Terahertz sources based on dynamic negative differential conductivity due to hot electron bunching in momentum space.

A. Andronov, I. Nefedov and A. Sosnin
Institute For Physics of Microstructures Russian Academy of Sciences
Nizhny Novgorod GSP-105 603600 Russia, andron@ipm.sci-nnov.ru

Introduction. Emergence of quantum cascade lasers permits now to cover by semiconductor sources the high frequency part of the Terahertz range. The low frequency part (0.5 – 10 THz) is still out of the semiconductor sources One possible approach to the sources for this range is to use the dynamic negative differential conductivity (DNDC) due to electron bunching in the momentum space. Such sources could be based on the two different mechanisms discussed for several years (and even decades) now [1-3]: Optical Phonon Transit Time Resonance (OPTTR) in the bulk and the Bloch oscillations (BO) under multiminiband transport in superlattices. Recently the breakthrough in the utilization the bunching takes place: **observation of stimulated emission in millimeter wave range in InP due to the OPTTR** [4]. And this report gives short discussion of DNDC under OPTTR with recent simulation of its possibility in the Terahertz range in GaN [5] and concentrated on our recent results on discussion and simulation of DNDC under multiminiband superlattice transport and feasibility of its utilization in the Terahertz BO. These results are a substantial extension of the work [6].
It is worth noting that not long ago H.Kroemer discovered existence of the DNDC in the standard (single miniband) superlattice transport [7]. He pointed out that the NDC arises as a result of electron bunching in the momentum space (in the superlattice Brillouin zone) produced by joint action of the both ac and dc electric fields. The DNDC implies that while (static) current-voltage (j-E) curve has no negative slope for the ac field for the high enough frequency around ω^* conductivity $\sigma(\omega)$ is negative (Fig 1). The current-voltage curve without negative slope means that there is no domain formation and one can have electronic system with homogeneous electric field of any length with negative high frequency ac conductivity: a dream of microwave engineer during the Gunn phenomena development times!

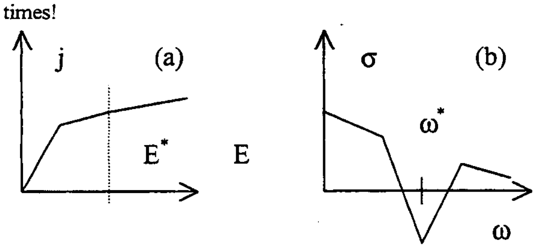

Fig 1. Current-voltage curve (a) and differential conductivity versus frequency (b) for the case of dynamic negative differential conductivity for electric field $E = E^*$

Kroemer considered large signal negative conductivity which is alike LSA mode in the Gunn diodes. At small (linear) signal in single miniband superlattice transport there is no DNDC what hinder advance of single miniband transport bases superlattice sources toward the Teraherz range. Though small signal DNDC was discussed long ago (see e.g. [8]) semms it is likely that DNDC is not widely known. And the mentioned above breakthrough: observation of millimeter wave emission in InP due to the OPTTR DNDC [4] (Fig 2) and simulation of the OPTTR DNDC in GaN [5] give strong empetus for general discussion of the utilization of the effects in a Terahertz source.
And this report gives: 1) Short discussion of the old and recent results on OPTTR DNDC in the bulk. 2) Recent results of the present authors on simulation of the DNDC under high electric field transport in narrow minigap superlattices which demonstrate **feasibility of the Bloch oscillator** at frequencies up to 2 THz.. 3) Discussion of the sketches of the source design based on the above effects and first attempt to observe emission under BO in the superlattices. .
Optical Phonon Transit Time Resonance. In a semiconductor with simple parabolic band and moderate doping level and at low temperature the following situation can occur. Scattering rate at electron energy åbelow an optical phonon energy ž ù$_0$ (the passive region) is due to impurity and acoustical phonon scattering and is low: í í $_p$. While at å> ž ù$_0$ (active region) the rate rises steeply and is about that of characteristic scattering rate of optical phonon í$_0$ with í $_0$ » í$_p$. Under such situation in moderate electric fields

$$E_p < E < E_0 ,$$

where $E_p = í_p\, p_0/e$, $E_0 = í_0\, p_0/e$ are characteristic fields and p_0 is momentum at an optical phonon energy: $(p_0)^2/2m = ž\, ù_0$, electrons move almost freely in the passive region ($p < p_0$) from p 0 up to p_0 and quickly return to p 0 after optical phonon emiss ion in the active region ($p > p_0$). In other words they perform repetitive motion in the momentum space with characteristic OPTTR frequency

$$ù_E = 2ðeE/p_0 \qquad (2)$$

Sketch of electron movement and one dimensional distribution versus momentum (p_E) along electric field is given in Fig 3. The distribution is shown for the two fields: E_1 and E_2 with $E_p < E_1 < E_2 < E_0$ .We see that for the higher field (E_2) electrons penetrate higher in the active region and take more time in free movement in the field. As a result there is no static NDC.

