Ultrafast Growth of Horizontal GaN Nanowires by HVPE through Flipping the Substrate†

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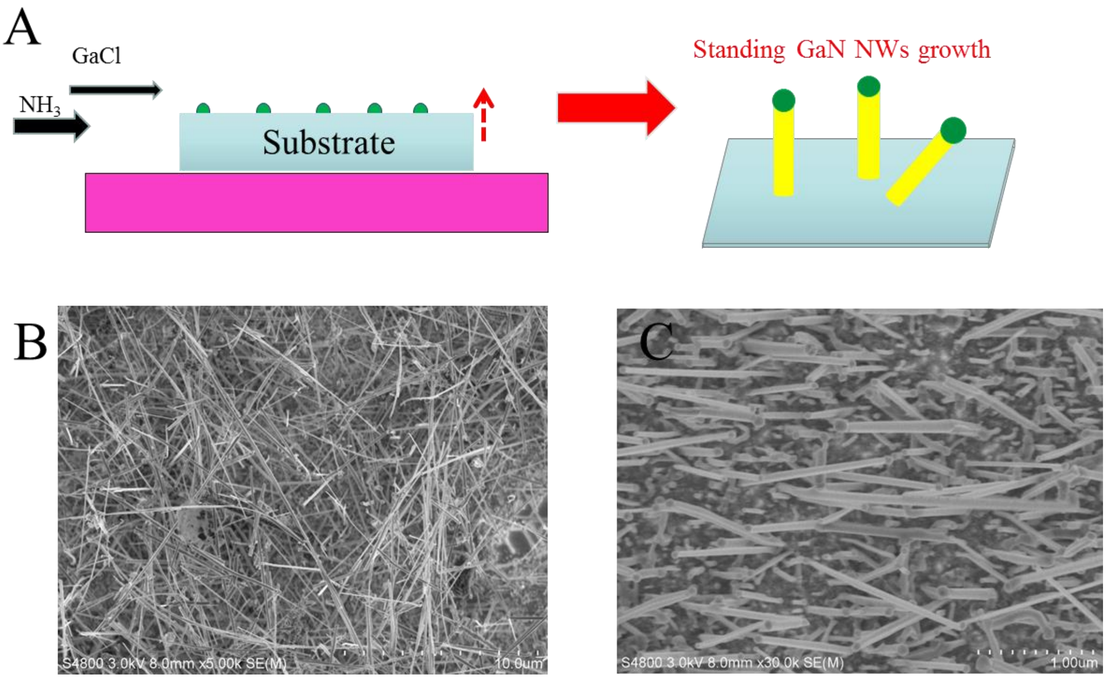

Figure S1. Conventional standing VLS growth with the substrate facing upward (A). Examples of standing NWs SEMs grown on C-plane (B) and R-plane sapphire (C).

