Subcycle Wannier-Stark Localization by Mid-Infrared Bias in Gallium Arsenide

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Abstract. The fundamental interband absorption in gallium arsenide shows a strong blue shift when biased by mid-infrared transients exceeding 10 MV/cm. This subcycle feature is induced by the localization of electronic wavefunctions from 3D to 2D.

1. Motivation

Dielectric materials undergo nonlinear changes in their electronic configurations when intense optical fields are employed as a source of bias. The resulting phenomena range from the Franz-Keldysh effect [1] to high harmonic generation in solids [2]. At extremely high fields, Wannier-Stark localization (WSL) might occur, leading to the localization of electronic wavefunctions. WSL has only been observed in semiconductor superlattices [3,4], where larger lattice constants decrease the required field strength. With the availability of intense mid-infrared few-cycle transients exceeding 10 MV/cm field strength, an analogous regime is now accessible also in bulk semiconductors.

2. Experiment and results

Intense mid-infrared few-cycle transients at 25 THz center frequency are generated by difference frequency mixing in GaSe with 1 kHz repetition rate [5]. Tight focusing allows for electric fields exceeding 10 MV/cm inside the GaAs samples. The center frequency of the non-resonant biasing pulse is set far above the phonon band of GaAs but also far below the electronic interband absorption, thus avoiding energy deposition into the material. Transmission of the 400-nm-thick intrinsic GaAs sample is probed by 7-fs pulses in the near infrared and visible, spanning from 1.3 to 3.4 eV photon energy (Fig. 1a). The short probe pulses allow subcycle detection of the transmission change induced by the biasing field. Data acquisition is based on a CCD-spectrometer and a double modulation scheme, allowing for enhanced background subtraction. The bias field is carefully oriented along the <111>-direction in the <110>-cut surface of the GaAs crystal as sketched in Fig. 1a. With this alignment, the combined width of the valence and conduction bands is narrower than the fundamental gap, avoiding significant impact ionization of carriers into the conduction band (Fig. 1b).

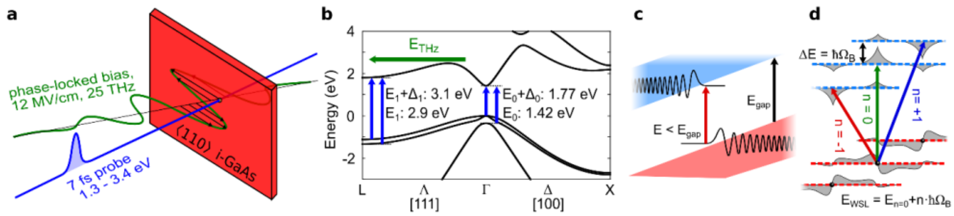

Fig. 1. (a) Measurement scheme: 400-nm-thick intrinsic GaAs grown in <110>-direction is biased by phase-stable mid-infrared transients with 25 THz center frequency and up to 12 MV/cm field strength. 7-fs probe pulses with 1.3-3.4 eV photon energy are used to probe the transmission with sub-cylce resolution. (b) Electronic band structure of bulk GaAs. Green arrow indicates the bias field in [111] direction, blue arrows show electronic transitions which are important for the experiment. (c) Sketch of the Franz-Keldysh effect: the bandstructure is tilted by an electric field. Electron wave functions reaching into the band gap create new optical absorption channels below the band gap. (d) Sketch of WSL: extreme electric fields lead to a localization of the electronc wave functions.

Strong electric fields lead to a spatial tilt of the electronic band structure, resulting in electronic wave functions reaching into the band gap (Fig. 1c). This effect leads to new absorption channels below the band gap energy and additional oscillatory behavior above the band edge: the Franz-Keldysh oscillations. For even stronger fields, when the potential drop per lattice site becomes relevant in comparison to the band width, optical absorption channels become discrete. Ultimately, this leads to one single possible absorption energy and localization in real space, called Wannier-Stark localization.

