Electrically adjustable intersubband absorption of a GaN/AlN superlattice grown on a transistorlike structure

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The authors report on electromodulated intersubband (ISB) absorption experiments on AlN/GaN superlattices (SLs) grown on a transistorlike structure. A sample containing five SL periods shows two distinct absorption peaks related to ISB transitions in the SL and in the two dimensional electron gas located at the interface of the lowest SL barrier and the underlying GaN buffer. The ratio of those two absorption peaks can be adjusted by applying an external field, which influences the overall band structure and, more specifically, the free carrier density in the SL. This is a proof of concept of an on-off electro-optical modulator at 1.5 μm.

Intersubband (ISB) transitions in III-nitride based semiconductor superlattices (SLs) attract an increasing interest due to the large conduction band discontinuity and fast ISB relaxation time of this material system.[1] Optimized plasma-assisted molecular-beam epitaxy (PAMBE) allows the synthesis of GaN quantum wells (QWs) with thicknesses in the range of 1–2 nm, which yield ISB transitions in the commercially interesting telecommunication wavelength range[2,3] around 1.5 μm. An attractive application for ISB devices in this spectral region is electro-optical modulators, for which coupled QWs (Ref. 4) are a classical approach. Unfortunately, coupled QW modulators using III nitrides and absorbing around 1.5 μm require very thin barrier layers[5] and are thus extremely sensitive to thickness fluctuations on the monolayer ($\sim$2.5 Å) scale. In addition, the strong ($\sim$5 MeV/cm) built-in piezo- and pyroelectric fields complicate the design. In this letter, we present an alternative solution for an electro-optical AlN/GaN modulator. It is based on the transfer of electrons between a regular SL and the two dimensional electron gas (2DEG) located in the triangular well at the interface between the lowest AlN barrier and the underlying GaN buffer. In other words, the structure resembles a high electron mobility transistor as presented in Ref. 6 whose AlGaN barrier layer has been replaced by a SL. We investigated three PAMBE-grown samples with identical layer thicknesses of 1.5 nm for both the AlN barriers and the GaN wells, but with different numbers of SL periods (samples A/B/C: 2/5/10 periods). All SLs were deposited on a 300 nm thick GaN:Si (5×10^{17} cm^{-3}) layer which was grown on a 10 μm thick GaN-on-sapphire commercial template. The SLs were terminated by a 2 nm AlN barrier. All GaN QWs are *n* doped with Si in the 10^{19} cm^{-3} range. For the 2DEG, a sheet carrier density of 2.2×10^{13} cm^{-2} is extracted from a capacitance-voltage profile of sample A.

All samples were polished into the standard 45° wedge multipass geometry, followed by the evaporation of a contact stripe directly on the AlN cap [metal-semiconductor (MS) contact]. A second contact was then evaporated on a 100 nm thick Si_3N_4 layer grown by plasma enhanced chemical vapor deposition [metal-insulator-semiconductor (MIS) contact]. All contacts consist of Ti/Au (5 nm/200 nm). A schematic drawing of a processed sample is presented as an inset of Fig. 1. For absorption measurements, these multipass waveguide samples were illuminated by the internal white light source of a Fourier transform infrared (FTIR) spectrometer. A sensitive differential electromodulated absorption (EMA) method[7] was used to measure the relatively small absorption signals. In these measurements, a voltage square wave is applied between the two contacts. This voltage periodically enhances or depletes the carrier density in the QWs below the contact and thus modulates the transmission of the FTIR light beam. In this work, the voltage polarity is defined in such a way that for a positive sign, the potential at the illuminated contact is higher than at the dark contact, which is considered as a reference.

Figure 1 shows normalized EMA measurements when illuminating the MIS contact using a voltage amplitude of −2 V. Although the periods of the three SLs are identical, we observe two very different absorption peaks. The different

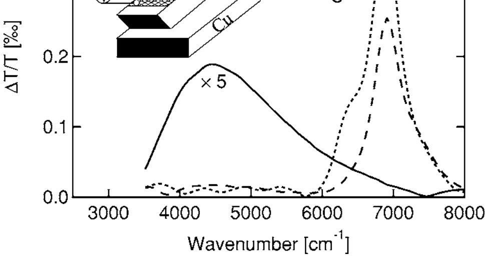

FIG. 1. EMA of samples A, B, and C measured under the MIS contact. The absorption peak at 4500 cm^{-1}/2.2 μm (A) originates from the 2DEG and the ones at 6850 cm^{-1}/1.46 μm [(B) and (C)] from the SL region. The cutoff at 3500 cm^{-1} marks the lower end of the measurement range. Inset: schematic view of the sample mount.