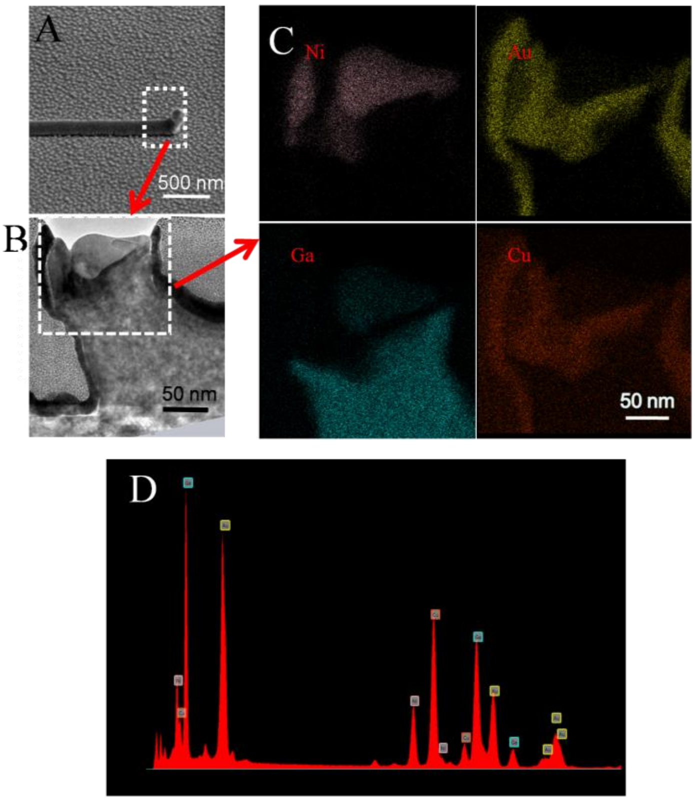

Figure S2. EDX analysis and element map on the GaN nanowire (NW) tip. A and B shows the measured area by the SEM and TEM observation. Gold, nickel,copper and gallium with a different distribution area was observed on the NW tip from EDS mapping (C). These metal elements also been confirmed by the EDS element analysis (D). Here, the copper and most of the gold comes from the FIB sample preparation. The nickel element on the NW tip shows the horizontal NWs is dominated by the VLS mechanism.

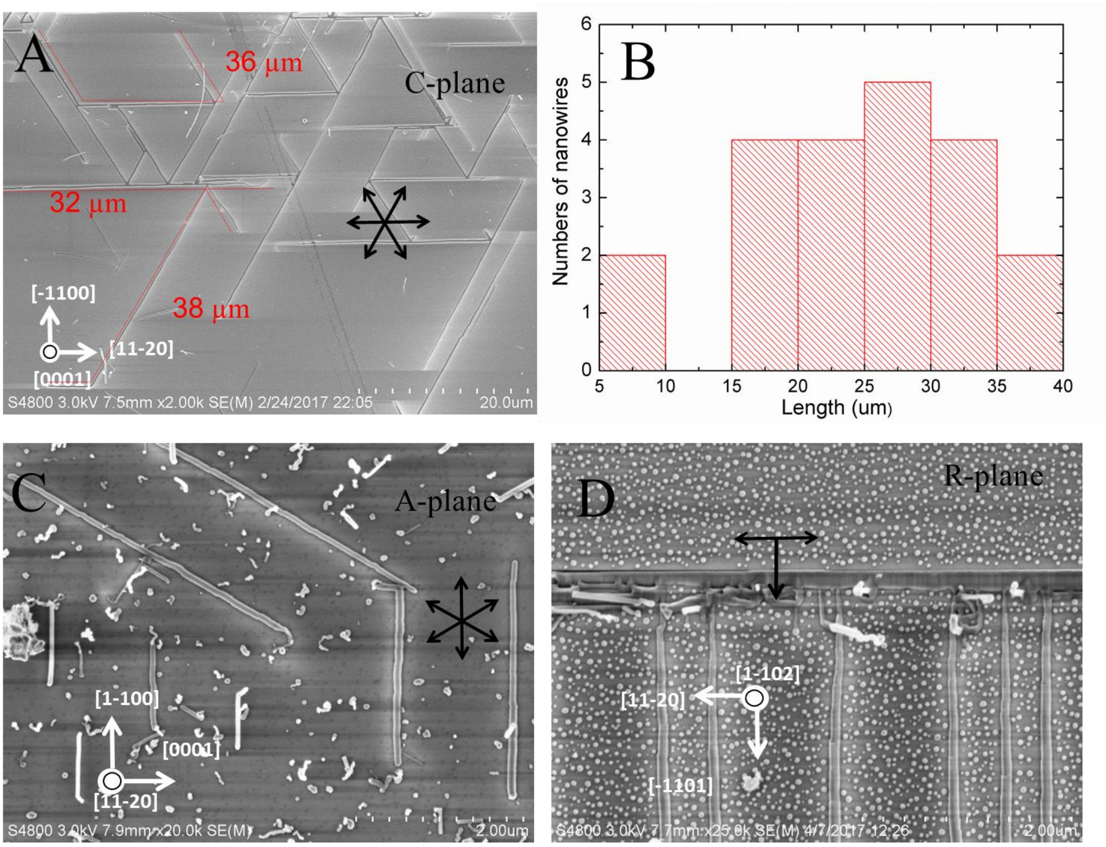

Figure S3. More SEM images of horizontal GaN nanowires grown on sapphires: (A) C-plane, (C) A-plane, (D) R-plane. (B) The histogram of NW length which grown on C-plane sapphire shown in picture A.

