Supporting Information for

Reliability Enhancement of Germanium Nanowires Using Graphene as a Protective Layer: Aspect of Thermal Stability

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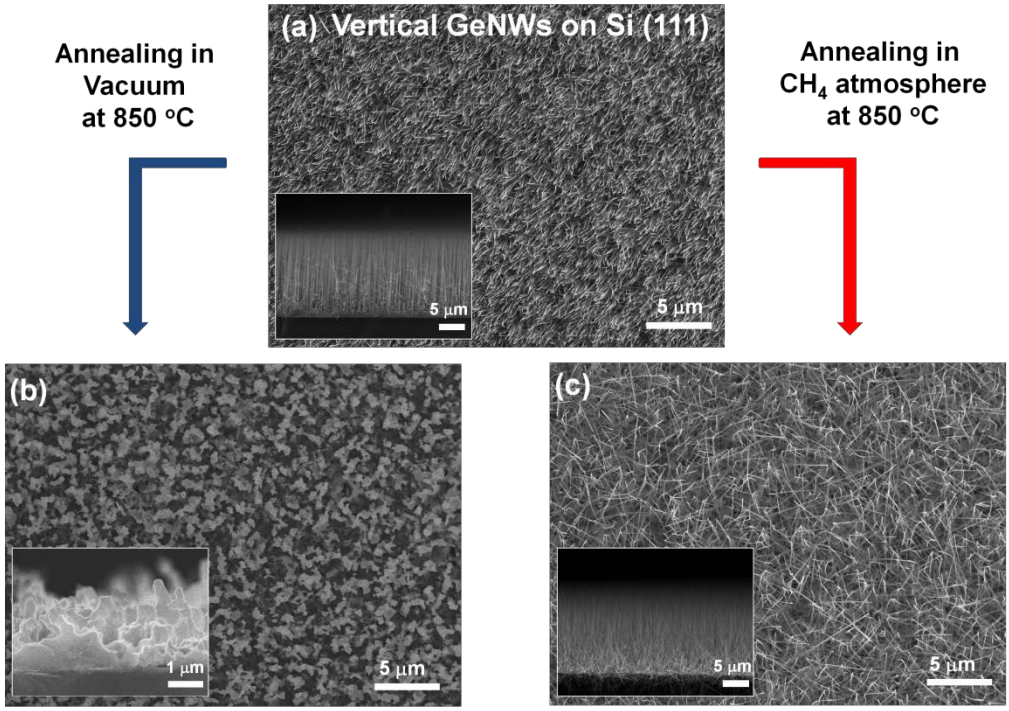

Figure S1. Graphene shell effects. Plan- and cross-sectional- SEM images of (a) vertically grown Ge NWs on Si (111); (b) thermal annealing of Ge NWs in vacuum for 5 min at 850 °C ; (c) thermal annealing of Ge NWs in CH_4 atmosphere for 5 min at 850 °C.

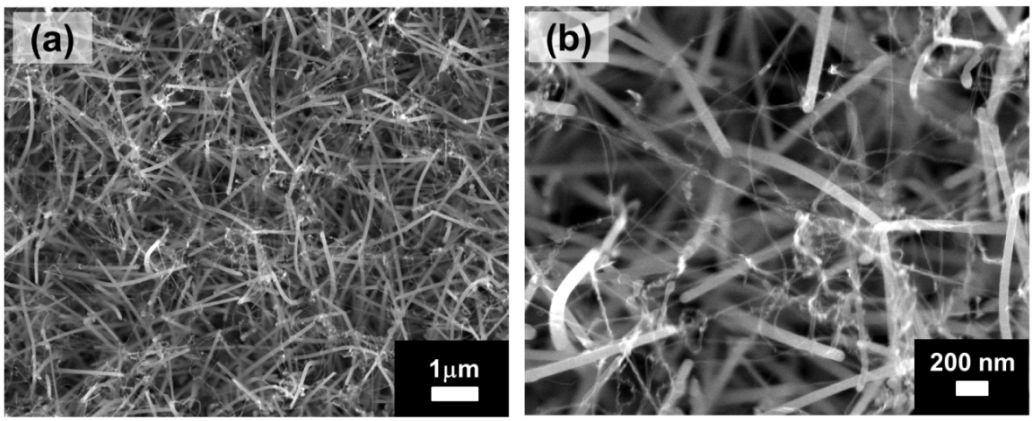

Figure S2. SEM image of Ge@G NWs grown at 900 °C.