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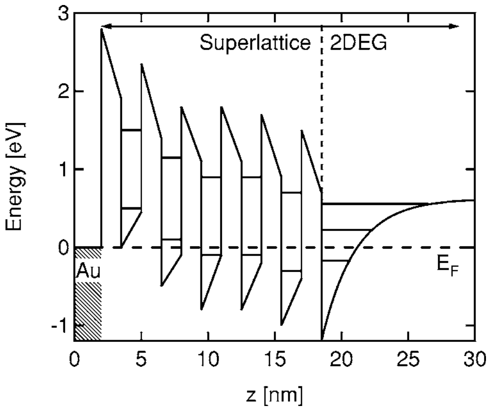

FIG. 2. Schematic conduction band diagram for sample B.

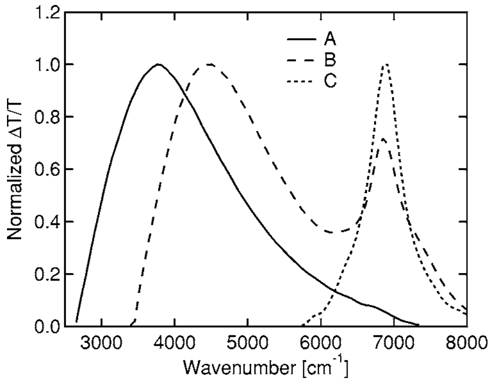

FIG. 3. EMA of samples A, B, and C measured under the MS contact, normalized to 1 at the respective peak wave number.

absorption spectra can be explained by analysis of the band diagram of these samples (illustrated schematically for sample B in Fig. 2). Samples B and C have a narrow absorption peak at 6850 cm^{-1} (1.46 μm) with full widths at half maximum (FWHMs) of 509 and 523 cm^{-1}, respectively. This transition energy agrees well to our simulations for 1.5 nm wide GaN QWs. In contrast, sample A exhibits a very broad absorption feature around 4500 cm^{-1} (2.2 μm) with a FWHM of 1850 cm^{-1}. This signal is attributed to absorption in the 2DEG located at the interface between the lowest AlN barrier and the underlying GaN buffer (see Fig. 2), the existence of the 2DEG being due to the difference in piezoelectric and spontaneous polarizations between GaN buffer and the SL. The large FWHM of the absorption is due to multiple ISB transitions in the 2DEG. Assuming that the electric field in the triangular well is constant, the barrier is infinitely high, and the 2DEG does not penetrate into it, the transition energy between the ground and the first excited state in the triangular potential of the 2DEG can be estimated using the triangular potential approximation[8]

$$E_i = \left(\frac{\hbar^2}{2m_w^*}\right)^{1/3}\left[\frac{3\pi}{2}eF\left(i+\frac{3}{4}\right)\right]^{2/3}, \qquad (1)$$

where E_i is the ith energy level and $F=5.3$ MV/cm the constant electric field in the triangular well assuming a strained $Al_{0.5}Ga_{0.5}N$/GaN interface[9,10] (50% AlGaN being the average composition of the regular SL). The calculated transition energy $E_1-E_0=5000$ cm^{-1} (620 meV) is in reasonable agreement with the measured 4500 cm^{-1} (560 meV), taking into account the error bars in the elastic and piezoelectric constants.

Therefore, the different absorption spectra as a function of the number of QWs can be explained by a subtle balance between conduction band bending, total SL thickness, and number of electrons in the three samples. Contacts on AlN lead to an upward band bending at the top of the SL, and the area probed by the EMA corresponds to the edge of the depletion region below the contact. For the two period SL sample, the upward band bending fully depletes both QWs already at zero external field, so that free electrons are transferred to the 2DEG. The external electric field modulates the charge in the 2DEG; hence, only the ISB absorption in the 2DEG is observed. For samples B (see Fig. 2) and C, only the topmost QWs are fully depleted by the upward band bending, whereas the rest of the SL remains in "flatband" condition. In this case, the external electric field modulates the charge in the QWs, and the 2DEG absorption is not observed because of the insufficient depth of the depletion region below the MIS contact.

