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OBSERVATION OF BLOCH OSCILLATIONS IN A SEMICONDUCTOR SUPERLATTICE

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We report unambiguous experimental evidence for electron Bloch oscillations: The transient four-wave mixing signal of a biased semiconductor superlattice shows a periodic modulation with a time constant expected from Bloch oscillation theory. The oscillation frequency can be tuned over 400% with the applied electric field. The electron performs up to four oscillation cycles before the coherence is lost.

The dynamics of Bloch states in a homogeneous electric field has long been an intriguing problem in solid state physics[1]. The momentum of the electron should change according to the acceleration theorem

$$\hbar\dot{k} = eF \qquad (1)$$

where F is the electric field. The electron will move until it reaches the upper edge of the band. Then, it will be reflected and invert its path. In the ideal case, when scattering can be completely neglected, the electron will perform "Bloch oscillations" (BO) with a time constant given by

$$\tau_B = \frac{h}{eFd}\ , \qquad (2)$$

where d is the lattice constant. In a real case, the coherent oscillations of the Bloch state will be damped due to scattering processes.

Bloch oscillations in the time domain are related to the existence of a Wannier-Stark[2] ladder (WSL) in the frequency domain[3]. The extended Bloch states become localized due to the field. The continuous density of states is transformed into evenly spaced ladder states with energies

$$E_N = E_0 + n\Delta E, \quad n=0,\pm1,\pm2... \qquad (3)$$

with

$$\Delta E = eFd = h/\tau_B\ . \qquad (4)$$

Neither BO nor a WSL have ever been experimentally observed in bulk solids: A necessary condition for the observation of BO (WSL) is that the scattering time (coherence length) of the state is larger than the Bloch oscillation time (localization length). The electric field required for a sufficient localization of the Bloch functions in the bulk far exceeds the breakdown fields. The situation is rather different in a semiconductor superlattice[4] (SL): The much larger period of the superlattice will allow a strong localization at much lower fields than in the bulk. Recently, WSL have indeed been observed in semiconductor superlattices with various optical techniques[5,6].

The dynamics of coherent optical excitations in semiconductors have recently been an active field. A large number of studies have concentrated on the dephasing dynamics of excitonic excitation in III-V-compounds. Another topic which has been introduced recently are dynamics of coherent superpositions of transitions. Of particular interest are wavepacket experiments where a *spatial* oscillation is associated with the beating between the constituents. The observation of coherent tunneling oscillations in GaAs/AlGaAs double quantum wells was the first experiment which observed the spatial dynamics of wavepackets in a solid[7,8]. This experiment used time-resolved four-wave mixing (FWM) to detect the oscillations. Recently, it was proposed[9] to investigate Bloch oscillations in semiconductor superlattices with this technique. First investigations showed that the FWM signal showed a second maximum with a time delay linked to the period expected for Bloch oscillations[10].

The observation of Bloch oscillations is not only a proof of an important theoretical concept, but might also have an important application: It was predicted[4] that the electrons oscillating in a superlattice miniband emit coherent electromagnetic radiation. The frequency should be tunable with the applied electric field. It was recently shown that the oscillating wavepacket in an asymmetric double quantum well structure is emitting tunable radiation in the THz frequency range[11].

In this paper, we report the unambiguous observation of Bloch oscillations in a semiconductor superlattice. The transient four-wave mixing experiments in a GaAs/AlGaAs superlattice show a periodic modulation of the diffracted signal. The frequency of the oscillations is in very good agreement with the theoretically expected value. We observe up to four Bloch cycles before the oscillation is damped due to scattering.

The sample we have studied is grown by molecular beam epitaxy (MBE) and contains 40 periods of 100Å thick GaAs and 17Å thick $Al_{0.3}Ga_{0.7}As$ layers grown on n-doped substrate. On top of the sample, a transparent Cr/Au Schottky contact is evaporated. The substrate is removed by selective wet etching to allow experiments in transmission configuration. Results of a Kronig-Penney calculation give an electron miniband width of about 19meV and a heavy-hole miniband width of about 2meV. Cw optical characterization indicates that the strain induced by cooling the sample to the measurement temperature (8.5K) is homogeneous. Figure 1 shows peak positions in the low-temperature photocurrent spectrum of the sample as a function of the bias voltage. For higher fields, the spectra show clearly a Wannier-Stark ladder with spectral shifts as expected for the sample parameters.

