Extended Abstracts of the 2002 International Conference on Solid State Devices and Materials, Nagoya, 2002, pp. 576-577

P8-5

Miniband, Wannier-Stark Quantization, and Zener Breakdown in Wide Miniband Superlattices Investigated by Time-Domain Terahertz Spectroscopy

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1. Introduction

Bloch oscillation (BO) in semiconductor superlattices is attractive as a source of coherent THz electromagnetic waves. Since the first proposal of high frequency Bloch oscillators by Esaki and Tsu [1], considerable effort from both experiments [2-5] and theories [6-8] has been made to search for BOs and obtain terahertz (THz) emission. Even after three decades from the proposal, however, THz emitters using BOs have not been achieved yet. It is, therefore, of prime importance to establish an understanding of the dynamical electron motion in the THz regime.

We have investigated terahertz (THz) emission due to electron transport in biased wide-miniband GaAs/AlGaAs superlattices by time-domain THz-emission spectroscopy. With increasing bias fields, three distinct regimes are observed in the bias-field dependence of the emitted THz radiation. These three regimes are attributed to the miniband, Wannier-Stark quantization, and Zener tunneling regimes, respectively. In the Wannier-Stark regime, a few cycle Bloch oscillations were clearly observed. However, when the bias-field exceeds a critical value, it is found that the Bloch oscillations die out and the quasi-miniband-like transport is recovered due to resonant tunneling into higher minibands.

2. Experimental

The samples used in this work were GaAs/$Al_{0.3}Ga_{0.7}As$ superlattice m-i-n diodes. The samples were prepared by growing a 500 nm-thick undoped GaAs/AlGaAs superlattice on n^+-GaAs substrates by molecular beam epitaxy. We designed the GaAs wells and $Al_{0.3}Ga_{0.7}As$ barriers so that the first miniband width is 50 meV. A bias electric field, F, was applied between the semi-transparent surface Schottky contact and the bottom ohmic contact.

We used a quasi-autocorrelation geometry, *i. e.*, the power of THz radiation generated by a pair of time-correlated femtosecond laser pulses was measured as a function of the time interval, t, between the two laser pulses imposed by a Michelson interferometer. In our quasi-autocorrelation measurements, the signals detected by a Si bolometer are the convolutions of the two THz electric fields consecutively emitted from the sample surfaces. Since the miniband width for holes are much narrower, the emitted THz radiation is predominantly proportional to the acceleration of electrons in the superlattice. Experiments were performed at 10 K by using 100 fs laser pulses delivered from a mode-locked Ti:sapphire laser. The pump photon energy was set to be 1.54 eV, which excites electrons near the bottom of the miniband.

3. Bias-field dependence of emitted THz intensity

It is found that, at low electric fields (the miniband regime), the emitted THz radiation intensity increases with increasing F, which is consistent with ordinary band transport picture. However, when F exceeds 12 kV/cm, the THz intensity starts to roll off with increasing F, indicating that the dipole moment of oscillating electrons decreases with F (field-induced localization). Concomitantly, the time-domain autocorrelation traces of the THz emission for $F > 12$ kV/cm start showing clear oscillations in the trailing part of the traces. Furthermore, the oscillation periods become shorter with increasing F and are in agreement with the expected Bloch frequencies. This is a clear evidence for the formation of a Wannier-Stark ladder above a critical electric field and the onset of Bloch oscillations.

4. Zener breakdown of the superlattice miniband

When F exceeds 20 kV/cm, however, the reduction of the THz intensity saturates and the emission becomes brighter again. In this bias-field range, it is found that the oscillations in the THz autocorrelation traces gradually diminish and are completely washed out for $F > 30$ kV/cm. At the same time, the THz spectra become very broad and eventually similar to those in the low-bias miniband region. This reentrant feature of the quasi-miniband-like transport can be understood by resonant tunneling of electrons from the first miniband to the second miniband (Zener breakdown). Such an interpretation is further supported by the result of weak excitation interband photocurrent spectroscopy [9].

