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Normal Incidence Mid-Infrared Photocurrent in AlGaN/GaN Quantum Well Infrared Photodetectors

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We report the growth and characterization of AlGaN/GaN multiple quantum well structures designed to have intersubband transitions in the mid-infrared region of the spectrum. The samples were nominally undoped but were found to contain a high electron population in the wells induced by the local polarization fields. The sample was characterized by the use of the Raman spectroscopy and photocurrent spectroscopy. The Raman spectroscopy shows electronic Raman scattering from intersubband transitions in the AlGaN/GaN quantum wells. The e_1–e_2 and e_1–e_3 transitions of the confined $2d$ electron population in the wells can clearly be observed. A sample designed to absorb at 4 μm was fabricated into mesa structures and the vertical photocurrent measured under normal incidence illumination from the free-electron laser FELIX. A wavelength and bias dependent photocurrent was observed in the mid-IR region of spectrum. The peak responsivity was of the order of 50 μA/W at 4 K, the photocurrent still being measurable at room temperature.

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1. Introduction

Devices based on intersubband transitions are realizing their potential as optoelectronic devices with widely tunable wavelength responses. Since the report of the first mid-IR quantum cascade laser (QCLs) [1], the technology has been applied to commercial applications such as environmental monitoring [2], communications [3] and other sensing applications [4]. Equally, quantum well infrared photodetector (QWIP) technology has advanced so that room temperature operation has been demonstrated in the (7−10 μm) atmospheric window. The progress in devices based on intersubband transitions has centred on arsenide based III–V materials. QWIP technology has already reached the point where the operating performances of the devices are mainly limited by fundamental material properties. A number of workers in the field have observed that for room temperature operation in the mid and far IR region of the spectrum the main limitation is the device dark current I_{d}. One way to reduce I_{d} is to utilize a higher carrier effective mass, which means looking at other material systems.

The GaN/AlN heterojunction system has attracted interest for several years as a possible basis for a QCL system operating in the near-IR part of the spectrum. The 2 eV offset between GaN and AlN means that intersubband transitions at wavelengths as low as 1.35 μm have been observed [5, 6], leading to the possibility of QCLs operating at the 1.55 μm telecommunications wavelength. Although such a QCL has not yet been demonstrated, QWIP operation was recently reported at 1.55 μm in a prospective QCL structure [7].

In this article we focus on another aspect of this system; the high electron effective mass, which makes it a promising system for applications in mid-IR intersubband based devices. We report the fabrication of simple normal incidence QWIP devices in the AlGaN/GaN system for applications in the mid-IR. We also demonstrate how the mid-IR intersubband transitions of such structures can be measured by electronic Raman scattering (ERS) circumventing the problems associated with absorption in the sapphire substrate. Finally we report the observation of a normal incidence photocurrent in a prospective device in the 5–7 μm region of the spectrum using a free-electron laser as a source of intense mid-IR radiation.

2. Design/growth

The samples were grown by metalorganic vapour phase epitaxy (MOVPE) at the National Centre for III–V Technologies. The MQW structure consisted of 10 periods of 6 nm thick GaN barrier layers and 28 nm of $\mathrm{Al_{0.3}Ga_{0.7}N}$ quantum wells grown on a sapphire substrate. The sample was designed to absorb at 4 μm. Figure 1 shows a magnified top view of the AlGaN device.

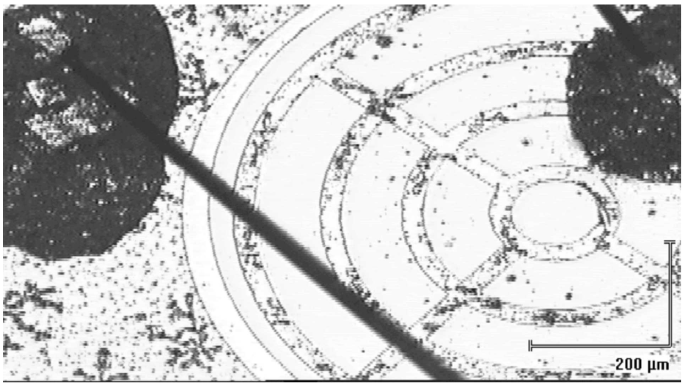

Fig. 1. Magnified top view of AlGaN device.

3. Sample preparation

The sample was prepared by patterning with standard photolithography techniques, followed by dry etching to leave a mesa containing the quantum wells. Top and bottom contacts were formed by depositing Ti/Au, which were then annealed at 900°C to form ohmic contacts. The sample was mounted in a carrier package and bonded to allow for electrical characterization.