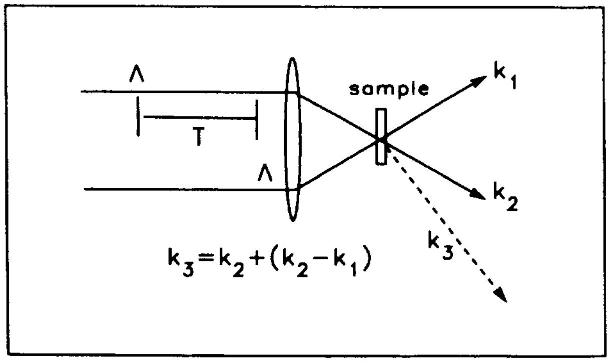

Figure 2: Scheme of the self-diffracted four-wave mixing experiment. Detected is the time-integrated signal in direction $\mathbf{k}_3$ as a function of the delay time T.

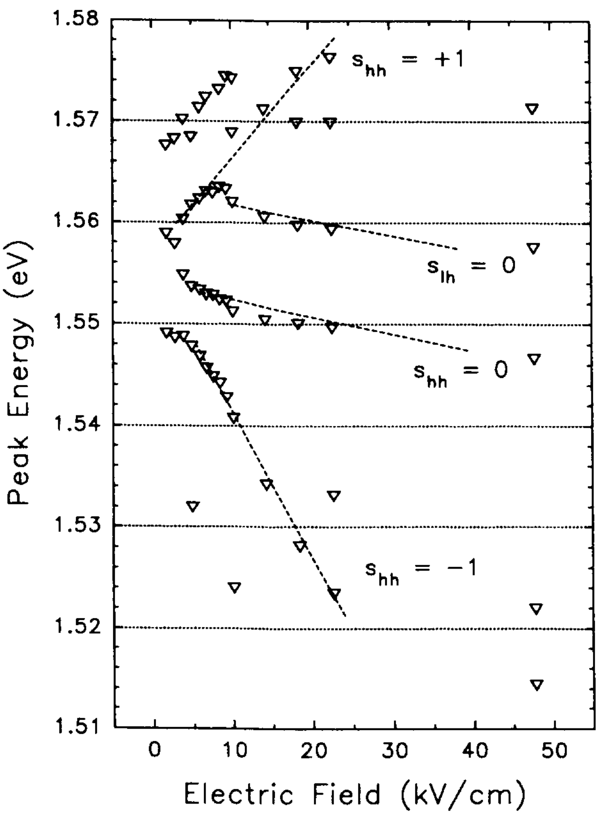

Figure 1: Wannier-Stark ladder of the 100Å GaAs/17Å $Al_{0.3}Ga_{0.7}As$ superlattice. Plotted are the photocurrent peaks taken at 8.5K as a function of the electric field. The solid lines are guides for the eye to indicate some stairs of the WSL [heavy-hole (hh) and light-hole (lh) transitions].

