GaN/AlN quantum disc single-nanowire photodetectors


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We demonstrate single-nanowire photodetectors based on nanowires containing GaN/AlN quantum disc heterostructures. The structural and electronic properties are investigated by photocurrent and microphotoluminescence spectroscopy, as well as scanning transmission electron microscopy. Single-nanowire photodetectors are visible-blind with photoresponse in the ultraviolet spectral range arising from interband absorption in the multi-quantum disc GaN/AlN heterostructure. The photoconductive gain as high as $10^4$ is measured.

1 Introduction III-nitride nanowires are emerging as key building blocks for a new generation of efficient, ultra-compact, and inexpensive technologies, including nanolight emitting diodes [1], lasers [2], detectors [3], and optical communications devices. Thanks to their small cross-section, nanowires can accommodate for high strain without formation of dislocations, which makes it possible to fabricate defect-free nanowires containing lattice-mismatched heterostructures on strongly lattice-mismatched substrates [4]. The inclusion of quantum disc heterostructures inside GaN nanowires has been demonstrated by different authors [5–7] opening new prospects for quantum devices.

The excellent transport and optical properties expected from dislocation-free nitride nanowires can be exploited for fabricating efficient single-wire nanophotodetectors [3]. The single-wire photoconductive devices along with their emitter counterparts offer prospects for novel photonic architectures of great interest for on-chip optical data communication systems. Another appealing aspect of heterostructured nanowire detectors is the wide spectral range achievable (infrared to ultraviolet) by making use of intersubband and interband absorptions in the quantum discs (QDiscs). So far no quantum-disc-based single nitride nanowire photodetectors has been demonstrated.

In the present work, we demonstrate single-nanowire detectors based on nanowires containing GaN/AlN QDisc heterostructures. The structural and electronic properties are investigated by photocurrent and microphotoluminescence (micro-PL) spectroscopy, as well as scanning transmission electron microscopy (STEM). Single-nanowire photodetectors are shown to be visible-blind and to exhibit photoresponse in the ultraviolet spectral range arising from interband absorption in the GaN/AlN multi-QDisc heterostructure.

2 Experimental Nanowires were grown by plasma-assisted molecular beam epitaxy on Si(111) substrates at 790 °C under nitrogen rich conditions. Growth details can be found in Refs. [8, 9]. The structure consists of 20 periods of GaN/AlN QDiscs sandwiched between two $n^+$-doped GaN extremities. The nanowire diameter is 25–60 nm and the total nanowire length is 1.1–1.3 μm. The heterostructure is located in the middle of the nanowire. The average QDisc
The QDisc thickness slightly increases toward the nanowire top, as assessed by high-angle annular dark-field scanning transmission electron microscopy (HAADF STEM) image of the QDisc region shown in Fig. 1 left. The image shows that an AlN shell is formed during the barrier growth surrounding the QDiscs and the lower GaN part of the nanowire. This is due to the lateral growth of AlN [10].

The optical properties of nanowires were first characterized by photoluminescence spectroscopy on nanowire ensembles and micro-PL on individual nanowires. Single nanowires were detached by ultrasound bath and dispersed on Si/SiO2 templates patterned by e-beam lithography. The nanowires were placed in a continuous flow liquid He cryostat and excited with a cw frequency-doubled Ar++ ion laser (λ = 244 nm) focused into a spot with diameter ~3 μm. The excitation power was kept in the range 50 μW–1 mW.

The micro-PL spectra were measured using a HR460 spectrometer with a 600 grooves/mm grating and a CCD camera. The energy resolution of the setup during these experiments was kept in the range of 1 meV.

The photodetectors were fabricated from dispersed single nanowires using e-beam lithography. Ti/Al/Ti/Au contacts were deposited on the nanowire doped extremities and annealed in order to obtain ohmic behavior. Figure 1 right displays a scanning electron microscopy (SEM) image of a single contacted nanowire. The nanowire current–voltage characteristics were tested using a probe station. The nanowire photocurrent spectrum was measured using a tunable Vis–UV light source (Xe lamp coupled with a spectrometer).

3 Photoluminescence

The room temperature photoluminescence of nanowire ensembles presents two main contributions peaked at 3.406 and 3.185 eV (Fig. 2). The first peak corresponds to the GaN near band gap emission, whereas the peak below the bandgap is attributed to the emission from the QDiscs. The emission energy is consistent with calculations for the average QDisc size (described in more details in Section 4.3).

Single dispersed nanowires were probed by micro-PL at 4.2 K. A typical spectrum is shown in Fig. 3. The emission is broad with a main contribution peaked at 3.55 eV and additional emissions at 3.7 and 3.35 eV. The energy and relative intensity of additional peaks changes from wire to wire. The peak at 3.55 eV is attributed to the emission from GaN nanowire core [11]. The important broadening of this emission as well as the blue shift with respect to the GaN bandgap is due to the compressive strain exercised by the AlN shell. The additional peaks at higher and lower energies are attributed to the fundamental interband transition in the QDiscs. Because of a high dispersion of QDisc size, its
energy can be either higher or lower than the GaN core emission as a result of quantum confinement and Stark effect in the QDiscs.

It should be noted that the spectral shape is different for the PL of the nanowire ensemble and of single nanowires. This is due to the different excitation/collection geometry. Indeed, for the ensembles, the nanowires are perpendicular to the substrate, so that the laser excitation coming from the top is mainly absorbed in the upper GaN part. The photoluminescence is also collected from the top, so that both the excitation and collection are perpendicular to the nanowire axis. In this configuration high energy contributions can be easily observed.

