Extended Abstracts of the 1994 International Conference on Solid State Devices and Materials, Yokohama, 1994, pp. 440-442

Invited

Bloch Oscillations in Semiconductor Superlattices

H. G. ROSKOS, C. WASCHKE, K. VICTOR,* and H. KURZ

Institut für Halbleitertechnik II,
* Institut für Theoretische Physik B,
Rheinisch-Westfälische Technische Hochschule (RWTH) Aachen,
Sommerfeldstr. 24, D-52056 Aachen, Germany

The recent observation of optically induced bias-voltage-tunable electromagnetic radiation from Bloch oscillations in semiconductor superlattices has opened a new approach to the spectroscopy of the dynamics of coherent charge carriers in periodic potentials. We report new results that indicate that the coherence of charge carriers excited into continuum states is maintained longer than previously expected. We then address the feasibility of optically pumped Bloch (or Esaki-Tsu) oscillators as a practical source for electromagnetic signals with a frequency continuously tunable from several hundred GHz to 6 THz. The efficiency of the emission process is discussed and concepts for an increase of the output power are proposed.

1. INTRODUCTION

Since the first observation of Bloch oscillations in $GaAs/Al_xGa_{1-x}As$ semiconductor superlattice structures by degenerate four-wave-mixing[1,2] and THz-emission spectroscopy[3,4], the investigation of Bloch oscillations has taking two routes. First, the spectroscopy of Bloch oscillations continues to reveal fascinating aspects of coherent charge carriers in superlattice structures. Second, the observation of electromagnetic radiation from Bloch oscillations has stimulated new studies of the feasibility of practical bias-tunable Bloch (or Esaki-Tsu) oscillators. In the following, we first report on new results of THz-emission spectroscopy that raise fundamental questions concerning the coherence of charge carriers excited with some excess energy above the bandgap. We then address the question of practical emitters, discussing the potential of optically pumped coherent THz sources.

2. COHERENCE OF WAVE PACKETS AT HIGH EXCITATION ENERGY

In the experiments of Refs. 1-4, Bloch oscillations are excited by ultrafast optical preparation of wave packets consisting of several Wannier-Stark states. The excitation process is illustrated in Fig. 1. The electric bias field across the superlattice is chosen such that the heavy hole states are nearly completely localized in single wells whereas the electron states due to their lower effective mass are only partially localized still extending over several periods of the superlattice. A laser pulse of 100 fs duration simultaneously excites electrons from a heavy hole state into several Wannier-Stark states. The electron wave functions superimpose to form a wave packet with well defined starting condition. After excitation, the wave packet begins to perform spatial and temporal oscillations with a time period determined by the energy separation of the Wannier-Stark states.

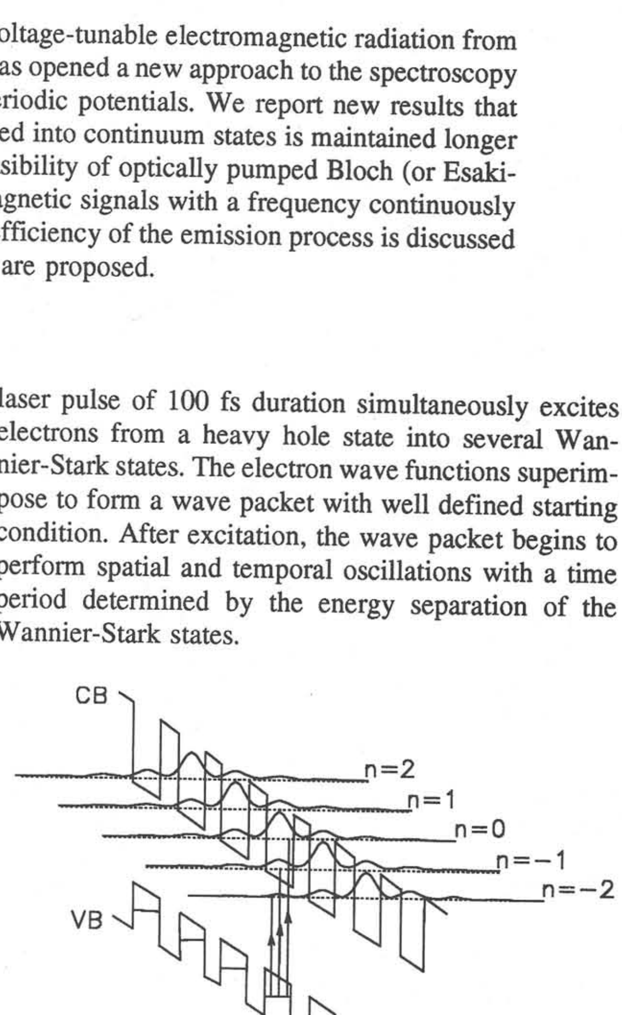

Fig. 1 Scheme for optical excitation of Bloch oscillations in a superlattice biased into the Wannier-Stark regime. Only heavy-hole transitions are indicated

The experiments of Refs. 1-4 have all been performed under band-edge excitation of exciton transitions. In degenerate four-wave-mixing (DFWM) experiments, excitation at higher energy does not permit observation of Bloch oscillations. For excitation of continuum states above the excitonic resonances, the DFWM signal decays on a time scale of 100 femtoseconds. From this result, it has been concluded that above-bandgap states experience ultrafast dephasing that prevents completion of even a single Bloch oscillation cycle by wave packets composed of such states.