As shown in picture A, some of large sized NWs have the length more than 30 μm and the longest reaches to 38 μm. The growth rate of the longest length of NWs is evaluated to be around 400 μm/h, which is threefold faster than that of the standing GaN NWs, representing a record growth rate for either standing or horizontal III-V NWs. The histogram of NW length indicates the NWs length is not uniform which is due to metal drops that are not catalyzed at the same time. The histogram also shows most of the NWs have the length larger than 20 μm. Picture D shows a lots of $[1\text{-}10\text{-}1]_{sapphire}$ axis NWs extended from a $[11\text{-}20]_{sapphire}$ axis NW.

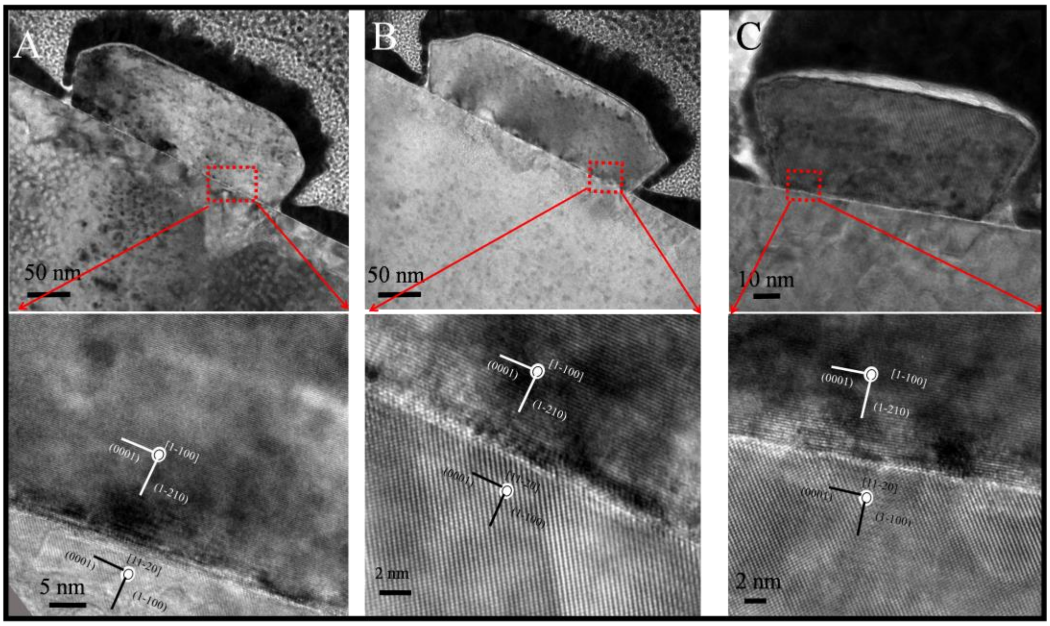

Figure S4. TEM analysis of the horizontal GaN NWs grown on C-plane substrate. All of the NWs have the same epitaxial relationship with the substrate, exhibiting nearly trapezoidal cross section (A-C).

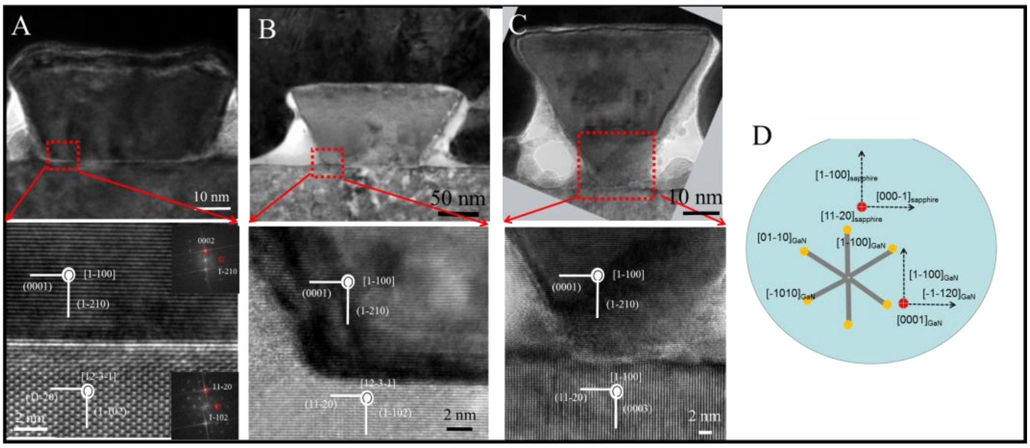

Figure S5. TEM analysis of the horizontal GaN NWs grown on A-plane substrate. All of the NWs have the same growth orientation of m-axis, exhibiting trapezoidal cross section. (A) and (B) Detailed analysis of a m-axis NW along [12-31]sapphire direction (one of the high index directions). (D) Schematic illustration of the epitaxial relationship between GaN NWs and A-plane sapphire.

