Ann. Physik 3 (1994) 137–144

Annalen
der Physik

Response of a Bloch oscillator to a THz-field

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Received 12 January 1994, last revised version 17 March 1994, accepted 17 March 1994

Abstract. In this paper we report on the observation of response of a Bloch oscillator at room temperature to a THz-field of a frequency larger than the Bloch frequency. The oscillator consisted of a semiconductor superlattice structure, with an applied dc voltage giving rise to a dc electron drift current. Submitting the oscillator to a field at a frequency of 3.3 THz caused a sizeable reduction of the current; the THz-field was generated by use of intense THz-radiation pulses focused on an antenna coupled to the superlattice. We attribute the THz-field induced reduction of the current to a frequency modulation of the Bloch oscillations of electrons at the frequency of the THz-field, leading to reduction of the electron drift velocity and, consequently, of the current.

Keywords: Superlattice; Bloch oscillator; Terahertz radiation.

According to Bloch [1], the electric conductivity by electrons moving in a periodic potential of atoms in a crystal superimposed with a potential of a homogeneous dc electric field is a consequence of scattering of the electrons due to defects and thermal vibrations of the atoms. Zener [2] pointed out that ballistic electrons, i.e. electrons moving without being scattered, should perform oscillations, today denoted as Bloch oscillations, because of the Bragg reflection of the electrons when their kinetic energy corresponds to the upper boundary of the energy band due to the periodic potential. Besides Bloch oscillations, i.e. electron motion within a band, electron transport between different bands separated by forbidden bands was recognized as origin of dielectric breakdown at high dc fields [2]. The eigen frequency of the Bloch oscillation, the Bloch frequency, is determined by the dc voltage across a spatial period of the periodic potential. Esaki and Tsu [3] proposed to study Bloch oscillations in semiconductor superlattices with periods that are, on the one hand, large enough for sustaining, without dielectric breakdown, a sufficiently large voltage across a period and, on the other hand, small enough to allow almost ballistic propagation of electrons over many periods and predicted that under the condition of the occurrence of Bloch oscillations a negative differential conductance should appear in the current-voltage characteristic

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of a superlattice structure. A negative differential conductance was concluded, for short-period GaAs-GaAlAs superlattice structures, from the observed current-voltage characteristic [4], from the propagation properties of electrons injected into a superlattice [5] or generated in a superlattice by optical excitation [6].

Following a theoretical study [7] Bloch oscillations have been excited and detected by a technique of nonlinear optics using femtosecond visible light pulses [8, 9]. In a superlattice structure cooled to a temperature of 5 K electrons performing Bloch oscillations were created by pulsed interband excitation and the dynamics of the excitation was monitored with delayed probe laser pulses. It was found that the dynamics was influenced by the Bloch oscillations in the superlattice structure [8, 9]; the Bloch frequency was chosen by a dc voltage applied to the superlattice. Interband excitation of a superlattice structure at a temperature of 5 K with femtosecond optical pulses resulted in the emission of THz-radiation pulses caused by Bloch oscillations in the superlattice [10]. The experiment demonstrated that a freely oscillating Bloch oscillator can be used as a broad band source of THz-radiation; the THz-radiation was created by the spontaneous decay of the excited Bloch oscillator. In a theoretical study Ignatov et al. [11] have shown that a Bloch oscillator connected to an external resonant circuit could, under the condition of a negative differential conductance, generate electromagnetic radiation up to THz-frequencies. In this paper we report the first observation of interaction of a Bloch oscillator with an intense THz-field; we studied the interaction for a superlattice structure at room temperature.

