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GaN/AlN electro-optical modulator prototype at telecommunication wavelengths

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We report on a prototype electro-optical modulator at telecommunication wavelength based on intersubband (ISB) transitions in a short-period GaN/AlN superlattice (SL). The device has a vertical architecture resembling a nitride-based high-electron mobility transistor, whose barrier layer has been replaced by a 5 period SL. By applying an electrical field, we were able to influence the bandstructure and as a consequence to quench the ISB absorption peak originating from the SL.

1 Introduction Due to their large conduction band discontinuity of 1.8 eV and the ultra-short intersubband (ISB) scattering times, nitride semiconductor devices based on ISB transitions are very promising candidates for fast opto-electronic applications at optical-fiber telecommunication wavelengths (1.3 µm, 1.55 µm) [1–4]. Consequently, we present here a GaN/AlN-based prototype electro-optical modulator designed for 1.55 µm and grown by plasma-assisted molecular-beam epitaxy (PAMBE). It is a novel structure of an electro-optical ISB modulator based on a SL/2DEG structure. Such a structure is believed to be less demanding concerning the growth than a doubled QW design requiring very thin barriers [5].

2 Preparation and design Since layer thickness and interface roughness of our devices must be controlled at the monolayer (∼2.5 Å) scale, the structure presented here is grown by PAMBE on c-face sapphire substrates. The template used for this structure is a 10 µm thick GaN:nid layer on sapphire, on top of which we deposited a 300 nm GaN:Si buffer layer. The active region consists of a 5 period superlattice (SL) with identical layer thicknesses of 1.25 nm for both the AlN barriers and the GaN:Si wells and is terminated by a 2 nm AlN barrier. The sample was polished into the standard 45° multi-pass waveguide, followed by the evaporation of a contact stripe directly on the last AlN layer (metal-semiconductor, MS contact) and a second contact on a 100 nm thick Si_3N_4 layer (metal-insulator-semiconductor, MIS contact). All contacts consist of Ti/Au (5 nm/200 nm).

The design is based on the electron transfer beween the SL and the underlying two-dimensional electron gas (2DEG) formed at the interface of the last AlN barrier and the underlying GaN buffer layer. This 2DEG is induced due to different piezoelectric and spontaneous polarization between the GaN buffer and the overlying SL, analogous to the 2DEG in an AlGaN high-electron mobility transistor. Figure 1 shows schematically the conduction band of the modulator. It is seen that at zero external field the ISB absorption will take place both in the SL and the 2DEG. At negative external voltage the upward bending at the contact/SL interface is more pronounced, as seen in the right part of Fig. 1. By increasing the negative voltage

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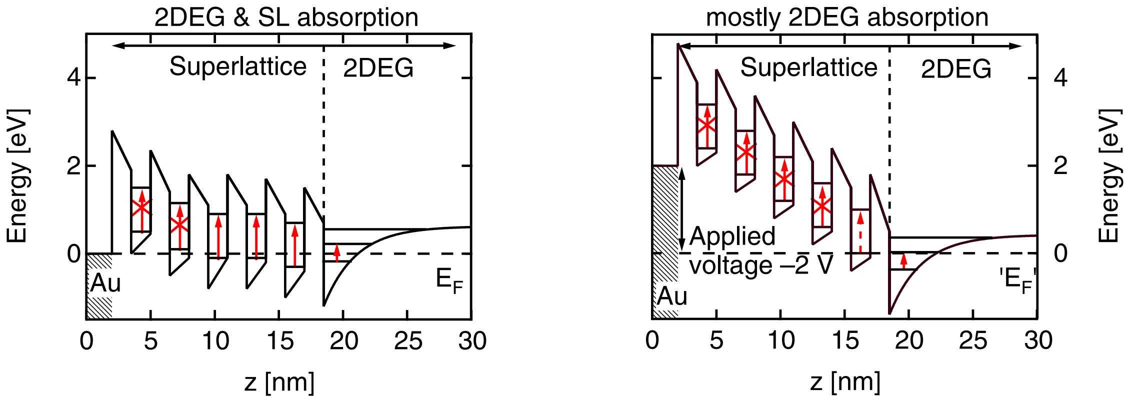

