Quantum cascade NIR-detection at room temperature in GaN\AlN heterostructure

A. Vardi, G. Bahir, F. Guillot, E. Monroy and S. E. Schacham

***Abstract*— We present a new concept of quantum cascade detection in which the saw tooth level structure of a single cascade is formed by the internal electric field existing in the GaN\AlN material system. The device operates at room temperature in the near-IR spectral range with a responsivity of 10mA/W. The photovoltaic nature of the structure is discussed with respect to the spectral response and the current-voltage characteristic of the device.**

***Index Terms*—AlN, GaN, intersubband transition, photo-current, near-infrared, polarization.**

Lately there is a growing interest in the so called Quantum Cascade Detector (QCD) [1, 2]. In this type of detector the energy levels in a unit cell of the structure are designed to form a saw tooth structure so that excited carriers can be efficiently extracted from one stage to the next. As a result of a charge separation over a large distance (which depends on the number of stages), these devices can operate at null bias with a responsivity of a few tens of mA/W. The QCD mode of operation (zero dark current) makes it highly suitable for small pixel large-area plane arrays. Typically, the energy slope in a QCD structure is accomplished by increasing the well width along the stage. In order to increase the detection efficiency, the energy levels are designed to form a phonon ladder, where the energy spacing equals to the relevant LO-phonon energy. The improvement in the device performance due to the use of a phonon ladder is expected to be largely enhanced in the III-nitride material system, where the LO-phonon interaction is an order of magnitude stronger than in other III-V materials. In this work we demonstrate quantum cascade detection in a structure that relay on a unique property of the III-nitride material system, namely the strong polarization field, in order to create a phonon ladder. In our design, the active region is a doped GaN quantum well with two levels in the conduction band coupled to an AlN\AlGaN short period superlattice (SPS). The expected miniband at zero bias in this kind of structure is broken due to the internal polarization field, and a saw tooth structure is formed.

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The design of the structure is based on the self consistent solution of the Ben-Daniel Duke and Poisson equations. The doping level in the GaN quantum well was assumed to be 5e18 cm^{-3} and all the AlGaN material parameters were linearly interpolated from the AlN and GaN known parameters, except for the conduction band offset in which a bowing parameter of 1 eV was taken into account. The internal field in each layer was calculated assuming zero potential drop over one cascade and the continuity of the normal displacement vector. Under these assumptions it can be shown that the field in the j'th layer of the structure is given by [3]

$$E_j = \frac{\sum_k \left(P_k - P_j\right)\frac{l_k}{\varepsilon_k}}{\varepsilon_j \sum_k \frac{l_k}{\varepsilon_k}}$$

Where ε, P and l are the dielectric constant, the total static polarization and the width of the layer, respectively. The summation goes over all the layers in one stage of the structure. Figure 1 show the conduction band profile and the energy levels which were calculated using the above model for the investigated structure. The width of the SPS layers was design so that the energy spacing in the ladder will be as close as possible to the GaN LO phonon energy (92 meV). Next to each possible optical transition (marked with an arrow) the exact value of the energy transition and the oscillator strength are stated. The device is designed to operate in the following mode: carriers are optically excited from E1 to E7, from E7 carriers are extracted to the next stage via the phonon ladder.

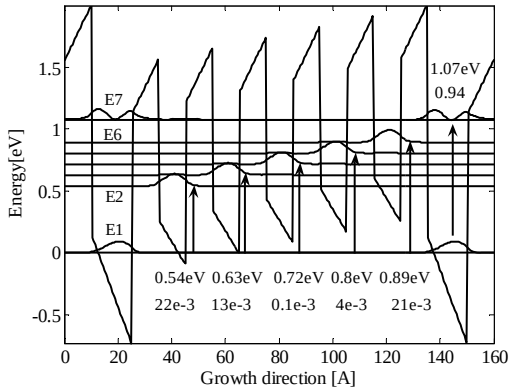

Figure 1: band diagram and energy levels in one stage of the structure. Next to each marked transition (with an arrow) appears the exact transition energy in eV and the oscillator strength.

The sample was grown by plasma-assisted molecular beam epitaxy on 1-μm-thick AlN-on-sapphire templates. The structure consists of 40 periods of a 6-monolayer-thick (6 ML) GaN quantum well followed by a short period superlattice consisting of 5 periods of AlN\$Al_{0.25}Ga_{0.75}N$ (4 ML \ 4 ML). N

type doping (Si) was introduced during the growth of the GaN. The nominal doping level was 5e19 cm^{-3}. The active region was sandwiched between Si-doped $Al_{0.25}Ga_{0.75}N$ contact layers. In order to perform both absorption and photocurrent measurements, the facets of the sample were polished at 45^0 to meet the requirement for TM polarized light. Standard photolithography and dry etching techniques were use to form a 200 x 200 μm^2 mesa structure. Ohmic contacts were introduced by the deposition of Ti\Al\Ti\Au on the $Al_{0.25}Ga_{0.75}N$ top and bottom contact layers. The reliability of the ohmic contacts was confirmed by measuring the resistance between two adjacent common-contacts. The contact resistance was found to be less the 100Ω. Optical and electrical characterizations were preformed in a Bruker Fourrier-transform spectrometer (FTIR) using the internal near IR source.

