Tera-Hertz Acousto-Electric Modulation in Piezoelectric InGaN/GaN Quantum Wells Using Nano Acoustic Waves

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Abstract: We demonstrated an ultrafast electron distribution modulation up to THz frequency by using nano acoustic waves in InGaN/GaN multiple-quantum-wells. With amplitude-fixed acoustic waves, the electron energy distribution modulation was observed by using femtosecond optical technique.

OCIS codes: 300.6380 Spectroscopy, modulation; 320.7130 Ultrafast processes in condensed matter, including semiconductors

1. Introduction

We have recently demonstrated large amplitude coherent acoustic phonon oscillation in InGaN/GaN MQWs [1]. Due to lattice-mismatch of the InGaN layer (well region) to the substrate (GaN), a strain-induced piezoelectric field on the order of MV/cm was expected. The oscillation frequency, on the order of THz, can be varied by tuning the period width of MQWs. Due to piezoelectric-coupling, a time-varying electric field, also with THz oscillation frequency, accompanied the coherent acoustic waves. This electric-field-modulation resulted in absorption variation through quantum-confined Franz-Keldysh (QCFK) effect [1]. Here we report THz dynamic modulation of the electronic system in InGaN/GaN multiple quantum wells (MQWs) by nano acoustic waves. This dynamic acousto-electric coupling is different from the QCFK effect that describes the electric-field-induced absorption changes of the intrinsic band-to-band transitions. We also demonstrate an ultrafast electron energy distribution modulation up to a frequency scale of THz.

2. Experiments

The experiments were performed at room temperature on 14 periods InGaN/GaN MQWs by optical pump-probe technique [1]. In our experiment, the pump-1 first excited a fixed amount of carriers within the MQWs, and the pump-2 was for modifying the amount of photocarriers in the MQWs. By observing the probe transmission changes when the pump1-induced echo returned into the MQWs, the THz acouso-electric modulation can be analyzed.

In Fig. 1 we show the measured time-domain traces at a laser wavelength of 370 nm with [trace (a)] and without [trace (b)] the pump-2 pulse. The center oscillation frequency was 0.72 THz. The acoustic pulse bounced at the cap-air interface and re-entered into the MQWs region after ~35 ps. the echo-induced absorption modulations had approximately the same amplitude for both traces. This carrier density independent modulation is attributed to the THz modulation of wavefunction overlap of the quantum electronic states due to piezoelectric and deformation couplings. However, with a longer laser wavelength of 390 nm, the probe photon energy is closer to the quasi-Fermi levels of photocarriers, and we are thus able to study the time-varying energy-distribution of photocarriers caused by the coherent acoustic waves. In Fig. 2, the echo-induced transmission changes is obviously enhanced while the carriers are increased in the MQWs. We call this phenomenon the acousto-electronic enhancement.

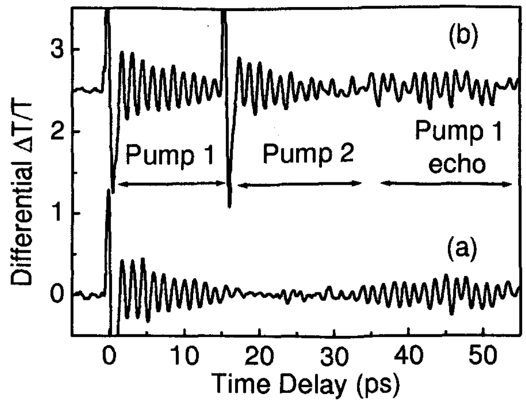

Fig. 1. Time-domain traces without (a) and with (b) a second pump pulse. The laser wavelength is 370 nm.

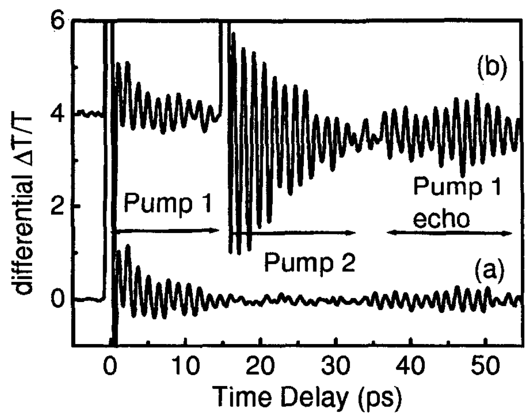

Fig.2. Time-domain traces without (a) and with (b) a control pulse. The laser wavelength is 390 nm.

In Fig. 3, we show a schematic diagram for the dynamic modulation of the electronic system induced by the echo. Since the absorption constant α is proportional to the occupation factor $1-f(E_r)$, where E_r is the resonant energy corresponding to the probe photon absorption, and f is the carrier distributions. Here we consider transitions among the first quantized band of electron or hole. E_1 is the quantized energy of the first subband and ΔE_1 is the corresponding bnad-edge shift due to coherent phonon echo. This shift comes from both deformation potential coupling and the time-varying electric field accompanying the acoustic waves. As a THz acoustic wave passing through the quantum well, the photocarriers were found to adiabatically follow the THz modulated band-structure with a shifted band-edge. This in turn results in a shift of the energy distribution as shown in Fig. 3. In the 370 nm case [Fig. 3(a)] E_r is far away from the quasi-fermi-level, and this shift has negligible change of the occupation factor f. However, in the case of 390 nm, the resonant energy is close to quasi-fermi-level, and the corresponding shift in energy-distribution leads to a occupation shift Δf. As a result, a larger absorption and transmission changes were obtained as demonstrated in Figs. 1 and 2.

In the presentation, we will discuss more detailed experimental results with well-controlled nano acoustic wave amplitude and background carrier density. A macroscopic theory will be presented for this acousto-electric modulation effect. Its possible application on future THz devices will also be discussed.

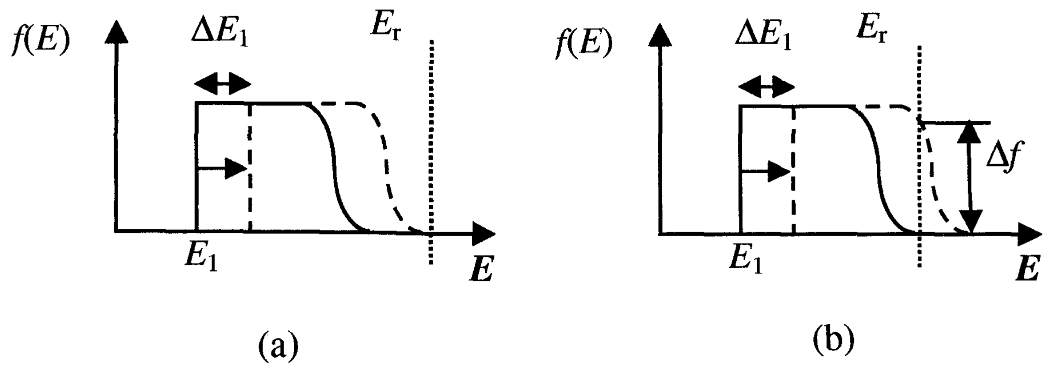

Fig. 3. Dynamic modulation of QW band-structure by coherent acoustic waves. Note that ΔE_1 is the band-edge shift caused by acoustic waves. The probe wavelength is (a) 370 nm, and (b) 390 nm for our case.

5. References

[1] C.-K. Sun et al., "Coherent acoustic phonon oscillation in semiconductor multiple quantum wells with piezoelectric fields," Phys. Rev. Lett. **84**, 179 (2000).