By extending Eqn (29) we obtain the total power of the N-well structure,

$$P(N) = N\,\frac{2\tilde{Q}}{9}\,, \tag{33}$$

i.e., is proportional to the number of wells N.

6. Conclusions

In this work we have proven that coherent generation is possible in a structure containing any number of wells in the absence of dissipation processes. As is known, the emission of a photon requires decay, which in large systems is due to interaction with phonons. In the structure studied, decay is due to the exit of electrons from the lowest level of the rightmost well. The stationary interband current 'transmits' this decay to all the wells and causes the emission of photons in each well. Electrons delivered by resonant tunnelling make N transitions from upper to lower levels, retain their phase in doing so, and this process is independent of level population. Hence, amplification and generation in such a structure are bulk phenomena, unlike the non-coherent situation [5]. The total generation power is proportional to the number of wells N.

As found out in the present study, there are a number of requirements for the generation to be effective: the resonance condition for each of the wells, choosing the optimal energy of the supplied electrons, a narrow enough electron energy distribution ($\Delta\varepsilon$), and, finally, coherence conditions for the electronic subsystem.

It is shown that these requirements can be met in superlattices of quantum wells and wires and, especially, in quantum dot superlattices.

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Transport in weak barrier superlattices and the problem of the terahertz Bloch oscillator

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1. Introduction

The subject matter of this work is the transport properties of weak barrier semiconductor superlattices and whether these

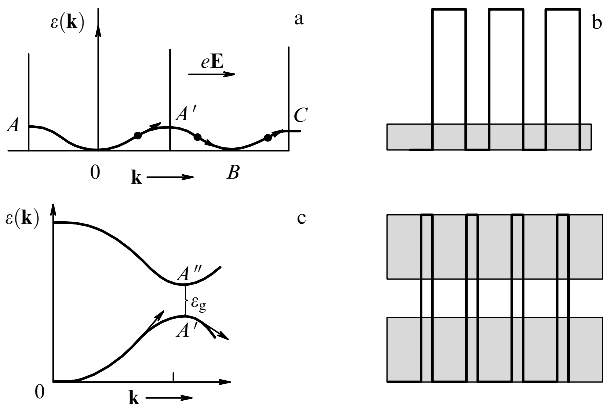

Figure 1. Superlattices with wide (b) and narrow (d) forbidden bands; (a) shows Bloch oscillations, and (c) shows the Zener breakdown.

superlattices can be used as a basis for creating the terahertz Bloch oscillator. Because of interminiband tunneling occurring in strong fields, the current is a growing function of the field. At the same time, in such superlattices tunneling and Bloch oscillations can lead to dynamic negative differential conductivity in the terahertz frequency range. It is pointed out that such a system is a no-inversion laser because the laser transition occurs between equally populated (Wannier–Stark) levels. Monte Carlo calculations for weak barrier n-GaAs–GaAlAs superlattices are presented which show that dynamic negative conductivity can exist in the frequency range of 1–7 THz for superlattices with moderate mobility at 77 K. The first experimental results on the transport properties of such superlattices are presented.

The idea of a Bloch oscillator (or generator) dates back to the work of Bloch (1928), Kroemer (1954), Keldysh (1962), Esaki and Tsu (1970), a.o., and is based on the following argument (see also Ref. [1]). If an electric field E applied along an axis of a semiconductor superlattice (SL) with period d is strong enough that an electron moves nearly unscattered between Brillouin zone boundaries ($A - A'$ in Fig. 1a) within one energy band, then an electron performs Bloch oscillations (BOs) at the (Bloch) frequency

$$\omega_{\mathrm{B}} = \frac{eEd}{\hbar}\,.$$

Taking $E = 3$ kV cm^{-1}, $d = 150$ Å we obtain the frequency $f_{\mathrm{B}} = \omega_{\mathrm{B}}/2\pi = 1$ THz. This frequency is continuously tuned by the applied electric field, creating prerequisites for developing a universal tunable radiation source (generator) in the terahertz range. Clearly, the fact that oscillations exist does not guarantee that they can be used for radiation generation purposes. It is negative conductivity near the Bloch frequency which makes the generator.

