GaN-based quantum dot infrared photodetector operating at 1.38 µm

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A GaN/AlN quantum-dot infrared photodetector based on intraband absorption and lateral carrier transport has been demonstrated for the first time. The photocurrent spectrum is peaked at $\lambda = 1.38$ µm at a temperature of 77 K and it is *p*-polarised. The signal is due to the dot absorption from the *s*- to the p_z-shell.

Introduction: The operating principles of unipolar devices, i.e. devices based on intersubband (ISB) transitions in semiconductor heterostructures, have already been successfully demonstrated at mid- and far-infrared (IR) wavelengths using materials such as GaAs/AlGaAs or InGaAs/AlInAs-on-InP. Because of their large conduction-band offset (~1.75 eV for GaN/AlN), nitride heterostructures are promising materials to reach the near-IR spectral range of fibre-optic telecommunications (1.3 µm < λ < 1.55 µm). Nitride-based semiconductors exhibit additional potential advantages such as high power handling, material hardness and high speed, given their extremely fast (150–300 fs) ISB recovery times. ISB absorption at 1.55 µm has already been observed at room temperature in GaN/AlGaN quantum wells [1], and the first quantum-well infrared photodetector based on III-nitrides operating in photovoltaic mode has been recently demonstrated [2]. Devices based on intraband transitions in quantum dots (QDs) are potentially interesting especially for photodetection applications.

They should exhibit an intrinsically lower noise due to the reduction of electron-phonon scattering. Moreover, conduction-band bound-to-continuum transitions in QDs can be nearly independent of the polarisation of excitation [3]. Intraband absorption linked to *s*- to p_z-shell transition have been observed in undoped GaN/AlN QDs [4], and more recently in heavily Si-doped GaN/AlN QD superlattices [5]. With respect to existing interband semiconductor detectors at telecom wavelengths, nitride QDs offer prospects for high-speed narrowband photodetection. In this Letter, we report the fabrication and characterisation of the first nitride-based quantum dot infrared photodetector. The device relies on bound-to-bound absorption and in-plane transport. The peak detection wavelength is $\lambda \simeq 1.38$ µm at 77 K.

Sample growth: The sample consists of 20 periods of Si-doped GaN QD layers separated by 3 nm-thick AlN barriers, grown on a 1.5 µm-thick AlN buffer on c-sapphire by plasma-assisted molecular-beam epitaxy (PAMBE). The QDs are formed by deposition of five monolayers (ML) of GaN on an AlN surface under nitrogen-rich conditions. Under these conditions, the growth starts layer-by-layer, leading to a 2 ML-thick GaN wetting layer. Further deposition of GaN results in the formation of three-dimensional islands (Stranski-Krastanov growth mode) [6]. An additional QD plane was deposited on the surface to allow atomic force microscopy (AFM) characterisation of the QD shape and density. Fig. 1 shows a typical AFM image of the uncapped QD layer. The QD density is approximately $(6.4 \pm 0.7) \times 10^{12}$ cm^{-2}, and their average height and diameter are $\simeq 1.2 \pm 0.6$ and $\simeq 17 \pm 3$ nm, respectively.

Measurements: Photoluminescence (PL) experiments were performed at room temperature using the 244 nm line of a frequency-doubled CW Ar$^+$ laser. The PL spectrum is peaked at 3.821 eV, with a full width at half maximum (FWHM) of 0.264 meV [5]. This is a remarkably small value for nitride QDs.

The structure of a typical device is schematically shown in Fig. 2. Ti (15 nm)/Al (50 nm)/Ti (30 nm)/Au (100 nm) contacts with a size of 0.9×3.0 mm^2 and separated by 800 µm were deposited on the sample surface and annealed at 600°C for 30 s in a helium-rich atmosphere to let the metal diffuse inside the sample and to contact the buried QD layers. The linear *I–V* characteristics demonstrate the ohmic behaviour of the contacts. The sample edges were then mechanically polished to form a 45° multi-pass waveguide with six total internal reflections. The sample was finally soldered to a copper block, wire bonded, and mounted in a cryostat. For transmission and photocurrent measurements, the sample was placed at the output port of a Fourier transform infrared (FTIR) spectrometer. The polarised IR light from the internal source of the FTIR spectrometer was focused onto the sample between the two contacts. For photocurrent measurement, the IR light is mechanically chopped at 240 Hz for lock-in detection purposes.

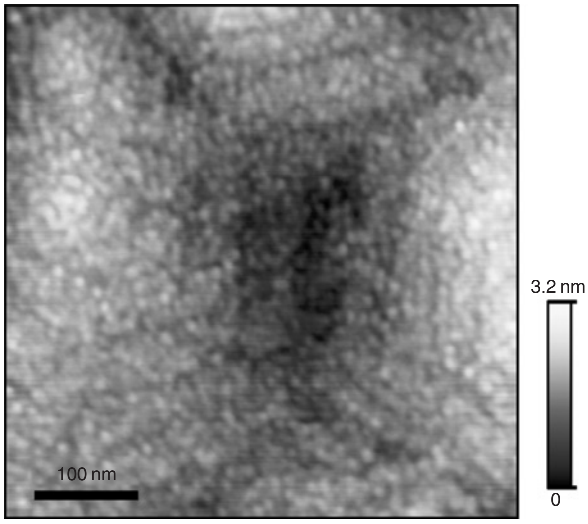

Fig. 1 *Atomic force microscopy image of QDs deposited on surface of structure*

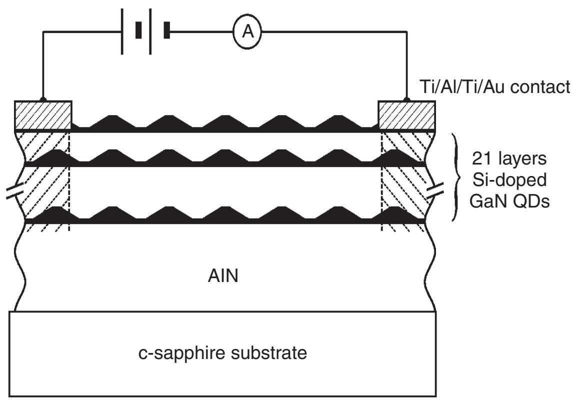

Fig. 2 *Schematic description of QDIP device*

I–V curve perfectly linear for bias in range −10 ao 10 V with resistance of 66 MΩ

