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Photocurrent characterization of intraband transition in GaN/AlN quantum dots

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Abstract. Photoconductivity (PC) in GaN/AlN quantum dot (QD) matrix due to in-plane transport is characterized. When exposed to near infrared (NIR) radiation a peak is observed at 1.4 µm. Based on its energy and the polarization dependence, it is associated with the polarized S to P_z intra-band transition in the QDs. This PC signal turns from positive to negative as temperature is raised, increasing exponentially from 50K to 300K. UV excitation at 2.8 eV renders a positive PC at all temperatures, and when combined with NIR radiation, negative PC is observed even at 12 K. We claim that following NIR excitation the electrons get trapped in deep levels in the AlN barrier, from which the UV radiation re-excite them into the QDs.

1. Introduction
Epitaxially grown GaN QDs embedded in AlN form an intriguing quantum structure due to huge internal electric field and the large band offset of up to 1.8 eV. The large band discontinuities facilitate intersubband (ISB) / intraband (IB) transitions in the near-infrared (NIR) spectral range (1-3 µm) [1]. Recently devices based on ISB transitions in GaN/AlN structures were implemented, such as all-optical switches [2], electro-optical modulators [3], lateral Quantum Dot IR Photodetectors (QDIPs) [4] and Quantum Cascade Detectors (QCD) [5].

Photoconductivity in ISB quantum structures is usually based on excitation of carriers from bound states in the QDs to extended states in the wetting layer (WL) or in the continuum. Most ISB devices relay on vertical carrier transport, in which photoexcited carriers in the continuum are drifted by the electric field along the growth direction. Photocurrent related to Bound-to-Bound (BtB) electronic transition is not likely, since the excited-state energies are below the effective potential barrier and excited carriers have a low escape probability [6].

In this work we investigate the photo response of lateral QDIPs. Exposing the device to NIR radiation, result in a reduction of the device conductivity with respect to its dark value. This phenomenon, known as Negative Photo Conductivity (NPC), was observed in several material systems [7-10] and is mainly attributed to either a reduction in the number of carriers available for transport [7-9] or to a reduction of carriers mobility [10], induced by the radiation. In our samples, the NPC intensity decreases exponentially as the temperature is reduced, and eventually the PC signal turns positive at low enough temperature (12K). The response time of the NPC is extremely slow, up to hundreds of seconds. Further insight to the origin of the NPC was obtained by employing ultra-violet (UV) excitation along with the NIR one. The physical processes involved in these photo responses are investigated in the following.
2. Experimental

The measurements were performed on a sample consisting of a single GaN QD layer deposited on a 1 µm thick AlN-on-sapphire substrate using plasma-assisted molecular-beam epitaxy. QD growth starts by deposition of 2 monolayers of GaN as wetting layer (WL) followed by 2 additional GaN monolayers from which QDs are self-assembled by the Stranski-Krastanov growth mode. The structure was covered by a 3 nm AlN cap. AFM measurements on a similar uncapped sample were used to determine the QD density \((10^{12} \text{ cm}^{-2})\), average height \((1.2\pm0.5 \text{ nm})\), and diameter \((15\pm3 \text{ nm})\) [11]. A lateral photodetector was formed by implementing 2 contacts, 150µm wide and 6µm apart. Rapid-thermal annealing (RTA) was used for the ohmic contacts which consist of a multi-layer metallization of Ti:Al:Ni:Au (15 nm: 220 nm: 40 nm: 300 nm). The substrate was polished at 45° to enable irradiation at both S and P configurations, allowing for analysis of polarization effects on intersubband transitions.

The spectral response at the NIR range was investigated. FTIR measurements, using step-scan at fixed frequency, show photocurrent spectra which peaks at 1.4 µm. These spectra are completely P polarized. The peak intensity increases exponentially with temperature, as seen in figure 1.

Additional photocurrent experiments were performed by exposing the sample to a 20 mW laser radiation at 1.55 µm. The measurements show negative photoconductivity, i.e. the current decreases following irradiation, as shown in the inset of figure 1. As the temperature is lowered the negative effect decreases, and eventually the PC signal turns positive, as described later-on. The recovery of the current to its dark value is orders of magnitude faster at 300 K than at 50 K.