The micro-PL of “as-dispersed” nanowires was compared with the micro-PL of contacted nanowires. It shows the same luminescence contributions as “as-dispersed” nanowires. No degradation of optical properties due to the processing steps has been observed.

The polarization of the nanowire emission was analyzed. It was shown that the QDisc emission is polarized perpendicular to the nanowire axis. The perpendicular polarization of the QDisc emission stems from the selection rules for $X_A$ exciton in wurtzite semiconductors [12].

### 4 Single-nanowire photodetector

#### 4.1 Operation principle

The operation principle of nanowire photodetector is illustrated in Fig. 4. The photodetector consists of an n–i–n structure, the isolating region corresponding to the GaN/AlN QDiscs. Under UV illumination carriers are generated in the QDiscs. The carrier separation and collection is favored by the built-in electric field, which creates a natural band bending in the QDisc region.

The presence of the GaN/AlN heterostructure is expected to lower the dark current with respect to a photodetector based on a homogeneous GaN nanowire.

#### 4.2 Transport

First, the current–voltage characteristics of the fabricated single-wire photodetectors were probed in the dark and under illumination. Figure 5 presents the room-temperature $I$–$V$ curves showing a Schottky behavior. It should be noted that a reference sample containing homogeneous n$^+$-doped GaN nanowires exhibits ohmic $I$–$V$ characteristics. This demonstrates that the Schottky behavior is related to the potential barrier induced by the multi-QDisc active region and not to the contacts. The dark resistance at zero bias is as high as $10^3 \, \Omega$ which is much higher than in the reference homogeneous nanowire (0.2 $\Omega$). This high dark resistance is due to the efficient current blocking by AlN barriers.

The $I$–$V$ curves remain unchanged under illumination with visible light but the current strongly increases under ultraviolet light ($\lambda = 300$ nm). This shows that the photodetector response is in the ultraviolet spectral range and there is no photocurrent related to the defects. The photosensitivity factor, defined as the ratio of the photocurrent and the dark current $I_{ph}/I_{dark}$, equals $9 \times 10^2$ at $-1$ V bias. It should be noted that the presence of heterostructure considerably enhances the photosensitivity factor: for comparison, in GaN p–n junction single-wire photodetectors $I_{ph}/I_{dark} \sim 1$ [13]. The photodetector also presents a high photoconductive gain $G$ (defined as the number of photogenerated electrons per absorbed photon). $G$ as high as $10^4$ is measured at $-6$ V. High values of photoconductive gain have also been reported in other nanowire systems such as ZnO [14] or CdSe [15]. This can be explained by the spatial separation of the
photogenerated carriers: the holes are attracted to the lateral nanowire surface whereas the electrons remain in the central part of the nanowire [16]. Because of this separation, the photoexcited electron passes many times in the circuit before it recombines.

4.3 Photocurrent spectroscopy To determine the spectral range of operation, the photocurrent spectra of single-wire photodetectors were measured from visible to ultraviolet domain. Figure 6 shows the photocurrent spectrum collected under −3 V and +3 V applied bias at room temperature. The photocurrent appears at energies above 2.6 eV (slightly below the GaN bandgap). It increases at higher energies presenting broad structures.

The decrease of the photocurrent above 4 eV corresponds to the decrease of the illumination source power above this energy. It should be noted that the photocurrent signal is not strictly proportional to the incident power density, but follows a power law \( I \propto P^{0.6} \). This makes difficult the normalization by the spectral response of the optical system.

To interpret the different spectral contributions of the photocurrent, the band structure and the confined levels of the heterostructured nanowire were simulated using a one dimensional Schrödinger–Poisson solver. The simulation neglects the lateral confinement in nanowires, which is justified by the large nanowire diameter.

Due to the quantum confined Stark effect the hh\(_1\)–e\(_1\) transition for 2 nm thick or thicker QDisc is expected below GaN bandgap. Therefore, we attribute the photocurrent peak at 3 eV to the hh\(_1\)–e\(_1\) absorption in thick QDiscs. However, the contribution of these QDiscs to photocurrent is expected to be weak because of the difficult carrier extraction from QDiscs of large thickness. The fundamental transition in narrow QDiscs as well as the excited transitions in thick QDiscs contribute to the photocurrent above GaN bandgap.

Unfortunately, the high dispersion of the QDisc thickness within the single nanowire prevents us from giving an unambiguous attribution of the structures observed in the photocurrent spectra.

Due to the polarization discontinuity between GaN and AlN, a band bending appears in the QDisc region. The band bending is responsible for the non-symmetrical electrical response of photodetectors: depending on the bias sign, it can either increase or decrease the effective electric field in the active region. This is consistent with the experimental observations of Fig. 6, which shows that the photocurrent varies by a factor of 10 between negative and positive bias.

5 Conclusions A photodetector based on single nitride heterostructured nanowires was demonstrated. The photodetector is insensitive to the visible light and has the response in the ultraviolet domain. The photocurrent arises from the interband absorption between confined states in AlN/GaN multiple QDiscs.

It should be noted that AlN/GaN heterostructured nanowires can also be used to design intersubband photodetectors based on the absorption between electron confined states. The expected spectral response of intersubband photodetectors lies in the mid and near infrared spectral range.

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