The principle of our experiment is shown in Fig. 1. In the center of the experiment is a superlattice structure. The superlattice is electrically connected on one side to the inner wire of a coaxial cable and on the other side to an antenna that is connected (via a corner cube reflector) to ground. There are three electrical circuits, a dc and an ac circuit and a circuit for THz-currents. The THz-currents are induced by external THz-radiation via the antenna. For an effective coupling of the THz-radiation to the antenna, the antenna is located in a corner cube reflector. The THz-current flows from

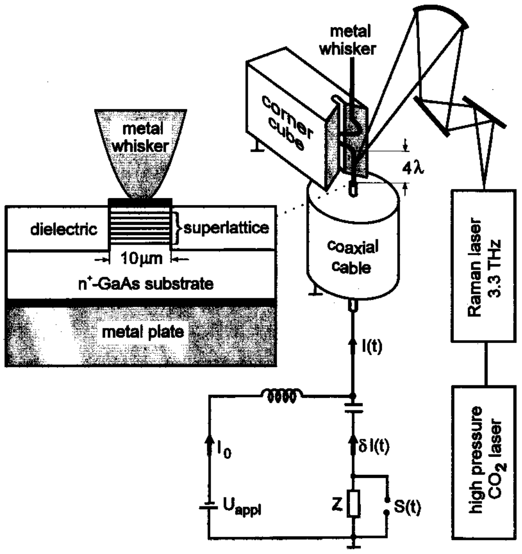

Fig. 1 Experimental arrangement with the superlattice structure (inset).

ground over the corner cube and the antenna through the superlattice to the wire of the coaxial cable and then as displacement and polarization current through the isolation of the coaxial cable to the metal shielding and back to ground. A current source delivers a dc current I_0 flowing through the superlattice structure, then through the antenna to the corner cube and to ground. The applied voltage U_{appl} corresponds to the dc voltage across the superlattice structure. An inductive resistance prevents flow of high frequency currents through the current source to ground. In our arrangement ac currents (frequency$\ll$THz) can flow from ground through an impedance Z and via the central wire of the coaxial cable through the superlattice and then through the antenna to the corner cube and to ground. The ac circuit is decoupled from the dc circuit by a capacitor.

The superlattice (inset of Fig. 1) has 80 periods, each consisting of 19 monolayers of GaAs and 4 monolayers of $\mathrm{Ga_{0.5}Al_{0.5}As}$. According to a monolayer thickness of 2.83 Å, the spatial period is $a \simeq 65$ Å (width of a quantum well 54 Å, of a barrier 11 Å). The total thickness of the superlattice is $L \simeq 0.5\ \mu\mathrm{m}$ and the cross section $A = 10\ \mu\mathrm{m} \times 10\ \mu\mathrm{m}$. The superlattice structure is doped with silicon and contains free charge carriers at a concentration of $\sim 10^{17}\ \mathrm{cm}^{-3}$. The superlattice has been grown by molecular-beam epitaxy on a n^+-GaAs substrate doped with silicon and containing a concentration of free carriers of $\sim 2 \cdot 10^{18}\ \mathrm{cm}^{-3}$. Au-Ge-Ni films (thickness $\sim 0.5\ \mu\mathrm{m}$) on the surface of the superlattice and on the GaAs substrate, respectively, served as metallic contacts. Abrupt heterojunctions between GaAs and the superlattice were avoided by layers with gradual composition [4]. The superlattice structure is soldered on the inner wire of the coaxial cable. On the other side it has electrical contact to the antenna, having a tip, which is pressed on the superlattice structure. The antenna is a part of a gold wire (diameter 25 μm) and has a length of 4λ ($\sim 4 \times 90\ \mu\mathrm{m}$) where λ is the wavelength of our THz-radiation of frequency $\omega = (2\pi \cdot 3.3\ \mathrm{THz})$. The gold wire has a knee, where the antenna range ends, and is guided into a slot in the corner cube where it has electrical contact to the corner cube. The gold wire is on the upper part connected with a screw (not shown in the figure) for adjustment of the pressure on the tip. The corner cube is adjusted relative to the antenna for optimum receiving of THz-radiation. The radiation induces in the antenna a THz-current that is continued in the superlattice. The dielectric relaxation frequency of electrons in a superlattice is smaller than the THz-frequency, therefore, the THz-current flows through the superlattice structure mainly as displacement and polarization current. The superlattice, together with the metallic contacts, represents for the THz-current a capacitor with the capacity $C = \varepsilon\varepsilon_0 A/L$ where ε_0 is the electric field constant, and ε the dielectric constant at the frequency of the THz-field; with $\varepsilon \simeq 15$ we find $C \simeq 3 \cdot 10^{-14}$ F. The THz-current charges the superlattice capacitor leading to a voltage across the superlattice and to a time-dependent electric field $E_\omega(t)$ in the superlattice. The time derivative of the field is $\delta E_\omega(t)/\delta t = (CL)^{-1} I_\omega(t)$ where $I_\omega(t)$ is the strength of the THz-current of frequency ω. The THz-field is almost homogeneous since the wavelength of our electromagnetic THz-radiation in GaAs ($\sim 30\ \mu\mathrm{m}$) is much larger than the sample thickness.

