Electronic Transport of Recrystallized Freestanding Graphene Nanoribbons

-- Supporting Information --

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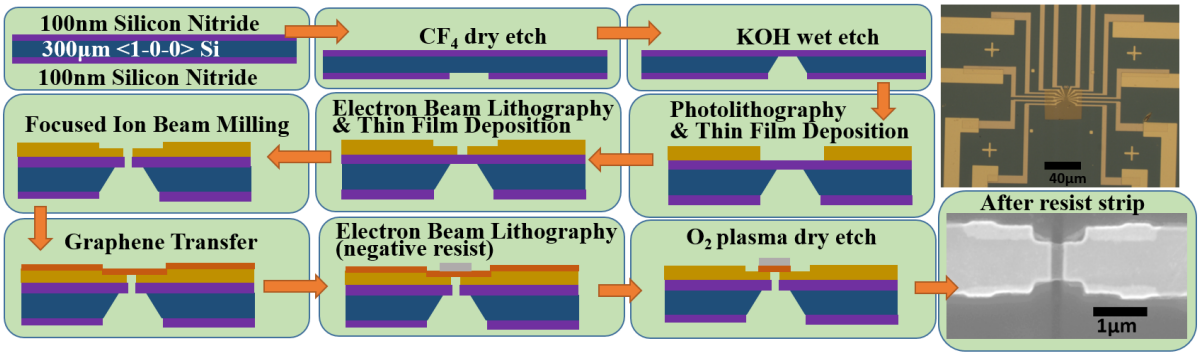


Figure S1. Process flow for device fabrication along with an optical micrograph of a completed TEM-compatible chip. SEM micrograph shows a suspended graphene ribbon contacted by Au source-drain electrodes.

Calculations for sputtering rate of C atoms from the electron beam

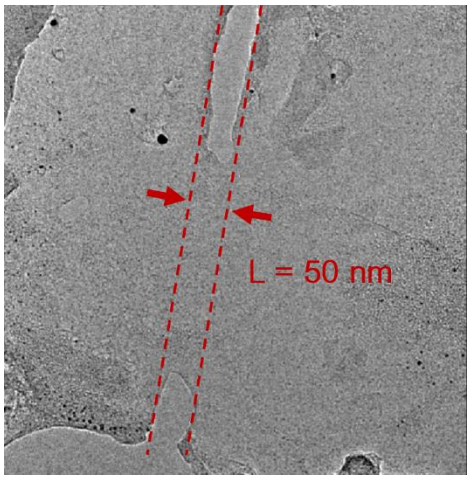
The displacement rate per atom is defined as $p = \sigma \times j$, where σ is the cross section for atom displacements and j the electron beam current density. Considering a current density of $j \sim 100$ A/cm^2, as in our imaging experiments, and $\sigma = 2.8 \times 10^{-27}$ m^2 (for a 15 eV threshold displacement energy[1]), the value for $p \sim 0.02$ displacements per C atoms in one second. For GNRs under high bias the displacement rate should be less than this, considering that the high temperature of the system allows filling of vacancies from nearby diffusing C atoms. Therefore, in 1 minute each atom of C should be displaced of order 1 time during observation. A stacked bonded bilayer GNR (Fig. 3a) under zero bias would require more than 1 hr of electron irradiation to fully collapse at 300 keV conditions. In our experiments, the time to breakdown was much shorter, less than 8 min, even under elevated temperatures that allowed for self-repair.[2, 3] For GNR cutting, the current density was increased two or three orders of magnitude.

Calculation of GNR thermal dissipation

We reference Eq. 3 from V. Dorgan *et al.*[4]:

$$T_{BD,vac} = \left(T_0^{1-g} + \frac{P_{BD} L (1-g)}{8 k_0 T_0^g W t} \right)^{\frac{1}{1-g}}$$

Where $T_{BD,vac}$ is the temperature before breakdown of a suspended GNR in vaccuum, γ is a fitting parameter measured to be 1.7 for CVD graphene, P_{BD} is the power sustained before breakdown, L, G, and t are the length, width and thickness of the GNR, respectively, and κ_0 is the thermal conductiviy at $T_0 = 300$ K. For the GNR in Fig. 1d, we define L = 50 nm (see reproduced figure below), W = 3 nm, t = 1.3 nm and κ_0 = 2000 $W/m^{-1}K^{-1}$ (measured for CVD graphene[4]). This provides a breakdown temperature of ~2150 K.



Red guiding lines superimposed on Figure 1d from main text.

