Femtosecond intersubband dynamics of electrons in AlGaN/GaN-based high-electron-mobility transistors

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Abstract

Ultrafast electron dynamics in the inversion layer of an AlGaN/GaN transistor is studied in pump–probe experiments with 50 fs mid-infrared pulses. Two-colour pump–probe measurements show an instantaneous transmission increase for all spectral positions of the probe, which demonstrates that homogeneous broadening is an important contribution to the total linewidth in this material. We observe the maximum of the induced transmission change around 5 μm. This large Stokes shift might be caused by the extremely large electron–LO-phonon scattering rate.

Optical intersubband excitations in semiconductor nanostructures provide direct insight into the ultrafast dynamics of coherent optical polarizations and nonequilibrium carriers and play a key role for novel devices such as quantum cascade lasers. Because of the huge conduction band discontinuity and thus the possibility of fabricating quantum cascade lasers at short wavelengths, nanostructures made of group-III nitrides have recently attracted considerable interest. In particular, intersubband absorption in GaN/AlGaN multiple quantum wells (MQWs) was observed in the spectral range up to the communication wavelength $\lambda \approx 1.55\,\mu$m [1]. The first time-resolved experiments on MQWs (intersubband absorption at $\lambda = 4.5\,\mu$m) gave a rough upper limit of 150 fs for intersubband relaxation [2].

Two-dimensional electron subbands can also be formed in the inversion layer of an AlGaN/GaN-based high-electron-mobility transistor (HEMT). Recently, e1–e2 intersubband absorption was observed for the first time in AlGaN/GaN-based HEMTs [3] showing a broad absorption centred at $\lambda = 4\,\mu$m [figure 1(*a*)]. This HEMT (GS1282 in [3]) was grown on a c-face sapphire substrate using MBE. The layer sequence is 20 nm pure AlN, 1.2 μm nominally undoped GaN, 13 nm undoped $Al_{0.8}Ga_{0.2}N$, and finally 2 nm undoped GaN as a contact layer. For reflection a gold layer was sputtered onto the contact layer. In this sample, a large piezoelectric field at the heterointerface is present due to the lattice mismatch and the hexagonal crystal structure. The piezoelectric field together with the heterointerface results in a deep triangular well.

Here, we present the first time-resolved study of the two-dimensional electron plasma in this $Al_{0.8}Ga_{0.2}N$/GaN-based HEMT, using direct intersubband excitation and probing of electrons via the e1–e2 intersubband transition. The intersubband absorption spectrum at a temperature of 300 K is plotted in figure 1(*a*). The broad absorption band is due to transitions of electrons from the $n = 1$ to the $n = 2$ subband in the triangular potential well.

In our time-resolved experiments, electrons are excited from the e1 to the e2 subband by 50 fs mid-infrared pulses resonant with the optical IS transition. Pump and probe pulses at 1 kHz repetition rate are derived from the output of an optical parametric amplifier by difference frequency mixing in a 1 mm thick GaSe crystal [4]. After interaction with the sample, the probe pulses are spectrally dispersed in a monochromator (3 meV resolution) and detected by a cooled HgCdTe detector. The coupling to the IS dipole moment is maximized using p-polarized pulses and a prism geometry of the sample.

We have performed two types of time-resolved experiments, one with pump and probe at the same wavelength and the other with pump and probe at different wavelengths. First we measured the transients with pump and probe at the same wavelength of 4 μm. In figure 1(*a*) the spectrum of