Negative conductivity is a traditional topic in the study of transport in semiconductor superlattices in the presence of strong electric fields (see, for example, a review in Ref. [2]). Most studies in this area consider transport *in superlattices with strong barriers and wide forbidden* (*mini*) *bands*. In this case Bloch oscillations in strong electric fields actually involve transport within one miniband only as shown in Fig. 1a. Negative differential conductivity (NDC) in such systems occurs in the frequency range from $\omega = 0$ to ω_{B} (Ktitorov, Simin, Sindalovskiĭ [3], Fig. 2b). A Bloch oscillator (generator) might look as follows (Fig. 3a). On a conducting

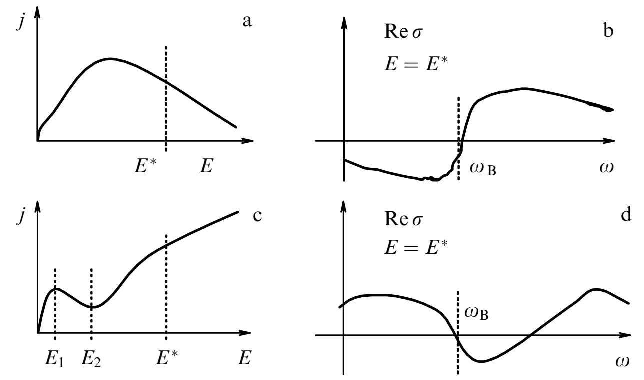

Figure 2. (a, c) Schematic current – voltage characteristics and (b, d) differential conductivity as a function of the frequency for the indicated value of electric field E^* for a superlattice with (a, b) narrow allowable and (c, d) narrow forbidden minibands; ω_B is the Bloch frequency. Characteristic fields for the onset of static NDC (E_1) and for the transition to interminiband tunnelling (E_2) are shown.

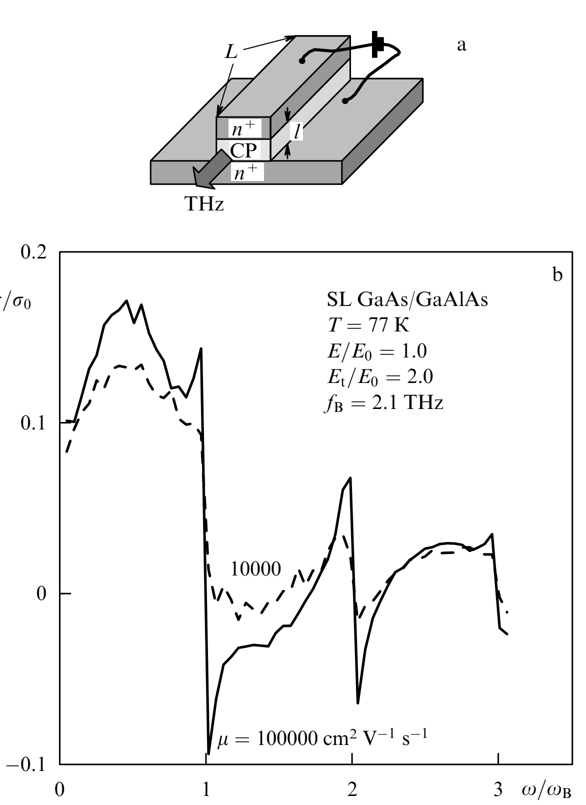

Figure 3. (a) Schematic of a Bloch oscillator. (b) Dimensionless differential conductivity in a field of about 6 kV cm^{-1} near the Bloch frequency $f_B = \omega_B/2\pi = 2.1$ THz, from model calculations for superlattices with a period of 150 Å (136 Å GaAs and 14 Å $Ga_{0.9}Al_{0.1}As$) with high and low bulk mobility μ.

