Plasma-assisted MBE growth of GaN nanowires on ZrN nucleation layers

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Introduction

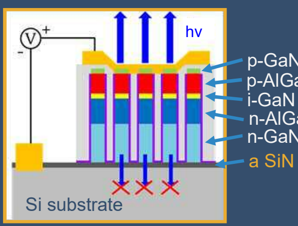
- Metals promising as nucleation layers for nitride-semiconductor nanowires (NWs)
- GaN nanowires grown by plasma-assisted MBE on ZrN nucleation layer deposited on Si(111) substrates
- Due to polycrystalline structure of the ZrN buffer and epitaxial link at the GaN/ZrN interface a random orientation of the NWs is anticipated
- X-ray diffraction and SEM applied to determine alignment of NWs to the substrate

Growth procedure

- Si (111) substrates etched in diluted (2%) HF
- 20 nm ZrN layer deposited on Si(111) by RF sputtering
- GaN NWs grown by PAMBE at ~750ºC under N-rich conditions
- Self-induced nucleation; no catalyst used
- XRD, SEM, AFM and electrical measurements utilized to characterize ZrN nucleation layer and the NWs

Motivation

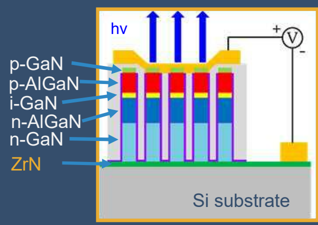
Problems with GaN based LEDs on Si substrates



- SiN amorphous layers inevitably forms at the Si/NWs interface
- Part of the emitted light passes through transparent SiN layer and is lost by absorbtion in the Si substrate which is not transparent in the visible part of the light spectrum
- Nonlinear GaN/SiN/Si electrical junction at the NW/substrate interface
- Unintentional Si doping of the NWs

Expected advantages of ZrN layers for GaN based LEDs

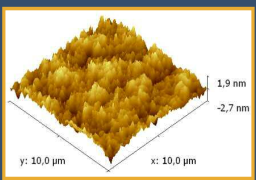
- High electrical and thermal conductivity
- Light emitted towards the substrate gets reflected back due to high light reflectivity of the metallic layer (a buried mirror)
- Low electrical resistance, ohmic electrical contact between ZrN and GaN
- No degradation of the ZrN layer during growth of NWs by PAMBE
- Higher optical output and better electrical characteristics of LEDs expected



III-N NWs on metallic layers - known issues

- Delamination of metal films at hight T Sarawar et al. Small (2015)
- Nanowires are uniformly tilted within a single grain only May et al. APL (2016)
- Conventional metal react with impinging species, mainly Ga – surface roughening
- Diffusion of O from Al_2O_3 substrate up to the top surface of the sputtered Ti and its incorporation into GaN Calabrese et al. Nanotechnology (2019)
- Nitridation of Ti films/foils preceding NW growth improves stability but does not provide a full protection from reactions with Ga Calabrese et al. APL. (2016)

Properties of ZrN nucleation layers

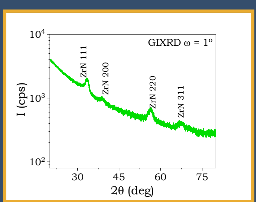


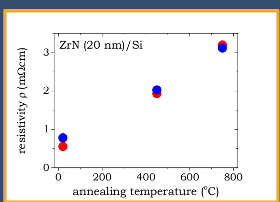
Preparation of ZrN films on Si

- 20nm thick films deposited on Si by RF sputtering from a ZrN target
- Ar atmosphere
- Substrate kept at RT
- No substrate bias applied
- Deposition rate 0.3 nm/s

Characterization of the ZrN layers

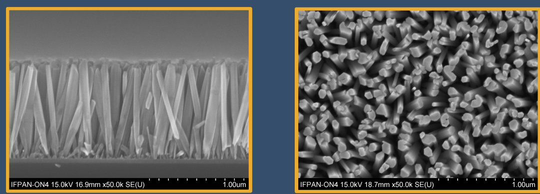
- AFM scans confirm very smooth surface of the nucleation layer – RMS = 0.58 nm for 10 µm x 10 µm scan
- Transmission line measurements show its low electrical resistivity of $1 \cdot 10^{-3}$ Ωcm
- XRD measurements confirm polycrystalline nature of the ZrN layer
- GIXRD returns ZrN grain size of ~15 nm
- No change after annealing in N plasma at NW growth T



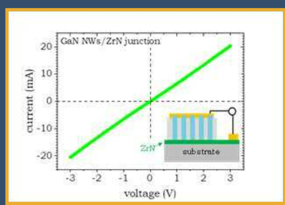


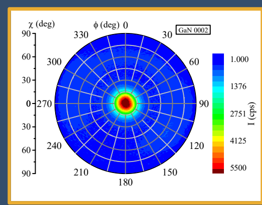
GaN nanowires on ZrN

- Growth takes place by self-assembly, NWs diameter < 100 nm
- Densely packed NWs without defects, small tilt dispersion



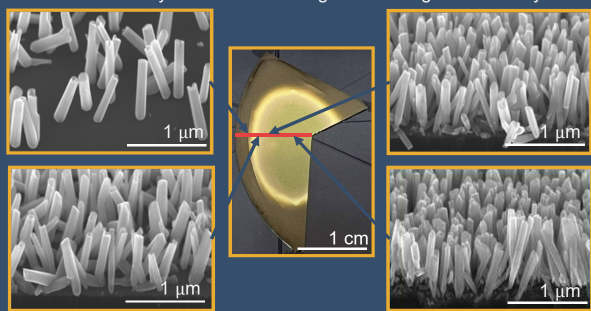
- Linear I-V characteristic confirms that an ohmic contact forms between GaN and ZrN
- XRD pole figure of GaN 0002 reflection describes dispersion of NWs tilt to the substrate as ± 12º (much larger than on amorphous buffers like SiN)
- Optical properties of GaN NWs on ZrN similar to those on nitridated Si (see MoP11)



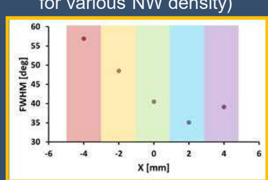


GaN NWs' tilt vs. NW density

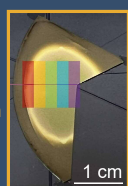
- Due to a T gradient a gradient of NWs density appears across the sample
- SEM images show that tilt dispersion decreases with an increase in NW density
- Small NWs that cannot develop into their final form are visible on the substrates surface between fully formed NWs in regions with high NW density



- XRD measurements of 0004 GaN reflection at various points of the sample
- X-ray spot 10 mm high, 2 mm wide moved across the sample in 2 mm steps
- FWHM of XRD ω-scans describes tilt distribution of NWs at various points (i.e. for various NW density)



- Tilt dispersion significantly smaller for denser NW arrays (in agreements with SEM observations)
- There must be a mechanism that for high NW density stops growth of strongly tilted NWS



Summary

- Successful growth of GaN nanowires on ZrN nucleation layer by PAMBE
- Confirmed applicability of ZrN as a low-resistive, ohmic electrical contact to the bottom of GaN NWs
- Distribution of NWs tilt is smaller than expected from random orientation of ZrN grains
  - Tilt dispersion decreases with an increase of NW density as observed by SEM and XRD measurements
  - Due to geometry of the sources in MBE growth chamber NWs strongly tilted to substrate normal receive smaller amount of constituents, grow slower and finally are blocked by more perpendicular NWs
- Our results demonstrate that application of ZrN buffers offers significant improvements in novel designs of NW based devices

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