At constant dc voltage U_{appl} across the superlattice structure the current through the superlattice, $I(t)$, can depend on time only when the superlattice is submitted to a pulsed THz-field. The time dependent change of current, $\delta I(t)$, is measured with a transient recorder by monitoring the voltage signal $S(t)$ that corresponds to the voltage across the entrance impedance Z ($\simeq 50\ \Omega$) of the transient recorder (time resolution 1 ns). From the voltage signal the change of current is obtained according to $\delta I(t) = -S(t)/Z$. The voltage signal thus gives information both on the strength and the sign of the current change.

Intense THz-pulses are produced by a laser system consisting of a high pressure (20 atmospheres) CO_2 laser used for exciting a Raman laser that in turn emits THz-radiation pulses [8]. The high pressure CO_2 laser has a broadband gain profile and allows to generate short pulses of frequency-tunable radiation in the wavelength region around 10 µm. We operated the laser near its threshold where self-mode locking results in the emission of a series of short pulses; each series consists of typically ten single pulses, each with a duration below 1 ns, with a separation of 24 ns that corresponds to the round trip time of the radiation in the laser cavity. The CO_2 laser radiation is focused into a tube containing $^{14}NH_3$ gas (of a pressure of ~ 30 mbar) and generates THz-radiation by stimulated Raman scattering via vibrational-rotational excitations of $^{14}NH_3$. The stimulated Raman scattering is resonantly enhanced if the CO_2 laser radiation has a frequency that is near the frequency that corresponds to a dipole-allowed vibrational-rotational transition; for a CO_2 laser frequency of 32.256 THz the Raman laser emits radiation at 3.3 THz. The THz-radiation consists of a series of short pulses (separation 24 ns), with a single pulse energy of typically 2 µJ and a duration below 1 ns. The repetition rate for the generation of the pulse series is about 1 Hz. The radiation of the Raman laser is focused by a spherical mirror onto the antenna, with the focus diameter being ~ 4 mm. The radiation reaches the antenna within an optimum cone angle of ~ 20 degrees, at an angle between the optical axis of the THz-radiation beam and the direction of the antenna of about 30 degrees. The radiation is polarized, with the electric field vector within the plane of incidence.

The superlattice structure is operated at room temperature and under atmospheric conditions.

The current-voltage characteristics of our superlattice structure (Fig. 2, solid line) exhibits a nonlinear increase of the current at small applied voltages U_{appl}, then a maximum at $U_{appl} \sim 2$ V and finally a decrease. The nonlinear increase is due to non-ohmic contacts formed at the surface of the superlattice or of the GaAs substrate; superlattices with ohmic contacts show a linear increase of the current with U_{appl} [4]. The decrease of current at large voltages represents a negative differential conductance due to Bloch