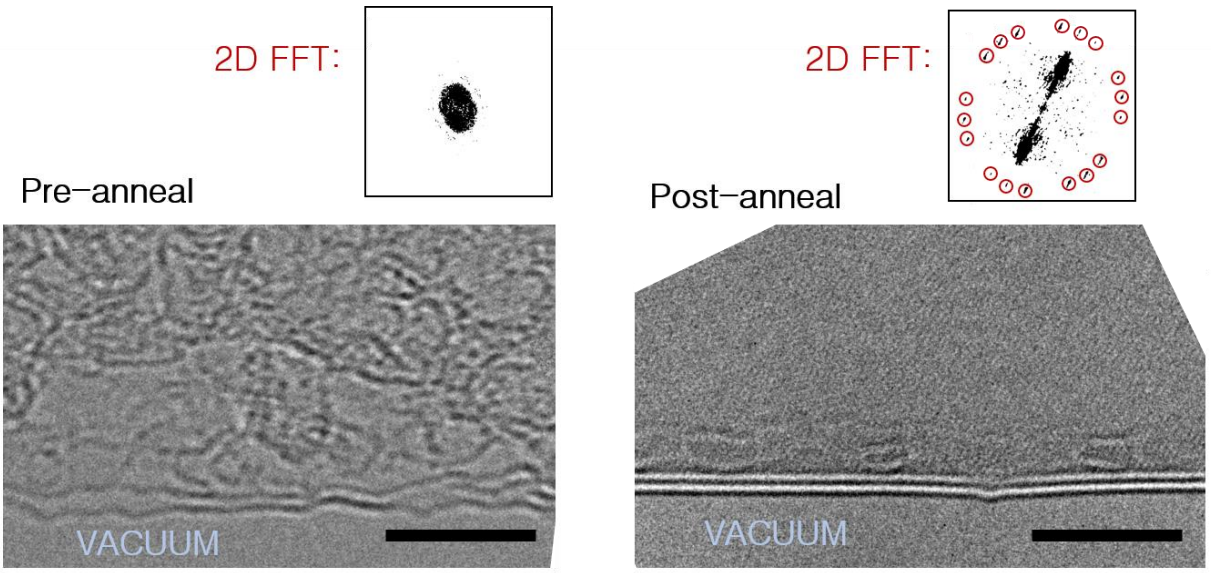


Figure S2. High-resolution TEM micrographs of GNR edge before and after annealing. After annealing, the edge is highly crystalline and sharp. Insets are corresponding 2D FFTs of the GNR image, with post-annealed devices showing three distinct 6-fold FFT peaks (shown by red circles), indicating a multi-layer graphene structure. Scale bar is 5 nm.

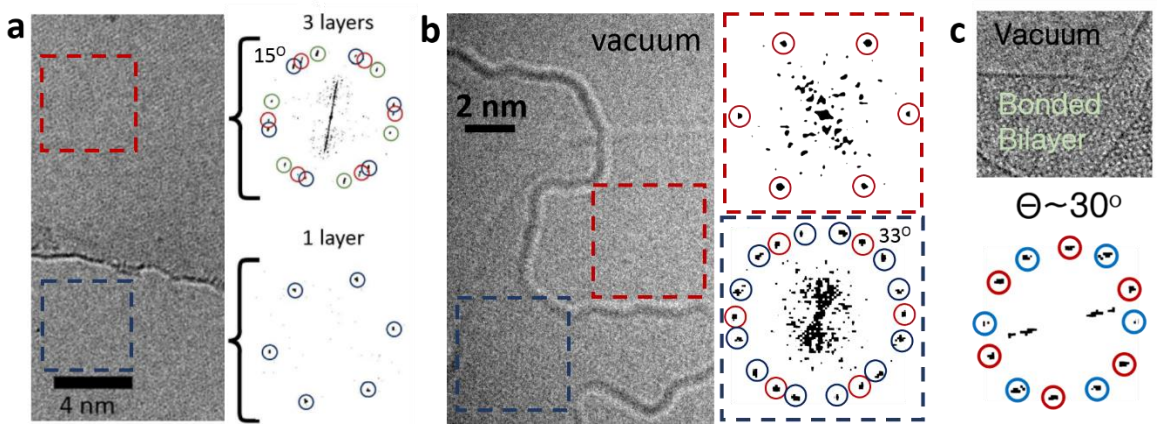


Figure S3. TEM images of bonded bilayers and analysis of their twist angles. **(a)** TEM image of a three-layer graphene sheet (upper region) and a single layer graphene sheet (lower region) separated by a single sp^2-bonded edge. Layer numbers for the two regions are extracted from the 2D FFTs associated with the boxed regions, as shown to the right. The bonded bilayer shows a twist angle of ~15° as extracted from the twisted 6-fold peaks in the 2D FFT. **(b)** TEM image of a three-layer graphene sheet (bottom) and a single layer graphene sheet (top) separated by a single sp^2-bonded edge. Layer numbers are extracted from the 2D FFT data shown to the right. The bonded bilayer has a twist angle of ~33°. **(c)** TEM image of a bonded bilayer and corresponding 2D FFT. Bonded bilayer shows a twist angle of ~30°.

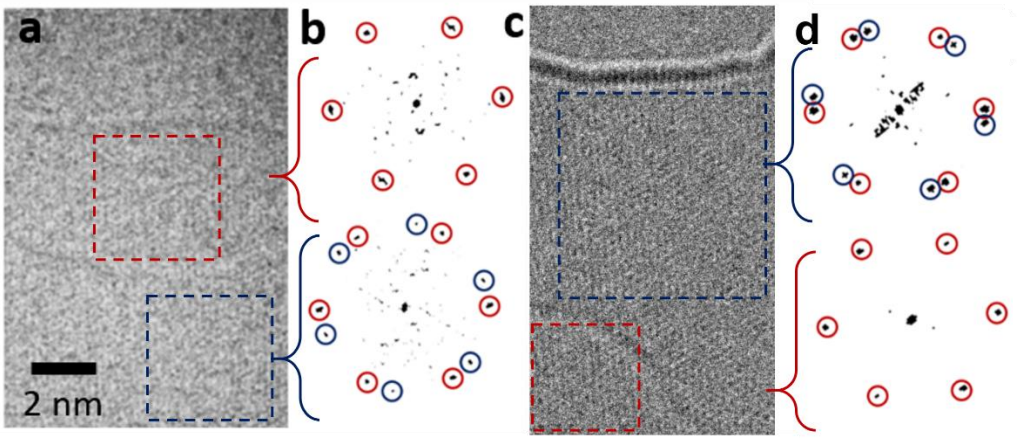


Figure S4. Reproduction of TEM images shown in Figure 2 from main text with dotted lines indicating the areas used to generate the 2D FFTs.

REFERENCES

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