Student Paper

High-Performance Graphene Nanoribbon Interconnects for Sub-10 Nanometer Half-Pitch Nodes

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The electrical performance of atomically resolved monolayer and few-layer graphene nanoribbons (GNRs) at feature sizes below 10 nm was explored to assess the material as a next-generation VLSI interconnect. We observed record-high sustained current per unit width for few-layered GNRs (~50 μA/nm) with a maximum current of 147 μA for a sample width of 3 nm, corresponding to an area current density of ~4×10^9 A/cm^2. Sub-10 nm suspended monolayer GNRs were found to support current densities in excess of 10^8 A/cm^2, however showed an order of magnitude lower current capacity and conductance in comparison to few-layer GNRs. Additionally, few-layer GNRs showed resistivity on the same order of magnitude as bulk copper, while monolayer graphene exhibited reductions in resistivity with narrowing width, in agreement with theory [1]. The low resistivity and superior current carrying capacity of GNRs show that the material is suitable for high-performance next-generation interconnects and is a potential Cu replacement.

Experiments were based on suspended graphene nanoribbons fabricated and electrically characterized within a transmission electron microscope (TEM) [2]. Briefly, few-layer (~4-10) and monolayer graphene was controllably grown on high purity copper using atmospheric pressure chemical vapor deposition (CVD). The graphene sheet was transferred onto a micromachined Si_3N_4 membrane with a predefined slit and patterned into a freely-suspended ribbon connected to large area contacts using conventional ebeam lithography (Fig. 1a,c). The electron-transparent Si_3N_4 membrane allowed compatibility within a TEM. Samples were mounted on a TEM holder with electrical feedthroughts to allow for simultaneous electrical biasing and imaging, providing the platform to quantitatively correlate the ribbon's physical and electrical properties (Fig. 1b). To reduce the graphene ribbon to relevant length scales, a 300 keV focused TEM electron beam was used to progressively and controllably narrow the ribbon, while its electrical properties were characterized *in-situ* (Fig. 1d) [3]. Continued sculpting leads to sub-10 nm monolayer and few-layer GNRs (Fig. 2).

The electrical properties of both monolayer and few-layer graphene devices at sub-10 nm critical dimensions were measured. Fig. 3a shows the measured current density as a function of width for a series of suspended monolayer and few-layer GNRs, showing current densities exceeding 10^8 A/cm^2 and 10^9 A/cm^2, respectively, surpassing projected milestones set by ITRS beyond 2026 [4]. Sustained current per nanometer (Fig. 3b) demonstrates that few-layer GNRs can support over an order of magnitude greater current capacity in comparison to monolayer GNRs of the same width, which we attribute to the ribbon's capability to form sp^2-bonded edges and structurally recrystallize with its surrounding carbon atoms [5-6]. This allowed few-layer GNRs to sustain constant conductance of ~$G_0=e^2/h$ until device breakdown (Fig. 3c) and a maximum current of 147 μA at a width of 3 nm (Fig. 2c). Monolayer GNRs, lacking additional carbon layers, did not restructure with narrowing width and reduced in conductance due to increased scattering from the edge (Fig. 3c). Resistivity was measured for sub-10 nm nanoribbons and compared to copper's bulk resistivity and theoretical resistivity at equivalent length-scales (Fig. 3d). Few-layer GNRs demonstrated resistivity similar to bulk Cu while monolayer GNRs showed reduced resistivity with narrowing width, as predicted theoretically for zigzagged edge sub-10 nm ribbons [1].

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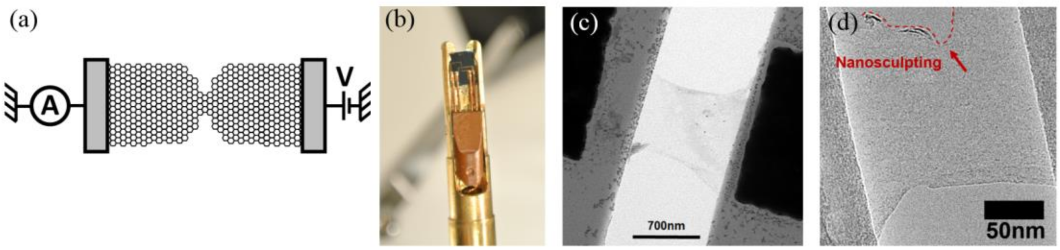

Figure 1: **a)** Schematic of device layout and measurement setup. **b)** Image of sample mounted on a TEM holder with electrical feedthroughs. **c)** TEM micrograph of a free-standing graphene ribbon contacted by Au source-drain electrodes (appears black), supported on a Si_3N_4 membrane. **(d)** TEM micrograph of a graphene ribbon after nanosculpting with the ablated region highlighted in red.