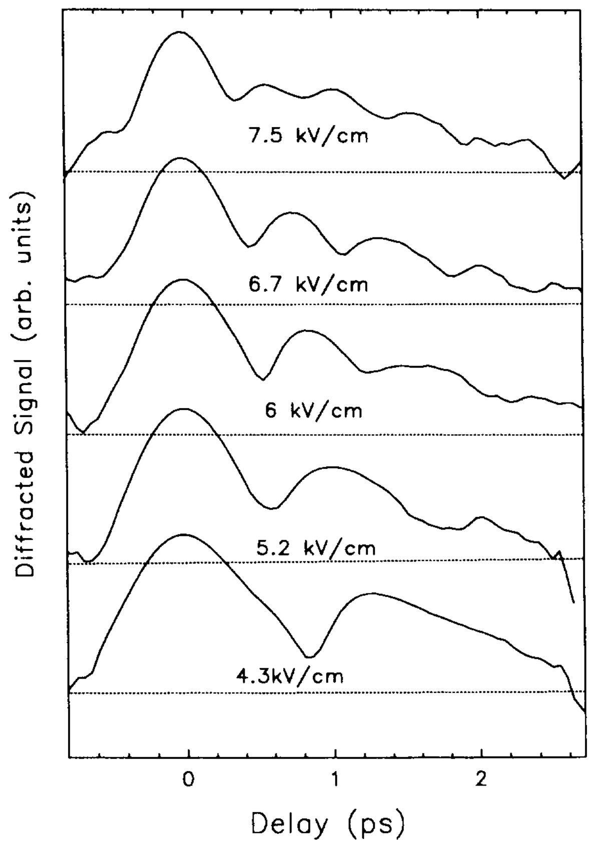

Figure 3: Semilogarithmic plot of the four-wave mixing traces as a function of the delay time for various electric fields. The lattice temperature is 8.5K, the excitation density about $2\times10^{9}cm^{-9}$ carriers per period.

As laser source, we use a Kerr-lens modelocked (KLM) Titanium-Sapphire laser emitting 100fs (FWHM) pulses. The set-up for the time-resolved optical experiments (see Fig. 2) is a standard two-beam degenerate four-wave mixing set-up[12]. Detected is the time-integrated signal in direction $\mathbf{k}_3=2\mathbf{k}_2-\mathbf{k}_1$. The decay of this signal as a function of the delay time T is reflecting the dephasing of the transition. For a homogeneously broadened transition, one can explain this as follows: The first pulse with wavevector $\mathbf{k}_1$ creates a macroscopic polarization which decays with the dephasing time T_2. The second pulse with wavevector $\mathbf{k}_2$ will form a grating with the polarization left over from the first pulse. Part of the second pulse can then be diffracted from this grating into the background-free direction $\mathbf{k}_3$. The decay of the transient response for homogeneous broadening is given by[12]

$$I_{FWM}(T) \propto \exp\left(\frac{-2T}{T_2}\right) \tag{5}$$

For inhomogeneous broadening, the diffracted signal is a photon echo occurring at t=2T. The time-integrated signal then decays with 4 times the dephasing time, i.e., twice as fast as for the case of homogeneous broadening. The excitation density in the experiments described here is about 2×10^9cm^{-2} carriers per period.

Figure 3 shows transient FWM signals as a function of the electric field. The excitation energy is at 1.537eV, which is slightly below the center of the superlattice transitions. The bandwidth of the laser (about 17meV) is large enough to cover several transitions of the WSL. The signals show a periodic modulation with a period which is strongly dependent on the electric field[13]. Up to four oscillations are visible. The overall decay time of the signals, which can be related to the dephasing of the excitation, is about 1.5ps. Figure 4 shows the time delay of the peaks of the FWM data as a function of the electric field. The peak spacing is inversely proportional to the electric field.

Figure 5 displays the energies calculated from the oscillation periods observed in the FWM signals using Eq. 4. The energy splitting shows the expected linear dependence on the electric field. The proportionality constant is in good agreement with that expected from the parameters of the superlattice (dashed line). We conclude that the modulation of the FWM signals *is caused by Bloch oscillations of the photoexcited electrons in the superlattice*. For the highest field, the electrons perform up to four oscillations with a period of about 450fs before the oscillation is damped due to relaxation processes. For lower field, the number of oscillations is correspondingly decreasing due to the increase of the oscillation period relative to the dephasing time. The absolute dephasing time