Fig. 1 Schematic conduction band diagram of an electro-optical modulator using ISB transitions in a GaN/AlN SL. The applied voltage is 0 V on the left figure and −2 V on the right figure.

amplitude the depletion edge can be moved towards the buffer, electrons are transfered into the 2DEG and the ISB absorption originating from the SL is strongly quenched. Under application of a positive voltage amplitude, the upward band bending can be reduced; this lowers the quantum well ground states below the global Fermi level, and thus the ISB absorption strength of the SL will be enhanced in comparison to the absorption strength of the 2DEG [5].

Compared to modulator structures involving charge transfer between two coupled quantum wells [6], this design has the advantage that the barrier between the 2DEG and the SL can be kept at a reasonably large thickness of roughly 5 monolayers (1.25 nm), that the electron reservoir (i.e. the 2DEG) is very large, and that the Fermi level of the structure is a good reference point for application of an external voltage.

3 Results and discussion Characterization of these devices relied on a measurement of the absorbance using a sensitive differential lock-in technique and the application of a periodic voltage square wave, which depletes (negative amplitude) or enhances (positive amplitude) the carrier density in the quantum wells below the illuminated contact. The other contact, which remains in dark, is considered as a reference.

In Fig. 2 the absorption of the prototype electro-optical modulator described in Section 2 is shown. Two features are observed in the absorption, a narrow high energy peak due to the ISB absorption in the SL and a broad low energy peak which originates from the 2DEG. As described above, free electrons can be transferred from the SL into the 2DEG by a negative voltage, whereas a positive voltage reduces the depletion region below the contact, resulting in an electron transfer from the 2DEG to the SL. It is therefore possible to quench (negative amplitude) or to enhance (positive amplitude) the ISB absorption taking place in the SL. Those effects are more pronounced under illumination of the region beneath the MS contact.

While the ISB absorption in the 2DEG was broadened, asymmetric, and Stark-shifted with electric field, the ISB absorption of the SL turned out to be narrow, Lorentzian-shaped, and wavelength-stable even under changing external field. Expressed in wavenumbers, the position (full width at half maximum) of the ISB transition in the SL is roughly $6850\,\mathrm{cm}^{-1}$ ($510\,\mathrm{cm}^{-1}$), whereas the corresponding numbers for the 2DEG amount to $4500\,\mathrm{cm}^{-1}$ ($1800\,\mathrm{cm}^{-1}$). The larger width of the 2DEG absorption is due to transitions into multiple upper states, all of them with non-zero oscillator strength [5].

In order to get a better insight about the conduction band structure and the influence of the external field two additional samples were characterized. They are identical to the structure described in Section 2, except that one has two and the other ten SL periods. In Fig. 3 electro-modulated absorption signals of all three samples are compared. For the ten period structure, the absorption peak at $4500\,\mathrm{cm}^{-1}$ is absent and

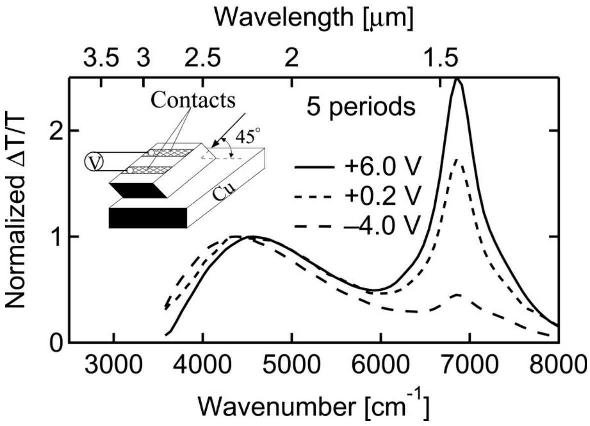

Fig. 2 ISB absorbance spectra of a 5 period electro optical ISB modulator as a function of wavenumber and under application of different voltages for an illuminated MS contact. For better visibility the absorption curves are normalized to one at the 2DEG absorption peak wavenumber. The inset shows the sample polished in 45° wedges and mounted on a copper platelet.

only the ISB absorption originating from the SL is observed. We interpret this observation as an insufficient penetration depth of the external field.