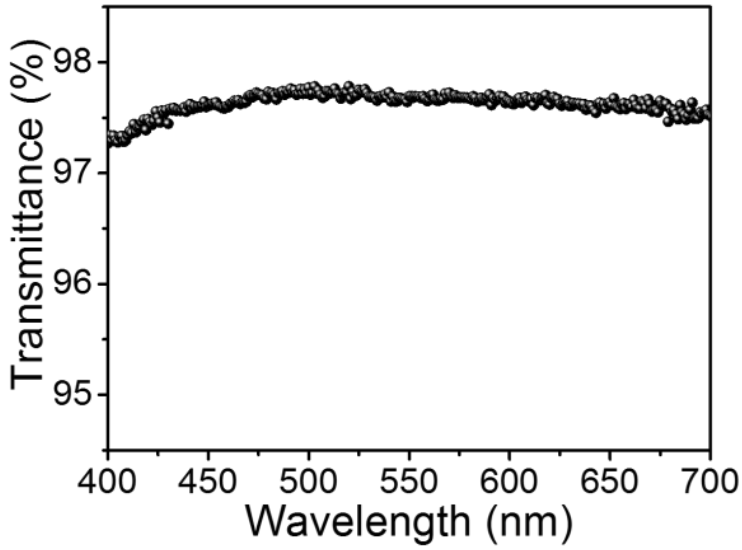

Figure S3. Transmittance of graphene film on quartz plate. Graphene was synthesized on the Ge substrate via a LPCVD technique, explained in experimental section. To transfer the as-grown graphene to the quartz plate, PMMA was used to prevent cracks during the transfer process and the sacrificial layer of Ge film was etched by H_2O_2/HCl/BOE mixture solution (Volume ratio of H_2O_2/HCl/BOE is 1:1:1).

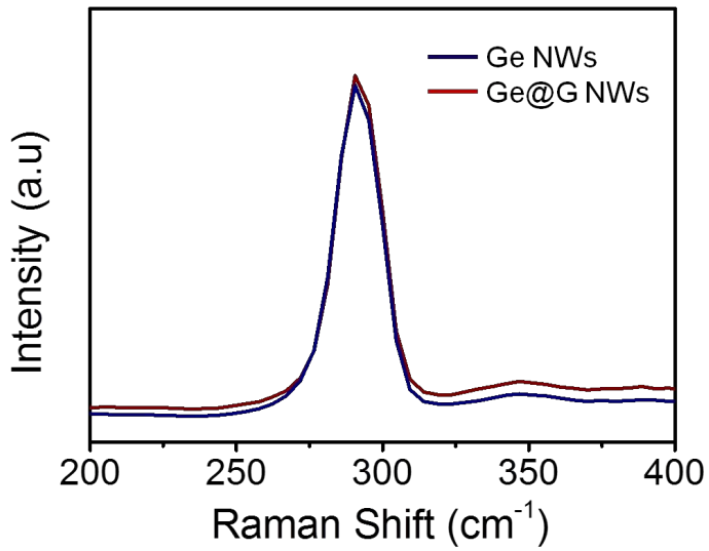

Figure S4. Raman spectra of Ge NWs and Ge@G NWs. From the FWHM of Ge NWs (~19 cm^{-1}) and Ge@G NWs (~20 cm^{-1}), crystallinity of Ge core is not affected by high growth temperature.