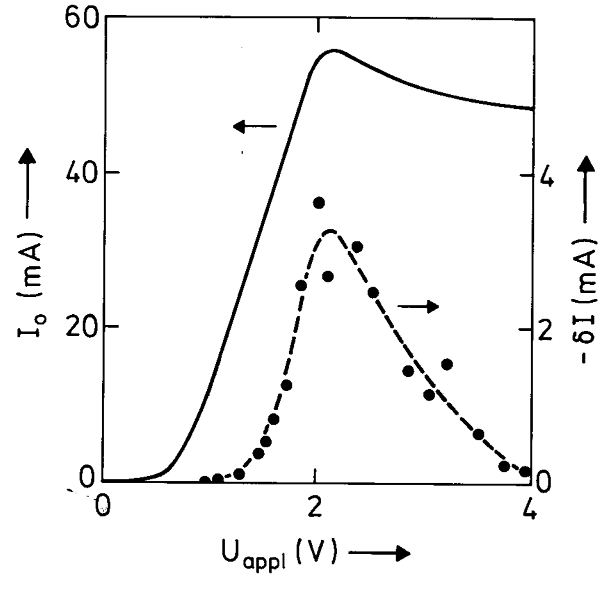

Fig. 2 Current-voltage (I_0/U_{appl}) characteristic of our superlattice structure and THz-field induced current change δI.

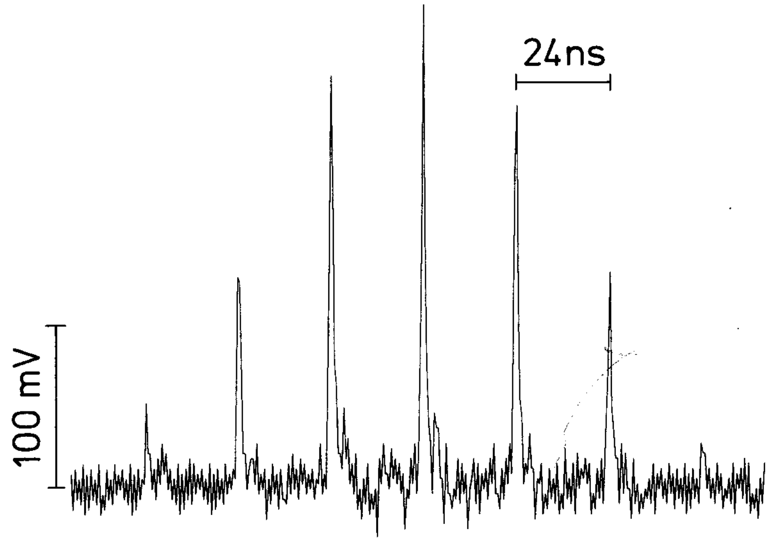

Fig. 3 THz-field induced signal; $U_{appl} = 1.9$ V, radiation frequency 3.3 THz.

oscillations in the superlattice [3, 4]. We estimated that at an applied voltage of 2 V, the voltage across the contacts and a series resistance due to the n^+-GaAs layers is ~ 1.5 V and the voltage across the superlattice ~ 0.5 V. Accordingly, the peak-current is obtained for a dc field of ~ 10 kV/cm within the superlattice. From the peak-current (~ 50 mA) follows a peak-current density of ~ 50 kA/cm^2.

Fig. 3 shows an experimental signal curve. There is a series of single pulses, each with a halfwidth of ~ 1 ns, which corresponds to the time resolution of our electronic system. The signal is well above the background that is due to nonperfect electromagnetic shielding of the electrical circuit. The signal corresponds to a THz-field induced *reduction* of the dc current through the superlattice. In the pulse maximum the current change is $\delta I \simeq -0.2$ V/50 $\Omega \simeq -4$ mA. The current reduction is about ten percent of the dc current. Our result demonstrates that an intense THz-field induces a strong reduction of the dc current through the superlattice. We found that a decrease of the laser power resulted in a linear decrease of the current signal pulses.

It follows from our measurement (Fig. 3) that the duration of the laser pulses was less than 1 ns, most likely ~ 0.5 ns. Our experiment with the superlattice was performed during the development of our high pressure CO_2 laser excited $^{14}NH_3$ Raman laser. The result indicates that the superlattice structure is most suitable for detection of THz-radiation, with high speed and high sensitivity.