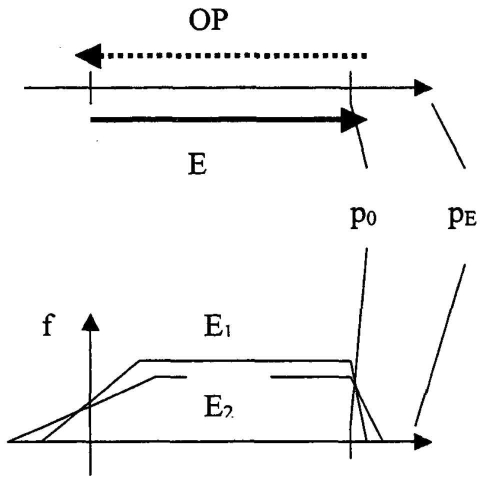

Fig 3. Sketch of electron movement and distribution under optical phonon transit time . situation

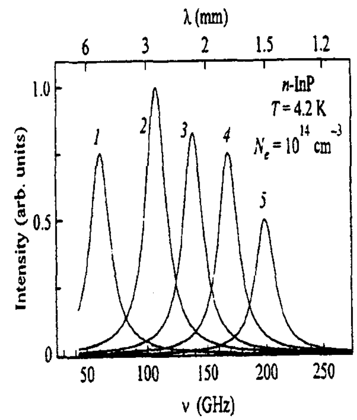

Fig. 2. Spectra of the detector signal (Schottky diode) for different electric fields: E = (1) 200, (2) 250, (3), 300, (4) 350, and (5) 400 V/cm.

At the same time under the action of both dc and ac fields ($E = E_{dc} + E_{ac}\cos ùt$) depending on the phase ùt of ac field total electric field change, changing penetration of electrons in the active region herewith changing the time of free movement (i.e. time of transit through the passive region). Such separation in dynamics of electrons versus their phases in ac electric field leads to the bunching of electrons in the momentum space and to a possibility of DNDC. Simplified calculation of the DNDC were performed in [1,2]. Then the DNDC was discovered in the Monte-Carlo simulation in InP in millimeter wave range [3] and recently the millimeter wave stimulated emission due to the DNDC in InP was observed [4] (Fig 2) and the Teraherz DNDC due to the OPTTR was simulated in [5].

Superlattice transport with electron bunching due to interminiband tunneling. Electron bunching effects and DNDC can occur also under superlattice transport due to interminiband (Zener) tunneling [6]. We consider the case of a superlattice with lowest miniband below an optical phonon energy and narrow minigaps (Fig 4). Appropriate superlattice consists of 150 A of GaAs a and 10A of $Ga_{1-x}Al_xAs$ with x in the range 0.05 –0.2 for which the Monte-Carlo results will be given below. In such superlattice with moderate doping and at low temperature in high electric fields the following transport processes take place: the BO with frequency

$$ù_B = 2ðeE/2p_B = eEd/ž, \qquad (3)$$

p_B is the electron momentum on the superlattice Brillouin zone boundary, and tunneling through narrow minigap to the second miniband with quick returning back to the first miniband due to optical phonon emission. Probability of interminiband tunneling may be written as

$$P_t = \exp(-E_t/E),\quad E_t = ð^2 \,å_g^2 /4\, å_B\, ed, \qquad (4)$$

Here E_t is the characteristic tunneling field. An electron approaching boundary of the Brillouin zone at p_B by freely moving in electric field can follow the two routes: it can perform the Bragg scattering to ($-p_B$) and continue the Bloch oscillation or it can perform the interminiband tunneling to the second miniband and then return to the first miniband after emission of an optical phonon in the second miniband (Fig 4). Probability of the Bragg scattering is $P_B = 1 - P_t$. It is important that P_t and P_B strongly dependon electric field. As a result in the case both dc and ac fields are presented the probabilities of the both processes depend on the phase of the ac field, and alike the OPTTR electron

bunching occur which can result in DNDC. We put the probability in the standard kinetic equation and perform calculation of both
current – voltage curves and differential conductivity for the two cases: GaAs (simplified two valley

