Terahertz-optical mixing in *n*-doped GaAs quantum wells

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Abstract: Non-linear mixing of a strong Terahertz and a weak near-infrared beam is observed for the first time in an *n*-doped GaAs quantum well. Our results are compared to those for undoped wells.

OCIS Codes: (230.2090) Electro-optical devices; (230.5590) Quantum-well devices; (190.5970) Semiconductor nonlinear optics including MQW;

The mixing of near-infrared (NIR) and terahertz (THz) lasers has been studied experimentally and theoretically as a way of achieving optical wavelength conversion [1] and of observing strong THz field effects [2]. The mixing results in sidebands at $\omega_{\text{sideband}} = \omega_{\text{NIR}} + n\omega_{\text{THz}}$, where $n = \pm1,2,3,\ldots$, as shown in Fig. 1a. The sideband signal has been shown to be strong primarily when ω_{NIR} and ω_{THz} are close to interband and intersubband resonances, respectively [3]. Previous studies dealt with undoped wells in which NIR and THz radiation coupled states which were well-described as excitons. In this paper, sideband generation in doped quantum wells is reported for the first time and compared to that in undoped wells. The presence of charge in the wells screens the excitons and dramatically changes both the resonant behavior of the sideband generation and the strength of the sidebands.

We studied a doped sample and an undoped sample. They consist of 10 periods of double GaAs quantum wells (QWs), nominally 100 and 120 Å wide and separated by a 25 Å $Al_{0.2}Ga_{0.8}As$ tunnel barrier (see inset of Fig. 2b). The doped sample has an electron concentration $n_e \sim 1.5\times10^{11}$ cm^{-2} per QW. These active QWs are in between two doped gate QWs, used for applying a DC electric field to the sample, thus tuning the intersubband transitions. Behind these QWs is a distributed Bragg reflector (DBR), which reflects the NIR beam and prevents absorption by the GaAs substrate. The experimental geometry is illustrated in Fig. 1b.

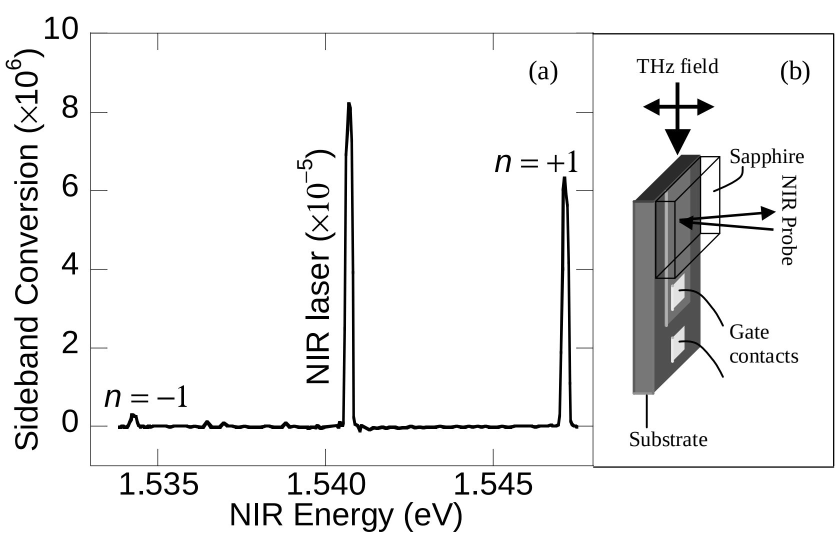

Fig. 1. (a) Sideband spectrum taken at 15 K with an FEL frequency of 1.5 THz (6.4 meV). The reflected beam at ω_{NIR} is multiplied by 10^{-5}. The THz power was approximately 500 W and the NIR power was 0.67 mW. (b) The experimental geometry.

The photoluminescence (PL) and reflectivity of the two samples are shown in Fig. 2. There are a number of absorption lines in both samples (Fig. 2a). A more detailed description of these transitions (in the undoped sample) can be found in ref. 3, but the lowest energy line comes from the heavy hole 1 to electron 1 transition (E1HH1). The reflectivity and PL lines are significantly broader in the doped sample, and the doped sample displays an energy shift between the PL and reflectivity, indicating significant charge in the wells.