substrate (n^+) an SL of thickness l is grown, on top of which a second, strongly conducting region n^+ is overgrown. From such a structure a strip of length $L = n\lambda/2$ (λ is the wavelength for the Bloch frequency in the strip, n being an integer) is etched. It is this *strip line* $n^+ - SL - n^+$ (substrate) with a voltage applied to it (as shown in Fig. 3a) which forms a Bloch generator, its resonance electrodynamic system being an (open) segment of the strip line an integer number of half-waves in length. The SL thickness l (the number of SL periods is N) is chosen from the condition that the decay of the strip mode in the n^+ 'rims' is less than its amplification due to NDC in the SL. The negative differential conductivity in an SL is not large: it does not increase with an increase in the quality factor of the Bloch resonance and has a value of the order of the static conductivity (cf. Refs [3] and [4, 5]). This is ultimately due to the fact that the Bloch generator is a non-inversion laser (see below). Therefore the excitation of a strip mode requires that an SL consist of a large number (200 or more) of periods. Importantly, a uniform electric field must be maintained in such an SL. Unfortunately, in narrow-miniband SL transport, in addition to the near-Bloch-frequency NDC, low-frequency NDC also exists, due to the descending portion of the $I-V$ curve (Fig. 2a). In 'thick' enough SLs (i.e., in ones with a large number of periods — as needed for producing a Bloch generator, see above), static NDC leads to the formation of domains (non-uniform distribution of electric field), preventing the existence and study of BOs and destroying NDC in strong electric fields at a frequency of the order of ω_B. This is why a narrow-gap SL terahertz oscillator has not yet been created. The only recently reported microwave SL generator ($f \sim 150$ GHz) functions in a Gunn-diode manner due to strong-field domains moving in the structure (presented in the talk by P S Kop'ev et al. at this session).

2. Weak barrier superlattices

NDC at low frequencies is due to the descending portion of the $I-V$ curve. The descending portion can be avoided, though, by considering transport in which many minibands are involved. This requires *a superlattice with weak barriers and narrow forbidden minibands*, a situation in which electric-field-induced interminiband transitions (or tunneling) — i.e., the Zener breakdown, see Figs 1c, d — play an important role. It would appear that BOs and (dynamic) NDC at $\omega \approx \omega_B$ will exist in this case as well (Fig. 2d). Theoretical work along these lines was performed long ago by Romanov and Orlov (see, for example, Ref. [6]), who considered situations in which dynamic NDC (DNDC) occurs at frequencies near the Bloch oscillation frequency and its harmonics. This work did not receive further development, however.

The present talk discusses the transport properties and possibility of DNDC in GaAs – GaAlAs SLs with narrow forbidden minibands under conditions which involve interminiband tunneling and the (rapid) return of electrons to the lower miniband due to the emission of optical phonons. The talk is based on the theoretical studies of Refs [4, 5] and also relies on the first experimental data recently obtained for such SLs. In Refs [4, 5] it was demonstrated that under the condition

$$\nu < \omega_B P_t < \omega_B < \nu_0 \tag{1}$$

DNDC can develop in the system. Here ν is the scattering frequency in the lower miniband, $P_t = \exp(-E_t/E)$ is the probability of tunneling to the second miniband, $E_t = \pi^2 \varepsilon_g^2 / 4\varepsilon_B ed$ is a characteristic field, ε_g is the minigap, ε_B is the mid-energy of the (narrow) gap, $\varepsilon_B \geqslant \hbar\omega_0$ being the optical phonon energy, and ν_0 is the characteristic frequency of the optical phonons emitted by an electron. The mechanism of DNDC here is the bunching of electrons in the SL's Brillouin zone, caused by the strong (exponential) electric-field dependence of the interminiband tunneling probability. For the combined action of the static, E_0, and alternating,

$E_{\sim}\cos\omega t$, electric fields, the tunneling probability $P_{\mathrm{t}} = \exp\left(-E_{\mathrm{t}}/E_0 + E_{\sim}\cos\omega t\right)$ (and hence, say, the electron lifetime in the lower miniband) depends on the phase of the alternating field ωt, making the electrons preferentially bunch — analogous to the (spatial) bunching in vacuum klystrons and impact avalanche transit time diodes — in different regions of the Brillouin zone depending on the field frequency – Bloch frequency relation. As a result, NDC develops at a frequency above the Bloch value [4, 5].