4. Experimental details

Due to strong absorption in the sapphire substrate, absorption measurements on nitride structures in waveguide geometry become problematic beyond 4 μm. For the work described in this article we avoided these problems by characterizing the intersubband processes using electronic Raman scattering and normal incidence photocurrent. The Raman spectra were recorded in backscattering geometry from a cleaved sample edge using a Raman microscope system. The 514 nm line of an argon-ion laser was used for excitation. The spectra were analyzed with the polarization axis being parallel to the growth direction (x) or at right angles to it (y).

Photocurrent measurements were conducted at the free electron laser (FEL) facility FELIX. The FEL was used as a source of intense, tunable IR radiation. The FEL output consists of a series of pulses each of duration 10 μs. The sample illumination is considered to be equivalent to CW excitation with an intensity of *ca.* 10 W over an area of 1 cm^2 at 5 μm. The mesa structure was mounted on the cold finger of a cryostat with ZnSe windows. The device was biased through a 12 kΩ load resistance and the voltage across the load recorded on an oscilloscope. In the following discussion positive voltages mean positive applied to the top contact. Scanning the FEL and monitoring the peak response (whilst correcting for the FEL output power) enables one to obtain wavelength scans. However, the large pulse-power variation of the FEL leads to high noise levels on such spectra.

5. Results

Figure 2 shows the polarized (using standard notation) $[z(y, y)\bar{z}]$ and depolarized $[z(x, x)\bar{z}]$ ERS spectrum obtained from the sample. Two features at 300 meV and 480 meV are clearly observed in the depolarized spectrum, which we ascribe to the e_1-e_2 and e_1-e_3 transitions, respectively. The ERS features are only observed in the depolarized spectrum as is appropriate for the Raman scattering from excitations of single carrier character.

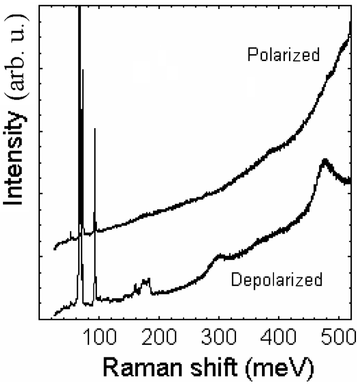

Fig. 2. Electronic Raman scattering spectra taken with perpendicular polarizations. The spectra were recorded at room temperature.

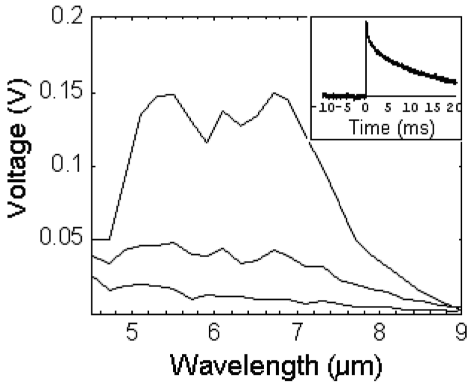

Fig. 3. Wavelength, bias, and temporal dependence of photocurrent upon excitation by FELIX. The spectra were recorded at 4 K.

Figure 3 shows the typical photocurrent response of the device to the FEL pulse as a function of wavelength for three different device biases. The upper spectrum shows the peak photocurrent at a bias of +40 V, the lower at +20 V and the lowest is reverse biased at –20 V. Inset in the figure is a screen capture of the typical temporal response to the FEL pulse. Let us note from the inset figure that the induced photocurrent decays with over a millisecond time scale, the FEL pulse length is 10 μs and the observed persistent photocurrent is almost certainly due to trapping in the contact layer region as has previously been observed [8]. It can be seen from the spectra that the device exhibits a broad band response to the infrared excitation. We expect to observe a large shift in the intersubband transition energy with applied field. In the figure, it can be seen that at a bias of 40 V we clearly observe a maximum in the photocurrent response in the region of 6 μm. At lower bias we only observe the low energy tail of the response with a much reduced photocurrent. Moreover, inverting the bias to –20 V results in a 30-fold reduction in the photocurrent in this spectral range. The reduced responsivity at lower biases may be caused either by a lower carrier collection efficiency and/or a shift in the peak responsivity out of the wavelength range studied. The existence of built in piezofields with specific polarity is expected to result in an asymmetric shift in the intersubband energy with applied external field. The results are thus in agreement with predictions.

6. Conclusion

We have prepared AlGaN/GaN mesa structures designed to absorb in the mid-IR. We have shown intersubband absorption in the QWIPS in the mid-IR via electronic Raman scattering and normal incidence photocurrent. We conclude that the system has great potential for exploitation in compact solid state mid-infrared spectrometers.

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