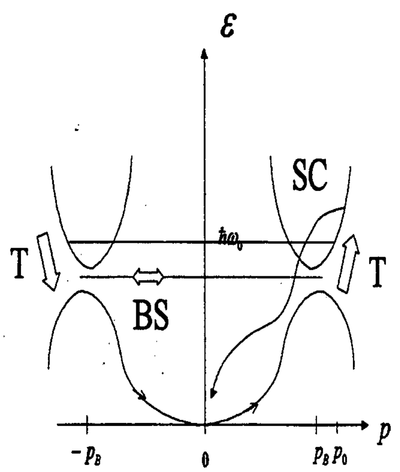

Fig 4. Scheme of the two lowest minibands with transport processes: the Bloch oscillation (arrows), tunneling (T), the Bragg scattering (BS) and optical phonon emission (SC) shown

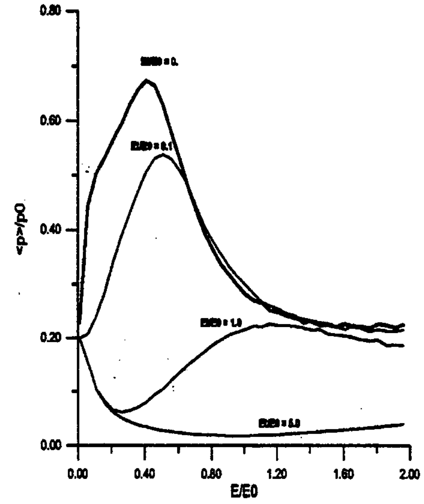

Fig 5. Simulated normalized drift momentum versus normalized electric field for different values of the tunneling field E_t

model of the band structure and scattering: the upper valleys play no role in the effects discussed) with introduced the Bragg scattering and the tunneling characterized by the tunneling field E_t and idealized one dimensional model without scattering at å< ž ù$_0$, with the Bragg scattering and the tunneling and instantaneous optical phonon emission. Result of simulations are given in Fig 5 and Fig 6. In the Fig 5 the average drift momentum <p> ratio to p_0 is given versus normalized electric field for different characteristic tunneling field E_t . In the simulations position of the Brillouin zone boundary p_B is chosen equal to 0.8 p_0 what correspond to the period (160A) of the GaAs-AlGaAs superlattice mentioned above: 150A of GaAs and 10A of $Ga_{1-x}Al_xAs$. Value of the alloy composition x=0.1 correspond to the Tunneling field $E_t = E_0$. Changing x value in the range 0.05 – 0.2 changes the tunneling field in the range shown in Fig 5 . We see that increase of the "strength" of superlattice potential (increase of x and herewith E_t) results in transformation of the curve from that of the bulk for $E_t = 0$ to the one of single miniband transport (for $E_t = 5.0$).In the latter case the rising portion of the curve in the low fields (with positive differential conductivity) is not seen due to inappropriate scale. We perform also simulation of frequency dependence of the differential conductivity ó and present here results for E/E_0 =0.5 for: E_t/E_0 = 0.1, 1.0 and 5.0. The conductivity at $E_t/E_0 = 0.1$ is positive in the whole range with fall in its value at of about the Bloch frequency ù$_B$. For E_t/E_0 =5.0 standard single miniband behavior is observed: ó < 0 at ù < ù$_B$ and ó > 0 at ù > ù$_B$ The conductivity for $E_t/E_0 = 1.0$ is given in Fig 6. At low frequency conductivity is positive (there is no static NDC - Fig 5) while nearby by the Bloch frequency and its harmonics there are regions on DNDC. The dotted curve in Fig 6 is results of the one dimensional model simulation. The Bloch frequency (angular) in this case corresponds to frequency of about 1 THz. (ë = 250ì m)

Possible sources schemes. The schemes of the sources are shown in Fig 7 for all three discussed above cases. The case A is already accomplished pulsed millimeter wave oscillator in bulk n-InP at 4.2K [4] (Fig 3). The oscillator uses the total reflection cavity modes in the InP crystal. The case B is the Terahertz oscillator which could be build basing on simulation results given in [5]. It consists of sapphire ($Al_2 O_3$) substrate and a GaN layer and presumably should use also the total reflection cavity modes in the substrate – layer system. Simulated amplification coefficient at 1 THz and 78K is of about 20 cm^{-1} [8] while losses in Terahertz range in sapphire can be quite low. What should permit to use very thin GaN layer in the oscillator that could provide high repetition rate or even CW operation. Thee case C is the BO based on the discussed DNDC. It consists of the superlattice (SL) layer sandwiched between two n^+ contact n-GaAs regions which form also strip waveguide. To estimate width of the superlattice layer (number of superlattice periods) needed we should compare the strip waveguide

losses with amplification coefficient in the superlattice. To estimate the latter we take the value of negative conductivity given in Fig 7 for ù ù$_B$: ó 0.05 ó$_0$ and take the electron concentration N = 10^{16} cm^{-3}. Though we simulate the conductivity without impurity scattering the above N value is not high and also simulation shows that the DNDC survives up to T =150K where such level of impurity is not crucial for sure. For these values we have amplification coefficient 100cm^{-1}. For estimate of the strip waveguide losses we can take data measured in [9] at ë =75 ìm: losses for 10 ìm wide strip wavguide is of about

