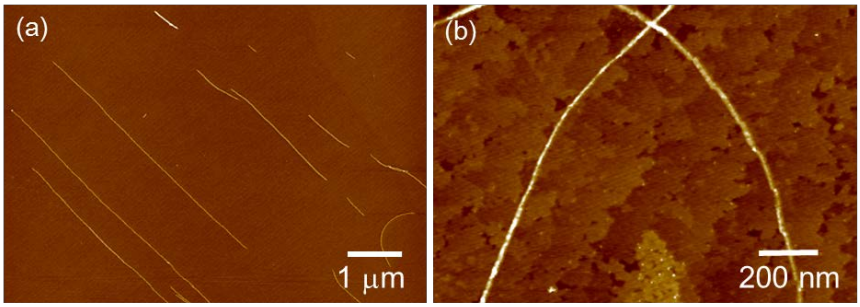

Figure 1: AFM images of amyloid fibrils on the sapphire substrate (a) before graphitization and (b) after graphitization at 1000 °C.

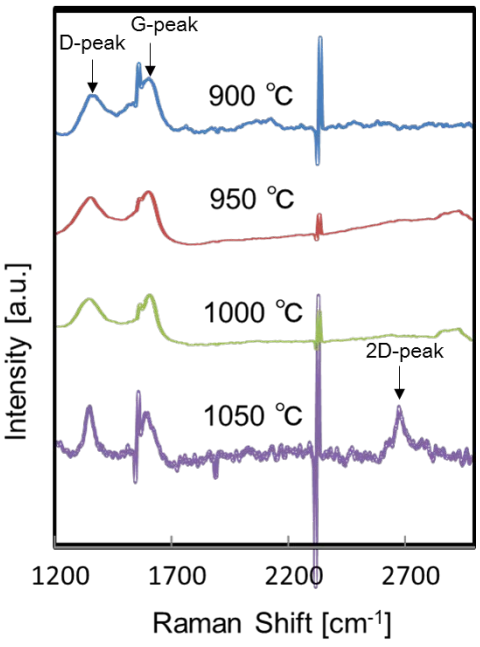

Figure 2: Raman spectra of GNRs synthesized at different temperatures.

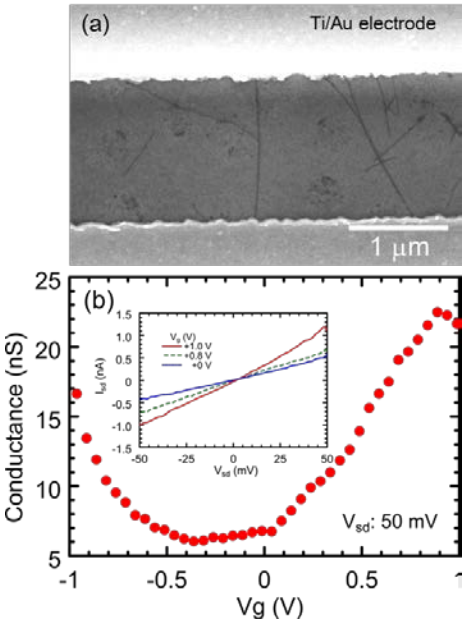

Figure 3: (a) SEM image of the FET based on the GNRs synthesized at 950 °C and (b) the gate-potential dependence of the conductance of the FET for a fixed source-drain bias (V_{sd}) of 50 mV. Shown inset are the I_{sd}-V_{sd} curves of the FET at various gate potentials.