Further insight into the processes involved was obtained by combining the NIR PC measurements with UV radiation at various temperatures. First, we examined the photo-response of the structure to UV excitation. The room temperature photocurrent spectrum, shown in figure 2 (in green), shows a peak at 2.8 eV. Also shown is the photo-induced experimental results, in which the photocurrent generated by the 1.55 µm is modulated by UV radiation from a Xenon source, showing a clear peak at 2.8 eV as well.

When the sample is exposed to both NIR and UV radiation, different processes are observed. The NIR light reduces the photocurrent generated by UV excitation even at a low temperature (12 K) at which the pure NIR PC signal is positive. The experimental results are shown in figure 3, presenting the effects of temperature and UV illumination on the sign and time response of the intraband NIR PC. At room temperature the NIR PC is always negative while the UV illumination results in a positive PC (figure 3a). At low temperature (12 K) the response to NIR radiation becomes positive with very short rise time as shown in figure 3b. However, in the presence of UV illumination, the NIR signal turns from positive to negative as shown in this figure.

![Figure 1](image1.png)  
**Figure 1.** Intraband PC spectra, under 1.55 µm laser radiation at increasing temperatures for single QDs layer.

![Figure 2](image2.png)  
**Figure 2.** Photocurrent (green) and photo-induced NPC (blue) for UV excitation.
3. Discussion

Lateral transport processes in the 2D QD layer is governed by tunnelling. Recently we have identified the origin of dark current as hopping conductivity between the QDs, facilitated by their high density, typical for this material system [12]. The negative response to the NIR radiation is attributed to trapping of conductive electrons in deep levels located in the AlN barriers, resulting in a reduction of available carriers for hopping.

The energy and the polarization of the radiation associated with NIR PC peak correspond to the S to P_z intra-band transition in the QDs [12]. Due to the polarization field in nitrides, the wavefunction of carriers in the P_z state extends into the AlN conduction band, as described in figure 4 (dashed purple circle). Thus, the probability for electrons in these states to be trapped in the AlN barriers deep levels increases substantially, with respect to trapping of carriers from the QDs ground state (brown dotted-dashed arrow in figure 4). This probability is determined mostly by the cross-section for trapping, which is proportional to the thermal velocity and to the square root of temperature [13]. Therefore, the trapping becomes less effective as the temperature is lowered. The extension of the P_z wavefunction into the AlN barrier is larger for smaller QDs, therefore, the negative PC favours small QDs.

The blue shift between the absorption spectrum to the
negative PC at room temperature was observed in samples containing 20 layers of QDs (figure 5). The energy of the AlN deep level can be estimated by the UV photocurrent spectrum (figure 2) which is peaked at 2.8 eV and marked by the dashed line in the band diagram (Figure 4). These results are consistent with recent results of cathodoluminescence obtained on pure AlN [14].

As the AlN deep levels are lower in energy than the QDs ground state, the reverse process of re-emission of the trapped carriers into the QDs requires thermal energy and thus takes seconds at room temperature but minutes at 50 K (inset of figure 1). The extremely long time constant results in two opposing findings. On one hand the relative decrease in current is much larger at low temperatures. On the other hand, since the PC spectrum is recorded at a sampling rate of 130 Hz, as the temperature is lowered, the very slow response results in an ever decreasing measured peak amplitude (figure 1).

Figure 2 shows the effects of temperature and UV illumination on the sign and time response of the intraband NIR PC. At room temperature the NIR PC is always negative. UV illumination results in a positive PC due to release of trapped carriers from the AlN deep levels into the QDs (figure 3a). As the temperature is lowered, the traps become populated and the cross-section for trapping decreases. Hence, at low enough temperatures, carriers which are excited into the Pz level of the QDs remains in the GaN channel, thus, contributing to the hopping conductivity. Since the hopping probability of excited Pz carriers is higher than that of carriers in the S states [12], the response to NIR radiation becomes positive with very short rise time as shown in figure 3b. UV illumination, even at low temperatures, releases trapped carriers and results in a positive PC (blue arrows in figure 4). Finally, the NIR signal in the presence of UV illumination evolves with time from positive to negative as shown in figure 3b. As the UV excitation is turned off, the dark current original value is not restored, suggesting that carriers which originates from the AlN deep levels (by the UV illumination) stay within the QDs. Carriers which are excited by the UV light into the AlN continuum are drifted by the polarization field into the QDs, while the transfer of carriers from the QDs to the AlN deep levels relays on tunnelling. This irreversible process is demonstrated schematically in figure 4. Further modelling of trapping processes is under study.

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