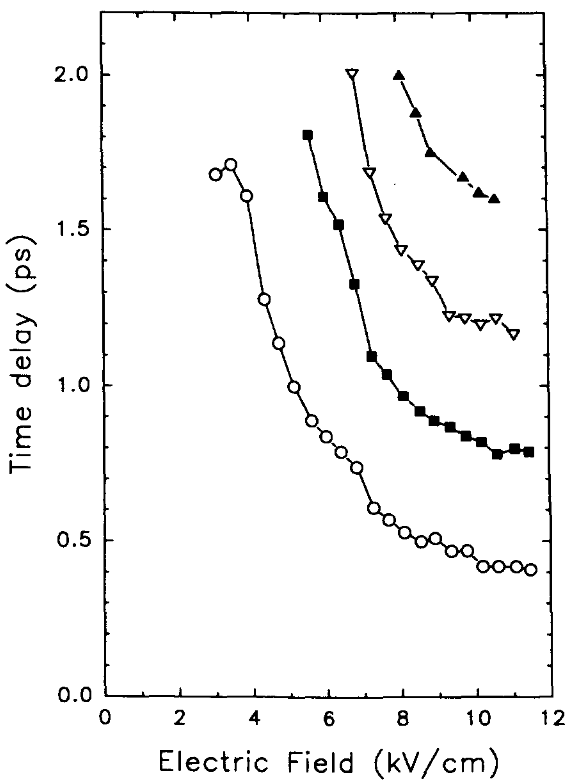

Figure 4: Peak positions of the FWM traces of Fig. 3 vs. electric field.

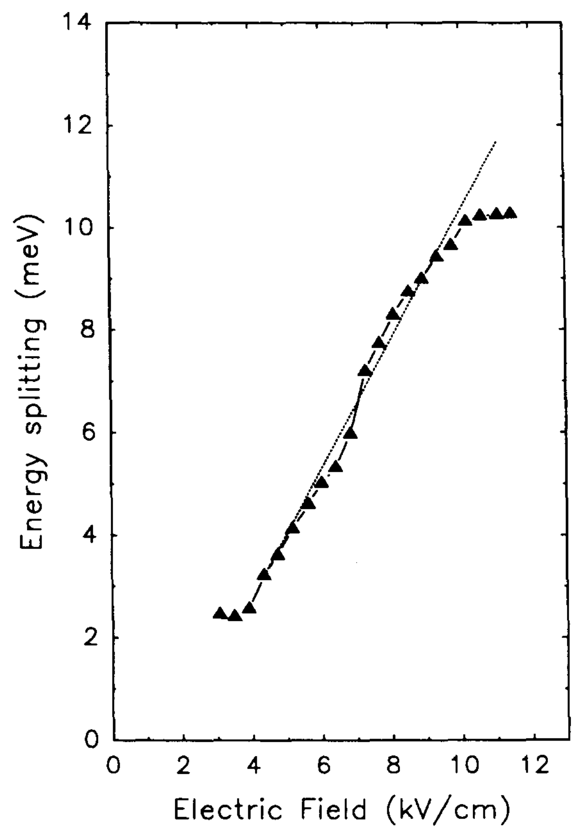

Figure 5: Energy splitting eFd calculated from the Bloch oscillation period using Eq. 4 vs. electric field. The dashed line is a fit with a slope expected for the SL period of 117Å.

of the signals is rather field-independent in the range studied here.

There are many aspects of Bloch oscillations in SL which have to be addressed in further studies: One effect which we have ignored in the previous analysis is the influence of excitonic effects on the static and dynamic behavior. It is well known that excitonic effects can strongly influence the energies and oscillator strengths of the optical spectra of semiconductor SL[14]. Also, they can completely prevent the formation of the Wannier-Stark ladders in samples with narrow minibands[15]. It would be very interesting to investigate the influence of such effects on the dynamics of the Bloch oscillations by performing experiments in minibands of various widths.

Also, it would be very interesting to search for the predicted THz radiation which should be emitted by the Bloch oscillations. The experimental technique has been demonstrated for the double quantum well emission[11]. The advantage of SL over double quantum wells is the much larger tunability range. Our results indicate that a tuning range of more than 400% is attainable. Presently, we are performing THz emission experiments on the same sample.

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