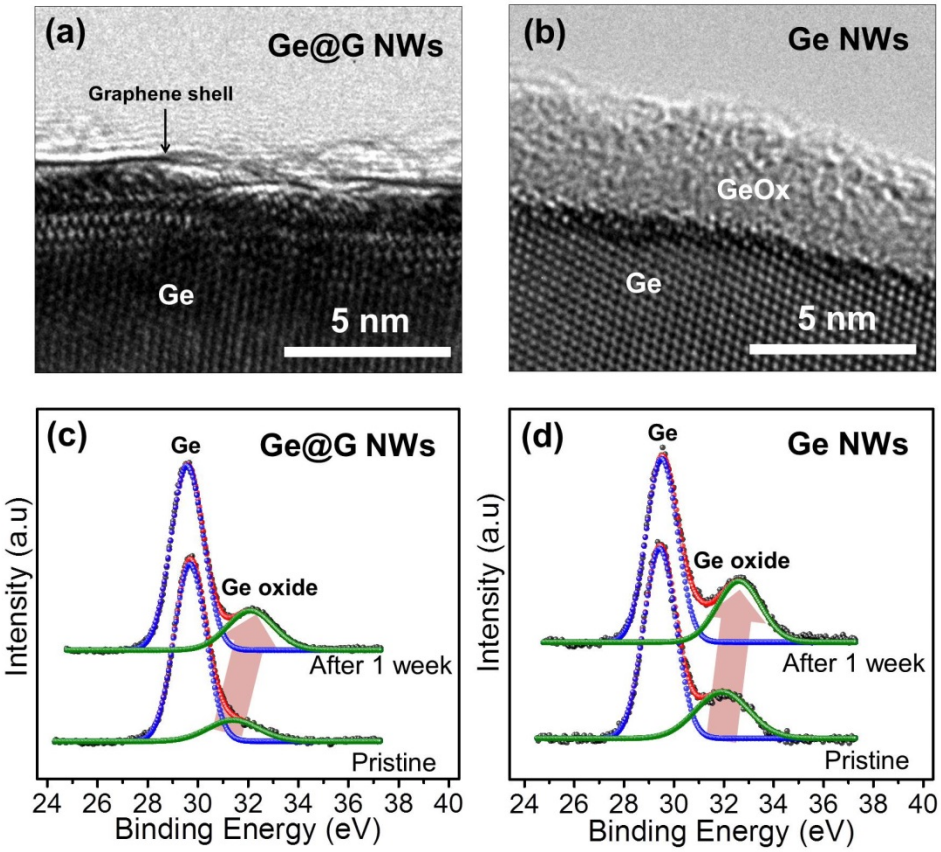

Figure S5. Oxidation behavior of Ge NWs and Ge@G NWs. TEM image of (a) Ge@G NWs and (b) Ge NWs after 1 week exposure in air. XPS spectra of (c) Ge@G NWs and (d) Ge NWs and after 1 week exposure in air.

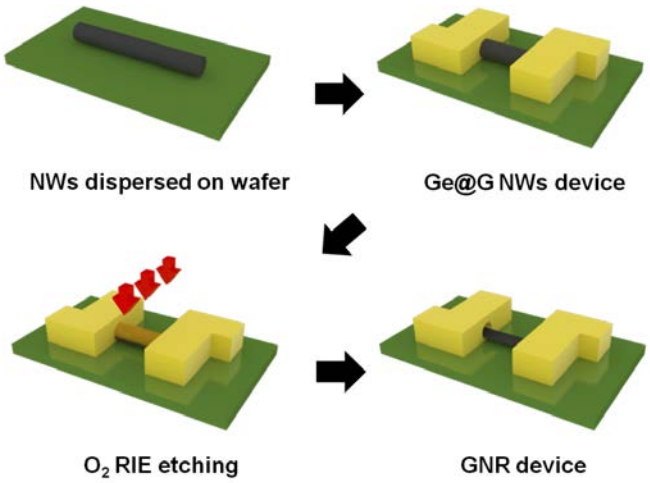

Figure S6. Schematic illustration of the fabrication of single-GNR devices. First, Ge@G NWs were deposited on a p^{++} (100) silicon wafer with 100 nm thick SiO_2. Then, the processes were performed of PR coating, prebaking, UV exposure, development (MF 300) and DI rinsing. Metal electrode material of 10 nm nichrome (NiCr, 80% Ni and 20% Cr) and 140 nm Au was deposited by a thermal evaporator. We used O_2 plasma to etch the graphene shell except at the contact region between the NWs and the substrate. Exposed Ge was etched by pure DI water at 80 °C for 12h, leaving a single GNR.