In the range of the nonlinear current-voltage characteristic (for $U_{appl} < 1$ V) we also observed signal pulses, but corresponding to an *enhancement* of the current probably by rectification of THz-radiation due to the non-linear behaviour of the Schottky diode formed at the contact regions. These signals were by several orders of magnitude smaller than the signals obtained for the voltage range near the region of negative differential conductance.

We have measured the dependence of the signal height on the applied voltage U_{appl} and determined, for fixed pulse power of the THz-radiation, the current change δI corresponding to the signal height. The result is shown in Fig. 2 (dots), where we have plotted $-\delta I$ (right scale). While δI is small and positive for $U_{\text{appl}} \leq 1$ V, it is negative at higher values of U_{appl} and shows an extremum at the voltage (near 2 V) of maximum dc current. At higher voltages the value of δI decreases strongly and becomes small at our largest voltage $U_{\text{appl}} \sim 4$ V, while the strength I_0 of the dc current decreases only slightly. Our result shows that the THz-field induced current reduction has its maximum at the maximum of the dc current.

In a recent experiment by Guimarães et al. [13] the influence of THz-radiation on a multiquantum structure (size 100 μm × 100 μm) was studied at a sample temperature of about 80 K. The THz-radiation (duration 0.5 μs) was produced by a free electron laser. Guimarães et al. also found an influence of the radiation on the current-voltage characteristic, but they observed an *increase* of the current under the influence of irradiation. This increase has been attributed [13] to photon-assisted tunneling, with tunneling of electrons from one well to the adjacent well and simultaneously loosing energy and momentum by scattering; this transport process occurs when the mean free path of an electron is almost equal to the superlattice period.

We attribute the THz-field induced current reduction to an interaction of the THz-field with the Bloch oscillations of the electrons in the superlattice. In a Bloch oscillation an electron performs a harmonic oscillation with a velocity $v = v_0 \sin \omega_B t$ where [2] $\omega_B = eE_0 a/\hbar$ ($\omega_B/2\pi \sim 1.5 \cdot 10^{12}$ Hz for $E_0 = 10$ kV/cm) and where e is the elementary charge, $\hbar$ Planck's constant, E_0 the dc field strength and $v_0 = \frac{1}{2}\Delta a/\hbar$ the maximum velocity in the miniband of width Δ ($\simeq 65$ meV) that is formed by the periodic potential. The quantum energy of the Bloch oscillator corresponds to the energy gain of the electron per superlattice period. An electron moving along the superlattice axis, X, performs an oscillatory motion through the potential barriers (height 0.6 V) along a trajectory (Fig. 4) that has a length $X_0 = \Delta/(eE_0)$ (~ 600 Å for $E_0 = 10$ kV/cm). By each scattering process the electron looses energy and jumps to a lower energy trajectory where it starts to oscillate again. In an ensemble of electrons each of them performs Bloch oscillations with random phases relative to each other. The drift of the oscillating

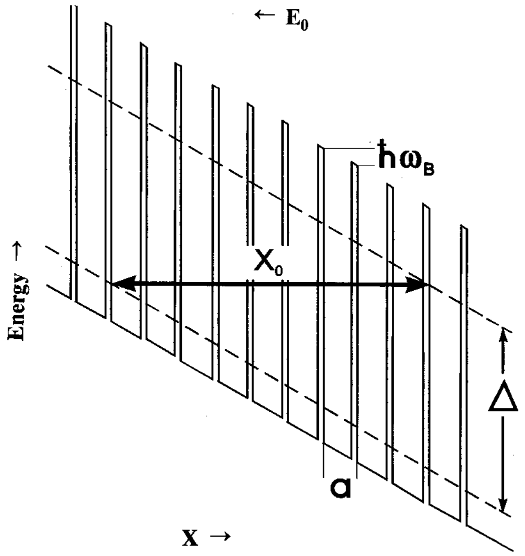

Fig. 4 Bloch oscillation of an electron in a superlattice.