Acknowledgements

This work was supported by CREST of Japan Science and Technology Corporation, NEDO International Collaboration Program, the Grant-in-Aid from Japan Society for Promotion of Science (#12450140), and Grand-in Aid for COE research from the Ministry of Education, Culture, Sports, Science and Technology, Japan (#12CE2004).

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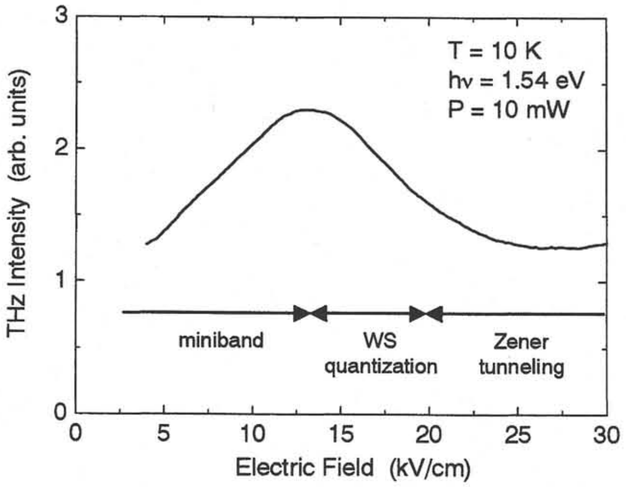

Fig. 1 The bias-field dependence of the emitted THz intensity from the superlattice. Arrows indicate the three distinct regimes; namely, the miniband, Wannier-Stark quantization, and Zener tunneling regimes.

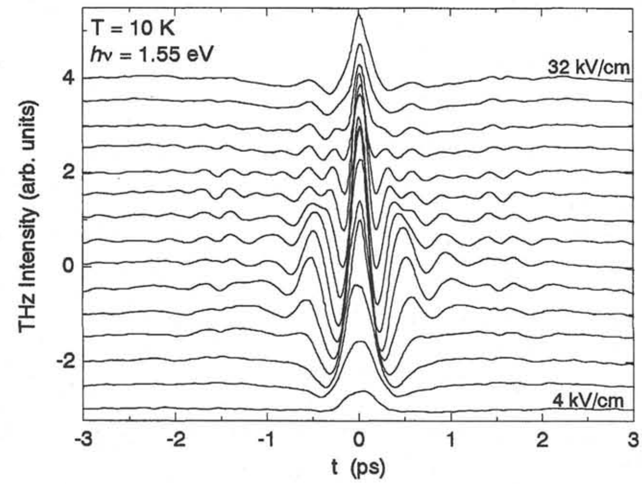

Fig. 2 The autocorrelation traces of the THz radiation emitted from the superlattice measured at various bias electric fields (every 2 kV/cm from 4 kV/cm to 32 kV/cm). Each trace is shifted for clarity.

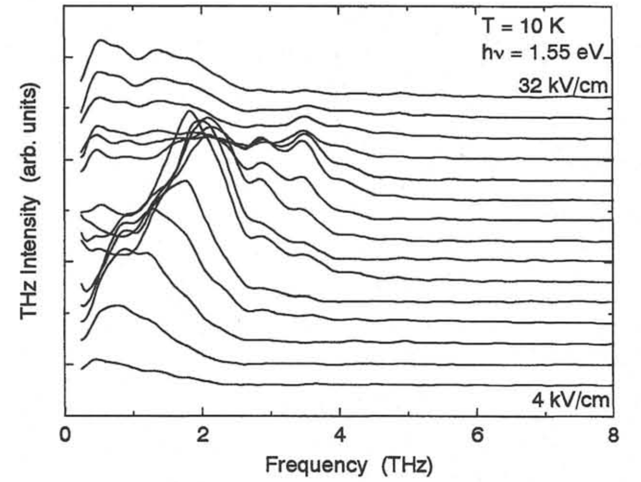

Fig. 3 The Fourier spectra of the THz autocorrelation traces shown in Fig. 2. Each trace is shifted for clarity. In the Wannier-Stark regime, a clear emission peak that shifts to higher frequencies with bias-field F is observed. However, for F > 20 kV/cm, the peak becomes very broad. Furthermore, when F ~ 30 kV/cm, a quasi-miniband-like transport is recovered.