For the two period sample, the upward conduction band bending almost completely depletes the SL. Only a highly positive voltage amplitude of 12 V beneath the MIS contact produces the ISB absorption originating from the SL as a small shoulder on the dominant 2DEG absorption. The redshift (reduced Stark shift) [7] of the 2DEG absorption between the measurement below the MS and the one below the MIS contact is due to the different upward band bending of the two contacts: the MS contact introduces a strong upward bending of the conduction band, such that the depletion edge at zero bias already lies beneath the SL; therefor, the two period SL is fully depleted and the ISB absorption peak originating from the 2DEG is less Stark shifted.

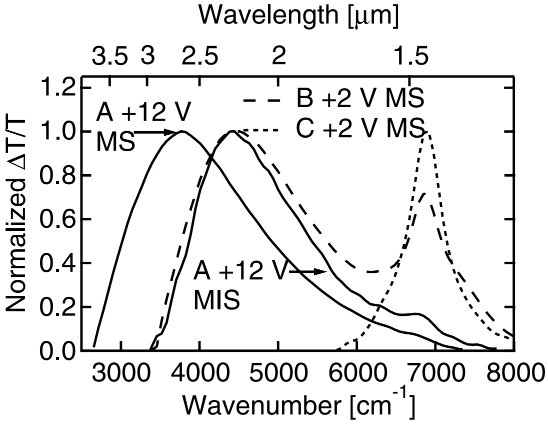

Fig. 3 ISB absorbance spectra of three samples with different number of SL periods as a function of wavenumber and under application of a positive voltages amplitude. Sample A has 2 periods, the modulator sample 5 periods and sample C 10 periods.

As the achieved on-off ratio of the 5 period modulator is still small, we propose a ridge waveguided version of the modulator in order to improve the performance of the above described device. The ratio between the absorbancecs, $\alpha_{ISB} \times L$, would remain the same, but the ratio between the on- and off-state absorption ($e^{-\alpha_{ISB} \times L}$) would become considerably larger due to the increased optical interaction length L between the optical field and the active region. One-dimensional waveguide propagation simulations show that under the MIS contact, a reasonably low absorption loss on the order of 10 cm^{-1} can be expected (see Fig. 4). Since the ISB absorption coefficient α_{ISB} is quite high, namely on the order of 100 cm^{-1}, an optical overlap of some percent would be sufficient to ensure that the on-off ratio becomes larger than the waveguide losses.

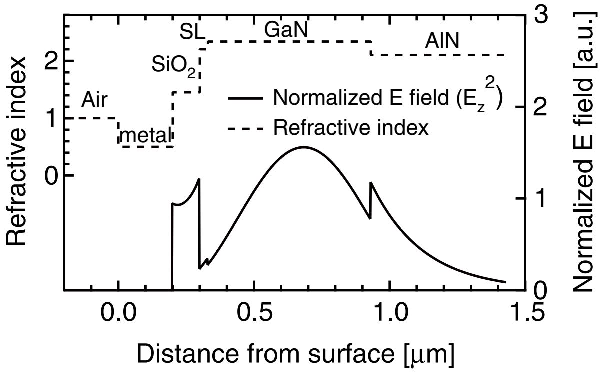

Fig. 4 Simulated waveguide structure. The AlN buffer beneath the GaN contact layer acts as lower index waveguide cladding.

4 Conclusion We have measured the differential electro-modulated absorption of a 5 period superlattice grown on a GaN substrate. The results show that it is possible to quench the SL absorption by application of an external field. This is a proof of concept of an on-off-electro-optical modulator at telecommunication wavelength. To improve the modulation depth, a waveguide design is presented.

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