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Polarization revival of a Bloch-oscillating wave packet in conjunction with resonant Zener tunneling

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We investigate the dynamics of a Bloch-oscillating wave packet in the presence of strong coupling to delocalized above barrier states (Zener tunneling), using time-resolved intraband polarization-sensitive measurements. At a threshold electric field, the resonance of localized and delocalized states causes a quantum beating which is observed as a revival in the intraband polarization. Our numerical simulation visualizes the spatial wave packet decomposition and reformation. The wave packet moves on a ps time scale over a distance of more than 100 nm and sequentially undergoes Bloch oscillations in the below- and above-barrier bands.

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In 1960, Wannier[1] analytically discovered that the energy spectrum of an electron, subjected to both a periodic potential and an electric field F, consists of equally spaced eigenvalues, the Wannier-Stark ladder (WSL), with energies $E_n = neFd$, where n is an integer and d is the length of the elementary cell in direction of F. The time domain analogue to the WSL is the periodic motion of the electron along its dispersion relation in k space, the spatial Bloch oscillation (BO) in real space.

The invention of the semiconductor superlattice (SL) in 1970 (Ref. 2) has allowed to obtain key experimental results, like observation of the WSL in linear optical spectra[3] and of BO,[4] including observation of tunable THz emission[5] and harmonic spatial motion.[6] Also, in alternative systems, like atoms in a light lattice, BO's have been reported.[7]

Besides these one-band phenomena, effects based on the interaction of several bands have been explored. Resonant coupling of different WSL's, interminiband Zener tunneling, field-induced delocalization of a WSL state, and the damping of a Bloch-oscillating wave packet was reported.[8–12]

The observation of BO's as discussed above is one of the few experiments where spatial wave packet motion was directly traced in solid-state systems.[13] Much of the original interest in wave packets, and still the vast majority of research on them, has been done in atomic systems. In particular, the optical excitation of wave packets composed of Rydberg states, both with and without angular electron localization, and the observation of their time evolution, also in electric or magnetic fields, provided the fundamental insight in the physics of wave packet dynamics.[14] Several analogies between experiments in atomic physics and recent ones in solid-state physics can be found: e.g., the basic spatial radial oscillation of a Rydberg wave packet corresponds to a BO in a solid. The transient field ionization of an angularly localized revolving Rydberg wave packet in an electric field has its analogue in the field-induced Zener tunneling of a Wannier-Stark wave packet into higher bands.

In this paper we report the experimental observation and numerical simulation of a polarization revival due to spatial wave packet decomposition and reformation in a semiconductor superlattice. The physical origin of this effect in the solid is somewhat different from Rydberg wave packet revivals reported in atomic physics,[15] where the wave packet dephasing is, in general, due to both energy dispersion of the nearly equally spaced Rydberg states and the different anharmonic effective potentials the respective Rydberg states see. There, the wave packet made of high-quantum-number states spreads from a classically localized particle to become nonclassical and, after the revival time, rephases and travels on its classical trajectory again. Hereby, due to the discrete number of states excited, the loss of phase caused by the anharmonicity of the atomic potential can be fully recovered; after several oscillatory cycles (period determined by the energy spacing of the Rydberg states) the full revival can occur (full revival time proportional to the number of excited states).

In our case, a wave packet of both localized WSL states and nearly degenerate, delocalized above barrier states is optically excited and the revival originates from a quantum beating between these few discrete states.

We have performed degenerate, spectrally integrated interband pump-probe experiments which are sensitive to the intraband polarization.[16] Our shallow superlattice contains only one electron miniband (30 meV width) in the below-barrier region. We are thus able to directly address the effects of coupling to a process between localized WSL states and delocalized above-barrier states. The 90-fs transform-limited optical pulses were spectrally tuned to be energetically centered between the hh_{-1} and the hh_0 WSL transition, exciting a coherent, Bloch-oscillating wave packet. By applying a voltage over the 50/54-Å GaAs/$Al_{0.11}Ga_{0.89}As$ SL structure, the BO period was continuously tuned from 900 to 160 fs. Simultaneously to the pump-probe analysis, spectrally resolved four-wave mixing (SRFWM) was employed to monitor the exact excitation conditions. The excitation density was $\sim 2\times10^9$ cm^{-2} per well. The sample was held at 8 K.

Figure 1(a) shows several pump-probe transients from 5 kV/cm up to 24 kV/cm. The increase in the BO frequency ω_{BO} with applied electric field is nicely seen: ω_{BO}

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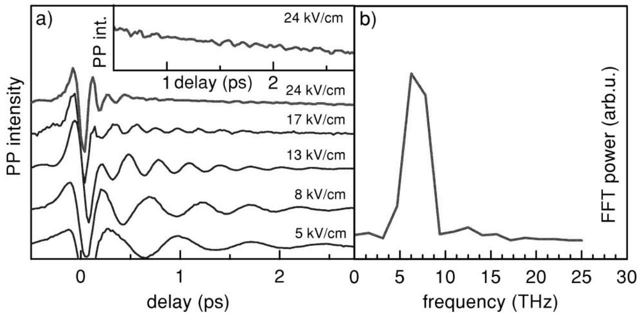

FIG. 1. (a) Pump-probe (pp) traces for various dc electric fields from 5 to 24 kV/cm. Inset: enlarged PP trace for 24 kV/cm. (b) Power of the Fourier transform of the PP trace for 24 kV/cm from 1.4 to 2.5 ps with maximum at the Bloch period (166 fs).