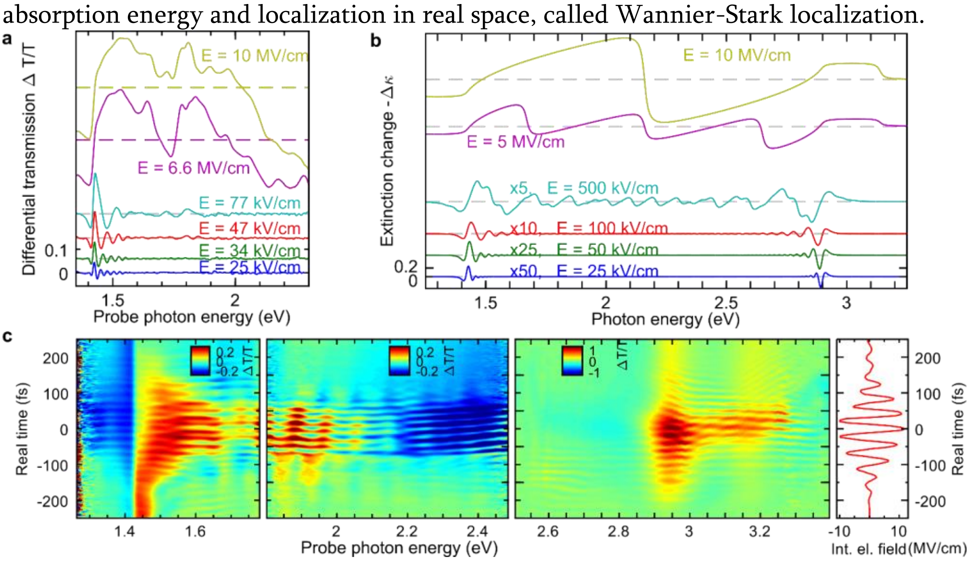

Fig. 2. (a) Differential transmission measurements of 400 nm bulk GaAs. For bias fields below 100 kV/cm transient Franz-Keldysh oscillations are visible. At extreme fields reaching 10 MV/cm inside the material a strong blueshift of the fundamental absorption from 1.42 to 2.1 eV is observed. (b) Calculation of extinction coefficient change based on cosine-shaped band structure that reproduce the essential features of the experimental data. (c) colormap of the differential transmission measurements as a function of delay time and probe photon energy from NIR to UV. Far right panel: electric field inside GaAs over time.

Differential transmission measurements with probe photon energies tuned between 1.35 and 3.5 eV are depicted in Fig. 2a. For bias fields below 100 kV/cm, the transmission shows a clear signature of the transient Franz-Keldysh effect: induced absorption below the band edge and oscillatory transmission change above. The oscillation period in photon energy space is increasing with the bias field. For higher field strengths, the system transits into the Wannier-Stark regime: at fields above 1 MV/cm the fundamental absorption moves from 1.42 eV to higher energies, finally reaching 2.1 eV at 10 MV/cm (full color map in Fig. 2c). Spectral absorption weight is moved away from the edges of the band at 1.42 and 2.9 eV and into the middle of the band. This is the signature of Wannier-Stark localization as the density of states is transferred from a 3-dimensional system to a layered 2-dimensional one: the former square-root-like distribution transitions to a step-like function, resulting in a sharp onset of absorption in the middle of the conduction band. Theoretical calculations of the absorption coefficient assuming simple cosine-shaped electronic bands are shown in Fig. 2b. This picture is in good agreement with the experimental results.
The absence of the intermediate Wannier-Stark ladder regime with several absorption peaks in periodic distance is explained by more detailed calculations adopting a more realistic band structure derived from density functional theory.

3. Conclusion

Electric bias of bulk GaAs by mid-infrared light reveals the transient Franz-Keldysh effect at field strengths below 100 kV/cm and transitions into the localization from a 3-dimensional electron gas to a layered 2-dimensional system when the field amplitude exceeds approximately 6 MV/cm [6]. Theoretical calculations support the measurements in proving the experimental observation of Wannier-Stark localization in GaAs.

References

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