electrons gives rise to current flow. The negative differential conductance occurs for $\omega_B \tau \geq 1$ where τ is an average relaxation time of the electrons. At the dc field (~ 10 kV/cm) for which the peak dc current occurs within the superlattice we have $\omega_B \tau = 1$ [3]. From this relation we derive an average relaxation time $\tau \simeq 10^{-13}$ s for the electrons in our superlattice sample. Accordingly, at $\omega_B \tau = 1$, the electrons move in our superlattice almost ballistically over about 10 superlattice periods (Fig. 4) before being scattered. Under the influence of both a dc and a THz-field the velocity of an oscillating electron is frequency modulated, according to an expression [11] $v = v_0 \sin(\omega_B t + \mu \cos \omega t)$ where $\mu = eE_{\omega,0} a/(\hbar \omega)$ is the degree of modulation, and $E_{\omega,0}$ the amplitude of the THz-field of frequency $\omega (2\pi \cdot 3.3\,\mathrm{THz})$ respectively. The modulation of the Bloch oscillation causes a slowing down of the electron drift along the superlattice axis.

A detailed theoretical treatment, which will be published separately, shows that the observed maximum reduction of the dc current corresponds to a degree of modulation of ~ 0.1, for a THz-field of 3 kV/cm compared to a dc field 10 kV/cm. An ac field amplitude comparable to the dc field leads to sizeable reduction of the current through the superlattice. An ac field amplitude large compared to the dc field ($\mu > 1$) is expected to result in an almost complete suppression of the dc current.

The theory also shows that for THz-frequencies larger than the Bloch frequency ($\omega > \omega_B$), the maximum current reduction is expected for the voltage of maximum dc current – as observed in our experiment. It also follows from the theoretical analysis that at smaller frequencies ($\omega < \omega_B$) the frequency modulation of the Bloch oscillation leads to a field induced current reduction that is strongest at voltages of strong current changes, as it is well known for conventional radiation detection by use of systems, like the Schottky diode, having nonlinear current-voltage characteristics.

Our results demonstrate that a quantum mechanical oscillator, consisting of an electron moving almost ballistically across many superlattice periods, can have a strong interaction with a THz-field and that this interaction is observable for electrons in a superlattice structure at room temperature. An application, indicated by our experiment, is the detection of THz-radiation with ultrafast speed of the order of the relaxation time (10^{-13} s) and with very high sensitivity. The THz-field induced reduction of the dc current is a new quantum phenomenon based on the ballistic motion of electrons through tunnel barriers and on Bragg reflection occurring when the accelerated electrons reach the energetic top of the allowed miniband (Fig. 4). Our results show that this quantum effect is well observable at room temperature.

In conclusion, we have shown that exposing a superlattice Bloch oscillator to an intense THz-field can lead to a strong current reduction due to a dramatic change of the dynamics of the Bloch electrons in the superlattice, with quantum effects well observable at room temperature. Our experiment demonstrates that THz-radiation is most suitable to study the exciting phenomenon of Bloch oscillations.

We have shown that the superlattice Bloch oscillator can exhibit ultrafast response to THz-radiation. This result opens a new development in the field of THz-electronics: The superlattice Bloch oscillator is a new device suitable for application as passive and active electronic device with nonlinear response of the conductance to THz-fields. As a *passive* device it can be used as an ultrafast detector for THz-radiation, as already demonstrated, but probably also for the detection of THz-radiation by frequency mixing, by frequency down-conversion and for frequency multiplication. At high radiation power the THz-induced current reduction is expected to be as large as the total dc current giving rise to a full suppression of current. In this sense the superlattice Bloch oscillator would act as a current switch operated by incident THz-radiation. By applying a probe technique the device could perhaps be used for the analysis of picosecond THz-radiation pulses. As an *active* device the superlattice Bloch oscillator should be suitable for amplification as well as generation of THz-radiation [11] and, due to its parametric properties, also as parametric oscillator.

One of us (A. A. I.) would like to thank the Deutscher Akademischer Austauschdienst (DAAD) for financial support. The work was supported by the Bayerische Forschungsstiftung through the Bayerischer Forschungsverbund Hochtemperatur-Supraleiter (FORSUPRA).

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