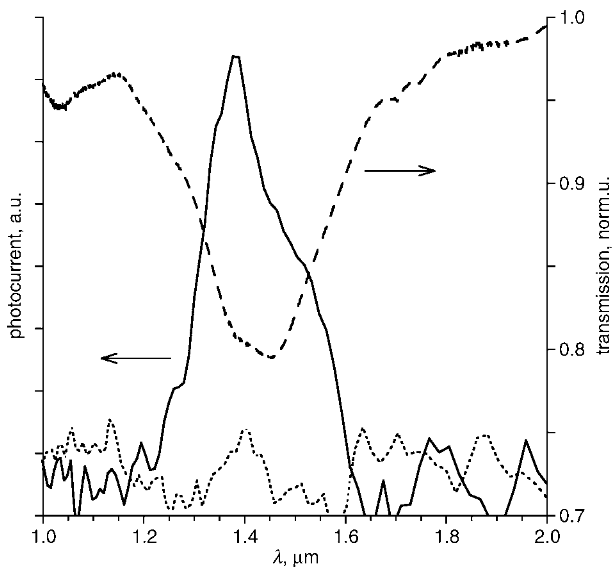

Fig. 3 *Photocurrent spectrum for p-polarised (full curve) and s-polarised (dotted curve) light, measured at 77 K*

FTIR spectra only shown in arbitrary units because of difficulty of calibration. *p*-polarised transmission (dashed curve) also shown

Results: Fig. 3 shows at a temperature of 77 K the p-polarised transmission spectrum and the photocurrent spectrum under 5 V bias for both p and s polarisation. The p-polarised absorption is peaked at 0.856 eV ($\lambda \sim 1.42$ µm) with a FWHM of 150 meV. Based on previous studies [4, 5], the observed absorption is ascribed to the electronic intraband transition from the ground state (s-shell) to the excited state with one node of the envelope wavefunction along the c-axis (p_z-shell). The absorption efficiency is $\sim$20%. The photocurrent spectrum exhibits a p-polarised peak at 0.896 eV (1.38 µm) with a FWHM of 150 meV, while the response to s-polarised light is negligible. The p-polarised photocurrent signal persists at room temperature, in spite of a dramatic increase of the noise level.

The photocurrent spectrum at 77 K is only slightly blue-shifted with respect to the s–p_z intersubband absorption. The fact that the photocurrent signal follows the absorption spectrum and that it obeys the same polarisation selection rules, is clear evidence that the photocurrent originates from intraband absorption in the nitride QDs. Electrons are excited from the s-shell to the p_z-shell (bound-to-bound absorption), and are then transferred to the wetting layer where a current is generated. As expected from a lateral transport photoconduction device, the frequency response is rather slow [3]. A decrease of the response by 13 dB is observed when increasing the frequency from 50 to 500 Hz.

Conclusion: We have reported the fabrication and characterisation of the first GaN/AlN quantum dot infrared photodetector. The device relies on in-plane transport and operates at telecommunication wavelengths in the range $\lambda \simeq 1.2$–1.6 µm at 77 K. The photocurrent signal is p-polarised and it originates from the s–p_z electronic absorption in the QDs.

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References

1 Helman, A., Tchernycheva, M., Lusson, A., Warde, E., Julien, F.H., Moumanis, Kh., Fishman, G., Monroy, E., Daudin, B., Le, S.D., Bellet-Amalric, E., and Jalabert, D.: 'Intersubband spectroscopy of doped and undoped GaN/AlN quantum wells grown by molecular-beam epitaxy', *Appl. Phys. Lett.*, 2003, pp. 5196–5198

2 Hofstetter, D., Schad, S.-S., Wu, H., Schaff, W.J., and Eastman, L.F.: 'GaN/AlN-based quantum-well infrared photodetector for 1.55 µm', *Appl. Phys. Lett.*, 2003, **83**, pp. 572–574

3 Chu, L., Zrenner, A., Bichler, M., and Abstreiter, G.: 'Quantum-dot infrared photodetector with lateral carrier transport', *Appl. Phys. Lett.*, 2001, **79**, pp. 2249–2251

4 Moumanis, Kh., Helman, A., Fossard, F., Tchernycheva, M., Lusson, A., Julien, F.H., Damilano, B., Grandjean, N., and Massies, J.: 'Intraband absorptions in GaN/AlN quantum dots in the wavelength range of 1.27–2.4 µm', *Appl. Phys. Lett.*, 2003, **82**, pp. 868–870

5 Tchernycheva, M., Guillot, F., Nevou, L., Monroy, E., Doyennette, L., Helman, A., Colombelli, R., Julien, F.H., Shibata, T., and Tanaka, M.: 'Intraband absorption of doped GaN/AlN quantum dots at telecommunication wavelengths', *Appl. Phys. Lett.*, 2005, p. 87

6 Daudin, B., Widmann, F., Feuillet, G., Samson, Y., Arlery, M., and Rouvière, J.L.: 'Stranski-Krastanov growth mode during the molecular beam epitaxy of highly strained GaN', *Phys. Rev. B*, 1997, **56**, pp. R7069–R7172