Current-voltage (I-V) curves of the device in the dark and under illumination of a 1.55 μm laser at different intensities are presented in figure 2. The photovoltaic effect is clearly observed in these curves were the laser illumination shifts the entire curve right (or down). The linear dependence of the detector response on the laser power (inset) also suggests that the photovoltaic effect takes place within the structure and not in a rectifying contact. Taking into account the losses of the optical path, the size of the detector and the coupling efficiency of the light we found that the peak current responsivity of the device is 10 mA/W. Since these are preliminary results and there is still room for optimization of the structure and the device, this result is promising.

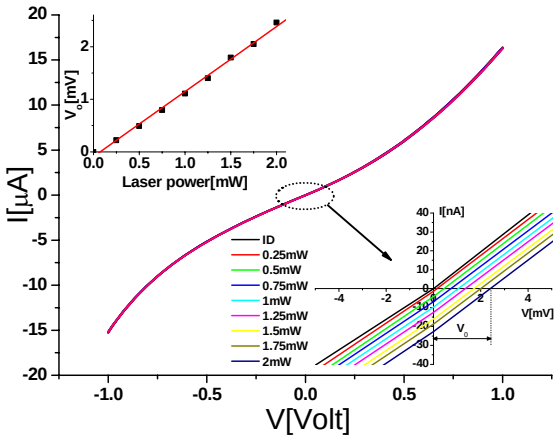

Figure 2: I-V curve of the device at dark conditions and under 1.55μm laser illumination at different intensities (low right corner). Inset: The photovoltaic signal at zero current vs. laser power.

Figure 3 shows a comparison between the p polarized transmittance and the detector photoresponse at zero bias. In order to isolate the absorption in the structure, the transmittance of the sample was normalized by the transmittance of a reference sample consisting only of AlN on a sapphire substrate. The transmittance shows several absorption peaks at the range 0.5-1eV. The photovoltaic response is composed of only three clear lorentzians (fitted curve). These three lorentzians are related to diagonal transitions from the ground state to a broken miniband in a manner of absorption to a stark ladder. In order to interpret the results, the relevant transition energies indicated in Fig. 1 are marked in Fig. 3 by black squares. The strongest absorption peak at the low energy side (0.66eV) is probably related to E1-E2 transition which has the strongest oscillator strength. The consecutive absorption peaks are associated with the following E1-E3 and E1-E4 transitions. Although the measured transition energies differ by about 100 meV from the theoretical calculations, the spacing between peaks agrees extremely well with theory. The discrepancy between theory and experiments can be attributed to a combination of several inaccuracies of the model such as depolarization effects, and graded transitions between materials [4], which should result in higher ladder energies. Although the strongest absorption is for the peak associated with E1-E2 transition (Fig. 3), the photovoltaic response is the strongest for the E1-E3 transition (at 0.72 eV) This result is due to the fact that for this transition the charge separation and the oscillator strength are optimized. The transmittance dip, present at around 1eV, is related to E1-E7 transition. This weak absorption signal is in contrast to the large oscillator strength of the transition. The reason for this weak absorption is not clear, but it seems that the photons in this energy range are absorbed by other processes such electron excitation form the abundance of trap levels in the 1 micron AlN template. Indeed, a strong unpolarized absorption is observed at this energy range (not shown in the figure).

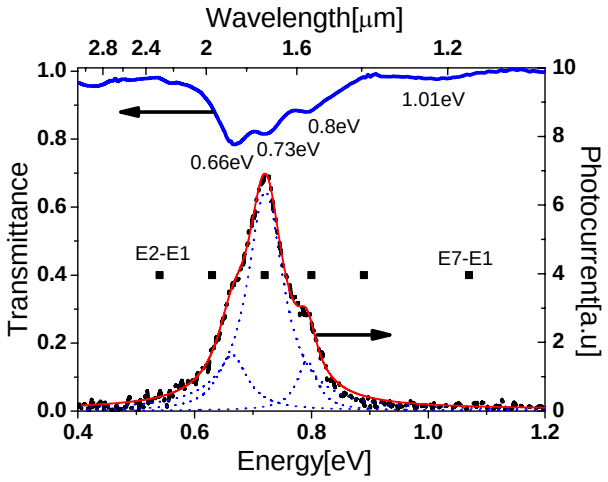

Figure 3: P polarized transmittance of the sample normalized to the transmittace of AlN\Sapphire template (top). Spectral response of the detector in room temperature and at zero bias (bottom). The response was fitted by three lorentzians.

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