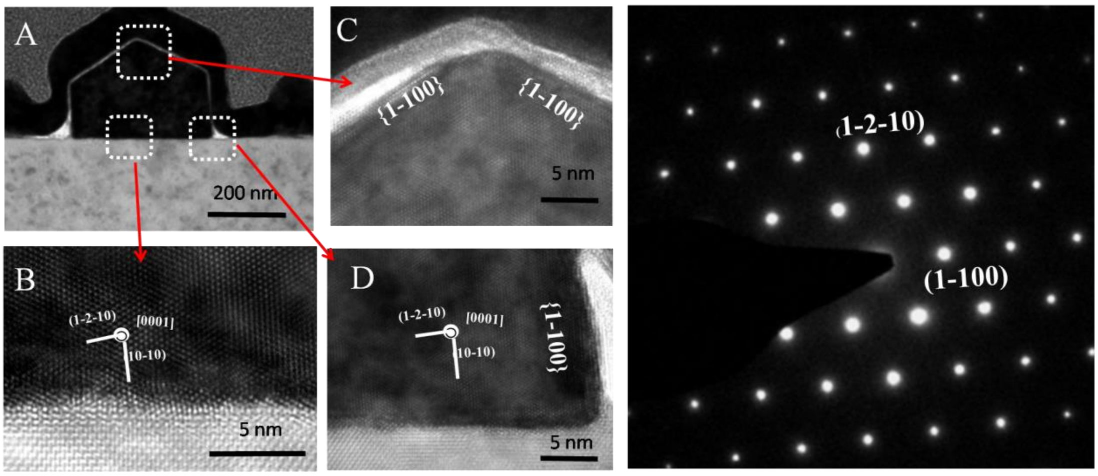

Figure S6. More TEM images of the $[0001]_{GaN}$ axis horizontal GaN NWs grown on R-plane substrate. The NW is high quality with no defects and threading dislocations and exposed four {1-100} planes.

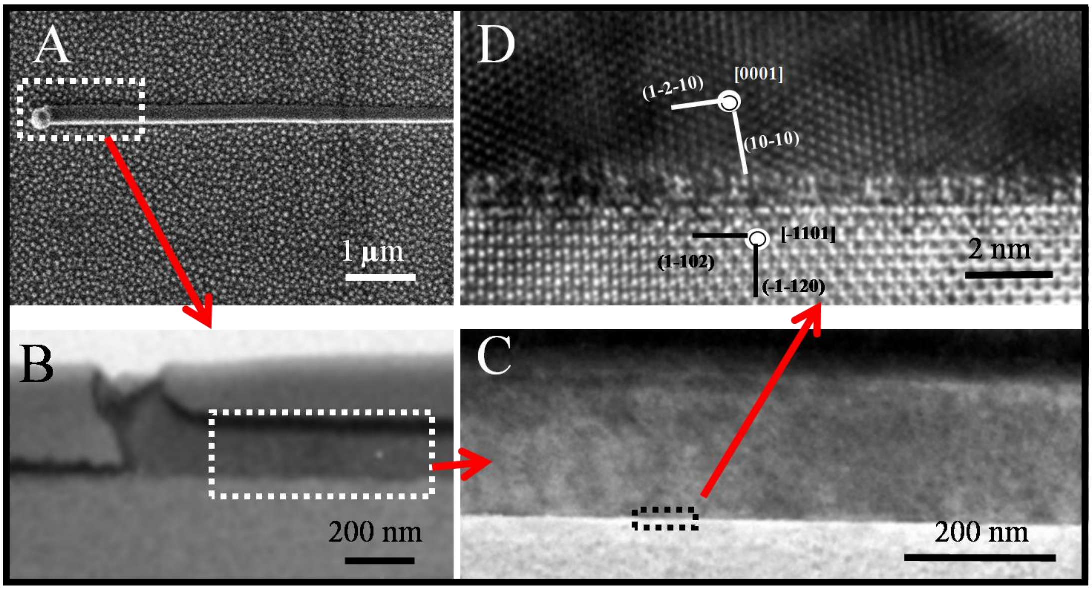

Figure S7. TEM analysis of the m-axis horizontal GaN NWs grown on R-plane substrate. The horizontal epitaxial relations is determined to be (1-210)$_{GaN}$/(1-102)$_{sapphire}$, with [10-10]$_{GaN}$/[1-120]$_{sapphire}$ along the axis of the GaN NWs and [0001]$_{GaN}$ /[-1101]$_{sapphire}$ perpendicular with the axis of the NWs.