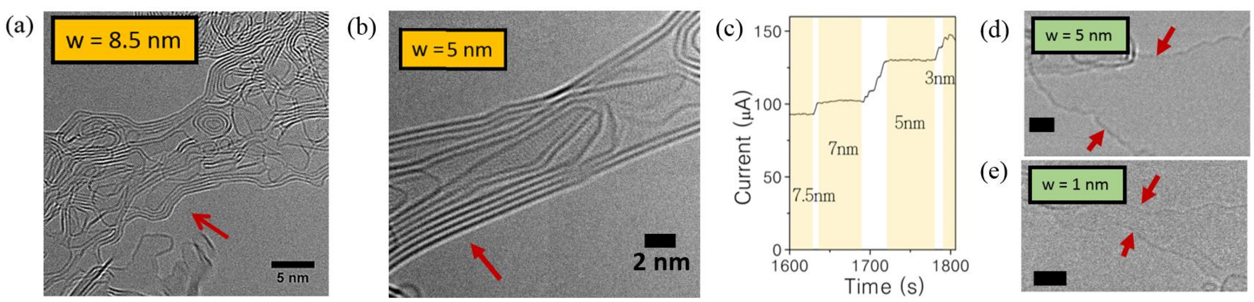

Figure 2: **a-b)** Consecutive TEM mircographs of few-layer GNRs undergoing structural transformation and width reduction from 8.5 nm to 5 nm. Arrows indicate the recrystallization and later smoothing of an edge, allowing for the reduction of scattering as width decreases. The dark contrast edge (in comparison to monolayer graphene) is due to expected sp^2-edge-bonding between interlayers. **c)** Time evolution of few-layer GNR sustained current with varying widths. Measured width values are extracted from correlated TEM micrographs. **d-e)** Consecutive TEM micrographs of monolayer GNRs from 5 nm to 1 nm in width. Scale bar is 2 nm.

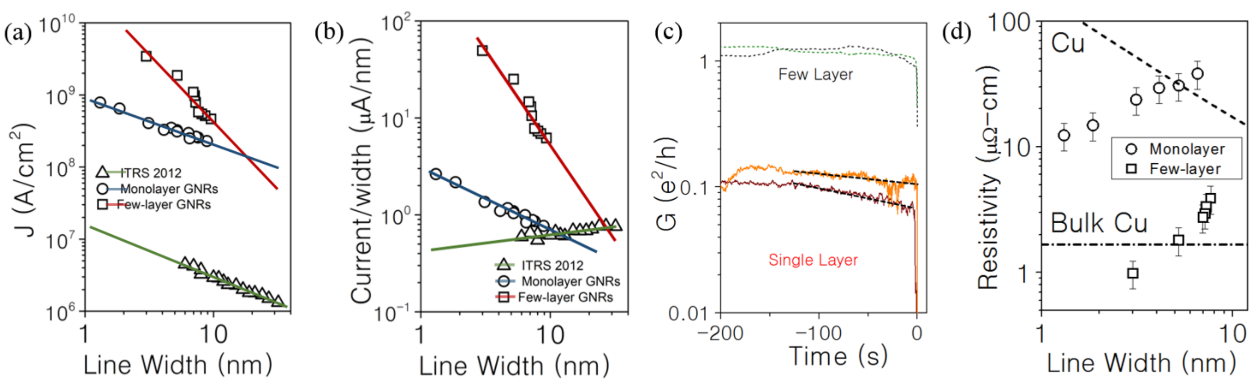

Figure 3: **a)** Current density of few-layer and monolayer GNRs as a function of device width, compared to the ITRS 2012 Interconnect Technology Requirements benchmarked from 2012-2026. **b)** Current sustained per nanometer-width for few-layer and monolayer GNRs as a function of device width, compared to the ITRS 2012 Interconnect Technology Requirements. **c)** Conductance as a function of time until breakdown (t=0) for monolayer and few-layer GNRs. **d)** Resistivity as a function of line-width for Cu (theoretical), measured monolayer and few-layer GNR, and bulk Cu.