3. Superlattice conductivity as a result of transitions between Wannier – Stark levels

In a quantum picture Bloch oscillations correspond to transitions between the states of the Wannier – Stark ladder (Fig. 4). In a uniform electric field these levels are equally populated, so that the system has no population inversion, and the real part of the conductivity at exactly the transition frequency vanishes (which is precisely what a kinetic equation calculation yields). The shape of the entire transition line near the Bloch frequency depends on the type of process which determines the broadening of the Bloch transition line and which combines photon absorption (emission) with the line broadening process (scattering and a uniform electric field). Thus far quantum calculations of the transition line have not been performed for this case. The available quasi-classical kinetic equation calculations yield the following picture. Negative conductivity develops at frequencies for which, for any chosen Wannier – Stark level, the probability of a transition up is lower than the down transition probability. This, in its turn, depends on the energy deficit $\Delta\varepsilon$ which a Bloch electron receives (or loses) when interacting with an alternating field in the presence of the broadening. If $\Delta\varepsilon < 0$, as is the case for a superlattice with narrow allowed minibands (left side of Fig. 5) — when the broadening is determined by scattering, which takes away the energy of the kinetic motion of a Bloch electron (for example, when the electron energy is translated into motion along the superlattice layers) — then negative conductivity appears at frequencies $\omega < \omega_{\mathrm{B}}$. Indeed, note that in a transition down the quantum $\hbar\omega$ adds to the energy $|\Delta\varepsilon|$ giving a sum which is comparable with $\hbar\omega_{\mathrm{B}}$ and so 'stretches down' to the next lower Wannier – Stark level. Conversely, for a transition up $|\Delta\varepsilon|$ is subtracted from $\hbar\omega$, and the difference only moves away from the upper Wannier – Stark level. That is, here transitions down dominate at lower frequencies.

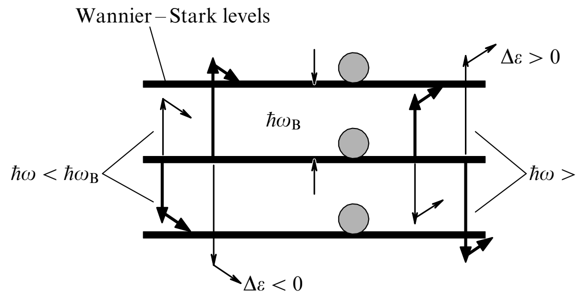

Figure 5. Schematic diagram of transitions between Wannier – Stark levels near the Bloch frequency for different signs of the energy $\Delta\varepsilon$ which transition line broadening processes supply to an electron.

In the presence of interminiband tunneling, when a Bloch electron gains energy in the field ($\Delta\varepsilon > 0$, see Fig. 5, on the right), negative conductivity appears at frequencies $\omega > \omega_{\mathrm{B}}$ because at a transition down $|\Delta\varepsilon|$ is subtracted from $\hbar\omega$, and the sum stretches to the next lower Wannier – Stark level. For a transition up, $\hbar\omega$ adds to $|\Delta\varepsilon|$, and the sum only moves away from the upper Wannier – Stark level. Thus, in this case transitions down dominate at high frequencies. This picture, to repeat, emerges from quasi-classical calculations within the framework of the kinetic equation; actual quantum calculations are of much interest but are not available, however. In particular, the effect of intersubband tunneling on transitions between Wannier – Stark levels is a kind of Franz – Keldysh effect, whose analysis is undoubtedly of interest.

We re-emphasize that our treatment is, strictly speaking, limited to the case in which scattering in the upper miniband is strong: an electron there emits an optical phonon before it can perform a Bloch oscillation [see the last condition in Eqn (1)]. Therefore the Wannier – Stark levels here are strongly broadened and are not shown in the upper miniband in Fig. 4. If this is not so, a kinetic equation calculation with tunneling as one of scattering mechanisms is apparently invalid. In this case already a quasi-classical wave packet starts to break up [7], and the analysis and modeling of this situation in the presence of real scattering processes is an interesting challenge to the quantum theory of transport.

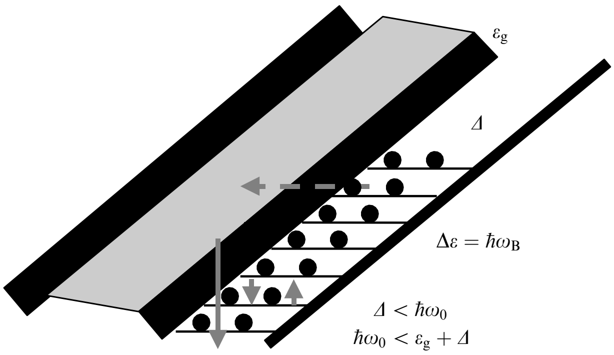

Figure 4. Wannier – Stark ladder in a superlattice. Shown are Wannier – Stark levels in the lower miniband, their equal population, and the processes involved in the transport: intersubband tunneling (dashed arrow) and the emission of optical phonons (solid arrow). Wannier – Stark levels in the second miniband are not shown; they are assumed to be 'washed out' by optical phonon emission processes.