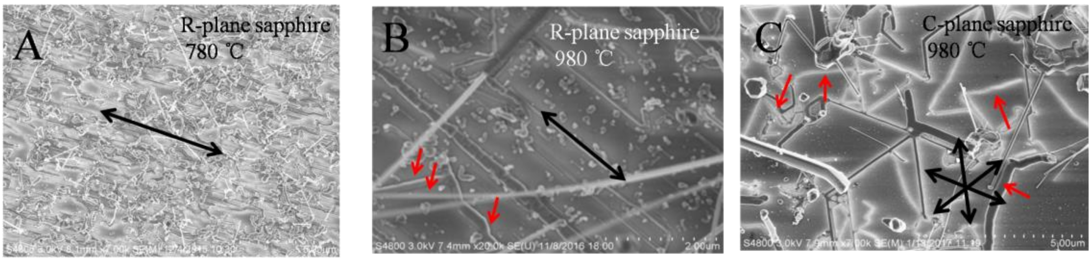

Figure S8. SEM images of horizontal GaN nanowires grown on different sapphires (R-plane and C-plane sapphire) under two different growth temperature (780 ℃) by normally placed substrate with GaCl and NH_3 precursor flow rate to be 4 sccm and 100 sccm. As shown in these pictures, numbers standing NWs and crystal particles were accompanied with the horizontal NWs growth. Some of horizontal NWs which grew in disorder are marked by red arrows.

Horizontal NWs also can be grown on the normally placed substrate by directly reducing the precursor flow. However, under these growth conditions, a few horizontal NWs are unordered and the growth also accompanied with large numbers standing NWs and crystal particles. More experiments will be carried out further in order to fully explain why the flipping situation is more conducive to the growth of horizontal NWs.

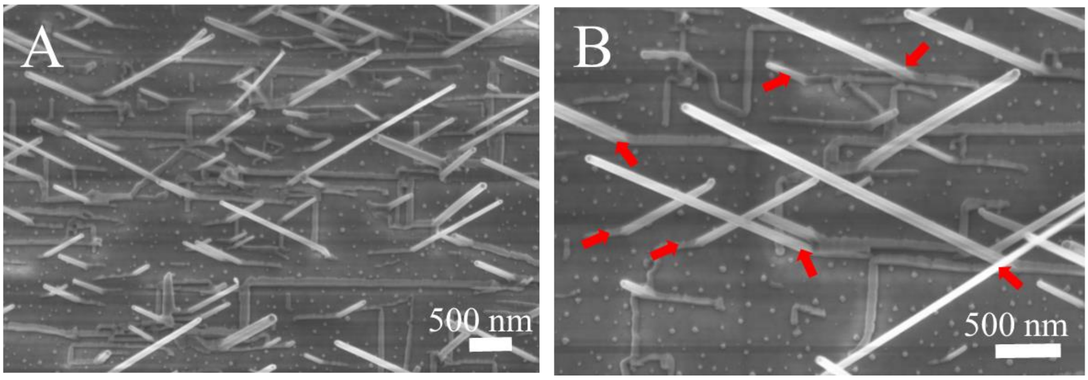

Figure S9. Grazing incidence SEM of the NWs when growth model changes during growth. Red arrows denote the point when growth model of the NWs changes.

It could be found that the horizontal NWs can also grow out of the substrate surface and followed by standing growth. This phenomenon is observed at the substrate edges of the R-plane sapphire. As the local precursor flow on these edges is relatively large, the ±[11-20]sapphire and [1-10-1]sapphire direction horizontal NWs and standing NWs co-exist. However, the rotation of the tray will has a large effect on the substrate edge. As the gas sources are horizontal input, the precursor partial pressure will gradually decreases in the horizontal direction. Thus, the precursor flow near the substrate edges will be changed as the tray is rotated, which leads to the changes of NW growth model.