In contrast to the DFWM experiments, THz-emission measurements reveal a completely different behavior when the photon energy of the excitation pulses is increased. Figure 2 shows the detected coherent THz radiation from a 35-period superlattice with 11.1 nm wide GaAs wells and 1.7 nm wide $Al_{0.3}Ga_{0.7}As$ barriers at a temperature of 10 K. The amplitude of the THz transients is plotted as a function of time for different photon energies of the optical excitation pulses. The bias voltage is held constant. It is known for a long time that ultrashort single-cycle transients can be observed for above-bandgap excitation. The surprising aspect of the data of Fig. 2 is the occurrence of oscillatory transients not only for excitation of excitonic band edge transitions (photon energy: 1.54 eV), but also for excitation into the band continuum. We have verified that the transients are caused by emission, not absorption. The frequency of the oscillations can be tuned with the bias voltage in the same way for all excitation energies. We hence conclude that the oscillatory emission results in all cases from Bloch oscillations of charge carriers.

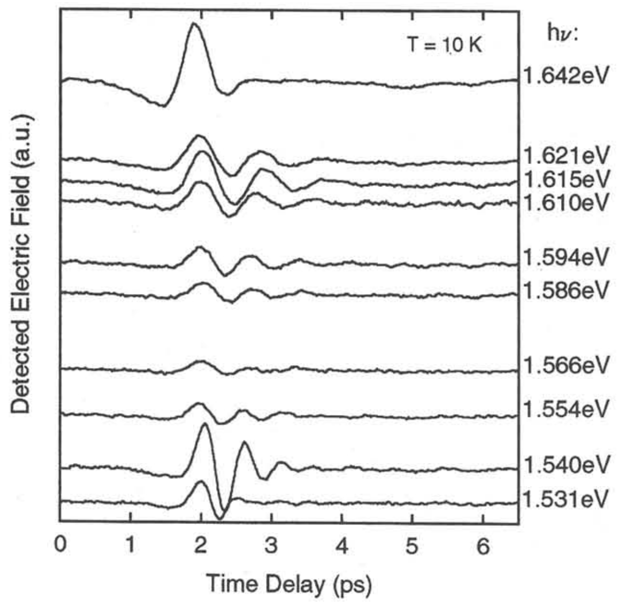

Fig. 2 Detected THz transients emitted by Bloch oscillations for excitation at the band edge (~1.54 eV) and above. The photon energy of the exciting laser pulses is given on the right side of the graph.

The long dephasing time of the oscillations is not understood in the case of above-bandgap excitation. Mainly two scenarios are discussed: (i.) The oscillatory radiation may result from Bloch oscillations of electrons (or holes) in the band continuum. (ii.) It may be generated by charge carriers that have been excited into continuum states but have relaxed to the band edge. Both explanations have extremely surprising implications. The first model is based on the assumption that charge carriers may retain their coherence in continuum states for several picoseconds without being scattered. The second explanation implies that energy relaxation processes may exist that do not destroy the phase of intraband polarization.

At present, experiments are performed to narrow down the options for the explanation of the results. Whatever the outcome may be, the experiments reported here already show that the dynamics of the interband (i.e. valence-to-conduction-band) polarization as probed by DFWM differs considerably from the dynamics of the intraband polarization responsible for THz emission.[4]

3. SUPERRADIANCE AND THE FEASIBILITY OF OPTICALLY PUMPED THZ SOURCES

A driving force behind the interest in Bloch oscillations is the idea to develop tunable THz signal generators based on coherent charge oscillations. As the realization of an all-electrical version of such Esaki-Tsu oscillators is still rather remote, we have recently proposed quasi-optical oscillator concepts based on the superradiant character of the emission.[5] Superradiance in a general sense is defined as collective emission of oscillators into the same electromagnetic mode. In our case, N oscillators are excited into a coherent, non-inverted state. The coherence results in cooperative emission with a tremendous enhancement of the emission rate. For N >> 1, the macroscopic polarization of the coherent system is equivalent to that of a classical phased array of dipoles.

To estimate the emission efficiency, we calculate the power of the electromagnetic wave emitted from a two-dimensional array of N coherent dipoles distributed evenly over a rectangular area axb. Dividing the spatially integrated radiaton power $P_{rad}(t=0)$ by the initially available interexcitonic energy E_{max} yields an effective radiative transition rate g_{rad}. $1/g_{rad}$ is the radiative lifetime, i.e. the time that the coherent system would need to emit the complete stored energy if dephasing would be negligibly slow. The calculations in Ref. 5 show that the emission rate is considerably enhanced by the coherence of the ensemble, however not all N dipoles participate generally in the cooperative emission process. The effective number N' of participating dipoles depends on the exact excitation geometry. For our experimental situation as reported in Refs.