4. Numerical and actual experiments

Our transport models (the $I - V$ curve and the differential conductivity) are conducted in the framework of a kinetic equation in which tunneling is treated as a scattering process (as it can because it is virtually always followed by an actual scattering event, the emission of an optical phonon). The simulation [4, 5] revealed that in superlattices of 140 Å GaAs and 10 Å $\mathrm{Ga}_{1-x}\mathrm{Al}_x\mathrm{As}$ with x from 0.1 to 0.2, DNDC can exist in the absence of static NDC in the range of 1.0 to 7.0 THz and that at $T = 77$ K DNDC persists at very moderate mobilities of $\sim 10{,}000 - 20{,}000$ cm^2 V^{-1} s^{-1} (Fig. 3b). This paves the way for constructing the Bloch generator. As has been said above, such a generator must be a diode consisting of an SL layer sandwiched between two contact n$^+$ regions which also serve as strip line, or resonator (Fig. 3a). The thickness of the superlattice layer is estimated by comparing losses in the strip line with the amplification due to NDC. The amplification and the strip line losses were estimated by taking the calculated [5] and measured [8] values, respec-

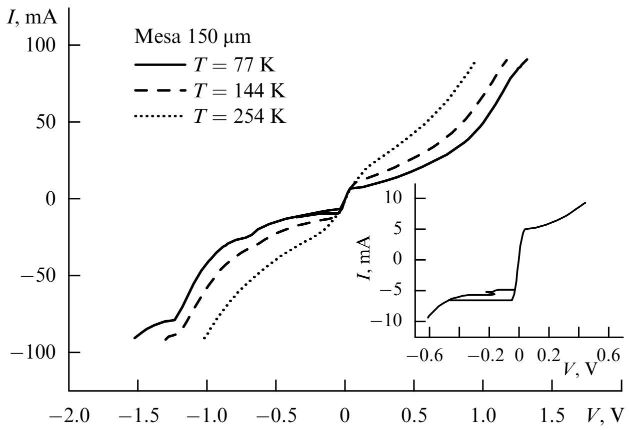

Figure 6. The $I-V$ curve of a 195-Å-period GaAs – GaAlAs superlattice showing the transition from Bloch oscillations to the Zener tunneling. Inset: low-voltage low-current region displaying hysteresis, N-shaped $I-V$ curve, and the transition to tunneling.

tively. From these estimates we find that the SL must be 5 – 10 μm (350 – 700 periods) thick. The number of periods can be reduced by a factor of three by employing the two-dimensional plasmon mode as done in the recently-created terahertz quantum cascade laser [9 – 11]. Such a generator will supposedly operate in a continuous mode at a temperature of 78 K, which is beyond the reach of cascade terahertz generators [11].

We have started experimental studies aimed at the creation of a Bloch generator. Below are the very first, preliminary results of the studies. On a conducting n^+ substrate, an unintentionally doped weak-barrier SL containing hundred 195 Å periods (185 Å GaAs and 10 Å $Ga_{0.9}Al_{0.1}As$) was grown, on top of which a heavily doped n^+ layer was overgrown. From this structure mesadiodes of various diameter were fabricated, for which $I-V$ curves were measured at various temperatures in the continuous regime using 100-Hz sinusoidal current as shown in Fig. 6. The SL period differs from the (optimum) value used in the calculations. For the value grown, the forbidden band is positioned at half the optical phonon energy — instead of at exactly this energy as is the case for the optimum superlattice. Nevertheless, the $I-V$ curve clearly demonstrates the transition from one-miniband transport (with static NDC manifesting itself in an $I-V$ curve hysteresis at one polarity) either to interminiband tunneling (with increasing current) or — if the temperature is increased — to the disappearance of all these effects because of thermal excitation to the upper minibands. Our nearest future plans include measuring as-yet-unobserved BO-related spontaneous radiation on this structure. Estimates show that spontaneous Bloch radiation can be intense enough for it to be observed and its spectrum measured. The growth of superlattices with the structure of a two-dimensional plasmon, similar to those studied in Refs [7, 8], is also planned.

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