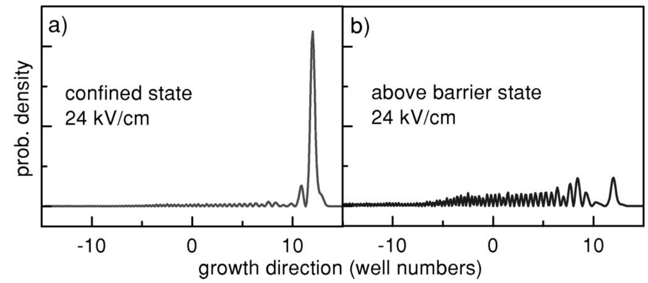

FIG. 2. Calculated spatial electron probability density of (a) confined state of the 12th SL quantum well and (b) the associated above-barrier state at 24 kV/cm. Both states partially overlap spatially and have an energetic splitting of about 1.65 meV, which gives a theoretical revival period of about 2.5 ps.

$= eFd/\hbar$. The internal field was calibrated using the obtained Bloch frequency and the known lattice parameter *d*. The result agrees with the observed WSL spacing from the SRFWM. Obviously, the duration of the signal modulation caused by the wave packet dynamics decreases for increasing electric field. Surprisingly, at a threshold field of 24 kV/cm, we observe a sudden drop of the intraband decay time, as discussed previously.[12] A comparison with theory has shown that BO's are quickly damped by resonant Zener coupling to the second miniband.[12]

Here we focus on the observation of a *polarization revival* [enlarged in inset of Fig. 1(a)]. Figure 1(b) shows the Fourier transform of the 24 kV/cm trace from 1.4 to 2.5 ps with the maximum being exactly at the initial BO frequency.

To model these experimental results quantitatively, we have calculated both the confined and above-barrier electronic states of our finite 35-well superlattice, subjected to an electric dc field. We used a plane-wave expansion method[17,18] in the framework of effective-mass envelope theory. The plane waves of the ideal bulk material form an orthonormal and complete basis set, and thus can be used to expand the envelope function of a biased SL. Implicitly, using the plane-wave bases for the finite SL means that periodic boundary conditions were adopted. The localized and delocalized states can be obtained on the same footing by directly diagonalizing the Hamiltonian matrix. Our simulation shows that at this threshold electric field the confined WSL states nearly overlap energetically and, to some extend, spatially with delocalized states that lie above the barrier at flat field (shown in Fig. 2). This resonance was directly observed experimentally as an avoided crossing of the hh_0 transition with a transition to an above-barrier state in SRFWM (not shown). At 24 kV/cm the wave packet is constructed by two below-barrier states centered in, say, well 12 and 13 with calculated eigenenergies of 345.3 and 370.3 meV with respect to the band bottom, each confined state being accompanied by an above-barrier state shifted by ~1.65 meV in energy from the confined state. Hereby, the above barrier state associated with the confined state of, e.g., well 12 is dispersed largely from wells 7–10, but has its density spread over more than 12 lattice periods. Respectively, the above-barrier state associated with the confined state from well 13 is shifted by one lattice period.

The wave packet repeatedly Zener-tunnels resonantly between discrete confined states and discrete above-barrier states within the theoretical revival time of ~2.5 ps (experiment: ~1.8 ps). In both, below- and above-barrier bands, the wave packet undergoes Bloch oscillations with the same frequency $\omega_{\rm BO} = eFd/\hbar$, but different amplitude $a = \Delta/2eF$, where Δ is the band width at zero electric field. However, the Bloch oscillation in the first band is effectively damped by the interferometric dephasing due to Zener resonant tunneling to the second band.

The electron density is sequentially transferred spatially over more than 10 wells, i.e., about a 100 nm. Figure 3 visualizes the spatial dynamics of this wave packet. While in Ref. 12 we were focusing on the field-induced damping of the wave packet motion, we here show that under these resonant conditions the initially created Wannier-Stark wave packet quickly delocalizes in space, but partially reconstitutes. As this tunneling is resonant, the electronic coherence is, to some extent, conserved even though the electron probability density is transferred into another band. Obviously, damping in the sense of coupling to a bath is not enhanced

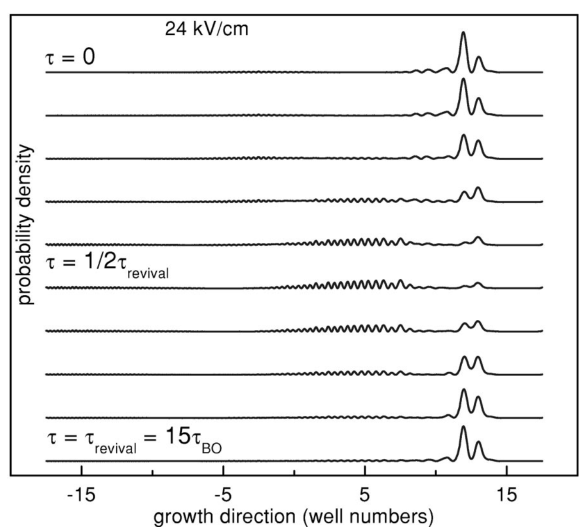

FIG. 3. Calculated time evolution of the spatial probability density of the Bloch-oscillating wave packet composed of two confined and two above-barrier states from $\tau = 0$ to 2.5 ps.

while the electron is situated in or transferred to an above-barrier state; the BO ceases to exist in one band because its electron density has vanished.

From our results, it follows that the observed initial drop in the ensemble coherence time is due to destructive quantum interference, caused by the confined states and above-barrier states. Besides the Bloch beating within one band, a beating of confined states with delocalized above-barrier states is observed. In other words, the Zener tunneling retains coherence when the electron tunnels to one discrete state only. It would be interesting to extend these studies to higher fields where the Bloch wave packet is coupling to several higher transitions, leading to a polarization decay due to decoherence, without rephasing on a reasonable time scale.

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