Following the above reasoning, the magnitudes of the EMA of samples B and C should be identical for measurements performed under the same voltage amplitude as both samples have identical geometry and depletion depth. The slight difference between them can be explained by small processing and measurement fluctuations. On the other hand when comparing the integrated EMA for samples A and B, we see that sample A accounts for only 43% of that of sample B. Since the 2DEG of sample A is at the same distance from the contact as the SL of sample B, Fermi's golden rule can be applied to make a theoretical comparison: Assuming a dipole matrix element of 3.88 Å (3.1 Å) for sample A (B), a sheet carrier density of 2.2×10^{13} cm^{-2} (1.5×10^{12} cm^{-2}), and one (three, see Fig. 2) absorbing well(s), the absorption of sample A should be roughly five times stronger than for sample B. However, the EMA signal is proportional to the modulation of the absorption by the external field amplitude. Since the carrier density in the QWs is lower than that in the 2DEG, the external field introduces a higher relative charge carrier modulation in the QWs than in the 2DEG; this translates into a more intense EMA signal, in spite of the weaker total absorption.

The effects described above are even more pronounced if the absorption of all three samples is measured under the MS contact (see Fig. 3), where the depletion region below the contact penetrates deeper. By comparing the spectra in Figs. 1 and 3, we observe that for sample C the depletion region remains always smaller than the SL thickness (32 nm); therefore, the ISB absorption in the QWs is dominant and the 2DEG absorption is not observed. In the case of sample B (17 nm thick, five period SL), the depletion region already reaches the 2DEG, and hence absorptions in both the SL and 2DEG are visible. In sample A, finally, the 2DEG signal becomes the dominant feature of the absorption spectrum, whereas the SL signal is almost entirely absent. In addition, the 2DEG signal of sample A beneath the MS contact exhibits a redshift compared to the one below the MIS contact due to the more efficient depletion of the 2DEG achieved in the MS configuration.

The observation of the two absorption lines in sample B when illuminating the MS contact opens the possibility to fabricate an electro-optical modulator. Free electrons can be transferred from the SL into the 2DEG by a negative voltage, whereas a positive voltage reduces the depletion region be-

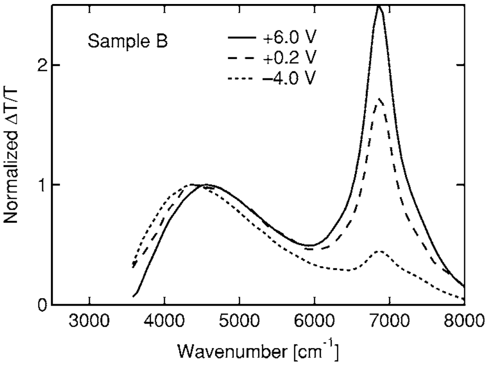

FIG. 4. EMA of sample B for different voltages, normalized to 1 at the 2DEG peak wave number. The cutoff at 3500 cm^{-1} marks the lower end of the measurement range.

low the contact, resulting in an electron transfer from the 2DEG to the QWs. Accordingly, when applying a negative voltage, the ISB absorption mainly takes place in the 2DEG, whereas positive voltage results in an enhancement of the SL-related EMA line at 6850 cm^{-1} (see Fig. 4). Note that in Fig. 4, the SL-related EMA line peaks at 6850 cm^{-1}, independently of the voltage, since the influence of the external field on the ISB energy is negligible. In contrast, the external field modifies the shape of the triangular well at the SL/GaN buffer interface, inducing a redshift (Stark) of the absorption for negative voltage amplitudes between 2 and 4 V which is in the range of 60 cm^{-1}/V. The still relatively weak ratio of the on (−4 V) and off (+6 V) absorbances could be improved by using a waveguided structure, where the ratio between the absorbances, $\alpha \times L$, would remain the same, but the ratio between the on- and the off-state absorption ($e^{-\alpha \times L}$) could become considerably larger. To improve $\alpha \times L$, the doping level of the wells, the number of SL periods, and the contacts must be further optimized.

In conclusion, we present a detailed study of ISB EMA measurements in AlN/GaN SLs with different numbers of periods and grown on a transistorlike structure. We show that for a certain SL thickness (17 nm=five periods), it is possible to modulate the SL absorption by transferring electrons to or from the 2DEG. This is a proof of concept of an on-off electro-optical modulator in the telecommunication range.

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