3 and 4, we estimate a radiative lifetime on the order of 1 ns, approx. three orders of magnitude larger than the experimentally observed low-temperature dephasing time constant of 1-3 ps. Hence, most of the energy available for emission is lost. From the calculations, we expect a time-averaged power of the emitted THz pulses of 2 nW. This is one order of magnitude more than what is found in the experiment but still is indicative for the superradiant character of the emission.

The efficiency of the conversion of optical power into THz radiation power is fundamentally limited to 10^{-3}-10^{-2} as each optical photon (1.5 eV) at best can produce one photon of THz frequency (1-10 meV). Compared to this theoretical limit, the experimentally determined power conversion efficiency of 10^{-6} leaves room for improvement.

Neglecting absorption and reflection losses, the calculations of Ref. 5 indicate that the emission efficiency can be enhanced by an increase of the radiative transition rate. To extract all available energy with the emitted THz beam, a geometry that couples as many dipoles as possible must be found. It is a remarkable result of our calculations that an increase of the excited spot area with constant excitation density does not raise the transition rate. The two parameters that can be optimized are the excitation density and the emission angle. An increase of the excitation density in praxi will be limited by the concomitant reduction of the dephasing time constant. Optimization of the emission angle leads to a geometry with excitation and THz emission parallel to the surface. The theory predicts that for this and only this special choice of the emission angle, N' can be raised by an increase of the length a of the excited spot area. This suggests a travelling-wave geometry with tilted wave front of the optical beam. The tilt angle must be chosen such that the excitation beam hits the sample surface at each point just at the moment when the THz wave travelling parallel to the surface reaches that point. In this way, phase synchronization between the optical and the THz beam is achieved permitting coherent amplification of the propagating THz wave along its path through the sample. This concept is especially promising for large-area THz-wave generation with the help of amplified high-power laser systems.

The single-pass concept for optimized power extraction can be generalized to multi-pass concepts based on amplification of the THz wave by phase-locked feed-back of the wave into the coherently prepared material with the help of an external cavity. Related approaches have been termed "lasing without inversion", although this expression should be avoided as no coherence is created by the emission process as in laser systems with inversion. The coherent material oscillation is synchronously pumped by an optical pulse train. If a continuous material oscillation is to be maintained, stringent synchronization requirements for the pump pulse have to be fulfilled. As the excited interband polarizations carry the optical phase information, interferometric time precision at optical frequencies is required to ensure constructive wave function interference in the material. The condition for the timing precision becomes rather relaxed, however, if the coherence of the material oscillation is lost between successive optical pulses. Then, the phase of the returning THz wave has to match the phase of the quasi-static intraband polarization (i.e the pump-pulse-prepared phase of the envelopes of the wave functions), but phase matching at optical frequencies is not required. It should be pointed out that principally both continuous-wave THz radiation as well as pulsed emission from the resonator should be possible. Furthermore, it has been predicted, that coherent pumping of the gain medium reduces the photon number noise and the phase noise of the radiation considerably. Hence, a quasi-optical Bloch oscillator could combine the advantages of wide-range tunability by dc-biasing, inversionless amplification of the THz waves by the superradiant nature of the emission, pulsed operation of the oscillator, and finally quantum-noise quenching by the coherent gain preparation.

4. REFERENCES

1.) J. Feldmann, K. Leo, J. Shah, D. A. B. Miller, J. E. Cunningham, T. Meier, G. von Plessen, A. Schulz, P. Thomas, and S. Schmitt-Rink, Phys. Rev. B46 (1992) 7252; K. Leo, P. Haring Bolivar, F. Brüggemann, R. Schwedler, and K. Köhler, Solid State Commun. 84 (1992) 943.

2.) for reviews see J. Feldmann, in *Festkörperprobleme / Advances in Solid State Physics* 32, U. Rössler, Ed., Vieweg Verlag, Braunschweig, 1992, p. 81; P. Leisching, P. Haring Bolivar, W. Beck, Y. Dhaibi, F. Brüggemann, R. Schwedler, H. Kurz, K. Leo, and K. Köhler, accepted for publication in Phys. Rev. B.

3.) C. Waschke, H. G. Roskos, R. Schwedler, K. Leo, H. Kurz, and K. Köhler, Phys. Rev. Lett. 70 (1993) 3319; C. Waschke, P. Leisching, P. Haring Bolivar, R. Schwedler, F. Brüggemann, H. G. Roskos, K. Leo, H. Kurz, and K. Köhler, Solid-State Electron. 37 (1994) 1321.

4.) for a review see H. G. Roskos, in *Festkörperprobleme / Advances in Solid State Physics* 34, Helbig, Ed., Vieweg Verlag, Braunschweig, 1994, in press.

5.) K. Victor, H. G. Roskos, and C. Waschke, J. Opt. Soc. Am. B (1994) in press.