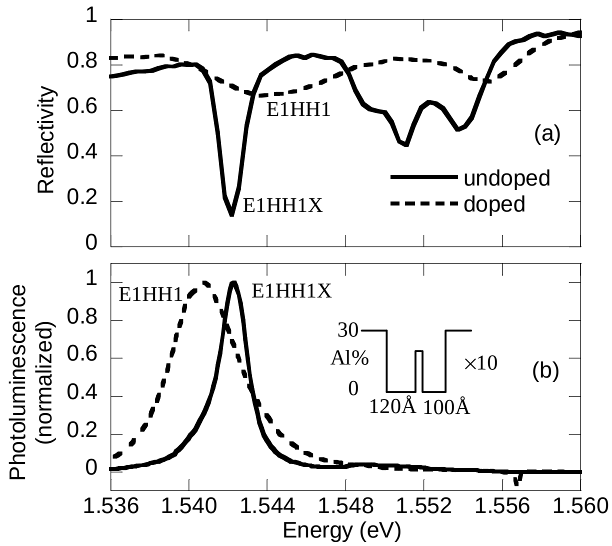

Fig. 2. (a) Reflectivity spectra of the undoped (solid) and doped (dashed) samples at ~20 K. The lowest lines come from transitions between the 1st heavy hole subband (HH1) and 1st electron subband (E1) but are excitonic (E1HH1X) in the undoped sample. (b) Photoluminescence spectra taken with excitation power less than 1 mW at ~1.6 eV. The spectrum of the undoped sample was taken at 21 K, while that of the doped one was recorded at 15 K. The peak PL of the doped sample is ~10 times weaker than that of the undoped sample. Conduction band profile of the QWs is inset in the figure.

The maps in Fig. 3 show the $+1\omega_{THz}$ sideband resonances of the two samples. For each point, the sideband intensity is measured at the NIR laser energy (varied on the vertical axis) plus ω_{THz}. The DC electric field is varied to bring the THz field into resonance with the intersubband transitions. The two maps look very different. The undoped sample (Fig. 3b) has a lower resonance involving only an electron transition and two upper resonances involving hole transitions (see ref. 3 for details). While sideband resonances involving hole transitions should still be possible in *n*-doped wells, they should be weaker. In the doped sample (Fig. 3a), however, only the E1HH1→E2HH1 resonance remains. The peak sideband signal is an order of magnitude weaker in the doped sample compared to the undoped one and much broader. These observations can be explained by the interband oscillator strength being more spread out in the doped wells. This study provides interesting new phenomena to explore and also opens the possibility of optically observing strong THz field effects such as period-doubling bifurcations [4].

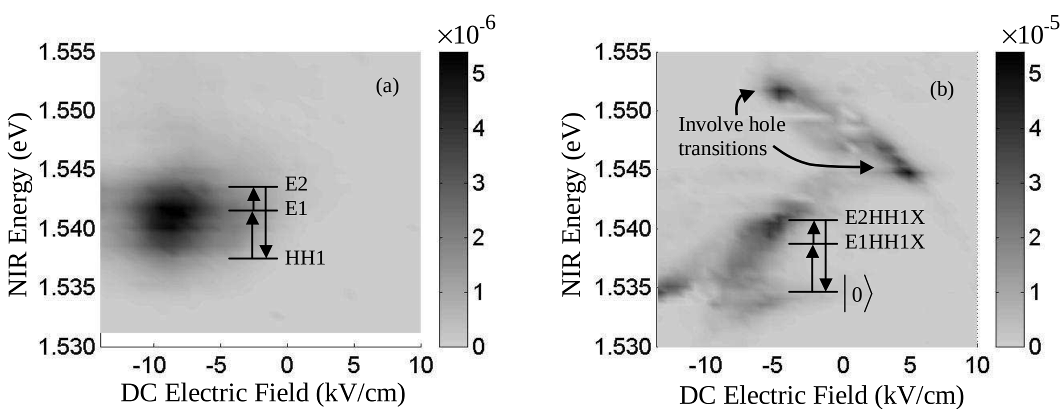

Fig. 3. Sideband maps taken with a NIR power less than 1 mW and THz power of about 300W. Each point represents the $n = +1$ sideband conversion efficiency when the NIR laser energy is tuned to the value on the vertical axis. (a) Map of the doped well sample at 15K with ω_{THz}=1.5 THz (6.4 meV). The resonance appears near where the E1→E2 intersubband transition is expected and near the E1HH1 energy. (b) Map of the undoped well sample at 21K with ω_{THz}=2.0 THz (8.2 meV). The resonances are excitonic and are labeled according to ref. 3.

[1] S. G. Carter, V. Ciulin, M. S. Sherwin, M. Hanson, A. Huntington, L. A. Coldren, and A. C. Gossard, "THz electro-optic wavelength conversion in GaAs quantum wells: Improved efficiency and room-temperature operation," Appl. Phys. Lett. (to be published).
[2] M. Y. Su, S. G. Carter, M. S. Sherwin, A. Huntington, and L. A. Coldren, "Strong-field terahertz optical mixing in excitons," Phys. Rev. B **67**, 125307(1-5) (2003).
[3] M. Y. Su, S. G. Carter, M. S. Sherwin, A. Huntington, and L. A. Coldren, "Voltage-controlled wavelength conversion by terahertz electro-optic modulation in double quantum wells," Appl. Phys. Lett. **81**, 1564-1566 (2002).
[4] B. Galdrikian and B. Birnir, "Period Doubling and Strange Attractors in Quantum Wells," Phys. Rev. Lett. **76**, 3308-3311 (1996).