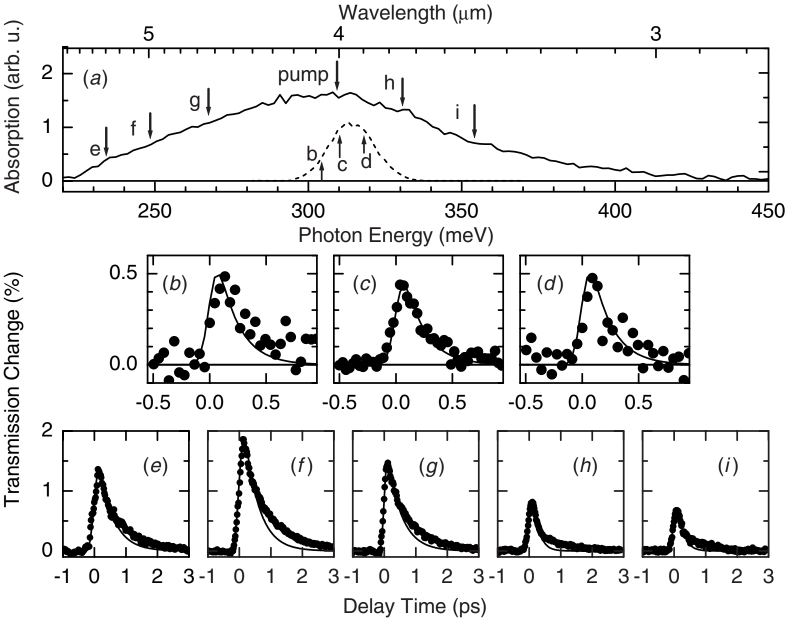

Figure 1. (*a*) Solid line: mid-infrared absorption spectrum [3] of the $\mathrm{Al_{0.8}Ga_{0.2}N/GaN}$-based HEMT sample at 300 K. The broad p-polarized absorption band is due to transitions of electrons from the $n = 1$ to the $n = 2$ subband in the triangular potential well. Dashed line: spectrum of the pump pulse. (*b*)–(*i*): transmission change as a function of the time delay between pump and probe pulses. (*b*)–(*d*): transients measured with pump and probe at the same wavelength of 4 μm for different detection wavelengths within the probe spectrum. (*e*)–(*i*): transients measured with a pump wavelength of 4 μm for different probe wavelengths (see the arrows in (*a*)).

pump and probe pulses is shown for comparison. We present in figures 1(*b*)–(*d*) transients at selected spectral positions E_{det} within the broad spectrum of probe pulses (see arrows in figure 1(*a*)). The transmission change of the HEMT sample is plotted as a function of the delay between pump and probe. For all E_{det} we observe almost identical transients, an instantaneous (within the time resolution of our experiment (50 fs)) bleaching of the e1–e2 absorption and a subsequent recovery with a time constant of 180 fs. Interestingly, the spectral amplitude of the bleaching profile does not follow the intensity spectrum of the mid-infrared pulses, i.e., no spectral hole is burned.

Since the probe spectrum covers only a small portion of the large width of the absorption band in this material, we additionally performed two-colour pump–probe measurements. Pump and probe pulses are independently generated from two optical parametric amplifiers by difference frequency mixing. In our experiment, the pump pulse at 4 μm resonantly excites electrons from the e1 to the e2 subband. The resulting transmission changes of the probe pulse are monitored at different spectral positions on the broad absorption band (see arrows in figure 1(*a*)). Figures 1(*e*)–(*i*) show the results. Like the one-colour data, the two-colour data also show an instantaneous transmission increase for all spectral positions of the probe. For short probe wavelengths ((*h*) and (*i*)) the recovery time is 180 fs, for long wavelengths ((*e*)–(*g*)) it is 500 fs.

From the instantaneous transmission increase for all spectral positions we conclude that the homogeneous linewidth of individual e1–e2 transitions within the total absorption band is considerably larger than the spectral width of our probe pulses. This demonstrates that homogeneous broadening is an important contribution to the total linewidth in these $\mathrm{Al_{0.8}Ga_{0.2}N/GaN}$-based HEMTs. An explanation for such strong homogeneous broadening may be given by the strong electron–phonon coupling in these materials, caused by their large effective masses ($\approx 0.23m_0$) [5] and their high LO-phonon frequencies ($\approx$92 meV) [6]. This leads to very high electron–LO-phonon scattering rates, which may be even higher than the electron–electron scattering rates.

Another result seen from figure 1 is that the maximum of the induced transmission change is at longer wavelengths than the maximum of the linear absorption.

In conclusion, the ultrafast electron dynamics of an AlGaN/GaN transistor is studied. Two-colour pump–probe measurements show that homogeneous broadening has a considerable impact on the total intersubband linewidth. The maximum of the induced transmission around 5 μm occurs at a longer wavelength than the absorption maximum.

References

[1] Gmachl C, Ng H M, Chu S N G and Cho A Y 2000 *Appl. Phys. Lett.* **77** 3722

[2] Iizuka N, Kaneko K, Suzuki N, Asano T, Noda S and Wada O 2000 *Appl. Phys. Lett.* **77** 648

[3] Hofstetter D, Diehl L, Faist J, Schaff W J, Hwang J, Eastman L F and Zellweger C 2002 *Appl. Phys. Lett.* **80** 2991

[4] Kaindl R A, Wurm M, Reimann K, Hamm P, Weiner A M and Woerner M 2000 *J. Opt. Soc. Am.* B **17** 2086

[5] Hang D R, Liang C T, Huang C F, Chang Y H, Chen Y F, Jiang H X and Lin J Y 2001 *Appl. Phys. Lett.* **79** 66

[6] Azuhata T, Matsunaga T, Shimada K, Yoshida K, Sota T, Suzuki K and Nakamura S 1996 *Physica* B **219–220** 493