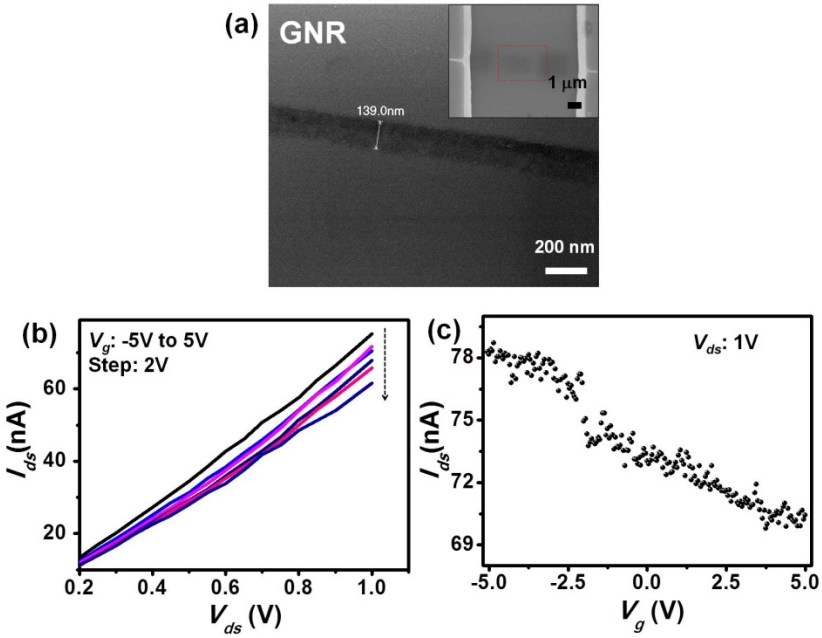

Figure S7. Electrical properties of GNR device; (a) A SEM image of a single-GNR device; (b) current–voltage (I_{ds}–V_{ds}) characteristics at various V_g. (c) Transfer characteristics (I_{ds}–V_g) at V_{ds} = 1 V. The GNR device exhibited p-type behavior with small on/off ratio (~1.13) because the width of GNR is not enough for bandgap opening.

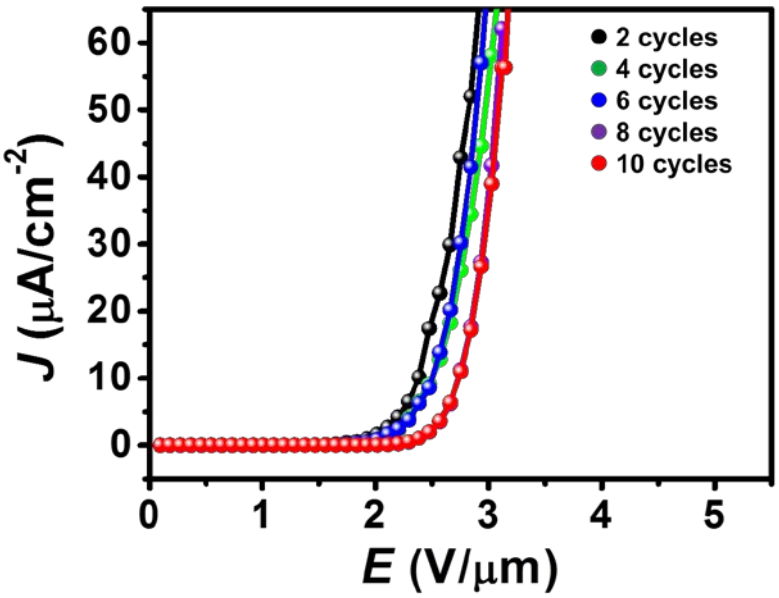

Figure S8. Field emission results of Ge@G NWs. The average turn-on voltage is maintained at 2.25 V with small amount of fluctuation (±0.19 V)

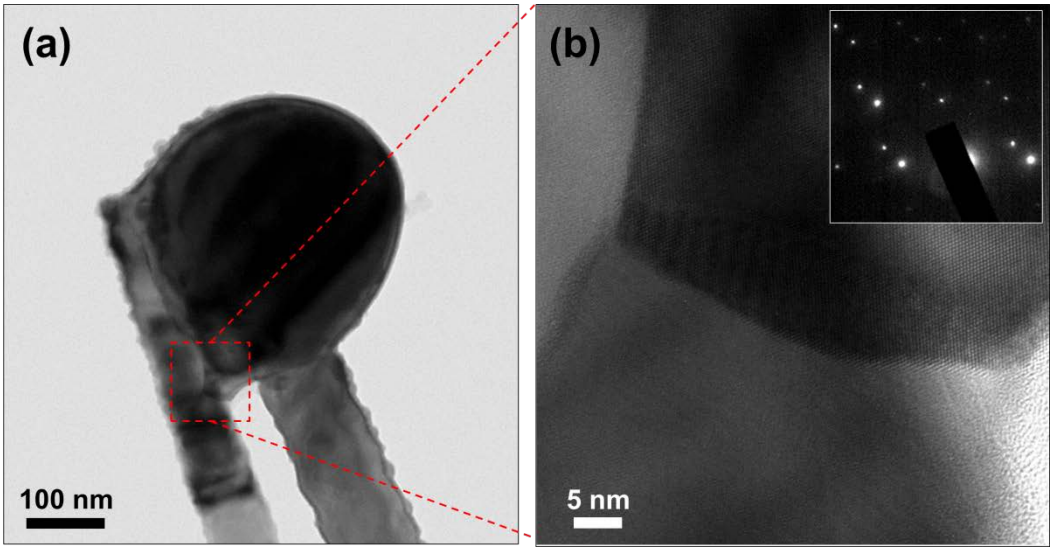

Figure S9. (a-b) TEM images of pure GeNWs after 15 cycles of FE measurement. (Inset of (b)) SAED patterns of welded region of NWs.