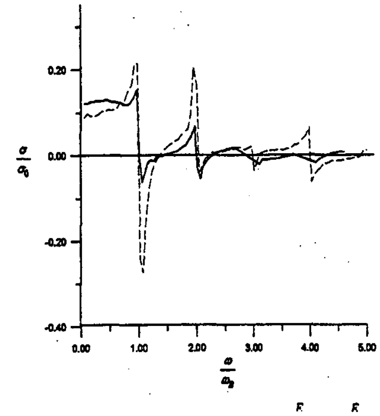

Fig 6. Simulated differential conductivity In the GaAs-GaAlAs superlattice for $E/E_0 = 0.5$ and $E/E_t = 1.0$; ó$_0$ =2e^2N/mí$_0$. Dashed line is the model calculations

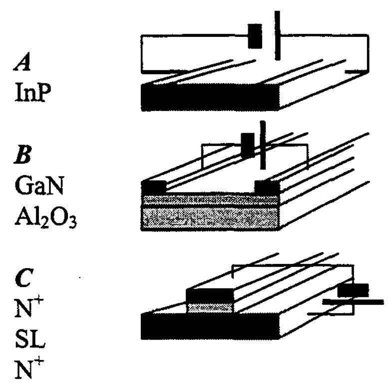

Fig 7. Sketches of the sources based on DNDC n momentum space: InP oscillator –A; GaN on Sapphire – B, GaAs-GaAlAs superlattice - C

50 cm^{-1}. The losss should follow ù$^{1/2}$ law. For our case ë =250 ìm we can take value of waveguide losses as 30 cm^{-1}. This figure can be even improved if one uses heavily doped (than in [9]) contact regions. From these estimates we can conclude that the Bloch oscillator with superlattice region width 5 – 10 ìm (500 – 700 periods) should work. It should be operational at 78K in CW mode also.

Conclusion. We present experimental and simulation data (both published and original) which give strong support for the emergence of Terahertz sources based on DNDC due to electron bunching in momentum space. We will present more simulation data on the Bloch oscillator for both GaAs and InP based superlattices and hopefully experimental results on the Bloch Oscillation Terahertz emission in GaAs-based superlattices at the Symposium. The authors are indebted to Prof. Leonid Vorobjev for permission to reproduce here data from [4].
This work is supported by Russian State Program "Physics of Microwaves" (Project 3.17).

References

[1] V.L.Bonch-Bruevich and M.A.El-Sharnuby, "To the theory of absorption of electromagnetic wave by hot electrons in semiconductors", Vest. Mos. State Univ., v.13, ser.3, N5, pp 616-619, 1972.
[2] A.Andronov and V.Kozlov Dynamic negative conductivity of hot electrons due to strong electron-optical phonon interaction", JETF Lett., v.17, 87,1973.;
[3] E.Starikov and P.Siktorov , " Simulation of optical phonon due dynamic negative conductivity in n-InP",Litov.Fiz.Sb., v.32,N 4, p471, 1992.
[4] L.E.Vorobjev, S.N.Danilov et al, " Generation of Millimeter Wave Radiation due to Electric-Field-Induced Electron-Transition Resonance in InP", Pizma v ZETF, v.73, N 5, p 253-257, 2001
[5] E.Starikov, P.Siktorov et al, " Simulation of optical phonon due dynamic negative conductivity in GaN up to the Terahertz range", IEEE Trans.Electron Devices, v. 48, N 3, 2001.
[6] A.Andronov and I.Nefedov "Bloch Oscillations and DNDC under a Multiminiband Transport in Superlattices", Proc. 9th Inter.Conf. on Hot Carriers in Semicon., pp153-156, Plenum Press NY, 1996.
[7] H. Kroemer, "Large amplitude oscillation dynamics and domain suppression in a superlattice Bloch oscillator", cond-mat/0009311
[8] J.C.McGroggy and P.Gueret, "Dynamic Bulk Negative differential conductivity in semiconductors", Sol.St.eEectronoca,v.14, pp 1219-1224, 1971
[9] M.Rochat, M.Beck, J.Faist and U.Oesterle "Measurement of FIR waveguide loss using multisection single-pass technique", Appl.Phys.Letters, v. 78, N 14, pp 1967-1969, 2001